CREEP BUCKLING OF SMALL, SLENDER WOOD COLUMNS UNDER CYCLIC ENVIRONMENT

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ABSTRACT

Creep buckling of small, slender Douglas-fir columns was studied under two types of cyclic environmental conditions. Three load levels were used for an environment with severe changes (Type A), while one load level was used for a less severe one (Type D). Experimental data show in both cases an increase of deflection during the low humidity cycle and recovery during the higher humidity cycle. The reduction of deflection during the wet cycle was more pronounced in Type A than in Type D cycling. Time to buckling failure was nearly one order of magnitude less, at the same load level, in Type A as compared to Type D. Small initial deflections did not appear to have a significant effect on time to failure. The relationship between load level and time to failure under Type A cycling was similar to published data for beams of similarly small size.

Keywords: Douglas-fir, columns, creep, cyclic environment, relative humidity, temperature, deflection, failure, duration of load, buckling.

INTRODUCTION

The unique aspect of creep leading eventually to buckling failure of loaded columns is that initial deflection due to eccentricity or imperfection will cause nonuniform distribution of stresses at column cross sections in order to balance the external moment. This produces an internal moment that will increase deflection, and that in turn further increases the moment and initiates a process that may accelerate to failure. The time from initial loading to failure by buckling, namely the critical time, is the main interest of long-term column studies, because the designer must insure that buckling will not occur during the intended service life. Early analytical studies considered only secondary creep in attempts to predict the critical time, but it was found that instantaneous elastic and plastic deformations as well as primary creep should also be taken into account (Hoff 1954, 1958; Odqvist 1954; Hult 1955). Higgins (1952) developed an iterative method using so-called iso-stress-strain curves to predict column deflection. The actual stress distribution over the cross section can then be determined. The disadvantage is that the iterative process involved is lengthy even if handled by computer. Shanley (1952) proposed an approximation method using a tangent modulus obtained directly from the iso-stress-strain curves. The results were found to be quite accurate yet slightly conservative.

For wood columns, in addition to stress, the effect of moisture content and temperature is believed to be substantial. The main interest of this study was to examine the behavior of wood columns under cyclic humidity changes and their effect on critical time. The rate of creep in wood is higher at high than at low moisture content under constant conditions (Youngs 1957). Under cyclic moisture changes total creep is found to be substantially larger. The creep rate increases during the drying cycle and there is recovery during the wetting cycle (Hearmon

TABLE 1. *Type of environmental conditions used.*

	Temperature			Relative humidity			
Type of cycling	Min. (¼F)	Max. (¼F)	Functional form	Min. (%)	Max. (%)	Functional form	Period (h)
A	75	75	Constant	35	87	Square wave	24
D*	60	90	Sinusoidal	35	87	Sinusoidal	24

* Temperature and relative humidity cycles are 180° out of phase so that maximum temperature coincides with minimum relative humidity.

and Paton 1964; Eriksson and Norén 1965). Schniewind (1967) investigated the time to failure of small Douglas-fir beams subjected to constant load with five types of cyclic environment. Reduction in creep rupture life time as compared to constant conditions was found to be proportional to the amplitude of cyclic variation in average moisture content. Furthermore, Schniewind (1973) observed that an increase in beam size, from 10 by 20 mm (0.4 by 0.8 in.) to 2 by 2 in., increased the average time to failure by more than one order of magnitude. A widely suggested mechanism to explain the phenomenon of increased creep during sorption is that under the bias of an external force, the breaking and reformation of hydrogen bonds during moisture sorption lead to molecular chain displacements in the direction determined by the external force (Bethe 1969; Eriksson and Norén 1965; Gibson 1965). However, the above explanation is insufficient to account for the observed recovery during adsorption. Gibson (1965) proposed that such recovery is due to energy provided by the exothermic heat of adsorption from the vapor phase. Armstrong (1972) showed that the creep effects observed in wood subjected to the simultaneous action of load and moisture content change cannot be explained in terms of water movement alone, and proposed that it is related to shrinking and swelling of the wood substance.

Humphries and Schniewind (1982) investigated small, slender Douglas-fir columns loaded at 1.67× design load based on measured modulus of elasticity and subjected to cyclic relative humidity conditions. Some failures occurred in less than three days, but the experiments were not continued sufficiently long to develop statistically based time-to-failure characteristics. Lateral deformation of columns followed a classical creep curve, with regions of primary, secondary, and tertiary creep.

MATERIALS AND METHODS

Long columns under constant load to failure were studied under two types of cyclic environment. Straight-grained, clear Douglas-fir specimens measured 0.375 by 0.250 by 11.5 in. with the tangential direction as the least dimension. Specimens were conditioned to a nominal moisture content of 12% before test. The modulus of elasticity (MOE) of each column specimen was determined in static bending over an 8-in. span at 0.05 in./min head speed up to 5 lb. of loading.

Details of the two environmental conditions, one at constant temperature with cyclic humidity (Type A) and the other with both temperature and humidity cycling (Type D), are shown in Table 1. Both patterns had previously been used by Schniewind (1967). Type A was designed to give the maximum variation in EMC about a mean of about 12% that was within the capabilities of available equipment. Type D was designed to give simultaneous changes in temperature

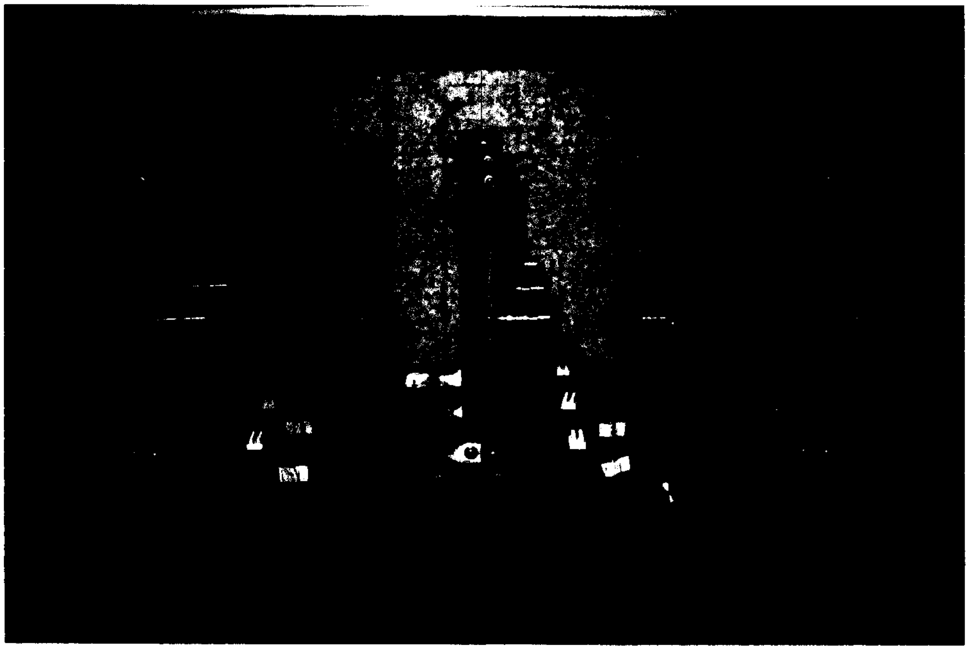

FIG. 1. Loading frames in the testing cabinet showing specimens and LVDT's for deflection measurement.

and relative humidity simulating diurnal changes that might be found in real situations. In either case, changes in wood moisture content are expected to be confined to surface layers. Three load levels (1.8×, 1.6×, and 1.4× design load) were tested under Type A conditions, and only one load level (1.8× design load) was used under Type D conditions. Load levels for each specimen were calculated individually based on measured modulus of elasticity values. Nineteen specimens were chosen for each of these four sets of testing conditions from a pool of 326 samples. The required 76 specimens were selected by stratified, randomized sampling so that nearly the full spectrum of MOE values between 1.25 and 3.28 × 10^6 psi was represented in each of the four sets.

Nine simple-hinged loading frames with 12.5-in. span were used for column loading (Fig. 1). Specimens were fitted and clamped into steel blocks at both ends. The load was applied through levers at the lower end. At the center of the span of each frame, a linear variable differential transformer (LVDT) was used to continuously record the lateral deflection of all columns with a multi-point recorder. All tests were conducted in a humidity cabinet connected to an Amico-Aire unit with cam-controlled temperature and relative humidity. Time to failure was automatically recorded through digital clocks.

Tests were started at the beginning of the wet cycle and nine specimens were maintained in the testing cabinet at all times. In order to control the experimental time span, it was planned to truncate each of the tests after sixteen out of nineteen specimens had failed. However, the two sets with milder conditions, 1.4× design load under Type A and 1.8× design load under Type D, had much higher average times to failure. These two tests were truncated after eleven and thirteen specimens

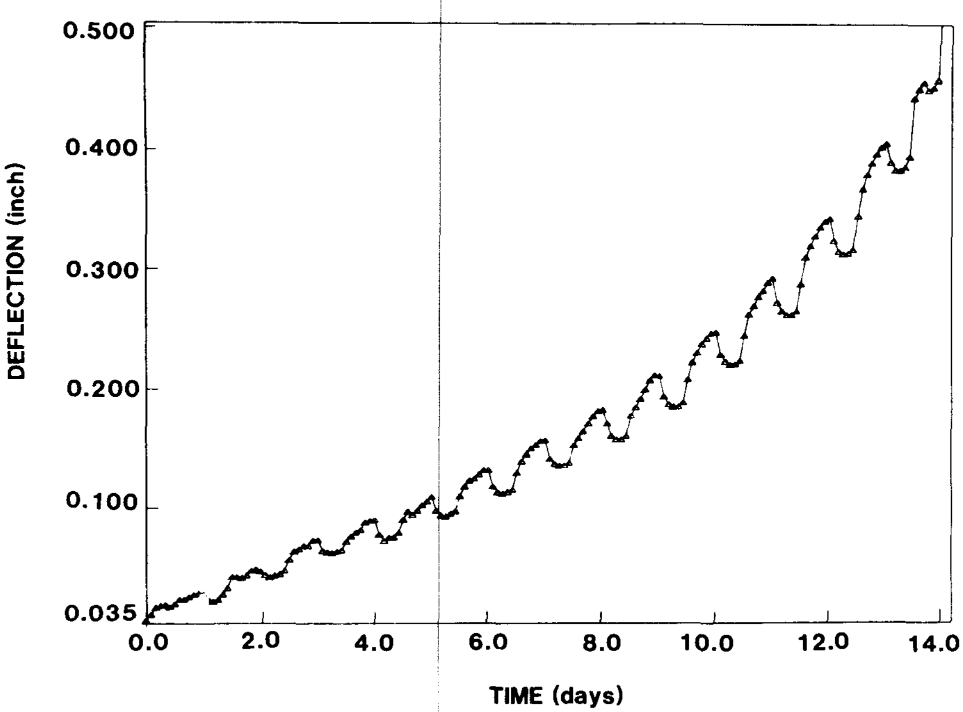

FIG. 2. Deflection history of a specimen under Type A environmental condition illustrating sudden reduction of deflection when entering the wet cycle.

had failed, respectively. The recorded deflection curves were replotted in compact form by computer.

RESULTS AND DISCUSSION

Deflection patterns

The recorded deflections of each specimen generally showed a tendency to increase during drying cycles and to recover during wetting cycles except the first (Fig. 2). In the first wet cycle, most specimens tend to increase deflection; this period is similar to the primary creep stage. However, some of the specimens showed a slight reduction of deflection or no change at all in the first wet cycle, especially for specimens with small eccentricity or those that did not fail within the period of the experiment.

The pattern of deflection under Type A environment with its sharp transition from one humidity level to the other showed correspondingly sudden changes from increases to recovery of deflection (Fig. 2). In comparing Type A and Type D environments, the cyclic changes in deflection are much smoother in the Type D environment (Fig. 3), probably because humidity changes are also gradual. The amplitude of cyclically increasing and decreasing deflections has large variations not only between specimens but also within the same curve.

One general pattern that was noted in most specimens was that recovery was usually smaller in the first few wetting cycles. The magnitude of recovery increased thereafter, but decreased again as failure was approached. On the other hand, the increase in deflection during desorption either became continually larger with

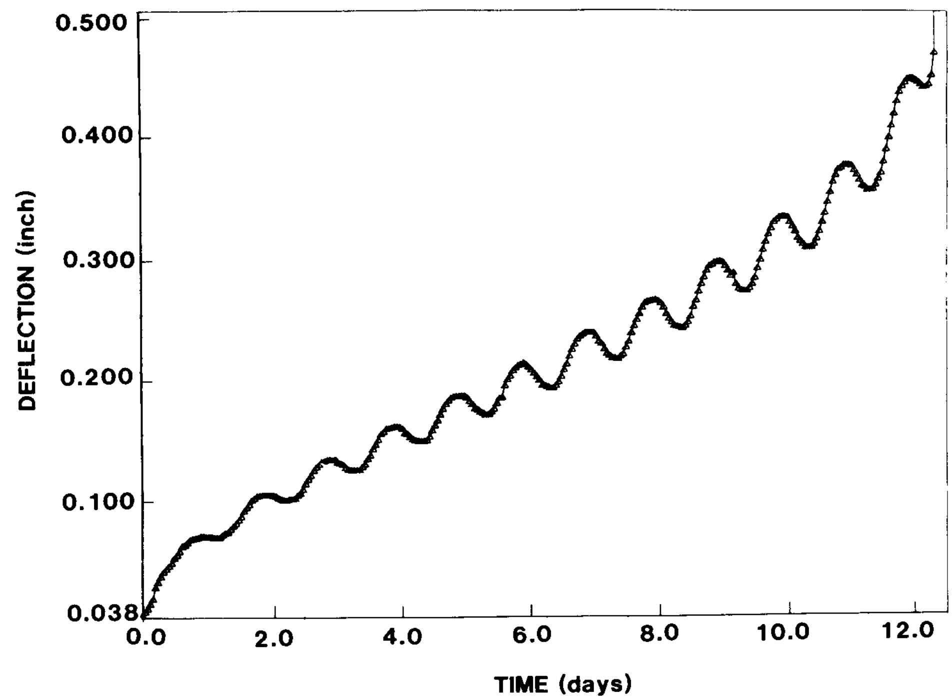

FIG. 3. Deflection history of a specimen under Type D environmental condition illustrating smooth transition between wet and dry cycle.

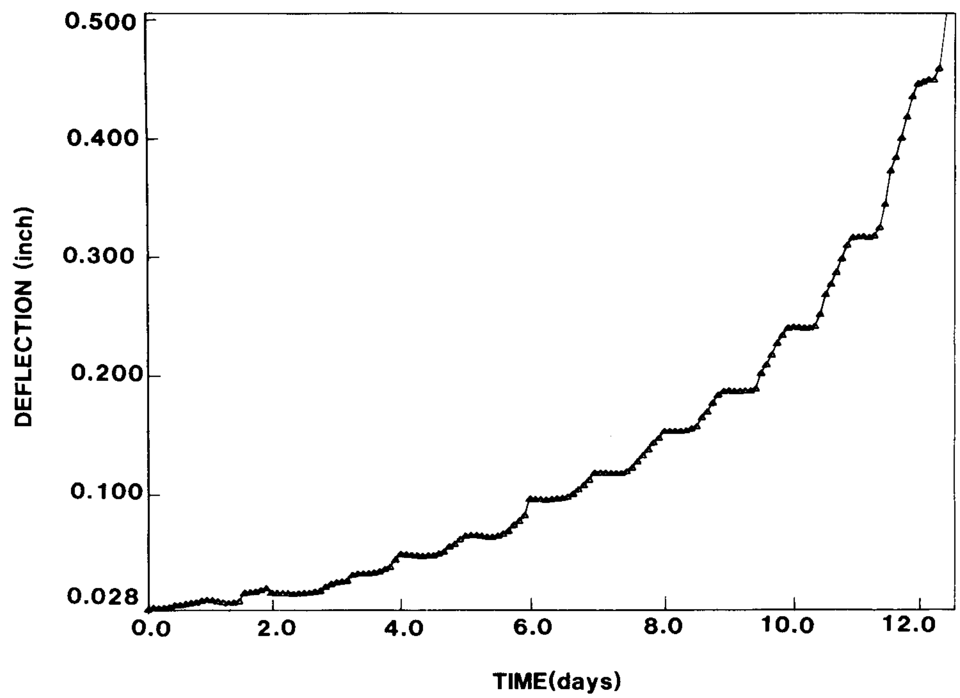

FIG. 4. Deflection history of a specimen illustrating exponential type of curve.

TABLE 2. *Average time to failure and truncation time of each set of tests.*

Type of environment	Load (design load)	Number of specimens	Number of specimens failed	Truncation time (min)	Average time to failure (min)
A	1.8×	19	17	23,600	5,850
	1.6×	19	16	28,900	7,870
	1.4×	19	11	60,363	50,600
D	1.8×	19	13	75,983	41,500

time, or showed a growth in the beginning and near failure with an intermediate region of increments of constant magnitude.

Some specimens, usually those that failed within a few days, never did show actual recovery but reduced creep rate or constant deflection during wet cycles (Fig. 4). The deflection history plots could be divided into two types on the basis of their overall configuration; sigmoid and exponential shapes. The type was determined by connecting the point corresponding to the initial deflection and the initial points of each wet cycle (usually the local peaks in the curve), which are the same points measured by Humphries and Schniewind (1982). Most of the deflection curves were found to be sigmoid, whereas all of Humphries and Schniewind's curves were of that shape. Several specimens gave the exponential curve (Fig. 4). It should be pointed out that some curves with sigmoid shape might be regarded as exponential if the average deflection of each cycle is connected instead of the peak deflection (Fig. 2).

Column failure

Most of the specimens that failed did so during the wetting cycle, similar to the columns of Humphries and Schniewind (1982) where all failures occurred during the period of high relative humidity. This was also observed by Schniewind (1967) for beams, who attributed this to the reduction of strength at higher moisture content. The general deflection patterns as failure is approached are large deflections in the last drying cycle, followed by a short period of little or no change at the beginning of the last wet cycle, with subsequent rapid increase in deflection to failure.

The average time to failure of each group, calculated according to the method of the one-sided censored distribution (Hald 1952), is shown in Table 2. Although this method also provides for estimating the standard deviation, no values are shown because the calculations are based on log time. While the means can be readily transformed to linear time, the same is not true for the standard deviation. An indication of variability may be obtained from the ranges of values in Fig. 5. Within the three load levels of Type A, the 1.4× design load has much higher average time to failure than the other two load levels. The distribution of survival probability vs. duration of loading is presented in Fig. 5. A linearized regression equation was calculated of the form $\text{Log } Y = a + bX$, where Y is the average time to failure for each load level in minutes, X is design load level, and a and b are regression coefficients. The resulting equation was $\text{Log } Y = 7.870 - 2.342X$. The above regression equation can also be expressed in terms of Euler load, $\text{Log } Y = 7.870 - 6.421X_E$, where X_E is load level expressed as a fraction of the Euler load. The three load levels 1.8×, 1.6×, and 1.4× design load correspond to fractions

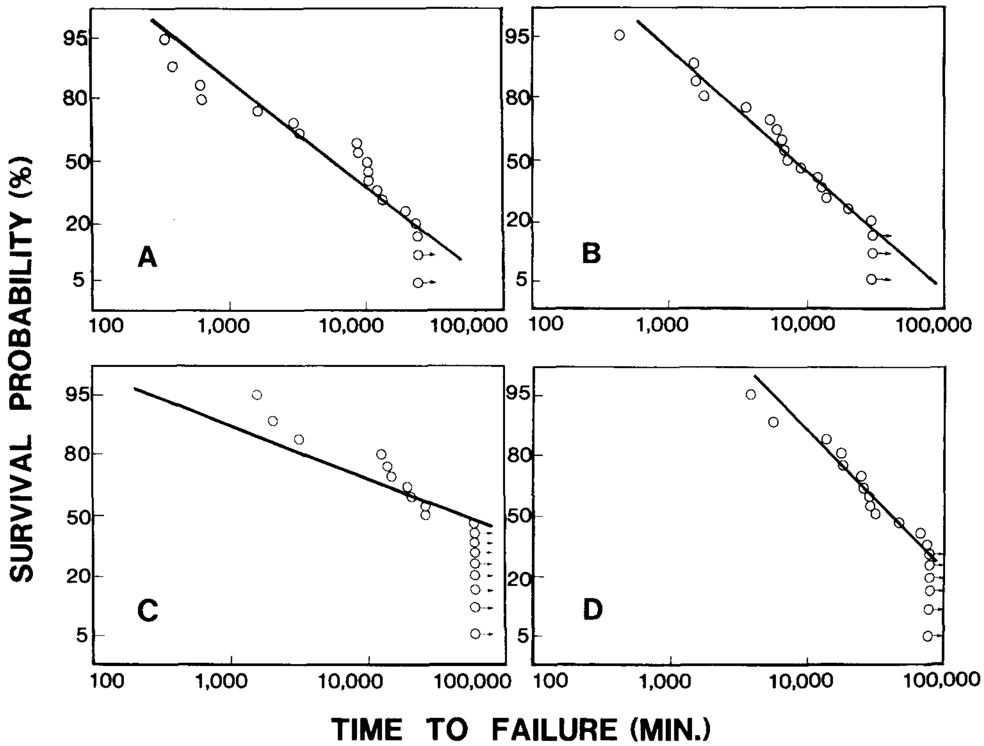

FIG. 5. Distribution of time to failure—A: 1.8× design load under Type A condition; B: 1.6× design load under Type A condition; C: 1.4× design load under Type A condition; D: 1.8× design load under Type D condition. (Arrows indicate specimens that had not failed at time of truncation.)

of 0.656, 0.584, and 0.511 of the Euler load, respectively, as obtained by removing the safety factor from the design formula. Results are plotted in Fig. 6, along with a similar regression for small beams tested under the same Type A environment by Schniewind (1967). As has been common practice, log time-to-failure was taken as the independent variable by Schniewind in calculating the regression line. The results of this study were also treated in the same manner for comparison, and the regression line with load level as the independent variable is also presented in Fig. 6.

The results of this study as shown in Fig. 6 appear to be very close to results of beam tests by Schniewind. However, although both investigations used the same type of cyclic environment, other factors would have led to an expectation of larger differences. First, the cross sections of the specimens in the two tests were different (10 mm by 20 mm for the beams and 9.5 by 6.4 mm for the columns), which affects the extent of moisture content changes within the specimens. Second, although both tests involve bending, the beam tests involve constant bending moment, while in columns the moment changes during test as they deflect.

According to the regression equation obtained in this study, the predicted time to failure for 1 × design load (0.365 of Euler load) is 234 days. This value appears much too low, as the design formula for columns is intended for long-term loading.

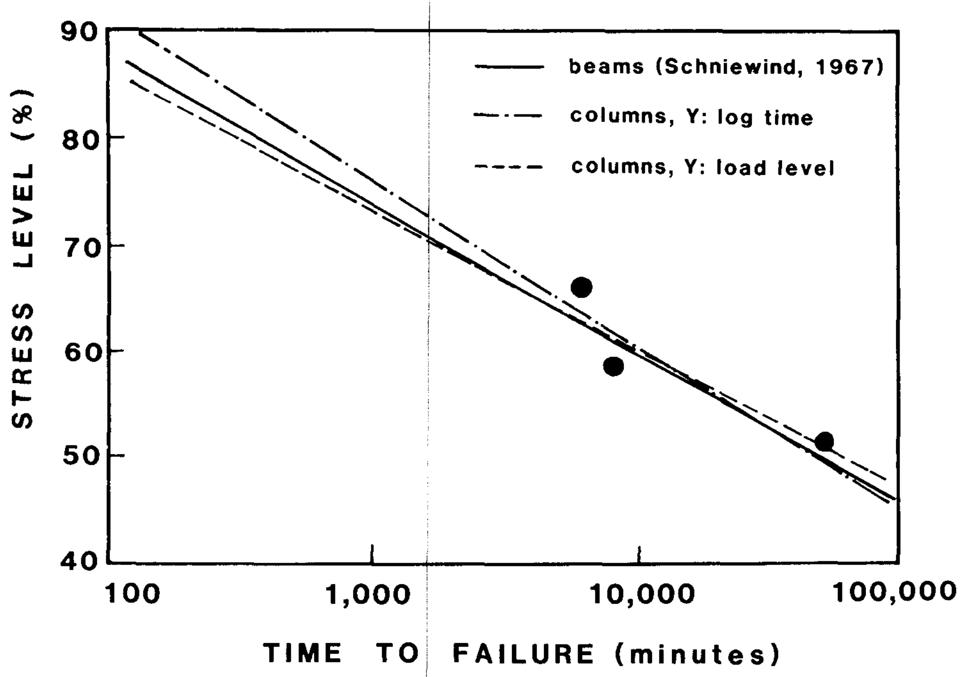

FIG. 6. Relationships between stress level and time to failure for Douglas-fir columns and beams. Points shown are average values for each load level.

Consequently, the results of this experiment cannot be applied directly to full size wood columns because internal moisture content changes are greatly affected by column size. Schniewind (1967, 1973) found that under the same Type A test conditions and 70% of modulus of rupture load level, an increase in beam size from 10 by 20 mm (0.4 by 0.8 in.) to 2 by 2 in. resulted in an increase of the average time to failure by more than one order of magnitude.

Possible relationships between initial deflection and the time to failure were studied in each set of tests. Linear regression results showed that the slope was negative, indicating longer times to failure as the initial deflection decreases, in all of the four groups tested. However, only for 1.6× design load, Type A environmental condition, was the slope significantly different from zero.

A further analysis was made by combining the data of the four groups. Data were normalized by dividing the log of time to failure of each observation by the log of the average time-to-failure of each group. Linear regression analysis showed a statistically significant relationship at the 5% level. The regression equation was $Y = 0.957 - 0.231X$, where X is the initial deflection and Y is the normalized time to failure. However, the correlation coefficient was only 0.30. Thus, $R^2 = 0.09$, indicating that only 9% of the variation can be attributed to the regression.

The results of those analyses do not provide strong evidence that small variations in initial deflection will have a major effect on time-to-failure. Gerard (1956) pointed out that small imperfections have a random and relatively unimportant effect on the critical time of loading of columns. Nevertheless, as observed in this study, there was a small but statistically significant effect of initial deflection on time-to-failure. Furthermore, the average initial deflection of spec-

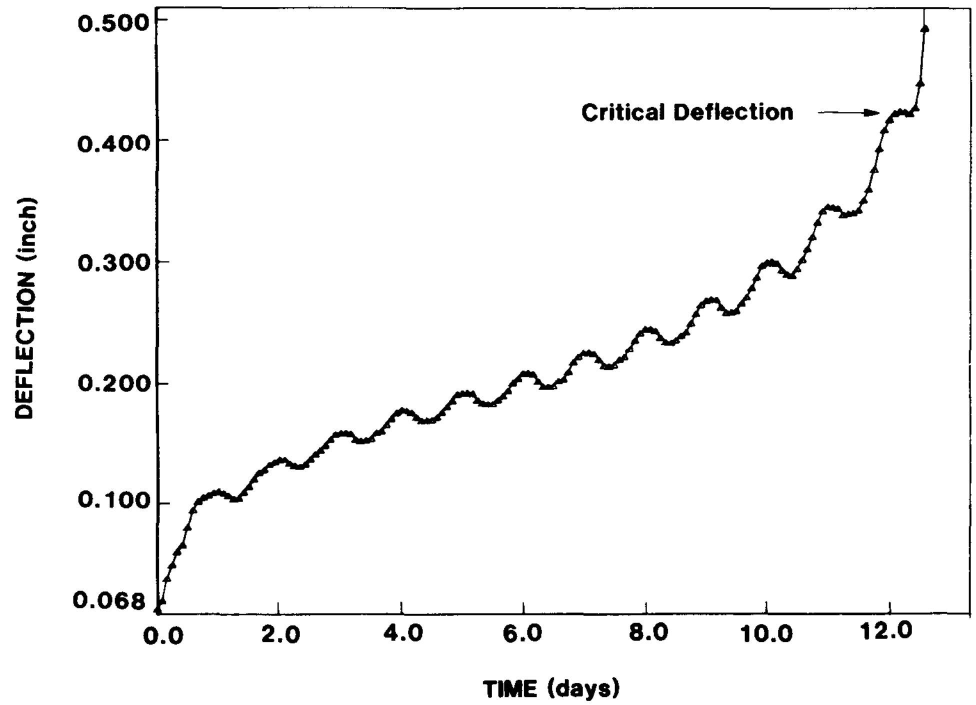

FIG. 7. Deflection history of a typical specimen showing location of critical deflection.

imens that did not fail before truncation time in each group generally was smaller than that of the specimens that did fail. Combining all groups, the average initial deflection of specimens that failed was 0.055 in., whereas it was 0.027 in. for those that did not fail.

An attempt was also made to study the magnitude of deflection that small Douglas-fir columns can endure. The deflection at the point in the last wetting cycle, which is defined by the last plateau in the deflection history, was arbitrarily named critical deflection (Fig. 7). This particular point was chosen because it is the only well-defined deflection as failure is approached.

Several specimens appeared to have a critical deflection greater than 0.5 in., which is beyond the range of the LVDT used. However, almost all of those specimens had large creep rates when the deflection approached 0.5 in. They also failed soon after exceeding 0.5 in. deflection, making it very unlikely that these specimens had a critical deflection very much greater than 0.5 in. In order to estimate the average value of critical deflection, the specimens with a critical deflection beyond the chart range were assumed to have a critical deflection of 0.5 in. The average as calculated on that basis was 0.424 in. This value is approximately $\frac{1}{30}$th of the effective length, which is more than 10 times larger than the limit state deformation ($\frac{1}{400}$th of effective length) that was arbitrarily chosen by Keresztesy (1974). However, the former value was the maximum deflection of columns observed in this study, while the latter was a general criterion for design purposes. Furthermore, a deflection of $\frac{1}{30}$th of column length means considerable bow which would also be visually unacceptable.

CONCLUSIONS

The results of this study have shown that small wood column deflections increase during desorption and decrease during adsorption as observed in beam and other creep tests of wood under cyclic humidity changes. Because the column specimens had small cross sections, average moisture changes under the experimental conditions were very large. Thus, deflections were affected correspondingly. However, variations in deflection behavior between specimens were large.

The critical times to failure were much shorter than any reasonable service life, as based on the results under Type A environmental conditions. The major factors that contributed to this reduction are believed to be the small dimensions of the column cross section as well as the severe humidity changes. Type D conditions that are less severe in their humidity transition resulted in an average time to failure about 7 times higher than under Type A conditions at the same load level ($1.8 \times$ design load).

Most of the deflection plots were sigmoid in shape, like the typical creep curve with primary, secondary, and tertiary periods. However, several curves were found to have an exponential shape.

The relationship between initial deflection and time to failure was found to be statistically significant, but did not show a high degree of correlation. Nevertheless, the average of the initial deflections for specimens that did fail before the tests were truncated was much higher than those that did not fail. Thus the effect of initial deflection appears to be larger than is evident from the statistical analysis as the latter had to be confined to specimens that did fail.

A point on the deflection curve at the beginning of the last wet cycle before failure was defined as critical deflection in this study. The results indicated that its average value is approximately $\frac{1}{30}$th of the effective length for Douglas-fir columns.

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