MOISTURE EFFECTS ON LOAD-DURATION BEHAVIOR OF LUMBER. PART I. EFFECT OF CONSTANT RELATIVE HUMIDITY

Kenneth J. Fridley[1]

Assistant Professor of Wood Engineering
Department of Forestry and Natural Resources
Purdue University
West Lafayette, IN 47907

R. C. Tang

Professor
School of Forestry and Alabama Agricultural Experiment Station
Auburn University, AL 36849-5418

and

Lawrence A. Soltis

Supervisory Research Engineer
Forest Products Laboratory, USDA Forest Service
Madison, WI 53705-2398

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ABSTRACT

The effect of moisture content on the load-duration behavior for structural lumber is presented. Select Structural and No. 2 Douglas-fir 2 by 4 specimens were tested in bending at relative humidities (RH) of 35%, 50%, and 95% with a constant temperature of 73 F maintained during the tests. Constant loads based on the 15th percentile of the static strength distribution for each grade at 73 F and 50% RH were used to load the beams. The results indicate a trend toward shorter times-to-failure at higher moisture contents subjected to equal mechanical stress ratios. The effect, however, was no more evident in the No. 2 grade specimens than in the Select Structural specimens. Survival rates were likewise reduced at higher humidities.

Keywords: Load-duration, failure, relative humidity, moisture content, lumber.

INTRODUCTION

Current design procedures in wood engineering recommend the use of allowable stress adjustment factors for load-duration (NFPA 1986). The adjustment factors are based on the Madison curve which was derived from data from early tests (Wood 1951) of small clear wood specimens. A number of researchers (Foschi and Barrett 1982; Gerhards 1977, 1988; Madsen 1971; Madsen and Barrett 1976) have found the load-duration response in structural lumber to deviate somewhat from the Madison curve, thus causing some doubt as to the accuracy of the current design factors and procedures. The apparent discrepancy between the Madison curve and the observed behavior of structural lumber has inspired new research and modeling efforts in the area of load-duration effects in structural lumber.

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[1] Formerly, Research Associate, School of Forestry, Auburn University.

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A significant amount of load-duration research on structural lumber has been and is being conducted at various institutions worldwide (e.g., Barrett and Foschi 1978a, b; Fewell 1986; Gerhards 1986a; Karacabeyli 1988; Madsen 1986). These studies typically were conducted at constant, or nearly constant, mild environmental conditions. However, wood is used structurally in a variety of environments. From past creep-rupture experiments on small clear samples of wood (Schniewind 1967; Schniewind and Lyon 1973), the need to include environmental factors in models that predict the load-duration behavior of structural lumber is readily apparent. However, these effects apparently have never been reported, nor has any attempt been made to include them in any load-duration models.

A complete and versatile load-duration model is required to fully and accurately design for the time-dependent behavior of structural lumber. Furthermore, it must accordingly include any factors contributing to the ultimate failure of a wood member. Since the environment can be expected to influence the failure of wood, environmental factors certainly must be included in the modeling and structural design processes. A comprehensive research effort is in progress at Auburn University in cooperation with the Forest Products Laboratory (FPL) of the USDA Forest Service to define the effect of environmental influences on the load-duration behavior of structural lumber in bending. This paper addresses the effect of moisture content on load-duration performance of structural lumber. This information may allow engineers and wood scientists better designs of wood structural systems subjected to changing environments. Previous results from this study involved the effect of temperature on the load-duration of solid lumber (Fridley et al. 1988, 1989a, b, 1990).

TEST PROGRAM

Materials

Select Structural and No. 2 Douglas-fir nominal 2 in. × 4 in. × 8 ft beams were tested in this investigation. The lumber was obtained by the FPL for use in various load-duration studies (Gerhards 1982, 1988). 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 10.0%. At the FPL, 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 edgewise bending at a rate of 300 lb/min at the FPL to estimate the static strength distributions within each group. Least-squares regressions of the static strength data (Gerhards 1988) yield

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

for the Select Structural lumber, and

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

for the No. 2 specimens. In Eqs. (1) and (2), f_{ult} is the ultimate static strength

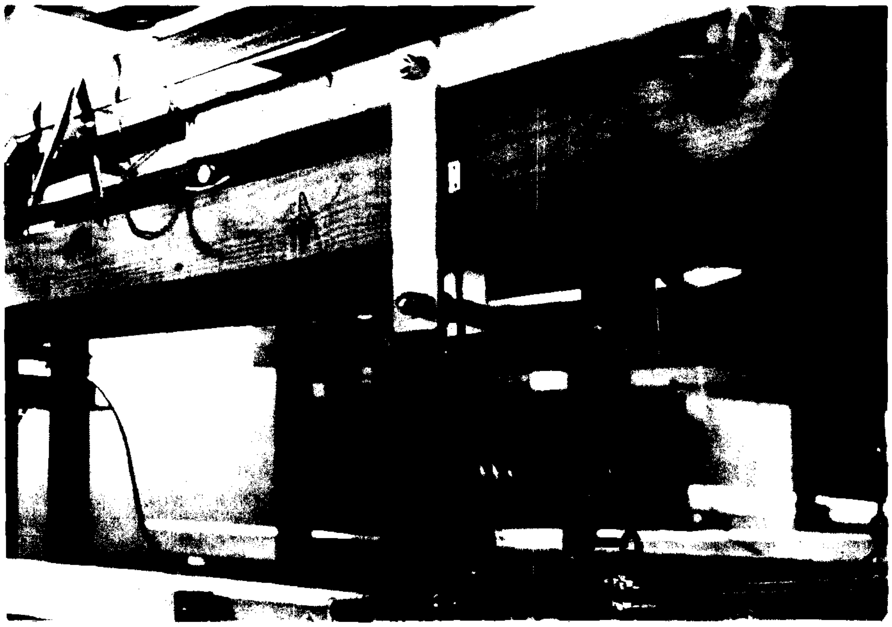

FIG. 1. Duration of load test frames.

(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.

Loading apparatus and instrumentation

At Auburn University, seven test frames were built to allow the simultaneous testing of 28 specimens in a computer-controlled environmental chamber (Fig. 1). Since the experimental results are to be used in conjunction with the data obtained at the FPL, an effort was made to duplicate the loading system at FPL.

A simple span of 84 in. was provided, with load applied symmetrically 12 in. about the midspan. The load was applied using a cantilever and pulley system with an actual mechanical advantage of approximately 7. Half of the 28 testing positions were calibrated for Select Structural beams and half for No. 2's. Lateral bracing was provided at the supports only.

Midspan deflection was read using a rotary potentiometer. A deflection-chain was attached to each beam at midspan which, as the beam deflected, fell through a toothed wheel mounted on the potentiometer shaft. Times-to-failure and partial failures 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, yielding elapsed times-to-failure under constant load.

Procedures

Since the results reported here are used with results previously obtained from the FPL, every effort again was made to duplicate loading procedures previously used and reported by Gerhards (Gerhards 1986b, 1988).

Constant loads of 4,104 and 2,248 psi 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 described by Eqs. (1) and (2) and 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. These loads were expected to provide a 50% failure rate in approximately 7 weeks at a moderate moisture condition.

Two groups of each grade were tested at the FPL in an environment of 73 F and 50% RH (Gerhards 1988). At Auburn University, two more groups of each grade were tested in environments of 35% and 95% RH, both at 73 F.

Prior to testing, the moisture content of each beam was determined, and a map of all defects was made. The beam was then brought into the testing environment, allowed to equilibrate, then loaded. A deflection measurement was made at the time the load was fully applied, and the elapsed timer was started. At time of failure, the moisture content was again measured, and the failure mode was plotted on the defect map. The deflection vs. time data were printed out, and times-to-partial-failures and time-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. Because of the 50% criterion, the testing time for the 35% RH condition had to be doubled to 14 weeks.

MODELING APPROACH

For those materials that have failures governed by a creep-rupture phenomenon, the damage accumulation approach to modeling the time-dependent strength properties seems appropriate (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, 1988; Gerhards and Link 1987).

The general form of a damage accumulation model can be written as follows (Hwang and Han 1986):

$$d\alpha/dt = F(\sigma, T, M, \ldots) \tag{3}$$

where α is a damage parameter, $d\alpha/dt$ is the time rate of damage accumulation, F is the general functional defining $d\alpha/dt$ in terms of stress, temperature, moisture, and any other factors that may influence failure. The damage parameter α ranges from zero, implying no damage, to unity, indicating total failure.

It is the purpose here to select a damage model that has been shown to adequately predict load-duration effects in structural lumber, then modify it to include factors related to relative humidity effects. Thermal effects will not be examined here since all tests were conducted at a constant temperature of 73 F.

Basic damage equation

Several damage accumulation models have been proposed to define the stress-dependent load-duration behavior 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 (Barrett and Foschi 1978a, b; Foschi and Barrett 1982) 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 (1977) and Gerhards and Link (1987) opted to neglect any such threshold. Since in this investigation the applied stress ratios are 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 selection of a stress-dependent damage accumulation function depends on model fit at some typical constant environmental conditions. The exponential damage model proposed by Gerhards (1977) and Gerhards and Link (1987) was shown to adequately represent the load-duration behavior of a lumber sample similar to that which is used in this investigation in an environment of 73 F and 50% RH (Gerhards 1988; Gerhards and Link 1987). Also, Gerhards (1988) and Gerhards and Link (1986, 1987) showed the validity of the model for various stress histories. Therefore, it will be used here to represent the stress-dependent function.

As presented by Gerhards and Link (1987), the exponential stress-dependent damage accumulation model can be written as

$$d\alpha/dt = \exp(-A + B\sigma) \tag{4}$$

where 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.

Moisture effects

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

$$\omega = (M - M_0)/M_0 \tag{5}$$

where ω is the relative moisture content, 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.

To account for moisture effects, an additional damage function can be introduced. Therefore, the following arbitrary moisture dependent damage function is introduced:

$$g(\omega) = \exp(C\omega + D\omega^2) \tag{6}$$

where C and D are model constants.

By assuming multiplicative damage functions (Hwang and Han 1986), Eqs. (4) and (6) can be combined to yield the final form of the damage accumulation model which includes moisture effects:

$$d\alpha/dt = f(\sigma)\cdot g(\omega) \tag{7}$$

or

$$d\alpha/dt = \exp(-A + B\sigma + C\omega + D\omega^2) \tag{8}$$

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 addition factors associated with the constants C and D. Equation (8) is very similar to that used by Fridley et al. (1989b, 1990) to predict thermal effects on the load-duration behavior of the lumber sample.

Application of modified damage model

The damage model (Eq. 8) 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, which is of interest here, integration of Eq. (8) yields

$$\Delta\alpha_i = \Delta t_i \exp(-A + B\sigma + C\omega + D\omega^2) \tag{9}$$

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

With the stress and moisture content all remaining constant through time, the time-to-failure could be determined by substituting $\Delta\alpha_i = 1$ into Eq. (9) and then solving for Δt_i, that is

$$t_f = \exp(A - B\sigma - C\omega - D\omega^2) \tag{10}$$

or,

$$\ln(t_f) = A - B\sigma - C\omega - D\omega^2 \tag{11}$$

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.

RESULTS

The mean and standard deviation of the moisture contents of each group at the various environmental conditions are listed in Table 1. Although the data are presented as sets corresponding to specific moisture content levels, data analyses and modeling procedures were conducted on an individual basis, specimen by specimen.

The cumulative frequencies of the natural logarithm of time-to-failure for the Select Structural and No. 2 grade samples are presented in Figs. 2 and 3, respectively. These distributions include data only from constant load failures, that is, ramp loaded failures and constant load survivors are excluded from the data base. Table 2 lists the number of failures during various stages of the load history and the survival rates of the various groups. As evidenced in Figs. 2 and 3 and in Table 2, a higher probability of failure exists with higher moisture contents.

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. The approach is advantageous

TABLE 1. *Moisture contents.*

Relative humidity (%)	Moisture content (%) Group average	Standard deviation
	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

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 (Murphy 1983). Therefore, the predicted static strength for any failed beam under constant load can be determined by using either Eq. (2) or (3), depending on the grade, and its corresponding expectation of the normal order, R. A plot of predicted stress ratio against the natural logarithm of time-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.

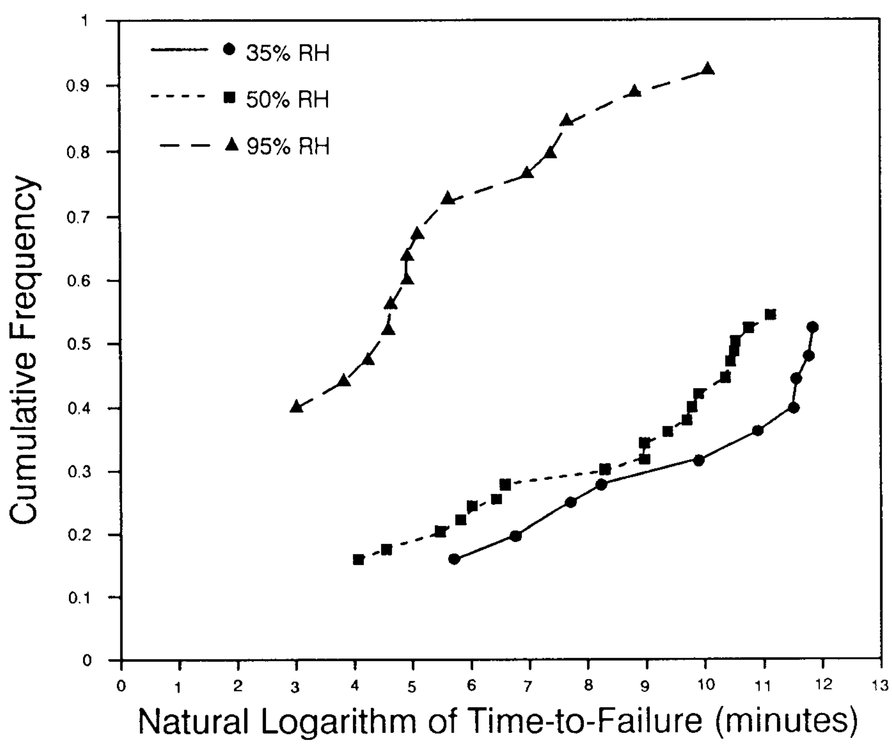

FIG. 2. Cumulative frequencies of time-to-failure for Select Structural lumber.

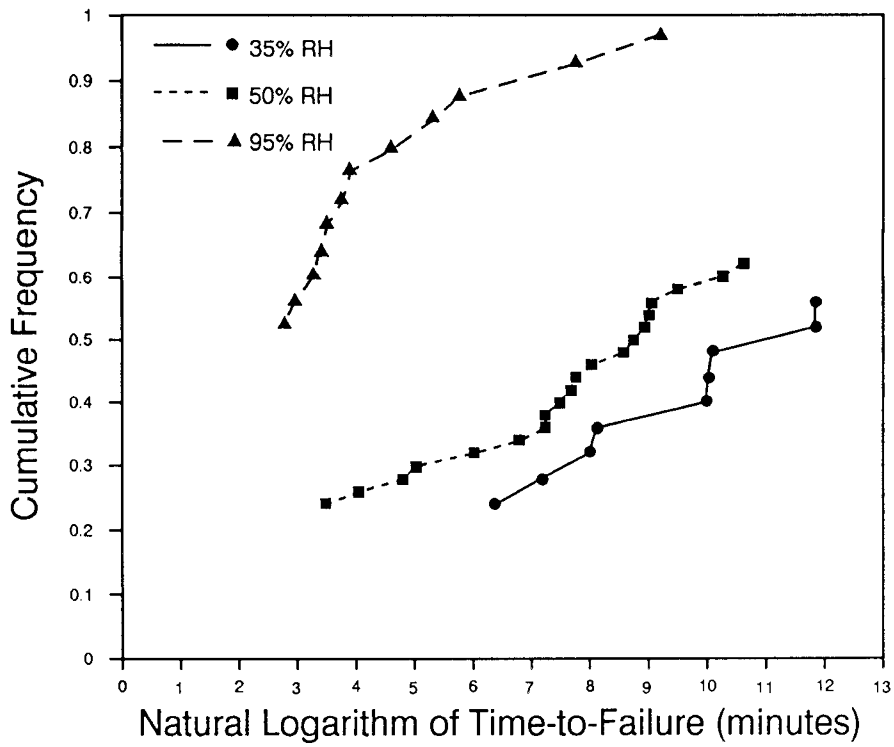

FIG. 3. Cumulative frequencies of time-to-failure for No. 2 lumber.

The constants for the damage equation can be estimated from the data presented in Figs. 2 and 3 using Eq. (11) and the moisture factor ω for each sample (Table 1). A multiple least-squares regression procedure was used to determine the values of constants A, B, C, and D. The following expression can be written for the two grades of material:

$$\text{SS:} \quad \ln(t_f) = 25.038 - 21.360\sigma - 6.861\omega + 1.642\omega^2 \tag{12}$$

$$\text{No. 2:} \quad \ln(t_f) = 23.599 - 20.296\sigma - 8.016\omega + 2.204\omega^2 \tag{13}$$

TABLE 2. *Number of failures during constant load tests.*

Loading phase	Number of failures at 35, 50 and 95% RH	Cumulative number at 35, 50, and 95% RH
	Select Structural	
Ramp to constant	3, 7, 9	3, 7, 9
Constant load	10, 20, 14	13, 27, 23
Survived constant load	12, 23, 2	25, 50, 25
	No. 2	
Ramp to constant	5, 11, 12	5, 11, 12
Constant load	9, 20, 12	14, 31, 24
Survived constant load	11, 19, 1	25, 50, 25

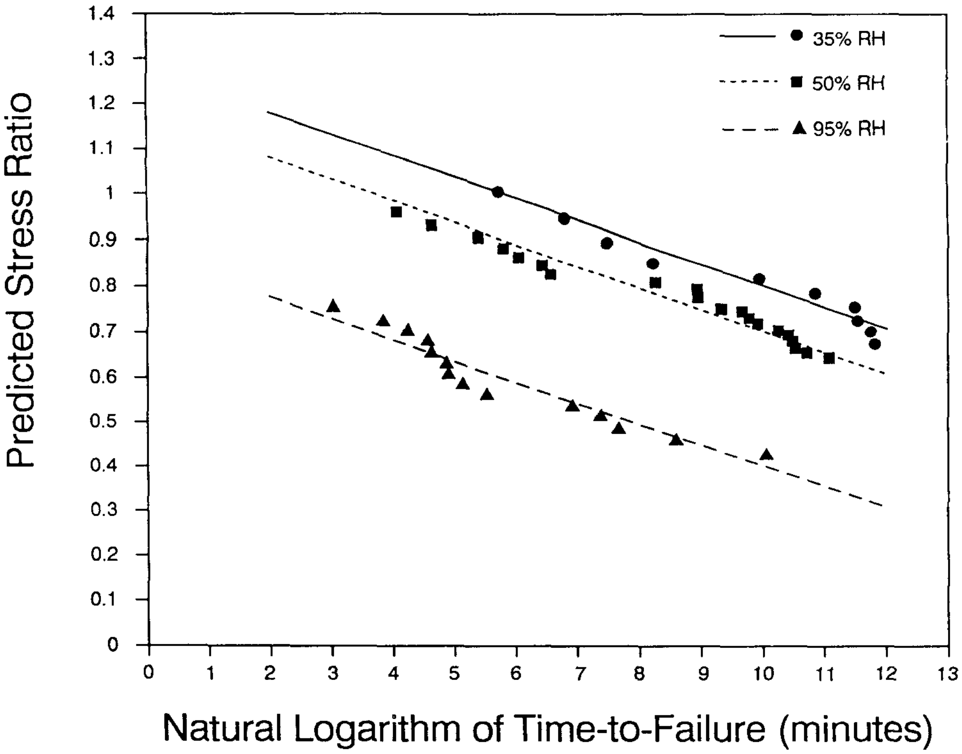

FIG. 4. Load-duration relationships for Select Structural lumber.

Table 3 provides 95% confidence intervals and standard errors for the two regressions. The adjusted R-square values[2] for the two regressions are 0.958 for Eq. (12) and 0.956 for Eq. (13).

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. (12) and (13). However, to plot Eqs. (12) and (13) in Figs. 4 and 5, the mean group moisture contents (Table 1) were used to determine ω with the mean group moisture contents at 73 F and 50% RH used as M_0 in Eq. (5).

The predictive capabilities of Eqs. (12) and (13) are shown in Figs. 6 and 7 for the Select Structural and No. 2 grade 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 constraint of the experiment.

DISCUSSION

Although the actual load-duration relationship beyond the 7-week loading period used in this study is uncertain, the observed trends due to the effect of moisture content may be assumed to continue relative to the reference condition (i.e., 73

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[2] R-squared statistic adjusted for the number of independent variables in the regression.

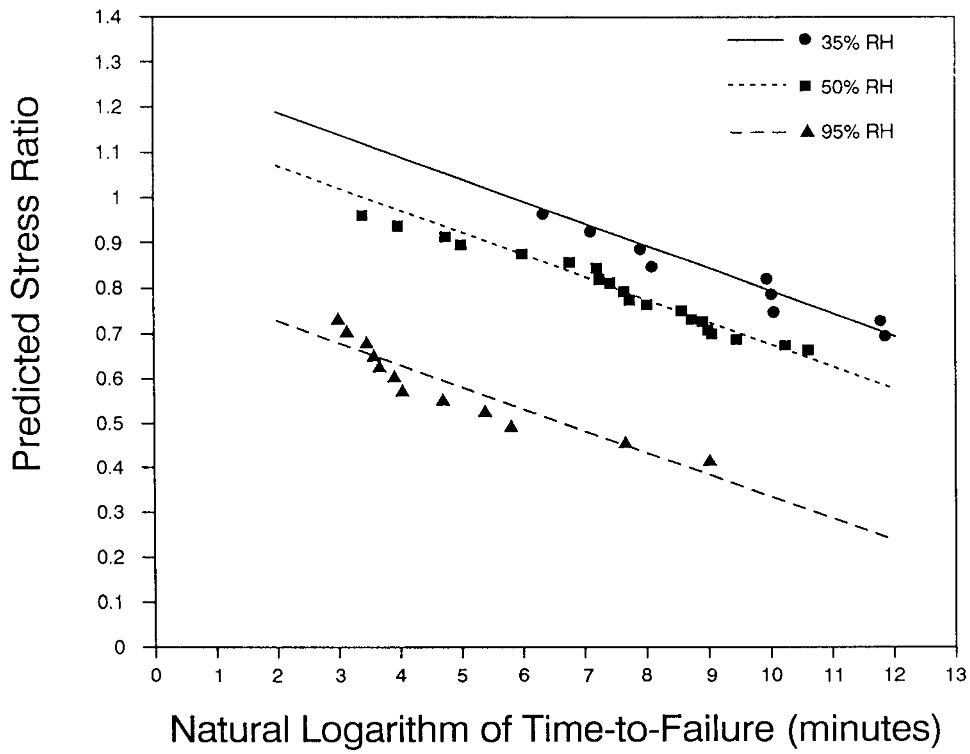

FIG. 5. Load-duration relationships for No. 2 lumber.

F and 50% relative humidity). When data become available for lower stress ratios and longer durations of load at conventional environmental conditions, extrapolated moisture effects can be calibrated.

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. (12) and (13) with respect to ω, it can be seen that the assumed models are not reasonable above about 27% moisture

TABLE 3. *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

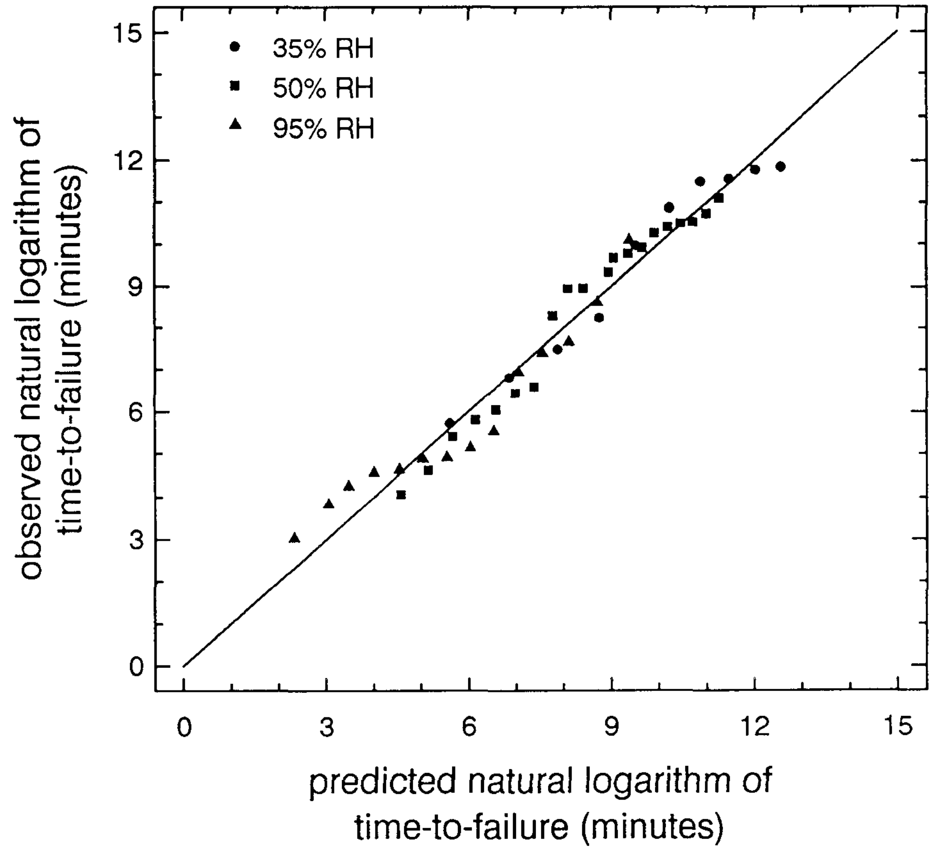

FIG. 6. Relationship between predicted and observed natural logarithm of time-to-failure for Select Structural lumber.

content, which is very close to the fiber saturation point of Douglas-fir (FSP = 28% reported by Stamm 1964).

Furthermore, Eqs. (12) and (13) 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 non-zero, that is $\sigma > \sigma_0$ where σ_0 is a stress threshold below which no damage would accumulate; but the high stress levels and corresponding short times-to-failure used in this investigation do not allow the definition of such a parameter.

SUMMARY

Groups of 2 by 4 Select Structural and No. 2 Douglas-fir lumber were tested under constant load at three different constant relative humidity (RH) levels: 35%, 50%, and 95%. The experimental results and their analysis were the focus of this paper. The experimental results presented here were obtained at Auburn University and were used in conjunction with results obtained at the FPL by Gerhards (1988) to evaluate the effects of moisture content on the load-duration behavior.

The load-duration data plotted in Figs. 4 and 5 indicate that a trend exists

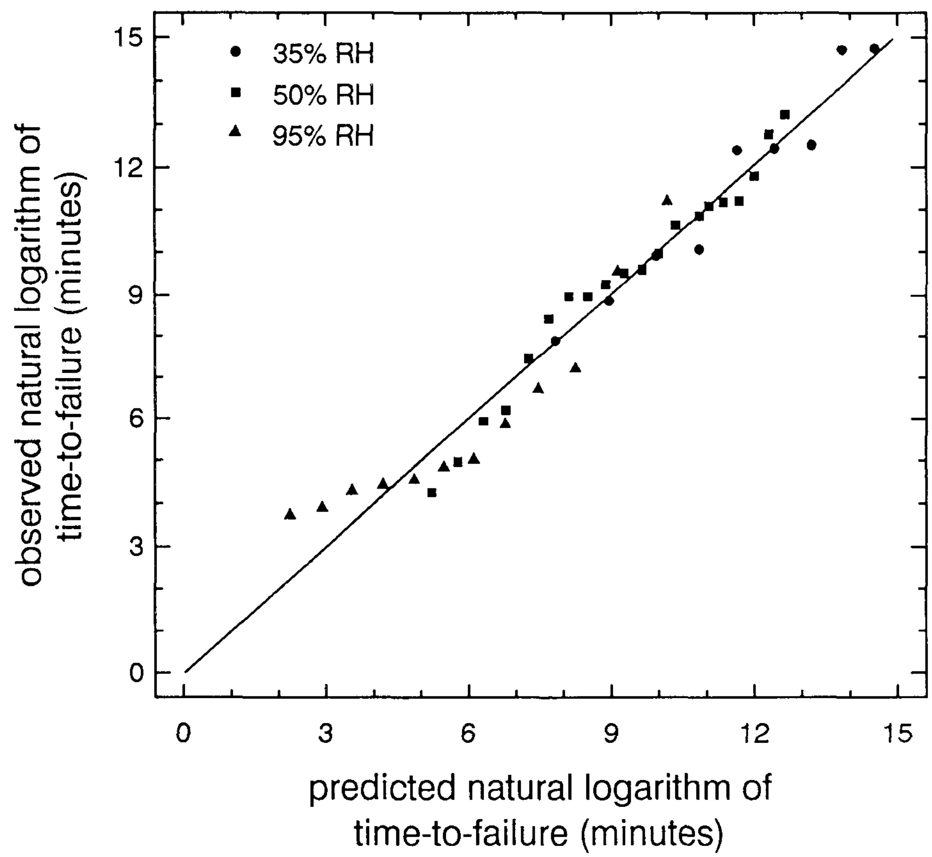

FIG. 7. Relationship between predicted and observed natural logarithm of time-to-failure for Select Structural lumber.

toward shorter times-to-failure at higher moisture contents for equal mechanical stress ratios. The effect was no more pronounced in one grade as opposed to the other.

An existing damage accumulation model modified to include moisture effects was used to describe the observed load-duration behavior of the lumber sample. It should be noted that the strength was not adjusted for moisture content in this study since, in part II of this research, the effects of cyclic humidity will be examined, and the definition of moisture-dependent strength in a cyclic environment is troublesome. Therefore, moisture effects on 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. Admittedly, other modeling approaches may be used.

CONCLUSIONS

Moisture effects on the load-duration behavior were shown to be significant. That is, large reductions in time-to-failure were observed with increased moisture content. The life of a wood structure could be jeopardized if moisture histories are not accounted for in the design process. The damage model presented here is one way of accomplishing this; however, calibration of the model into a design format is required. Further, the effect of changing moisture conditions on the load-duration behavior and predictive model needs to be addressed. Possible mechano-sorptive effects, which are commonly observed in creep tests conducted in changing moisture conditions (e.g., Hoyle et al. 1986), need to be investigated.

The research reported herein is part of a larger project to define the effects of environmental conditions on the load-duration behavior of structural lumber. Subsequent papers will deal with the effect of changing moisture content and combined temperature and moisture content on the load-duration relationships.

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