BENDING CREEP AND LOAD DURATION OF DOUGLAS-FIR 2 BY 4S UNDER CONSTANT LOAD

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ABSTRACT

Douglas-fir 2 by 4 beams of different grades were tested under various constant-load levels in a controlled environment to evaluate load duration and creep behavior. A two-parameter equation was used to model relative creep of wood beams free of partial fracture. Both parameters M and N of this equation vary considerably between specimens but can be highly correlated with each other, depending on the time base used to determine N. Stress level was partially correlated with M and N together, but with neither parameter alone.

Additional matched beams were tested at near design loads in an unheated building to determine the effect of an uncontrolled environment on load duration and creep. Based on load duration results for the controlled environment already reported, load durations do not appear to have been shortened by the uncontrolled environment, although relative creep was considerably increased.

The most important result of this study, which has implications for the safety of wood structures, is that more beams failed when loaded at near design stress than are commonly assumed would fail. This result, coupled with results from a previous study, suggests that Douglas-fir bending allowable properties should reflect greater load duration reduction factors or shorter load durations. This research is important to structural engineers and to 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, creep modeling, deflection, wood beams, lumber grade, controlled and uncontrolled environments, wood engineering, load duration, design criteria.

INTRODUCTION

This paper evaluates bending creep data obtained in a comprehensive study of the effect of lumber grade on duration of constant load (Gerhards 1988). It also evaluates constant load failures in wood beams during the first 3.5 years of a planned 10-year duration at near design levels of stress. Results contribute to knowledge about variations in creep characteristics of wood under both controlled and uncontrolled environments and load durations for long-time loading.

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 wood structures. Floors may have a permanent sag as a result of transverse bending creep, or sides of beams may have differential amounts of creep over posts as a result of lateral crushing. Creep can occur longitudinally in

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compression and tension, contributing to permanent sag in trusses. Accounting for lumber creep should result in better wood structures.

Various equations have been proposed to model creep behavior (e.g., Holzer et al. 1989; Nielsen 1972; Schniewind 1968). Although none of the models provides perfect fit of wood creep data, the power law creep model

$$D = D_0 + A(T - T_0)^M \tag{1}$$

appears to fit bending creep data on clear wood (Clouser 1959) and lumber (Gerhards 1985). In the power law model, D is total deflection, D_0 is the initial deflection resulting from constant load, T is total time under load, T_0 is the time to apply the load, and A and M are constants to be evaluated. Experience has shown that the fit to Eq. (1) and other creep models to experimental data is very sensitive to D_0. Therefore, D_0 must be considered a constant to be evaluated along with A and M.

Recently, the four-element, five-parameter viscoelastic-viscous model ($T_0 = 0$)

$$D = \beta_1 + \beta_2[1 - \exp(-\beta_3 T)] + \beta_4 T^{\beta_5} \tag{2}$$

was proposed as the best model for fitting chipboard creep data (Pierce et al. 1985). Such an equation should be used with caution, because it is questionable whether a unique fit of creep data can be acquired; that is, some parameters may not be significantly different from zero. (For example, see problems associated with fitting a four-element, four-parameter model by Pierce and Dinwoodie 1977.) Note that Eq. (2) reverts to Eq. (1) if either β_2 or β_3 equals zero.

Another form of the power law creep model

$$RC = (D - D_0)/D_0 = N(T - T_0)^M \tag{3}$$

relates relative creep (RC) to time. Note that A in Eq. (1) represents unit creep deflection ($D - D_0$) at whatever the time unit of measure. For example, if $T - T_0 = 1$ h, then A is the creep deflection 1 h after load. Similarly, $N = A/D_0$ represents the relative creep deflection at whatever the time unit of measure.

As creep leads to collapse, load duration is another important lumber characteristic. Although several studies have evaluated load duration characteristics (for references, see Gerhards 1988), environmental effects on long-time loading have been neglected. 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.

EXPERIMENTAL PROCEDURES

Controlled environment

As most of the experiment was described in detail in Gerhards (1988), only a summary is given here with one exception. The exception concerns a related test phase that involves bending tests in an uncontrolled environment.

The objectives of the experiment were to evaluate both the effect of lumber grade (ASTM 1981) on duration of load and a cumulative damage model to predict duration of load. Three grades of Douglas-fir 2 by 4 lumber were used: Select Structural (SS), No. 2, and No. 3. The lumber was specially selected to have a control knot in the central 24-in. length of each piece within the particular

FIG. 1. Bending test apparatus. Load applied to specimen with low-friction air cylinder. Deflection measured by potentiometer attached to specimen and monitored by computer (not shown). (M 83 0172-2)

lumber grade but to have warp characteristics restricted to SS. Control knots were not restricted in lateral location to either centerline or edge. With the exception of the tests in the uncontrolled environment, bending tests were carried out in a controlled environment (73 F, 50% relative humidity) using the test apparatus shown in Fig. 1 for the load durations indicated in Fig. 2. The beams were tested on an 84-in. span with symmetrically located load points 24 in. apart, and the control knot was stressed in tension.

Three different series of step-constant load levels were applied: high, medium, and low (Fig. 2), depending on the level of load in the first step. The planned loads in the first step were equivalent to the 40th percentile of the static strength distribution for the high series, the 15th percentile for the medium series, and the 5th percentile for the low series. The loads indicated in Fig. 2 represent the approximate 5th, 15th, 40th, and 70th percentiles of the estimated static strength distributions. For example (Fig. 2a), the 40th percentile step-constant load of 1,123 lb for SS was held for 7 days in the first step; then the load was raised to the 70th percentile at 1,501 lb for SS and held for 14 days. Residual strengths of surviving specimens were determined at the end of a step-constant-load series as indicated by the upward-pointing arrows in Fig. 2. All changes in load, including residual strength determinations, were at the ramp loading rate of 300-lb bending

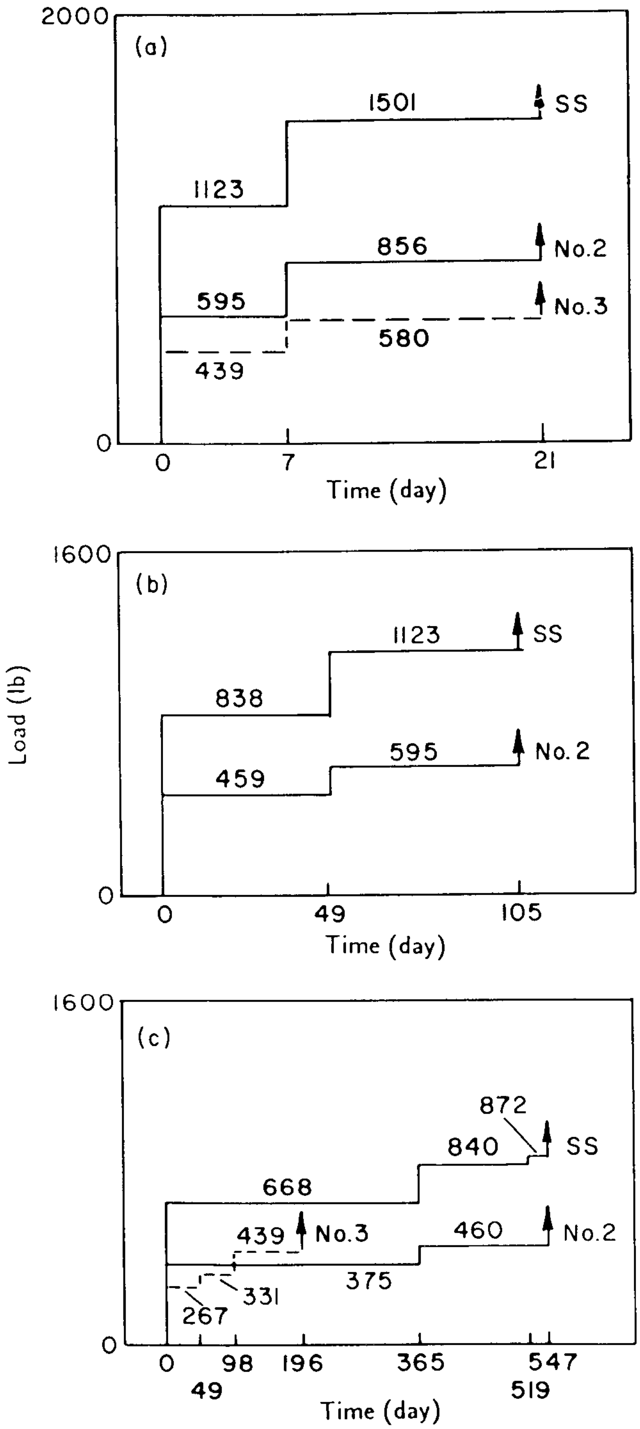


FIG. 2. Experimental load durations at 73°F, 50% relative humidity: (a) High step-constant-load series, (b) medium step-constant-load series, (c) low step-constant-load series. Change in step-constant-load levels within a series at 300 lb/min. One pound of load equals 5.13 lb/in.^{2} bending stress. (ML90 5368)

load per minute. A set of 50 specimens was tested at each grade step-constant-load series indicated in Fig. 2; each set of a grade was matched to the others by equal distributions of static edgewise bending modulus of elasticity (E), with control knots stressed in tension. An additional 50-specimen set of SS matched to the other SS sets was loaded at 1,123 lb for 56.7 days (high extended). Specimen moisture contents in this experiment averaged 10%.

In all the tests at 73 F, 50% relative humidity, deflections were measured with a precision potentiometer rigged to sense midspan bending deflection. The potentiometer was attached to a yoke that rested on rails located at the specimen neutral axis over the bending frame supports. A computer scanned the potentiometer outputs from all 50 specimens under a given load every 0.1 sec; a deflection reading was saved only when the last read value differed from the last saved value by a set increment, typically 0.015 to 0.025 in. Creep data had to be edited to eliminate spurious data because of intermittent electrical noise.

Uncontrolled environment

In this test 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 grade and E-distribution to those used in the controlled environment have been under test for over 3.5 years out of a planned 10-year duration. The specimens have been carrying constant dead loads of 412.7 lb for SS and 232 lb for No. 2 on the same spans (support and load points) as used in the controlled environment study. As in the controlled environment tests, control knots in these dead load bending tests have been stressed in tension. Dead load testing has taken place in an unheated, enclosed building with some natural ventilation.

The uncontrolled environment 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 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.

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 strengths by 1.62, the 10-year duration factor in common use. 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 1988). Results revealed that the 232-lb dead load times 1.62 represents the 8th percentile of the No. 2 static strength distribution. Note that the dead load is equivalent to 2,120 lb/in.^{2} for SS and 1,190 lb/in.^{2} for No. 2. Current design bending stresses for Douglas-fir 2 by 4s in the dry use condition are 2,100 lb/in.^{2} for SS and 1,450 lb/in.^{2} for No. 2. 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 0.0005 in.) mounted in a rigid frame. The digital gauge

TABLE 1. *Number of controlled environment specimens that failed at various stages of loading.*

Load levels and lumber grade[b]	Failed specimens in constant-load series[a]						
	Upload to first constant	Under first constant load	Upload to second constant	Under second constant load	Upload to third constant	Under third constant load	Ramp load of surviving specimens
High (40–70)							
SS	18	15	1	7	NA	NA	9
SS extended	21	13	NA	NA	NA	NA	16
No. 2	24	13	3	9	NA	NA	1
No. 3	18	16	1	13	NA	NA	2
Medium (15–40)							
SS	7	21	0	11	NA	NA	11
No. 2[c]	10	21	0	9	NA	NA	10
Low (5–15)							
SS	5	17	0	5	NA	NA	23
No. 2	7	25	0	3	NA	NA	15
Low (5–15–40)							
No. 3[c]	3	21	0	7	0	14	5
Total	113	162	5	64	0	14	92

[a] Each load series started with 50 specimens for each grade; NA means not applicable.
[b] Numbers in parentheses indicate percentiles of static strength distribution.
[c] No creep data.

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 over the supports to allow full-span deflection measurements. The upper surface at the marked spots and at the center was lightly planed and varnished to minimize surface imperfections.

No attempt was made to model creep of specimens in the uncontrolled environment because daily and seasonal variations in the environment caused unsystematic changes in deflection.

ANALYSES

Several different bending creep properties were analyzed. Creep was modeled using Eqs. (1) and (3). Also analyzed were total bending deflection at selected times, relation of relative deflection to relative stress level (SL) and time, and effect of environment on relative creep and load duration. Note that deflections beyond the first step of a constant-load series are not evaluated in this paper.

RESULTS AND DISCUSSION

Controlled environment

Table 1 shows the number of specimens tested in the constant-load series that failed during the various load histories. In the controlled environment experiment (Table 1) in which 450 specimens were tested, 113 specimens failed in uploading to the first constant-load level, leaving a potential 337 specimens for creep model evaluation. Of the 337 potentials, only 163 specimens had creep data that could be represented by the power model. Three reasons can be given for the reduced number of specimens: (1) missing creep data as result of a technical error in

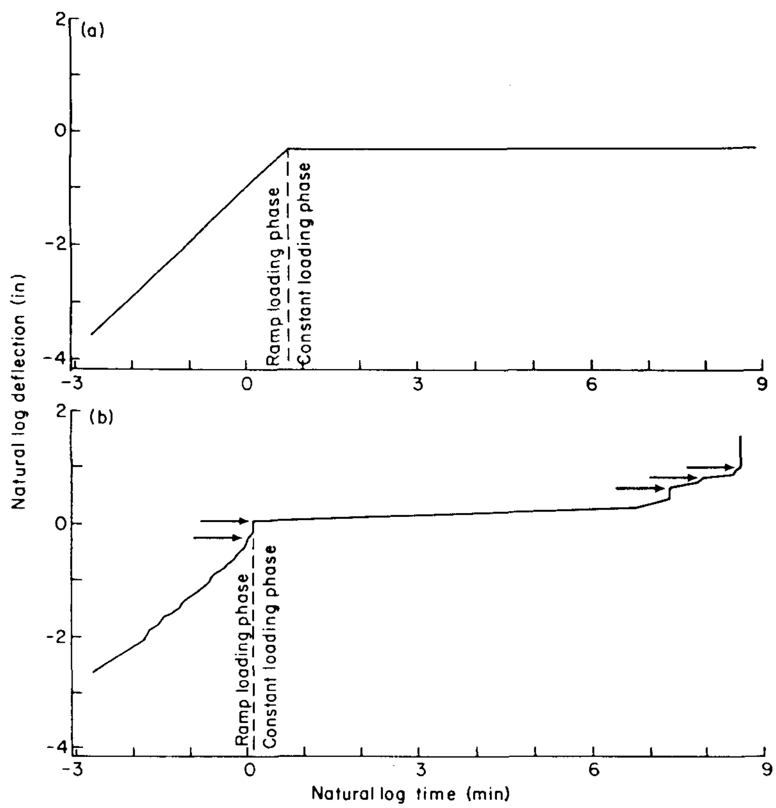


FIG. 3. Examples of log-log plots of total deflection as a function of total time at test. (a) SS specimen without failure during first step of low step-constant-load test (668 lb). (b) No. 2 specimen of low step-constant-load test (375 lb) with several partial failures (arrows) before complete failure. (ML 90 5369)

starting deflection monitoring of 50 No. 2 and 50 No. 3 specimens in the medium step-constant-load series, (2) partial failure in some specimens during ramp loading, and (3) partial or total failure in other specimens early during the first step of constant load.

Creep modeling using equations (1) and (3)

Equation (1) was fit by nonlinear least squares to the constant-load deflection-time data for each specimen that had valid creep data; that is, apparent freedom from partial fracture for an extended period. Figure 3 shows two examples of deflection-time behavior during ramp uploading and under constant loading in log space. No failures are apparent in Fig. 3a, but several are highlighted by arrows in Fig. 3b.

The estimated creep model parameters (D_0, A, and M), along with ln N[N = A/D_0 in Eq. (3)], are presented in Table 2 for SS, in Table 3 for No. 2, and in Table 4 for No. 3. The tables exclude specimens where D_0 differs from D_{0R} by $\pm 5\%$ or more, the predicted deflection at end-of-ramp loading based on the linearized ramp loading-deflection relationship for a specimen. The tables also exclude short-time creep model (valid for <1 day) specimens. A lack of direct correspondence between D_0 and D_{0R} can result from a significant component of creep or partial fracture occurring during ramp loading, particularly from higher stresses or from data that fit the creep model poorly. Of the 163 specimens with modeled creep data, only 90 specimens passed the restrictions on D_0 and 1 day (64 in Table 2, 21 in Table 3, and 5 in Table 4).

Tables 2, 3, and 4 reveal considerable variation in parameters between specimens. For some perspectives on variation, consider the SS low constant-load data in Table 2. Coefficient of variation (COV) on E is 13%, a value consistent with graded lumber. For comparison, COV is 31% for M, 155% for A, but only 21% for ln N. Outside of an expected high correlation between D_0 and E, only M and A or M and ln N appear to be correlated.

Plots of A as a function of M, not shown here, suggest an exponential relationship. Recall that for a given time base, A is the creep deflection at one unit of time after loading—1 min for A values in Tables 2, 3, and 4; similarly, N is relative creep at 1 min after loading. The correlations are as follows:

M on A	$r^2 = 0.58$	Linear
M on ln A	$r^2 = 0.90$	Exponential
M on ln N	$r^2 = 0.94$	Exponential

These correlations show the improvement of an exponential assumption over a linear one and an additional improvement if creep deflection is normalized by dividing by initial deflection. A plot of M on ln N for the 64 SS specimens (Fig. 4) has the least squares fit of

$$M = -0.11043 - 0.07260 \ln N \tag{4}$$

Although Fig. 4 summarizes the M and N coefficients of the creep model for SS specimens, it also in general represents the trend of M − ln N data for No. 2 and No. 3 specimens. The few exceptions in the trend are for No. 2 specimen frames 68 and 99 under low constant load and frame 110 under high constant load.

In Fig. 4, note that the high constant-load data are within the right half of the scatter of data but that the medium and lower constant-load data essentially cover the full range. The more limited data for No. 2 and No. 3 specimens follow the same trend.

Even though Eq. (4) has a high r^2, a change in the time base for N changes how well M and ln N are correlated. Consider the ith equation with an error term, ϵ_i:

$$M_i = a + b \ln N_i + \epsilon_i \tag{5}$$

To change N_i in Eq. (5) from a minute base to an hour base, N_i must be multiplied by 60^{M_i}. That is,

$$M_i = a + b \ln(N_i \times 60^{M_i}) + \epsilon_i \tag{6}$$

When Eq. (6) is rewritten as

$$M_i = \frac{a + b \ln N_i + \epsilon_i}{1 - b \ln 60}$$

the error term is confounded by the reciprocal of $(1 - b \ln 60)$, thereby affecting

TABLE 2. *Creep model parameters and related data for Select Structural specimens in a controlled environment.*[a]

Bending frame number	Constant-load level[b]	Predicted stress level	E ($\times 10^6$ lb/in.^{2})	Creep model parameters[c]				Model limit (days)	D_0/D_{0R}	T_0 (s)
				D_0 (in.)	M	A (in.)	ln N			
44	High	0.786	1.830	1.255	0.15726	0.03420	−3.60276	4.745	1.010	224.1
35	High	0.514	2.035	1.130	0.13291	0.04135	−3.30754	6.991	1.007	224.1
13	High	0.691	1.546	1.435	0.17164	0.02940	−3.88787	6.998	0.969	224.1
28	High	0.599	1.846	1.249	0.09388	0.07326	−2.83621	6.991	1.021	224.1
4	High	0.516	1.860	1.256	0.16868	0.02176	−4.05540	6.999	1.028	224.1
26	High	0.999	1.801	1.308	0.14919	0.07085	−2.91561	2.894	1.036	224.1
3	High	0.764	1.767	1.330	0.24337	0.01130	−4.76788	6.999	1.036	224.1
124	High-Ext.	0.639	1.886	1.192	0.13794	0.04883	−3.19534	53.241	0.981	224.1
116	High-Ext.	0.674	1.630	1.396	0.17940	0.02464	−4.03709	52.083	0.986	224.1
142	High-Ext.	0.723	1.630	1.382	0.13211	0.04361	−3.45570	48.611	0.976	224.1
146	High-Ext.	0.397	2.078	1.117	0.10700	0.05261	−3.05568	54.398	0.999	224.1
137	High-Ext.	0.739	1.523	1.514	0.15887	0.05048	−3.40069	48.611	1.015	224.1
143	High-Ext.	0.600	2.084	1.124	0.17652	0.01909	−4.07577	56.713	1.023	224.1
115	High-Ext.	0.691	1.796	1.297	0.20308	0.01582	−4.40639	48.611	1.022	224.1
130	High-Ext.	0.555	2.058	1.133	0.07034	0.06319	−2.88634	53.241	1.019	224.1
121	High-Ext.	0.770	1.902	1.182	0.07570	0.10163	−2.45382	21.991	0.986	224.1
122	High-Ext.	0.579	1.719	1.330	0.13058	0.03827	−3.54819	21.991	1.000	224.1
3	Medium	0.622	1.787	0.958	0.18340	0.01972	−3.88356	49.000	0.993	166.5
37	Medium	0.414	1.623	1.091	0.37474	0.00156	−6.55143	49.000	1.034	166.5
49	Medium	0.462	1.618	1.107	0.27335	0.00592	−5.23107	49.000	1.037	166.5
46	Medium	0.296	2.128	0.817	0.19645	0.00761	−4.67627	49.000	1.001	166.5
4	Medium	0.476	2.080	0.817	0.12067	0.03033	−3.29333	49.000	0.984	166.5
47	Medium	0.610	1.993	0.883	0.21348	0.00853	−4.64008	49.000	1.025	166.5
50	Medium	0.528	2.290	0.768	0.18317	0.01020	−4.32126	49.000	1.017	166.5
25	Medium	0.395	2.070	0.833	0.16842	0.01520	−4.00315	49.000	0.999	166.5
22	Medium	0.540	2.013	0.866	0.20160	0.00992	−4.46870	49.000	1.007	166.5
30	Medium	0.587	1.677	1.045	0.45872	0.00072	−7.28340	49.000	1.022	166.5
45	Medium	0.432	1.673	1.024	0.13723	0.01866	−4.00464	30.093	0.995	166.5
26	Medium	0.342	1.960	0.906	0.16423	0.02205	−3.71577	49.000	1.035	166.5
38	Medium	0.682	1.651	1.050	0.15396	0.03505	−3.39955	24.306	1.001	166.5
35	Medium	0.598	1.616	1.076	0.20433	0.02130	−3.92288	49.000	1.008	166.5
41	Medium	0.707	1.600	1.111	0.32679	0.00391	−5.64979	9.259	1.027	166.5
19	Medium	0.490	1.706	0.982	0.09784	0.06606	−2.69868	49.000	0.973	166.5
51	Medium	0.633	1.853	0.950	0.24081	0.00733	−4.86467	49.000	1.028	166.5

TABLE 2. *Continued.*

Bending frame number	Constant-load level[b]	Predicted stress level	E ($\times 10^6$ lb/in.^{2})	Creep model parameters[c]				Model limit (days)	D_0/D_{0R}	T_0 (s)
				D_0 (in.)	M	A (in.)	ln N			
21	Medium	0.563	1.899	0.899	0.12268	0.03064	−3.37868	49.000	0.981	166.5
40	Medium	0.763	2.125	0.847	0.35295	0.00162	−6.25930	5.347	1.045	166.5
44	Medium	0.810	1.313	1.372	0.13005	0.05705	−3.17972	2.083	1.045	166.5
43	Low	0.477	2.255	0.614	0.38694	0.00049	−7.14407	364.583	1.017	132.0
28	Low	0.449	1.906	0.736	0.24959	0.00614	−4.78553	103.009	1.024	132.0
45	Low	0.296	1.816	0.764	0.25036	0.00318	−5.48151	364.583	1.012	132.0
18	Low	0.763	1.609	0.845	0.11835	0.05537	−2.72537	1.157	0.997	132.0
15	Low	0.659	1.721	0.829	0.30502	0.00714	−4.75509	9.259	1.041	132.0
20	Low	0.514	1.658	0.810	0.17825	0.01406	−4.05413	364.583	0.996	132.0
48	Low	0.608	1.773	0.808	0.43227	0.00106	−6.63907	180.093	1.050	132.0
30	Low	0.430	1.886	0.747	0.29564	0.00205	−5.89777	364.583	1.038	132.0
37	Low	0.585	1.461	0.956	0.20380	0.01128	−4.44027	223.380	1.028	132.0
25	Low	0.330	1.765	0.790	0.41729	0.00045	−7.47282	364.583	1.022	132.0
12	Low	0.575	1.300	1.070	0.28808	0.00484	−5.39860	347.222	1.023	132.0
24	Low	0.486	1.381	1.000	0.28953	0.00254	−5.97517	364.583	1.018	132.0
8	Low	0.369	1.839	0.766	0.25363	0.00299	−5.54709	364.583	1.026	132.0
32	Low	0.646	2.159	0.635	0.22758	0.00460	−4.92796	76.389	1.005	132.0
44	Low	0.273	2.004	0.703	0.25304	0.00370	−5.24711	364.583	1.048	132.0
47	Low	0.315	1.865	0.751	0.35142	0.00102	−6.60595	364.583	1.023	132.0
29	Low	0.564	1.634	0.848	0.33178	0.00183	−6.14095	364.583	1.017	132.0
23	Low	0.411	1.666	0.831	0.25859	0.00448	−5.22235	364.583	1.022	132.0
41	Low	0.344	1.998	0.698	0.24276	0.00487	−4.96489	364.583	1.026	132.0
40	Low	0.380	1.702	0.798	0.37200	0.00069	−7.05900	364.583	1.009	132.0
38	Low	0.396	1.617	0.859	0.16272	0.01504	−4.04511	364.583	1.013	132.0
46	Low	0.620	1.819	0.782	0.36580	0.00139	−6.33594	94.907	1.039	132.0
31	Low	0.391	2.083	0.662	0.25359	0.00366	−5.19893	364.583	1.013	132.0
5	Low	0.543	1.570	0.880	0.30016	0.00276	−5.76621	364.583	1.011	132.0
52	Low	0.524	1.654	0.829	0.23788	0.00882	−4.54382	364.583	1.005	132.0
51	Low	0.689	1.320	1.072	0.46348	0.00122	−6.77828	18.981	1.045	132.0
4	Low	0.505	1.846	0.757	0.13238	0.02457	−3.42771	364.583	1.015	132.0

[a] Excludes specimens with $0.95 < D_0/D_{0R} < 1.05$ and with model only valid for less than 1 day.
[b] Ext. is extended.
[c] Values of A and N based on time in minutes.

TABLE 3. *Creep model parameters and related data for No. 2 specimens in a controlled environment.*[a]

Bending frame number	Constant-load level	Predicted stress level	E ($\times 10^6$ lb/in.^{2})	Creep model parameters[b]				Model limit (days)	D_0/D_{0R}	T_0 (s)
				D_0 (in.)	M	A (in.)	ln N			
139	High	0.482	1.526	0.845	0.30382	0.00370	−5.42956	6.991	1.050	118.2
146	High	0.741	1.241	1.033	0.16740	0.02563	−3.69687	6.991	1.040	118.2
117	High	0.650	1.695	0.710	0.12070	0.02203	−3.47201	6.991	0.973	118.2
110	High	0.791	1.360	0.909	0.26037	0.02305	−3.67475	1.389	0.999	118.2
112	High	0.390	1.875	0.652	0.04277	0.06933	−2.24053	2.909	0.988	118.2
77	Low	0.445	1.280	0.598	0.22939	0.00620	−4.56885	159.722	0.999	73.2
67	Low	0.648	1.139	0.692	0.17150	0.03108	−3.10306	15.046	1.045	73.2
83	Low	0.478	1.572	0.509	0.32953	0.00091	−6.33015	364.583	1.024	73.2
102	Low	0.508	1.538	0.504	0.20738	0.00545	−4.52696	69.444	1.005	73.2
69	Low	0.383	1.753	0.445	0.25405	0.00201	−5.39736	364.583	1.037	73.2
99	Low	0.730	1.412	0.538	0.28143	0.01542	−3.55235	4.259	0.985	73.2
78	Low	0.329	1.789	0.455	0.36983	0.00046	−6.89158	364.583	1.038	73.2
84	Low	0.625	1.267	0.610	0.19977	0.01265	−3.87676	5.787	0.993	73.2
100	Low	0.396	1.370	0.533	0.16394	0.01773	−3.40396	364.583	0.973	73.2
82	Low	0.304	1.331	0.598	0.27156	0.00359	−5.11635	364.583	1.026	73.2
68	Low	0.686	1.139	0.711	0.80558	0.00006	−9.30080	11.921	1.038	73.2
61	Low	0.467	1.566	0.469	0.13858	0.01716	−3.30749	364.583	0.957	73.2
63	Low	0.350	1.401	0.559	0.16363	0.01874	−3.39494	364.583	1.030	73.2
96	Low	0.570	1.581	0.501	0.57046	0.00011	−8.44670	138.889	1.037	73.2
64	Low	0.434	1.515	0.528	0.33396	0.00067	−6.67426	364.583	1.047	73.2
55	Low	0.367	1.371	0.606	0.22526	0.00545	−4.71091	364.583	1.049	73.2

[a] Excludes specimens with $0.95 < D_0/D_{0R} < 1.05$ and with model only valid for less than 1 day.
[b] Values of A and N based on time in minutes.

TABLE 4. *Creep model parameters and related data for No. 3 specimens in a controlled environment.*[a]

Bending frame number	Constant-load level	Predicted stress level	E ($\times 10^6$ lb/in.^{2})	Creep model parameters[b]				Model limit (days)	D_0/D_{OR}	T_0 (s)
				D_0 (in.)	M	A (in.)	ln N			
55	High	0.730	1.434	0.651	0.17766	0.01270	−3.93653	6.991	1.041	87.2
89	High	0.605	1.521	0.589	0.06766	0.05167	−2.43308	6.991	0.984	87.2
76	High	0.583	1.794	0.521	0.18398	0.01169	−3.79660	6.991	1.032	87.2
91	High	0.644	1.180	0.793	0.19788	0.02048	−3.65688	6.991	1.036	87.2
74	High	0.462	1.273	0.732	0.24074	0.00603	−4.79862	6.991	1.025	87.2

[a] Excludes specimens with $0.95 < D_0/D_{OR} < 1.05$ and with model only valid for less than 1 day.
[b] Values of A and N based on time in minutes.

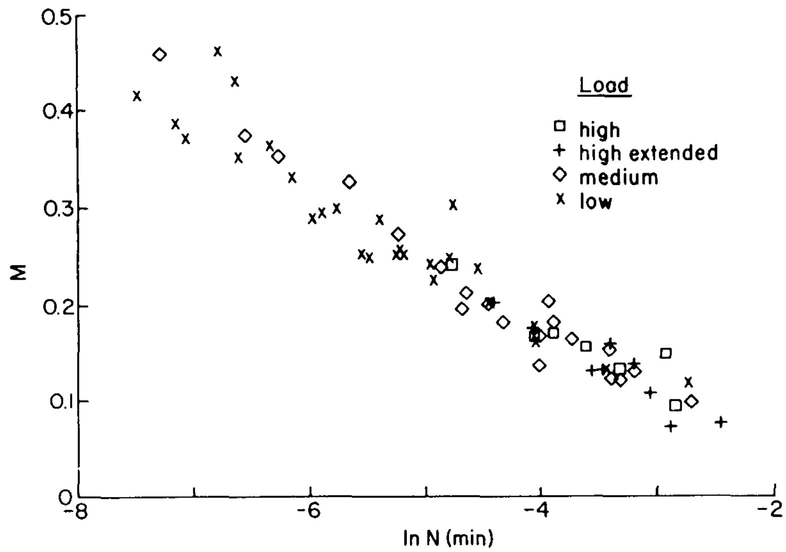


FIG. 4. Correlation of creep parameters, M and ln N, for 64 SS specimens. (ML90 5370)

correlation between M and ln N. The change in r^2 for the SS M − ln N correlations resulting from a changing time base for N are as follows:

Time base	r^2
Minute	0.94
Hour	0.87
Day	0.74
Month	0.31
Year	0.01

Figure 5 shows how the relative positions of N change between specimens from one time base to another (1 min at the extreme left to 1 year at the extreme right), thereby affecting correlation with M.

Another point of interest in Tables 2 and 3 is that relative SL is correlated to a combination of M and N but to neither alone. Stress level is the applied constant load divided by the estimated strength based on order of failure (see Gerhards 1988 for details). Least squares fits of SL on M and ln N (minute time base) for the 64 SS and 21 No. 2 specimens are

$$\text{SS} \quad SL = 1.114 + 3.443M + 0.2893 \ln N, \quad r^2 = 0.43 \tag{7}$$

$$\text{No. 2} \quad SL = 0.741 + 1.534M + 0.1326 \ln N, \quad r^2 = 0.41 \tag{8}$$

These fits suggest that for any given value of N (e.g., Fig. 5), SL tends to increase with M. Equations (7) and (8) are significantly different. Incidentally, changing the time base of N does not change r^2 for Eqs. (7) and (8); it changes only the coefficient of M. Equations (7) and (8) are of little more than academic interest

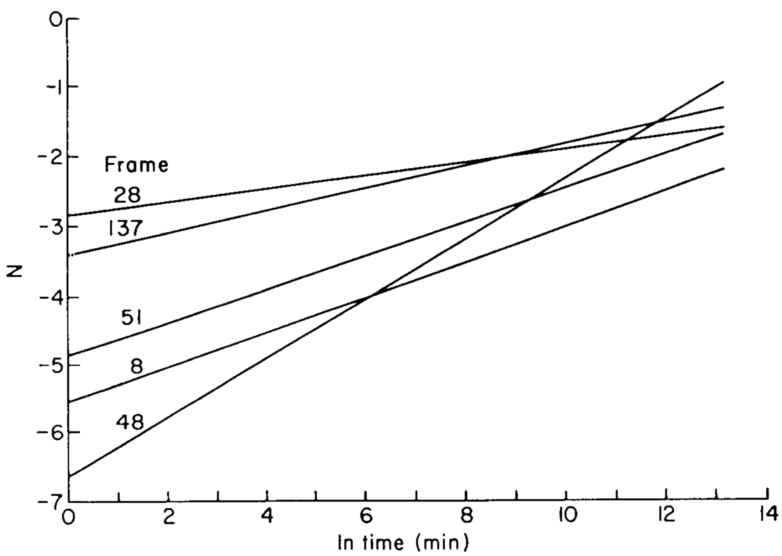


FIG. 5. Examples of how N changes with time base for several SS specimens (refer to Table 2). (ML90 5371)

because, in practice, one would want to predict how relative creep responds to SL, rather than the other way around.

Total bending deflection at selected times

To summarize deflection data, deflection values were interpolated at selected times from the record of actual specimen deflection times. Selected times, spaced approximately equal on a log scale, included end-of-ramp loading, 3,600 sec, and 36,000 sec. Cumulative distributions of deflection, based on all 50 specimens in a set, at the selected times after start-of-ramp loading are presented in Fig. 6 for SS specimens and Fig. 7 for No. 2 and No. 3 specimens.

Some general comments can be made concerning Figs. 6 and 7. First, because some specimens failed before the end-of-ramp loading, none of the cumulative distributions extends to the top of the figures. Second, the cumulative distributions shift toward larger deflections as time-under-load increases. The differences in deflection between any of the distributions and the end-of-ramp distribution reflect the creep portion of deflection. Third, the distributions stop at lower levels of probability as time-under-load increases, reflecting the loss of some additional specimens to failure with time-under-load. Fourth, deflections increase significantly with each constant-load level, i.e., low to high.

Another more practical point needs to be considered. Each set of distributions in Figs. 6 and 7 can be thought of as representing a sample of structural lumber under a given constant bending load (50 specimens per set here). If the sample represents a structure, one could consider the structure to have failed, even under the low constant load, because more than the 5th percentile (strengthwise) specimen failed. In other words, the portions of specimens of interest to engineers were loaded too high to provide useful data for a deflection design criterion; their relative SLs were too high. However, the lower portions of the deflection distri-

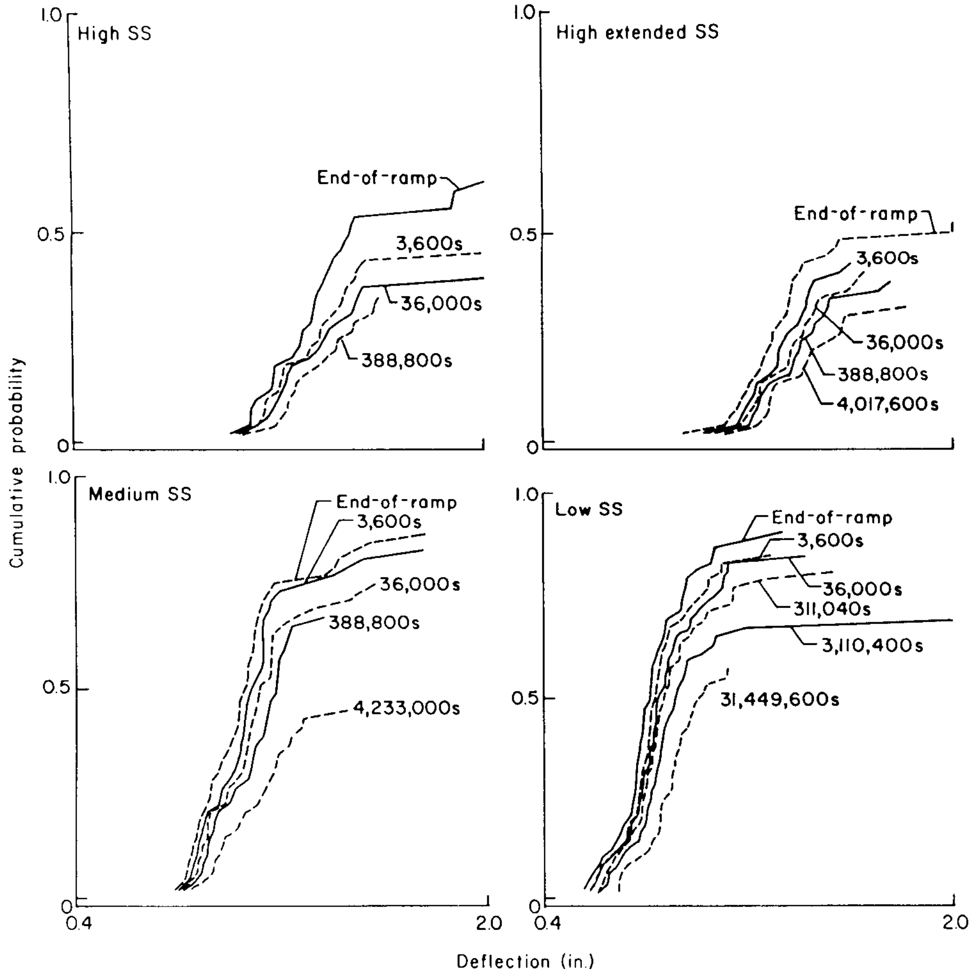


FIG. 6. Cumulative distributions of SS specimen deflections at selected times in seconds after start of ramp loading. End-of-ramp loading is T_0 in Table 3. (ML90 5382)

butions represent specimens under lower relative SLs. The deflection data relative to initial deflection are evaluated next as they relate to SL.

Relation of relative deflection to relative stress level and time

Relative deflection (D/D_{0R}) is total deflection divided by initial deflection, i.e., the deflection at end-of-ramp loading. Note that relative creep is obtained by subtracting 1 from relative deflection.

Figure 8 shows the experimental relation between D/D_{0R}, SL, and time for specimens at the low constant loads (SS and No. 2). Lower values of SL and consequently lower values of D/D_{0R} have been excluded for clarity. All the data points represent surviving specimens, except for the highest SL at each indicated time. Ratios of D/D_{0R} for the highest SLs were arbitrarily set at three times D_{0R} for SS and two times D_{0R} for No. 2, thus allowing estimates of upper trends for D/D_{0R} compared to SL at the designated times. The factors of 3 and 2 were chosen

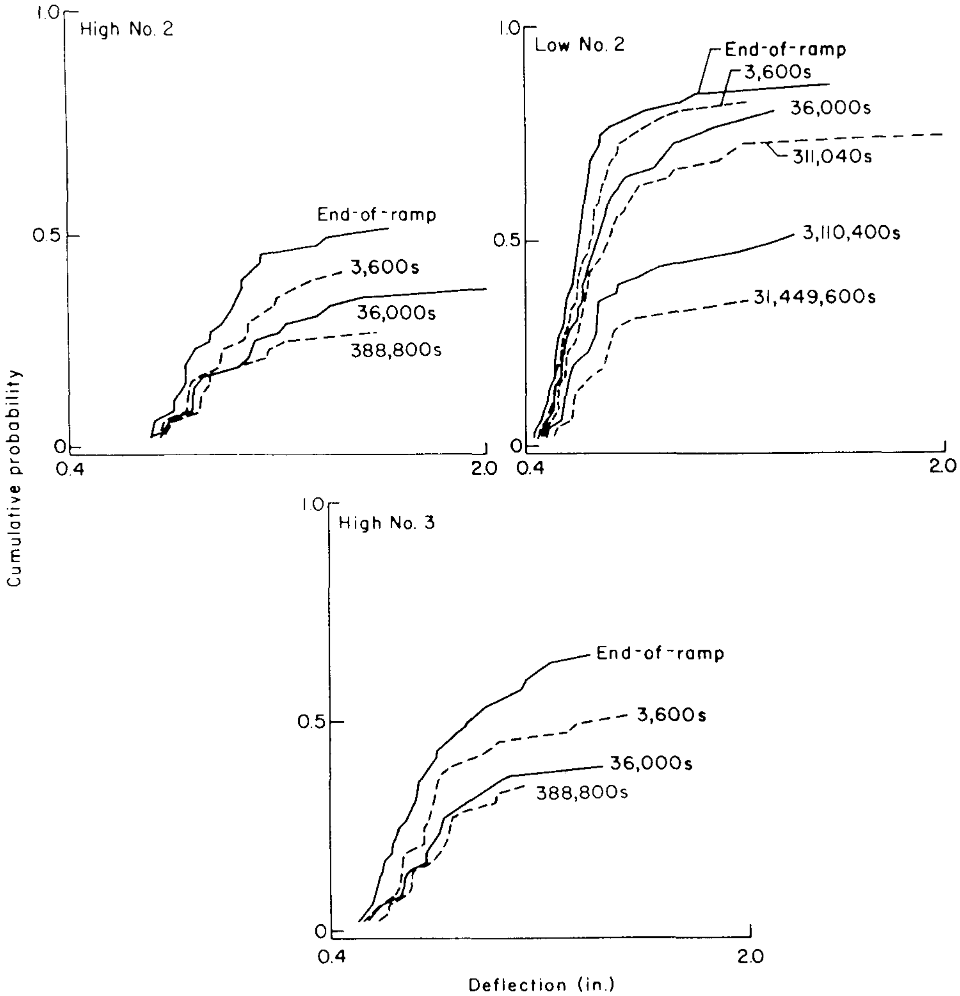


FIG. 7. Cumulative distributions of No. 2 and No. 3 specimen deflections at selected times in seconds after start of ramp loading. End-of-ramp loading is T_0 in Tables 4 and 5. (ML90 5381)

for scaling purposes. The most conservative value of D/D_{0R} for the highest SLs is infinity, resulting in vertical upper trends.

Upper trend lines at the selected experimental times are shown in Fig. 9 along with a probable range for a 10-year load duration extrapolated from the experimental time trend lines. These trend lines can be used as deflection limit criteria. For example, if total deflection in 10 years was limited to three time initial deflection, then load should not exceed about 52% of static strength for SS specimens or about 46% of static strength for No. 2 specimens.

Uncontrolled environment

Creep deflection.—Select Structural and No. 2 specimens under constant dead load in an uncontrolled environment exhibited relatively large increases in deflection between about 175 and 210 days (Fig. 10). The large increases in deflection

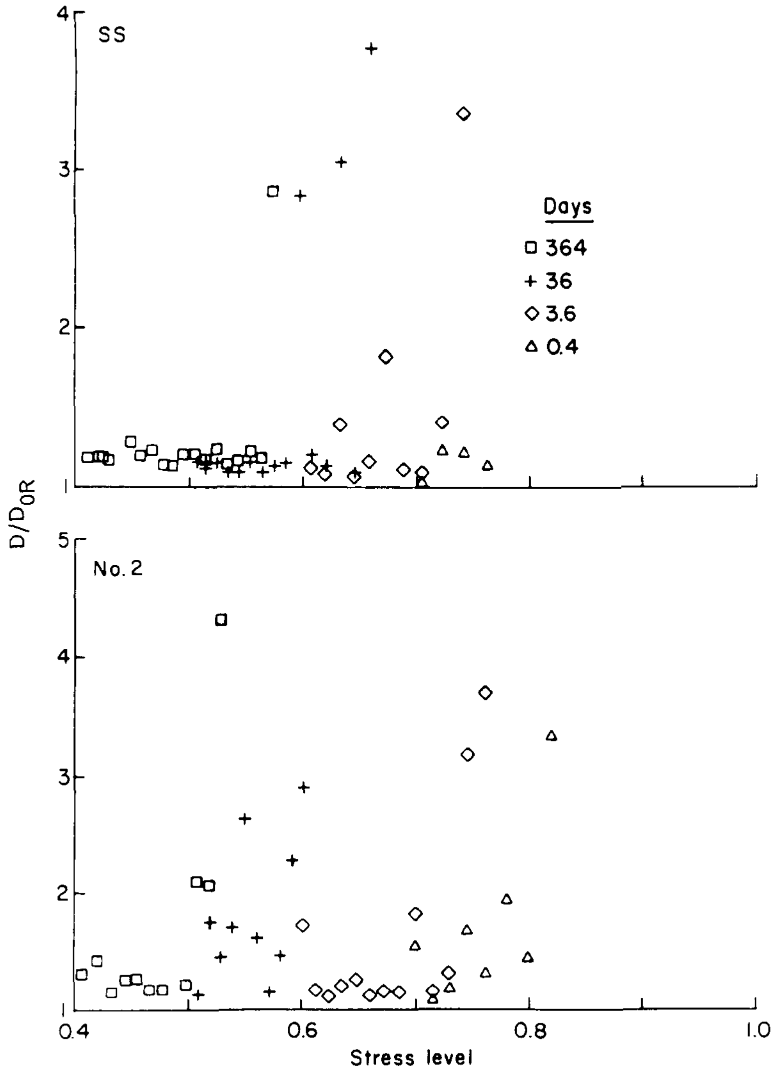


FIG. 8. D/D_{0R} relative to SL and time for low step-constant-load specimens. Excludes specimens with SL <0.4 for 364 days, <0.5 for 36 days, <0.6 for 3.6 days , and <0.7 for 10 h. (ML90 5372)

occurred between the end of August and the end of October during the first year of loading. Also, small up and down changes apparently occurred at least during the first 100 days. These increases or changes suggest environmental effects, and consequently no attempt was made to model creep in the uncontrolled environment. Creep deflection proceeded to failure in 6 of the 50 SS specimens and in 8 of the 50 No. 2 specimens. These failures are discussed later with respect to load duration.

Cumulative frequencies of total deflection (compared to creep deflection in Fig. 10) for the 50 SS and 50 No. 2 specimens are shown in Fig. 11 at selected times during the first 3.5 years of constant dead load in the uncontrolled environment. As for cumulative frequencies of deflections in the controlled environment, those

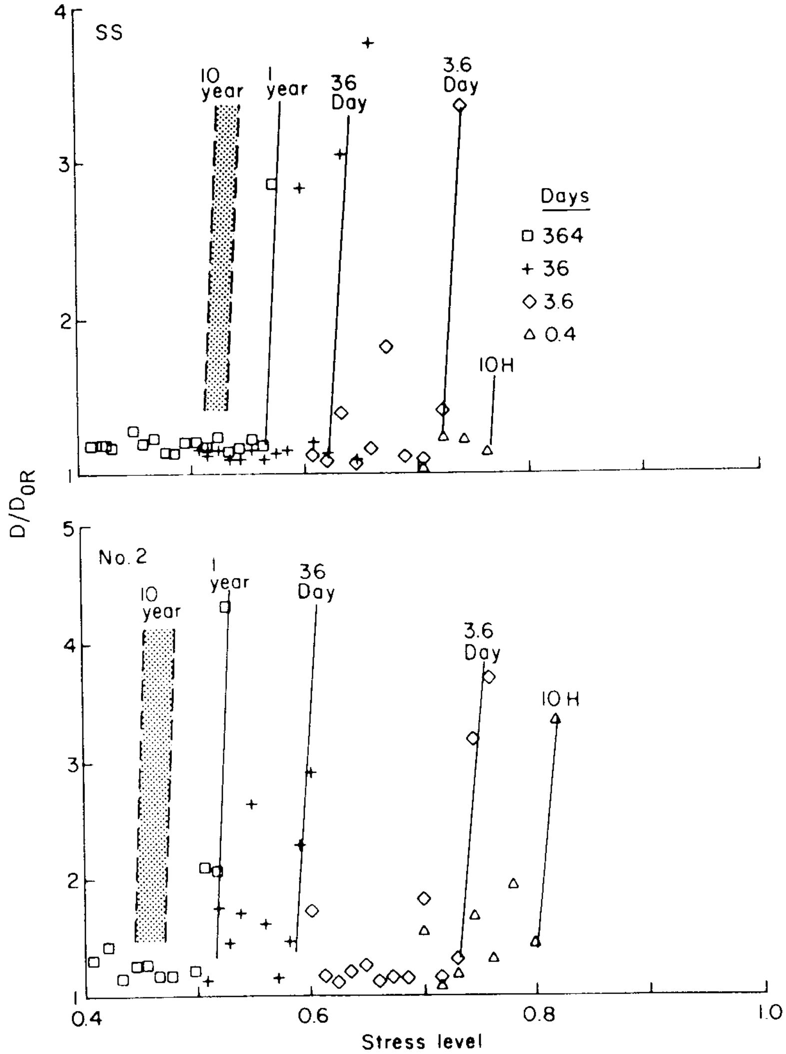


FIG. 9. D/D_{OR} relative to SL and time overlaid with maximum predicted trend lines. (ML90 5373)

of Fig. 11 exhibit similar increased deflections with time. However, much fewer specimen failures are evident in Fig. 11 than in the previous figures, owing to the much lower level of sustained constant load.

Relative creep.—Relative creep data $(D - D_i)/D_i$, where D_i is initial deflection for the uncontrolled environment, are summarized in Fig. 12 at different percentiles of the sample populations of SS and No. 2 specimens.

Three points are of interest in the relative creep percentile curves. First, the SS specimens have a tighter distribution of relative creeps than the No. 2 specimens, both at the start and at later times. Second, the large increases in deflections during the first year shown in Fig. 10 are evident in the total sample population. Third, for at least 10% of both sample populations, deflections increased to more than double the initial deflections in less than 2 years, and if the trend continues as

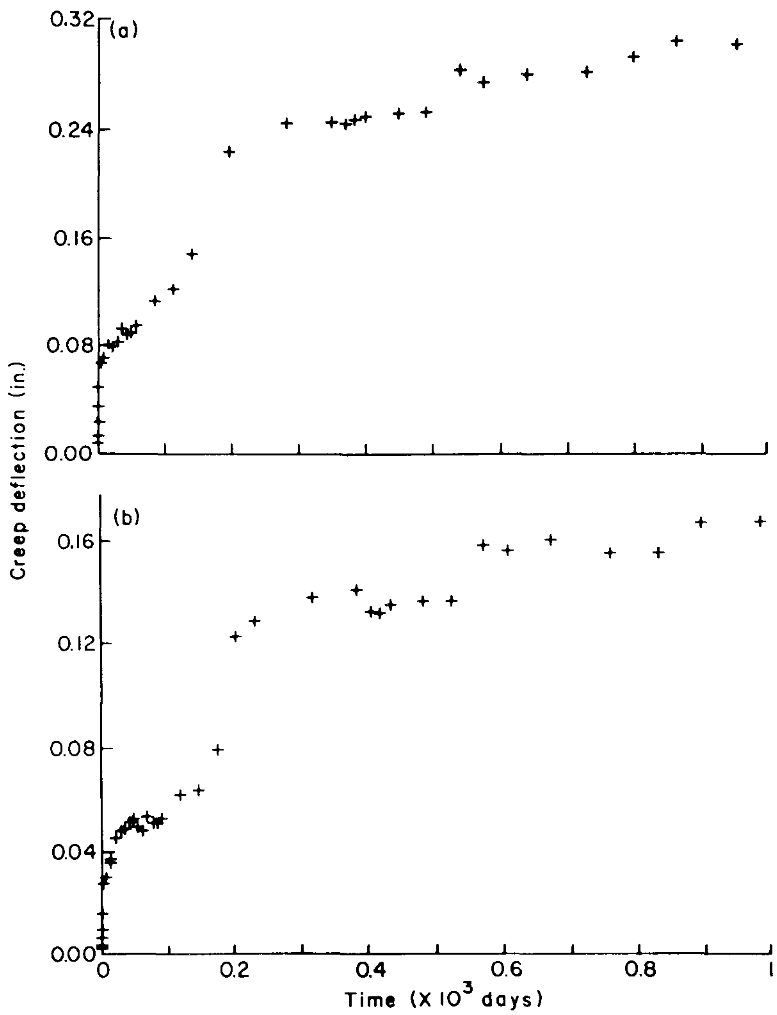


FIG. 10. Examples of creep deflection in an uncontrolled environment. (a) SS D_0 = 0.484 in., (b) No. 2 D_0 = 0.357 in. (ML90 5374)

shown in Fig. 12b, 50% of the No. 2 specimens will have doubled their initial deflections in 10 years. The early doubling of initial deflection is contrary to the long time assumed for doubling at design levels of stress.

Comparison of creep between constant and uncontrolled environments

To include all load levels for comparison, relative creep values were determined for each load level and environmental condition at the sample population 20th percentiles (Fig. 13). Relative creep bases are slightly different between controlled and uncontrolled environments because of the different methods of recording data: automatic by computer for controlled environment and manual for uncontrolled environment. The initial deflection was recorded for each specimen when loaded individually in the uncontrolled environment; however, the actual initial

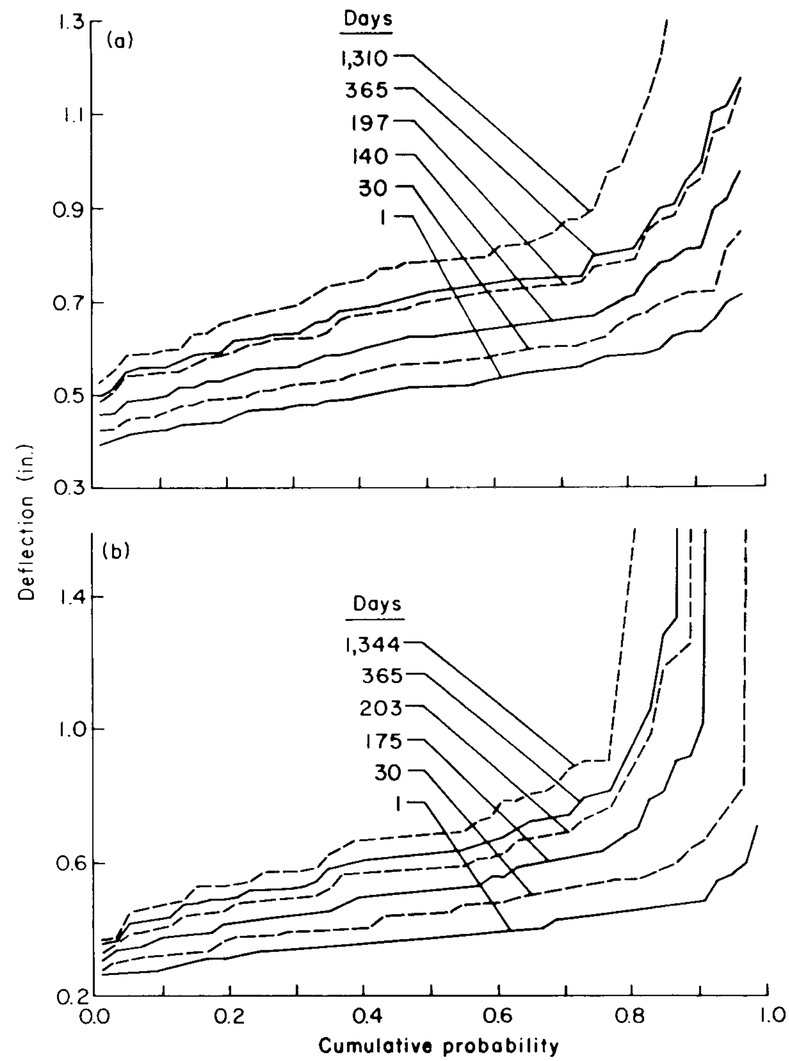
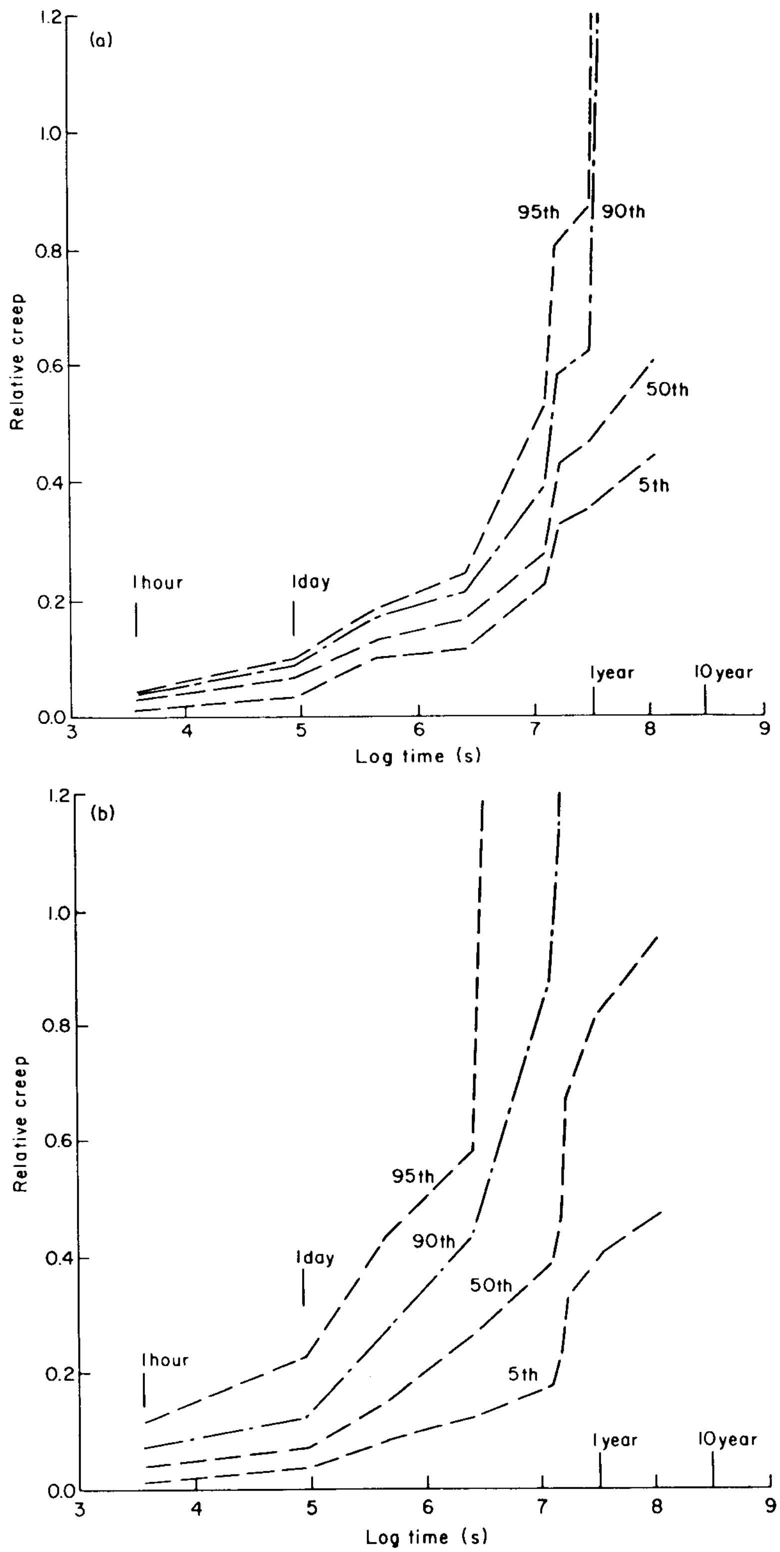


FIG. 11. Cumulative frequencies of total deflections of SS and No. 2 specimens at selected times during the first 3.5 years under sustained constant load in an uncontrolled environment: (a) 50 SS specimens, (b) 50 No. 2 specimens. (ML90 5375)

deflection under constant load for the controlled environment was seldom saved in the automatic recording process. Although the actual initial deflection was used as the basis for relative creep in the uncontrolled environment, the base for relative creep in the controlled environment specimens was D_{0R}, the predicted deflection at end-of-ramp loading based on the linearized ramp loading-deflection relationship for a specimen. The D_{0R} value does not account for any creep or partial fracture during ramp loading. Thus, relative creep values should be higher, the higher the level of constant load, implying higher short-term relative creep values for the controlled environment.

In Fig. 13, No. 2 specimens tend to have higher relative creep than SS specimens,


(a)
Relative creep
1.2
1.0
0.8
0.6
0.4
0.2
0.0
95th
90th
50th
5th
1hour
1day
1year
10year
3
4
5
6
7
8
9
Log time (s)
(b)
Relative creep
1.2
1.0
0.8
0.6
0.4
0.2
0.0
95th
90th
50th
5th
1hour
1day
1year
10year
3
4
5
6
7
8
9
Log time (s)

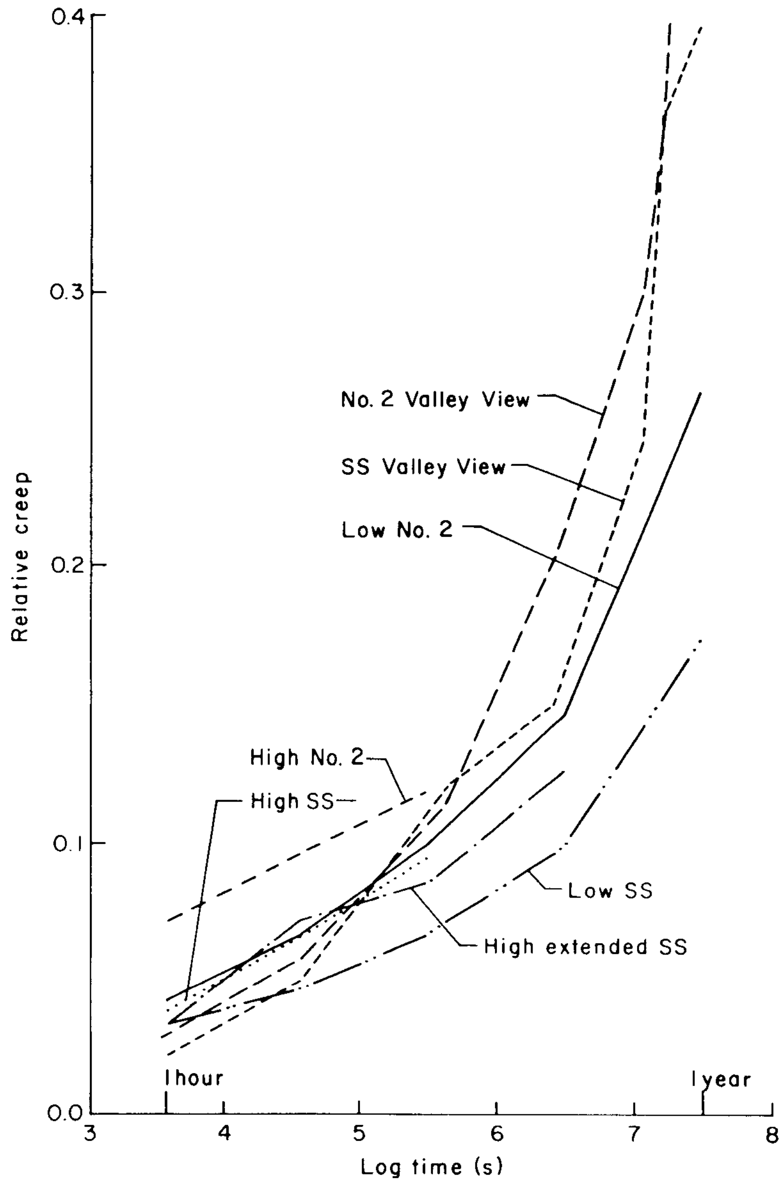


FIG. 13. Comparison of relative creep at 20th percentile of sample populations in controlled and uncontrolled environments. No. 2 and SS Valley View are for uncontrolled environment, others for controlled environment. (ML90 5378)

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FIG. 12. Relative creep at specified percentiles of the sample populations of SS and No. 2 specimens under sustained constant load in an uncontrolled environment: (a) SS, (b) No. 2. (ML90 5377, ML90 5376)

TABLE 5. *Predicted stress levels and failure times of specimens under sustained constant load during 3.5 years in an uncontrolled environment.*

Specimens	Predicted stress level	Time (days)
Select Structural[a]	0.760	8
	0.657	490
	0.605	808
	0.569	1,198
	0.543	1,251
	0.521	1,264
No. 2[b]	0.838	23
	0.726	61
	0.669	100
	0.630	149
	0.600	214
	0.576	505
	0.556	910
	0.538	1,299

[a] Based on dividing the 412.7-lb constant load by the predicted static strength [see Eq. (4), Gerhards 1988].
[b] Based on dividing the 232-lb constant load by the predicted static strength [see Eq. (5), Gerhards 1988].

and high constant loads tend to have higher relative creep than low constant loads. (Relative creep for SS medium constant load was very similar to SS low constant load; therefore, it was omitted from Fig. 13 for clarity.)

The most important fact revealed in Fig. 13 is the effect of environment type on relative creep. Whereas relative creep at 1 day was lowest for the uncontrolled environment, as a result of the different basis and perhaps lower load level, relative creep rates become higher with time for the uncontrolled environment, particularly by 100 days and beyond. Figure 13 thus provides definite proof that an uncontrolled environment causes more creep than a controlled environment while wood beams are sustaining constant load. After 1 year, beams in the uncontrolled environment have attained more than twice the relative creep of beams in the controlled environment.

Load duration

Times to failure during the first 3.5 years of sustained constant loading in the uncontrolled environment are listed in Table 5 for the 6 SS and the 8 No. 2 specimen failures along with predicted SLs based on Eqs. (4) or (5) from Gerhards (1988). The sustained constant-load times to failure are plotted in Fig. 14 for SS and Fig. 15 for No. 2 for comparison with previous load duration data at the higher constant loads for the controlled environment (Gerhards 1988).

Note that the trend for relative creep between the two types of environments is not readily apparent in the load duration data. Although the SS trend appears to be toward shortened failure times in the uncontrolled environment after about 3 years, no such trend is apparent for No. 2. Proof of an uncontrolled environmental effect (unheated room conditions), if any, must await the completion of the planned 10-year load duration of the tests in the uncontrolled environment. Also, see recent research on controlled environmental effects (Fridley et al. 1989a, b, 1990).

The number of failures in the uncontrolled environment supports the need for

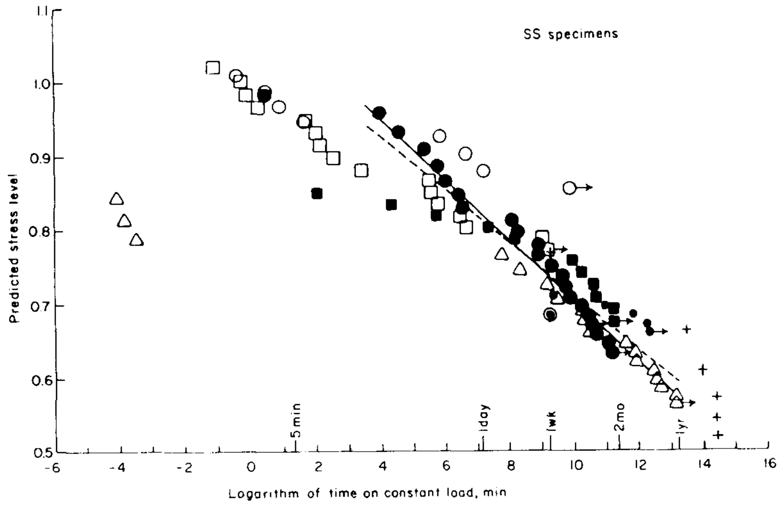

FIG. 14. Relation between time to failure and SL in SS specimens. Arrows indicate incomplete tests. Solid line indicates regression; broken line indicates alternate regression with SL as dependent variable. Data point +, 412.7 lb (uncontrolled environment). Other data points from Gerhards (1988, controlled environment). (ML90 5379)

a change in design criteria previously suggested by the study on grade effects (Gerhards 1988). Recall that the 2 by 4s were loaded at 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

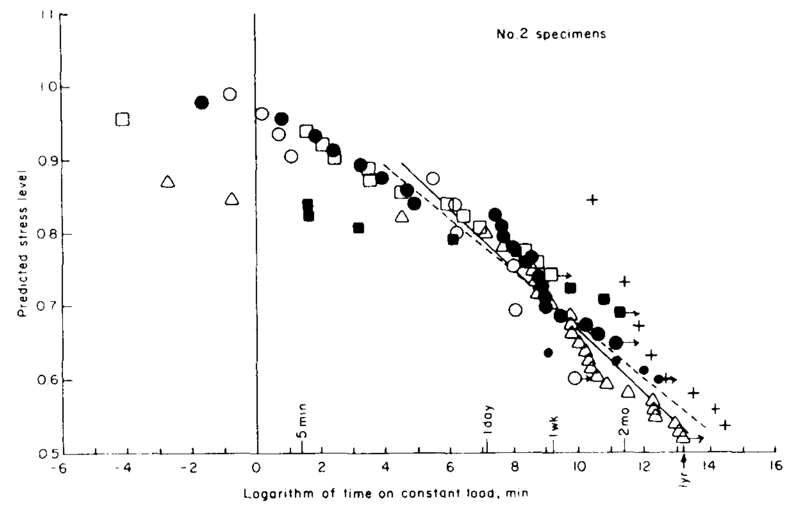

FIG. 15. Relation between time to failure and SL in No. 2 specimens. Arrows indicate incomplete tests. Solid line indicates regression; broken line indicates alternate regression with SL as dependent variable. Data point +, 232 lb (uncontrolled environment). Other data points from Gerhards (1988, controlled environment). (ML90 5380)

No. 2 specimens should have failed within 10 years. However, in the samples under load for a planned 10-year duration, 12% of the SS and 16% of the No. 2 have failed in less than 3.5 years (Table 5). Indeed, 6% of the SS specimens failed in less than 2¼ years, and 8% of the No. 2 specimens failed in less than ½ year. To date, these results suggest that those responsible for safe wood designs need to apply a greater reduction factor for a 10-year full design load for Douglas-fir in bending.

CONCLUSIONS

Several conclusions may be derived from this study. The most important is that the 1.62 reduction factor for 10-year full design load is liberal for Douglas-fir lumber in bending. The results to date from the planned 10-year loading tests support previous load-duration results (Gerhards 1988), which indicate a shorter associated load duration should be considered by those responsible for safe wood structural design. Another important conclusion is that load durations to failure do not appear to have been shortened by an unheated uncontrolled environment, at least during 3.5 years of loading, compared to predicted values from test results for a controlled 70 F, 50% relative humidity environment. This is true even though relative creep is considerably greater in the uncontrolled environment than in the controlled environment.

The relative creep of wood beams that do not have partial failure can be modeled using Eq. (3). The parameters M and N of that creep model vary considerably between specimens but can be highly correlated with each other, depending on the time base used to determine N. Stress level is partially correlated with M and N together but with neither parameter alone.

Contrary to the long time assumed for deflection doubling, 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.

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