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Time dependence of Poisson's effect in wood II: volume change during uniaxial tensile creep

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Abstract To determine the viscoelasticity of wood three-dimensionally, a longitudinal tensile creep test was conducted on 12 species of wood to examine the change in the rate of volume increase ($\Delta V/V$) with time. Immediately after the beginning of creep, $\Delta V/V$ was positive, and during creep, $\Delta V/V$ decreased rapidly, then more gradually. The decrease in tangential strain was considered to mainly contribute to the decrease in $\Delta V/V$ during creep. Immediately after the removal of the load, $\Delta V/V$ decreased to a negative value; thereafter, it decreased slowly and finally reached a certain value. The value of $\Delta V/V$ during creep tended to decrease with increasing density of wood. Also, there was a negative correlation between wood density and the rate of increase in $\Delta V/V$.

Key words Viscoelasticity · Lateral strain · Longitudinal strain · Rate of volume increase · Poisson's ratio

Introduction

When a material undergoes uniaxial tensile normal stress, the material stretches in the load direction and shrinks in the vertical direction according to Poisson's effect; that is, the volume changes. The changes in volume of various polymer materials undergoing uniaxial creep or stress relaxation have been examined.[1–4] An indicator of Poisson's effect is Poisson's ratio,[5,6] which is an important elastic constant in the investigation of the elasticity of wood, an orthotropic material. Recently, Poisson's ratio has been recognized as a valuable index for evaluating the microdamage in some composite materials[7–9] and in bone.[10]

In previous reports,[11,12] we defined the apparent Poisson's ratio as the negative value of the lateral strain divided by the longitudinal strain measured during creep and creep-recovery, and we determined the three-dimensional viscoelastic compliance of wood[11] and examined the lateral strain behavior of 12 species of wood[12] by conducting tensile creep tests with the aim of determining the viscoelasticity of wood three-dimensionally. As a logical next step, in this study we evaluated the volume change in wood during creep resulting from Poisson's effect.

Theory

It is assumed that uniaxial normal stress is applied to a rectangular parallelepiped with side lengths a, b, and c and that each side increases in length to $a(1 + \varepsilon_1)$, $b(1 + \varepsilon_2)$, and $c(1 + \varepsilon_3)$, respectively. Here, ε_i ($i = 1, 2$, and 3) is the normal strain and i refers to the orthogonal direction. The initial volume is expressed by the following equation:

$$V = abc \quad (1)$$

After the application of stress, V increases to

$$a(1+\varepsilon_1)b(1+\varepsilon_2)c(1+\varepsilon_3) \quad (2)$$

Thus, the change in volume, ΔV, is expressed by the following equation:

$$\Delta V = a(1+\varepsilon_1)b(1+\varepsilon_2)c(1+\varepsilon_3) - abc \quad (3)$$

where $\varepsilon_1\varepsilon_2$, $\varepsilon_1\varepsilon_3$, $\varepsilon_2\varepsilon_3$, and $\varepsilon_1\varepsilon_2\varepsilon_3$ are assumed to be infinitesimal. Therefore:

$$\Delta V \cong abc(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) \quad (4)$$

Accordingly, the rate of volume increase can be defined as follows:

$$\Delta V/V = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (5)$$

Equation 5 has the same form as the equation for volume strain.

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Materials and methods

Materials

In this study, Japanese beech (*Fagus crenata*), Japanese ash (*Fraxinus mandshurica*), Japanese zelkova (*Zelkova serrata*), Japanese chestnut (*Castanea crenata*), teak (*Tectona grandis*), and balsa (*Ochroma lagopus*) were used as hardwood species, and Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*), ezo spruce (*Picea jezoensis*), *Agathis* (*Agathis* sp.), Douglas-fir (*Pseudotsuga menziesii*), and western red cedar (*Thuja plicata*) were used as coniferous woods. Table 1 shows the mean density and moisture content of the 12 species.

Figure 1 shows an overview of a tensile test specimen. The specimen measured 300 mm along the fiber, 17.5 mm radially, and 17.5 mm tangentially. A tapered shape with a central cross section of 12 mm × 12 mm and a parallel section along the fiber with a length of about 30 mm were formed on the longitudinal-tangential (LT) and longitudinal-radial (LR) planes. Tabs made of a hardwood were attached to the grip sections on both ends of the specimen for reinforcement. Specimens were conditioned at a constant temperature of 25°C and relative humidity of 55% over a period of 3 months to reach an equilibrium moisture content.

Tensile creep test

For the tensile test, a servo-controlled fatigue-testing machine (Shimadzu Servopulser EHF-ED10/TD1-20L) was used. We were able to simultaneously control both the uniaxial load and the torque using this machine, and we confirmed that all samples could be held without the possibility of twisting. Biaxial strain gauges (gauge length, 2 mm; Tokyo Sokki Kenkyujo, FCA-2-11) were pasted onto the central regions of the opposite LT and LR planes (four planes) of the specimen to measure the longitudinal strain (ε_L) and lateral strains [tangential strain (ε_T) and radial strain (ε_R)] serially.

Beforehand, a static tensile test was conducted with a loading speed of 98 N/s to measure the tensile strength. All specimens of each species used in the static and creep tests were prepared from the same lumber. At least five specimens of each species were used in the static test.

A 24-h longitudinal tensile creep test was conducted with a load equivalent to 50% of the tensile strength. The applied stress is shown in Table 1. Thereafter, the load was removed immediately and maintained at 0 N until all strains became constant; this comprised the creep-recovery test. Temperature (25°C) and humidity (55% RH) were kept constant during both tests.

Table 1. Mean density and moisture content, and applied stress for creep test of the 12 species

Species	Density (kg/m^3)	Moisture content (%)	Applied stress (MPa)	*n*
Japanese cypress	410	9.6	67	2
Japanese cedar	370	9.8	55	2
Ezo spruce	340	10.0	56	2
Genus *Agathis*	470	9.8	76	3
Douglas-fir	460	9.3	63	3
Western red cedar	460	10.2	56	4
Japanese beech	570	9.9	69	3
Japanese ash	560	9.5	61	2
Japanese zelkova	630	10.4	60	2
Japanese chestnut	580	9.6	63	2
Teak	680	9.8	82	3
Balsa	110	9.0	9.5	1

n, Number of specimens
Applied stress is equal to 50% of tensile strength

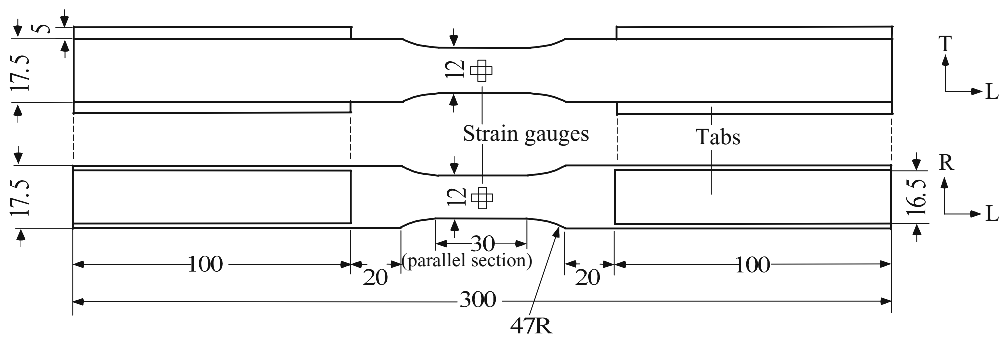

Fig. 1. Tensile test specimen. A biaxial strain gauge was pasted on each of the four planes. Unit, mm

Results and discussion

Change in $\Delta V/V$

Figure 2 shows the change in the value of $\Delta V/V$ with time for Japanese cypress. Figure 3 shows the changes in the normal strains (ε_L, ε_T, and ε_R) with time, accompanying the change in $\Delta V/V$, for Japanese cypress. Each strain is the average value for the opposite planes. The load was removed 24 h after the beginning of the creep test. The creep-recovery test was continued until all strains became constant.

Immediately after the beginning of creep, the volume increased. It then decreased sharply and subsequently decreased more gradually. After 24 h, $\Delta V/V$ reached about 1000×10^{-6}, and the volume did not return to its original value. However, for some species with high density, the volume became smaller than the original volume after 24 h of creep. This difference is explained later.

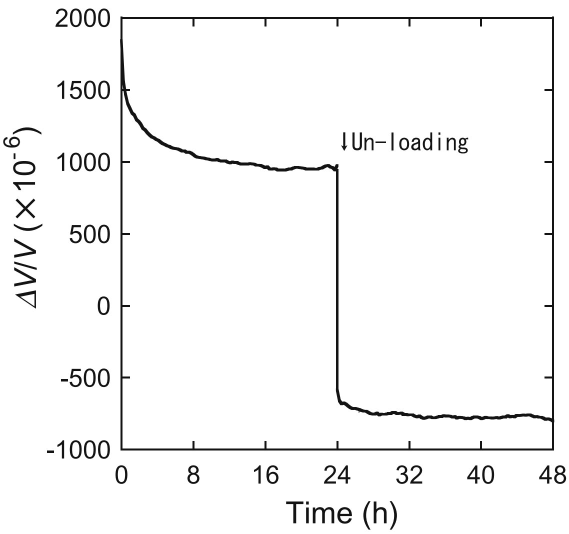

Fig. 2. Typical progression of rate of volume increase ($\Delta V/V$) for Japanese cypress, measured during creep and creep-recovery. The applied stress was 67 MPa. $\Delta V/V$ is defined in Eq. 5

Upon applying tensile load, the longitudinal strain (ε_L) increases, whereas the lateral strains (ε_T and ε_R) decrease. Considering that $\Delta V/V$ is expressed as the sum of three strains (see Eq. 5), it can be concluded that the decrease in volume during creep occurred because the sum of the decreases in lateral strains was greater than the increase in longitudinal strain. This result is consistent with the cause of the increase in apparent Poisson's ratio during creep in our previous report.[12]

Upon the removal of the load, $\Delta V/V$ decreased to a negative value and subsequently continued to decrease slowly because the decrease in longitudinal strain was larger than the sum of the increases in lateral strains during creep-recovery. Thereafter, $\Delta V/V$ finally reached a certain value.

Relationship between density and $\Delta V/V$

The density of wood is greatly dependent on its porosity. We examined the effect of porosity on $\Delta V/V$. Figure 4 shows the relationship between the density of the 12 species and $\Delta V/V$ immediately after the beginning of creep [$(\Delta V/V)_0$] and that between density and $\Delta V/V$ after 24-h of creep [$(\Delta V/V)_{24}$]. We cannot discuss the characteristics of species here because the number of samples of each species is small; thus, we examined the relationships considering the wood as a homogeneous anisotropic material.

Only $(\Delta V/V)_{24}$ tended to decrease with increasing density. The volume of Japanese cypress (see Fig. 2) did not return to its original value after 24 h of creep [$(\Delta V/V)_{24}$ was positive], but Fig. 4 shows that, in the species with greater

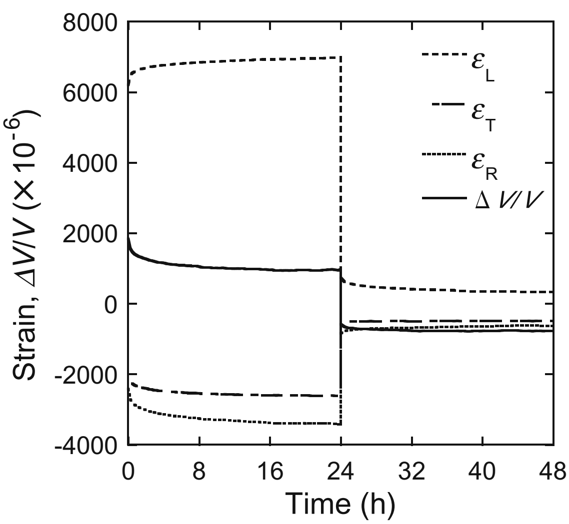

Fig. 3. Typical progression of the normal strains (ε_L, ε_T, and ε_R), with that of $\Delta V/V$, for Japanese cypress, measured during creep and creep-recovery. The applied stress was 67 MPa. The values of $\Delta V/V$ are the same as those in Fig. 2

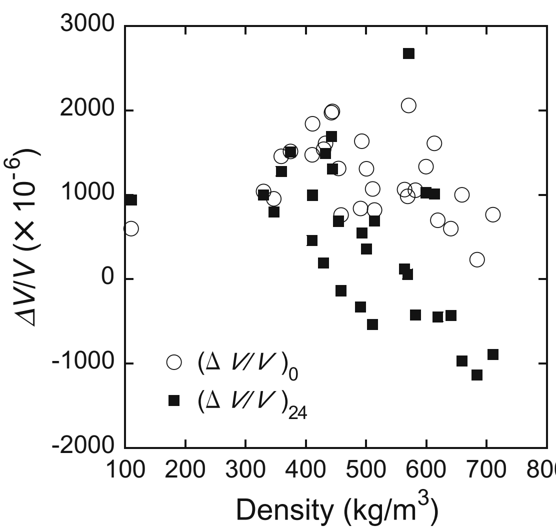

Fig. 4. Relationship between $\Delta V/V$ and the density of 12 species. $(\Delta V/V)_0$, $\Delta V/V$ at time = 0 h (immediately after loading); $(\Delta V/V)_{24}$, $\Delta V/V$ at time = 24 h (immediately before unloading)

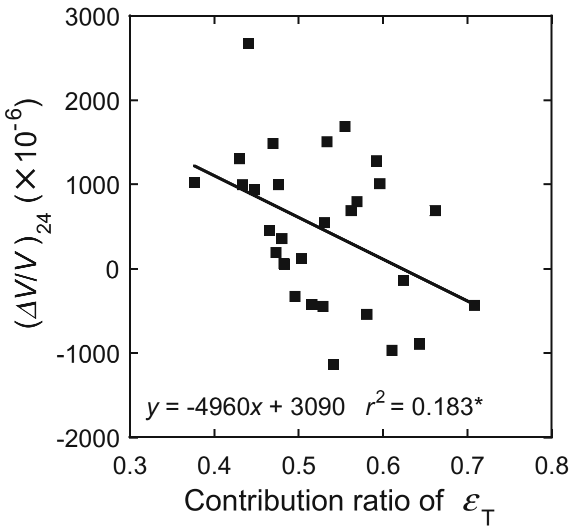

Fig. 5. Relationship between the contribution ratio of ε_T to the sum of lateral strains and $(\Delta V/V)_{24}$. The contribution ratio of ε_T is defined in Eq. 6. $(\Delta V/V)_{24}$, $\Delta V/V$ at time = 24 h. *Asterisk*, significant at 5% level

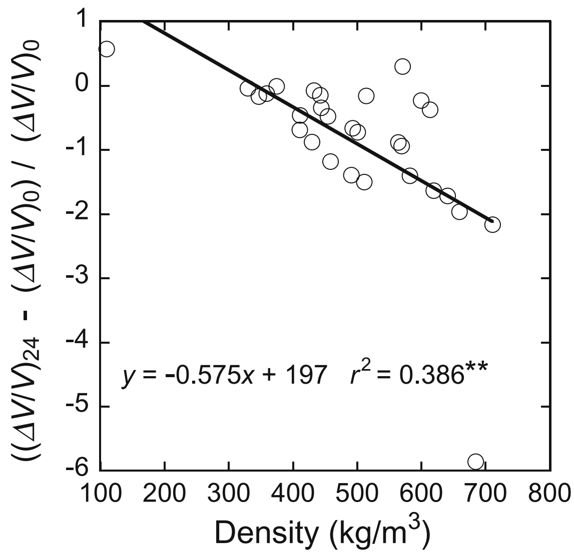

Fig. 6. Relationship between the rate of increase in $\Delta V/V$ from the beginning of creep to after 24 h of creep and the density of 12 species. *Double asterisk*, significant at 1% level

density, the volume tended to become smaller than the original volume.

Figure 5 shows the relationship between the contribution ratio of ε_T to the sum of lateral strains (ε_T and ε_R) and $(\Delta V/V)_{24}$. The contribution ratio of ε_T is defined as follows:

$$\text{Contribution ratio of } \varepsilon_T = \frac{\varepsilon_{T24}}{\varepsilon_{T24} + \varepsilon_{R24}} \quad (6)$$

Here, ε_{T24} is ε_T at time = 24 h and ε_{R24} is ε_R at time = 24 h. From this equation it is possible to determine which lateral strain has the greater effect on the decrease in $\Delta V/V$. As shown, there was a negative correlation between the contribution ratio of ε_T and $(\Delta V/V)_{24}$. That is, for specimens with a low value of $(\Delta V/V)_{24}$, the decrease in ε_T predominantly contributed to the decrease in $\Delta V/V$ during creep.

Relationship between density and the rate of increase in $\Delta V/V$

Figure 6 shows the relationship between the rate of increase in $\Delta V/V$ from the beginning of creep to after 24 h of creep $\{[(\Delta V/V)_{24} - (\Delta V/V)_0]/(\Delta V/V)_0\}$ and the density of the 12 species. A tendency for $\Delta V/V$ to decrease during creep was generally observed in wood. However, for only two specimens (Japanese ash and balsa), the rate of increase in $\Delta V/V$ became positive because of the increase in volume.

There was a negative correlation between the density, which is affected by the porosity, and the rate of increase in $\Delta V/V$. Morooka et al.[13] and Ohgama[14] have shown that the porous structure of wood strongly affects the Poisson's ratios (ν_{RT} and ν_{TR}), according to the results of numerical analysis using a model. As a result of this study, we propose that the smaller the coefficient of porosity in wood, the greater the rate of decrease in $\Delta V/V$ during creep.

Conclusions

A longitudinal tensile creep test was conducted on various species of wood to examine the changes in $\Delta V/V$ with time. $\Delta V/V$ increased immediately after the beginning of creep, after which it decreased rapidly, then gradually. For specimens with a lower value of $\Delta V/V$ after 24 h of creep, the decrease in ε_T was considered to predominantly contribute to the decrease in $\Delta V/V$ during creep. The value of $\Delta V/V$ after 24 h of creep tended to decrease with increasing density. Also, there was a negative correlation between density and the rate of increase in $\Delta V/V$.

References

1. Ol'khovik OE (1982) Volume deformation of polytetrafluoroethylene under uniaxial tension. Strength Mater 14:553–559
2. Delin M, Rychwalski RW, Kubát MJ, Kubát J (1995) Volume changes during stress relaxation in polyethylene. Rheol Acta 34:182–195
3. Castagnet S, Gacougnolle JL, Dang P (1999) Macroscopic volume changes of PVF_2 undergoing uniaxial tension and creep. J Mater Sci 34:5133–5138
4. Addiego F, Dahoun A, G'Sell C, Hiver JM (2006) Volume variation process of high-density polyethylene during tensile and creep tests. Oil Gas Sci Technol 61:715–724
5. Hearmon RFS (1948) The elastic constants of wood. In: The elasticity of wood and plywood. Forest products research special report no. 7. His Majesty's Stationery Office, London, pp 5–44
6. Sawada M (1956) A test method of Poisson's ratio of wood. Mokuzai Gakkaishi 2:233–236
7. Surgeon M, Vanswijgenhoven E, Wevers M, van der Biest O (1999) Transverse cracking and Poisson's ratio reduction in cross-ply carbon fibre-reinforced polymers. J Mater Sci 34:5513–5517
8. Kashtalyan M, Soutis C (2000) Stiffness degradation in cross-ply laminates damaged by transverse cracking and splitting. Compos Part A Appl Sci Manuf 31:335–351

9. Amara KH, Tounsi A, Benzair A (2005) Transverse cracking and elastic properties reduction in hygrothermal aged cross-ply laminates. Mater Sci Eng A Struct Mater 396:369–375
10. Pidaparti RM, Vogt A (2002) Experimental investigation of Poisson's ratio as a damage parameter for bone fatigue. J Biomed Mater Res 59:282–287
11. Taniguchi Y, Ando K, Yamamoto H (2010) Determination of three-dimensional viscoelastic compliance in wood by tensile creep test. J Wood Sci 56:82–84
12. Taniguchi Y, Ando K (2010) Time dependence of Poisson's effect in wood. I: The lateral strain behavior. J Wood Sci 56:100–106
13. Morooka T, Ohgama T, Yamada T (1979) Poisson's ratio of porous material (in Japanese). J Soc Mater Sci Jpn 28:635–640
14. Ohgama T (1982) Poisson's ratio of wood as porous material (in Japanese). Bull Fac Educ Chiba Univ Part II 31:99–107