



Analysis of shear creep properties of wood via modified Burger models and off-axis compression test method

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Received: 22 February 2024 / Accepted: 9 July 2024 / Published online: 24 July 2024
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Abstract

In this study, the rheological Burger model combining Maxwell and Voigt–Kelvin model units as well as modified mechanical models were employed to analyze the shear creep mechanism of wood. Off-axis compression tests were conducted on Japanese Hinoki cypress specimens (*Chamaecyparis obtusa*), and a mechanical analysis of the shear creep mechanism was performed. First, the measured creep compliance curves [$J_{TL}(t)$] were fitted using this Burger model, which is a typical model used to explain the creep behavior of wood. Furthermore, three modified Burger models with non-Newtonian dashpots were proposed to explain the measured data more accurately: model 1—only the dashpot in the permanent strain unit is non-Newtonian; model 2—both dashpots are non-Newtonian; and model 3—only the dashpot in the delayed elastic strain unit is non-Newtonian. The mean value of the coefficient of determination was highest for model 1. The number of specimens that could be fitted with a tolerance error of 0.1% was 43 out of 50 with the Burger model, 45 with model 1, 25 with model 2, and 45 with model 3. The Burger model exhibited large discrepancies between the theoretical and measured values, model 2 could not be used to explain several specimens, and model 3 exhibited a delayed elastic strain behavior that was inconsistent with the definition. Therefore, we conclude that model 1 is the most appropriate for studying the shear creep behavior of wood.

Introduction

Shear creep properties of wood

Wood has been used as a building material for several years. Wood, being a viscoelastic material, exhibits an elastic response to short-term loading but behaves

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more viscously under long-term loadings. Therefore, it is important to understand the deformation of wood under long-term loading to ensure serviceability issues and efficient use. Furthermore, various loads that were not observed in the past are expected to occur; hence, it is necessary to understand the response of wood to these loads. Shear is one of the most important mechanical properties for the advanced use of wood, particularly when it is more pronounced in large asymmetric wooden beams or rigid joints such as ramen structures.

Although review articles (Holzer et al. 1989; Navi and Stanzl-Tschegg 2009) have been published on the viscoelasticity of wood, few studies have been conducted on long-term shear loading (Norimoto et al. 1965; Schniewind and Barrett 1972; Vermaas 1989; Hayashi et al. 1993; Ando et al. 2005, 2023; Entwistle 2005; Vincent et al. 2006; Fan and Enjily 2009; Akter et al. 2022; Bengtsson et al. 2023). Norimoto et al. (1965), Vermaas (1989), and Entwistle (2005) tested wood samples for torsional creep, and Vincent et al. (2006) tested wood samples for torsional stress relaxation. These studies reported changes in the shear strain as a function of temperature or humidity. In particular, Entwistle (2005) considered the changes in shear strain during wood creep in terms of the shear forces along the direction of microfibrils in the S2 layer, shear force between microfibrils and the hemicellulose, and adsorption/desorption of water molecules within the hemicellulose. Schniewind and Barrett (1972), Akter et al. (2022) and Hayashi et al. (1993) measured the changes in shear creep strain using the plate-shear, rolling shear, and off-axis tensile methods, respectively. Ando et al. (2023) investigated the relationship between the shear creep properties of wood and the macro- and micro-structural factors and found that, in Japanese Sugi cedar, the shear creep properties are strongly influenced by a micro factor, namely the microfibril angle (MFA). In addition, studies on the shear creep characteristics of several commercial wood-based products have been conducted from a practical standpoint (Hong and Arima 1998; Ohashi et al. 2009; Ogawa and Kobayashi 2020; Allemand et al. 2021).

Most studies conducted to date on the shear creep of wood have been limited to measuring the creep strain or compliance trends and estimating the influence of microstructural factors, with no direct reference to its mechanics. Bengtsson et al. (2023) used the Voigt–Kelvin model to study the mechanism of shear creep in three orthogonal sections of Norway spruce; however, because this study focused on reversible elastic solicitation, the model did not take permanent strain into account. To overcome this limitation, in this study, the Burger model combining the Maxwell and Voigt–Kelvin model units as well as modified mechanical models were used to analyze the shear creep mechanism of wood.

Modeling wood creep

Two elements are used to explain the creep and stress relaxation phenomena in materials: (1) spring, which represents ideal elastic deformation, and (2) dashpot, which represents linear viscous flow. Several models using these elements have been proposed. The Maxwell model connects both elements in series, whereas the Voigt–Kelvin model connects the elements in parallel. The generalized Kelvin

model consists of a spring and N Voigt–Kelvin model units. The Burger model is a combination of the Maxwell and Voigt–Kelvin model units and is also called a four-element model because it consists of two springs and two dashpots (Fig. 1). In the Burger model, the spring in the Maxwell model unit represents the instantaneous elastic strain, the dashpot in the Maxwell model unit represents the permanent strain, and the Voigt–Kelvin model unit represents the delayed elastic strain.

These models have been applied to study the creep behavior of wood. Kojima and Yamamoto (2004) investigated the MFA dependence of the tensile creep behavior of cedar using a three-element model that introduces reversible elastic solicitation. They found that the parameters in the three-element model were significantly influenced by the MFA. Hering and Niemz (2012) performed bending creep tests on European beech wood at several moisture contents and applied a generalized Kelvin–Voigt model with 6 units that considered the effect of moisture content. Kawahara et al. (2015) applied a two-dimensional model to the viscoelastic Poisson effects measured by off-axis tension creep tests on cypress and Kalopanax at fiber inclination angles from 0° to 90° . The two-dimensional model they proposed represents the viscoelastic Poisson's ratios by vertically connecting two Burger models, and the theoretical viscoelastic Poisson's ratios obtained by this model showed good agreement with the measured ones. Huč and Svensson (2018) applied three two-dimensional creep models (three-element, Burger, and five-element models) to literature values of the strain–time curve for the tensile and shear creep of wood. They concluded that although all models could explain the literature values, even the simplest three-element model had small errors and was sufficient as a model of wood creep phenomena. Nguedjio et al. (2024) used the eight-parameter Kelvin–Voigt model and three fractional models to predict the non-linear bending creep behavior of sapele. The fractional models replaced the dashpot of the conventional rheological model with a spring-pot with fractional viscosity. They showed that the eight-parameter generalized Kelvin–Voigt model was inadequate for representing the experimental values, whereas fractional models better described the creep behavior of the sapele. As shown in these studies, various analyses have been conducted on creep phenomena in wood using rheological models.

The Burger model is most commonly used to model the creep behavior of wood. The Burger model represents instantaneous elastic, delayed elastic, and permanent strains

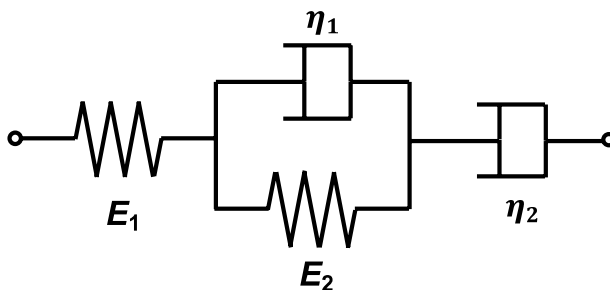


Fig. 1 Rheological Burger model combining Maxwell and Voigt–Kelvin model units

and is considered a simple model. Pot et al. (2013) performed cantilever bending tests on tensile reaction and opposite woods and showed that the bending creep behavior of green poplar wood follows the Burger model. Dong et al. (2021) demonstrated that the Burger model can be applied to the bending creep of furfurylated poplar wood. Saadallah et al. (2024) conducted bending creep tests on olive wood under three different loads and investigated the relationship between creep loads and the parameters of the Burger model. They found that the theoretical deflection–time curves from the Burger model fit the experimental ones well at all loadings tested. Wang et al. (2021) performed nanoindentation creep tests on the compound middle lamella of the wood cell wall and the middle layer of the secondary wall and showed that the Burger model is applicable to the compression creep of the cell wall. Hermawan and Fujimoto (2019) investigated the creep behavior of wood at various temperatures, and the results showed that the bending creep behavior of sugi boxed-heart wood was well fitted by the Burger model and that the instantaneous and delayed elastic creep compliance tended to increase with increasing laboratory temperature. Yildirim et al. (2020) predicted the creep behavior of oriented strand board (OSB) using the Burger model based on the property values obtained from bending tests and compared them with the measured values. They concluded that the Burger model can predict the creep behavior of OSB in the case of long-term creep. Georgiopoulos et al. (2015) applied the Burger model to a composite material containing wood fiber and discussed how the parameters of the Burger model change with stress level and temperature.

In addition, modified and improved Burger models have been proposed by changing a few parameters of the original Burger model. Hou et al. (2021) used a five-parameter model, with one parameter added to the Burger model, and obtained better fitting results than those obtained using the conventional Burger model for the bending creep of white oak wood under the assumption that the permanent strain, one of the creep strains, increased nonlinearly.

As suggested by the findings of these previous studies, the Burger model can be applied to study creep phenomena such as the bending and compression of wood. However, few studies have been conducted on shear creep. The Burger model consists of four elements including the permanent strain unit, and the physical meaning of each element is clear; hence, we believed that the model would be effective for examining the mechanism of the creep phenomena. Therefore, in this study, we applied the Burger model to study the shear creep behavior of wood. In addition, because we expected modified/improved Burger models to better match the actual measurements than the conventional Burger model, modified/improved Burger models that can explain the shear creep behavior in more detail were considered.

Experimental method

Material

In this study, off-axis compression creep tests were conducted on wood with a fiber inclination angle to induce shear stress by applying a constant compressive load. An

off-axis method (Zhang and Sliker 1991; Hayashi et al. 1993; Yoshihara and Ohta 2000; Liu 2002; Xavier et al. 2004; Mascia and Vanalli 2012; Aira et al. 2014; Jeong and Park 2016; Zhang and Yang 2017; Ando et al. 2023; Bengtsson 2023) does not require any specialized equipment or experimental techniques, nor does it impose any restrictions on the shape of the specimen.

The specimens were prepared from an air-seasoned log of 43-year-old Japanese Hinoki cypress (*Chamaecyparis obtusa*) tree collected from the Nagoya University Experimental Forest in Aichi Prefecture, Japan. The specimens were cut continuously from the pith of the log toward the bark side. A schematic of the specimen is shown in Fig. 2. The dimensions of the specimens were 60 (length) $\times$ 20 (width) $\times$ 20 mm (thickness), and the specimen was prepared such that the angle of fiber inclination with respect to the loading direction was 15° in the tangential (T) longitudinal (L) plane. Under this condition, the shear stress (τ) and shear strain (γ) were measured as τ_{TL} and γ_{TL} , where the first subscript represents the normal direction of the shear plane and the second represents the shear direction, respectively. For the off-axis testing of wood, a fiber inclination of 15° has been reported to be optimal based on finite element analyses and experiments (Yoshihara and Ohta 2000; Liu 2002; Xavier et al. 2004).

A triaxial rosette strain gauge (FRA-5-11; gauge length, 5 mm; Tokyo Sokki Kenkyujo) was attached to the center of both wide faces of the specimen. Here, the longitudinal strain, 45° strain, and transverse strain were defined as ϵ_A , ϵ_B , and ϵ_C , respectively. The average number of annual rings on the surface of the specimen, as counted from the pith, was defined as the annual ring number of the specimen. A total of 15 specimens were prepared for the static tests to determine

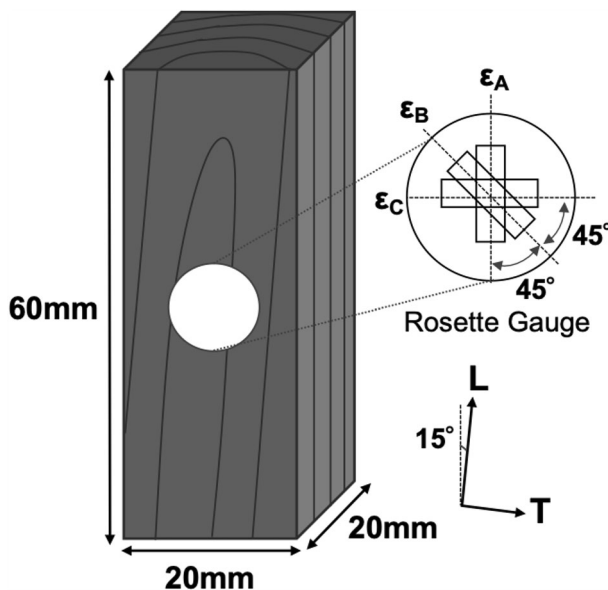


Fig. 2 Schematic of the off-axis test specimen. A three-axis rosette gauge was attached on each side of the wide faces

the compressive strength, and 50 specimens were prepared for the creep tests. The specimens were stored under a constant temperature and humidity of 25 °C and 55% relative humidity (RH) until the moisture content (MC) reached equilibrium. The average density and MC were $478 \pm 32 \text{ kg/m}^3$ and $10.5 \pm 0.6\%$, respectively.

Off-axis compression creep test

A universal testing machine (Shimadzu AG-X100 kN) was used. Figure 3 shows the general view of the off-axis compression creep test setup. Compressive strength was determined by the static compression test. Wood exhibits linear viscoelasticity up to loads of 50% of its compressive strength (Kuwamura 2012). The compressive creep stress applied to the specimens in this study was set to 8.75 MPa, which corresponds to approximately 45% of the compressive strength. A constant load was maintained for 12 h from the start of the creep tests. A temperature of 25 °C and 55% RH were maintained during the tests.

Shear stress τ_{TL} and shear strain $\gamma_{\text{TL}}(t)$ were calculated using Eqs. 1 and 2, respectively (Greszczuk 1966; Zhang and Sliker 1991), as follows:

$$\tau_{\text{TL}} = \sigma \cdot \sin\alpha\cos\alpha, \quad (1)$$

$$\gamma_{\text{TL}}(t) = 2\varepsilon_{\text{A}} \cdot \sin\alpha\cos\alpha - 2\varepsilon_{\text{c}} \cdot \sin\alpha\cos\alpha + (2\varepsilon_{\text{B}} - \varepsilon_{\text{A}} - \varepsilon_{\text{c}})(\cos^2\alpha - \sin^2\alpha), \quad (2)$$

where α is the fiber inclination angle (15°) and σ is the uniaxial compressive stress in the load direction. The apparent shear modulus $G_{\text{TL}}(t)$ was calculated using Eqs. 1 and 2 as follows:

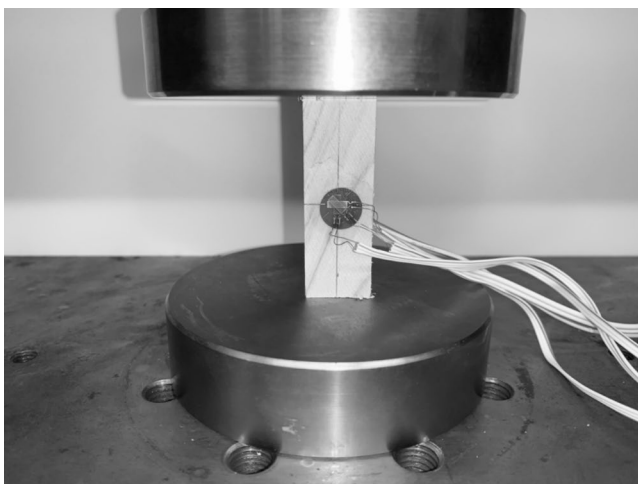


Fig. 3 General view of the off-axis compression creep test setup

$$G_{TL}(t) = \frac{\tau_{TL}}{\gamma_{TL}(t)}. \quad (3)$$

The creep compliance $J_{TL}(t)$ expressed in Eq. 4 was used to analyze the creep behavior as follows:

$$J_{TL}(t) = \frac{1}{G_{TL}(t)}. \quad (4)$$

In addition, the relative creep (*RC*) (e.g., Armstrong and Kingston 1960) was defined as an index to evaluate the creep properties as follows:

$$RC = \frac{J_{TL}(t=12)}{J_{TL}(t=0)} \times 100(\%), \quad (5)$$

where $J_{TL}(t = 0)$ is the creep compliance at the start of the creep test and $J_{TL}(t = 12)$ is the creep compliance after 12 h.

Results and discussion

Transition of creep strain and creep compliance

Strain in three directions measured using the compressive creep test (longitudinal strain ϵ_A , 45° strain ϵ_B , and transverse strain ϵ_C) and shear strain calculated using Eq. 2 are shown in Fig. 4. A typical example of the change in creep compliance over time is shown in Fig. 5. The creep compliance tended to increase logarithmically with time and then gradually plateaued. This trend was similar to previous reports on the shear creep of wood (Hayashi et al. 1993; Ando et al. 2023; Bengtsson et al. 2023).

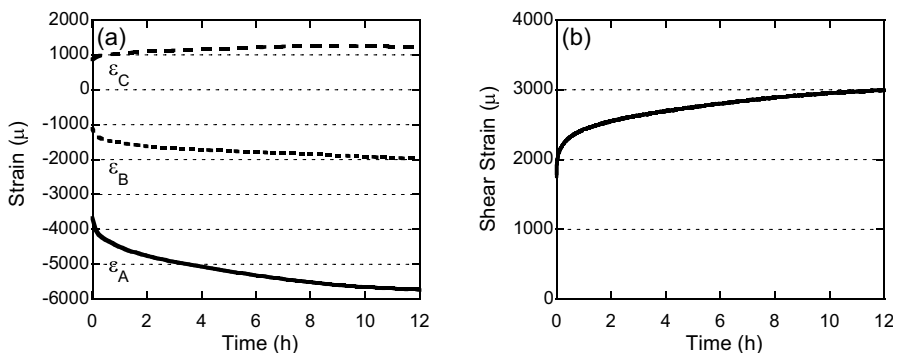
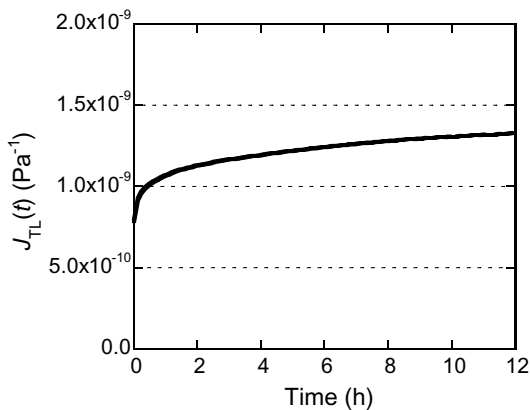


Fig. 4 **a** Typical transition of the compression creep strain in each direction: longitudinal strain ϵ_A , 45° strain ϵ_B , and transverse strain ϵ_C **b** Typical transition of the shear creep strain calculated using Eq. 2 (annual ring number 2)

Fig. 5 Typical creep compliance curve (annual ring number 13)



Radial distribution of shear properties within a stem

The shear modulus [$G_{TL}(0)$] and RC were used as indices to evaluate the distribution of shear properties within a stem. $G_{TL}(0)$ was calculated using Eq. 3 immediately after starting the creep test. The averages of the $G_{TL}(0)$ and RC were 1.45 ± 0.25 GPa and $135 \pm 21\%$, respectively. The radial (R) distributions of the shear modulus and RC are shown in Fig. 6. Schniewind and Barrett (1972) determined the RC of wood in shear using the plate-shear method, reporting an RC of 112.8% (Douglas-fir, TL plane, after 1000 min), whereas Hayashi et al. (1993) applied the off-axis tensile method (with an off-axis angle of 12.2°), reporting an RC of 130% (Norway spruce, RL plane, after 24 h). The average RC value obtained in this study was higher than those reported in these previous studies.

No differences by location in the radial position within the stem in terms of $G_{TL}(0)$ and RC were observed. Ando et al. (2023) investigated the distribution of shear creep properties within a stem in Japanese Sugi cedar using off-axis tensile creep tests and found that $G_{TL}(0)$ and RC decreased with increasing annual ring

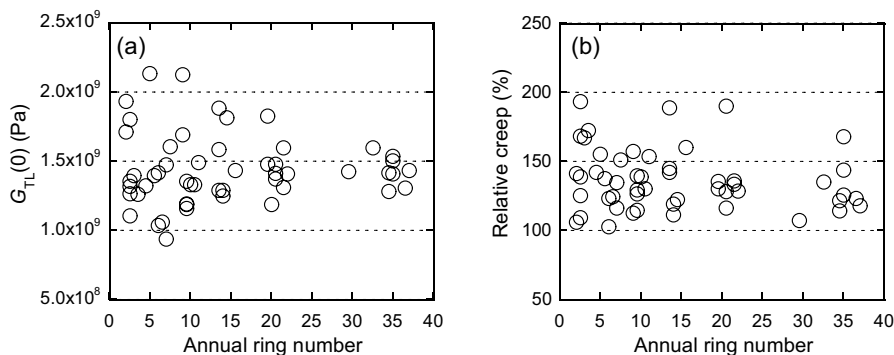


Fig. 6 Distribution of **a** shear modulus [$G_{TL}(0)$] and **b** RC along the radial direction within a stem

number. The differences between the results of this study and those of the previous study may be attributed to the differences in tree species or loading methods (tension and compression).

Analysis of the creep compliance curve using the Burger model

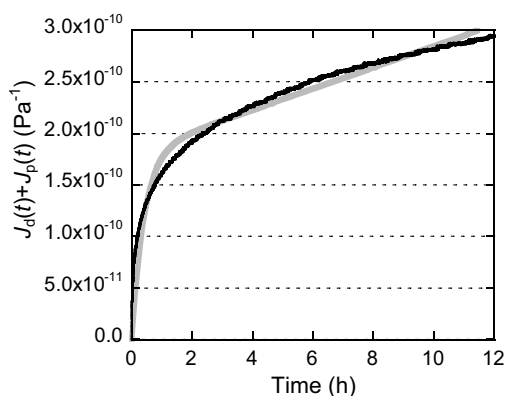
The Burger model (Fig. 1) is often used to describe creep phenomena in wood. To verify whether the Burger model also applies to shear creep, shear creep compliance curves obtained from off-axis compression creep tests were analyzed. In the Burger model, the creep compliance $J_{TL}(t)$ can be divided into three creep compliance units: $J_e(t)$ derived from the instantaneous elastic strain, $J_d(t)$ derived from the delayed elastic strain, and $J_p(t)$ derived from the permanent strain (Eq. 6).

$$J_{TL}(t) = J_e(t) + J_d(t) + J_p(t) = \frac{1}{E_1} + \frac{1}{E_2} \left(1 - e^{\frac{-E_2 t}{\eta_1}} \right) + \frac{t}{\eta_2}, \quad (6)$$

where E_1 and E_2 are the moduli of elasticity of the springs, η_1 and η_2 are the viscosities of the dashpots, and t is the time (h). In this study, we focused on the viscoelastic properties of wood and analyzed the behavior of $J_d(t) + J_p(t)$. Figure 7 shows a typical example of the results of fitting the Burger model using Eq. 6. Overall, 43 of the 50 specimens tested for creep were fitted with the theoretical equation of the Burger model within a tolerance error (allowable error) of 0.1%, and the average value of the coefficient of determination R^2 for the 43 specimens was 0.940 ± 0.061 . The theoretical values of the Burger model were in good agreement with the measured values, indicating that the Burger model is applicable to the shear creep behavior observed in this study. The Burger model is reported to be applicable to bending creep (Pot et al. 2013; Dong et al. 2021; Hermawan and Fujimoto 2019; Saadallah et al. 2024) and compressive creep (Wang et al. 2021) phenomena in wood, and we believe that the Burger model can explain creep phenomena of wood generally.

However, large discrepancies were observed between the theoretical and measured values for both the initial and late parts of the creep curve. For most specimens, the measured values exhibited a curvilinear increase in the latter part of

Fig. 7 Typical example of the creep compliance curve. Black line: measured values and gray line: theoretical values (Burger model Eq. 6; annual ring number 10)



the curve. By contrast, in the Burger model, the viscosity of the dashpot η_2 , which represents the permanent strain, was a constant value, and the unit connecting η_1 and E_2 (Voigt–Kelvin unit), which represents the delayed elastic strain, reached equilibrium at some point such that there was a linear increase in the latter part of the theoretical creep curve. In this study, we focused on the early and late shear creep behaviors that the Burger model cannot represent and analyzed other models that explain the creep compliance curve more accurately.

Proposal and validation of models that include dashpots with time-dependent changes in viscosity

As mentioned above, the measured creep compliance curves behaved in such a manner that the dashpot was a non-Newtonian (not proportional to time) type; thus, models 1–3 with non-Newtonian dashpots were proposed. As shown in Fig. 8, the shaded dashpot is non-Newtonian; in model 1, only the permanent strain dashpot is non-Newtonian; in model 2, the dashpots in the delayed elastic strain and permanent strain units are non-Newtonian; and, in model 3, only the dashpot in the delayed elastic strain unit is non-Newtonian. In this study, the time-dependent apparent viscosity is defined as

$$\eta_a(t) = K_i(t+1)^{n_i} (i = 1, 2), \quad (7)$$

where K_i is a proportional constant.

Using Eq. 7, the creep compliance related to viscoelasticity for models 1–3 is expressed in Eqs. 9–11. Equations 8–11 are the equations for the Burger model and models 1, 2, and 3, respectively, where the first item on the right side is the creep compliance $J_d(t)$ derived from the delayed elastic strain, and the second item is the creep compliance $J_p(t)$ derived from the permanent strain.

$$J_d(t) + J_p(t) = \frac{1}{E_2} \left(1 - e^{\frac{-E_2 t}{\eta_1}} \right) + \frac{t}{\eta_2} \text{ (Burger model)}, \quad (8)$$

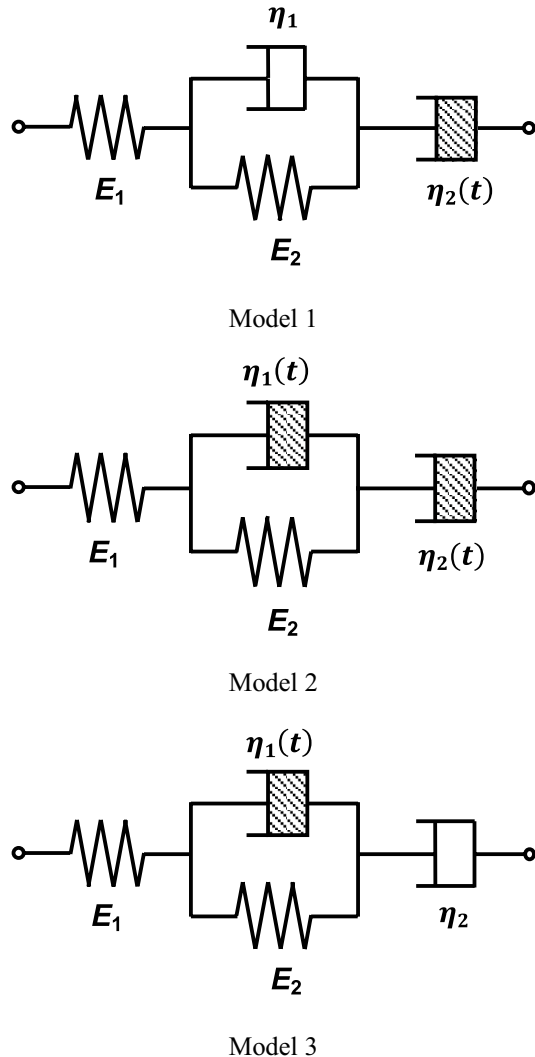
$$J_d(t) + J_p(t) = \frac{1}{E_2} \left(1 - e^{\frac{-E_2 t}{\eta_1}} \right) + \frac{t}{K_2(t+1)^{n_2}} \text{ (model 1)}, \quad (9)$$

$$J_d(t) + J_p(t) = \frac{1}{E_2} \left(1 - e^{\frac{-E_2 t}{K_1(t+1)^{n_1}}} \right) + \frac{t}{K_2(t+1)^{n_2}} \text{ (model 2)}, \quad (10)$$

$$J_d(t) + J_p(t) = \frac{1}{E_2} \left(1 - e^{\frac{-E_2 t}{K_1(t+1)^{n_1}}} \right) + \frac{t}{\eta_2} \text{ (model 3)}. \quad (11)$$

A representative example of the fitting results for models 1–3 is shown in Fig. 9. The average values of the coefficients of determination for models 1 and 2 were 0.979 ± 0.034 and 0.978 ± 0.024 , respectively; hence, models 1 and 2 explained the measured values with very high accuracy, including both the initial and late parts of

Fig. 8 Models with non-Newtonian dashpots. The shaded dashpots are non-Newtonian



the creep curve. By contrast, the average value of the coefficient of determination for model 3 was 0.889 ± 0.132 , indicating that model 3 resulted in a slightly less accurate fitting than models 1 and 2. Furthermore, because wood is a biological material, the creep compliance curves exhibited various behaviors depending on the specimen, and we believe that being able to explain them in general is also an important aspect of modeling. The number of specimens that could be fitted with a tolerance error of 0.1% was 45 for model 1, 25 for model 2, and 45 for model 3. In other words, although model 2 had a large coefficient of determination, several specimens could not be explained by model 2.

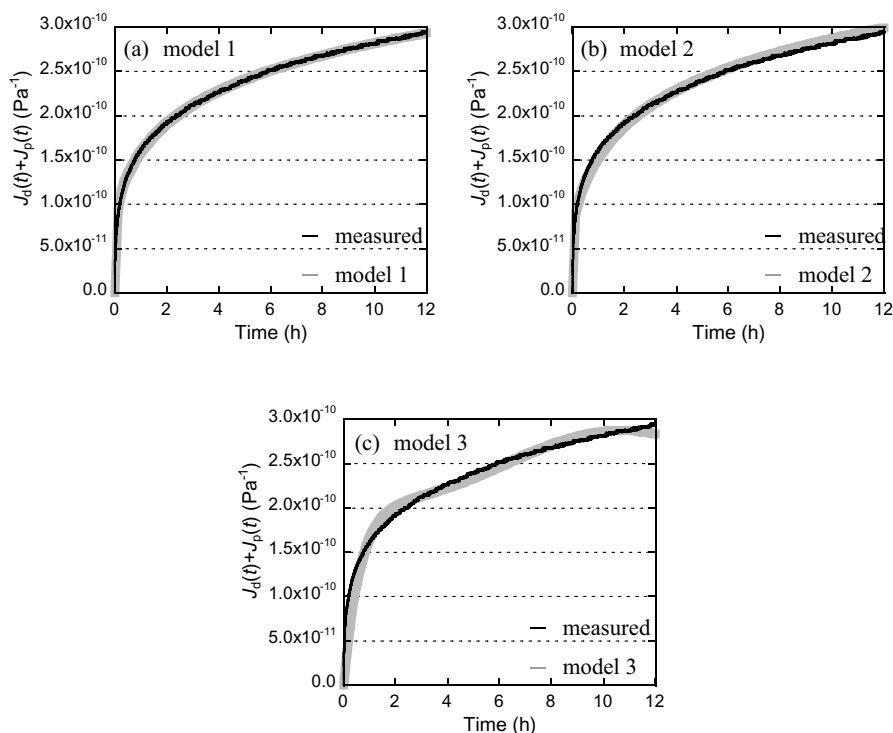


Fig. 9 Typical example of a creep compliance curve. Black line: measured values and gray line: theoretical values. Fitting by **a** model 1, **b** model 2, and **c** model 3 (annual ring number 10)

The fitting curve of $J_{TL}(t)$ was then divided into $J_d(t)$ and $J_p(t)$, and their respective behaviors were examined. Figures 10, 11, 12, and 13 show the results of the Burger model and models 1, 2, and 3, respectively. For models 1 and 2, a figure detailing the analysis values for up to 1 h is also included. Although the delayed elastic strain, by definition, increases with time and then saturates, the delayed elastic strain behavior of model 3 was inconsistent with the definition [Fig. 13a]. Therefore, model 3 is not an appropriate model to study creep behavior.

Based on these considerations, we concluded that model 1 best explained the measured values satisfactorily. Hou et al. (2021) used a five-parameter model, with one parameter added to the Burger model, and obtained better fitting results than those obtained using the conventional Burger model for the bending creep of white oak wood. In their five-parameter model, the viscosity of the dashpot in the permanent strain unit was time-dependent similar to model 1 proposed herein. Bengtsson et al. (2023) applied a three-element model without a permanent strain unit to the shear creep behavior of Norway spruce. They conducted off-axis compression creep tests in the LT plane of five specimens and determined the model parameters. Furthermore, they calculated (in Voigt–Kelvin) the average

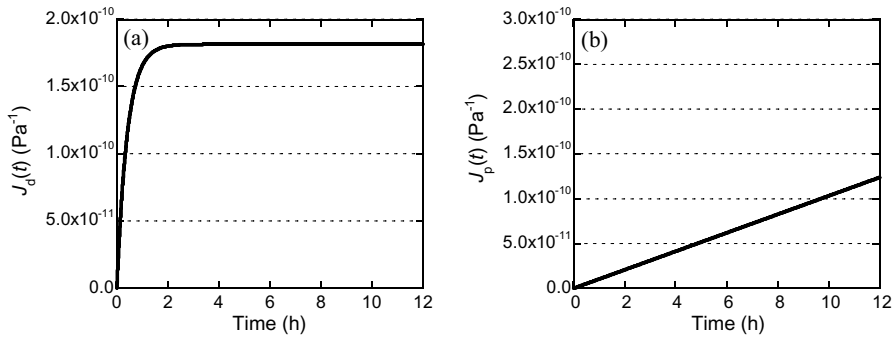


Fig. 10 Typical example of a theoretical creep compliance curve by the Burger model, which is divided into a **a** curve derived from the delayed elastic strain and **b** curve derived from permanent strain (annual ring number 10)

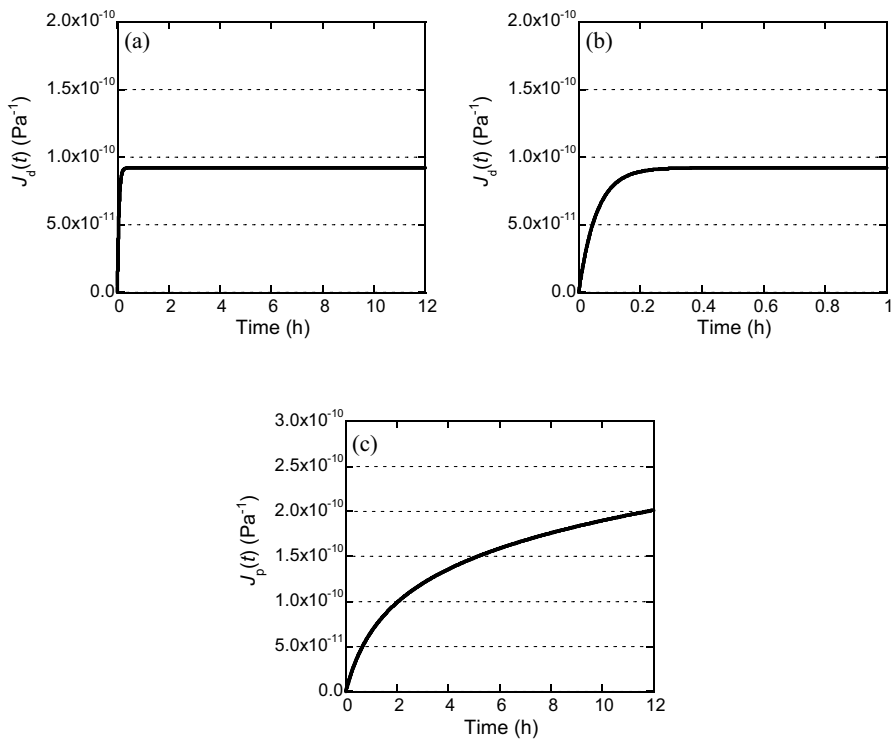


Fig. 11 Typical example of a theoretical creep compliance curve by model 1, which is divided into a curve derived from the delayed elastic strain [**a** for up to 12 h and **b** 1 h] and **c** a curve derived from permanent strain (annual ring number 10)

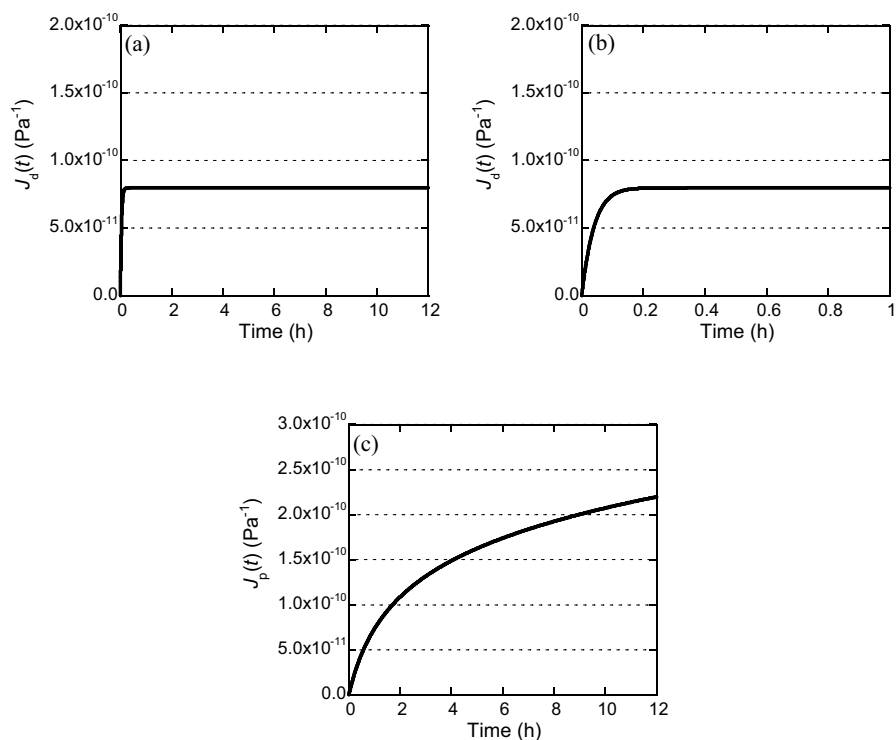


Fig. 12 Typical example of a theoretical creep compliance curve by model 2, which is divided into a curve derived from the delayed elastic strain [a up to 12 h and b 1 h] and c a curve derived from permanent strain (annual ring number 10)

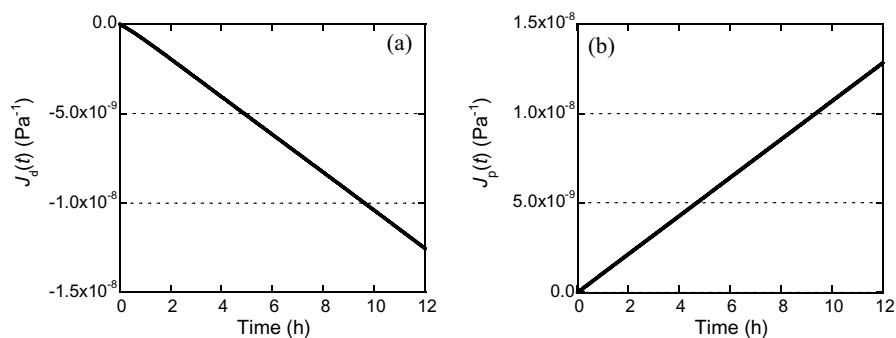


Fig. 13 Typical example of a theoretical creep compliance curve by model 3, which is divided into a a curve derived from the delayed elastic strain and b curve derived from permanent strain (annual ring number 10)

modulus of elasticity of the spring to be 11.56 GPa and the average viscosity of the dashpot to be 103 GPa•h. On the other hand, the mean values of E_2 and η_1 for model 1 in the present study were 19.85 GPa and 1.30 GPa•h, respectively (see supplementary information file). Thus, E_2 was comparable to the literature value, whereas η_1 differed significantly from the literature value. This difference can be attributed to the presence or absence of a permanent strain unit in the rheological model. Note that there are few examples to determine material parameters in the rheological model for the shear creep phenomena in wood, and further research is needed to discuss these values.

In addition, a comparison was performed between model 1, which was concluded to be the most appropriate, and the conventional Burger model. The results demonstrated differences in the permanent strain behavior and the ratio of the delayed elastic strain to permanent strain between the models. The ratios of J_d ($t = 12$) to J_p ($t = 12$) shown in Figs. 10 and 11 were approximately 1.5 for the Burger model and approximately 0.5 for model 1, respectively. The time at which the delayed elastic strain became saturated also differed between the two models. The delayed elastic strain saturated at approximately 3 h for the Burger model [Fig. 10a] and at less than 1 h for model 1 [Fig. 11b]. These differences are attributed to the material parameters.

Conclusion

The Burger model is a mechanical model commonly applied to study the wood creep phenomena. However, there are only a few examples of its application to evaluate the shear creep of wood. The Burger model is practically applicable to study the shear creep behavior of wood, as evident in this study. However, some behaviors are not explained by the Burger model. Therefore, in this study, three models (modified Burger models) with non-Newtonian dashpots were proposed to explain the measured data more accurately: model 1, in which only the dashpot in the permanent strain unit is non-Newtonian; model 2, in which both dashpots are non-Newtonian; and model 3, in which only the dashpot in the delayed elastic strain unit is non-Newtonian. The results showed that the average values of the coefficients of determination for models 1 and 2 were 0.979 ± 0.034 and 0.978 ± 0.024 , respectively. This indicated that models 1 and 2 could explain the measured values with high accuracy. Furthermore, the average value of the coefficient of determination for model 3 was 0.889 ± 0.132 , and the delayed elastic strain behavior of model 3 was inconsistent with the definition. Considering these findings, we concluded that model 1 is the most appropriate to study the shear creep behavior of wood from two perspectives. First, model 1 represents the measured values well, and second, it can be applied to a larger number of specimens.

The validity of the elastic and viscous moduli of each element (spring and dashpot) needs to be examined in the future. The structural factors at the micro- and macro-levels responsible for each parameter also need to be considered.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00226-024-01578-7>.

Author contributions All authors designed the experiments. K. Shimazaki performed the experiments. All authors contributed to the interpretation and discussion results and to the reading and approval of the final manuscript.

Funding Open Access funding provided by Nagoya University.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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