CREEP OF DOUGLAS FIR BEAMS DUE TO CYCLIC HUMIDITY FLUCTUATIONS

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ABSTRACT

This report describes tests of the hypothesis that creep in Douglas fir beams of commercial size is influenced by cyclic humidity fluctuations.

Twenty 3.5- × 3.5-inch (89- × 89-mm) beams were creep-tested for a period of approximately 1,200 hours (7 weeks). Deflection data were recorded for loaded beams while the relative humidity of their environment was cycled at 70 F. The environmental EMC was varied from 7 to 20% for periods of 24 and 168 hours, respectively. Three regression models were fitted to the relative creep data. The effect of stress levels and humidity cycles were compared.

The study showed that creep for cycled specimens greatly exceeded creep for uncycled specimens.

Keywords: Beams, deflection, relative creep, creep, humidity.

INTRODUCTION

One of the most important characteristics of wood is its time-dependent deformational behavior. Like most other structural materials, wood deforms instantaneously when loaded, but under sustained load it continues to deform. This continued time-dependent deformation is called creep. Relative creep is creep expressed as a percentage of the initial instantaneous deformation. Its magnitude is dependent on a number of variables, which include the load history and changes in the humidity and temperature of the ambient environment (Armstrong and Kingston 1960; Armstrong and Christensen 1961; Armstrong 1962; Hall et al. 1977).

Wood is highly hygroscopic, and any variation in the humidity and temperature of the environment will affect its moisture content. Since wood's properties are affected by moisture content, the creep can vary considerably under such conditions. This is the result not only of the effect of moisture on mechanical properties, but also on the forming and breaking of hydrogen bonds on the cellulose molecules. Severe moisture content fluctuations are known to affect creep rate and dramatically reduce the time to failure for small, highly stressed pieces.

The purpose of this research was to obtain a measure of the effect of moisture content fluctuation on the creep behavior of commerical size Douglas fir beams of typical size for columns in light frame structures.

LITERATURE REVIEW

The Uniform Building Code (1985) recognizes that wood members under sustained load creep more when they season under load than when seasoned prior to loading. It recommends that creep deflection be calculated as one-half the dead load deflection for seasoned lumber and as equal to the dead load deflection for unseasoned lumber. Where wood members are exposed to significant regular

TABLE 1. *Conditions of testing.*

Group number	Specimens tested	Stress level (psi)	Humidity cycle (hr)	Temperature
1	5	1,900	24*	70 F
2	5	2,600	24*	70 F
3	5	1,900	168**	70 F
4	5	2,600	168**	70 F

* 24-hour cycle: High humidity for 12 hours (88% relative), low humidity for 12 hours (40% relative).
** 168-hour cycle: High humidity for 84 hours (90% relative), low humidity for 84 hours (40% relative).

humidity fluctuations, creep deflections can be greater. In cases where members are initially green and are allowed to season under load, relative creep as large as 700% has been reported (Kingston and Armstrong 1951). Therefore, current design procedures may greatly underestimate the long-term deflection of wood members subjected to varying environmental relative humidity and temperature.

Armstrong and Kingston (1960) studied the effect of moisture content changes on the creep of small wood specimens. Beams of 0.75-inch (19-mm) square cross-section were exposed to three different moisture conditions, namely, continuously above the fiber saturation point; initially above the fiber saturation point and allowed to dry while under load; and initially air-dried to 12% moisture content before loading and maintained at that value during creep measurement. They found that the relative creep of the beams allowed to dry under load was twice that of specimens at constant moisture content, either above or below the fiber saturation point. They concluded that changes in moisture content under load greatly influenced creep rate and total creep deformation.

Armstrong and Christensen (1961) examined the influence of moisture content changes on the deformation of wood under stress. Small specimens 0.8 × 0.8 × 36 in. (20 × 20 × 900 mm) were stressed in bending to approximately 25% of their modulus of rupture (MOR), while the moisture content was cycled between 12 and 22%. They found that the first wetting cycle always produced an increase in deflection and during each subsequent moisture cycle increased deflection during desorption and partially recovered during adsorption. Most of the change in deformation occurred during the period when the wood moisture content was actually changing. They confirmed that when wood is subject to sustained bending load, a change in moisture content influences the rate and magnitude of deformation.

Schniewind (1967) performed creep-rupture tests on small beams, 0.4 × 0.8 × 8.8 in. (10 × 20 × 220 mm), of Douglas fir. Five different environmental conditions were employed. These included three at constant temperature, while humidity was cycled at varying magnitudes. The specimens were loaded at various levels ranging from 46 to 88% of the MOR. His results suggested that temperature cycling was of minor importance and that large humidity changes at constant temperature had a significant effect on creep-rupture life.

Senft and Suddarth (1971) studied the phenomenon of creep in terms of the magnitude and duration of load for small specimens of Sitka spruce. They measured creep for 0.25- × 0.25- × 0.75-in. (6.25- × 6.25- × 18.75-mm) specimens stressed in compression parallel-to-grain. They examined the use of three-element and four-element spring and dash-pot models to describe creep response curves

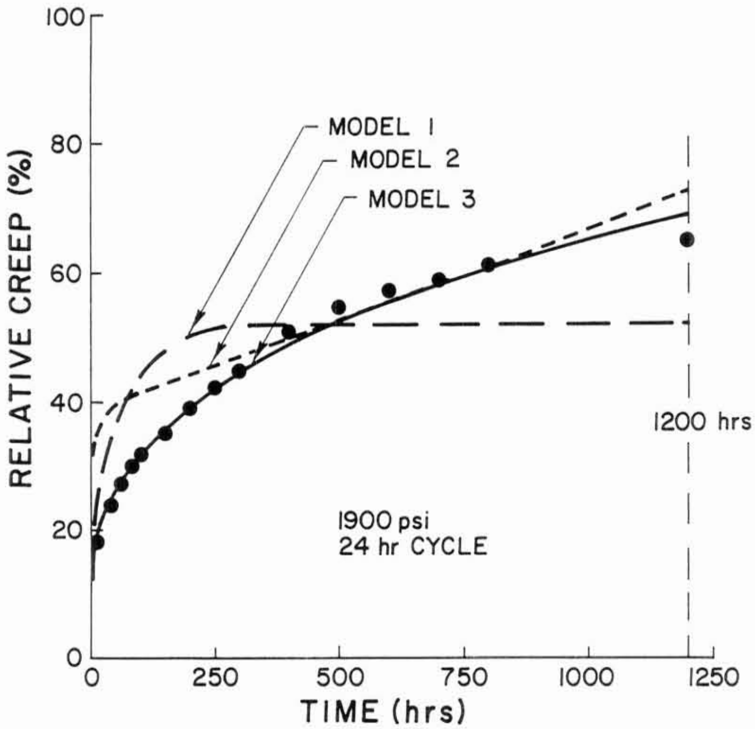

FIG. 1. Relative creep vs. time, 12 hours at 40% RH and 12 hours at 88% RH; 1,900 psi.

and recommended, for time periods greater than 24 hours, the use of a four-element model. This was especially so if the load levels were larger than 40% of ultimate stress. This may have been associated with a stress level that developed tertiary creep.

Schniewind and Lyon (1973) continued the investigation of cyclic environmental changes on creep-rupture life. Two sizes of simply supported beams were tested: small beams 0.4 × 0.8 in. on an 8-in. span (10 × 20 mm on a 200-mm span) and larger beams which had a 2-in. square (50.8 mm) on a 40-in. span (1,020 mm). All of the specimens were loaded to 70% of the static MOR and were subjected to different environmental conditions. Nineteen of these beams were tested while the relative humidity varied from 35 to 87% at constant temperature (7 to 20% EMC). This caused an average amplitude of moisture content variation in the larger specimens of only 1.4%. They found that the larger specimens were less affected by changing moisture content than the smaller ones. Most large specimens showed a net increase in deflection during the adsorption part of the cycle, which is at variance with the findings of Armstrong and Christensen (1961). Schniewind and Lyon found that the creep rate was always less for the large than for the small specimens. Overall, changes in deflection due to cycling were small compared to total deflection, resulting in nearly smooth curves. These curves followed the classical patterns of primary, secondary, and tertiary creep. They recommended that for critically stressed members, subject to large fluctuations of the environment, an adjustment of the load duration factor be made.

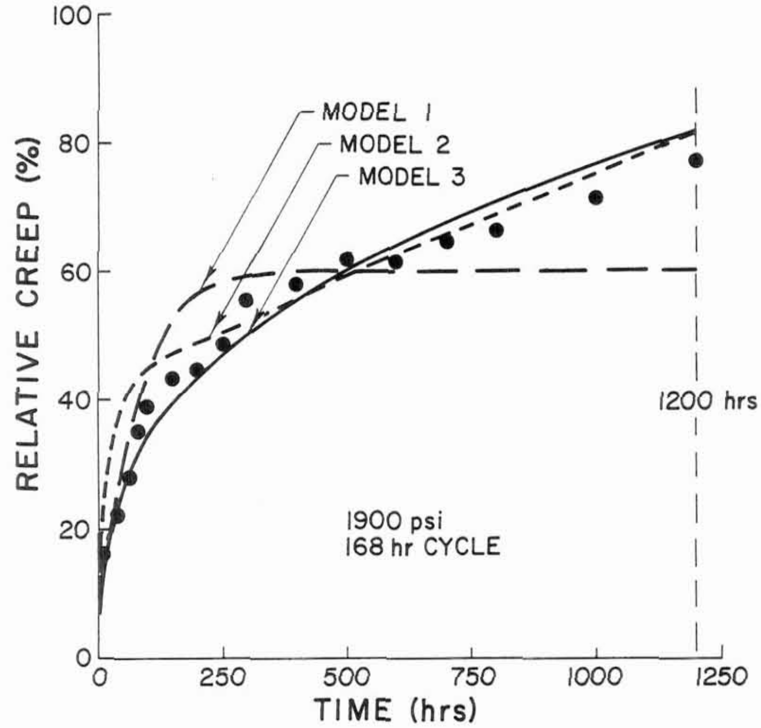

FIG. 2. Relative creep vs. time, 84 hours at 40% RH and 84 hours at 90% RH; 1,900 psi.

Hoyle et al. (1985) presented creep results for No. 2 and better 3.5- × 3.5-in. (89- × 89-mm) Douglas fir beams. Four groups of beams (five specimens each) were loaded at different stress levels, namely: 1,250, 1,900, 2,600, and 3,150 psi (8.62, 13.1, 17.9, and 21.7 MPa). Creep was measured at constant 12% EMC, 70 F, for 400 to 600 hours. They found that relative creep in this time period (which did not encompass tertiary creep) could be expressed as:

$$\delta_r = 2.03t^{0.331} \tag{1}$$

with δ_r in percent and t in hours. Other models were fitted, but this one was most satisfactory. The study has been repeated at the 1,900 and 2,600 psi stress levels for the same size and grade of Douglas fir, at cyclic EMC, and is the subject of this report.

EXPERIMENTAL PROCEDURES

Test material for this study was No. 2 and better Douglas fir (*Pseudotsuga menziesii*) nominal 4 in. × 4 in. × 12 ft (89 mm × 89 mm × 3.66 m) obtained from a local lumber supplier. The pieces were sorted into test groups each having similar mean and range of elastic properties. Four groups of five beams were creep-tested in a controlled humidity room. While under load, the relative humidity of the environment was cycled and the midspan deflections were measured. Two cyclic conditions shown in Table 1 were used in this study. The resulting data were used to plot deflection versus time curves for a period of approximately 1,200 hours.

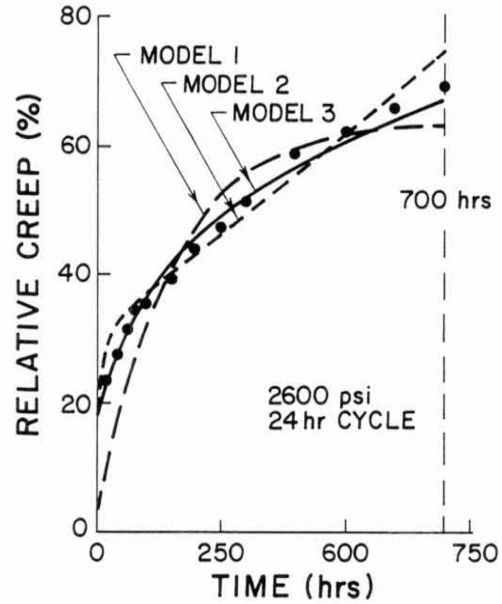

FIG. 3. Relative creep vs. time, 12 hours at 40% RH and 12 hours at 88% RH; 2,600 psi.

During the creep tests, moisture content gradients were measured on two control specimens using a Delmhorst moisture meter. The control specimen dimensions were the same as the beams but only 48 in. (1.22 m) long. Their ends were sealed with aluminum paint to prevent end grain moisture transfer. They were located near the center of the humidity room and were not subject to loading.

Seven sets of moisture pins were placed at depths of 0.25 in. (6.35 mm), 0.5 in. (12.7 mm), 0.75 in. (19.1 mm), and 1.0 in. (25.4 mm), near the midlength of the control specimens. The insulated pins were driven into the specimens and remained in place during testing. Moisture content was measured at each set of pins each time deflection readings of the beams were taken. The relative humidity of the room was also measured using a recording hygrothermograph continuously throughout the tests.

Beam tests

Each creep test specimen was initially conditioned to 12% moisture content, its end grain was coated with aluminum paint, and its modulus of elasticity (MOE) was measured. Four groups of five beams were tested at the stress levels and humidity conditions shown in Table 1.

The load, consisting of concrete blocks, was applied equally at mid- and quarter-points of the span. Moisture content cycling was started 8 hours after the beams were loaded. During this 8-hour period the specimens were subjected to the minimum relative humidity conditions (40%) and a constant temperature of 70 F (21.1 C). The deflections of the beams were carefully watched during this period, so any abnormality in deflection could be observed and any inadvertent damage to the testing apparatus could be prevented.

Initially, two five-specimen groups were tested, one at 1,900 psi and the other

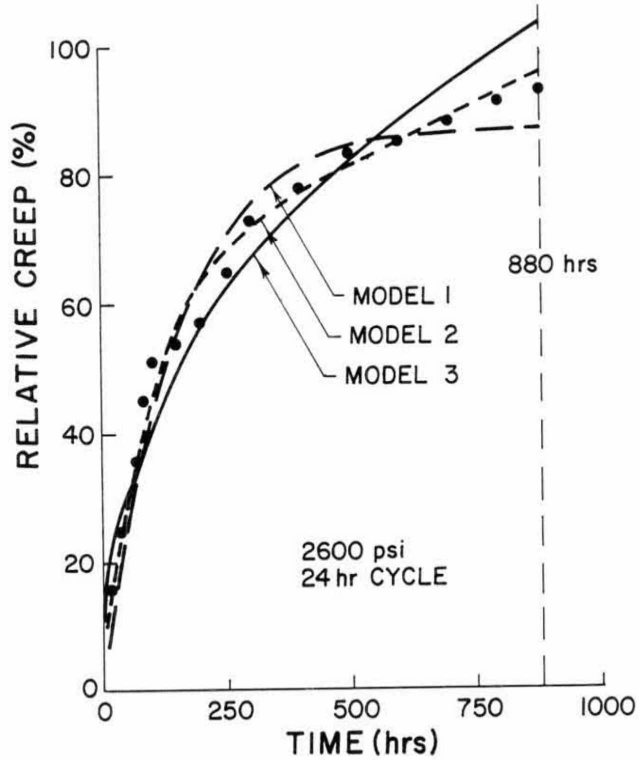

FIG. 4. Relative creep vs. time, 84 hours at 40% RH and 84 hours at 90% RH; 2,600 psi.

at 2,600 psi. They were subjected to relative humidity cycling between 40 and 88%, 12 hours at each condition, 24-hour cycle period. The second pair of five-specimen groups was tested at the same stress levels; however, the relative humidity was cycled between 40 and 90%, 3.5 days at each condition, 168-hour period of cycle.

Deflection readings were recorded every 2 hours for the first 10 hours and every 4 hours for the first few days. After that, readings were taken every 6 to 8 hours. This was continued for 7 weeks or until one of the specimens failed. At 1,900 psi all specimens survived 7 weeks, but a 2,600 psi specimen failed at 700 hours (4.16 weeks) under the 24-hour cycle and 880 hours (5.24 weeks) under the 168-hour cycle.

EXPERIMENTAL RESULTS

The test groups are identified by their stress level and cycle period, as 1,900/24, 1,900/168, 2,600/24, and 2,600/168.

Creep curve modeling

Three regression models were fitted to the relative creep data. The first, Model 1, was of the form:

$$\delta_r = B_5[1 - \exp(B_2 t)] \tag{2}$$

Notations for constants B_2, B_3, and B_5 are consistent with that of Hoyle et al.

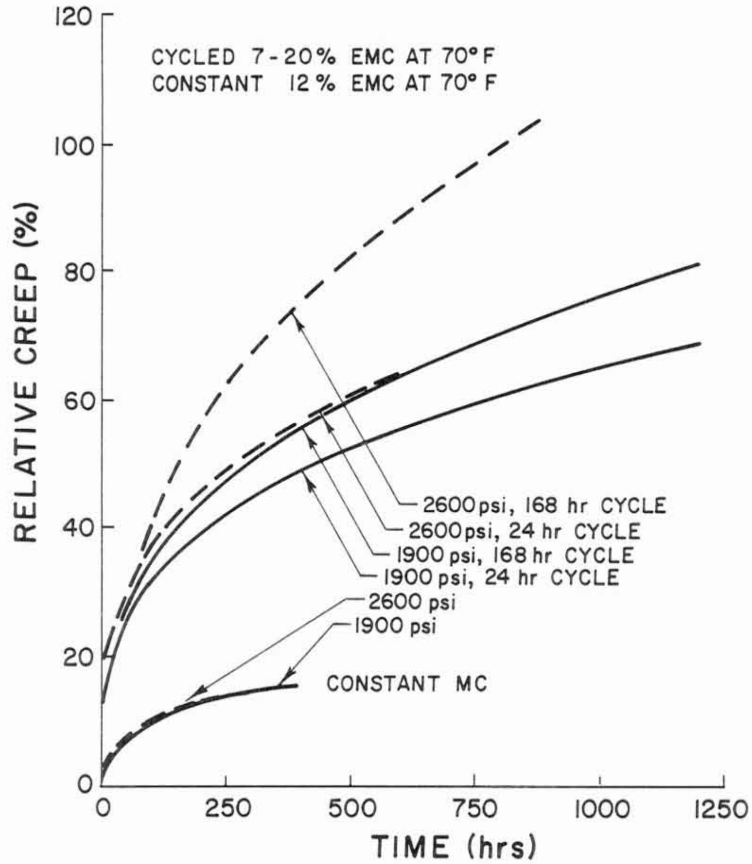

FIG. 5. Model 3 relative creep for cyclic and constant EMC environments.

(1985). This is the linear viscoelastic model of Senft and Suddarth (1971). The regression was performed by the SAS NLIN (Statistical Analysis System Nonlinear) program (1979). This program uses the Gauss-Newton least-square technique. The results of this analysis for each group, with δ_r in percent and t in hours are:

$$1{,}900/24: \quad \delta_r = 51.99[1 - \exp(-0.0253t)] \tag{3}$$
$$2{,}600/24: \quad \delta_r = 63.54[1 - \exp(-0.007t)] \tag{4}$$
$$1{,}900/168: \quad \delta_r = 60.56[1 - \exp(-0.0134t)] \tag{5}$$
$$2{,}600/168: \quad \delta_r = 87.1[1 - \exp(-0.0067t)] \tag{6}$$

Model 1 curves in Figs. 1–4 are these results. To show data, the mean creep values at intervals of 20 hours up to 100 hours, 50 hours from 100 to 300 hours, and 100 hours thereafter to 1,250 hours or failure, are plotted on these graphs.

Inspection reveals that Model 1 does not adequately fit the data; therefore, a second model, Model 2, was employed for an improved fit. Model 2 was of the form:

$$\delta_r = B_5[1 - \exp(B_2t)] + B_3t \tag{7}$$

This was the model recommended by Senft and Suddarth for periods longer than

TABLE 2. *Average moisture content changes in the control specimens.*

	Moisture pin depth (in.)	Change in moisture (%)
24-hour humidity cycle:	¼	0.9
	½	0.4
	¾	0.2
	1	0.1
168-hour humidity cycle:	¼	3.8
	½	3.0
	¾	1.8
	1	0.6

24 hours. The regression analysis was also performed by the SAS NLIN program with the following results:

$$1{,}900/24: \quad \delta_r = 38.12[1 - \exp(-0.1406t)] + 0.029t \qquad (8)$$
$$2{,}600/24: \quad \delta_r = 30.74[1 - \exp(-0.0713t)] + 0.062t \qquad (9)$$
$$1{,}900/168: \quad \delta_r = 41.75[1 - \exp(-0.0488t)] + 0.034t \qquad (10)$$
$$2{,}600/168: \quad \delta_r = 62.74[1 - \exp(-0.0115t)] + 0.037t \qquad (11)$$

The addition of the B_3t term dominates the expression at high t values, resulting in inflection of the creep curves (Model 2 in Figs. 1–4). In our tests, 1,200 hours was an insufficient time for creep to enter the tertiary stage. The 24-hour time period in Senft and Suddarth's recommendation was characteristic only of their very small size specimens.

Seeking an improved fit, a simple exponential or power model, Model 3, of the following form was employed:

$$\delta_r = At^n \qquad (12)$$

The analysis was performed by the linear regression program to fit the equation:

$$\log \delta_r = \log A + n \log t \qquad (13)$$

The results of this analysis, the equations, and their correlation coefficients are:

$$1{,}900/24: \quad \delta_r = 7.37t^{0.316} \quad r = 0.59 \qquad (14)$$
$$2{,}600/24: \quad \delta_r = 8.45t^{0.317} \quad r = 0.76 \qquad (15)$$
$$1{,}900/168: \quad \delta_r = 6.44t^{0.359} \quad r = 0.73 \qquad (16)$$
$$2{,}600/168: \quad \delta_r = 5.66t^{0.432} \quad r = 0.62 \qquad (17)$$

Figure 5 presents the Model 3 curves for the cycled humidity conditions and for the constant humidity conditions from Hoyle et al. (1985).

Moisture content changes at different depths beneath the surface of the beams for each cycle period are listed in Table 2.

DISCUSSION OF RESULTS

The most striking result was the large increase in creep in the cyclic humidity environment, shown in Fig. 5. At 400 hours, the largest period for which constant moisture content creep data were available, the creep under cyclic conditions was three to five times as much as at constant moisture content. This result bears out

TABLE 3. *"t" test, group comparison, for constants in equation (12).*

Groups	df	Coefficient A "t"	Coefficient A P*	Coefficient A F²**	Exponent n "t"	Exponent n P*	Exponent n F²**
1,900/24							
vs. 1,900/168	8	0.91	39	1.06	2.58	2.8	1.48
vs. 2,600/24	8	0.09	<50	2.00	0.83	42.8	1.80
1,900/168							
vs. 2,600/168	8	0.71	50	1.51	2.89	1.8	2.00
2,600/24							
vs. 2,600/168	8	1.94	9	1.41	3.09	1.37	2.00

* Probability of a larger "t" by chance, percent.
** F for homogeneity of variance is 6.39 at 5% probability, and 16.0 at 1%.

the information in the literature and provides a numerical value on the amount to be expected for moderately thick commercial lumber.

Table 2 shows that moisture content changes within the specimens were much larger for the long cycle period, and penetrated more deeply. The equilibrium moisture content (EMC) change of the environment was 13%. The average moisture content change for the outer inch of the specimens was 0.4% for the 24-hour cycle and 2.3% for the 168-hour cycle. The material at the top and bottom sides of the beams, where the stresses are highest, experienced four times the moisture content increase at the 168-hour cycle period. As expected, thick pieces do not respond rapidly to changes in the ambient surroundings. Of particular interest were the similar increases in creep for both cyclic EMC exposures, suggesting that small and frequent fluctuations have nearly as much effect on creep as do large and more gradual periodic changes.

It is of interest to note that a study of the fluctuation of equilibrium moisture content in a large wood sports arena in Moscow, Idaho, over a period of one year, showed a 3 to 5% change for periods of the general order of 168 hours. The moisture content changes in thick wood members would, of course, be less than the EMC changes.

Table 3 assesses the significance of differences in creep for the four exposure conditions. Values of A and n of Eq. (12) were obtained by fitting curves to the results for each of the twenty specimens. The means and standard deviations of A and n were calculated for each group. Tests for homogeneity of variance showed homogeneity. Student's t tests showed no significant difference between the coefficients, A, for any of the paired groups. The exponent, n, was significanly different at the 5% level (or lower) between the two cyclic conditions at both stress levels. For the 168-hour period, n was significantly different between the 1,900 and 2,600 psi stress levels, but for the 24-hour period the difference was not significant.

A general observation from the experiment was that the first adsorption period always produced large deflections. In subsequent periods, the specimens showed partial recovery during adsorption and increased deflection during desorption. This agrees with the observations reported by Armstrong and Kingston (1960) and Armstrong and Christensen (1961). During the 24-hour humidity cycle we saw very slight fluctuation in the relative creep curves. During the 168-hour cycle the fluctuations were more apparent.

CONCLUSIONS AND RECOMMENDATIONS

1. A cyclic humidity environment increased the relative creep of No. 1 and No. 2 Douglas fir 4 × 4s by factors of 3 to 5. Fluctuations in equilibrium moisture content of the environment, of 7 to 20%, imposed in this experiment were larger than would usually be expected in heated buildings. It is extremely unusual to encounter a 20% equilibrium moisture content environment. Fluctuations of this magnitude will not occur in ordinary service, only in most exceptional situations. There is no immediate cause for concern about current design practice for estimating creep, as a result of this study.

2. Frequent small fluctuations of *wood moisture content* have nearly as much effect on creep as do large fluctuations of a long period. It appears that creep is related to the cumulative gains and losses of cell-wall moisture.

3. There was a large time lag in the response of pieces of common size material to changes in the environmental equilibrium moisture content. Data supporting this observation are not formalized in this paper.

4. Studies of creep in commercial size lumber at stress levels and moisture content variations expected to occur in real service are desirable. Information on the moisture content change in the wood of heated and unheated buildings and in structures exposed to the weather is needed to define conditions under which provision should be made for exceptional creep.

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