MOISTURE EFFECTS ON LOAD-DURATION BEHAVIOR OF LUMBER. PART II. EFFECT OF CYCLIC RELATIVE HUMIDITY

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ABSTRACT

The effect of cyclic moisture conditions on the load-duration behavior of structural lumber is presented. Select Structural and No. 2. Douglas-fir nominal 2 by 4 specimens were tested in bending in two cyclic relative humidity (RH) environments: 35% to 95% RH on 24- and 96-hour cycles. A constant temperature of 73 F was maintained in both tests. Constant bending loads based on the 15th percentile of the static strength distributions for each grade at 73 F and 50% RH were used to load the beams. The load-duration behavior in the two cyclic RH environments is compared to previously reported results observed from three constant RH environments (35%, 50%, and 95% RH at 73 F). Analysis of test results indicated a trend toward shorter times-to-failure in cyclic RH conditions as compared to constant RH conditions. The effect, however, was no more evident in the No. 2 specimens than in the Select Structural specimens. To predict the load-duration behavior, an existing damage accumulation model was modified to account for the effect of changing moisture contents on the long-term strength of structural lumber. The developed model was found to predict the observed behavior quite well.

Keywords: Load-duration (creep-rupture), strength, failure, relative humidity, moisture content, lumber, damage models.

INTRODUCTION

In part 1 of this paper (Fridley et al. 1991), the effect of three constant relative humidity (RH) conditions on the load-duration (creep-rupture) behavior of structural lumber was presented. It was found that significant shifts in the times-to-failure were observed with respect to the various levels of moisture. An existing damage accumulation model was modified to account for the observed shifts in the load-duration response. Previously, Fridley et al. (1988, 1989a, b, 1990) have investigated and modeled constant and cyclic thermal effects on the load-duration response of structural lumber.

The current investigation deals with possible additional moisture effects caused by cyclic RH, thus changing moisture conditions. The

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so-called mechano-sorptive effects (nonlinear interaction of applied stress and changing moisture content) apparent in the creep behavior of wood (e.g., Hoyle et al. 1986) will be shown to be present also in the load-duration behavior. This is considered to be an important finding since it apparently never has been definitely described in the literature. This information may allow engineers more reliable designs of wood structural systems subjected to changing environments. The experimental results and their analysis are the focus of this paper.

TEST PROGRAM

The test procedures were given in detail in part 1 of the paper (Fridley et al. 1991) and are reviewed here in brief. Discussion is further directed toward the cyclic RH environments which are of particular relevance in this report.

Materials

Select Structural and No. 2 nominal 2 in. × 4 in. × 8 ft Douglas-fir lumber, part of a larger sample acquired from an Oregon mill by the U.S. Forest Products Laboratory (Gerhards 1982), were used 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 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 to estimate the static strength distributions within each group. Gerhards (1988) determined that lognormal statistical distributions fit the observed strength populations reasonably well. The resulting strength distributions are given in the inverse form as follows for Select Structural and No. 2 specimens, respectively:

$$f_{ult} = 6{,}364 \exp(0.3682R) \qquad (1)$$

$$f_{ult} = 3{,}224 \exp(0.3657R) \qquad (2)$$

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

Loading apparatus and instrumentation

Seven test frames were built to allow the simultaneous testing of 28 specimens in a computer-controlled environmental chamber. A simple span of 84 in. was provided with load applied 24 in. apart and symmetric about the midspan. Lateral bracing was provided at the supports.

Midspan 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 based on the 15th percentile of the static strength distributions (Eqs. 1 and 2) were applied to the test beams. The resulting sustained stress was 4,104.5 and 2,248.2 psi for the Select Structural and No. 2 lumber, respectively. These stresses are approximately double the allowable stress prescribed by the National Design Specification for Wood Construction (NFPA 1986) for these grades. Obviously, a trade-off exists between realistic loads and test time. The loads provided at least 50% failure within approximately 7 weeks at a moderate constant RH condition (Fridley et al. 1991).

One group of each lumber grade was tested

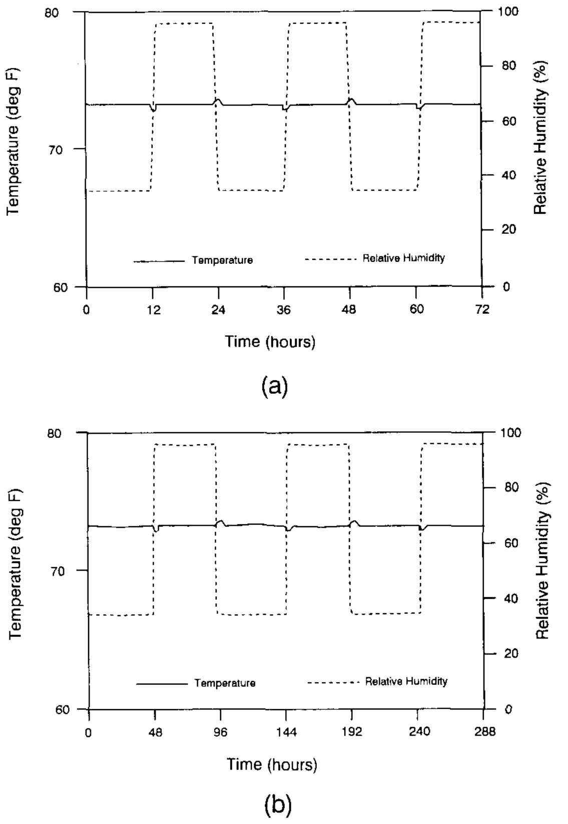


FIG. 1. Environments used in the investigation: (a) 24-hour 35% to 95% RH; (b) 96-hour 35% to 95% RH.

in each of two cyclic environments: 24-hour 35% to 95% cyclic RH, and 96-hour 35% to 95% cyclic RH. A constant 73 F was maintained in the tests. Figure 1 is a plot of a sample of the two cyclic environments. The following three constant environments were used in part 1 (Fridley et al. 1991): 35%, 50%, and 95% RH, all at 73 F.

The beams were preconditioned to 73 F and 35% RH, then brought into the testing chamber and loaded at the initiation of an environmental cycle (i.e., 73 F and 35% RH). Note that for the constant environment tests, the beams were brought into the testing environment, allowed to equilibrate, then loaded. Prior to loading, the moisture contents of all beams were determined using an electronic resistance-type moisture meter. Table 1 lists the average moisture contents of all specimens prior to load-duration testing. After the tests were complete, samples were taken from each 2 by 4 specimen and allowed to equilibrate with a 95% RH environment. Then, the moisture contents of these samples were taken. This provided moisture content data for each specimen at 35%, 50%, and 95% RH.

TABLE 1. *Moisture contents.*

Relative humidity (%)	Moisture content (%)	
	Group average	Standard deviation
	Select Structural	
35[a]	7.0	0.28
35[b]	7.1	0.26
50[b]	10.0	0.35
95[b]	24.3	0.79
	No. 2	
35[a]	6.9	0.25
35[b]	6.9	0.27
50[b]	10.0	0.40
95[b]	24.0	0.85

[a] Initial moisture content from cyclic environment.
[b] From constant moisture environment (Fridley et al. 1991).

Deflection measurements were made at the time the loads were fully applied, and the elapsed timers were started. At time of failure, the moisture contents were again measured and the failure modes were noted. The deflection vs. time data were printed out 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.

MODEL DEVELOPMENT

The damage accumulation approach to modeling the time-dependent strength properties seems appropriate for those materials that have failures governed by a creep-rupture phenomenon (Miner 1945). The damage accumulation modeling approach has been applied to the load-duration problem by several researchers (Barrett and Foschi 1978a, b; Foschi and Barrett 1982; Gerhards 1979 and 1988; Gerhards and Link 1987).

In part 1 of this paper (Fridley et al. 1991), the damage model proposed by Gerhards (1988) and Gerhards and Link (1987) was modified to account for moisture content. As presented by Gerhards and Link (1987), the exponential stress-dependent damage accumulation model can be written as

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

where α is a normalized damage parameter, A and B are model constants to be determined from experimental data and σ is the ratio of applied stress to the ultimate static strength determined from a conventional ramp test. The damage parameter α is defined as zero in the virgin state (no damage) and unity at failure (complete damage).

To account for moisture effects, an additional damage function was introduced (Fridley et al. 1991). The form of the moisture-dependent damage function was chosen to be exponential so as to be compatible with Gerhards' original damage equation. Therefore, the following moisture-dependent damage function, $g(\omega)$, was introduced:

$$g(\omega) = \exp(C\omega + D\omega^2) \qquad (4)$$

where C and D are model constants, and ω is a dimensionless moisture factor defined by

$$\omega = (M - M_0)/M_0 \qquad (5)$$

where M is the current moisture content of the lumber, and M_0 is a reference moisture content. The moisture content factor, ω, is therefore equal to zero in a reference condition, which is defined as some typical or standard moisture content. In this study, M_0 is assumed as the moisture content at conditions of 73 F and 50% RH.

By assuming multiplicative damage functions (Hwang and Han 1986), Eqs. (3) and (4) were combined to yield the modified damage accumulation model presented in part 1 (Fridley et al. 1991):

$$d\alpha/dt = f(\sigma)\cdot g(\omega) \qquad (6)$$

or

$$d\alpha/dt = \exp(-A + B\sigma + C\omega + D\omega^2) \qquad (7)$$

where σ 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 additional factors associated with the model constants C and D.

The present study includes cyclic moisture effects. If mechano-sorptive effects are assumed to be present in the load-duration behavior, an additional damage function must be included to account for such effects. It is assumed that damage accumulation related to mechano-sorptive behavior can be written as a function of the time rate of change of the moisture factor, or

$$h(\dot{\omega}) = \exp(E|\dot{\omega}|t_\omega) \qquad (8)$$

where $\dot{\omega}$ is the time rate of change of the moisture factor, t_ω is the time associated with the change, and E is a model constant. The absolute value of the time rate of change is used so that an increase in the rate of damage accumulation will be predicted for any change in moisture content during the time of the change.

Again, by assuming multiplicative damage functions (Hwang and Han 1986), the final form of the modified damage model, including the mechano-sorptive function, is written as follows:

$$d\alpha/dt = \\ = \exp(-A + B\sigma + C\omega + D\omega^2 + E|\dot{\omega}|t_\omega) \qquad (9)$$

For any combination of load and moisture history, Eq. (9) can be numerically integrated to yield a time-to-failure, i.e., $\alpha = 1$.

Application of modified damage model

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

$$\omega_t = \omega_e + (\omega_i - \omega_e)\exp[-B_\omega t] \qquad (10)$$

where ω_t is the average moisture content factor of the member at a time t following the change,

ω_e is the eventual equilibrium moisture content, ω_i is the initial moisture content, and B_ω is a constant associated with the time required to achieve moisture equilibrium. Obviously, B_ω is dependent on the size of the member and can vary if the change in moisture content is positive or negative. However, B_ω will be assumed constant for simplicity in modeling.

The damage model (Eq. 9) 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. (8) yields

$$\Delta\alpha_i = \Delta t_i \exp(-A + B\sigma + C\omega + D\omega^2) \quad (11)$$

where $\Delta\alpha_i$ is the amount of damage accumulated during an interval of time Δt_i in which σ is constant.

With the stress and moisture content all remaining constant through time, the time-to-failure can be determined by substituting $\Delta\alpha_i = 1$ into Eq. (10) and then solving for Δt_i, that is

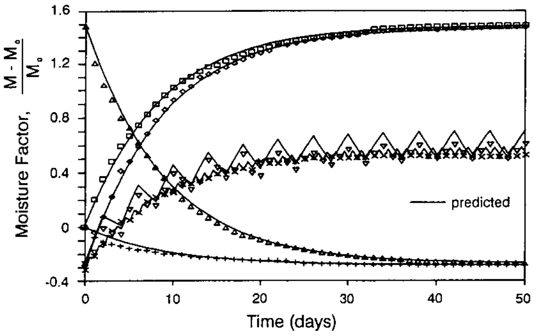
$$t_f = \exp(A - B\sigma - C\omega - D\omega^2) \quad (12)$$

or,

$$\ln(t_f) = A - B\sigma - C\omega - D\omega^2 \quad (13)$$

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. Such a procedure was used in part 1 of the paper (Fridley et al. 1991).

The integration of Eq. (9) for other stress histories and changing environments can become complex and possibly undefined. Such is the case with changing moisture content. Equation (10) can be used to model the average moisture content of a sample after an abrupt change in the environment. When Eq. (10) is substituted into Eq. (9), the resulting expression is quite lengthy and does not allow for closed-form integration. However, numerical integration procedures allow the evaluation of the expression for virtually any load or environmental history once the constants are known.



Legend		
marker	initial environment	test environment
□	73 F, 50% RH	constant 73 F, 95% RH
+	73 F, 50% RH	constant 73 F, 35% RH
◇	73 F, 35% RH	constant 73 F, 95% RH
△	73 F, 95% RH	constant 73 F, 35% RH
×	73 F, 35% RH	constant 73 F, 35% to 95% RH on 24-hr cycle
▽	73 F, 35% RH	constant 73 F, 35% to 95% RH on 96-hr cycle

FIG. 2. Observed and predicted moisture content factors as a function of environmental history.

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. The specimens were 2-ft 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. 2. The data points are averages of appropriate specimen data and are in the form of the moisture factor ω as defined by Eq. (5). The lines plotted with each data set are best fit predictions using Eq. (10) with B_ω determined using a nonlinear best fit procedure from all the sin-

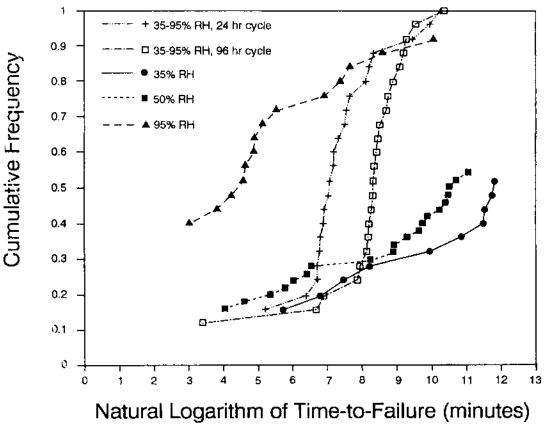


FIG. 3. Cumulative frequencies of time-to-failure for Select Structural lumber.

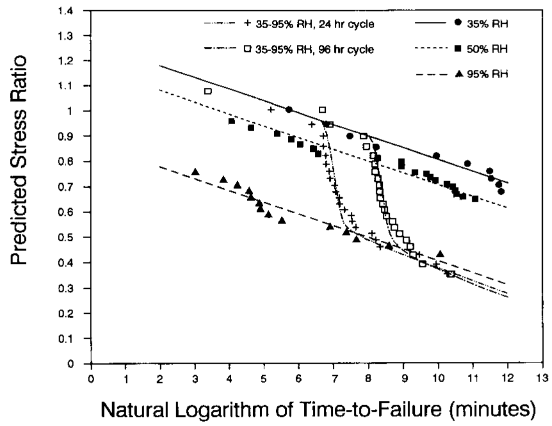


FIG. 5. Load-duration relationships for Select Structural grade lumber.

gle change data (four sets). Equation (10) can now be written as follows:

$$\omega_t = \omega_c + (\omega_i - \omega_e)\exp[-0.0000785t_\omega] \quad (14)$$

where t_ω is the time in minutes following the change in the environment. A standard error of the fit to the four single change data sets is 7.9%.

Equation 14 was then used to predict the data from 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. It should be noted that the moisture content data in Fig. 2 were taken every 24 hours; therefore, data from the 24-hour cycle were taken only at the completion of a cycle.

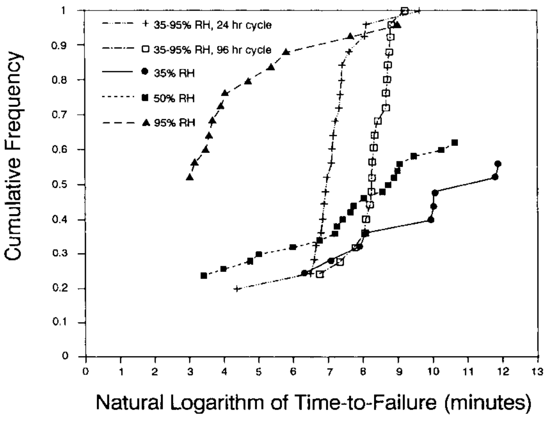


FIG. 4. Cumulative frequencies of time-to-failure for No. 2 lumber.

Load-duration response

The cumulative frequency distributions of the natural logarithm of times-to-failure for the Select Structural and No. 2 samples are presented in Figs. 3 and 4, respectively, for all the tests. Data from part 1 (Fridley et al. 1991) are included in Figs. 3 and 4 for illustrative purposes. These distributions include data only from constant load failures, that is, ramp load failures and constant load survivors are excluded from the data base. As evidenced in Figs. 3 and 4, a higher probability of failure exists with higher moisture contents and with cyclic RH conditions.

Calibration of damage model

Load-duration relationships have been traditionally presented as functions of the stress ratio, σ, 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

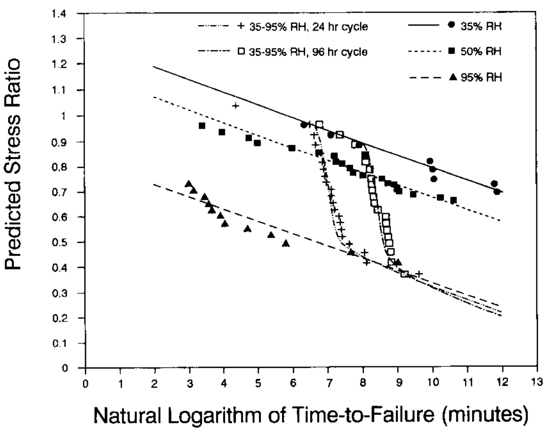


FIG. 6. Load-duration relationship for No. 2 grade lumber.

TABLE 2. *Regression statistics (from Fridley et al. 1991).*

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

(Murphy 1983). 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 Douglas-fir beams subjected to constant loads is shown in Fig. 5. A similar plot for No. 2 grade beams is shown in Fig. 6. Again, data from the constant moisture conditions (Fridley et al. 1991) are included in Figs. 5 and 6.

Constant moisture content.—The following expressions were determined in part 1 (Fridley et al. 1991) for the Select Structural and No. 2 material, respectively:

$$\ln(t_f) = 25.038 - 21.360\sigma - 6.861\omega + 1.642\omega^2 \quad (15)$$

$$\ln(t_f) = 23.599 - 20.296\sigma - 8.016\omega + 2.204\omega^2 \quad (16)$$

Table 2 provides 95% confidence limits and standard errors for the two regressions.

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. (15) and (16). However, to plot the equations in Figs. 5 and 6, the mean group moisture contents (Table 1) were used to determine the moisture factor ω with the mean group moisture contents measured at 73 F and 50% RH used as M_0 in Eq. (5).

Mechano-sorptive effects.—To evaluate the mechano-sorptive parameter, the following procedure was employed to estimate the model constant E. The moisture equation, Eq. (14), was used to estimate the average member moisture content during testing. The moisture factors for each specimen were known at 35%, 50%, and 95% RH at 73 F and were used in Eq. (14). The time-to-failure data for all specimens that failed under constant-load and after at least one environmental change were predicted by numerically integrating Eq. (9) for α 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. (9) 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. The final damage models can be written as follows:

$$d\alpha/dt = \exp[-25.038 + 21.360\sigma + 6.861\omega - 1.642\omega^2 + 84.359|\dot{\omega}|t_\omega] \quad (17)$$

for Select Structural lumber and

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, 35/95% RH[a]	14.1	15.8
73 F, 35/95% RH[b]	13.7	14.2
73 F, 35% RH[c]	12.6	13.6
73 F, 50% RH[c]	12.9	14.3
73 F, 95% RH[c]	12.7	13.9

[a] 24-hour cycle.
[b] 96-hour cycle.
[c] From Fridley et al. (1991).

$$\begin{aligned} d\alpha/dt = \exp[-23.599 + 20.296\sigma + 8.016\omega - \\ - 2.204\omega^2 + 89.432|\dot{\omega}|t_\omega] \quad (18) \end{aligned}$$

for No. 2 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 suggests that grade effects may be absent with respect to mechano-sorptive effects in the load-duration behavior.

Equations (17) and (18) were used to predict the load-duration responses of the lumber subjected to the cyclic RH environments. Predicted responses were calculated based on average moisture values for the samples and are included in Figs. 5 and 6.

Predictive ability of the damage model.—The errors associated with predicting time-to-failure for the various environmental data sets are listed in Table 3. Note that no distinct trends associated with any environmental treatments are observed, but the errors related to the cyclic environments 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 (14) is used to predict the moisture factor ω, but it is an approximation. The predictive capability of the damage model is shown in Figs. 7 and 8 for the Select Structural and No. 2 samples, respectively. The predicted natural logarithm of time-to-failure in minutes is plotted against the observed log time-to-failure. The data are distributed fairly uniformly about the diagonal line, indicating that the developed model is reasonable within the constraints of the experiment.

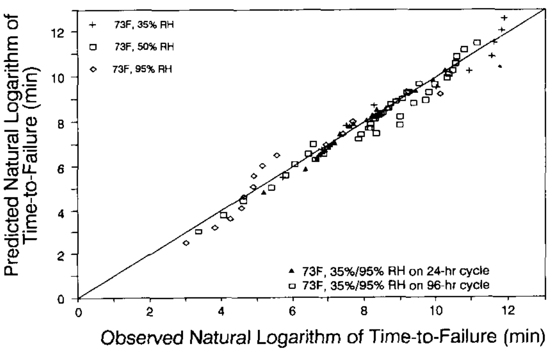


FIG. 7. Relationship between predicted and observed natural logarithm of time-to-failure for Select Structural lumber.

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 (e.g., 10-year load-duration study in progress at the FPL), 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 deriv-

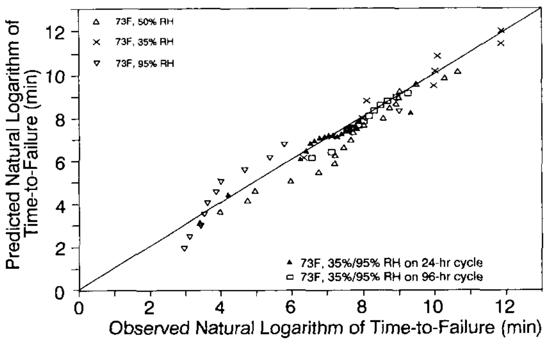


FIG. 8. Relationship between predicted and observed natural logarithm of time-to-failure for No. 2 grade lumber.

atives of Eqs. (15) and (16) with respect to ω, 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 by Stamm 1964).

Furthermore, the basic damage equation can predict failure without any applied stress (i.e., $\sigma = 0$). This condition is not considered realistic, and therefore the constraint that $\sigma > 0$ must be placed on the model. The imposed constraint for the applied stress may be nonzero, that is $\sigma > \sigma_0$ where σ_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 with changing moisture contents 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 lumber 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 lumber strength were accounted for solely by the quadratic shifting function. This allows the effect of moisture on the long-term lumber 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 never has 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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