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RAPID COMMUNICATION

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Determination of three-dimensional viscoelastic compliance in wood by tensile creep test

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Key words Normal strain · Poisson's ratio · Viscoelasticity · Creep compliance · Viscoelastic matrix

Introduction

The objective of this study was to extend the hitherto biaxial, two-dimensional approach to determination of the viscoelastic functions in wood to three dimensions, by making measurements to obtain all components of the viscoelastic compliance tensor concerning normal strain. Two-dimensional viscoelastic compliance has been determined by Schniewind and Barrett[1] and Hayashi et al.[2] However, three-dimensional viscoelasticity of wood has rarely been discussed, although wood has three axes of symmetry.

In the present work, we determined three-dimensional viscoelastic compliance concerning normal strain in wood by conducting longitudinal-, tangential-, and radial-tensile creep tests.

Theory

Three orthogonal normal strains for time-independent elastic bodies are defined by the following elastic compliance:

$$\begin{bmatrix}\varepsilon_L\\ \varepsilon_T\\ \varepsilon_R\end{bmatrix}=\begin{bmatrix}\frac{1}{E_L} & -\frac{\nu_{TL}}{E_T} & -\frac{\nu_{RL}}{E_R}\\ -\frac{\nu_{LT}}{E_L} & \frac{1}{E_T} & -\frac{\nu_{RT}}{E_R}\\ -\frac{\nu_{LR}}{E_L} & -\frac{\nu_{TR}}{E_T} & \frac{1}{E_R}\end{bmatrix}\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_R\end{bmatrix} \tag{1}$$

where ε_i (i = L, T, R) is normal strain when i refers to the direction; σ_i is normal stress; E_i is Young's modulus; and ν_{ij} is Poisson's ratio, when i refers to the direction of positive (longitudinal) strain and j to passive (lateral) strain, respectively. In this study, during the creep test, the absolute value of the ratio of passive strain to positive strain was defined as the viscoelastic, i.e., apparent Poisson's ratio.[3] The apparent Poisson's ratio can be expressed by the following equation:

$$\overline{\nu_{ij}}(t)=\left|\frac{\varepsilon_j+\kappa_j(t)}{\varepsilon_i+\kappa_i(t)}\right| \qquad (i, j = \mathrm{L, T, R}) \tag{2}$$

where, $\kappa_i(t)$ is the increase in the positive strain during creep and $\kappa_j(t)$ is the increase in the passive strain during creep.

The ratio of $\kappa_j(t)$ to $\kappa_i(t)$ is defined by the following equation:

$$\psi_{ij}(t)=\left|\frac{\kappa_j(t)}{\kappa_i(t)}\right| \qquad (i, j = \mathrm{L, T, R}) \tag{3}$$

When a viscoelastic material such as wood is put under a time-dependent load condition, the resulting normal strains can be expressed by the following equation:

$$\begin{bmatrix}\varepsilon_L(t)\\ \varepsilon_T(t)\\ \varepsilon_R(t)\end{bmatrix}=\begin{bmatrix}\frac{1}{E_L} & -\frac{\nu_{TL}}{E_T} & -\frac{\nu_{RL}}{E_R}\\ -\frac{\nu_{LT}}{E_L} & \frac{1}{E_T} & -\frac{\nu_{RT}}{E_R}\\ -\frac{\nu_{LR}}{E_L} & -\frac{\nu_{TR}}{E_T} & \frac{1}{E_R}\end{bmatrix}\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_R\end{bmatrix} + \begin{bmatrix}Q_{LL}(t) & Q_{LT}(t) & Q_{LR}(t)\\ Q_{TL}(t) & Q_{TT}(t) & Q_{TR}(t)\\ Q_{RL}(t) & Q_{RT}(t) & Q_{RR}(t)\end{bmatrix}\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_R\end{bmatrix} \tag{4}$$

where $Q_{ij}(t)$ (i, j = L, T, R) is the viscoelastic compliance. The first square matrix in Eq. 4 is derived from the instantaneous elastic strain, and the second one is from the delayed elastic strain and the permanent strain. Considering Eq. 3, Eq. 4 can be transformed into the following Eq. 5:

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$$
\begin{bmatrix} \varepsilon_{\mathrm{L}}(t) \\ \varepsilon_{\mathrm{T}}(t) \\ \varepsilon_{\mathrm{R}}(t) \end{bmatrix} = \begin{bmatrix} \dfrac{1}{E_{\mathrm{L}}} & -\dfrac{\nu_{\mathrm{TL}}}{E_{\mathrm{T}}} & -\dfrac{\nu_{\mathrm{RL}}}{E_{\mathrm{R}}} \\ -\dfrac{\nu_{\mathrm{LT}}}{E_{\mathrm{L}}} & \dfrac{1}{E_{\mathrm{T}}} & -\dfrac{\nu_{\mathrm{RT}}}{E_{\mathrm{R}}} \\ -\dfrac{\nu_{\mathrm{LR}}}{E_{\mathrm{L}}} & -\dfrac{\nu_{\mathrm{TR}}}{E_{\mathrm{T}}} & \dfrac{1}{E_{\mathrm{R}}} \end{bmatrix} \begin{bmatrix} \sigma_{\mathrm{L}} \\ \sigma_{\mathrm{T}} \\ \sigma_{\mathrm{R}} \end{bmatrix} + \begin{bmatrix} Q_{\mathrm{LL}}(t) & -\psi_{\mathrm{TL}}(t)Q_{\mathrm{TT}}(t) & -\psi_{\mathrm{RL}}(t)Q_{\mathrm{RR}}(t) \\ -\psi_{\mathrm{LT}}(t)Q_{\mathrm{LL}}(t) & Q_{\mathrm{TT}}(t) & -\psi_{\mathrm{RT}}(t)Q_{\mathrm{RR}}(t) \\ -\psi_{\mathrm{LR}}(t)Q_{\mathrm{LL}}(t) & -\psi_{\mathrm{TR}}(t)Q_{\mathrm{TT}}(t) & Q_{\mathrm{RR}}(t) \end{bmatrix} \begin{bmatrix} \sigma_{\mathrm{L}} \\ \sigma_{\mathrm{T}} \\ \sigma_{\mathrm{R}} \end{bmatrix} \tag{5}
$$

The uniaxial normal stress in i-direction, σ_i, generates the stress state with $\sigma_j = \sigma_k = 0$ (i, j, k = L, T, R). Thus, $Q_{ii}(t)$ can be expressed as follows:

$$
Q_{ii}(t) = \frac{\varepsilon_i(t)}{\sigma_i} - \frac{1}{E_i} \tag{6}
$$

Materials and methods

Japanese cypress (*Chamaecyparis obtusa*) was used as the specimen material. All the specimens were prepared from neighboring portions of a log. The average density and equilibrium moisture content of the specimen were 411 kg/m^3 and 9.6%, respectively. The uniaxial tensile test specimens were grouped into the following three types. (1) L-specimen: the external dimensions were 300 (L) × 17.5 (T) × 17.5 (R) mm; a tapered shape with a central cross section of 12 mm × 12 mm and a parallel portion of about 40 mm along the fiber was formed on the LT and LR planes. The length of the grip section was 90 mm. E_{L}, σ_{L}, ν_{LT}, ν_{LR}, $\psi_{\mathrm{LT}}(t)$, $\psi_{\mathrm{LR}}(t)$, and $\varepsilon_{\mathrm{L}}(t)$ were measured. (2) T-specimen: the dimensions were 120 (T) × 20 (L) × 20 (R) mm. The length of grip section was 35 mm. E_{T}, σ_{T}, ν_{TL}, ν_{TR}, $\psi_{\mathrm{TL}}(t)$, $\psi_{\mathrm{TR}}(t)$, and $\varepsilon_{\mathrm{T}}(t)$ were measured. (3) R-specimen: the dimensions were 120 (R) × 20 (L) × 20 (T) mm. The length of grip section was 35 mm. E_{R}, σ_{R}, ν_{RL}, ν_{RT}, $\psi_{\mathrm{RL}}(t)$, $\psi_{\mathrm{RT}}(t)$, and $\varepsilon_{\mathrm{R}}(t)$ were measured. There were eight specimens of each type.

For the tensile test, a servo-controlled fatigue-testing machine (Shimadzu Servopulser EHF-ED10/TD1-20L) was used. The biaxial strain gauges (gauge length, 2 mm; Tokyo Sokki Kenkyujo, FCA-2-11) were pasted to the respective center parts on the opposite planes (four planes) of the specimen to measure the longitudinal and lateral strains serially. Beforehand, a static tensile test was conducted to measure the tensile strength. A 24-h tensile creep test was conducted: 40, 1.4, and 2.3 MPa, which correspond to the 30% of tensile strength in the L, T, and R directions, respectively, were applied to the specimen. Temperature (25°C) and humidity (55% RH) were kept constant during the test.

Results and discussion

E_i and ν_{ij} were measured immediately after the beginning of creep, and $\psi_{ij}(t)$ was continuously measured during creep.

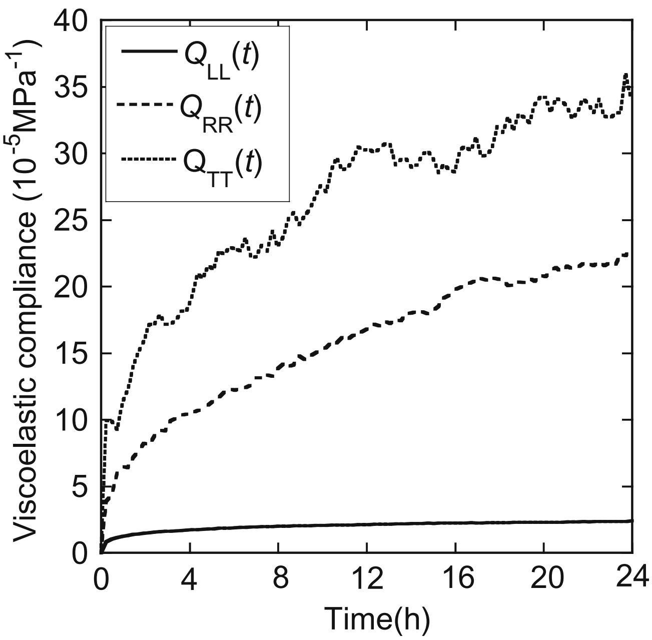

Fig. 1. Typical progression of the $Q_{\mathrm{LL}}(t)$, $Q_{\mathrm{TT}}(t)$, and $Q_{\mathrm{RR}}(t)$ during creep

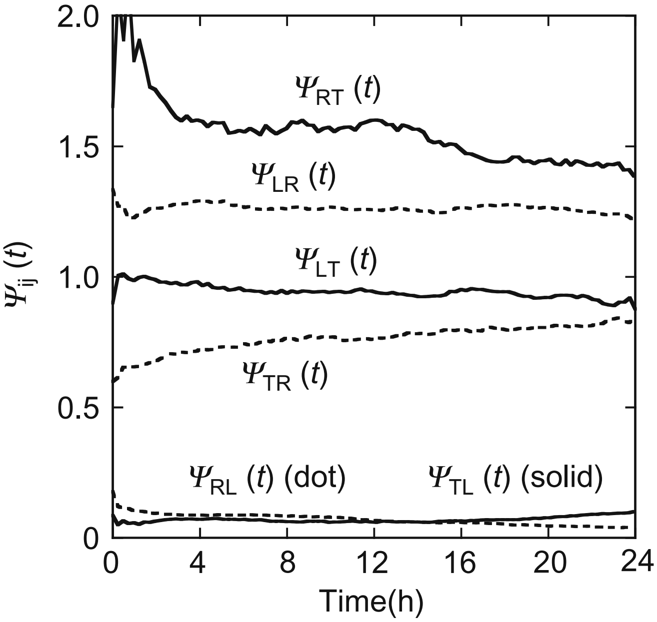

Fig. 2. Typical progression of the $\psi_{ij}(t)$ during creep. $\psi_{ij}(t)$ is defined in Eq. 3. *Dotted line*, $\psi_{\mathrm{RL}}(t)$; *solid line*, $\psi_{\mathrm{TL}}(t)$

Figure 1 shows the typical progression of $Q_{\mathrm{LL}}(t)$, $Q_{\mathrm{TT}}(t)$, and $Q_{\mathrm{RR}}(t)$ during creep. All three parameters, which were in proportion to the longitudinal strain induced by uniaxial creep, had a tendency to increase parabolically whereas the value of $Q_{\mathrm{LL}}(t)$ was far smaller than the values of $Q_{\mathrm{TT}}(t)$ and $Q_{\mathrm{RR}}(t)$. Figure 2 shows the typical progression of six values of $\psi_{ij}(t)$, which were considered to represent the Poisson's effect during creep. Recently, Poisson's ratio has been recognized as a valuable index to evaluate the microdamage in some composite materials.[4] The values of $\psi_{ij}(t)$, except for $\psi_{RT}(t)$ and $\psi_{TR}(t)$, were considered to become almost constant at the relative initial stage.

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