MECHANO-SORPTIVE DEFORMATION OF DOUGLAS-FIR SPECIMENS UNDER TANGENTIAL TENSILE STRESS DURING MOISTURE ADSORPTION[1]

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(Received September 1994)

ABSTRACT

Small specimens (3.2-mm thick) of Douglas-fir heartwood were tested for mechano-sorptive (MS) deformation in tangential tension during moisture adsorption. Tests were made at 65.5°C with moisture content (MC) changing from 5 to 20% under four levels of stress: 0.276, 0.552, 0.827, and 1.24 MPa. The results confirmed that a large MS deformation occurs during the first MC increase after the load is applied. In a sorption history of matched loaded and load-free specimens, the MS strain was shown to be proportional to applied stress, and the material parameters describing the interaction of stress and moisture change were independent of stress level.

Keywords: Softwood, strain, swelling, tension, wetting.

INTRODUCTION

An increase in the strain rate, known as the mechano-sorptive (MS) effect, occurs when wood under stress is subjected to a change in moisture content (MC), an effect first observed in wooden beams (Armstrong and Kingston 1960; Armstrong and Christensen 1961). The magnitude of the MS deformation was later shown to vary with sorption mode and loading conditions (Armstrong and Kingston 1962; Hearmon and Paton 1964). In particular, a reduction in MC causes enhanced deformation, whereas an increase, except when it is the first moisture change, causes only a small increase or even a reduction in deformation. When the first change in MC is an increase, wood deformation in bending and tension increases markedly, even after allowance is made for swelling (Armstrong 1972).

In an attempt to quantify the deformation, constitutive equations have been proposed (Leicester 1971; Ranta-Maunus 1975; Wu 1993; Wu and Milota 1995). The simplified one-dimensional form of the equation for a single change in MC is

[1] This work was funded under the USDA National Research Initiative, Competitive Grants Program, 92-37103-7979. The authors are grateful for this support. This is Paper 3046 of the Forest Research Laboratory, Oregon State University, Corvallis, OR.

$$\dot{\epsilon}_M = k_m \sigma |\dot{M}| \quad (1)$$

where

ϵ_M = MS strain (mm/mm);
k_m = material parameter for the interaction between stress and moisture change (MPa^{-1} $\%MC^{-1}$);
σ = stress (MPa);
M = moisture content (%);

and the overdot represents the time derivative. Equation (1) assumes a linear dependence of MS strain on stress and MC change, but this has been experimentally verified only to a limited extent. To completely describe the phenomena, Ranta-Maunus (1975) proposed using three material constants: k_m^- for moisture reduction, k_m^{++} for first moisture increase at any moisture level, and k_m^+ for any subsequent moisture increases at the same moisture level. Limited experimental studies indicate that those constants vary with wood species and loading direction (Ranta-Maunus 1975). How those material constants are affected by stress, temperature, and MC history is still not fully understood. A quantitative relationship is required for modeling the mechanical behavior of wood under load during moisture change.

Experimental determination of the material parameters for MS deformation requires detailed knowledge of MC change, but it is difficult to determine quantitative relationships between deformation and MC change in tests of large specimens because the moisture gradient is large and only a mean MC may be known from measurement. However, Christensen (1962) demonstrated that MC gradients are small, and the test time is shorter when the total pressure is gradually changed in the absence of air.

The objective of this study was to quantify the effect of stress on the MS effect in small specimens that underwent rapid adsorption while stressed in tension at an elevated temperature, and to evaluate the material constants for the specified sorption and loading condition. Other experiments in desorption with further background and experimental details can be found in Wu and Milota (1995).

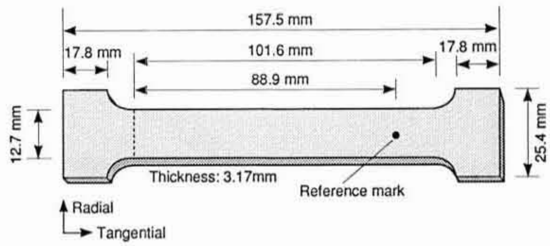

FIG. 1. Test specimen with reference mark for strain measurement.

MATERIAL AND METHODS

A heartwood sample of kiln-dried, flat-sawn Douglas-fir (*Pseudotsuga menziesii*) lumber (50.8 × 203.2 mm × 1.2 m) was selected for study. To facilitate rapid moisture equilibrium and to minimize internal moisture gradients, specimens for loading (Fig. 1) were machined with growth rings parallel to the long axis of the sample and with the end grain exposed on the wide face. One specimen for testing swelling-strain and one for testing MC were end-matched with each specimen to be loaded and were cut to the same thickness so that MC change, which was determined gravimetrically, would occur at the same rate. Black reference marks (dots 0.5 mm in diameter) were placed on the loaded and load-free specimens for strain measurement (Fig. 1). All samples were weighed before and after testing and after oven-drying.

Tests were performed in tangential tension with a small test machine in a pressure vessel. After test specimens were prepared and mounted, the vessel was sealed and heated to the target temperature, 65.5°C, at a rate of about 0.9°C per minute. The elevated temperature was used both to show the temperature effect on mechano-sorptive deformation and to shorten the sorption time, thus to limit the time-dependent effect. Simultaneously with heating, air was evacuated and the pressure of the water vapor in the vessel was made to correspond to the initial 5% equilibrium moisture content (EMC). This condition was main-

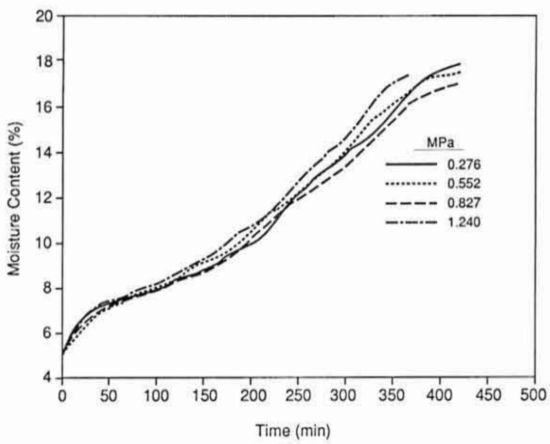

FIG. 2. Moisture-content change as a function of sorption time at four stress levels.

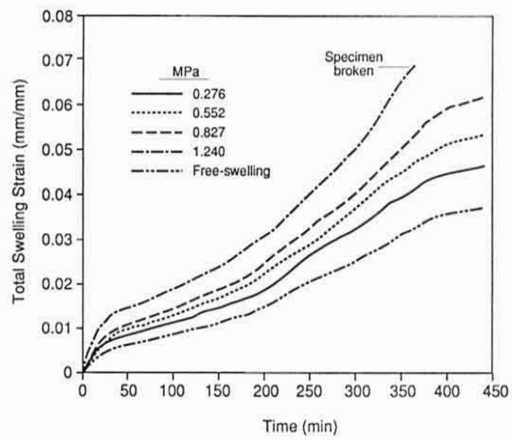

FIG. 3. Total swelling strain as a function of time at four stress levels. The curve for free-swelling samples is the mean for the four tests. Load was applied at time zero.

tained for 1 h to allow the entire system to reach thermal equilibrium before the load was applied.

Steel weights were then used to slowly apply a tensile force to the loaded specimen. Loading of the specimens was chosen to give the stress values 0, 0.276, 0.552, 0.827, or 1.24 MPa. The test was replicated once for each stress level. Strain development in the loaded and load-free specimens was resolved by monitoring the motion of the reference marks with an optical scanning system (Wu 1993).

The initial deformation was measured 12 sec after load application. Specimen deformation and load at that time were used for calculating the instantaneous strain. Pressure was ramped up at a rate of 38 Pa per min over a 7-h period until 20% EMC was reached. The MC specimen was continuously weighed with a quartz spring balance.

The MS strain was calculated by subtracting the initial instantaneous and load-free swelling strain from the total strain of the loaded specimen. The calculated strain included a creep component because of the imposed-stress history, but creep, being time-dependent, should be relatively small because of the short sorption time (Armstrong 1972; Wu and Milota 1995). To obtain material parameter k_m^{++} for each test condition, least-squares regression, with MS strain as the dependent variable and MC as the independent variable, was used to fit Eq. (1).

RESULTS AND DISCUSSION

The MC of test specimens did not reach the tabulated EMC corresponding to the surrounding pressure; actual MC change was from 5% to almost 18% (Fig. 2). The likely reason for the lower MC is a lower EMC during adsorption. The final MC varied slightly among tests, perhaps because of different sorption behavior among test specimens.

At any given stress level, there was initial instantaneous deformation in the direction of swelling (positive strain) after the load was applied (Fig. 3). However, the magnitude of the instantaneous strain was much smaller than the swelling strain due to MC increase. Soon after pressure was increased, swelling under load accelerated, causing the swelling curve for loaded specimens to depart from that for the matched load-free specimens. The effect of increased stress on total deformation over the matched sorption history is clearly evident in Fig. 3. Due to the large deformation developed at 1.24 MPa, the specimen broke 5.8 h after the load was applied.

Total swelling strain was corrected for load-free swelling strain to obtain net stress-induced strain. The correction was based on the mea-

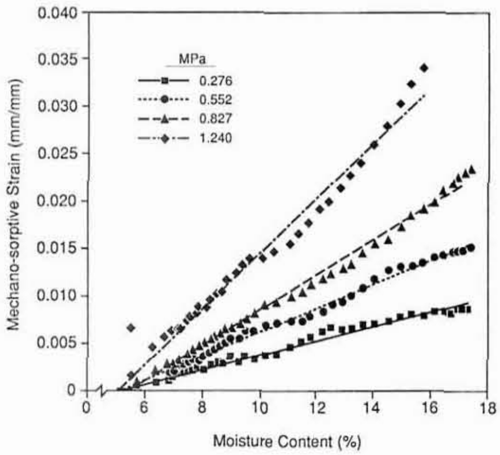

FIG. 4. The relationship between mechano-sorptive strain and moisture-content change at different stress levels. Lines show the linear fits.

sured mean swelling strain of load-free specimens. Swelling strain of those specimens was almost linearly related to MC change. The swelling coefficient, i.e., the slope of the swelling versus MC curve, was 0.0030 $\%MC^{-1}$, which compares well with the published tangential shrinkage coefficient of 0.0027 $\%MC^{-1}$ for Douglas-fir (United States Department of Agriculture 1987).

The net stress-induced strain was linearly related to MC change over the specified MC range (Fig. 4). Table 1 gives the results of data fitting, in which the parameter k_m^{++} was obtained by dividing the slope of the curve for MS strain versus MC change by the corresponding stress. The values of parameter k_m^{++} among different stress levels were not significantly different at the 0.05 level, which suggests that the MS strain would increase linearly with stress. The mean value for the coefficient k_m^{++} among four stress levels is 2.38×10^{-3} (MPa^{-1} $\%MC^{-1}$). In a previous study (Wu 1993; Wu and Milota 1995), k_m^{-} was found to be only 7.31×10^{-4} (MPa $\%MC^{-1}$) for Douglas-fir in tension during desorption. Thus, in tension, the first moisture adsorption process under load resulted in MS strain more than three times larger than that for desorption with the same amount of MC change. Similar behavior has been observed in longitudinal tension of pine (Armstrong and Kingston 1962; Eriksson and Norén 1965) and in longitudinal bending of pine (Armstrong and Christensen 1961; Raczkowski 1969) and birch (Ranta-Maunus 1975).

TABLE 1. *Mechano-sorptive (MS) parameter as a function of stress during moisture adsorption under tangential tension at 65.6°C.*

Stress, σ (MPa)	MS parameter $\times 10^3$, k_m^{++} (MPa^{-1} $\%MC^{-1}$)	Correlation coefficient*, r^2
0.276	2.65	0.98
0.552	2.28	0.99
0.827	2.25	0.98
1.240	2.35	0.97

* Correlation between MS strain and moisture-content (MC) change.

No satisfactory mechanistic explanation has been advanced for the interaction of moisture change, load, and deformation, or for the different magnitudes of deformation with desorption, adsorption, and cyclic changes in MC (Armstrong 1972). The magnitude of effect varies with type of loading. In tension parallel to the grain, Eriksson and Norén (1965) attributed the large deformation during first moisture increase under load to a conditioning process for equalizing stresses inside the specimen, which might also occur with a thick sample perpendicular to the grain.

CONCLUSIONS

Moisture adsorption under tangential tension produces a large deformation due to the MS effect. Total MS deformation increases in proportion to the increase in applied stress. The material constants describing the interaction of stress and moisture change are independent of the stress for the specified sorption and loading conditions. The data present a further experimental basis to establish the constitutive equation for the effect of temperature and stress on the MS deformation.

REFERENCES

ARMSTRONG, L. D. 1972. Deformation of wood in compression during moisture movement. Wood Sci. 5(2): 81–86.

———, AND G. N. CHRISTENSEN. 1961. Influence of moisture changes on deformation of wood under stress. Nature 191(4971):869–870.

———, AND R. S. T. KINGSTON. 1960. Effect of moisture changes on creep in wood. Nature 185(4716):862–863.

———, AND ———. 1962. The effect of moisture content changes on the deformation of wood under stress. Aust. J. Appl. Sci. 13(4):257–276.

CHRISTENSEN, G. N. 1962. The use of small specimens for studying the effect of moisture content changes on the deformation of wood under load. Aust. J. Appl. Sci. 13(4):242–256.

ERIKSSON, L., AND B. NORÉN. 1965. The effect of moisture changes on the deformation of wood with tension in fiber direction. Holz Roh-Werkst. 23:201–209.

HEARMON, R. F. S., AND J. M. PATON. 1964. Moisture content change and creep of wood. Forest Prod. J. 14(8): 357–359.

LEICESTER, R. H. 1971. A rheological model for mechano-sorptive creep of beams. Wood Sci. Technol. 5:211–220.

RACZKOWSKI, J. 1969. Effect of moisture content changes on the creep behaviour of wood. Holz Roh-Werkst. 27: 232–237.

RANTA-MAUNUS, A. 1975. The viscoelasticity of wood at varying moisture content. Wood Sci. Technol. 9:189–205.

UNITED STATES DEPARTMENT OF AGRICULTURE (USDA). 1987. Wood handbook: Wood as an engineering material. USDA Agric. Handb. 72, USDA Forest Serv., Forest Prod. Lab. Madison, WI.

WU, Q. 1993. Rheological behavior of Douglas-fir as related to the process of drying. Ph.D. dissertation, Oregon State University, Corvallis, OR. 228 pp.

———, AND M. R. MILOTA. 1995. Rheological behavior of Douglas-fir at elevated temperature. Wood Fiber Sci. (3):285–295.