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High-temperature drying of southern pine 2 by 4's: Effects on strength and load duration in bending

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Summary. Southern pine lumber specimens dried by conventional (82 °C maximum) and high temperature (116 °C for less than 1 day) schedules were tested to determine if high-temperature drying affects load duration. Results show that high-temperature drying has no appreciable effect on load duration, probably because it has no appreciable effect on static strength. Results from combining the data from both kinds of drying suggest that the load duration effect is less severe for lumber than for small clear specimens.

Introduction

We recognize two advantages of high-temperature kiln drying (HTD) over conventional drying: Lumber warp is significantly reduced, and drying times are much shorter. As HTD is typically done at about 116 °C, drying stresses that would cause warp are reduced by plastic flow and drying schedules are completed within 1 day rather than about 5 or 6 days for conventional drying.

HTD has some known disadvantages, too, at least for some species of wood. For example, many hardwood species are prone to honeycomb. While that problem does not seem to occur for most softwood species, Douglas-fir and western hemlock do suffer loss in static strength (Gerhards 1979a; Kozlik 1968, 1976). Southern pine, however, does not exhibit a significant loss in strength (Koch 1971, 1972; Price, Koch 1980; Yao, Taylor 1979) unless drying times are extended (Price, Koch 1980). Yellow-poplar also does not exhibit a significant loss in strength (Gerhards 1983). The related problem of duration of load has not been studied.

This study was chosen to evaluate the effect of HTD on the duration of load characteristics of southern pine lumber for two reasons. First, the average static strength results in two of the studies on southern pine lumber were 3–4% lower for HTD than for conventional drying (Koch 1971; Price, Koch 1980). Second, even though the HTD effect on strength is insignificant in a statistical sense, a real reduction of 3–4% in strength could cause a significant reduction in the duration of load characteristics of wood, at least according to an analysis based on cumulative damage theory (Gerhards 1979b).

Experimental procedure

For this study 316 green rough-sawn 8-foot-long southern pine 2 by 4's (51 by 102 mm) were obtained from a mill in Mississippi in February 1982. Each selected lumber specimen was to be pith-free and of at least No. 2 quality overall but with a strength controlling knot or slope of grain of No. 1 or No. 2 quality in the central 610-mm length. (No. 1 and No. 2 lumber knots and slope of grain cover the strength ratio (ASTM 1976) range from 67 to 45%, implying that percentage of clear wood strength. Strength ratio ranges from 67 to 100% for Select Structural, a stronger grade, and 25 to 45% for No. 3, a weaker grade.) These characteristics were chosen to limit variation in strength between specimens. The specimens were dip-treated to prevent blue stain and wrapped in a vapor barrier to prevent drying during shipping to the Forest Products Laboratory (FPL). At FPL, they were stored as wrapped, at 2 °C.

Sorting before kiln drying

At FPL each specimen was tested nondestructively for bending modulus of elasticity flatwise (EF) on a span of 1.14 m with two symmetrical load points located 457 mm apart. The strength-controlling characteristic was located between the load points.

After four specimens were set aside as kiln control samples, the lumber was sorted into four groups. The sorting was done by ranking the specimens according to EF, blocking the ranked specimens into sets of four, and then randomly assigning the four specimens in a set to the four groups. This resulted in four groups of 78 specimens, with each group having a like distribution of EF's.

After EF testing and sorting, specimens were stored under wrap outside at cold temperatures until kiln dried.

Kiln drying

Three kiln runs were used to dry the four groups of lumber. Two of the groups were dried separately, one on March 25 (Group 3) and the other on March 29 (Group 4), using a high-temperature schedule adapted from Koch (1971). The other two (Groups 1 and 2) were dried together from April 22 through April 28 using the conventional schedule, T12-C5 (Rasmussen 1961).

The kiln controller for the high-temperature schedule was set to run 21 hours at 116 °C dry bulb and 71 °C wet bulb for drying and 3 hours at 91 °C dry bulb and 85 °C wet bulb for equalizing. Air speed through the kiln was 290 to 335 m/min with fan reversal about every 90 minutes.

The high-temperature runs had some brief excursions in the dry bulb temperature, but these probably had little effect on the properties of the lumber. These excursions occurred at fan reversal. Two excursions to about 121 °C and one to about 130 °C in the first run (Group 3) cooled rapidly (less than 1/2 hour) to the set point. The second run (Group 4) also had three excursions:

1. a drop to 80 °C with rapid recovery to 96 °C where it stayed for the 90 minutes between fan reversal,

2. an overshoot to about 130 °C, and
3. an overshoot to about 138 °C.

Both overshoots in the second run took about 90 minutes to cool to the set point.

The conventional schedule ran as planned, requiring 6 days rather than 24 hours to dry the lumber. Based on the extra 2 by 4's as kiln samples, the maximum temperature of 82 °C was reduced to 77 °C after 30 hours, then to 71 °C after another 20 hours. It remained at 71 °C for the remainder of the schedule. The equalizing portion was at 71 °C dry bulb and 66 °C wet bulb.

The lumber in each kiln run was dried with a top loading of 439 kg/m^2.

Lumber quality after kiln drying and surfacing

After kiln drying, the lumber was further conditioned for about 4 months at 23 °C and 50% relative humidity (the conditions of strength and duration of load testing). Then the specimens were surfaced to the 38- by 89-mm standard size and graded for strength ratio (SR) of knots and slope of grain (ASTM 1976) in the central 711-mm length and for warp overall (SPIB 1977). Lumber grade for SR was more variable than originally sought. Only 64% qualified as No. 1 and No. 2, 25% was Select Structural and 11% was No. 3. Also, 11% contained the tree pith.

Lumber grade for warp was good to excellent. As Koch (1971) found, warp was less prevalent in HTD than in conventional drying – 96% of HTD and 87% of conventional drying met Select Structural requirements for straightness and only one HTD specimen and four conventional specimens failed to meet No. 2 for straightness.

Final selection of test specimens

Due to changes in grade from drying and surfacing, additional work was required so that matched groups of 50 specimens in each group could be made. Thus, specimens having 100% SR in the central 711-mm length or with too much warp (bow >7.6 mm, crook >10.2 mm, twist >12.7 mm) were culled. The remaining specimens were remeasured for EF using the same procedure as for the rough, green condition.

Final selection decisions were based on predicted modulus of rupture (PMOR). The predicting equation was (Ethington 1970)

$$\text{PMOR} = \exp\,(2.603 + 0.05468\,\text{EF} + 0.00947\,\text{SR}) \qquad (1)$$

where PMOR is in MPa, EF (dry) is in GPa and SR is in %. The PMOR's were ranked within each group and compared across groups. I switched a few specimens between Groups 1 and 2 so that 50 specimens in Group 1 matched 50 specimens in Group 3 and 50 specimens in Group 2 matched 50 specimens in Group 4 for distribution of PMOR. Specimens having lowest EF's were excluded from all groups. Selected specimens differed by less than 1% in average PMOR between the four groups. Overall, PMOR averaged 47.5 MPa. For the 200 selected specimens, EF (dry) ranged from 6.9 to 17.9 GPa and SR ranged from 28 to 94%.

Static strength and duration of load testing

A 50-frame setup (Fig. 1) was used to test for both static strength and duration of load. Each frame contains a strongback with supports for holding a specimen and an air cylinder for applying load to the specimen on edge through a loading bar. Supports are 2.13 m apart and load points, symmetrically located, are 610 mm apart. Roller bearings are used at each load and support point. The air cylinder has a folding diaphragm instead of piston rings and a piston rod linear ball bearing for near friction-free movement. All air cylinders are hooked to a common air supply along with a like air cylinder pushing against a load cell to monitor load. Specimen midspan deflection is measured with a specially rigged potentiometer mounted to a yoke which is supported by nails in the specimen. Time to failure is monitored by an electric clock and also by a computer that records time, load and deflection.

Specimens in Groups 2 (conventional drying) and 4 (HTD) were designated for static strength testing and specimens in Groups 1 (conventional drying) and 3 (HTD) were designated for duration of load testing. Two static strength runs were made with 25 specimens from Group 2 and 25 specimens from Group 4 making up each run. Static strength was measured at a loading rate of 136.2 kg/min bending load (10.14 MPa/min bending stress equivalent). Specimens were loaded with the strength-controlling characteristic on the tension side.

Times to failure were measured in two duration-of-load runs. Each run using 25 specimens from Group 1 and 25 specimens from Group 3 had the same 3-step constant-load history. Loading was at the same rate as for static strength runs. The

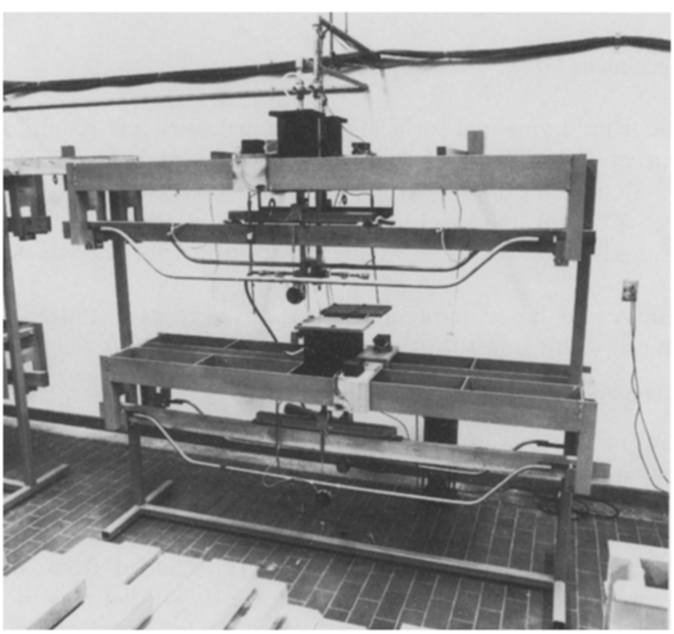

Fig. 1. Static-strength and duration-of-load test frames

total elapsed time from the start of loading was 288 minutes for the first step at 218.8 kg, 2880 for the second step at 305.2 kg, and 28 800 minutes for the third step at 389.4 kg. These three load levels were estimated as 5th, 20th, and 40th percentile static strengths. Surviving specimens were unloaded for at least 1 day. Then they were ramp-loaded to failure at the same rate as for static strength runs.

Besides the measures of static strength and duration of load, the edgewise modulus of elasticity (EE) was determined for each specimen from load-deflection data measured during the ramp loading portions of the tests.

After strength or duration tests, moisture content (ovendry basis) was measured on 25-mm-long wafers cut from each specimen.

Results and discussion

Physical properties

Moisture content averaged 9.8% for the conventionally dried specimens and 8.6% for the high-temperature dried specimens (Table 1). The difference of 1.2%, the effect of drying at high temperature, is a little more than that noted by Koch (1971). While the difference is significant in a statistical sense ($p < 0.01$), no adjustments are made for strength because all of the specimens came to equilibrium in the same environment.

The four groups of lumber did not differ significantly in either specific gravity (overall average ≈ 0.48), strength ratio (overall average $\approx 61\%$), or EF (dry) (overall average ≈ 12.1 GPa).

The edgewise modulus of elasticity (EE) for the HTD group tested for static strength – averaging 11.8 GPa – was significantly higher than those for the other three groups – averaging about 11.3 GPa.

Table 1. Physical properties of test specimens [a]

Test	Drying schedule	Moisture content, %	Specific gravity [b]	Strength ratio, %	Modulus of elasticity	
					Flatwise, GPa	Edgewise, GPa
Static strength	Conventional	9.9 (0.23)	0.49 (0.03)	60 (15)	12.2 (1.98)	11.4 (2.03)
	HTD	8.3 (0.37)	0.48 (0.04)	62 (14)	12.1 (2.23)	11.8 (2.35)
Duration of load	Conventional	9.7 (0.34)	0.49 (0.04)	62 (12)	12.1 (2.04)	11.2 (2.08)
	HTD	9.0 (0.48)	0.48 (0.04)	62 (13)	12.0 (2.02)	11.3 (2.12)

[a] Each value based on 50 specimens – upper number is average, lower number in parentheses is standard deviation

[b] Test volume, ovendry weight basis

Static strength

Conventionally dried and HTD specimens had very close to the same average and distribution of static strengths (Fig. 2). Averages and standard deviations are

	Static bending strength, kg	
	Average	Standard deviation
Conventional	474	193
HTD	466	193

Although the HTD specimens averaged 98.4% of the strength of conventionally dried specimens, near agreement with Koch's result (1971), the difference in averages is not statistically significant. Consequently, I combined the two sets of data to better determine the distributions of static strengths for estimating load levels for the constant-loading phase of this experiment.

The combined static strength data have a nearly lognormal distribution, as shown by the near linear alignment of the data on the cumulative distribution plot of Fig. 3. In equation form, the lognormal distribution is

$$\sigma_s = \sigma_0 \exp(\mathrm{w\,R}) \qquad (2)$$

where σ_s is static strength, σ_0 is median static strength, w is standard deviation of the lognormal distribution, and R is a standard normal random variate (e.g., -1.645 for the fifth percentile). The statistics of the lognormal distribution of the combined data are estimated as: $\sigma_0 = 432.7$ kg and $\mathrm{w} = 0.4145$. These estimates along with Eq. (2) yield estimates of 218.8 kg for the 5th percentile step, 305.2 kg for the 20th percentile step, and 389.6 kg for the 40th percentile step of the constant-load phase of this experiment.

Duration of load

As for static strengths, durations of load are distributed about the same for HTD specimens as for conventionally dried specimens (Fig. 4). While there are some differences between drying types in the number of failures occurring in the different loading phases (Table 2), I consider these significant. For example, 15 of the HTD specimens failed during the second constant-load step (including ramp and hold phases) compared to nine of the conventionally dried specimens, but that difference is balanced by the 14 HTD specimen failures during the third constant load step compared to the 20 conventionally dried specimen failures. Moreover, the distribution of the times to failure for the last six specimens of both drying types was longer for the HTD specimens than for the conventionally dried specimens. The differences in the distribution of times of failure for the two drying types, not nearly as great as I suspected when planning the study, are within the normal bounds of random variation and are thus considered insignificant. This result, primarily stemming from the lack of a significant effect of the HTD schedule on static strength of southern pine, is not expected to hold for other species, such as Douglas-fir, for which static strength is affected by HTD.

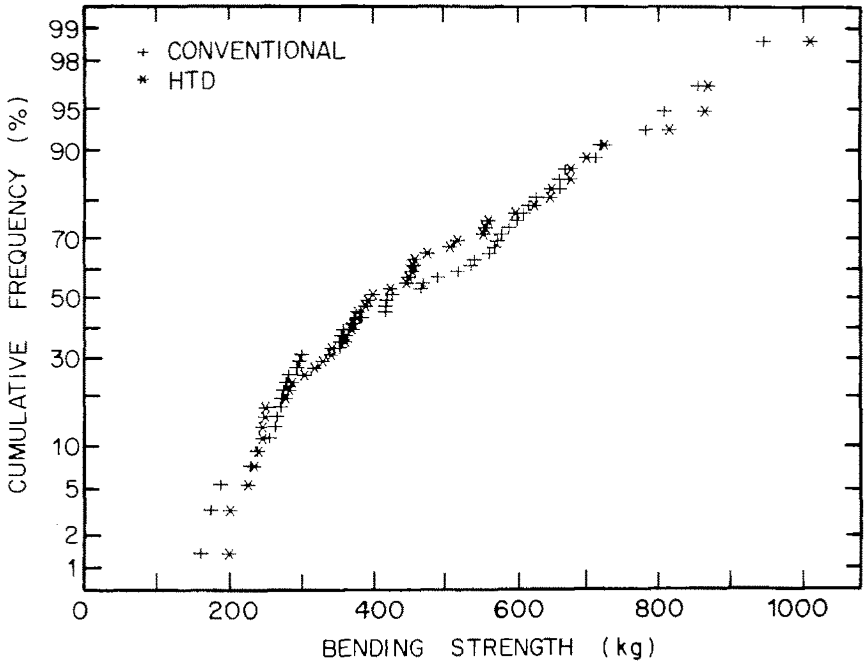

Fig. 2. Static strength distributions (normal distribution scale)

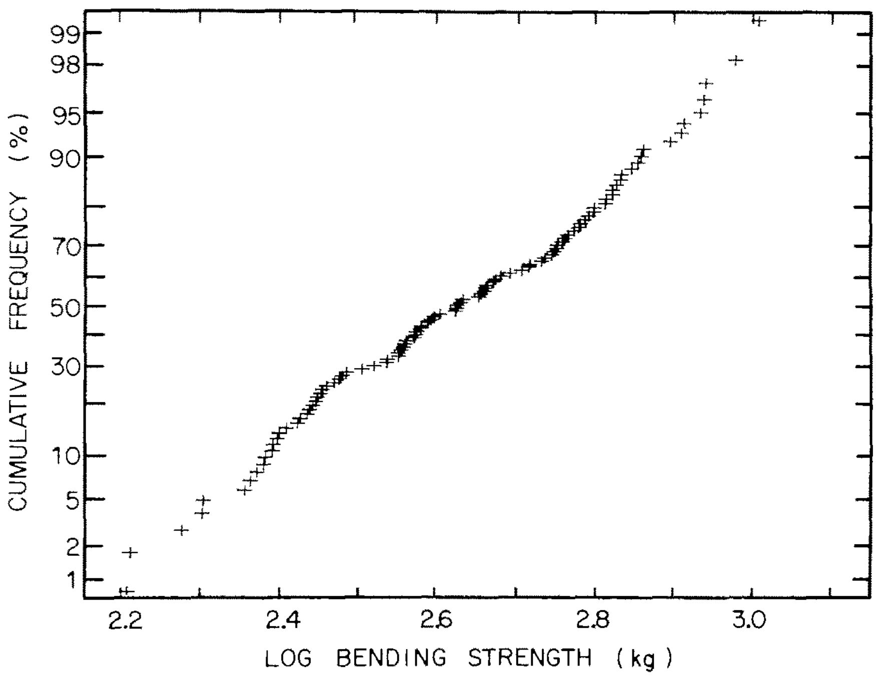

Fig. 3. Combined conventional and high temperature drying static strength distribution (log-normal distribution scale common logarithm basis)

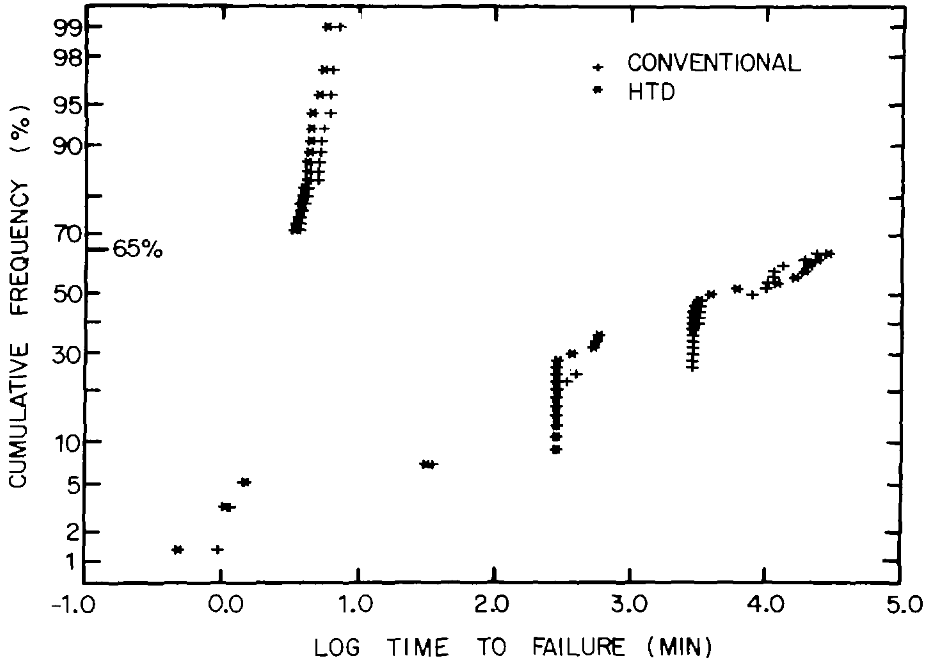

Fig. 4. Distributions of times to failure in the 3-step constant load test. Data above cumulative frequency = 65% are for time of final ramp loading only; other data are for total time on test

Table 2. Numbers of failures during constant load tests

Loading phase	Conventionally dried		HTD	
	Number	Cumulative number	Number	Cumulative number
Ramp to 218.8 kg	3	3	3	3
Holding at 218.8 kg	1	4	1	4
Ramp to 305.2 kg	4	8	8	12
Holding at 305.2 kg	5	13	7	19
Ramp to 389.4 kg	5	18	2	21
Holding at 389.4 kg	15	33	12	33
Final ramp of survivors	17	50	17	50

The distributions of times to failure in the final ramp loading of survivors of the constant load phase (for cumulative frequency above about 65% (Fig. 4), suggest that HTD survivors were somewhat weaker than conventionally dried survivors. In fact HTD survivors averaged only 84% of the strength of conventionally dried survivors. There are two possible reasons for that outcome. First, HTD may have made the lumber more susceptible to cumulative damage from the step constant loads than conventional drying. Second, the HTD survivors may have had lower strengths than the conventionally dried survivors before any drying or loading because random assignment to groups was less than perfect. Although I can

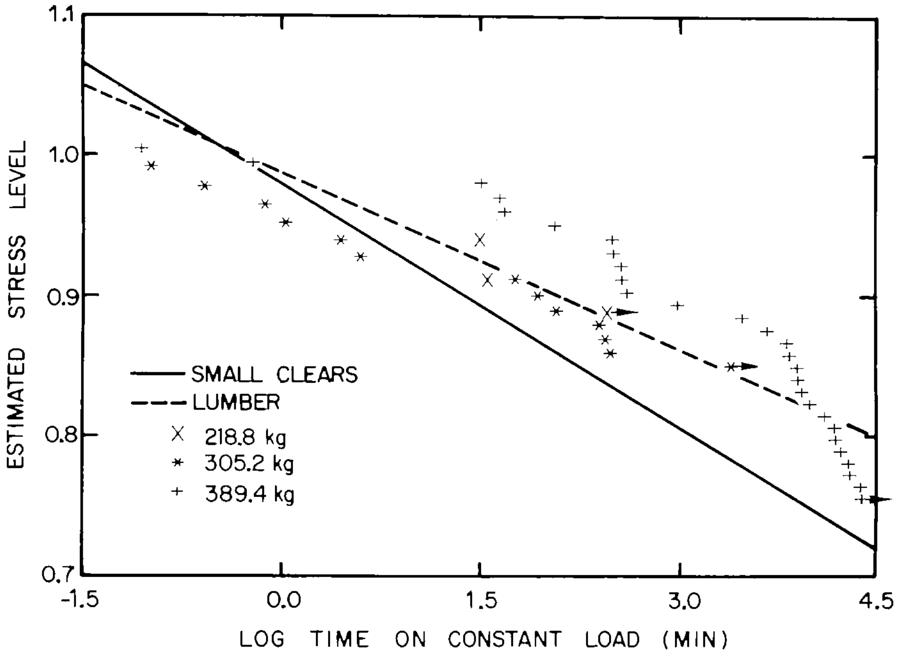

Fig. 5. Times to failure at the three different load levels versus estimated stress level. Arrows indicate survival of the constant load durations

offer no real proof, I prefer the second reason, because there is no evidence that the first two steps in the constant-load phase adversely affected (shortened) the duration of load of HTD specimens that failed during the third step.

Cumulative damage modelling

The step constant-load duration data along with the ramp loading strengths are useful for determining parameters in the stress level duration of load model (Gerhards 1977)

$$SL = A + B \log t \tag{3}$$

where SL is the constant load stress divided by static strength, A and B are constants, and log t is the common logarithm of time. Equation (3) results from integrating the cumulative damage rate model (Gerhards 1979 b)

$$d\alpha/dt = \exp(-a + b\,\sigma(t)/\sigma_s) \tag{4}$$

to failure, where α is damage, $a = 2.303\,A/B$, $b = -2.303/B$, $\sigma(t)$ is the stress history [$\sigma(t) = \sigma_c$, a constant for Eq. (3)], and σ_s is static strength. Using the equal rank assumption (i.e., that the order of specimen failures is the same for constant load as it would be for ramp loading), the combined data from conventional and HTD step constant-load specimens ordered by ascending times to failure, the constant load at failure, and Eq. (2) to represent static strength, I determined SL for each specimen that failed while on constant load (Fig. 5).

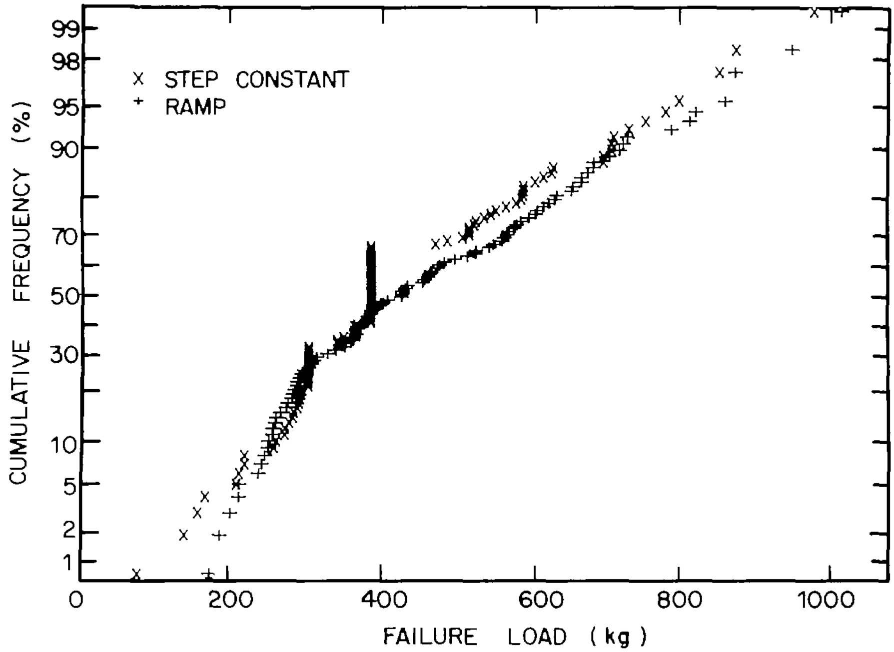

Fig. 6. Cumulative distributions of maximum failing loads in both step constant and ramp load phases

There are several points to be made regarding the stress level-time on constant load data. First, stress levels are estimates. For the number of specimens in this study, they can easily be off by about 10% in the midrange of static strengths and even further at the extremes. For example, the cumulative distributions of failure loads for both ramp and step constant load (Fig. 6) show that the lowest strength specimen in the step constant-load test had less than half the strength of its equal rank in the ramp load test. Similarly, the next three lowest ranked step constant-load specimens had seven- to eight-tenths the strength of the equal ranked ramp load specimens. For those extreme specimens, both types failed with a ramp load history, only; consequently, we should expect them to have the same strength distribution. Obviously, they differed due to random variation.

The second point regarding the data in Fig. 5 is that times on constant load could have been influenced by load history. For example, the two specimens that failed during the 218.8 kg load had the history of the ramp from 0 to 218.8 kg as well as the time on constant load at 218.8 kg, and the 12 specimens that failed during the 305.2 kg load had a history of the ramp load to 218.8 kg, the time on constant load at 218.8 kg, and the ramp up to 305.2 kg as well as the time on constant load at 305.2 kg. The cumulative damage model (Eq. (4)) implies that any load history subtracts time that a future load history can be applied before failure; however, the effect on time is significant only when the prior load history contains high-stress-level loading for some time. Consequently, the specimens that failed after 30 minutes of constant loading were probably not significantly affected by the prior load history.

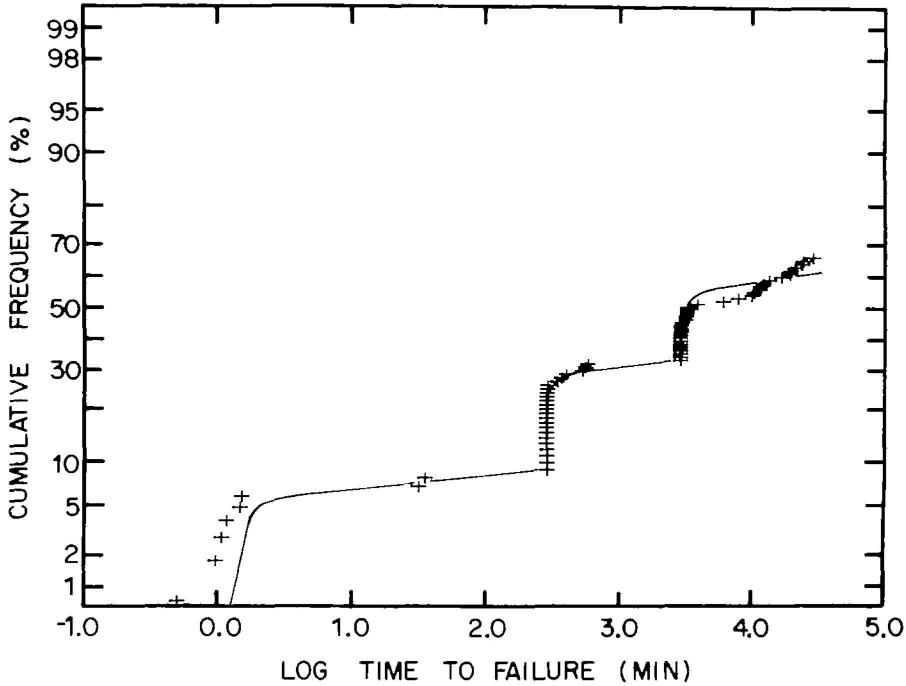

Fig. 7. Distribution of combined conventional and high temperature drying times to failure in the constant load test

Equation (3) and its transpose fit by least squares to the Fig. 5 data result in the two equations

$$\hat{SL} = 0.9825 - 0.03787 \log t \quad (3a)$$

$$\log \hat{t} = 20.938 - 20.781\ SL \quad (3b)$$

where t is in minutes. (If SL's were truly known and not just estimated, then only the transpose fit (3 b) would be logical, as time would be the response to the known SL.) The comparable equation for clear wood is $SL = 0.9809 - 0.058 \log t$ (Gerhards 1977, solid line in Fig. 5). Comparison of either Eq. (3 a) or (3 b) with the clear wood equation suggests that the load-duration effect is less for lumber than for clear wood. The difference in effect is significant as the 95% confidence intervals for the slope of either Eq. (3 a) or (3 b) do not include the comparable slope for clear wood.

Because SL's are estimated and a specimen cannot carry 100% of its static strength (5-min ramp test) immediately applied for more than about 1/2 minute (Gerhards 1977), I chose the relation

$$SL = 0.9875 - 0.0415 \log t \quad (3c)$$

(dashed line in Fig. 5) to represent the load-duration relation of the lumber of this study. The line for lumber results in Eq. (4) parameters of a = 54.78 and b = 55.47. These parameters, along with the estimates of the static strength distribution, were used to plot the damage theory line through the cumulative step constant-load times to failure of the combined data for HTD and conventionally dried specimens in Fig. 7. The damage model appears to describe the effect of load history reasonably well, although it over-predicts times to failure during the first ramp (cumulative frequency < 6%) and during the longest times at the third constant load level (cumulative frequency > 57%) and underpredicts those during the intermediate times at the third constant load level (cumulative frequency 50–57%).

Conclusions

For southern pine lumber, high-temperature drying at 116 °C for less than 1 day has no appreciable effect on load duration, probably a direct correlation to the lack of a significant effect on static strength.

The effect of load duration appears to be less for lumber than for small clear wood.

References

American Society for Testing and Materials 1976: Standard methods for establishing structural grades and related allowable properties for visually graded lumber. ASTM D 245-74. Philadelphia, PA: ASTM

Ethington, R. L. 1970: Some stress-grading criteria and methods of grade selection for dimension lumber. Res. Pap. FPL 148. Madison, WI: USDA Forest Serv., Forest Prod. Lab.

Gerhards, C. C. 1977: Effect of duration and rate of loading on strength of wood and wood-base materials. Res. Pap. FPL 283. Madison, WI: USDA, Forest Serv., Forest Prod. Lab.

Gerhards, C. C. 1979a: Effect of high temperature drying on tensile strength of Douglas-fir 2 by 4's. For. Prod. J. 29(3): 39–46

Gerhards, C. C. 1979b: Time-related effects of loading on wood strength: a linear cumulative damage theory. Wood Sci. 11: 139–144

Gerhards, C. C. 1983: Effect of high-temperature drying on bending strength of yellow-poplar 2 by 4's. For. Prod. J. 33(2): 61–67

Koch, P. 1971: Process for straightening and drying southern pine 2 by 4's in 24 hours. For. Prod. J. 21(5): 17–24

Koch, P. 1972: Drying southern pine at 240 °F – Effects of air velocity and humidity, board thickness and density. For. Prod. J. 22(9): 62–67

Kozlik, C. J. 1968: Effect of kiln temperatures on strength of Douglas-fir and western hemlock dimension lumber. Forest Res. Lab. Rep. D-11. Corvallis, OR: School of For., Oreg. State Univ.

Kozlik, C. J. 1976: Effect of high temperature drying on tensile strength of Douglas-fir and western hemlock lumber. For. Prod. J. 26(10): 30–34

Price, E. W.; Koch, P. 1980: Kiln time and temperature affect shrinkage, warp, and mechanical properties of southern pine lumber. For. Prod. J. 30(8): 41–47

Rasmussen, E. F. 1961: Dry kiln operator's manual. USDA Agric. Handb. No. 188. Washington, DC: U.S. Gov't Printing Office

Southern Pine Inspection Bureau. 1977 edition: Grading rules. Pensacola, FL: SPIB

Yao, J.; Taylor, F. 1979: Effect of high temperature drying on the strength of southern pine dimension lumber. For. Prod. J. 29(8): 49–51

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