BENDING CREEP AND LOAD DURATION OF DOUGLAS-FIR 2 BY 4s UNDER CONSTANT LOAD FOR UP TO 12-PLUS YEARS

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ABSTRACT

This paper finalizes research on graded Douglas-fir 2 by 4 beams subjected to constant bending loads of various levels and durations. Compared to results for testing in a controlled environment, results confirm that load duration did not appear to be shortened by tests in an uncontrolled environment, at least extending out to 12-plus years. By the same comparison, relative creep was considerably increased, however.

The extended data also confirm that no evidence was found for a threshold below which stress levels for lumber can be maintained indefinitely.

Based on the finalized prediction equations of this study and those of two previous studies, a factor of 2.0 for a 10-year load duration is more appropriate for Douglas-fir bending allowable properties than the 1.62 factor currently recommended. Also, bending deflections due to creep doubled sooner than commonly accepted. This research is important to structural engineers and code groups responsible for the safe design of wood structures when establishing new design criteria for load duration and deflection limits.

Keywords: Bending creep, relative creep, deflection, wood beams, lumber grade, controlled and uncontrolled environments, wood engineering, load duration, design criteria.

INTRODUCTION

The objective of the study leading to this final report was to evaluate the load duration characteristics of Douglas-fir graded lumber. The purpose of this paper is to finalize the evaluation of results from bending creep and load duration tests of graded Douglas-fir 38- by 89-mm (nominal 2- by 4-in.; hereafter called 2 by 4) beams under sustained loading for times out to 12-plus years. This paper necessarily includes some of the comprehensive results previously reported (Gerhards 1988a, 1991).

Creep, the time-dependent deformation of material under stress, is an important material characteristic because it sometimes leads to structural failure as either excess deformation or worse as collapse. The effect of creep can be seen as sag or distortion in old wooden structures. Floors may have a permanent sag as a result of transverse bending creep, or sides of beams where supported by posts may have differential amounts of creep as a result of lateral crushing perpendicular-to-grain. Creep can occur longitudinally in compression and tension, contributing to permanent sag in trusses. Accounting for lumber creep should result in better wood structures, especially when design is controlled by deflection limits. One conclusion of the previous study (Gerhards 1991) was that "at least 10% of both Select Structural and No. 2 beams in the unheated, uncontrolled environment doubled their initial deflections in less than 2 years, and 50% of the No. 2 beams appear to be headed for doubling in 10 years."

Since that earlier report, several studies on

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creep and load duration, as well as modeling of both, have been reported. Shen and Gupta (1994, 1997) evaluated creep deflections of Douglas-fir 2 by 4 beams under constant load in a protected natural environment out to 59½ weeks. Rouger et al. (1990) studied creep response of small spruce beams at various levels of stress in a constant moist environment out to 47 weeks; included were tests of four different species of large beams of both lumber and glulam in constant dry and moist environments. Toratti and Morlier (1994) evaluated creep of lumber beams of four different species and glulam beams in a protected natural environment for 4¾ weeks. Lumber creep has been modeled by Fridley et al. (1992b), Toratti and Morlier (1994), Rouger et al. (1990), and Toratti (1994).

As creep leads to collapse, load duration is another important lumber characteristic. Although several studies have evaluated load duration characteristics (for references, see Gerhards 1988a), few have dealt systematically with environmental effects on long-time loading. Fridley et al. (1992a) evaluated effects of constant and cyclic temperature and relative humidity on load duration of Douglas-fir beams. Lebatteux et al. (1996) studied the effectiveness of coating lumber beams on load duration in a protected natural environment with tests that began during each of the four seasons. They subjected the beams to increasing levels of stress until failure occurred, each step lasting perhaps 14 or 15 days (authors were not clear on time at each stress level). Structural engineers need to know how load duration characteristics determined from short-term tests in a controlled environment relate to design loads of long duration in uncontrolled environments. For structures that do not carry significant constant loads, reliability analyses by Ellingwood and Rosowsky (1991), Rosowsky and Fridley (1992) and Fridley et al. (1998) have shown that design is generally limited by a critical load pulse.

EXPERIMENTAL PROCEDURES

The experimental procedures were described in detail in Gerhards (1988a, 1991), but a summary is given here for the convenience of the reader.

Controlled environment

The objective of the experiment was to evaluate the effect of lumber grade (ASTM 1981) on duration of load; therefore, tests were conducted on three grades of Douglas-fir 2 by 4 lumber: Select Structural (SS), No. 2, and No. 3. The lumber was specially selected to have a control knot in the central 0.61-m (24-in.) length of each piece. The control knot was near the maximum allowed for each respective lumber grade, but warp characteristics were limited to those for SS. Control knots were not restricted in lateral location to either centerline or edge. With the exception of some tests in an uncontrolled environment, bending tests were carried out in a controlled environment (22.8°C, 50% relative humidity). The beams were tested on edge over a 2.13-m (84-in.) span. Load was applied at two points spaced 0.61 m (24 in.) apart and symmetrically located about midspan. The control knot was stressed in tension.

Three different series of two-step constant load levels were applied: high, medium, and low, depending on the level of load in the first step. Planned load levels included the 5th, 15th, 40th, and 70th percentiles of the static strength distribution. For the high series, the first step was 7 days at the 40th percentile followed by the second step of 14 days at the 70th percentile. For the medium series, the first step was 49 days at the 15th percentile followed by the second step of 56 days at the 40th percentile. For the low series, the first step was 365 days at the 5th percentile followed by the second step of 182 days at the 15th percentile. All changes in load were at the ramp loading rate of 136 kg (300 lb) bending load per minute. A set of 50 specimens was tested at each constant-load series; all sets of a grade were matched by equal distributions of static edgewise bending modulus of elasticity and control knot characteristics. An additional 50-specimen set of SS matched to the other SS sets

TABLE 1. *Average temperatures calculated from Weather Service records for Madison, WI in 1985.*

Month	Temperature (°C (°F))		
	High	Low	Mean
March	8 (46)	−1 (29)	3 (38)
April	17 (62)	7 (44)	12 (53)
May	22 (72)	11 (51)	16 (61)
June	23 (74)	13 (55)	18 (64)
July	27 (81)	16 (61)	22 (71)
August	24 (75)	14 (58)	19 (67)
September	21 (70)	12 (54)	17 (62)
October	15 (58)	5 (41)	10 (50)

was loaded at the 40th percentile for 279 days (high extended series). Specimen moisture content in this experiment averaged 10%.

Uncontrolled environment

In this phase, which was related to the main experiment, the objective was to determine how an uncontrolled environment affects constant load duration. Fifty SS and 50 No. 2 specimens matched by modulus of elasticity and knot characteristics to those of the same grade as used in the controlled environment were tested for 12-plus years (12.18 years for SS and 12.27 years for NO. 2). The specimens were loaded with weights totaling 187.2 kg (412.7 lb) for SS and 105.2 kg (232 lb) for No. 2 on the same spans (support and load points) as used in the controlled environment study. Dead load tests were conducted in an unheated, enclosed building with some natural ventilation at the Valley View test site of the USDA Forest Service, Forest Product Laboratory, located about 10 miles southwest of Madison, Wisconsin.

Over the life of the experiment, temperatures inside the building were only occasionally monitored, but humidity was not measured. These limited data were within a few degrees of official Weather Service records for Madison, Wisconsin. The Weather Service has recorded temperatures and relative humidities at 3-h intervals on a daily basis for many years. A summary of the Weather Service data for March through October of 1985 is presented in Table 1 for average temperature and in Table 2 for daily maximum and minimum relative humidity values. These data will be discussed later.

The uncontrolled environment specimens

TABLE 2. *Frequency of daily maximum and minimum relative humidity values calculated from Weather Service records for Madison, WI in 1985.*

Month	Relative humdity (%)							
	>90	90 > 80	80 > 70	70 > 60	60 > 50	50 > 40	40 > 30	30 > 20
Maximum								
March	7	18	5	1				
April	4	10	11	3	2			
May	2	13	10	3	3			
June	10	12	7		1			
July	20	10	1					
August	29	2						
September	24	6						
October	22	6	3					
Minimum								
March		3	4	3	6	9	5	1
April		1	1	1	3	13	11	
May			1	3	4	5	15	3
June			3		10	10	6	1
July		1	1	2	10	13	4	
August		1	2	8	10	4	6	
September		6	5	6	6	7		
October		2	4	5	9	5	3	3

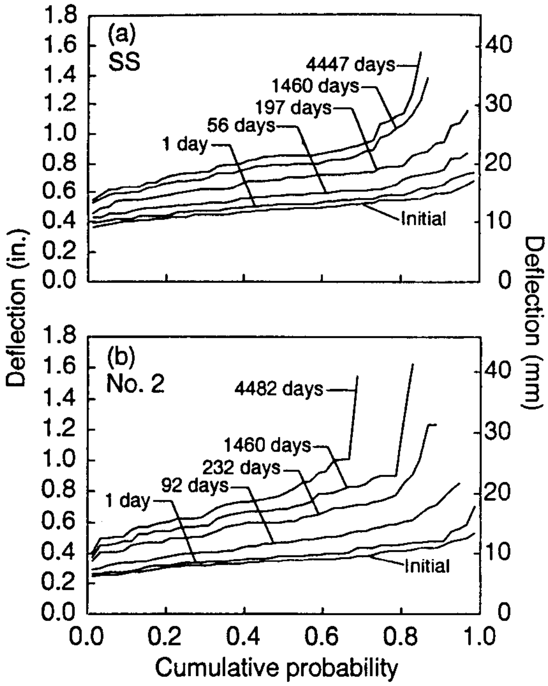

FIG. 1. Cumulative frequencies of beam deflections at selected times during the 12-plus years under sustained constant load in an uncontrolled environment: (a) 50 SS specimens, (b) 50 No. 2 specimens.

were loaded by hand. It took about 1 min to apply full load to a given specimen. Deflections were monitored as each preweighed steel weight was added to a load platform suspended from the specimen and several times during the first few hours after full load was attained. Because of the time needed for hand loading and monitoring, the 100th specimen was not loaded until more than 30 days after the first specimen was loaded. No. 2 specimens were loaded first, with the first of that set started on March 4 and the last on March 6, 1985. Loading of SS specimens was started on April 8, and the last of that set was loaded on April 10, 1985.

The dead loads in the uncontrolled environment were chosen to represent 10-year design loads. Based on the original 100 static strength tests of each grade, dead loads were determined by dividing the 5th percentile static strength values by 1.62, the 10-year load duration factor in common use (AF&PA. NDS. 1997). The 1.3 factor for safety was not included. Later, an improved estimate of static strength was determined by combining all ramp loading failure specimens (original static strength specimens and specimens that failed at loads below the first constant load level) (Gerhards 1988a). Results revealed that the 105.2-kg (232-lb) dead load times 1.62 represented the 8th percentile rather than the 5th percentile of the No. 2 static strength distribution. Note that the dead load is equivalent to 14.6 MPa (2,120 lb/in.^{2}) for SS and 8.2 MPa (1,190 lb/in.^{2}) for No. 2. Current design bending stresses for Douglas-fir 2 by 4s in the dry use condition are 15.5 MPa (2,250 lb/in.^{2}) for SS and 9.3 MPa (1,350 lb/in.^{2}) for No. 2 (AF&PA. NDS. 1997). The higher design stress used for commercial No. 2 Douglas-fir reflects the inclusion of lumber downgraded for nonstrength characteristics such as warp and wane.

Deflections of the uncontrolled environment specimens were monitored with a digital gauge (sensitive to 0.0127 mm (0.0005 in.)) mounted in a rigid frame. The digital gauge was zeroed in the rigid frame on a reference precision granite rail before specimen deflections were measured. The frame was designed to rest on marked spots on the upper beam surface of each 2 by 4 over the supports so that the deflection of the top of the beam at midspan could be measured without the influence of shrinking or swelling of beam height. The upper surfaces at the marked spots and at the center were lightly planed and locally varnished to minimize surface imperfections. Because of the remoteness of the test site, creep deflections were monitored periodically: several times during the first day, daily for the first work week, then weekly for a few months; but as time went on, less frequently until only three or four readings a year were made. The moisture content of the specimens in this environment were not monitored but would have changed with daily and seasonal changes in humidity. At the end of the 12-plus years of sustained loads, the residual deflec-

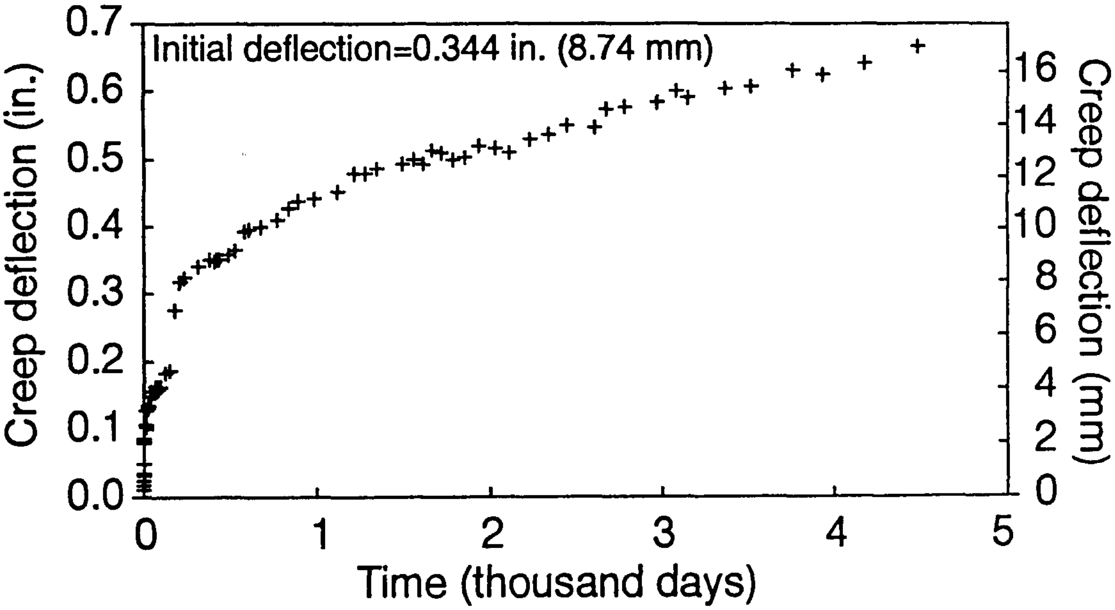

FIG. 2. Creep deflection data for specimen No. 2 2295 with an initial deflection of 8.74 mm (0.344 in.).

tion of each surviving specimen was measured immediately after the load was removed. Then, the survivors were brought back to the Forest Products Laboratory to be tested at the Engineering Mechanics Laboratory. These survivors were tested between 30 and 49 days after unloading for static bending strength and modulus of elasticity (MOE) on load and support spans consistent with the sustained load tests. The results of the tests on the survivors will be referred to later on as residual strength and residual MOE, respectively. The survivors averaged 11% moisture content when tested for residual properties.

ANALYSES AND PRESENTATION OF RESULTS

For analyses of the controlled environment results, see Gerhards (1991).

For the uncontrolled environment, bending deflections, i.e., the sum of initial and creep deflections, were interpolated at five periods ranging from 1 to 4,447 days for each SS specimen and to 4,482 days for each No. 2 specimen. These interpolated bending deflections, along with the initial deflections due to the applied loads, are summarized as cumulative frequency diagrams of deflection in Fig. 1. Figure 2 shows an example of creep deflection for a No. 2 specimen with initial deflection of 8.74 mm (0.344 in.).

Relative creep data, i.e., creep deflection for a specimen divided by its initial deflection, were calculated for each specimen. Relative creep data were interpolated after several periods at the 5th, 50th, 90th, and 95th sample percentiles (Fig. 3). Relative creep at the end of 12-plus years of loading is also compared with initial deflection (Fig. 4), and the ratios of residual deflection to initial deflection are compared with ratios of residual MOE to initial MOE determined at the time the specimens were uploaded to the constant load levels (Fig. 5). Residual strength (Fig. 6) is compared with the strength predicted by Eq. (2) or (3). Times to failure for sustained loading tests in the uncontrolled environment are combined with times previously reported for controlled environments, including times not previously included for an extended series tested at the 40% stress level on SS specimens (Fig. 7).

New load duration regressions were calculated for each of the two grades based on the following model:

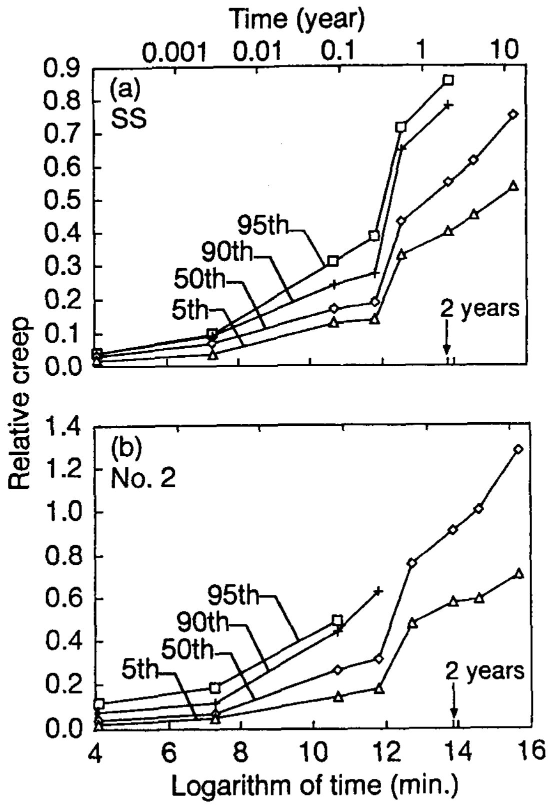

FIG. 3. Relative creep at specified percentiles of the sample populations of beams under sustained constant load in an uncontrolled environment: (a) SS, (b) No. 2.

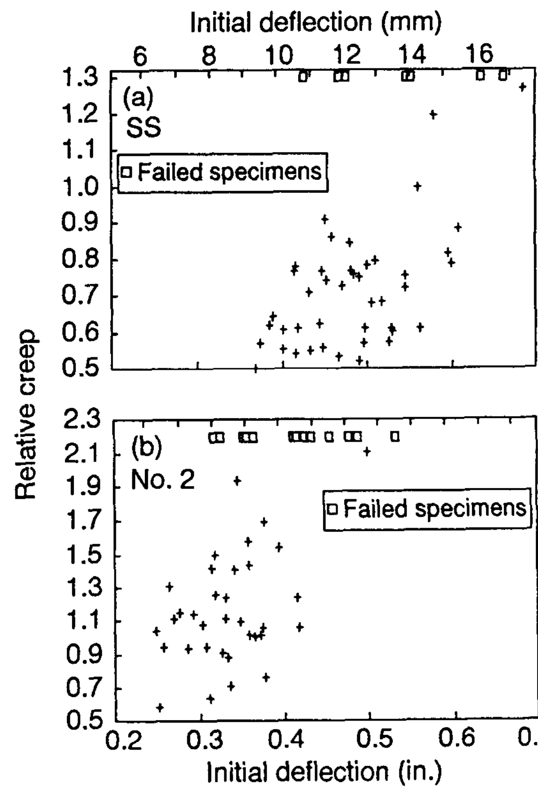

FIG. 4. Relative creep at the end of 12-plus years of beams under sustained constant load in an uncontrolled environment plotted against initial beam deflection: (a) SS, (b) No. 2. Initial deflections for failed specimens are plotted for reference as squares at the top of the figures.

$$SL = A + B\ LnTC \quad (1)$$

where *SL* is the applied load divided by the predicted static strength for a specimen, *LnTC* is the natural logarithm of time on constant load, and *A* and *B* are constants. The predicted static strength was based on the order of failure and the following (Gerhards 1988a):

$$\text{SS} \ln ML = 7.123296 + 0.368201R \quad (2)$$

$$\textit{No. } 2 \ln ML = 6.443158 + 0.365746R \quad (3)$$

where *ML* is the predicted static strength and *R* is the normal score based on the number of specimens in a set and the rank within that set.

RESULTS AND DISCUSSION

As expected, none of the SS or No. 2 specimens tested in the uncontrolled environment failed during uploading to the desired constant load.

Deflection with time

In the cumulative frequency diagrams of initial beam deflections and deflections after five periods (Fig. 1), the two middle curves represent the dates 5 June and 23 October 1985, a period when deflections showed the highest rate of increase. The lack of coverage over the full cumulative probability for the curves at the longer periods results from specimens that failed. Interpretation of the curves suggests that deflections of half (50% cumulative probability) the No. 2 specimens more than doubled in the 12-plus years; whereas

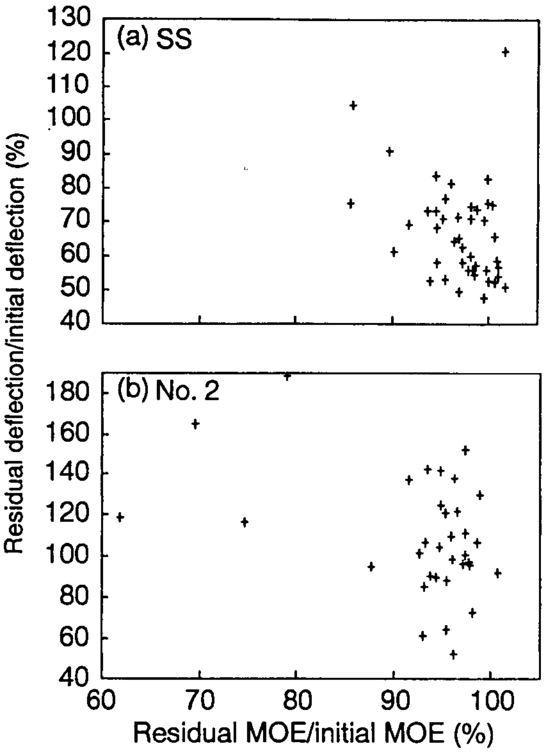

FIG. 5. Residual deflection as a percentage of initial deflection versus residual MOE as a percentage of initial MOE. (a) SS, (b) No. 2.

only about a quarter (75% cumulative probability) of the SS specimens doubled.

Creep dejection

All SS and No. 2 specimens that survived the constant load in the uncontrolled environment exhibited the typical large initial rate of creep deflection, with the rate decreasing over time until sometime after 5 June 1985. Then, the rate of creep deflection increased starting between 5 June and 3 July and ending some time between 25 September and 23 October, with the greatest change occurring after 28 August. Those dates were recording dates. 5 June and 23 October correspond to 92 and 232 days in Fig. 2. Thereafter, discounting small up and down changes in creep deflection, the creep rate decreased over time for most of the surviving specimens. The creep rate appeared to attain a constant level (Fig. 2 is an example) in about 30% of the SS specimens and about 20% of the No. 2 specimens. Because of the irregular changes in creep rate, creep models are not presented for the uncontrolled environment. Creep models developed for Douglas-fir in a controlled environment and their related problems are presented by Gerhards (1985, 1991).

Over the life of the experiment, none of the SS or No. 2 specimens that survived the total time under load exhibited a tertiary creep stage. A tertiary creep stage is reached when the rate of creep starts to increase, leading to eventual structural failure. Of the specimens that failed during the experiment, deflection data were recorded during a probable tertiary creep stage for only 3 of the 7 SS specimens that failed and only 6 of the 15 No. 2 specimens that failed. However, data were limited, and some of the possible tertiary creep stage data could have resulted from a step increase in deflection due to partial fracture in a specimen.

Relative creep

The increased rate of creep that occurred during the first summer of the experiment was associated with periods of high relative humidity. In the early part of the experiment, data in Table 2 support the observation that large daily swings in relative humidity occurred in March through June when temperature was cool to moderate. Although nighttime relative humidity reached high levels several times during those early months, daytime relative humidity reached low levels, too. But in July through October, relative humidity levels greater than 90% were recorded for most days; and for 6 days in September, the relative humidity did not drop below 80% nor did it drop below 60% for 17 days. Part of the time at high relative humidity levels in September were at warm nighttime temperatures, i.e. with temperature minimums greater than 21°C (70°F). It is highly likely that the warm humid periods contributed to the increased rate of creep observed before 23 October. Extended

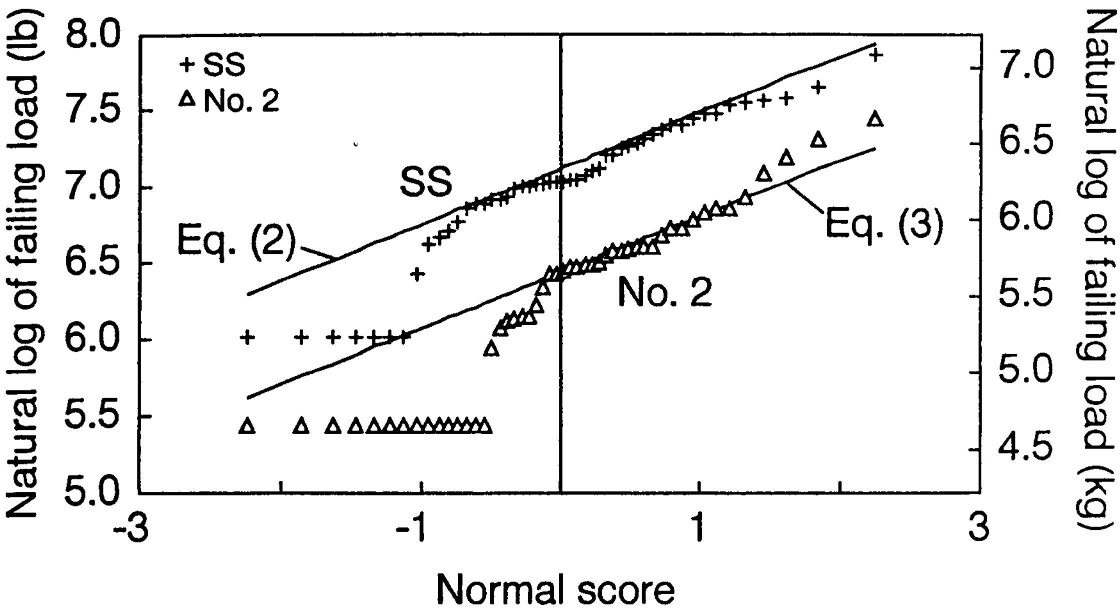

FIG. 6. Residual static strength distributions of SS and No. 2 specimens that survived 12-plus years of sustained loads, includes failure loads for nonsurvivors. Lines are predictions made using Eqs. (2) and (3).

periods of high relative humidity have been shown to accelerate creep (Fridley et al. 1992b).

The curves shown in Fig. 3 summarize relative creep histories for the SS and No. 2 specimens as population percentiles. For example, 5% of the specimens had relative creep less than or equal to that given by the 5th percentile line. Interpretation of the 50th percentile lines indicates that, within 2 years, relative creep was greater than 0.5 for 50% of the SS specimens and greater than 0.9 for 50% of the No. 2 specimens. By the end of 12-plus years, 95% (5th percentile line) of both SS and No. 2 specimens had relative creep greater than 0.5. A relative creep of 1.0 implies that creep deflection was as much as the initial deflection, or that the total deflection was double the initial deflection. For the 12-plus years of loading, relative creep was less than 1.0 for at least 50% of the SS specimens; whereas, it exceeded 1.0 for more than 50% of the No. 2 specimens. In fact, one can determine from Fig. 4 where individual relative creep data are plotted that about 80% of SS specimens had less than 1.0 for relative creep; whereas, only about 25% of No. 2 had less than 1.0.

When relative creep at the end of the 12-plus years is compared to initial deflection (Fig. 4), relative creep appears to have only a weak positive correlation with initial deflection. Initial deflections for failed specimens appear at the top of both scatter diagrams for reference only. Relative creep values calculated from deflection data on Douglas-fir 2 by 4 beams under constant load in a protected environment at 500 and 10,000 hours presented by Shen and Gupta (1994, 1997) are shown in Fig. 8. These data also show a lack of significant trend between relative creep and initial deflection. It is of interest to note, however, that Shen and Gupta's relative creep values are high when compared to those of this study for comparable times. In fact, their 10,000-h (417-day) data fall within the range of the 12% year data for the No. 2 specimens of this study. It is possible that their data are confounded with changes of beam depth if they measured beam deflections on the upper surface relative to mid-depth over supports, as suggested in the schematic of their experiment setup. This would seem to be the case because daily changes in their reported creep strains tended to follow daily changes in temperature, which were opposite to changes in relative humidity. On a daily basis, relative humidity usually increases as temperature decreases, producing a small increase in depth of beam as moisture increases. With that type of behavior, beam deflection would appear to decrease if measured as suggested by Shen and Gupta's schematic. The opposite would occur as temperature increases, i.e., beam deflection would appear to increase.

Dejection ratio versus MOE ratio

Ratios of residual deflection to initial deflection are plotted against ratios of residual MOE to initial MOE in Fig. 5 for the 43 SS and 35 No. 2 survivors. The following are medians of those properties:

	Residual Deflection/ Initial Deflection	Residual MOE/ Initial MOE
SS	0.65	0.976
No. 2	1.05	0.955

Several points are worth noting. First, the residual MOE values were generally greater than 85% of the initial MOE values, except for four of the No. 2 specimens that ranged between 62% and 80%. The values in the lower range undoubtedly represent partial fractures that occurred during sustained loading, as large cracks were noted in some specimens by the technicians monitoring the tests. Second, the deflection ratios tended to be higher for No. 2 than for SS even for comparable MOE ratios. Again, this likely represents more partial fractures in No. 2 than in SS. Third, more than 50% of the No. 2 specimens had residual unloaded deflections equal to, or greater than, the initial loaded deflections versus only two for SS. Finally, Fig. 5 suggests that deflection ratio has only a slight inverse relationship to MOE ratio.

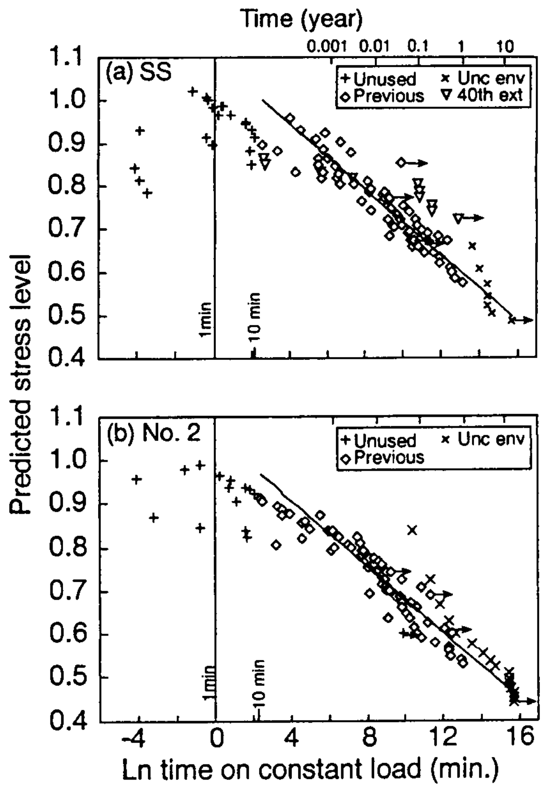

FIG. 7. Relationship between time to failure and *SL*. Arrows indicate incomplete tests. X indicates uncontrolled environment. All other data are for controlled environment. Except for data indicated by + and with *Ln* less than 2.143, the solid line is the regression of all data of the natural logarithm of time in minutes on *SL*. (a) SS, (b) No. 2.

Residual strength of survivors of 12-plus years of loading

Residual static bending strengths of the 43 SS and 35 No. 2 survivors of the 12-plus years of sustained loads plotted in Fig. 6 appear to be within reasonable limits with those predicted by Eq. (2) or (3), except for the few weakest survivors in both grades where strength levels fell below expectations, probably reflecting some accumulated damage from long-time loading. The highest residual strength levels for No. 2 survivors being above predicted show that variation can occur between sets of samples randomly chosen from a population. Figure 6 includes the data

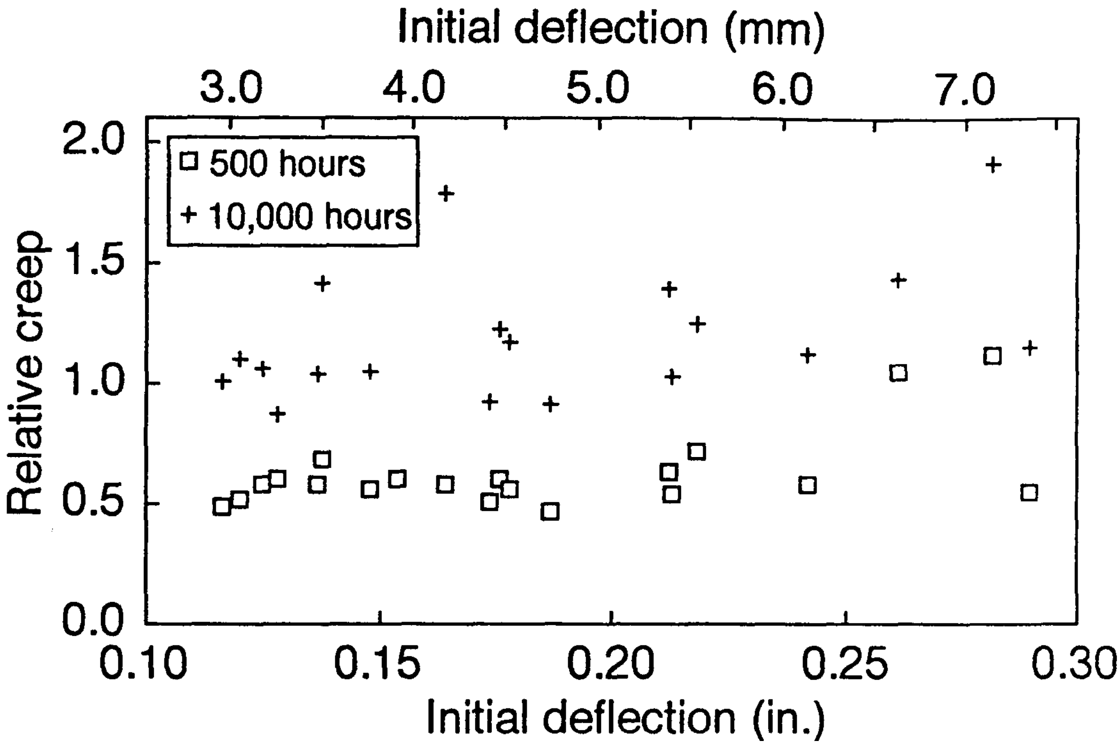

FIG. 8. Relative creep at 500 and 10,000 hours versus initial deflection of Douglas-fir beams calculated from data of Shen and Gupta (1994, 1997).

points for the 7 SS and 15 No. 2 constant load failures for reference.

Load duration

Times for the 7 SS and the 15 No. 2 specimens that failed during the 12-plus years of sustained constant loading in the uncontrolled environment are listed in Table 3 along with the predicted stress levels determined by dividing the constant load by the static strength predicted by Eq. (2) or (3). The times are given as a range, because monitoring of the specimens was manual and periodic. The medians of the natural logarithms of the ranges for sustained constant-load times to failure in the uncontrolled environment are plotted in Fig. 8 along with previous load duration data at the higher constant loads for testing in a controlled environment (Gerhards 1988a), including the extended 40th percentile SS results.

Considerable variation in data is evident for both grades. In Fig. 7(a) for SS, the early failures for the uncontrolled environment appear to have longer times than most of the tests in the controlled environment, but they do not appear out of line with the longer failure times for the extended high constant load series. The longer failure times for the uncontrolled environment tend to be more in line with the general trend of the other test results overall. In Fig. 7(b) for No. 2, the early failures for the uncontrolled environment tend to be overlong in time relative to the rest of the data; but as time under load increased, the results tend to be in line with the rest of the data. Because of the variable nature of wood, one must expect that strength and load duration properties of matched samples of a population will vary within and among samples of that population. Because of this variation, one cannot establish that the uncontrolled environment had a negative effect on load duration as

TABLE 3. *Predicted stress levels and failure times of specimens under sustained constant load during 12-plus years in an uncontrolled environment.*

Specimen	Predicted stress level	Time (days)
Select Structural[a]	0.760	7.204–8.204
	0.657	533.0–536.0
	0.605	808.6–811.6
	0.569	1,183.9–1,213.9
	0.543	1,216.1–1.248.1
	0.521	1.249.9–1,252.9
	0.502	1,526.0–1,574.0
	0.486	>4,483
No. 2[b]	0.838	22.97–23.01
	0.726	56.04–64.04
	0.669	90.9–102.92
	0.630	149.0–154.0
	0.600	213.2–214.2
	0.576	502.1–509.1
	0.556	896.9–909.9
	0.538	1,283.1–1,315.1
	0.522	1,677.1–1,705.1
	0.508	3,359.9–3,466.9
	0.495	3,506.9–3,511.9
	0.483	3,508.9–3,571.9
	0.472	3,755.0–3,924.0
	0.461	4,167.8–4,482.8
	0.452	4,168.0–4,483.0
	0.442	>4,483

[a] Based on dividing the 412.7-lb constant load by the predicted static strength (Eq. 2).
[b] Based on dividing the 232-lb constant load by the predicted static strength (Eq. 3).

might be expected from the effect of the uncontrolled environment on creep. The one possible explanation is that the samples used in the uncontrolled environment were relatively strong for those that failed, compared to the samples used in most of the controlled environment tests.

It is also important to note that the data in Fig. 7 confirm that there is no indication of a threshold below which loads can be sustained indefinitely. If there is a threshold, then it must be well below the 50% stress level.

Regressions of natural logarithm of time in minutes on predicted stress level were calculated for both grades of lumber using the combined data from both controlled and uncontrolled environments, excluding times shorter than 8½ minutes (*Ln* 2.143) and the one incomplete No. 2 data point at about *Ln* 10, *SL* 0.6 with an arrow. Data points with arrows flag the longest times under load for specimens that did not fail at a particular constant load history, thus reflect a conservative estimate of failure times for the next specimen that would have failed had the constant load continued. These data points generally had a neutral or positive effect, in the sense of increased life, on the regression results, so were used in the calculations. The one No. 2 data point just mentioned was excluded because it would have had a negative effect. The numbers of data used were 82 for SS and 85 for No. 2. The regression results where *SE* is the standard error and r is the correlation coefficient are the following:

SS $\ln TC = 28.606 - 26.020SL,$

with SE of 1.334 and r-square of 0.809 (4)

No. 2 $\ln TC = 27.753 - 26.183SL,$

with SE of 1.097 and r-square of 0.894 (5)

Shown as lines in Fig. 7, the transposes of those regression results are

SS $SL = 1.099 - 0.0384 \ln TC$ (6)

No. 2 $SL = 1.060 - 0.0382 \ln TC$ (7)

The alternate regressions of predicted stress level on logarithm of time, not shown, are

SS $SL = 1.031 - 0.0311 \ln TC$

with SE of 0.0461 (8)

No. 2 $SL = 1.022 - 0.0342 \ln TC$

with SE of 0.0396 (9)

Predictions for Eqs. (6) to (9) are given in Table 4, for 10 min, 10 years, and 50 years, and for the days corresponding to the reciprocal of the 1.62 factor. The 1.62 factor does not coincide with a constant loading time of 10 years; rather, it is more consistent with about 1/10th of that time. A factor of 2.0 is more appropriate for 10-year loading. Prediction equations from two other independent but more limited studies of Douglas-fir lumber support the 2.0 factor. The first study involved

TABLE 4. *Stress level predictions using the load duration Eqs. (6)–(9).*

	Predicted stress levels			
Time	SS Eq. (6)	SS Eq. (8)	No. 2 Eq. (7)	No. 2 Eq. (9)
10 minutes	1.01	0.96	0.97	0.94
195 days	1/1.62			
416 days		1/1.62		
75 days			1/1.62	
96 days				1/1.62
10 years	0.50	0.55	0.47	0.49
50 years	0.44	0.50	0.41	0.44

specially selected 2 by 4s with an edge knot (Gerhards and Link 1987). In that study regression models were fit to various combinations of the data. Extrapolations of regression models 2, 3, and 4 from that study yield 52% to 53% stress level at 10 years, based on a median static strength estimate determined at a rate to cause failure in about 2 h. Those stress levels would be somewhat lower if a more rapid ramp rate were used for the median strength estimate. The second study evaluated the effect of high temperature drying on load duration of Douglas-fir 2 by 4 lumber (Gerhards 1988b). Extrapolations of prediction models to 10 years yield a stress level of 50.4% for the conventionally dried lumber and 50.8% for the high-temperature dried lumber when the high-temperature drying effect on strength was removed. In this latter study static strengths were determined at a rate to cause failure in about 5 min for the median specimen. In both the edge knot and high-temperature drying studies, times on constant load were terminated after 220 and 84 days, respectively.

The number of failures in the uncontrolled environment supports, at least for Douglas-fir, the need for a change in design criteria previously suggested by the study on grade effects (Gerhards 1988a). Recall that the 2 by 4s were loaded at or near design levels. The 1.62 factor used in setting the loads is commonly associated with a 10-year full design load with the implication that only 5% of beams should fail in 10 years. Because of the applied loads used here, only 5% of SS specimens and 8% of No. 2 specimens should have failed within 10 years. However, 14% of the SS and 24% of the No. 2 failed in 10 years (Table 3). Indeed, 6% of the SS specimens failed in less than 2% years, and 8% of the No. 2 specimens failed in less than ½ year. Steve Verrill, Mathematical Statistician, at the Forest Products Laboratory made a probability analysis of the 1.62 factor. He determined that out of 50 tests, 7 failures at the 5th percentile and 12 failures at the 8th percentile had less than 3% and less than 0.1% chance of occurring, respectively.

The results of this research suggest that those responsible for safe wood designs should apply a 50% reduction factor to static bending strength of Douglas-fir when designing for a 10-year load. In the absence of long-time loading tests for other species and properties, a similar factor is suggested.

CONCLUSIONS

The most important conclusion of this study is that a factor of 2.0 is more appropriate for adjusting bending strength of Douglas-fir lumber for a full 10-year design load than the currently recommended factor of 1.62. Another conclusion is that testing in an uncontrolled environment out to 12-plus years did not appear to significantly affect the load duration effect observed in a controlled environment, even though relative creep was considerably higher in the uncontrolled environment.

At the end of 12-plus years in the uncontrolled environment, constant loading affected relative creep more in No. 2 specimens than in SS specimens. About 80% of SS specimens had relative creep less than 1.0 compared to only about 25% for No. 2 specimens. Slightly more than 50% of the No. 2 beams doubled their initial deflections in 10 years.

The extended tests to 12-plus years confirm that there is no 50% stress level threshold.

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