

Analysis of shear creep behaviors of hardwood and softwood using creep recovery curves

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Abstract

This study was aimed at exploring the shear creep behavior of wood through off-axis tensile creep and creep recovery tests. Using the creep recovery data, the shear creep properties of softwood (Japanese Hinoki cypress, *Chamaecyparis obtusa*) and hardwood (Japanese Buna beech, *Fagus crenata*) were compared.

The trends of three components of strain, i.e., instantaneous elastic, delayed elastic, and permanent strains, during shear creep were predicted by decomposing the total strain during creep recovery, assuming that the rate of increase in delayed elastic strain is the same as the recovery rate during creep recovery. Fitting a Burger model to each predicted strain yielded more reliable material parameters compared with those obtained by simply mathematically fitting the Burger model to the total creep strain. The Burger model demonstrated excellent accuracy in fitting the measured creep curves of hardwood. However, it could not explain the shear creep behavior of softwood.

This discrepancy in the fitting results was attributable to the differences in the behavior of permanent strain: The permanent strain of cypress exhibited a curvilinear trend, while that of beech displayed a more linear trend. To explain the curvilinear behavior of permanent strain, a modified Burger model, which assumes that the apparent viscosity of permanent strain changes in a strain-rate-dependent manner, was proposed. The modified Burger model yielded better fitting results than the conventional Burger model, suggesting that the viscous component of wood exhibits an apparent viscosity that depends on the strain rate rather than a constant value, as assumed in the conventional Burger model.

Introduction

Wood, a viscoelastic material, exhibits elastic behavior under short-term loads but viscoelastic behavior under long-term loads. Historically, wood has been widely used as a structural support material for buildings and has recently garnered significant attention as a sustainable material. With the increasing application of wood in non-residential and mid- to high-rise buildings, wood is anticipated to be subjected to complex stress states.

In particular, creep, the increase in strain over time under constant stress, considerably affects the long-term performance of wood. Although numerous studies have been conducted on creep in wood (Holzer et al. 1989; Navi and Stanzl-Tschegg 2009), most of them have been focused on creep in bending, compression, and tension, and research on creep in shear modes remains limited. Under complex loading conditions, shear stresses occur in addition to vertical stresses such as compression and tension. Thus, for advanced applications of wood, the viscoelastic properties under shear conditions must be examined. Notably, most of the research in this domain has been limited to the observation of creep strain and compliance (Schniewind and Barrett 1972; Hayashi et al. 1993; Akter et al. 2023), with few addressing the underlying mechanisms (Ando et al. 2023; Bengtsson et al. 2023; Shimazaki and Ando 2024).

Creep tests combined with creep recovery tests have been widely used to experimentally investigate creep phenomena in wood. For example, Zhang et al. (2006) investigated the effect of delignification on mechano-sorptive creep in cypress specimens by combining a moisture content cycle with bending creep and creep recovery tests. The authors observed that the deflection induced by creep in the untreated samples was nearly recovered during the recovery phase, whereas the delignified samples showed reduced recovery. Entwistle and Zadoroshnj (2008) conducted two cycles of torsional creep and creep recovery tests on radiata pine specimens under relative humidity (RH) levels of 38% and 84%. The authors reported that the creep strain recovered almost entirely after two loading cycles in both humidity conditions. Englund and Salmén (2012) conducted tensile creep and creep recovery tests on sliced sections of Norway spruce for 90 min each. The authors discussed the differences in strain behavior observed during creep and creep recovery in terms of differences in reactions of cell wall and middle lamellas. Kutnar et al. (2021) conducted bending creep (60 min) and creep recovery (180 min) tests on thermo-hydro-mechanical (THM)-treated European beech under three RH conditions. The authors reported that recovery compliance was influenced by RH level and THM treatment, while relaxation recovery (amount of deformation recovered after load release) was influenced only by THM treatment. Ella et al. (2024) explored the effects of viscoelastic and mechano-sorptive creep on flexural creep of three wood species under two test configurations: 11-d creep and 3-d creep recovery test and 5-d creep and 1-d creep recovery test. The instantaneous recovery strain in the recovery tests was similar to the instantaneous elastic strain at the start of the creep tests, and a “memory effect” was observed.

As discussed, most studies involving creep recovery tests have focused on the effects of temperature and humidity and primarily analyzed an amount of recovery strain. A few researchers have examined the viscoelasticity of wood by analyzing the creep recovery curves in detail. For example, Hanhijärvi and Hunt (1998) conducted bending creep and creep recovery tests on Baltic redwood under multiple loading cycles to investigate the relationship between viscoelastic creep and mechano-sorptive creep. The authors calculated the relative residual deflection (rate of deflection divided by the deflection value just before unloading) from the creep recovery test data and reported that the recovery rate was lower in the cyclic-humidity period compared with that in a constant-humidity period of the same duration. Roszyk et al. (2010) conducted tensile creep and creep recovery tests on pine wood slices and investigated the relationship between the proportions of the three strain components in the total strain and the microfibril angle (MFA). The authors reported that for larger MFAs, the contributions of instantaneous elastic recovery strain and permanent strain to the total strain were smaller and larger, respectively, while the contribution of delayed elastic strain was independent of MFA. Sala et al. (2022) conducted one-hour creep and one-hour creep recovery tests to compare the shear creep behavior of balsa wood panel, paper honeycomb, and recycled polyethylene terephthalate. From the recovery data, the residual shear strain and time-delayed strain during the recovery stage of each material were extracted. Taniguchi and Ando (2010) conducted tensile creep and creep recovery tests on 12 wood species for 24 h each and analyzed the recovery data to decompose the total creep strain into three components, i.e., instantaneous elastic, delayed elastic, and permanent strains. The observed increase in viscoelastic

Poisson’s ratio during creep tests was attributable to the rising contribution of permanent strain over time.

This literature review highlights that only a few researchers have comprehensively analyzed strain data during creep recovery. Notably, the elastic and viscous components of creep strain can be extracted from such data, facilitating exploration of the mechanisms of creep phenomena in wood. Considering these aspects, this study was aimed at investigating the shear creep phenomena of wood, using the method for creep recovery data analysis proposed by Taniguchi and Ando (2010). To examine the relationship between microstructural factors and shear creep, the differences in shear creep behaviors of cypress (softwood) and beech (hardwood), two wood species with different microstructures, were compared through creep and creep recovery tests.

Experiment Details

Materials

Air-seasoned Japanese Hinoki cypress (*Chamaecyparis obtusa* Endl.) and Japanese Buna beech (*Fagus crenata* Blume) were sourced from the Nagoya University Experiment Forest in Aichi Prefecture, Japan. Reaction wood was not detected in any of the specimens. Each tensile test specimen measured 160 mm (length) × 20 mm (width) × 6 mm (thickness), and the fiber inclination with respect to the loading direction was 15° in the longitudinal-tangential (LT) plane. The grip length was 40 mm, and the central part, excluding the grip area, had a length of 80 mm (Fig. 1). A triaxial rosette strain gage (Tokyo Measuring Instruments Lab. FRAB-5-11, gage length 5 mm) was attached to the center of each wide face of the specimen. The longitudinal strain, 45° directional strain, and transverse strain were denoted by ϵ_A , ϵ_B , and ϵ_C , respectively. The specimens were conditioned at a constant temperature of 25°C and RH of 55% until moisture equilibrium was attained. Table 1 lists the number of specimens, density, average annual ring width, and moisture content.

Table 1
Specifications of test specimens

	Number of specimens	Density (kg/m ³)	Average annual ring width (mm)	Moisture content (%)
Japanese cypress	21	448±26	2.8±1.4	9.3±0.3
Japanese beech	15	721±34	2.0±0.5	8.7±0.1

Off-axis tensile creep tests

Off-axis tensile creep tests were conducted on wood samples with a fiber inclination angle (to induce shear stress) by applying a constant tensile load using a universal testing machine (Shimadzu AG-X100

kN). Prior experiments and finite element analyses (Yoshihara and Ohta 2000; Liu 2002; Xavier et al. 2004) have identified a fiber inclination of 15° as optimal for analyzing the shear behavior of wood in off-axis tests. The tensile strength was determined through static tensile tests, and the applied tensile creep stress corresponded to approximately 45% of the tensile strength: 16 MPa for cypress and 27 MPa for beech. Each test involved an 8-h creep period under constant load followed by an 8-h creep recovery phase. Both tests were conducted at a temperature of 25 °C and RH of 55%. Figure 2 illustrates the setup for the tensile creep and creep recovery tests. The shear stress and shear strain were computed using Eqs. 1 and 2, respectively (Greszczuk 1966; Zhang and Sliker 1991).

$$\tau_{TL} = \sigma \bullet \sin\alpha \cos\alpha \# (1)$$

$$\gamma_{TL}(t) = 2\epsilon_A \bullet \sin\alpha \cos\alpha - 2\epsilon_C \bullet \sin\alpha \cos\alpha + (2\epsilon_B - \epsilon_A - \epsilon_C)(\cos^2\alpha - \sin^2\alpha) \# (2)$$

where α is the fiber inclination angle (15 °), and σ is the uniaxial tensile stress in the loading direction.

Results and Discussion

Transition of creep strain

Figure 3 shows the measured strains in three directions (longitudinal strain ϵ_A , 45 ° directional strain ϵ_B , and transverse strain ϵ_C) during the off-axis tensile creep and creep recovery tests. From 0–8 h, the absolute values of strain in the three directions exhibited a logarithmic increase or flat transition. Notably, the transverse strain ϵ_C showed both positive (negative Poisson's ratio) and negative values (positive Poisson's ratio). These outcomes are discussed in a later section.

Figure 4 shows a representative example of the shear strain $\gamma_{TL}(t)$ calculated using Eq. 2. Shear creep strain increased logarithmically during loading, with instantaneous recovery upon unloading, followed by gradual recovery and convergence. These observations are consistent with previous reports on the shear creep behavior of wood (Hayashi et al. 1993; Ando et al. 2023; Bengtsson et al. 2023; Shimazaki and Ando 2024).

Decomposition of creep strain using creep recovery data and Burger model

Creep strain consists of three components: instantaneous elastic strain (γ_e), delayed elastic strain [$\gamma_d(t)$], and permanent strain [$\gamma_p(t)$]. Instantaneous elastic strain occurs instantaneously upon loading and recovers instantaneously upon unloading. Delayed elastic strain develops progressively after loading and gradually recovers upon unloading. Permanent strain develops upon loading and does not recover upon unloading. Assuming that the delayed elastic strain recovers at the same rate as it develops, the shear creep strain can be decomposed into its three components using the creep recovery

curve (Taniguchi and Ando 2010). Strain decomposition involves the following steps (Fig. 5): The strain appearing immediately after loading is the instantaneous elastic strain (γ_e), which is identical to the recovery strain observed instantaneously upon unloading. Thus, the area on the left side of the diagram can be transferred to the right side (Fig. 5a). The strain gradually recovered after unloading corresponds to delayed elastic strain (γ_d) (Fig. 5b). The area is inverted vertically and transferred to the left side (creep period), and the remaining area is classified as permanent strain (γ_p) (Fig. 5c). In this study, this decomposition technique was used to investigate the behavior of delayed elastic strain and permanent strain during shear creep.

Figure 6 shows the typical transitions of the delayed elastic [$\gamma_d(t)$] and permanent [$\gamma_p(t)$] strains, predicted using the graphical decomposition method (Fig. 5). The delayed elastic strain $\gamma_d(t)$ generally reached saturation after 6–8 h, whereas $\gamma_p(t)$ exhibited a curvilinear trend rather than a linear trend for both wood species.

The Burger model (four-element model, Fig. 7) is often used to analyze creep phenomena in wood. It has been reported that the Burger model can be applied to compression and bending creep phenomena in wood (Pot et al. 2013; Georgiopoulos et al. 2015; Hermawan and Fujimoto 2019; Yildirim et al. 2020; Dong et al. 2021; Wang et al. 2021; Saadallah et al. 2024). However, few studies on shear creep have used the Burger model or other rheological models in their analyses (Bengtsson et al. 2023; Shimazaki and Ando 2024). By fitting the theoretical equation of the Burger model (Eq. 3) to the total measured creep strain, the elastic moduli of a spring (E_1, E_2) and viscosities of a dashpot (η_1, η_2) can be determined. In previous studies (Shimazaki and Ando 2024), these parameters were computed solely from creep data and were only mathematical estimates. Thus, in this study, the theoretical equations of the components of the Burger model (Eqs. 4 and 5) were fitted to each of the delayed elastic strain and permanent strain transitions estimated using the measured creep recovery curve to determine the elastic moduli of the spring and viscosities of the dashpot in the Burger model.

$$\gamma_e + \gamma_d(t) + \gamma_p(t) = \frac{\tau_{TL}}{E_1} + \frac{\tau_{TL}}{E_2} \left(1 - e^{-\frac{E_2 t}{\eta_1}} \right) + \frac{t}{\eta_2} \tau_{TL} \# (3)$$

$$\gamma_d(t) = \frac{\tau_{TL}}{E_2} \left(1 - e^{-\frac{E_2 t}{\eta_1}} \right) \# (4)$$

$$\gamma_p(t) = \frac{t}{\eta_2} \tau_{TL} \# (5)$$

We hypothesize that decomposing the creep strain into the delayed elastic strain and permanent strain components using the graphical decomposition method (Fig. 5) can enable more reliable application of the Burger model. Table 2 lists the resulting parameters for the Burger model. The elastic modulus associated with shear modulus (E_1), which determines the instantaneous elastic strain, was similar for cypress and beech. However, the parameters constituting the delayed elastic strain (E_2, η_1) were smaller for beech than for cypress. In contrast, the viscosity of the permanent strain (η_2) was larger for

beech than for cypress. The coefficient of determination (R^2) indicated that although the Burger model could accurately explain the measured values for beech, it was less effective for cypress.

Table 2
Parameters of the Burger model

	E_1 (GPa)	E_2 (GPa)	η_1 (GPa•h)	η_2 (GPa•h)	R^2
Japanese cypress	0.96 ± 0.14	9.49 ± 3.26	9.63 ± 9.84	41.2 ± 13.0	0.66 ± 0.24
Japanese beech	1.23 ± 0.52	5.80 ± 2.99	2.77 ± 1.07	74.1 ± 27.9	0.92 ± 0.05

Differences between shear creep behaviors of cypress and beech

Elastic behavior: Poisson's ratio at the start of the creep test

As discussed in the “Transition of creep strain” section, the transverse strain (ϵ_C) exhibited both positive and negative values. The Poisson's ratio at the start of the test ($t = 0$ h) was calculated using Eq. 6 to compare the transverse strain behaviors.

$$\nu = -\frac{\epsilon_C(t=0)}{\epsilon_A(t=0)} \quad \# (6)$$

Figure 8 shows the Poisson's ratios at the start of the test. The mean value of ν for cypress was -0.052 ± 0.192 , with nine specimens showing positive values and 12 specimens exhibiting negative values. The mean value of ν for beech was 0.290 ± 0.069 , with all specimens showing a positive value.

Although negative Poisson's ratios in small wood specimens with fiber inclination have been reported previously (Hearmon 1948; Yamai 1957; Sliker and Yu 1993; Bucur and Najafi 2003; Murata and Tanahashi 2010; Kawahara et al. 2015; Marmier et al. 2018, 2023), the underlying mechanism remains unclear. The histological structural differences between cypress and beech primarily pertain to the organization of ray and axial cells. Japanese cypress is composed primarily (over 90%) of tracheids with only uniseriate rays. In contrast, Japanese beech has vessel elements with large diameters and broad rays. In addition, the proportion of rays present in beech is greater than that in cypress. These differences in tissue structure likely contribute to the differences in Poisson's ratios.

Viscoelastic behavior: delayed elastic and permanent strains behavior

Figure 6 presents typical examples of delayed elastic strain and permanent strain behaviors, derived from the graphical decomposition of the creep recovery curve. The permanent strain [$\gamma_p(t)$] generally increased in a curvilinear manner, but many beech specimens exhibited a nearly linear behavior. This trend is quantitatively examined in a subsequent section. Two differences were observed between cypress and beech, in terms of the (i) proportions of delayed elastic strain and permanent strain in the total creep strain and (ii) behavior of permanent strain.

For cypress, the permanent strain was slightly greater than the delayed elastic strain in many specimens. Conversely, for beech, the delayed elastic strain was predominant. Figure 9 shows the ratio of permanent strain to delayed elastic strain at the end of the creep test [$\frac{\gamma_p(8)}{\gamma_d(8)}$]. The average values of $\frac{\gamma_p(8)}{\gamma_d(8)}$ were 1.54 ± 0.92 for cypress and 0.56 ± 0.32 for beech, with a statistically significant difference at the 0.1% level (t -test $p = .0005$). This difference was further corroborated by the Burger model parameters (Table 2). For cypress, the value of $\frac{\eta_1}{\eta_2}$ was 0.234, whereas for beech, it was 0.037, indicating that beech had a larger viscosity η_2 of the permanent strain unit compared with η_1 of the delayed elastic strain unit. Furthermore, $\frac{E_2}{E_1}$ was 9.89 for cypress and 4.72 for beech, indicating that the modulus of elasticity E_2 of the delayed elastic strain unit was smaller for beech than for cypress. These differences in material constants imply that the delayed elastic strain is more dominant in beech than in cypress. Notably, Roszyk et al. (2010) investigated the magnitude of delayed elastic and permanent strains using creep recovery curves. Tensile creep testing of pine, a softwood species, revealed that the permanent strain was approximately 10 times the delayed elastic strain. However, it may be possible that the delayed elastic strain had not fully recovered in this case owing to the inadequate creep recovery test time (60 min).

The permanent strain displayed a curvilinear transition in cypress, whereas in beech, it transitioned in a nearly linear manner (Fig. 6). The curvilinear behavior in cypress resulted from a more rapid decrease in the permanent strain rate $\dot{\gamma}_p(t)$ over time. In the case of the nearly linear transition, the change in the strain rate over time was small. To quantitatively assess the permanent strain rate transition, a regression analysis for the creep period was performed using Eq. 7.

$$\dot{\gamma}_p(t) = At^{-B} + C \quad (7)$$

where A , B , and C are constants. Figure 10 presents representative regression results of the permanent strain rate trends for cypress and beech. The permanent strain rate [$\dot{\gamma}_p(t)$] decreased sharply in the early stages and then stabilized. This rapid initial decrease was more pronounced in cypress than in beech. The decrease in strain rate was evaluated using the parameter B in Eq. 7. A larger B corresponds to a greater rate of decrease. Figure 11 shows the B values during the creep test (up to 8 h) for cypress and beech. The average value of B was 0.045 ± 0.030 for cypress and 0.012 ± 0.021 for beech, with a statistically significant difference at the 1% level (t -test, $p = .001$). These findings indicate that in terms of permanent strain, cypress was characterized by a significant decrease in permanent strain rate and a

significant increase in viscosity, while beech was characterized by a near-constant viscosity and permanent strain rate. This discrepancy was also reflected in the fitting results of the Burger model. For beech, where permanent strain was assumed to increase linearly, the Burger model provided a highly accurate fit, as indicated by the coefficient of determination (Table 2). However, for cypress, where the permanent strain exhibited curvilinear increase, the fitting results of the Burger model were not as accurate. These findings suggest that the applicability of the Burger model varies across wood species. The observed differences between cypress and beech indicate that the behavior of delayed elastic and permanent strain components in shear creep may be influenced by the microstructure of the wood.

Modified Burger model with strain-rate-dependent apparent viscosity

All specimens exhibited a curvilinear increase in permanent strain, although beech displayed a nearly linear behavior, which the conventional Burger model can not explain. In a previous study (Shimazaki and Ando 2024), we proposed improved Burger models, with the apparent viscosity of the dashpot [$\eta_a(t)$] varying with time (Eq. 8).

$$\eta_a(t) = K(t + 1)^n \quad (8)$$

where K is a proportional constant. In this study, we further refined this model by defining the apparent viscosity as a function of the permanent strain rate (Eq. 9). The modified Burger model in this study, an improvement of the Burger model presented in Eq. 3, can be mathematically expressed as in Eq. 10.

$$\eta_a(t) = K(\dot{\gamma}_p)^{n-1} \quad (9)$$

$$\gamma_e + \gamma_d(t) + \gamma_p(t) = \frac{\tau_{TL}}{E_1} + \frac{\tau_{TL}}{E_2} \left(1 - e^{\frac{-E_2 t}{\eta_1}} \right) + \frac{t}{K(\dot{\gamma}_p)^{n-1}} \tau_{TL} \quad (10)$$

The second term on the right-hand side in Eq. 10 represents the delayed elastic strain, and the third term describes the permanent strain. The components of the modified Burger model (Eq. 10) were fitted to each strain transition estimated from the measured creep recovery curves.

The fitting results for the modified Burger model are shown in Fig. 12. For cypress, the coefficient of determination was 0.94 ± 0.14 , demonstrating that the modified Burger model could accurately represent the shear creep behavior of cypress. The modified model could capture the curvilinear variation in permanent strain, effectively explaining the creep behavior of cypress. The coefficient of determination for beech using the modified model was 0.92 ± 0.04 , comparable with that achieved using the original Burger model (0.92 ± 0.05). This outcome suggests that the original Burger model can also sufficiently explain the shear creep behavior of beech. The fitting results indicate that the permanent strain of wood, especially cypress, does not conform to Newtonian fluid characteristics with constant viscosity. Instead, it exhibits non-Newtonian fluid-like behavior, where viscosity changes

depending on the strain rate. This result is consistent with the work of Taniguchi and Ando (2010), who observed non-Newtonian behavior of the permanent strain during tensile creep testing of 12 wood species, suggesting that the permanent strain likely exhibits non-Newtonian behavior under wood creep.

Conclusion

Off-axis tensile creep and creep recovery tests were conducted to investigate the shear creep behavior of wood using a creep strain decomposition technique based on the creep recovery curve. Additionally, the shear creep behaviors of cypress (softwood) and beech (hardwood) were compared.

Creep strain was graphically decomposed from the creep recovery curve to estimate the delayed elastic strain and permanent strain, assuming that the rate of increase in delayed elastic strain is the same as the recovery rate during creep recovery. These strain components were analyzed using the Burger model, which is commonly applied to study wood creep phenomena. Although the Burger model provided a highly accurate fit for beech, it failed to adequately explain the shear creep behavior of cypress.

Key differences between cypress and beech were identified in three aspects: i) Poisson's ratio at $t = 0$: Immediately after the start of the creep test, all beech specimens showed a positive Poisson's ratio, whereas approximately half of the cypress specimens showed a negative Poisson's ratio. ii) Contributions of delayed elastic strain and permanent strain to the total creep strain: In cypress, the permanent strain was approximately 1.5 times larger than the delayed elastic strain. In contrast, the delayed elastic strain was predominant in beech. iii) Behavior of permanent strain: Permanent strain in cypress exhibited a curvilinear increase, whereas that in beech displayed a nearly linear transition.

To explain the curvilinear behavior of permanent strain, we proposed a modified Burger model, in which the apparent viscosity varies as a function of the permanent strain rate. This model could accurately explain the shear creep behavior of both species, suggesting that the permanent strain in wood, particularly in cypress, exhibits non-Newtonian fluid-like properties rather than Newtonian fluid properties, as indicated by the original Burger model.

Cypress and beech differ in their microstructures, such as ray structures and axial cells. Future work can be focused on examining the influence of these microstructural factors on Poisson's ratio and viscoelastic properties under shear creep conditions.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

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

Data Availability

Data is provided within the manuscript or supplementary information file.

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Figures

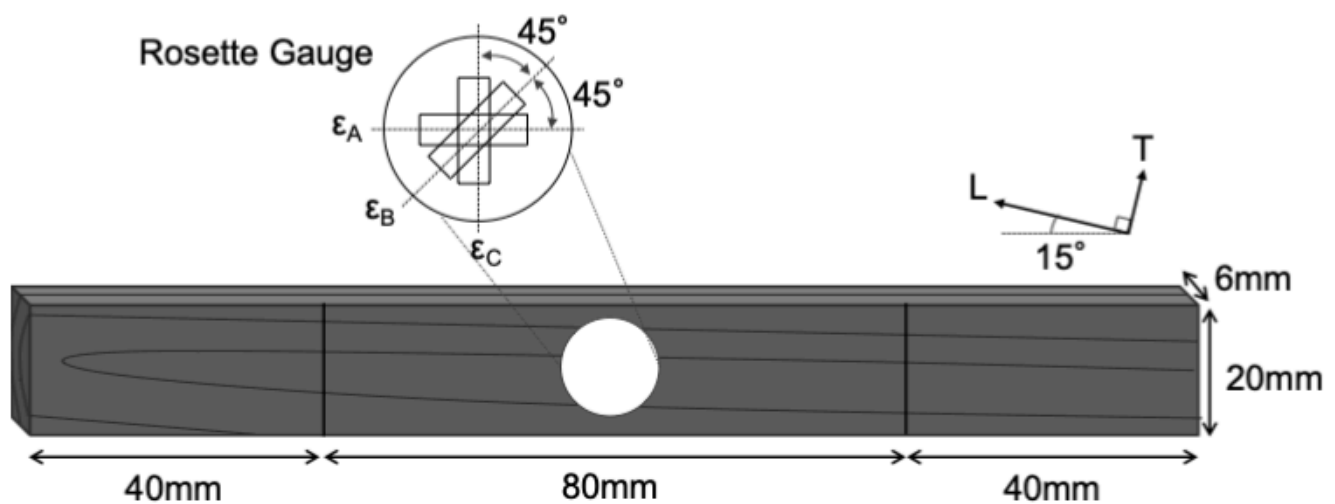


Figure 1

Schematic of the off-axis tensile test specimen. A three-axis rosette gage was attached to the center of each wide face.



Figure 2

Setup of the off-axis tensile creep and creep recovery tests.

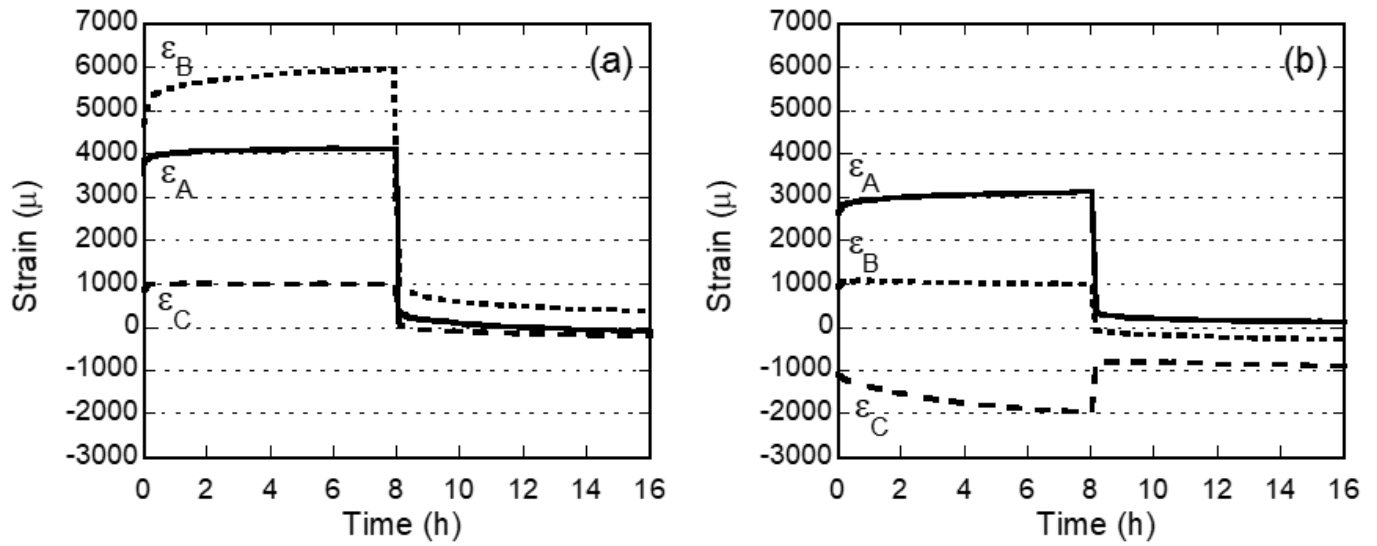


Figure 3

Typical transition of the tensile creep strain in each direction: longitudinal strain ϵ_A , 45° strain ϵ_B , and transverse strain ϵ_C for (a) Japanese cypress (b) Japanese beech.

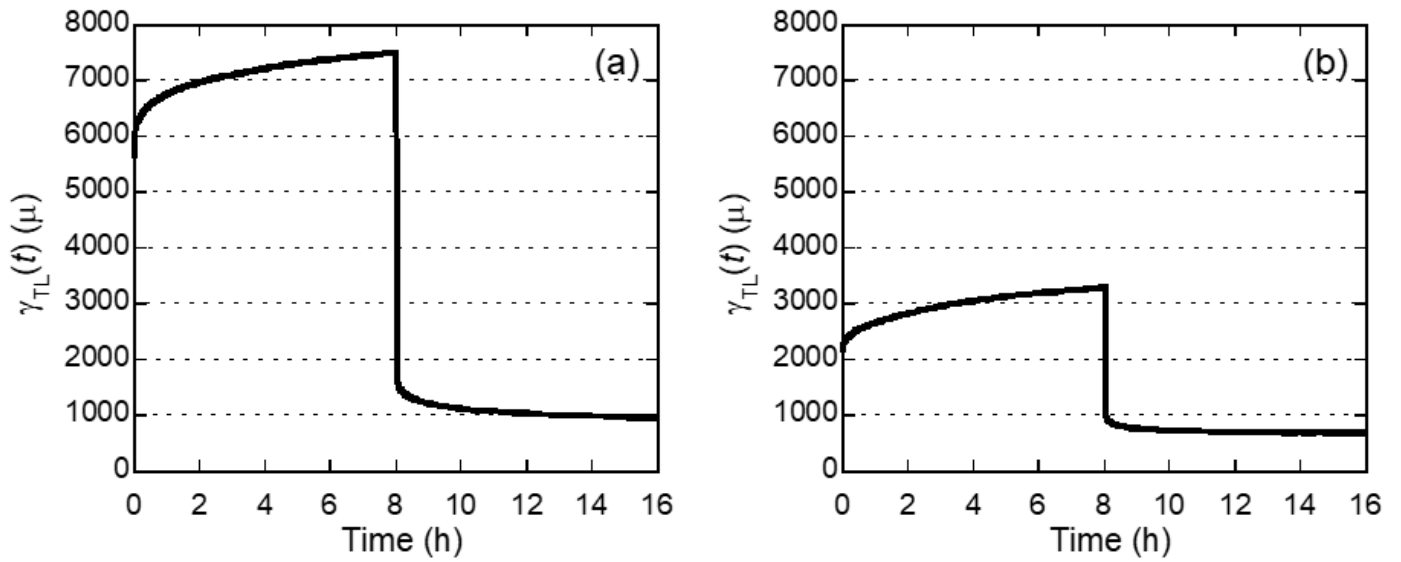


Figure 4

Typical transition of the shear creep strain calculated using Eq. 2: (a) Japanese cypress (b) Japanese beech.

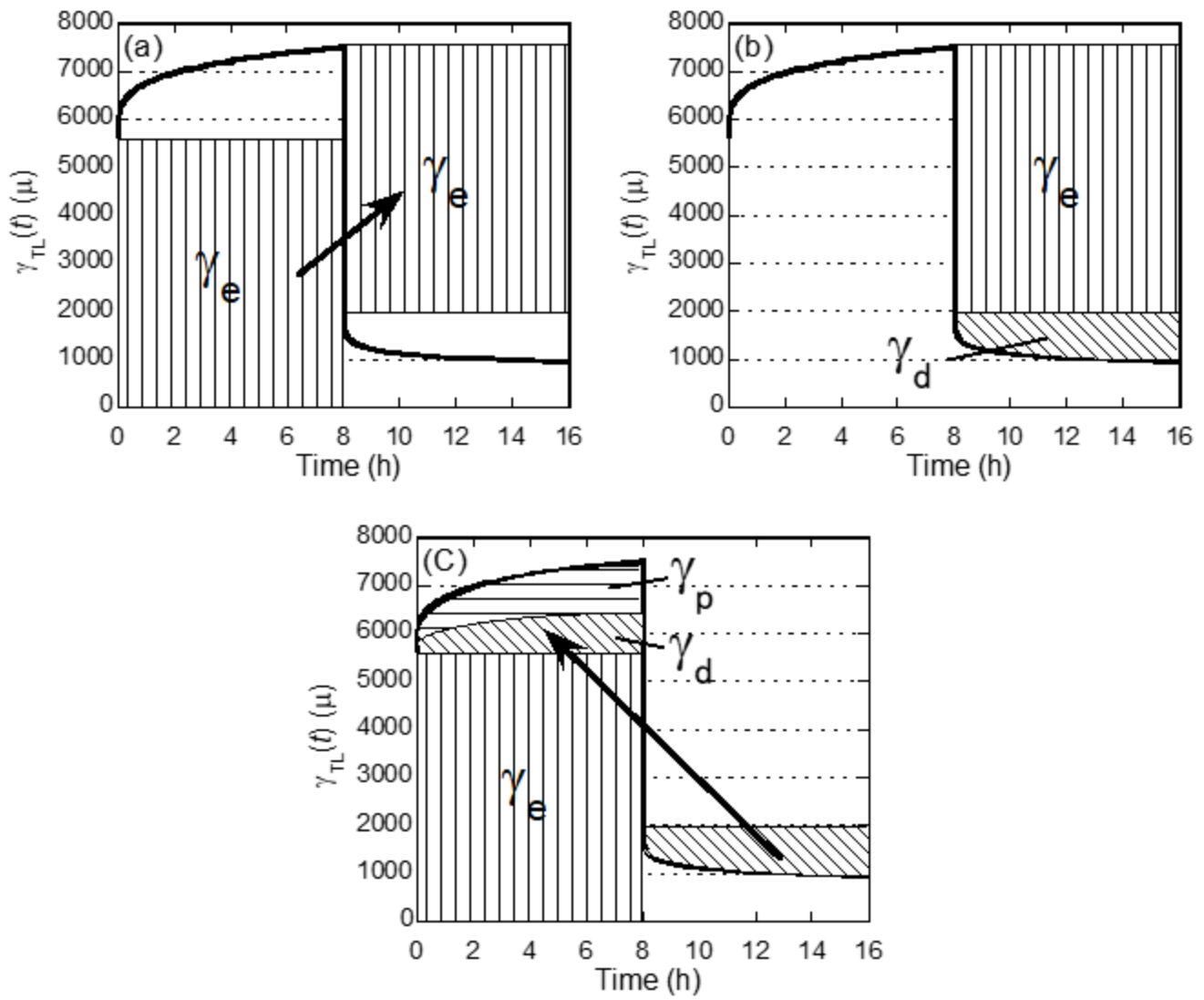


Figure 5

Decomposition method of shear creep strain using a creep recovery curve: instantaneous elastic strain γ_e , delayed elastic strain γ_d , and permanent strain γ_p .

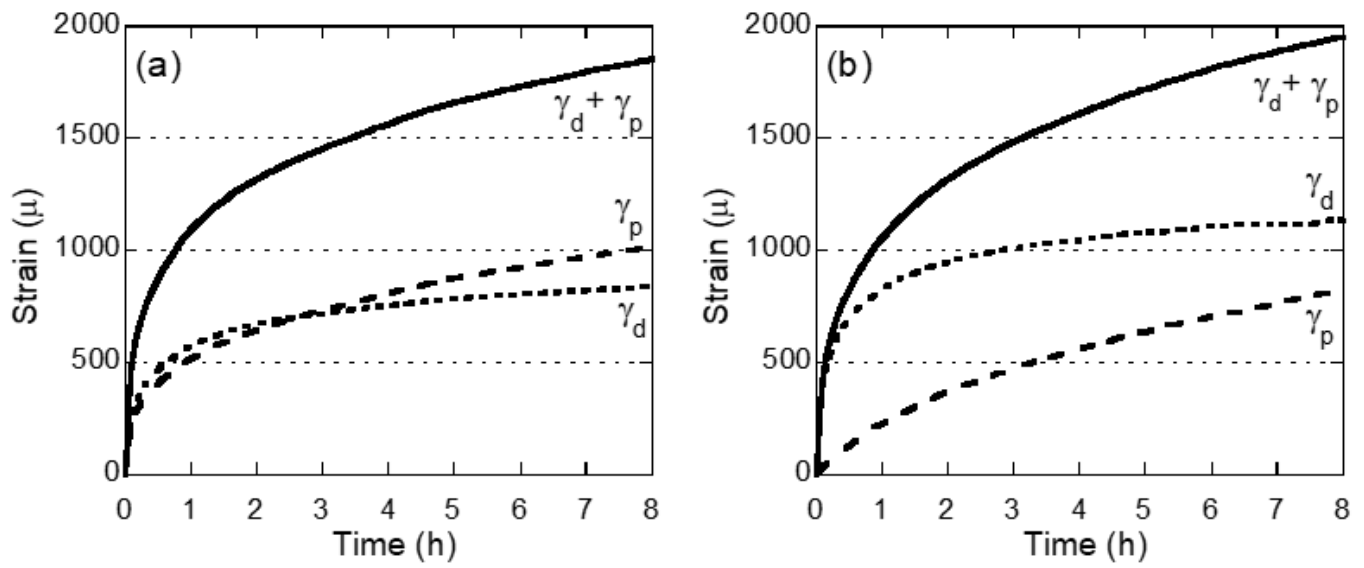


Figure 6

Transitions of delayed elastic strain (γ_d) and permanent strain (γ_p) determined using the graphical decomposition method (Fig. 5): (a) Japanese cypress (b) Japanese beech.

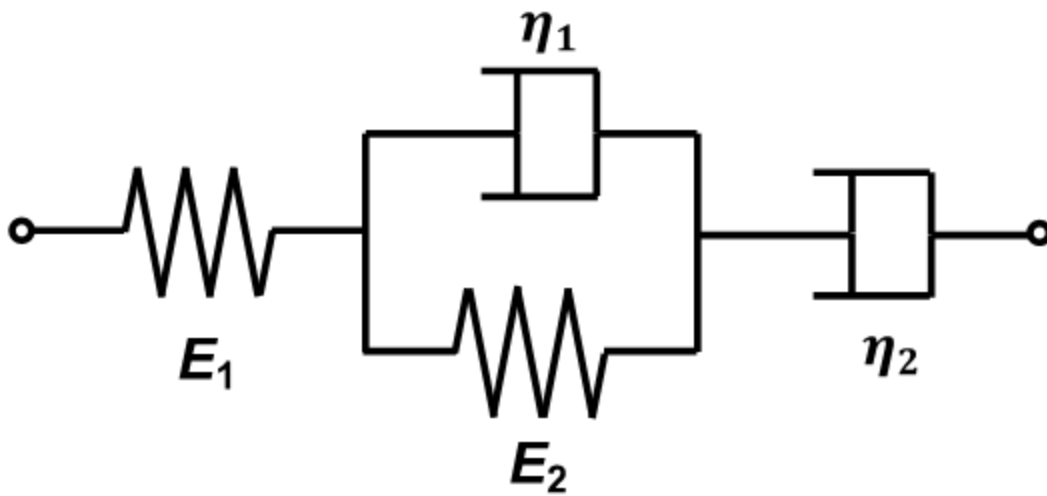


Figure 7

Rheological Burger model combining Maxwell and Kelvin-Voigt model units.

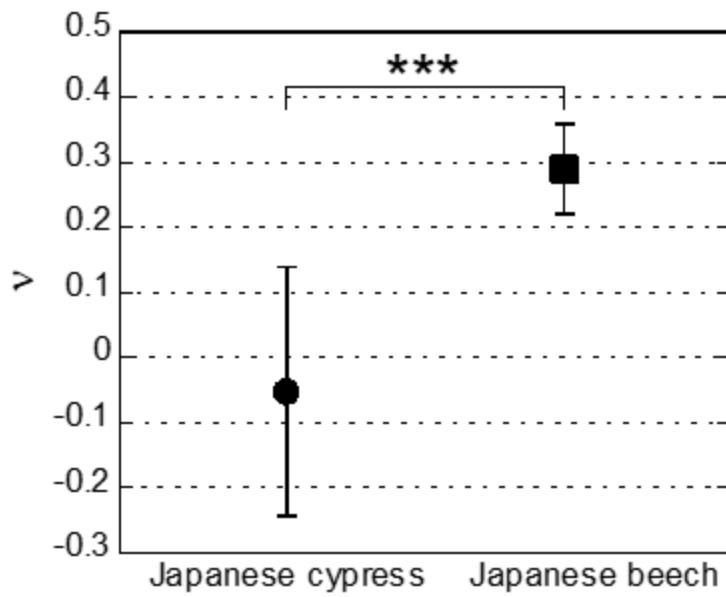


Figure 8

Poisson's ratio at the beginning of the off-axis tensile creep test. Error bars indicate standard deviations. * represents a significant difference (t-test) at $p < .001$.

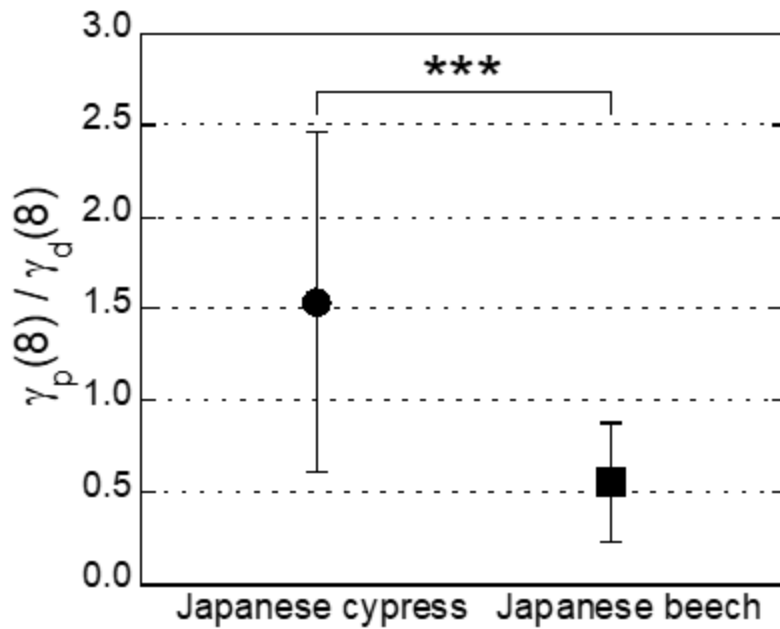


Figure 9

Predicted ratio of permanent strain to delayed elastic strain at the end of the creep test. Error bars indicate standard deviations. * represents a significant difference (t-test) at $p < .001$.

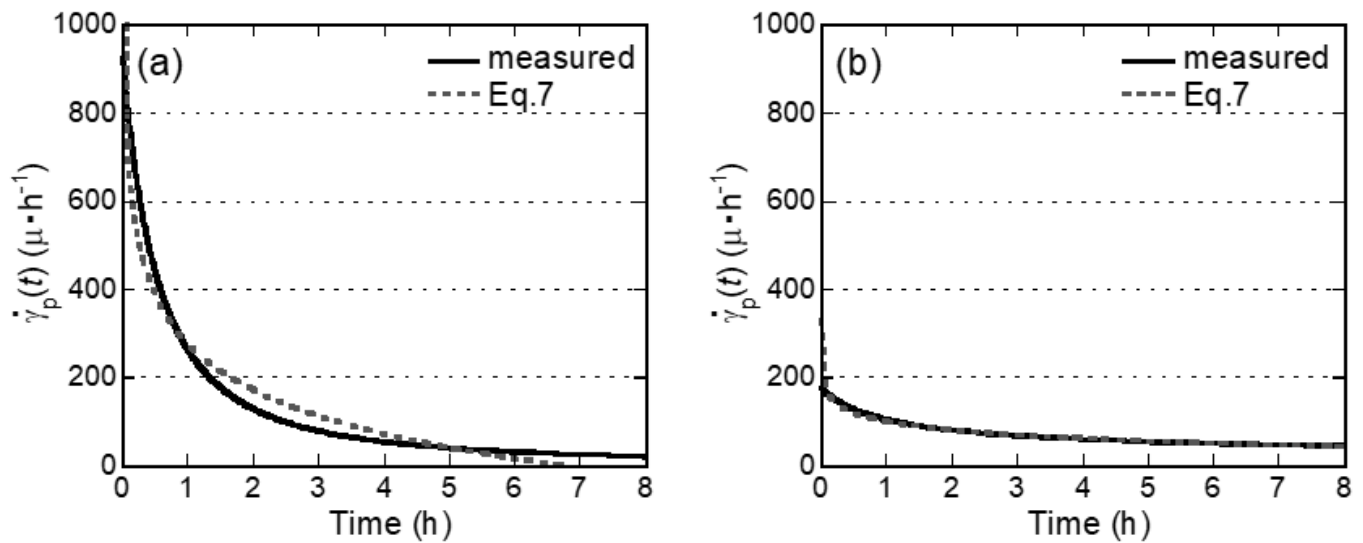


Figure 10

Typical predicted transition of the permanent strain rate: (a) Japanese cypress (b) Japanese beech.

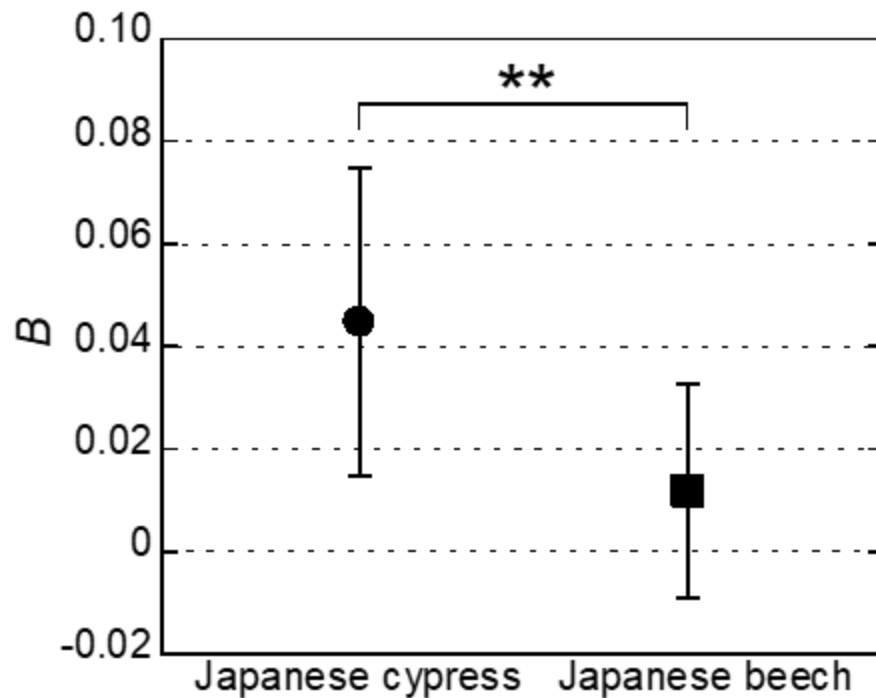


Figure 11

Values of B in Eq. 7 during the creep test (up to 8 h). Error bars indicate standard deviations. * represents a significant difference (t-test) at $p < .01$.

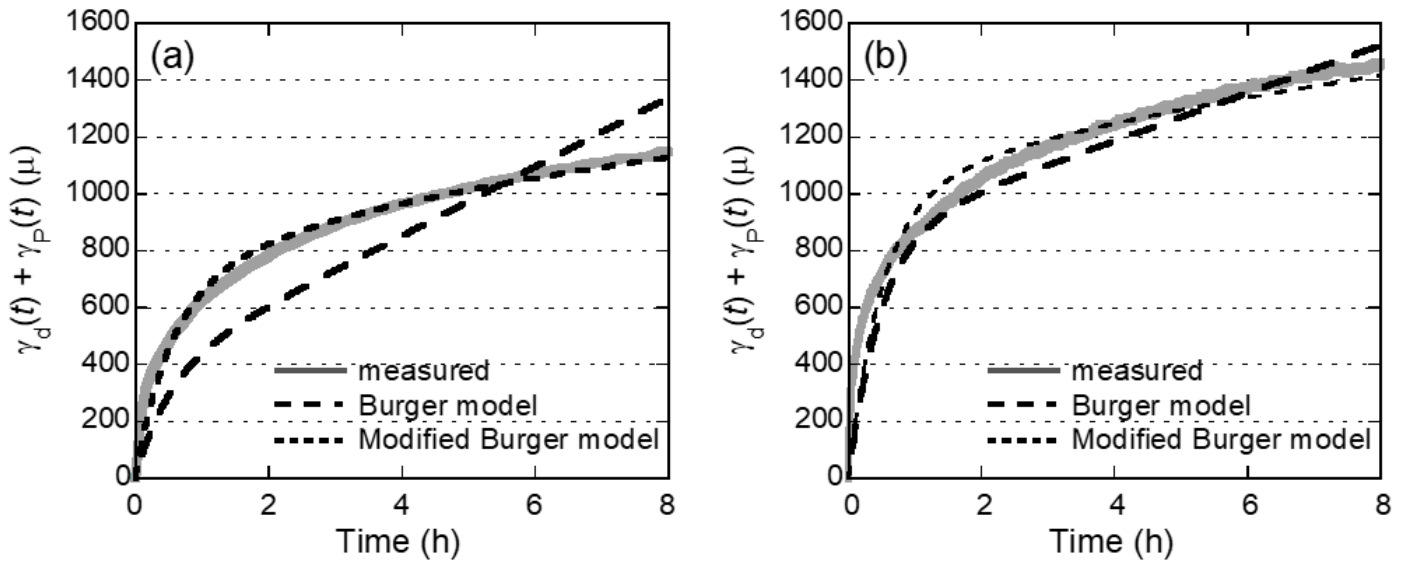


Figure 12

Typical example of fitting results of creep strain based on the Burger model (Eq. 3) and modified Burger model (Eq. 10): (a) Japanese cypress (b) Japanese beech.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [DataShimazaki.xlsx](#)