THERMAL EFFECTS ON LOAD-DURATION BEHAVIOR OF LUMBER. PART I. EFFECT OF CONSTANT TEMPERATURE

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ABSTRACT

The effect of constant thermal loadings on the load-duration relationships for structural lumber in bending is presented. Select Structural and No. 2 grade Douglas-fir nominal 2 by 4 (38.1 mm by 88.9 mm) beams were tested in bending under constant load. Constant temperature environments of 73 F, 100 F, and 130 F (22.8 C, 37.8 C, and 54.4 C) were used in the investigation. A constant 50% relative humidity (RH) was maintained for each temperature. The applied bending loads were based on the 15th percentile of the assumed static strength distributions for each grade at 73 F and 50% RH. An exponential damage accumulation model modified to account for temperature effects is used to define the load-duration response. The results indicate shorter times-to-failure with corresponding higher probabilities of failure for equal levels of mechanical stress as the temperature is increased.

Keywords: Load-duration, creep-rupture, temperature, lumber, Douglas-fir, bending, failure, modeling.

INTRODUCTION

Load-duration experiments on wood and structural lumber typically have been conducted at constant, or nearly constant, mild environmental conditions. However, wood is used structurally in various climatic conditions which, at times, can be quite severe. To evaluate the effect of environment on the load-duration behavior of structural lumber, a multi-phase research program was developed at Auburn University in cooperation with the Forest Products Laboratory (FPL) of the USDA Forest Service. As a first step in the investigation, the effect of constant thermal loadings on the load-duration relationship was studied and is the focus of this paper.

BACKGROUND

Currently, adjustment factors for load-duration in structural design with wood are based on the "Madison" curve (Wood 1951). This curve was derived from tests of small clear specimens subjected to various ramp and constant applied loads. Since then, a number of researchers (Foschi and Barrett 1982; Gerhards 1977, 1988; Madsen 1971) have found the load-duration response in structural lumber to deviate from the Madison curve. Much research has been conducted

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and various models have been developed to account for the actual effect in lumber (Barrett and Foschi 1978a, b; Gerhards and Link 1987; Johns and Madsen 1982; Madsen and Johns 1982). However, the research and subsequent models have not considered environmental effects. Early tests on small clear Douglas-fir beams (Schniewind 1967; Schniewind and Lyon 1973) subjected to constant load and various environmental conditions indicate that there is an environmental effect present in load-duration. What this effect is on structural lumber, however, is not fully understood.

SCOPE

The purpose of this paper is to present results from the constant temperature phase of the research program. An exponential damage accumulation model modified to account for thermal effects is used to interpret the test results. Subsequent papers will deal with the effects of other imposed environments.

TEST PROGRAM

The experimental program at Auburn University is designed to utilize test results previously obtained at FPL with results of additional experimental work to generate information needed for a better understanding of the load-duration behavior of structural lumber. Therefore, every effort was made to simulate the testing procedures at FPL so that direct comparisons of experimental data could be made.

MATERIALS

Select Structural and No. 2 grade nominal 2-in. by 4-in. by 8-ft Douglas-fir lumber was tested in this investigation and was part of that obtained by FPL from an Oregon mill for use in load-duration studies (Gerhards 1982). At FPL, the lumber was evaluated for modulus of elasticity and sorted into groups of 25 such that, for each grade, each group had similar distributions of moduli. Since in lumber the modulus of elasticity and strength are positively related, this sorting procedure is assumed to provide 25 matched samples for the testing program. The distributions of moduli of the lumber used in this study are summarized in Table 1.

Four groups (100 specimens) of each grade were ramp tested at 73 F and 50% relative humidity (RH) to estimate static strength distributions within each grade. For the purposes of this investigation, the static strength distributions were assumed to be lognormally distributed. Least-squares regressions of the static strength data (Gerhards 1988) yield

$$f_u = 6{,}364 \exp(0.36820R) \tag{1}$$

for the Select Structural lumber, and

$$f_u = 3{,}224 \exp(0.365746R) \tag{2}$$

for the No. 2. In Eqs. 1 and 2, f_u is the ultimate static strength in psi and R is a standard random normal variate. The coefficients of the exponential terms in Eqs. 1 and 2 are the median ultimate strengths in psi. A plot of the natural logarithm of strength versus the normal order R for the Select Structural and No. 2 grade lumber samples is given in Figs. 1 and 2, respectively. These plots should be

TABLE 1. *Modulus of elasticity distributions of test groups.*

Test condition (°F/%RH)	Load type	Sample size	Modulus of elasticity (10^6 psi)	Standard deviation (10^6 psi)
		Select Structural		
73/50	ramp	100	1.861	0.27
73/50	constant	50	1.862	0.26
100/50	constant	25	1.850	0.27
130/50	constant	25	1.851	0.27
		No. 2		
73/50	ramp	100	1.393	0.24
73/50	constant	50	1.392	0.24
100/50	constant	25	1.394	0.25
130/50	constant	25	1.390	0.24

linear if the assumption of a lognormal distribution is true. The scatter of data in the lower portion of the curves comes from the inclusion of ramp failures in the constant load tests. Note that the coefficients on R in Eqs. 1 and 2 are close approximations of the coefficients of variation (COV).

It is noted here that short-term tests were not conducted at the higher temperatures to establish baseline strengths at each condition. Future testing under cyclic environmental conditions prohibited the definition of such a baseline.

Loading apparatus and instrumentation

Seven test frames were built to allow the simultaneous testing of 28 specimens in a computer controlled environmental chamber (Fig. 3). A simple span of 84 in. was provided with load applied symmetrically 24 in. about midspan, the same as that used for the static strength ramp tests. The load was applied using a cantilever and pulley system with an actual mechanical advantage of approximately 7. (A pneumatic loading system was used at FPL). Constant loads based on the 15th percentile of the 73 F static strength distributions of each grade were used to test the beams: 4,104.5 psi for the Select Structural and 2,248.2 psi for the No. 2 specimens. Lateral bracing was provided at the supports.

Midspan deflections were read using rotary potentiometers. A deflection chain was attached to each beam at midspan which, as the beam deflected, fell through a toothed wheel mounted on the potentiometer's shaft. Times to failure and partial failure were found by analyzing the deflection versus time data. Also, elapsed timers were connected via microswitches to the beams. When the beams failed, the switches would stop the timers, yielding elapsed time-to-failure.

Procedures

The lumber samples were stored in an environment of 73 F and 50% RH, resulting in average group equilibrium moisture contents of 10%. Three different constant temperature levels were used in this investigation: 73 F, 100 F, and 130 F. A constant 50% RH was maintained for all tests. At Auburn University, one group of each grade was tested at each of the two higher temperature levels; two groups of each grade were previously tested at FPL under the 73 F condition. The moisture content of each beam was determined in the storage condition. The

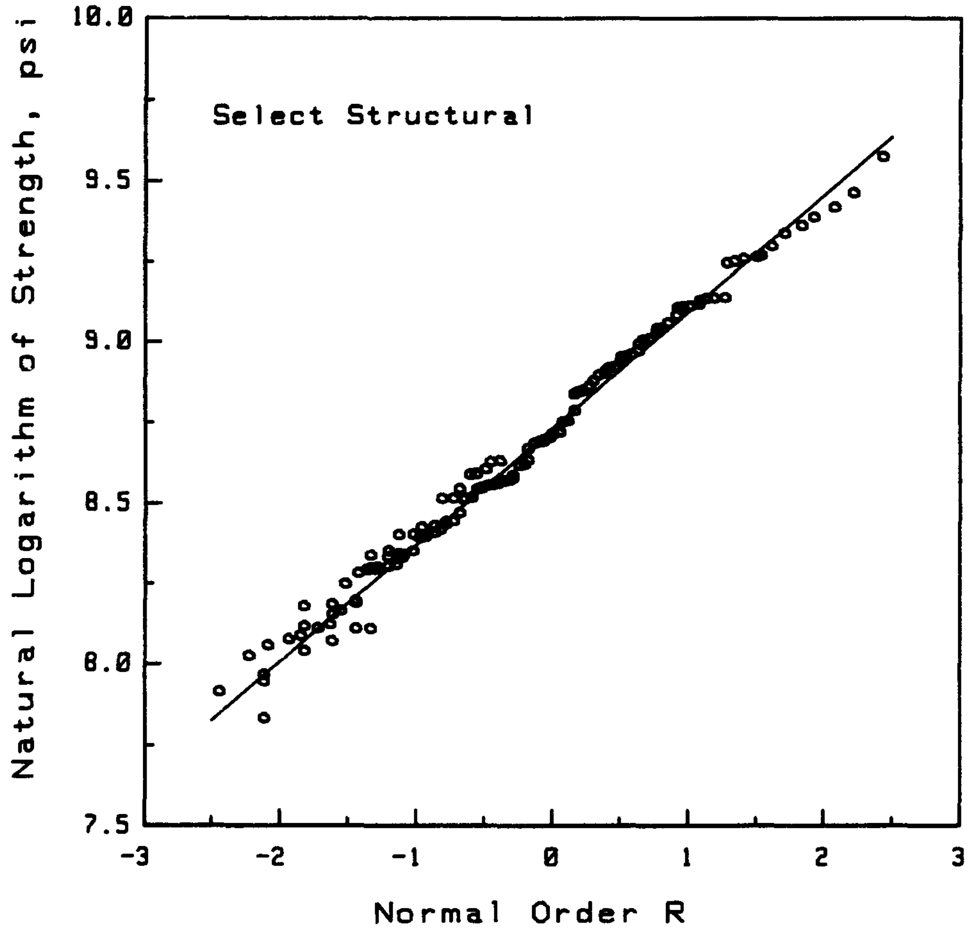

FIG. 1. Strength distribution of Select Structural Douglas-fir lumber sample (from Gerhards 1988).

beams then were brought into the test environment, allowed to equilibrate, and loaded. When the load was applied, the elapsed timer was started and an initial deflection measurement was made. Deflection data were stored directly into computer files in increments of 0.02 in. At the time of failure, the moisture content was again measured and deflection data were compared to the elapsed timer to obtain the actual time-to-failure. Daily observations were made to monitor and record any partial failures. These were likewise compared to the deflection data to match failure occurrences with creep behavior. As beams failed through time, new beams were loaded until all 25 specimens were loaded. The testing continued until the last loaded beam had been loaded for at least seven weeks. This procedure resulted in a failure rate of at least 50% in each temperature environment.

MODELING APPROACH

Since the failure of wood is known to be affected by a creep-rupture phenomenon, a cumulative damage approach to modeling (Miner 1945) load-duration seems appropriate. The damage model that could be used to define the load-

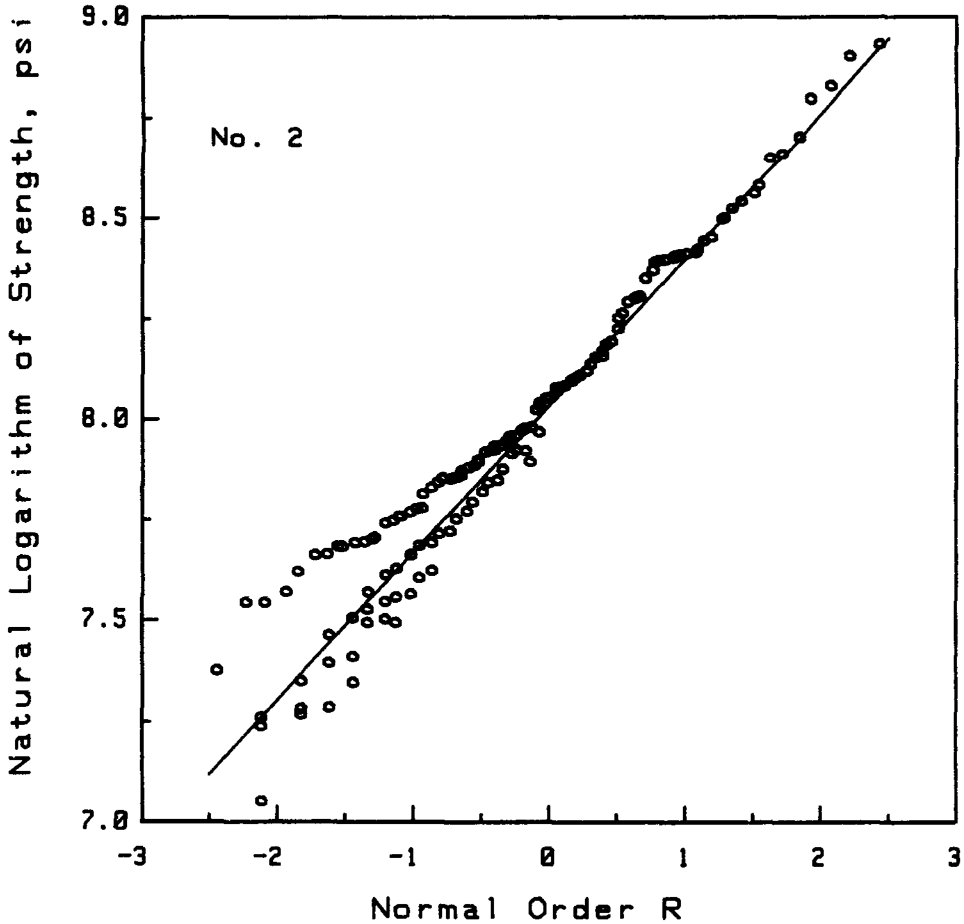

FIG. 2. Strength distribution of No. 2 Douglas-fir lumber sample (from Gerhards 1988).

duration response should include all factors perceived to affect failure (Hwang and Han 1986) and can be written in the general form

$$d\alpha/dt = F(\sigma, T, RH, MC, \ldots) \qquad (3)$$

where α is a damage parameter, $d\alpha/dt$ is the time rate of damage accumulation, F is a general functional defining $d\alpha/dt$ with the independent functions being the stress ratio, σ, temperature, T, relative humidity, RH, moisture content, MC, etc. The damage parameter, α, ranges from zero, meaning no damage, to unity, indicating failure. The stress ratio, σ, is defined as the applied stress, which is in general a function of time, divided by the member static strength found in a conventional pseudo-static strength test. Also, the temperature, relative humidity, moisture content, and any other parameters can be functions of time.

In order to simplify modeling, a separation of parameters into independent multiplicative functionals (Hwang and Han 1986) is performed. The following relationship is therefore assumed:

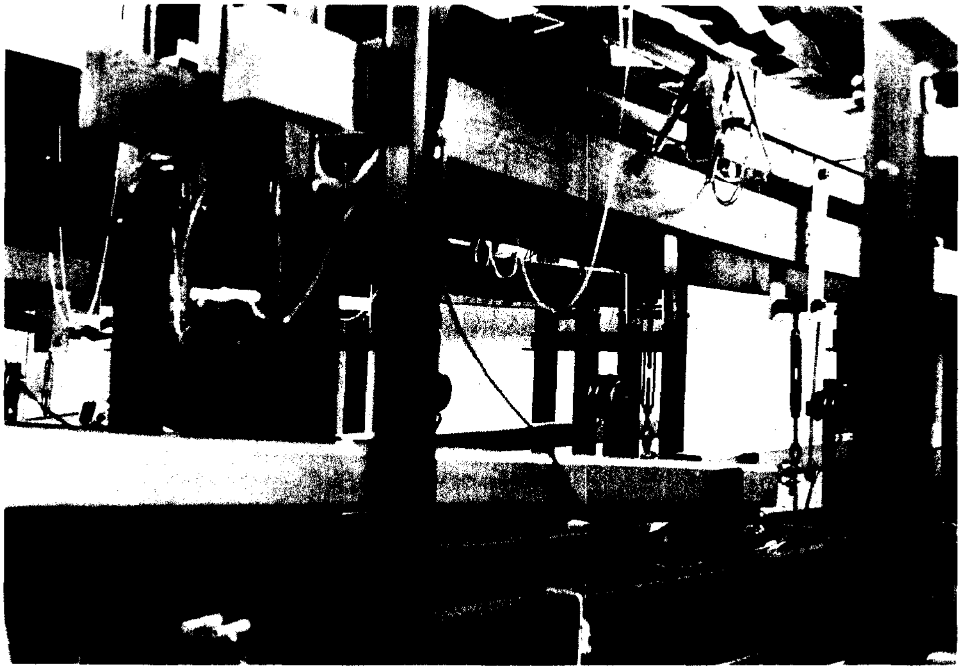

FIG. 3. Load-duration test facility at Auburn University.

$$d\alpha/dt = f(\sigma)g(T)h(RH)k(MC)\ldots \tag{4}$$

Several cumulative damage models have been proposed to define the load-duration condition, but environmental effects were not considered in the model development. Barrett and Foschi (1978a, 1978b) presented two models, both of which include the stress ratio as a function of time and a damage dependent factor as independent variables. The two models also include a stress threshold factor below which no damage is accumulated. A third damage model has been proposed by Gerhards (1979) and Gerhards and Link (1987). In this model, the rate of damage accumulation is related exponentially to the applied stress ratio. No stress threshold is assumed in this model.

The selection of one of these damage models to define the function $f(\sigma)$, and any other nonenvironmental functions in Eq. 4, would depend on model fit at some bench mark environmental conditions. Since the exponential damage model has been shown to adequately represent the load-duration response of the lumber samples used in this investigation in an environment of 73 F and 50% RH (Gerhards 1988; Gerhards and Link 1987), it will be used here to model other temperature levels.

As presented by Gerhards and Link (1987), the damage model may be written as

$$d\alpha/dt = \exp(-A + B\sigma) \tag{5}$$

where A and B are model constants to be determined from experimental data and all other parameters are as defined previously. Substituting this relationship into Eq. 4 yields

$$d\alpha/dt = g(T)h(RH)\exp(-A + B\sigma) \tag{6}$$

It will be assumed at this point that any moisture content effect is included in the temperature and relative humidity factors.

The functions g(T) and h(RH) should be defined so that they equal unity when the environment is the same as the assumed bench mark environment. Since the relative humidity is held constant at 50% throughout the testing program, h(RH) can be assumed to be unity.

The form of g(T) will be assumed the same as the stress function, that is

$$g(T) = \exp(-C + D\tau) \tag{7}$$

where τ is a temperature ratio defined as the actual temperature divided by the bench mark temperature, and C and D are constants related to the temperature variable. It should be noted that the temperature ratio and subsequent model constants depend on the temperature scale being used.

In order for g(T) to equal unity when τ equals one, C must equal D; it follows that

$$g(T) = \exp[C(\tau - 1)] \tag{8}$$

The damage model then can be written to include the temperature factors as follows:

$$d\alpha/dt = \exp[-A + B\sigma + C(\tau - 1)] \tag{9}$$

where A, B, and C are model constants as previously defined.

Since, in this investigation, σ and τ are constant through time and the time-to-failure is considered to be long in comparison to the ramp time to achieve σ, Eq. 9 can be integrated to yield an expression for time-to-failure:

$$t_f = \exp[A - B\sigma - C(\tau - 1)] \tag{10a}$$

or,

$$\ln(t_f) = A - B\sigma - C(\tau - 1) \tag{10b}$$

where t_f is the time-to-failure under constant load and temperature.

In choosing the exponential form for g(T), a linear shift in the load-duration response with respect to the logarithm of time is predicted. That is, for any particular constant stress ratio, the logarithm of time-to-failure is inversely proportional to the temperature ratio.

An alternative approach is to define the static strength of each lumber member as a function of the environment thereby changing the stress ratio, σ. This approach would produce a shift in the response proportional to the change in static strength. The difficulty of this approach lies in the definition of the static strength of a member under more complicated environmental histories. Therefore, the multiplicative functional approach will be used to define the load-duration response.

RESULTS AND DISCUSSION

Load-duration relationships traditionally have been presented as functions of stress ratio, σ. The stress ratio for a given member was determined in this investigation using the equal rank assumption; that is, a specimen that fails under

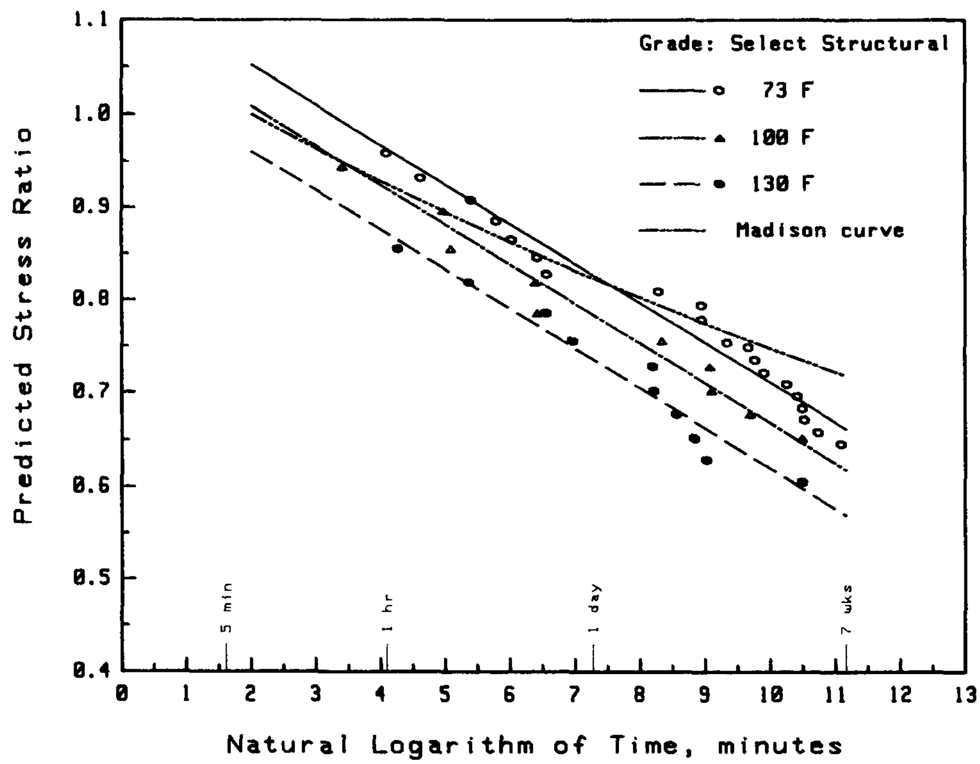

FIG. 4. Load-duration response of Select Structural Douglas-fir lumber at 73 F, 100 F, and 130 F.

constant load will have the same rank in time as it would in static strength (Murphy 1982). Therefore, the predicted static strength for any failed beam under constant load can be estimated using the least-squares regressions of the static strength data, Eqs. 1 or 2, with its appropriate random normal variate, R.

A plot of the predicted stress ratio against the natural logarithm of time-to-failure under constant load in environmental conditions of 73 F, 100 F, and 130 F and 50% RH is given in Figs. 4 and 5 for the Select Structural and No. 2 grade lumber, respectively. The data for the 73 F and 50% RH condition in both figures originally were presented by Gerhards (1988). His data included three loading levels: high, medium, and low. Only the "medium constant" load data are used here since they correspond directly with the loads used at the higher temperatures.

Data not included in Figs. 4 and 5 are the failures that occurred during the ramp loading and the first 15 minutes of constant load. These failures were not considered in the modeling procedures to allow the effect of ramp loading to be neglected. Also not included in Figs. 4 and 5 are the data from those beams which survived the entire loading period.

Figures 4 and 5 illustrate the extreme sensitivity of the time-to-failure to the applied stress ratio. Since the data are plotted on a logarithmic scale, small changes in the stress ratio can produce changes in the order of magnitude of the time-to-failure. Therefore, the prediction of the load-duration response using Eq. 10b will be sensitive to the constant B that is associated to the applied stress ratio, σ.

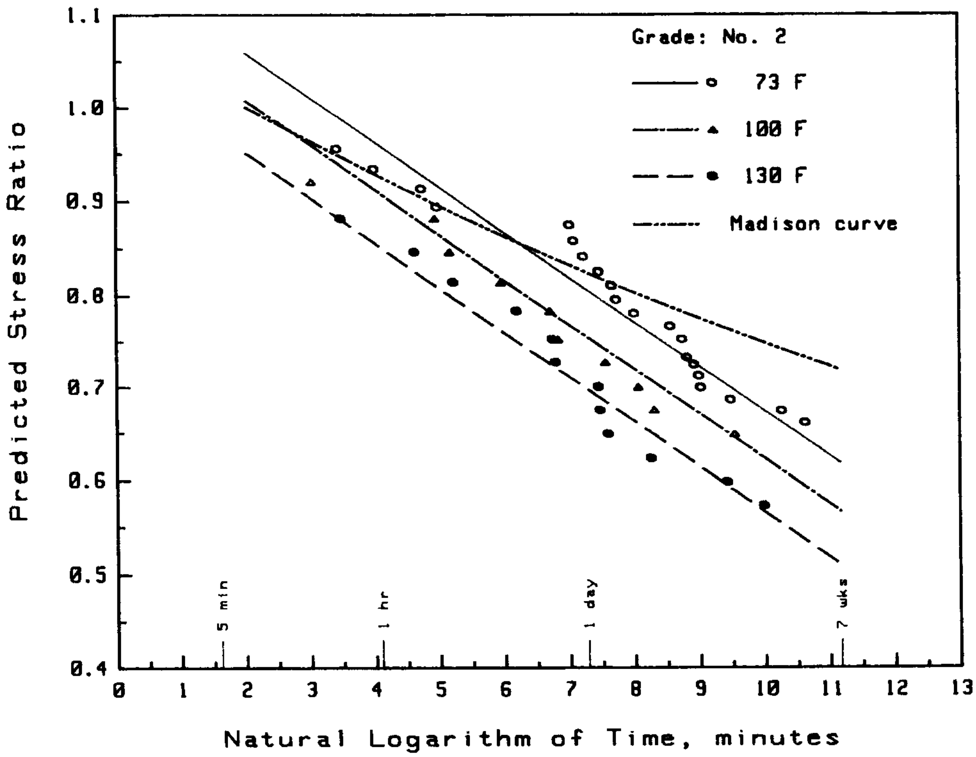

FIG. 5. Load-duration response of No. 2 Douglas-fir lumber at 73 F, 100 F, and 130 F.

A multivariate least-squares regression analysis was performed to determine the model constants A, B, and C in Eq. 10b for each grade of lumber. The stress ratio and the temperature factor, $\tau - 1$, were selected as the independent variables in the analysis with the natural logarithm of time-to-failure as the dependent variable. The variables were chosen in this manner so that the life of a given beam can be determined at some specified stress ratio and temperature ratio. Also, 73 F was selected as the bench mark temperature since most load-duration experiments were run at approximately that level.

The equations for the regression lines of the Select Structural (SS) and No. 2 data in Figs. 4 and 5 are then

$$\text{SS: } \ln(t) = 26.626 - 23.410\sigma - 2.742(\tau - 1) \tag{11}$$

TABLE 2. *Statistics of regression analysis.*

Statistic	Grade	
	Select Structural	No. 2
Standard deviation about regression	0.42	0.43
Coefficient of multiple determination	0.96	0.95
95% confidence limit on A	25.50–27.75	22.85–25.05
B	21.95–24.86	19.31–22.15
C	2.32–3.16	2.45–3.27

TABLE 3. *Moisture contents.*

Storage EMC (%)	Final EMC (%)	Temperature (F)
	Select Structural	
9.7	9.7	73
9.9	9.6	100
10.1	9.9	130
	No. 2	
9.7	9.7	73
10.0	9.8	100
10.1	9.7	130

and

$$\text{No. 2: } \ln(t) = 23.954 - 20.733\sigma - 2.864(\tau - 1) \quad (12)$$

where t is the time-to-failure in minutes (the subscript f has been dropped for convenience). The standard deviation about the regression, the coefficient of multiple determination, and the 95% confidence limits on each of the regression coefficients are listed in Table 2.

It is evident from Figs. 4 and 5 and Eqs. 11 and 12 that the load-duration behavior of lumber is adversely affected by elevated thermal loadings. However, the National Design Specifications (NDS) for Wood Construction (NFPA 1986) recommend reductions in strength properties for lumber subjected to prolonged exposure to temperatures greater than 150 F. This seems unconservative since the results here show adverse effects in the long-term behavior at a temperature as low as 100 F.

It should be stated that the observed effects are believed to be primarily due to temperature. This is supported by the fact that little change in individual or group moisture contents was observed. Table 3 lists the average group moisture contents in the storage condition (73 F and 50% RH) and the average group moisture contents at failure.

For comparative purposes, the curve proposed by Wood (1951), which is used as the basis for current load-duration design factors in the NDS (NFPA 1986), is plotted in Figs. 4 and 5 and is of the form:

$$t = 0.0949/(\sigma - 0.183)^{21.575} \quad (13)$$

where again t is the time-to-failure in minutes and σ is the applied stress ratio. It can be seen from both figures that the Madison curve becomes increasingly unconservative with increased temperature and longer load-durations.

A three-dimensional plot of Eqs. 11 and 12 is given in Fig. 6. The load-duration planes defined in Fig. 6 for each grade illustrate the combined effects of both temperature and time. Although the load-duration planes for each grade differ, that is, No. 2 grade lumber loaded at the same stress ratio and temperature tends to have shorter load-durations than Select Structural lumber, the difference may not be statistically significant within the constraints of this study. This observation agrees with Gerhards' conclusion (1988).

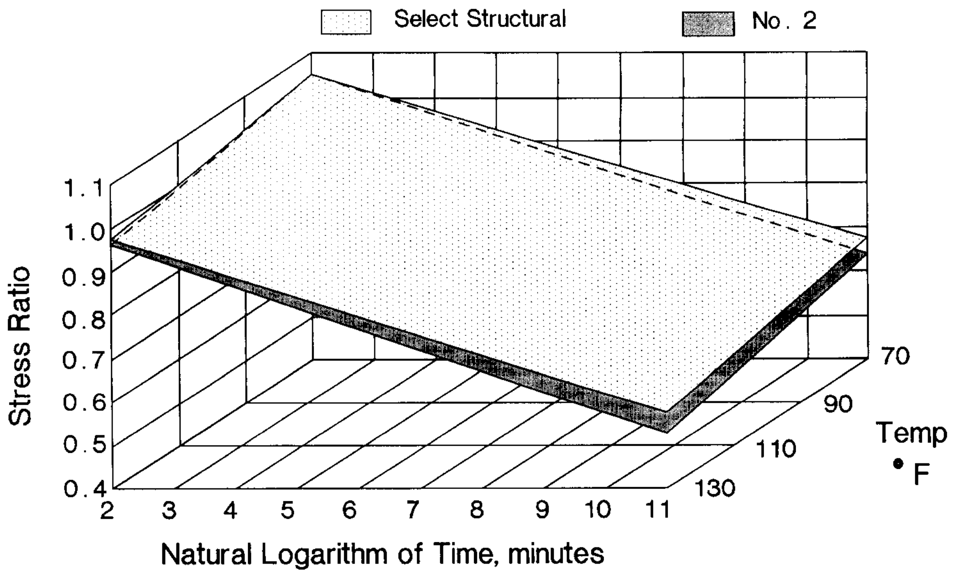

FIG. 6. Comparison of load-duration relationships including grade and temperature.

CONCLUSIONS

The results from this study indicate a trend to shorter times-to-failure at higher temperatures for equal stress ratios. An exponential damage accumulation model previously shown to predict the load-duration behavior of the Douglas-fir lumber at 73 F and 50% RH was modified to account for temperature. The modified model adequately predicted the observed temperature-dependent load-duration behavior within the load, time, and temperature constraints of the experiment.

In this investigation, the applied stress ratios were extremely high and, therefore, times-to-failure were short (less than 7 weeks). It is believed, though, the basic trend of the temperature effect can be predicted over time. As low stress load-duration data becomes available, such as the 10-year tests at FPL, these results from high stress ratios can be used as a basis for modeling long-term temperature effects.

The temperature effects observed in this investigation are believed to be independent of moisture content or relative humidity since tight control on the relative humidity was maintained and little change in individual or group moisture contents was observed. The effect of changing temperature and relative humidity on the load-duration behavior of solid lumber will be reported in separate articles.

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APPENDIX: S.I. EQUIVALENTS

$$1 \text{ psi} = 6.89 \text{ kPa}$$
$$1 \text{ in.} = 25.4 \text{ mm}$$
$$°\text{F} = 32 + 9/5°\text{C}$$

The following equations are rewritten using S.I. units:

$$\text{SS: } \ln(t) = 26.626 - 23.410\sigma - 1.014(\tau - 1) \quad (11)$$
$$\text{No. 2: } \ln(t) = 23.954 - 20.733\sigma - 1.060(\tau - 1) \quad (12)$$

where τ is the temperature ratio with 22.8 C used as the bench mark temperature.