THERMAL EFFECTS ON LOAD-DURATION BEHAVIOR OF LUMBER. PART II: EFFECT OF CYCLIC TEMPERATURE

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ABSTRACT

The effect of a cyclic thermal loading on the load-duration behavior of structural lumber in bending is presented. Select Structural and No. 2 grade Douglas-fir nominal 2 by 4 beams were tested under a constant bending load to determine time-to-failure. Two cyclic temperature environments were used in the investigation: 73 F to 100 F and 73 F to 130 F on a 24-hour cycle with a constant 50% relative humidity. An exponential damage accumulation model with a temperature factor was used to predict the observed times-to-failure. The damage model originally was fitted and calibrated using load-duration data from equivalent lumber samples subjected to constant temperature environments. The model predicted quite well the observed times-to-failure in the cyclic temperature environments. This is quantified using a standard errors analysis between the model predictions and the observed cyclic temperature data. These errors are comparable to those observed with the constant temperature data which were used to determine the model constants.

Keywords: Load-duration, lumber, damage model, temperature.

INTRODUCTION

A multi-phased research program having the overall goal to evaluate and model the effect of the environment on the load-duration, also known as creep-rupture, behavior of structural lumber is currently in progress at Auburn University and is conducted in cooperation with the United States Department of Agriculture, Forest Service, Forest Products Laboratory (FPL). The first phase, which has already been completed (Fridley et al. 1989), involved the testing and modeling of the load-duration behavior in various constant temperature environments. Since little information is available with respect to cyclic temperature, the second phase of the research program was designed to investigate and model the load-duration behavior of lumber under cyclic temperature and constant humidity environments and is the focus of this paper.

BACKGROUND

Adjustment factors for load-duration in structural design with wood currently are based on what is often referred to as the "Madison" curve. The Madison curve is based on experimental data from extensive load-duration tests on small clear samples of wood (Wood 1951). However, the design factors derived from the curve are applied indiscriminately to all wood members subjected to any loading scheme. The validity of extrapolating the load-duration behavior of small clear specimens to that of full-size structural lumber may be questioned. In fact, a number of researchers have reported the load-duration behavior in structural lumber to deviate somewhat from the Madison curve (Foschi and Barrett 1982; Gerhards 1977, 1988; Madsen 1971; Madsen and Barrett 1976). Several damage accumulation models (Barrett and Foschi 1978a, b; Gerhards 1979; Gerhards and Link 1987) have been developed to model the actual load-duration behavior in structural lumber. Also, a fracture mechanics approach has been used by several investigators (Johns and Madsen 1982; Madsen and Johns 1982; Nielson 1985a, b).

Previous research and model developments have been conducted typically in mild environmental conditions with no consideration toward environmental effects. Early creep-rupture tests on small clear wood beams subjected to constant loads and various temperature and relative humidity conditions indicated a definite effect on the long-term behavior (Schniewind 1967; Schniewind and Lyon 1973). Fridley et al. (1989) found that temperature likewise affects the long-term behavior of structural lumber. The current investigation concerns the load-duration behavior of structural lumber in cyclic temperature environment.

PREDICTIVE MODEL

Although several approaches for modeling the load-duration behavior of structural lumber are available, a cumulative damage approach has been selected in this investigation. The cumulative damage approach is well suited for materials governed by the creep-rupture phenomenon (Miner 1941) and has been used successfully in previous load-duration research (Foschi and Barrett 1982; Gerhards 1988).

A model originally proposed by Gerhards (1979) and Gerhards and Link (1987) was modified by Fridley et al. (1989) to account for temperature effects. The modified damage model can be written as follows:

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

where α is a damage parameter, $d\alpha/dt$ is the time rate of damage accumulation, σ is the applied stress ratio, τ is a temperature factor, and A, B, and C are model constants to be determined from experimental data. The damage parameter, α, ranges from zero, meaning no damage, to unity, which means failure. The applied stress ratio, σ, is defined as the applied stress, which is generally a function of time, divided by the ultimate static strength of the member found in a conventional ramp-load test. The temperature factor, τ, is the fractional change in temperature from some bench mark value, or

$$\tau = \frac{T - T_0}{T_0} \qquad (2)$$

where T is the actual temperature and T_0 is the bench mark temperature. Notice that there is no contribution from temperature when the actual temperature equals the bench mark temperature.

Equation (1) can be integrated directly when σ and τ are either constant or linear functions in time. Assuming constant σ and τ, integration of Eq. (1) yields the following expression for the amount of damage, $\Delta\alpha_i$, occurring during an interval of time, Δt_i:

$$\Delta\alpha_i = \Delta t_i \exp[-A + B\sigma + C\tau] \tag{3}$$

If τ is assumed constant and σ is assumed to be a linear function in time, or $\sigma = k_\sigma t$, then Eq. (1) can be integrated to yield the following:

$$\Delta\alpha_i = \frac{1}{Bk_\sigma}\{\exp[-A + Bk_\sigma\Delta t_i + C\tau] - \exp[-A + C\tau]\} \tag{4}$$

Likewise, if σ is assumed constant and τ is assumed to be a linear function in time, or $\tau = k_\tau t$, then Eq. (1) can be integrated to yield

$$\Delta\alpha_i = \frac{1}{Ck_\tau}\{\exp[-A + B\sigma + Ck_\tau\Delta t_i] - \exp[-A + B\sigma]\} \tag{5}$$

In the constant temperature phase of the investigation (Fridley et al. 1989), σ and τ were both constant through time and the times-to-failure were long in comparison to the ramp time to achieve σ. This second fact allowed the damage due to the ramp loading, Eq. (4), to be neglected. Equation 3 was then solved for the time-to-failure by substituting in $\Delta\alpha_i = 1$ and solving for Δt_i, that is

$$t_f = \exp[A - B\sigma - C\tau] \tag{6}$$

or,

$$\ln(t_f) = A - B\sigma - C\tau \tag{7}$$

where t_f is the time-to-failure under constant load and temperature. This situation was especially convenient in determining the model coefficients since linear multivariate fitting procedures could be used.

However, when either σ or τ are arbitrary functions of time, then the integration of Eq. (1) can become undefined, and approximate series solutions must be employed. The use of approximate series solutions to integrate and solve Eq. (1) quickly becomes cumbersome, and evaluation of model constants from experimental data becomes difficult, if not impossible. Therefore, in this investigation, the damage model constants A, B, and C were determined using data from constant temperature environments and are used to predict the load-duration behavior in cyclic temperature environments.

To predict the time-to-failure of a particular piece of lumber subjected to constant load and a varying temperature environment, a summation of damage until $\alpha = 1$ must be performed. That is, the damage in a member is assumed to accumulate according to

$$\alpha(t) = \sum_{i=1}^{m} \Delta\alpha_i \tag{8}$$

until $\alpha(t) = 1$. By definition, failure occurs when $\alpha = 1$, or

$$t_f = \sum_{i=1}^{m} \Delta t_i \tag{9}$$

Suppose the model constants in Eq. (1) are known, the stress ratio is constant, and the temperature factor is a known history of ramp and constant functions. The damage in a member can be calculated at any point in time by using Eqs. (3), (5), and (8). Throughout this investigation constant loads were used and the times-to-failure were assumed to be long in comparison to the ramp times to achieve σ. Therefore the effect of Eq. (4) was neglected. Once the condition that $\alpha = 1$ was determined, then Eq. (9) was used to calculate the time-to-failure.

It should be noted that this same procedure can be used for arbitrary load histories and combined load and temperature histories; however, this is outside the scope of the current investigation.

A few comments are in order concerning the damage equation (Eq. 1) used in this investigation. First of all, it is assumed that Eq. (1) is valid only if a mechanical stress is applied to the member, that is $\sigma > 0$. This precludes the accumulation of damage due to temperature alone.

The second comment concerns the performance of Eq. (1) to predicting the time-to-failure for a ramp-to-failure load history. If the conditions that $\alpha = 1$ and $\tau = 0$ is substituted into Eq. (4), then the time-to-failure can be determined as

$$t_f = \frac{1}{Bk_\sigma}\{\ln[Bk_\sigma + \exp(-A)] + A\} \tag{10}$$

It is acknowledged that Eq. (10) will not return an exact time-to-failure, that is $t_f = 1/k_\sigma$ since failure should occur at $\sigma = 1 = k_\sigma t$. In fact, Eq. (10) will over predict time-to-failure in a ramp test by about 20%.

Also, it should be noted that the stress ratio is not adjusted for temperature, that is the ultimate static strength is always based on the strength at 73 F and 50% RH. Therefore, all of the temperature effects are wholly included in the τ factor. This may not be as physically acceptable as adjusting the strength for temperature; however, it would be difficult to define the static strength in a cyclic environment. Also, this allows one to see the effect of not accounting for environmental effects on load-duration.

EXPERIMENTAL PROGRAM

Although the cyclic temperature load-duration experiments were conducted entirely at Auburn University, material characterization and a portion of the constant condition load-duration testing was conducted at FPL. Since testing occurred at two locations, care was taken to duplicate testing procedures so that direct comparisons of data were possible. Complete discussions of the experimental program, including materials, load frames, instrumentation, and basic testing procedures can be found in Fridley et al. (1989) and Gerhards (1988). Only the procedures specific to this paper are discussed here.

Materials

Select Structural and No. 2 grade nominal 2 by 4 by 8 ft Douglas-fir lumber was tested. The lumber was sorted into groups of 25 such that, for each grade, each group had similar distributions of flexural moduli of elasticity. Since the modulus of elasticity of lumber is in general assumed to be positively related to strength, the sort was assumed to provide matched samples of 25.

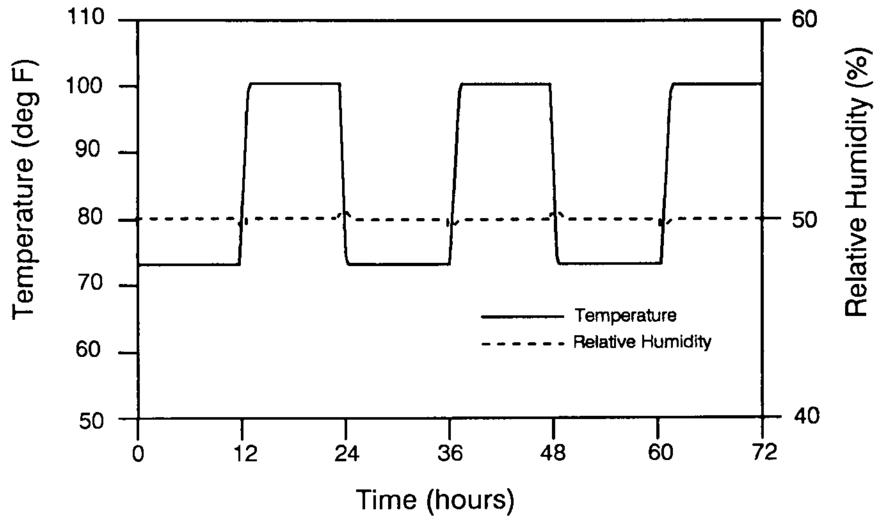

FIG. 1. Imposed 73–100 F temperature cycle.

The strength distribution within each group was determined (Gerhards 1988) to be lognormally distributed according to

$$f_u = 6364 \exp(0.36820R) \quad (11)$$

for the Select Structural lumber, and

$$f_u = 3224 \exp(0.36575R) \quad (12)$$

for the No. 2. In Eqs. (11) and (12), f_u is the ultimate static strength in psi and R is a standard random normal variate. Also, the tests run to determine the above two equations were conducted at 73 F and 50% RH.

Testing procedures

The lumber samples were tested in bending over a 84-in. span. Concentrated point loads were applied symmetrically 12 in. from midspan. Deflections at midspan were monitored continuously through a dedicated data acquisition unit. All tests were conducted inside an environmentally controlled chamber.

To investigate the effect of cyclic temperature environments on the load-duration behavior of lumber, two semi-square temperature cycles were used. The cycles were run on a 24-h period with a lower temperature bound of 73 F and upper temperature bounds 100 F and 130 F. The reason the cycles are termed semi-square is that since instantaneous temperature changes in the testing chamber are impossible, 1-h ramp changes were used. A constant 50% RH was maintained throughout the temperature cycling. A sample of each of the temperature cycles is illustrated in Figs. 1 and 2.

Each beam was moved into the test chamber and loaded at the beginning of the low temperature cycle. Constant loads based on the 15th percentile of the static strength distributions for each grade were used to load the beams: 4,104.5 psi for the Select Structural and 2,248.2 psi for the No. 2 specimens. As the beams were loaded, elapsed timers were started and initial deflection measurements were

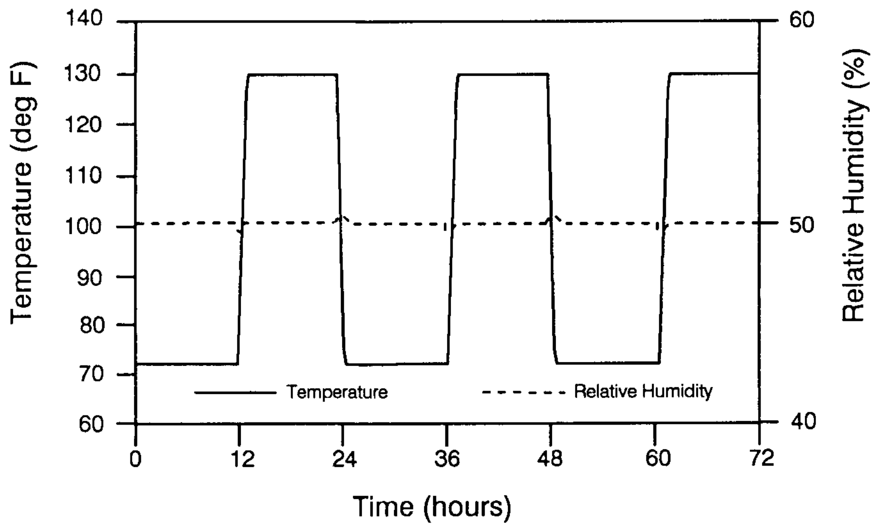

FIG. 2. Imposed 73–130 F temperature cycle.

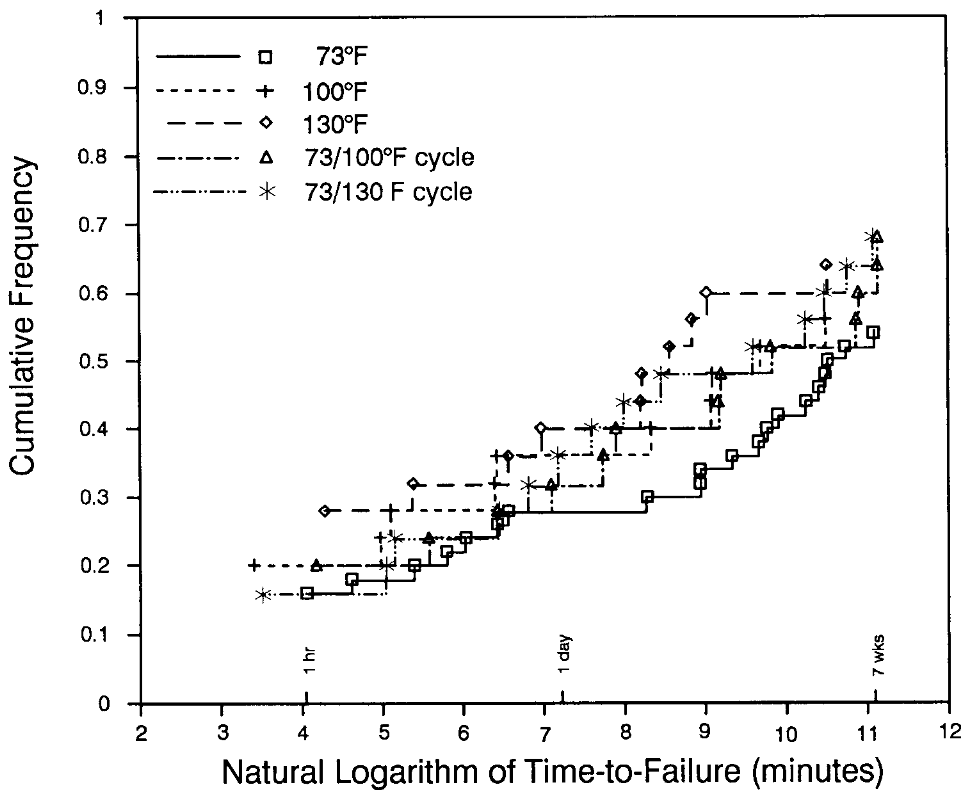

FIG. 3. Cumulative frequency cistribution of times-to-failure for Select Structural lumber.

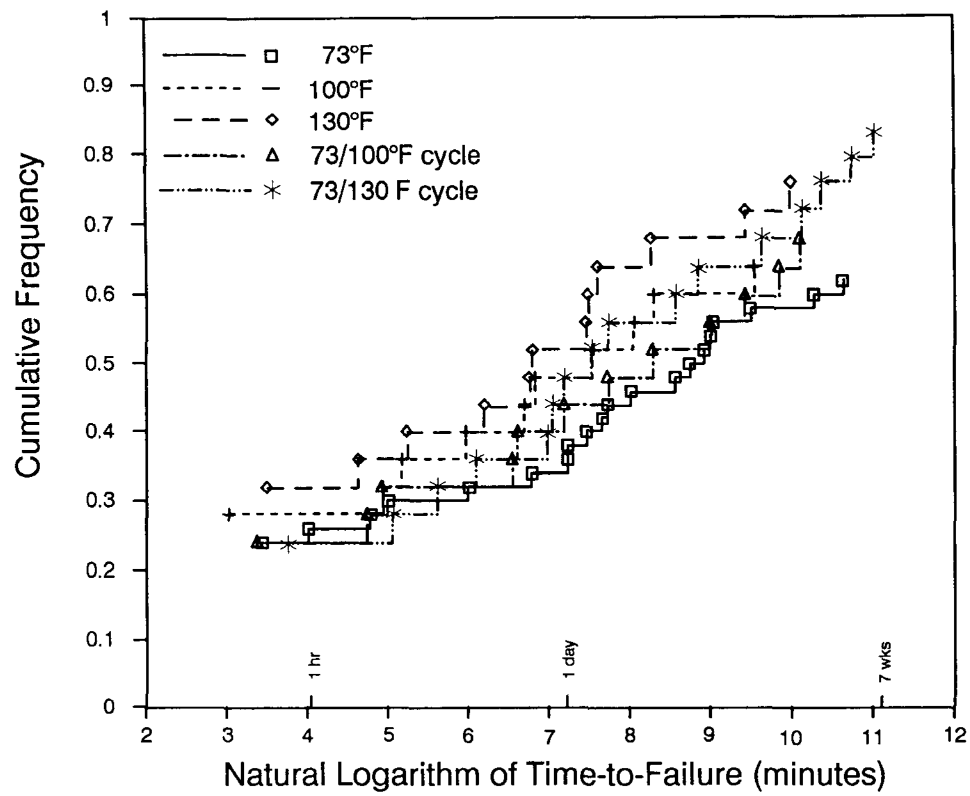

FIG. 4. Cumulative frequency distribution of times-to-failure for No. 2 lumber.

made. Failed beams were replaced with new beams at the initiation of a low temperature cycle until all specimens had been loaded. Testing continued until the last loaded beam had been tested for at least 7 weeks and at least 50% of the specimens of each grade group had failed.

RESULTS AND DISCUSSION

The times-to-failure for the two lumber samples subjected to constant load and the semi-square temperature cycles were ranked in time. The corresponding cumulative frequency distributions are plotted in Figs. 3 and 4 for the Select Structural and No. 2 grade lumber samples, respectively. Data not included in Figs. 3 and 4 are the failures that occurred during the ramp loading and the first 15 min of constant load. These failures were not considered in the modeling procedures to allow the effects of ramp loading to be neglected. Also not included in Figs. 3 and 4 are the data from those beams that survived the entire loading period. Table 1 summarizes how many beams failed during each section of time and how many beams survived. The cumulative frequency distributions from data originally reported by Gerhards (1988) and Fridley et al. (1989) for similar lumber samples subjected to constant load and constant temperature environments of 73 F, 100 F, and 130 F also are included in Figs. 3 and 4. These constant temperature

TABLE 1. *Summary of failures in cyclic temperature environments.*

Event	Number of occurrences	
	Select structural	No. 2
73/100 F cycle:		
Ramp loading	4	4
First 15 min of test	0	1
During a 73 F cycle	5	4
During a ramp to 100 F	2	3
During a 100 F cycle	6	4
During a ramp to 73 F	0	1
Survived test	8	8
73/130 F cycle:		
Ramp loading	3	4
First 15 min of test	0	1
During a 73 F cycle	4	5
During a ramp to 130 F	3	5
During a 130 F cycle	7	5
During a ramp to 73 F	2	1
Survived test	6	4

data originally were used to evaluate the proposed damage model, Eq. (1), and determine the model constants A, B, and C. Again, the failures that occurred during the ramp loading and those that occurred during the first 15 min of constant load were not considered in the modeling and model calibration procedures.

Referring to Table 1, a majority of the failures during the imposed cyclic temperature environment occurred during either the ramp to high temperatures or the high temperature cycles. This indicates that temperature indeed influences the load-duration behavior of structural lumber.

Load-duration relationships for wood traditionally have been presented as functions of the stress ratio, σ. Since both the static strength and long-term strength of a given piece of lumber cannot be simultaneously determined, the stress ratio for a given piece of lumber was determined using the equal rank assumption. The equal rank assumption eliminates the statistical prediction of strength by assuming that a specimen that fails under a constant load will have the same rank in time as it would in a static strength (Murphy 1982). Therefore, the predicted static strength for any failed piece of lumber under a constant load can be estimated using the least squares regressions of the static strength data, either Eq. (11) or (12) depending on the grade, and the appropriate random normal variate.

Figures 5 and 6 illustrate the experimentally observed relationships between the predicted applied stress ratios and the natural logarithms of the times-to-failure for the two grades of lumber subjected to a constant load and the cyclic temperature environments. Also included in Figs. 5 and 6 are the load-duration data originally reported by Gerhards (1988) and Fridley et al. (1989) for similar lumber samples subjected to identical mechanical loadings and constant temperature environments of 73 F, 100 F, and 130 F.

Fridley et al. (1989) evaluated the model constants A, B, and C, using Eq. (7) and data from the three constant temperature environments. The resulting damage models, Eq. (1), then can be written for the two grades as follows:

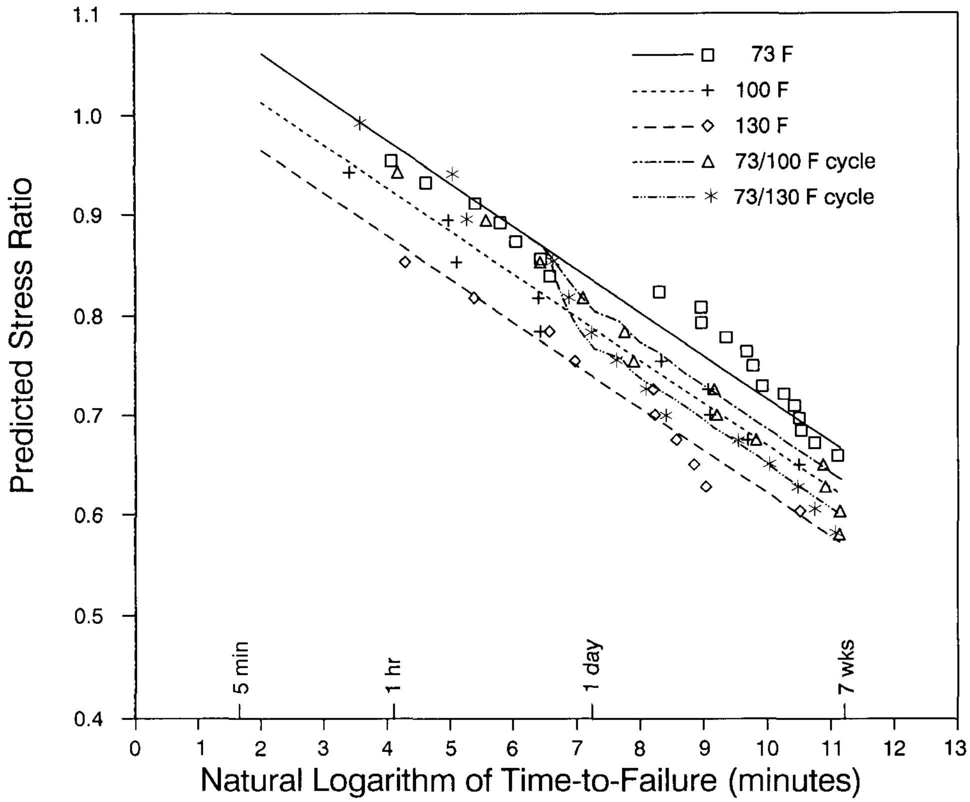

FIG. 5. Relationship between predicted stress ratio and the natural logarithm of time-to-failure for Select Structural lumber.

$$\text{SS: } d\alpha/dt = \exp[-26.626 + 23.410\sigma + 2.742\tau] \tag{13}$$

and

$$\text{No. 2: } d\alpha/dt = \exp[-23.954 + 20.733\sigma + 2.864\tau] \tag{14}$$

The integrated forms of Eqs. (13) and (14) are plotted with the constant temperature data in Figs. 5 and 6, respectively.

The constants A, B, and C determined from the constant temperature data were used in Eqs. (3), (5), (8), and (9) to predict the load-duration behavior in the cyclic temperature environment. The predicted load-duration curves for each grade corresponding to the imposed temperature cycle are illustrated in Figs. 5 and 6. Qualitatively, the cyclic temperature load-duration curve seems to fit the experimental data as well as the constant temperature curves fit their respective data. This match in fit indicates a prediction with an accuracy equivalent to that obtained in the original model development. Also, plots of the predicted natural logarithm of time-to-failure versus the observed natural log time-to-failure for Select Structural and No. 2 lumber are plotted in Figs. 7 and 8, respectively. Since the data are gathered uniformly around 45 degree lines in Figs. 7 and 8, the

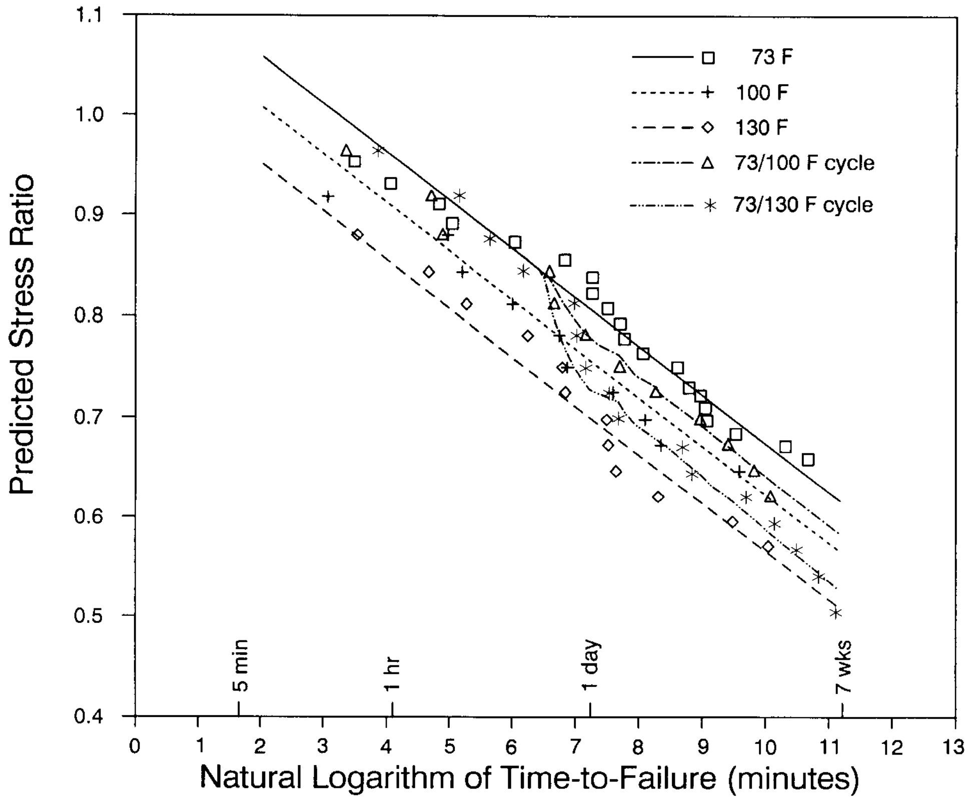

FIG. 6. Relationship between predicted stress ratio and the natural logarithm of time-to-failure for No. 2 lumber.

prediction of the time-to-failure seems reasonable. This observation is supported by an errors analysis for all of the data sets.

Table 2 lists the standard percentage errors associated with the prediction of the three constant temperature data sets, which originally were used to evaluate the model constants, and the standard percent error associated with the prediction of the cyclic temperature data sets. In the error analysis, the dependent variable was chosen as the natural logarithm of time-to-failure and the independent variables as the applied stress ratio and the temperature factor. The variables were chosen in this manner so the life of a given member can be evaluated as a function of the loading and environment.

As evidenced in Table 2, the errors associated with the prediction of the cyclic temperature data are very comparable to those of the constant temperature data. A certain amount of uncertainty and variability is common with lumber since it is a biological material and possesses natural grain and knot characteristics as well as processing variation. Also, a certain amount of uncertainty is present in the equal rank assumption for the prediction of the static strength of a given piece of lumber. This uncertainty directly affects the determination of the applied stress ratio, σ. Nonetheless, the errors associated with any of the load-duration predictions in Table 2 certainly are within an acceptable tolerance.

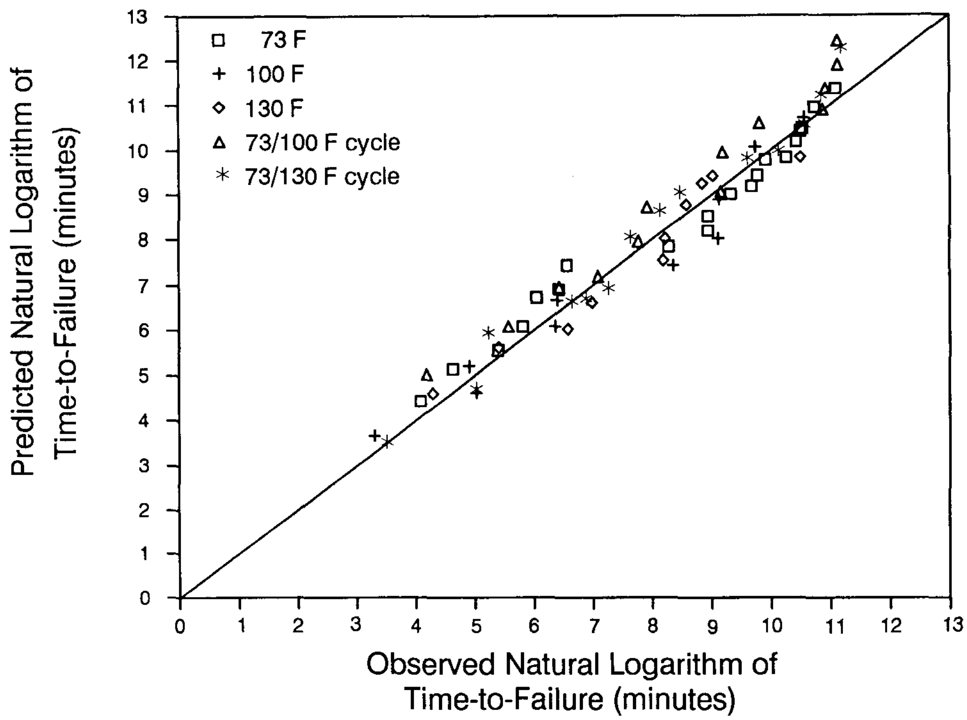

FIG. 7. Relationship between predicted and observed natural logarithm of time-to-failure for Select Structural lumber.

The extreme sensitivity of the time-to-failure to the applied stress ratio is noticed in Figs. 5 and 6. Since the data are plotted on a logarithmic scale, small changes in the applied stress ratio can produce changes in the order of magnitude of the time-to-failure. This sensitivity to the applied stress ratio is evident with respect to the coefficient B in the damage model, and any predictions using the model will be sensitive to σ.

It should be noted that the observed load-duration behavior of the lumber sample in the cyclic temperature environment is believed to be a result of the applied stress and the temperature environment; that is, no hygroscopic effects were assumed to be present. This is supported by the fact that moisture contents of each specimen were measured before loading and after failure, and little change in individual elements or groups was observed during the test program. Average

TABLE 2. *Errors in predictive modeling.*

Temperature environment	Standard errors of predictions (%)	
	Select Structural	No. 2
73 F	20.7	16.3
100 F	20.8	21.5
130 F	15.9	19.4
73/100 F cycle	20.8	15.9
73/130 F cycle	18.8	19.9

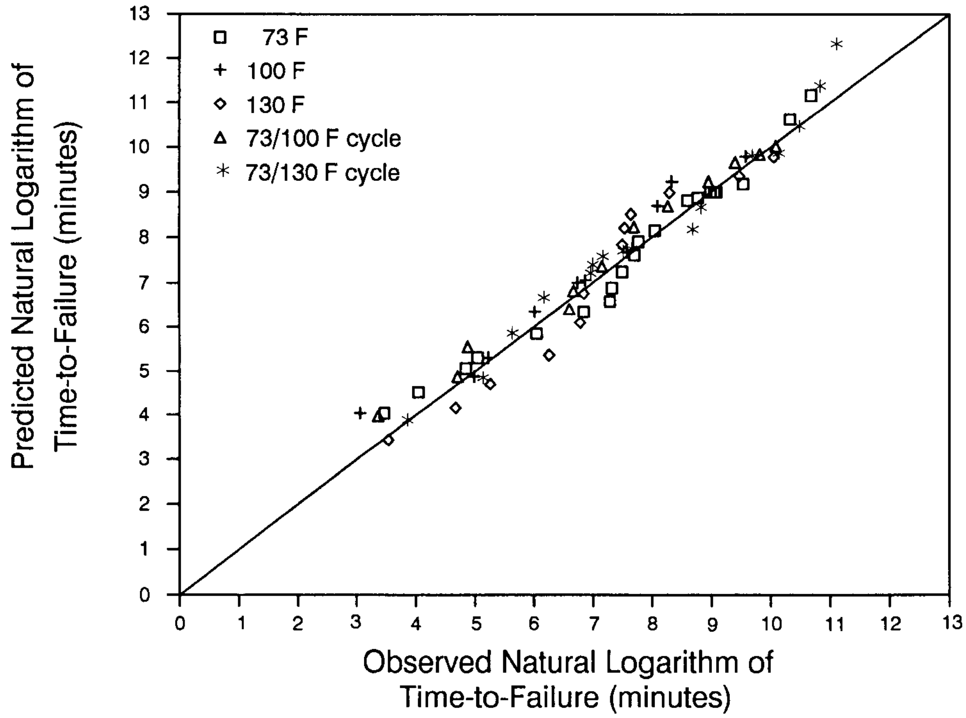

FIG. 8. Relationship between predicted and observed natural logarithm of time-to-failure for No. 2 lumber.

group moisture contents during the tests were 9.9% for the Select Structural lumber and 9.7% for the No. 2 lumber group.

CONCLUSIONS

The results of this study indicate that a damage model originally developed to predict the load-duration behavior of structural lumber in various constant temperature environments can be used successfully to predict the behavior in a cyclic temperature environment. Two semi-square temperatures cycles were used to illustrate the effects of a varying temperature environment on the load-duration behavior of structural lumber. Also, the numerical modeling procedures were illustrated for the temperature cycle. It is believed that the effect of any arbitrary temperature history can be modeled in this same manner. Uncertainty, however, exists in the extrapolation to higher temperatures and temperature cycles since it is not known whether any polymer phase changes in wood may occur at higher temperatures over time. Lumber, though, is typically not used structurally in temperature environments much higher than those used to develop the model, that is 130 F. Therefore, the model and modeling procedures should be valid in most circumstances.

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REFERENCES

BARRETT, J. D., AND R. O. FOSCHI. 1978a. Duration of load and probability of failure in wood. Part I: Modelling creep rupture. Canadian J. Civil Eng. 5(4):505–514.

———, AND ———. 1978b. Duration of load and probability of failure in wood. Part II: Constant, ramp, and cyclic loadings. Canadian J. Civil Eng. 5(4):515–532.

FOSCHI, R. O., AND BARRETT, J. D. 1982. Load-duration effects in western hemlock lumber. ASCE J. Struct. Div. 108(ST7):1494–1510.

FRIDLEY, K. J., R. C. TANG, AND L. A. SOLTIS. 1989. Thermal effects on load-duration behavior of lumber. Part I. Effect of constant temperature. Wood Fiber Sci. 21(4):420–431.

GERHARDS, C. C. 1977. Effect of duration and rate of loading on strength of wood and wood-based materials. USDA, Forest Service Research Paper FPL 283, Forest Products Laboratory, Madison, WI.

———. 1979. Time-related effects on wood strength: A linear cumulative damage theory. Wood Science 11(3):139–144.

———. 1988. Effect of grade on load duration of Douglas-fir in bending. Wood Fiber Sci. 20(1): 146–161.

———, AND C. L. LINK. 1987. A cumulative damage model to predict load duration characteristics of lumber. Wood Fiber Sci. 19(2):147–164.

JOHNS, K., AND B. MADSEN. 1982. Duration of load effects in lumber. Part I: A fracture mechanics approach. Canadian J. Civil Eng. 9:502–514.

MADSEN, B. 1971. Duration of load tests for dry lumber subjected to bending. Forest Prod. J. 23(2): 21–28.

———, AND J. D. BARRETT. 1976. Time-strength relationship for lumber. Structural Research Series Report No. 13, Univ. of British Columbia, Vancouver, BC, Canada.

———, AND K. JOHNS. 1982. Duration of load effects in lumber. Part II: Experimental data. Canadian J. Civil Eng. 9:515–525.

MINER, M. A. 1941. Cumulative damage in fatigue. ASME J. Appl. Mechanics 12(3):A159–A164.

MURPHY, J. F. 1982. Discussion of "Load-Duration Effects in Western Hemlock Lumber," by R. O. Foschi and J. D. Barrett. ASCE J. Struct. Eng. 109(12):2943–2846.

NIELSON, L. F. 1985a. Wood as a cracked viscoelastic material. Part I: Theory and applications. Pages 67–78 *in* J. D. Barrett et al., eds. Proceedings, International Workshop on Duration of Load in Lumber and Wood Products. Forintek Canada Corp., Vancouver, BC, Canada.

———. 1985b. Wood as a cracked viscoelastic material. Part II: Sensitivity and justification of a theory. Pages 79–89 *in* J. D. Barrett et al., eds. Proceedings, International Workshop on Duration of Load in Lumber and Wood Products. Forintek Canada Corp., Vancouver, BC, Canada.

SCHNIEWIND, A. P. 1967. Creep-rupture life of Douglas-fir under cyclic environmental conditions. Wood Sci. Technol. 1(4):278–288.

———, AND D. E. LYON. 1973. Further experiments on creep-rupture life under cyclic environmental conditions. Wood Fiber 4(4):334–341.

WOOD, L. W. 1951. Relation of strength of wood to duration of load. USDA Forest Service Report No. 1916, Forest Products Laboratory, Madison, WI.

APPENDIX: S.I. Equivalents

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

$$\text{SS: } d\alpha/dt = \exp[-26.626 + 23.410\sigma + 1.014\tau] \tag{12}$$

$$\text{No. 2: } d\alpha/dt = \exp[-23.954 + 20.733\sigma + 1.060\tau] \tag{13}$$

where τ is a temperature factor defined by Eq. (2) except that the bench mark temperature, T_0, is 22.8 C.