PRIMARY CREEP IN DOUGLAS-FIR BEAMS OF COMMERCIAL SIZE AND QUALITY

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ABSTRACT

Primary creep of nominal 4- × 4-inch Douglas-fir beams of No. 2 grade was measured at four levels of stress, at 12% wood moisture content.

Equations are presented for deflection and relative creep at the four stress levels. Results show relative creep to be nearly independent of stress level, with some evidence that relative creep shows a negative correlation with wood elastic modulus.

Keywords: Beams, deflection, relative creep, creep.

INTRODUCTION

The beam creep information in this paper was obtained as part of a larger study[1] of the behavior of axially loaded wood columns. It is offered as a contribution to the literature on creep of commercial size wood members.

Wood columns are never perfectly straight. Under axial load they experience both axial creep and flexural creep due to the secondary bending moment arising from the slight column curvature. Flexural creep contributes to the lateral deflection of the column. This increases the moment produced by the axial force and the column lateral displacement, raising the column flexural stress. Since creep rate increases as stress level increases (Cizek 1961; Schneiwind 1968), stresses may exceed those derived without the consideration of creep.

This aggravated creep condition can be modeled as beam creep with rising stress proportional to increasing lateral deflection. The relationship between creep deflection, time and stress level is needed to construct the model. The information was not available in the literature for wood members similar in size to the nominal

[1] A project sponsored at Washington State University by the U.S. Forest Products Laboratory.

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4- × 4-inch (89- × 89-mm) seasoned No. 2 grade Douglas fir lumber used in the column research. A beam creep study was undertaken using this type of material, loaded to cause stress at four distinct levels up to about half the ultimate bending stress for the grade.

Beam creep observations were made for a period of at least 400 hours, which is believed to lie entirely within the primary creep range, i.e., creep rate diminishing with time. We have observed that column creep proceeds rapidly at high levels of constant load, causing unsafe column combined stress in a time span that is too short for beam creep at the bending component of this stress to reach the tertiary, or rising, rate.

The beam creep study was conducted at a constant equilibrium moisture content of 12% at 70 F (21 C). This study, although limited, showed that creep of commercial grades of lumber, during this early period of activity, proceeds in the same way as creep of small clear wood specimens observed and reported by others.

OBJECTIVE

We sought to develop an equation for predicting creep deflection of beams in flexure as a function of time and stress level in a uniformly controlled environment. The constant temperature and humidity environment was chosen to coincide with companion research on columns. It is recognized that real environmental conditions vary, and a new and separate study will examine the influence of varying moisture content. From the study described in this paper, we expected to provide the fundamental flexural creep relationships for modeling column lateral deformation due to combined axial and flexural stress. We had found that flexural stress in columns with slight initial curvature could, as a result of creep, reach and exceed the direct initial axial compressive stress. We also knew the column stress at failure for a large number of axially loaded columns that had been under load for periods of 400 hours or less, which defined our interest in this short time period.

LITERATURE REVIEW

The literature contains reports of many studies conducted to examine wood creep under sustained load for conditions of constant as well as fluctuating temperature and humidity. Often these studies had been on specimens of less than useful structural size. Schniewind (1968) presented a comprehensive review of literature on wood rheology, including pertinent references on creep. We shall not repeat this review but only mention some references that give helpful insights into our relatively narrow problem; creep at constant temperature and moisture content at different levels of applied stress, below 50% of clear wood ultimate bending strength, at low moisture content.

Kingston and Armstrong (1951), presented a paper on beam creep. They tested 3¼- × 3¼-inch (83- × 83-mm) wood beams for periods up to 2½ years but did not develop an expression for the time-deflection relationships. In 1959, Clouser (1959) tested small Douglas fir beams and modelled their time-deflection curves with a power law equation.

Deflection-time relationships for beams are described by Cizek (1961) as a family of curves that are elevated as stress is elevated. He attributed these curves to F. P. Beljankin and F. Jacenko (Kiev). If the curves in Cizek's paper are redrawn in terms of relative creep, i.e., creep as a percentage of initial elastic deflection, one obtains a single relative creep vs. time curve, independent of stress level. Such a picture is not inconsistent with our own observations and is convenient for modeling column creep. Several investigators mentioned by Schniewind (1968) reported that deformation-time curves obtained at different stress levels were related in a linear fashion at stress levels below 50% of ultimate strength for clear wood specimens at low levels of moisture content and temperature.

The Wood Handbook (1974) depicts relative creep to actually increase with increasing stress level, attributing the information to R. S. T. Kingston et al. (1962). Neither Cizek nor the Wood Handbook provides comprehensive discussions of the experiments and the materials used. We sought to clarify the matter by replication and documentation.

In 1971, Senft and Suddarth (1971) presented a discussion of modeling based on compression creep experiments. They did not provide any useful creep vs. time data at various stress levels that might be used to depict the relationships needed for our purposes, but their discussions of modeling were quite relevant and valuable.

There have been many studies of beam creep behavior under cyclic conditions of temperature and humidity (Grossman et al. 1969; Kingston and Clarke 1961; Leicester 1971; Popov 1949; Rantu-Maunus 1975; Schneiwind 1967; Ugolev 1976). Most of this research was conducted on small specimens. There does not appear to be much information in the literature regarding correlation of creep for small and large specimens. Schniewind (1967, 1973) conducted studies on ¼- × ¼-inch (6.35- × 6.35-mm) and 2- × 2-inch (50.8- × 50.8-mm) specimens subject to cyclic environmental conditions. This provides insight into size influences, notably that creep response to cyclic moisture changes is more pronounced for smaller specimens.

Flugge (1975) describes the theory of viscoelastic creep investigated by Suddarth and Senft and by ourselves.

THEORY

Theoretical representations of deformation-time behavior are presented by Senft et al. (1971). Their three-element model for primary creep is:

$$\delta_t = B_0 + B_1[1 - \exp(B_2 t)] \tag{1}$$

where δ_t is total deformation, and B_0 is instantaneous elastic deformation. B_1 and B_2 are coefficients determined experimentally. (B_0 can also be calculated from the elastic modulus and size of the specimens for any given loading.) B_2 is a negative quantity.

Their four-element model is for deformation beyond the primary creep stage, where the slope of the deformation-time curve is either constant positive (secondary stage) or rising (tertiary stage). This will be discussed further at another place in this paper. This model is:

$$\delta_t = B_0 + B_1[1 - \exp(B_2 t)] + B_4 t \tag{2}$$

The B_4t term is for a flow component that occurs during the secondary and tertiary stages of creep.

Creep is commonly presented in relative terms as a percentage of the initial (instantaneous) elastic deformation of a member. Equation (1) can be arranged to express relative creep, δ_r, as:

$$\delta_r = B_3[1 - \exp(B_2t)] \tag{3}$$

where $B_3 = B_1/B_0$ and is a horizontal asymptote. Equation (2) can be arranged to express δ_r as:

$$\delta_r = B_3[1 - \exp(B_2t)] + B_5t \tag{4}$$

where $B_5 = B_4/B_0$. There is no horizontal asymptote.

Equations (1) and (3) only describe primary creep because they do not provide for the inflection of the relative creep curve that is known to occur, given sufficient time.

Clouser (1959) has employed a model that has an exponential form and is generally called the "power-model":

$$\delta_r = At^B \tag{5}$$

This, as it turned out, fitted our results rather well.

EXPERIMENTAL METHOD

Four groups of Douglas-fir (*Pseudotsuga menziesii*) beams were tested for creep in flexure while loaded at midspan and quarter points, one group each at stress levels of 1,250 psi (8.61 MPa), 1,900 psi (13.1 MPa), 2,600 psi (17.9 MPa), and 3,150 psi (21.7 MPa). The sample material was selected from the inventory of a large lumber mill in western Oregon. It was No. 2 grade (WWPA)[2], nominal 4- × 4-inch, 16 ft (4.9 m) in length. The sponsors of this project directed us to sample material from the low end of the elastic modulus spectrum. Accordingly we used an E-Computer (dynamic vibrational testing system) in the field to measure the stiffness of many pieces from which we chose material from below the mean of the material measured. This unseasoned material was transported to Pullman, Washington, where it was air-dried to about 14% moisture content before placing it in a conditioning room for final reduction to 12% moisture content at 65% relative humidity and 70 F (21 C). At these conditions the elastic modulus of each piece was measured by a simple span static bending test. Pieces were then sorted into four test groups with similar elastic properties, although, as we shall see (Table 1), the high stress level group turned out to have a higher elastic modulus average than the other three groups.

The creep tests were conducted in a controlled environmental chamber. The variables of beam size and length, load, temperature, and moisture content were then fixed, the only uncontrolled variable being the elastic modulus of the wood, which varied from specimen to specimen but was known. Each beam was 3½ × 3½ × 144 inches (89 × 89 × 3,658 mm), simply supported at each end of a 140-inch (3,556-mm) span and loaded at midspan and quarter points with equal concentrated loads. The moment diagram for this loading is similar to that for a uniformly distributed load. Values of midspan deflection and time were recorded

[2] Western Wood Products Association.

TABLE 1. *Statistical information.*

	E 10^6 psi (1)	B_0 in (1)	B_0 in (2)	B_2 (3)	B_3 % (3)	A % (3)	B (3)
			1,250 psi stress level				
Mean	1.63	0.80	0.85	−0.013	14.373	2.174	0.322
S.D.	0.04	0.068	0.066	0.0039	5.397	0.596	0.051
n	10	10	10	10	10	10	10
			1,900 psi stress level				
Mean	1.58	1.29	1.34	−0.0107	15.23	1.828	0.368
S.D.	0.09	0.153	0.16	0.0019	3.971	0.319	0.048
n	10	10	10	10	10	10	10
			2,600 psi stress level				
Mean	1.65	1.70	1.75	−0.0127	14.5	2.004	0.347
S.D.	0.05	0.094	0.097	0.0025	2.161	0.458	0.039
n	10	10	10	10	10	10	10
			3,150 psi stress level				
Mean	1.86	1.84	1.88	−0.0141	12.60	2.326	0.289
S.D.	0.09	0.122	0.133	0.0036	3.496	0.256	0.020
n	10	10	10	10	10	10	10
			Adjusted 3,150 psi stress level				
Mean						2.103	0.344
S.D.						0.232	0.024
n						10	10

(1) Measured values, (2) calculated values, based on measured E, (3) values from curves fitted to each beam's creep data.

for each beam. Readings were taken at 2-hour intervals for the first eight hours, then twice daily for 400 to approximately 600 hours. Some beams failed in the time period above 400 hours. The analytical work was confined to data taken from zero to 400 hours.

TABLE 2. *Student's "t" and Fisher's "F," group comparisons, for constants in equations 12–15 and 17.*

		Coefficient A			Exponent B		
Groups:	df	"t"	P[1]	F[2]	"t"	P[1]	F[2]
1,250 psi:							
vs 1,900 psi	18	1.61	13	3.5	1.82	9	1.1
vs 2,600 psi	18	0.72	47	1.7	1.20	28	1.7
vs 3,150 psi	18	0.74	45	5.4	1.95	7	6.2
vs 3,150 psi (a)[3]	18	0.35	50	6.6	1.21	44	4.6
1,900 psi							
vs 2,600 psi	18	1.00	33	2.0	1.02	33	1.6
vs 3,150 psi	18	3.95	1	1.6	4.77	1	5.6
vs 3,150 psi (a)	18	2.22	4	1.9	1.48	16	4.1
2,600 psi							
vs 3,150 psi	18	1.93	7	3.2	4.23	1	3.6
vs 3,150 psi (a)	18	0.61	50	3.9	0.28	50	2.7

[1] Probability of a larger "t" by chance, percent (two-sided "t"-table).
[2] F for homogeneity of variance is 3.18 at 5% probability, 4.03 at 2.5%, and 5.35 at 1%.
[3] (a) = 3,150 psi values adjusted to 1.6×10^6 psi for E.

TABLE 3. *Student's "t" and Fisher's "F," group comparisons, for constants B_3 and B_2 in equations 6–9.*

Groups:	df	Coefficient B_3 "t"	Coefficient B_3 P*	Coefficient B_2 "t"	Coefficient B_2 P*
1,250 psi					
vs 1,900 psi	18	0.40	50	1.65	11
vs 2,600 psi	18	0.07	50	0.17	50
vs 3,150 psi	18	0.87	39	0.85	40
1,900 psi					
vs 2,600 psi	18	0.51	50	2.0	7
vs 3,150 psi	18	1.57	13	2.6	2
2,600 psi					
vs 3,150 psi	18	1.46	16	1.0	33

* Probability of a larger "t" by chance, percent (two-sided "t"-table).

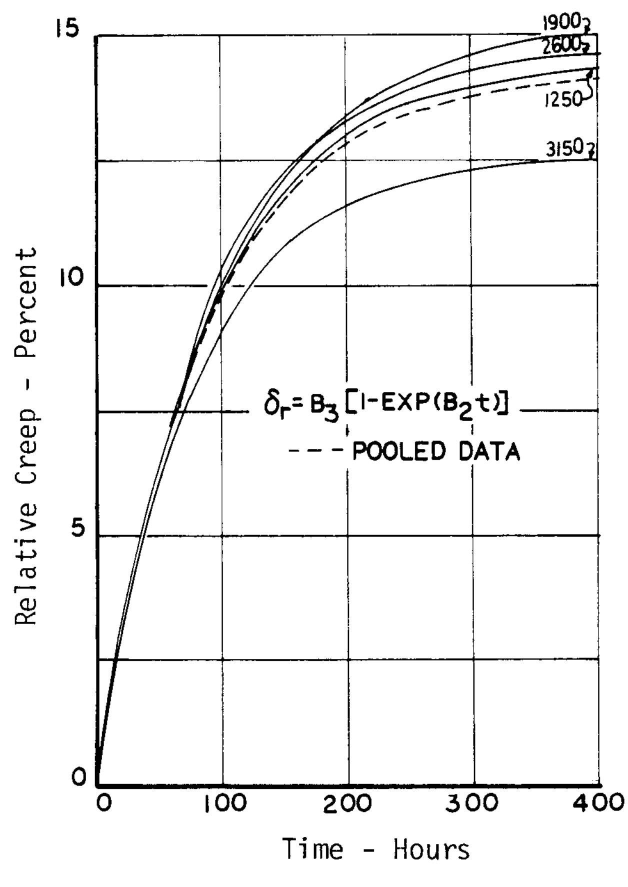

FIG. 1. Relative creep vs. time (Equation 3).

RESULTS

Relative creep curves were obtained by fitting Eq. (4) to the relative creep data, using the program SAS NLIN (Statistical Analysis System Non-Linear) (1979), with these results:

$$1{,}250 \text{ psi: } \delta_r = 14.444[1 - \exp(-0.01170t)] \quad (6)$$
$$1{,}900 \text{ psi: } \delta_r = 15.186[1 - \exp(-0.01086t)] \quad (7)$$
$$2{,}600 \text{ psi: } \delta_r = 14.766[1 - \exp(-0.01173t)] \quad (8)$$
$$3{,}150 \text{ psi: } \delta_r = 12.587[1 - \exp(-0.01280t)] \quad (9)$$

with δ_r in percent and t in hours. There are differences between the coefficients in Table 1 and in Eqs. (6) through (9). The equations were fitted to the data for ten beams for each stress-level group. The coefficients in Table 1 are the mean values of coefficients for curves fitted to each of the ten beams in each stress-level group. This was done to obtain a measure of between-beam variation for the coefficients, so tests for significance of difference between coefficients could be made, as in Tables 2 and 3.

There appears to be an effect of group average elastic modulus on the coefficients in these equations (E equals 1.63, 1.58, 1.65 and 1.86 million psi, respectively). No adjustment of the 3,150 psi curve has been made. The four equations are plotted in Fig. 1, together with a curve fitted to the pooled data (creep-time data for ten specimens at each of the four stress-levels, total of 40 specimens), which is:

$$\text{Pooled: } \delta_r = 14.299[1 - \exp(-0.01165t)] \quad (9a)$$

Figures 2 through 6 are computer plots of the relative creep data in which many points are hidden, as noted thereon. The hidden points tend to be in the portion of the field below the curve, where the points appear congested. The asterisks are points on curves fitted to the data using the model Eq. (3), actual Eqs. (6) through (9). Inspection shows that the curves depicted by the asterisks fit the data poorly in the time range below 100 hours and give a flatter curve in the range of 100 to 400 hours than the data points imply.

Seeking an improved fit, we used a simple exponential model of the form:

$$\delta_r = At^B \quad (10)$$

The fitting program was a linear least squares procedure to the equation

$$\log \delta_r = \log A + B \log t \quad (11)$$

The fitted equations and their correlation coefficients are:

$$1{,}250 \text{ psi: } \delta_r = 2.10t^{0.324} \quad r = 0.870 \quad (12)$$
$$1{,}900 \text{ psi: } \delta_r = 1.76t^{0.366} \quad r = 0.903 \quad (13)$$
$$2{,}600 \text{ psi: } \delta_r = 1.95t^{0.349} \quad r = 0.956 \quad (14)$$
$$3{,}150 \text{ psi: } \delta_r = 2.32t^{0.287} \quad r = 0.917 \quad (15)$$
$$\text{Pooled: } \delta_r = 2.03t^{0.331} \quad r = 0.905 \quad (16)$$

δ_r is in percent and t in hours. These curves are plotted in Figs. 2 through 6, and on a single set of axes in Fig. 7 for convenient comparison. It became evident that an equation using the data for all stress levels, pooled, might adequately express relative creep, as suggested by Cizek (1961).

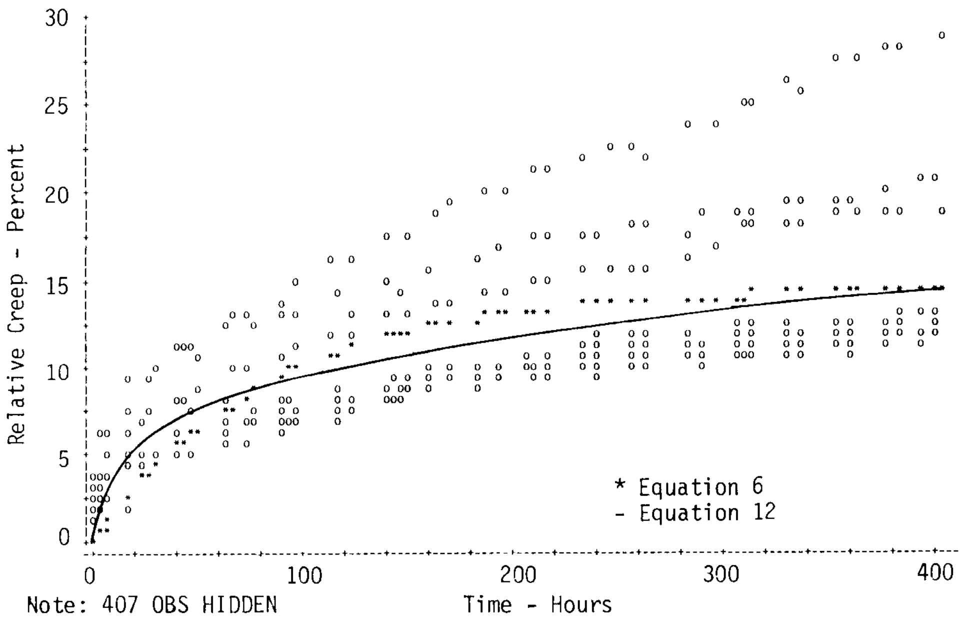

FIG. 2. Relative creep vs. time at 1,250 psi.

Before discussing the similarities of A and of B for the different stress-level groups, their regressions on E, shown in Figs. 8 and 9, should be mentioned. These regressions are fitted by the least-squares method to the data for all of the individual specimens. The regression of A on E does not appear very convincing,

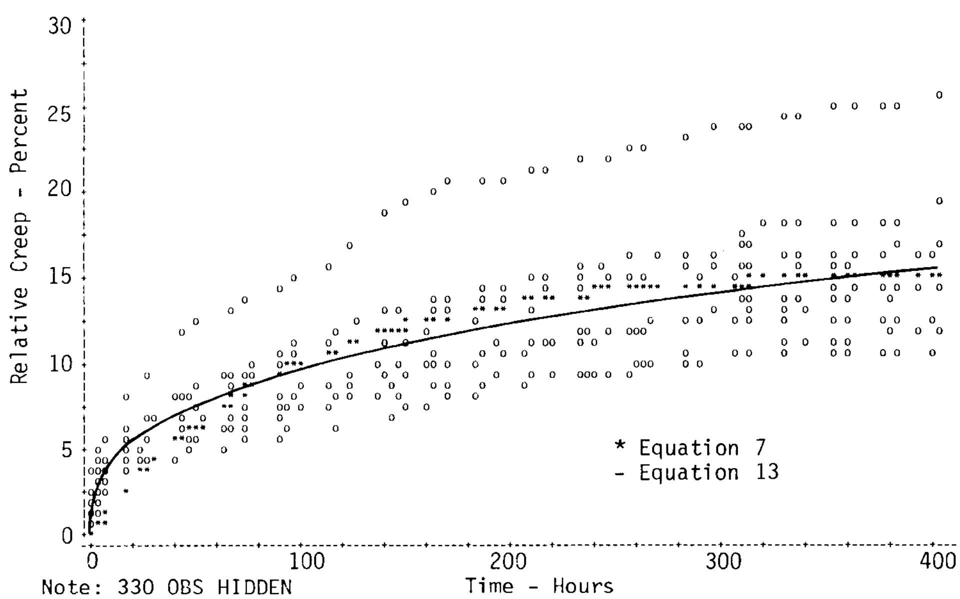

FIG. 3. Relative creep vs. time at 1,900 psi.

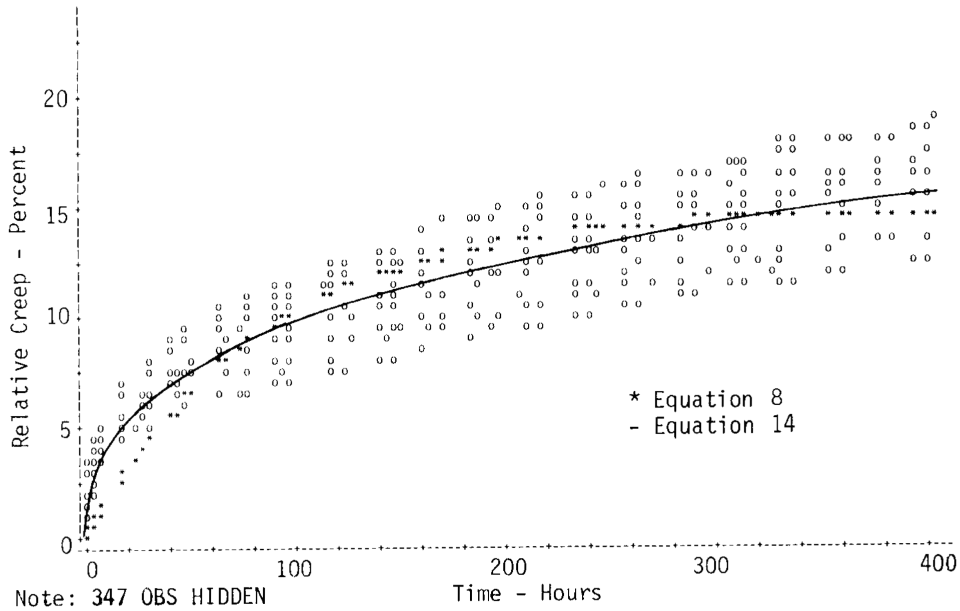

FIG. 4. Relative creep vs. time at 2,600 psi.

but that of B on E is better, with a correlation coefficient of 0.56. Using these regressions to adjust Eq. (15) to an average elastic modulus of 1.6 million psi, results in the following equation:

$$\text{Adjusted 3,150 psi: } \delta_r = 2.09t^{0.343} \quad (17)$$

The adjusted curve is shown in Fig. 7, and it lies much closer to its companions

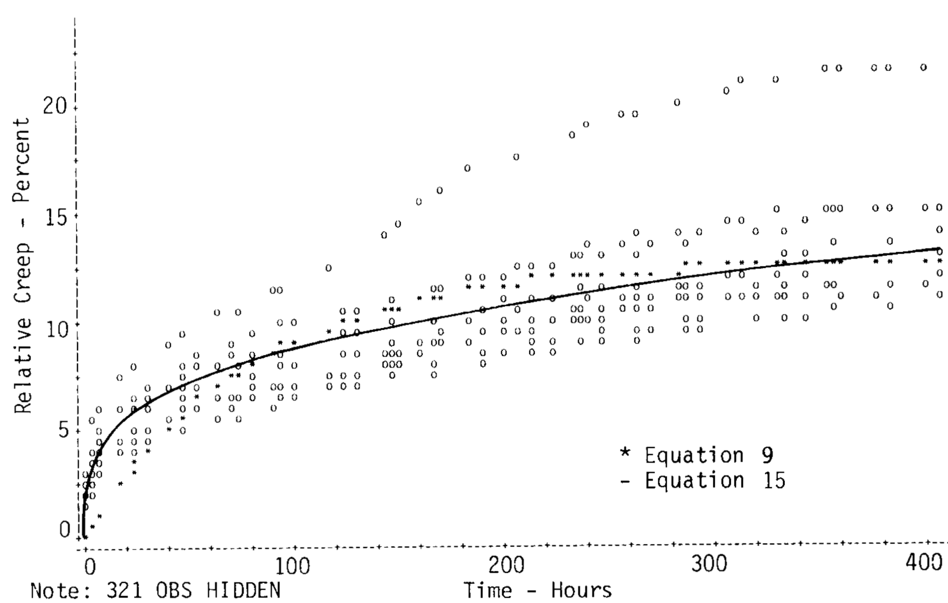

FIG. 5. Relative creep vs. time at 3,150 psi.

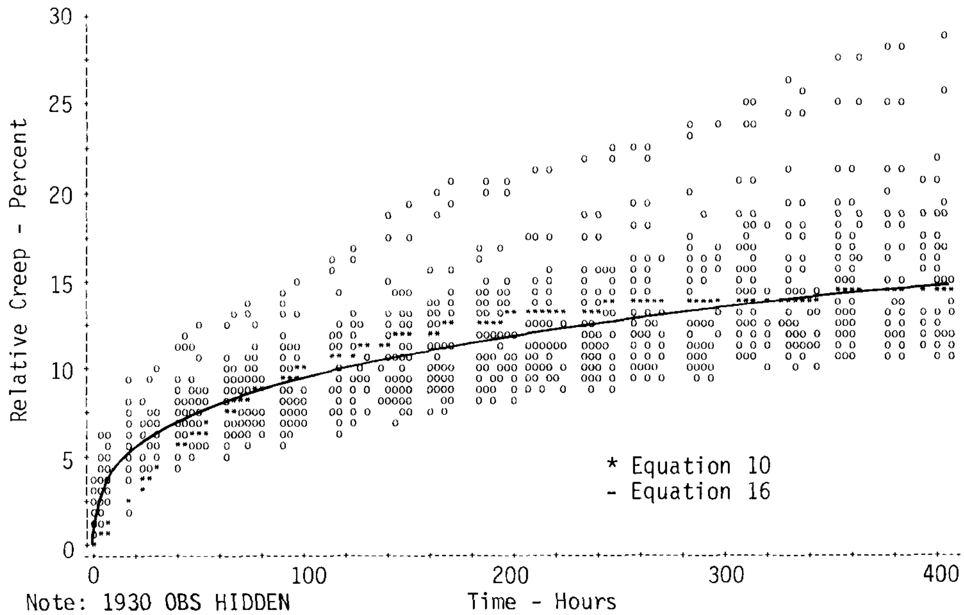

FIG. 6. Relative creep vs. time at all stress levels.

at other stress levels. The choice of beams in a narrow range of elastic moduli, while justified for the purpose of variability, does tend to obscure the elastic modulus effects. The accidentally chosen higher values of E in the high stress-level group drew attention to this elastic property effect. A test might be designed with a wider spectrum of elastic properties to explore the effect of E on the coefficient A, more satisfactorily.

Table 2 lists values of Student's "t" computed from Table 1 data. In all comparisons between stress-level groups, with the exception of 1,900 vs. 3,150 psi, the t test supported the conclusion that differences were not significant (at levels from 7 to 47%). With the adjusted value of A for the 3,150 psi group this exception disappeared.

Homogeneity of variance is required for the t test to accept significance of difference. According to Snedecor (1956, page 98), lack of homogeneity increases the chance of rejection of the null hypothesis about difference, by the common t test. Therefore the acceptance of the null hypothesis remains a correct interpretation, where non-homogeneity is shown.

For exponent B, Table 2 supports the similarity of values at the different stress levels, with the exception of 1,900 vs. 3,150, and 2,600 vs. 3,150 psi groups. However, when the adjustment was applied to the 3,150 psi stress-level group, all evidence for a difference in B between stress levels was removed.

Homogeneity of variance is evident for all compared groups except those involving the 3,150 psi stress-level. When the 3,150 psi group data were adjusted, F-values indicate a lack of homogeneity for comparisons to the 1,900 and 1,250 psi stress-level groups. However, the values of "t" indicate low probability of real difference in means for the 1,250 vs. 3,150 adjusted and the 1,900 vs. 3,150

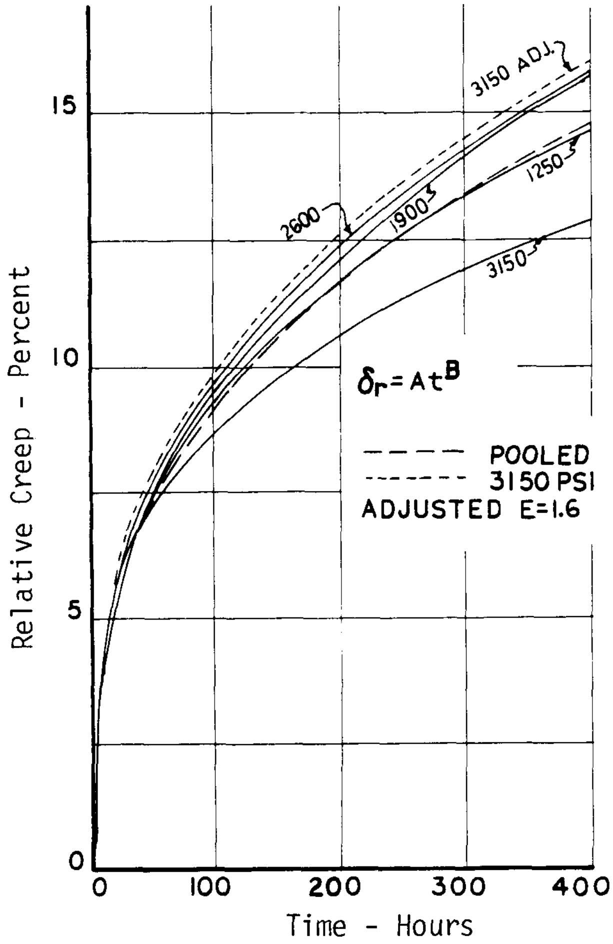

FIG. 7. Relative creep vs. time (Eqs. 12–15 and 17).

adjusted groups, so it is concluded that acceptance of the null hypothesis is reasonable.

A discussion of Table 3 would be similar to that for Table 2, and since the power-model appeared to be most acceptable, no detailed discussion is presented for Table 3.

In Figs. 2, 3 and 5 the upper outlying points are associated with particular beams. The use of commercial grade lumber containing the defects normal to the grade introduced a source of variation that is not present in clear wood specimens. This would account for some of the outliers on the upper edge of the data field.

The primary source of possible experimental error is believed to be in measuring the initial elastic deflection of each beam. Creep was fairly rapid after the loads were placed. Without some type of mechanized loading device to standardize the timing of the initial reading, the initial elastic deflection is subject to some reading error. Some beams were loaded more expeditiously than others and the initial elastic deflection measured more promptly. We calculated the initial elastic de-

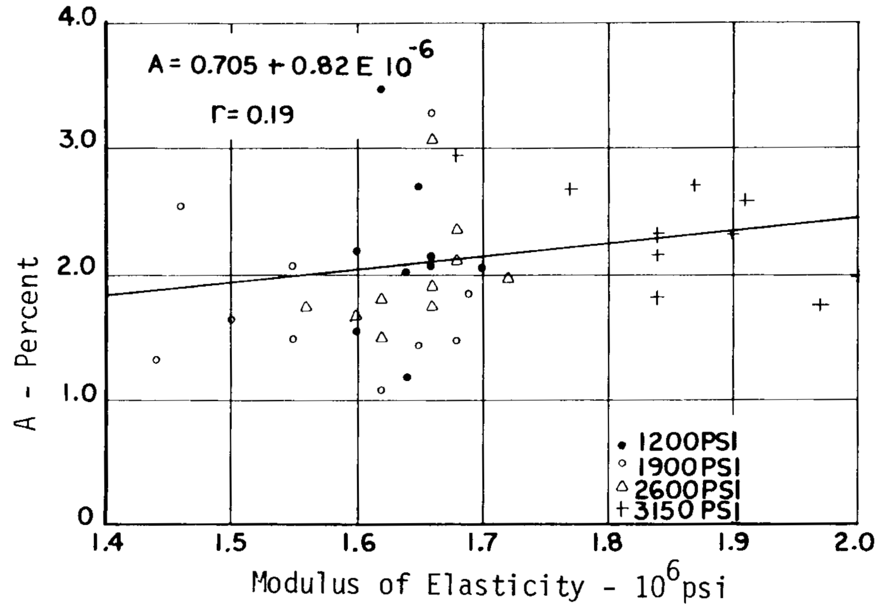

FIG. 8. Coefficient A vs. E.

flection of each beam and found it generally to be more than the measured value by 2 to 6%, as recorded in Table 1, which is a minor difference. The coefficients of variation of measured and calculated values of B_0 are very similar. Delay in making initial deflection readings would result in measured deflections exceeding calculated deflections. The conclusion is that no serious error was caused by the loading procedure.

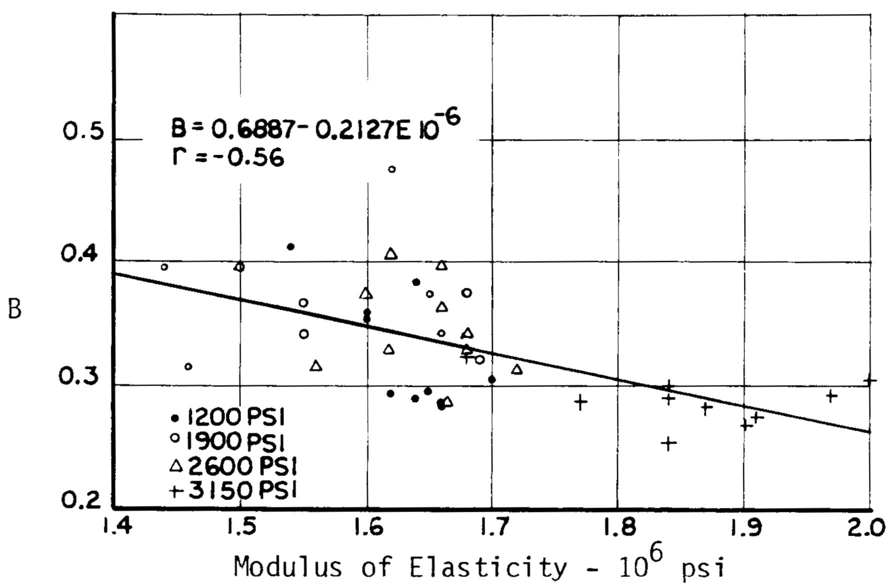

FIG. 9. Exponent B vs. E.