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EFFECT OF CYCLIC RELATIVE HUMIDITY ON THE LOAD DURATION BEHAVIOR OF STRUCTURAL LUMBER[1]

Kenneth J. Fridley[2]
Asst. Professor
Dept. For. & Nat. Resources
Purdue University
West Lafayette, Indiana, USA

R. C. Tang
Professor
School of Forestry
Auburn university
Auburn, Alabama, USA

Lawrence A. Soltis
USDA-Forest Service
Forest Products Laboratory
Madison, Wisconsin, USA

Abstract

The effect of several moisture conditions on the load-duration behavior of structural lumber is presented. Select Structural and No. 2 grade Douglas-fir nominal 2 by 4 specimens were tested under a constant bending load in two cyclic and three constant relative humidity (RH) environments. Analyses of test results indicate a trend toward shorter times-to-failure in cyclic humidity conditions as compared to constant humidity conditions. The effect, however, was no more evident in the No. 2 grade specimens than in the Select Structural specimens. To predict the load-duration behavior, an existing damage accumulation model was modified to account for the affect of both constant and changing moisture contents on the long-term strength of structural lumber. The developed model was found to predict the observed behavior quite well.

Introduction

A significant amount of load-duration research on structural lumber has been and is being conducted at various institutions worldwide (e.g., 1, 2, 3, 9, 13, 14). These studies typically were conducted at constant, or nearly constant, environmental conditions. However, wood is used structurally in ever changing environments. From past creep-rupture experiments on small clear samples of wood (17, 18), the need to include environmental factors in models which predict the load-duration behavior of structural lumber is readily apparent. The effect of temperature on the load duration behavior of lumber has been investigated (5, 6).

This paper addresses the effect of several relative humidity conditions on the load-duration performance of structural lumber. The mechano-sorptive effects apparent in the creep behavior of structural lumber (e.g., 11) will be shown to be also present in the load-duration behavior.

Test Program

Materials

Select Structural and No. 2 grade nominal 2 in. x 4 in. x 8 ft. (3.81 cm x 8.89 cm x 2.44 m) Douglas-fir beams were chosen for this investigation. The lumber was surfaced green and kiln-dried using a mild conventional schedule. The lumber then was stored in an environment of 73°F (22.8°C) and 50% RH, resulting in an average group equilibrium moisture content of approximately 10%. The lumber was evaluated for modulus of elasticity, strength ratio, warp, and predicted modulus of rupture. The lumber, after these evaluations, was sorted into groups of 25 such that for each grade, each group had similar distributions of modulus of elasticity, strength ratio, and predicted modulus of rupture.

Four groups (100 specimens) of each grade were ramp tested in the 73°F and 50% RH environment in edgewise bending at a rate of 300 lb./min. (136.08 Kg/min.) to estimate the static strength distributions within each group. Lognormal statistical distributions seemed to fit the observed strength populations reasonably well and are given as follows for Select Structural and No. 2 grade specimens, respectively:

$$f_{ult} = 6364 \exp(0.3682R) \qquad (1)$$

$$f_{ult} = 3224 \exp(0.3657R) \qquad (2)$$

In Eqs. 1 and 2, f_{ult}, is the ultimate static strength (modulus of rupture) in psi and R is the expectation of the normal order. The coefficients of the exponential terms in Eqs. 1 and 2 are

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[2] Formerly Research Associate, School of Forestry, Auburn University, Alabama, USA.

the median ultimate strengths in psi, and the coefficients on R are close approximations of the coefficients of variation(COV's).

Loading Apparatus and Instrumentation

Seven test frames were built to allow the simultaneous testing of 28 specimens in a computer-controlled environmental room. A simple span of 84 in. (2.134 m) was provided with load applied symmetrically 12 in. (30.48cm) about the mid-span using a cantilever and pulley system. Lateral bracing was provided at the supports only.

Mid-span deflections were read using rotary potentiometers. Times-to-failure and times-to-partial-failure were found by analyzing the deflection vs. time data. Also, elapsed timers were connected via microswitches to the beams. when the beams failed, the switches would stop the timers, thus yielding elapsed times-to-failure under constant load.

Procedures

Constant loads of 4104.5 and 2248.2 psi (28306.9 and 15504.8 Kpa) for the Select Structural and No. 2 grade lumber, respectively, were applied to the test beams. These loads were based on the 15th percentile of the static strength distributions (Eqs. 1 and 2) and are approximately double the allowable stress prescribed by the National Design Specification for Wood Construction (16) for these grades. Obviously, a trade-off exists between realistic loads and test time. These loads were expected to provide a 50% failure rate in approximately 7 weeks at a moderate constant relative humidity condition.

One group of each grade of material was tested in each of the following four environments: constant 35% RH, constant 95% RH, 24-hour 35% to 95% cyclic RH, and 96-hour 35% to 95% cyclic RH. Two groups of each grade were tested in a constant 50% RH environment. A constant 73°F was maintained in all the tests.

Prior to testing, the moisture contents of the beams were determined using an electronic resistance-type moisture meter and a map of all defects was made. The beams tested in the cyclic environments were preconditioned to 73°F and 35% RH, then brought into the testing chamber and loaded at the initiation of an environmental cycle. For the constant environment tests, the beams were brought into the testing environment, allowed to equilibrate, then loaded. Table 1 lists the average moisture contents of all specimens prior to load-duration testing.

Table 1. Moisture contents.

relative humidity (%)	moisture content (%) group average	moisture content (%) standard devitation
	Select Structural	
35	7.1	0.26
50	10.0	0.35
95	24.3	0.79
	No. 2	
35	6.9	0.27
50	10.0	0.40
95	24.0	0.85

The deflection vs. time data were printed out and times-to-partial-failures and times-to-failure were noted and compared to the data recorded by the elapsed timer. The testing continued until the last loaded beam had been loaded for at least seven weeks or until at least 50% of each group (i.e., 13 beams) had failed. Due to the 50% criterion, the testing time for the constant 35% RH condition had to be doubled to 14 weeks.

Model Development

Basic Damage Equation

Several damage accumulation models have been proposed to define the stress-dependent load-durationbehavior of structural lumber. Although differences are apparent in each of the models, they all predict a reduction in strength while under stress through time. Some researchers (1, 2, 4) include a stress threshold below which no damage accumulates. The existence of such a threshold is difficult to prove or disprove and is therefore the object of some controversy. The exponential model developed by Gerhards (7, 8) and Gerhards and Link (10) opted to neglect any such threshold. Since in this investigation the applied stress ratios accordingly high and hence the times-to-failure are relatively short, generally less than 7 weeks, the presence of a stress threshold would be impossible to establish or even estimate. Therefore, the existence of a stress threshold in structural lumber will not be acknowledged here.

The exponential stress-dependent damage accumulation model developed by Gerhards and Link (10) can be written as

$$d\alpha/dt = \exp(-A + B\sigma) \qquad (3)$$

where A and B are model constants to be determined from experimental data and s is the ratio of applied stress to the ultimate static strength determined from a conventional ramp test.

Moisture Effects

It is appropriate to introduce a dimensionless parameter related to the moisture content:

$$\omega = (M - M_0)/M_0 \qquad (4)$$

where w is the relative moisture content, M is the current moisture content of the lumber, and M, is a reference moisture content. The moisture content factor, w, is therefore equal to zero in a reference condition, which is defined as some typical or standard moisture content. In this study, M, is assumed as the moisture content at conditions of 73°F and 50% RH.

To account for moisture effects, an additional damage function can be introduced. Also, mechano-sorptive effects must be accounted for in the model. Therefore, the following arbitrary moisture-dependent damage function is introduced:

$$g(\omega) = \exp(C\omega + D\omega^2 + E|\dot{\omega}|t_\omega) \qquad (5)$$

where w is the time rate of change of the moisture factor, t_w is the time associated with the change in the moisture factor, and C, D, and E are model constants.

By assuming multiplicative damage functions (12) Eqs. 3 and 5 can be combined to yield the final form of the damage accumulation model which includes moisture effects:

$$d\alpha/dt = \exp(-A+B\sigma+C\omega+D\omega^2+E|\dot{\omega}|t_\omega) \quad (6)$$

where a is the applied stress ratio and is a function of the applied load and static strength at the reference moisture content. The moisture effects on the rate of damage accumulation are solely accounted for by the addition factors associated with the constants C, D, and E. This modification is quite similar to that used in the modeling of thermal effects on the load duration behavior of lumber (5, 6).

Application of Modifed

The difficulty now exists in the selection of an equation which can predict the moisture changes over time. The following equations are assumed to predict the actual averaqe moisture content factor of the lumber following an abrupt change in environmental conditions:

$$\omega_t = \omega_e + (\omega_i - \omega_e)\exp[-B_\omega t] \qquad (7)$$

where w_t is the average moisture content factor of the member at a time t following the change, w_e is the eventual equilibrium moisture content, w_i is the initial moisture content, and B_w is a constant associated with the time required to achieve moisture equilibrium. Obviously, B_w is dependent on the size of the member and can vary if the change in moisture content is positive or negative. However, Bw will be assumed constant for simplicity in modeling.

The damage model (Eq. 6) must be integrated for relevant mechanical and environmental load histories to predict time-to-failure. However, many histories may yield mathematically undefined closed-form solutions so approximate numerical procedures are employed.

Examining the simple case of constant stress and moisture, integration of Eq. 6 yields

$$t_f = \exp(A - B\sigma - C\omega - D\omega^2) \qquad (8)$$

or,

$$\ln(t_f) = A - B\sigma - C\omega - D\omega^2 \qquad (9)$$

where t_f is the time-to-failure under constant load and moisture content. This situation is especially convenient since linear multivariate statistical fitting procedures can be used to determine the model constants A, B, C, and D.

The integration of Eq. (6) for other stress histories and changing environments can become complex and possibly undefined as is the case of changing moisture content. Equation 7 can be used to model the average moisture content of a sample after an abrupt change in the environment. When Eq. 7 is substituted into Eq. 6, the resulting expression is quite lengthy. However, numerical integration procedures allow the evaluation of the expression for virtually any load or environmental history once the constants are known.

Results and Discussion

Moisture Contents in Cyclic Environments

Although the data are presented here as sets corresponding to certain humidity environments, data analyses and modeling procedures were conducted on a specimen by specimen moisture content basis. To predict the average moisture content of a specimen as the environment changes, the moisture contents of six sets of specimens were monitored daily through several environmental histories on an oven-dry weight basis. The specimens were 2-ft (61 cm) sections of Select Structural material and three specimens were included in each set. The data and exact environmental histories used for this study are given in Fig. 1. The data points are averages of appropriate specimen data and are in the form of the moisture factor w as defined by Eq. 4. The linea plotted with each data sot are best fit predictions using Eq. 7 with B_w determined using a nonlinear best fit procedure from all the single change data (four sets). Equation 7 can now be written as follows:

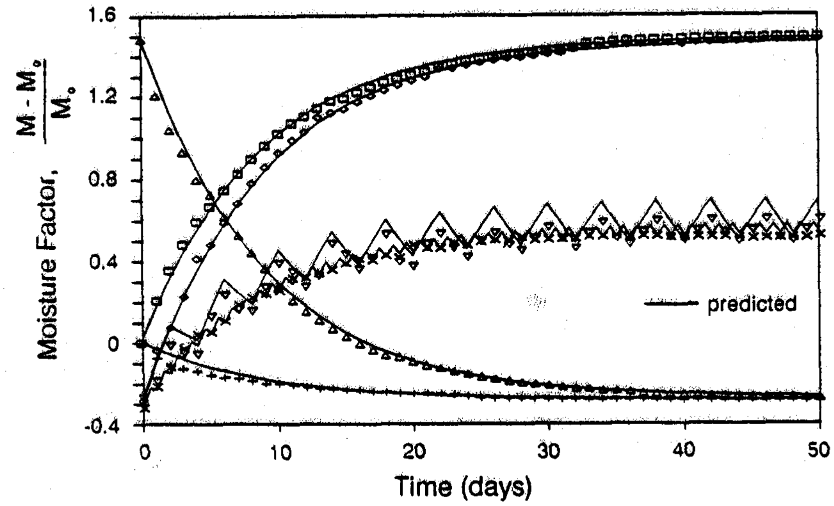
$$\omega_t = \omega_e + (\omega_i - \omega_e)\exp[-.0000785\, t_\omega] \quad (10)$$

where t_w is the time in minutes following the change in the environment. A standard error of the fit to the four single change data sets is7.9%.

Equation 10 was then used to predict the data Prom the two cyclic environments. Standard errors of prediction for the data sets were 5.8% for the 24-hour RH cycle and 9.1% for the 96-hour RH Cycle.

Load-Duration Response

The cumulative frequency distributions of the natural logarithm of times-to-failure for the Select Structural and No. 2 grade samples are presented in Figs. a and 3, respectively, for all the tests. These distributions include data only from constant load failures, that is, ramp loaded failures and constant load survivors are excluded from the data base, As evidenced in Figs. 2 and 3, a higher probability of failure exists with higher moisture contents and with cyclic humidity conditions.



Lengend		
marker	initial environment	test environment
□	73 F, 50% RH	constant 73 F, 95% RH
+	73F,50%RH	constant73F,35%RH
◇	73F,35%RH	constant73F,95%RH
△	73F,96%RH	constant73F,35%RH
×	73F,35%RH	constant73F,36%to99%RHon24-hrcycle
▽	73F,35%RH	constant73F,35%to95%RHon96-hrcycle

Fig. 1. Observed and Predicted Moisture Content Factors.

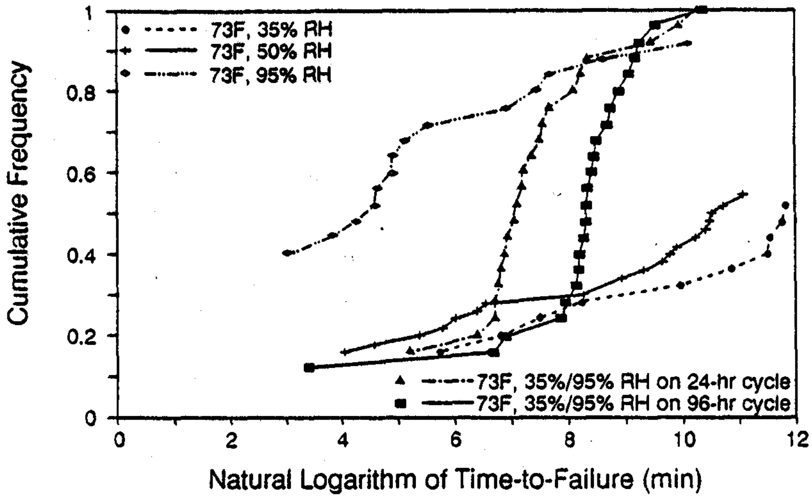


Fig. 2. Cumulative Frequencies of Time-to-Failure for Select Structural Lumber.

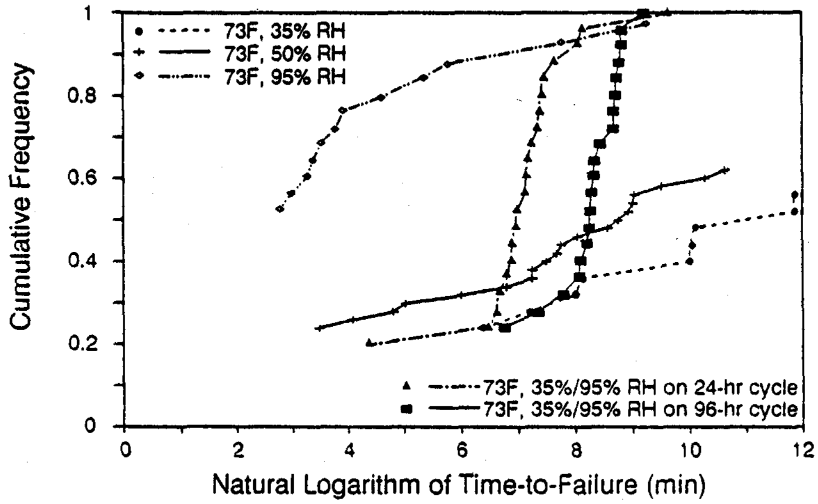


Fig. 3. Cumulative Frequencies of Time-to-Failure for No. 2 Lumber.

Calibration of Damage Model

Load-duration relationships have been traditionally presented as functions of the stress ratio, s, which is defined as the applied stress divided by the stress causing failure in a conventional static strength test. This approach is advantageous since it allows comparison across grade, species, and loadings. The stress ratio for a given sample was determined using the equal rank assumption, that is, specimens that fail under constant load will have the same rank in time as they would in static strength (15). Therefore, the predicted static strength for any failed beam under constant load can be determined by using either Eq. 1 or 2, depending on the grade, and its corresponding expectation of the normal order, R. A plot of predicted stress ratio against the natural logarithm of times-to-failure for Select Structural beams subjected to constant loads is shown in Fig. 4. A similar plot for No. 2 grade beams is shown in Fig. 5.

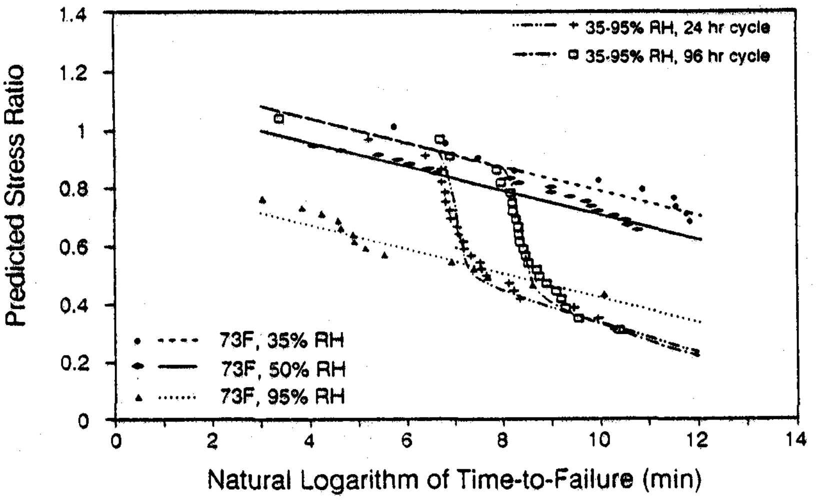


Fig. 4. Load-Duration Relationships for Select structural Lumber.

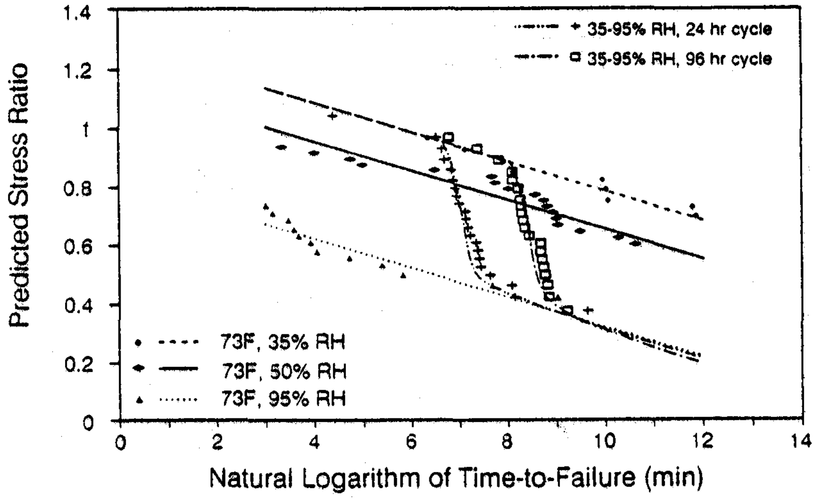


Fig. 5. Load-Duration Relationships for No. 2 Lumber.

Constant Moisture Content. For the constant moisture data, the moisture factor, w, is a known constant for each sample and Eq. 9 can be calibrated from the data presented in Figs. 4 and 5. A multiple least squares regression procedure was used to determine the values of constants A, B, C, and D. The following expressions can be written for the Select Structural (SS) and No. 2 grade material, respectively:

$$\text{SS:}\quad \ln(t_f) = 25.038 - 21.360\sigma - 6.861\omega + 1.642\omega^2 \tag{11}$$

$$\text{No. 2:}\quad \ln(t_f) = 23.599 - 20.296\sigma - 8.016\omega + 2.204\omega^2 \tag{12}$$

Table 2 provides 95% confidence limits and standard errors for the two regressions. The adjusted R-square values for the two regressions are 0.958 for Eq. 11 and 0.956 for Eq. 12.

Table 2. Regression Statistics.

coefficient	standard error	95% confidence intervals lower limit	upper limit
Select Structural			
A	0.659	23.704	26.372
B	0.831	19.680	23.041
C	0.655	5.536	8.185
D	0.468	-2.588	-0.697
No. 2			
A	0.746	22.086	25.111
B	0.929	18.414	22.178
C	0.678	6.641	9.390
D	0.484	-3.185	-1.222

Since the moisture content varied from piece to piece in each environmental condition, the actual moisture content was used to determine the constants in Eqs. 11 and 12. However, to plot Eqs. 11 and 12 in Figs. 4 and 5, the mean group moisture contents (Table 1) were used to determine the moisture factor w with the mean group moisture contents measured at 73°F and 50% RH used as M_o in Eq. 4.

Mechano-Sorptive Effects. To evaluate the mechano-sorptive parameter, the following procedure was employed to estimate the model constant E. The time-to-failure data for all specimens which failed under constant-load and after at least one environmental change were predicted by numerically integrating Eq. 6 for a from zero to one and time $t = 0$ to $t = t_f$ and assuming an appropriate value for E. Then, E was adjusted to reduce error and Eq. 6 was again integrated for the appropriate data. This continued until the errors were minimized. Difficulty in the convergence of E was encountered, but cautious selection and adjustment of the constant allowed for a convergent solution.

Values of 84.359 and 89.432 were found for the constant E for the Select Structural and No. 2 data sets, respectively, through the iterative procedure and the final damage models can be written as follows:

$$d\alpha/dt = \exp[-25.038 + 21.360\sigma + 6.861\omega - 1.642\omega^2 + 84.359|\dot{\omega}|t_\omega] \qquad (13)$$

for Select Structural lumber and

$$d\alpha/dt = \exp[-23.599 + 20.296\sigma + 8.016\omega - 2.204\omega^2 + 89.432|\dot{\omega}|t_\omega] \qquad (14)$$

for No. 2 grade lumber. The final values of E correspond to average total errors of 13.9% for the Select Structural lumber and 15.5% for the No. 2 material. The mechano-sorptive constant E associated with each grade is nearly equal, especially considering the relative errors in prediction. This indicates that grade effects may be absent with respect to mechano-sorptive effects in the load-duration behavior.

Predictive Ability of Damage Model. The errors associated to various environmental data sets are listed in Table 3. Note that no distinct trends associated with any environmental treatments are observed, but the errors are slightly greater than those found in the constant environments. This is partially due to the fact that assumed values for the moisture factor are used rather than real values. Equation 7 is used to predict the moisture factor w, but it is an approximation.

Table 3. Errors in the Prediction of Time-to-Failure for Lumber Subjected to Constant-Load and Various Environments.

Test Condition	Errors (%) Select Structural	No. 2
73°F, 35% RH	12.6	13.6
73°F, 50% RH	12.9	14.3
73°F, 95% RH	12.7	13.9
73°F, 35/95% RH[a]	14.1	15.8
73°F, 35/95% RH[b]	13.7	14.2

a: 24-hour cycle
b: 96-hour cycle

Although the actual load-duration relationship beyond the 7-week loading period is uncertain, the observed trends due to the effect of moisture content may be assumed to continue. When data become available for lower stress ratios and longer durations of load at conventional environmental conditions, extrapolation can be verified. Also, interpolation between the experimental conditions should be valid, but extrapolation into lower or higher moisture content conditions may not be valid. In fact, by taking the derivatives of Eqs. 11 and 12 with respect to w, it can be seen that the assumed models are not reasonable above about 27% moisture content, which is very close to the fiber saturation point of Douglas-fir (fsp = 28% reported in 19).

Furthermore, the basic damage equation can predict failure without any applied stress (i.e., $s = 0$). This condition is not considered realistic and, therefore, the constraint that $s > 0$ must be placed on the model. The imposed constraint for the applied stress may be non-zero, that is $s > s_0$ where s_0 is a stress threshold below which no damage would accumulate. However, high stress levels and corresponding short times-to-failure used in this investigation do not allow the definition of such a parameter.

Conclusions

The results from this study indicated that a trend exists towards shorter times-to-failure at higher moisture contents for equal mechanical stress ratios and that mechano-sorptive effects commonly observed in creep tests of structural lumber are also present in the load-duration behavior. The effect was no more pronounced in one grade as opposed to the other. It should be noted that the strength was not adjusted for the moisture content in this study since the definition of moisture dependent strength in a cyclic environment is troublesome. Moisture effects on the strength were accounted for solely by the quadratic shifting function. This allows the effect of moisture on the long-term strength to be visualized quite clearly.

The observation that mechano-sorptive effects are present in the load-duration behavior of structural size lumber is quite important since it apparently has never been definitively described in the literature. Additionally, the interdependence of creep and creep-rupture (load-duration) is quite evident with the observation of mechano-sorptive effects in load-duration. This suggests that new modeling approaches to the load-duration problem such as maximum strain (deflection) or strain energy models may provide further understanding of the long-term engineering performance of structural lumber in changing environments.

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