

Experimental study and modeling on determining the predictors of creep behavior on small clear wood

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Context and objectives

Wood has been used as a structural material since ancient times, so we have always had to face the challenges of time and climate on wood and wood-based materials. In those situations, it expresses the creep behavior, a mechanical phenomenon in which the deformation increases with time at a constant level of load. The additional deformation would affect the feeling of use, and serviceability for users, and sometimes the security of the structure. When deformation reaches the mechanical limits of the material, it can lead to failure. The creep behavior of wood has been mentioned in the study of Youngs (1957) and even earlier. Compared with the inorganic materials, wood is much complex composite with different levels of interactions and large variability. Matar (2003) presents the creep test results for different specific densities. Even with similar moisture content level and temperature, wood can express variability in creep deformation according to microstructural organization of the material and its specific density (Fig. 1). Additionally, the microstructure affects the creep behavior. Fig. 2 shows the longitudinal tensile creep test results on Sugi with different microfibril angle (Kojima & Yamamoto, 2004). These two examples show the diversity and complexity of creep behavior on wood materials. Considering the research objectives, we focused on the relationship between material properties and creep behavior under a constant hygrothermal environment.

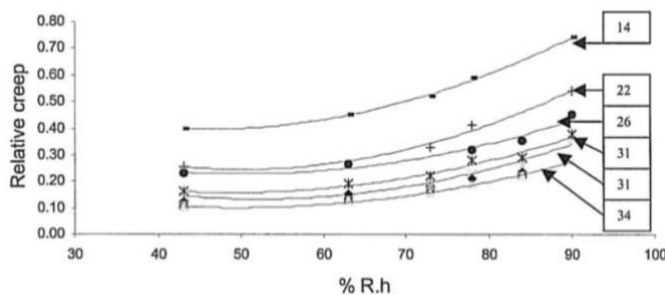


Fig. 1 : Evolution of relative creep after 1 week at various relative humidity levels and for different specific modulus (GPa) indicated on each curve. (Matar, 2003)

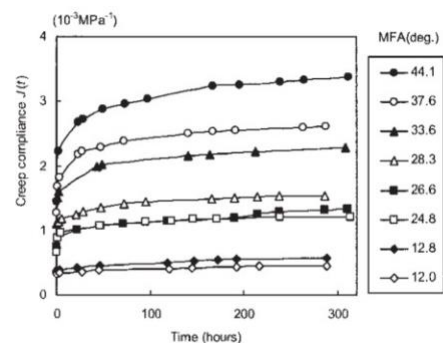


Fig. 2 : The longitudinal tensile creep test of Sugi earlywood values of specimens with different microfibril angle (MFA) (Kojima & Yamamoto, 2004)

Materials and Methods

In this study, a series of 4–point bending creep tests were conducted on 4 kinds of small clear wood specimens (Tab. 1). To simplify the influencing factors during the experiments and to focus more on the relationship between the properties of the wood and the creep behavior, small clear wood specimens were used in this study. Wood materials were cut into the small specimens with the size of 150 mm (L) × 12 mm (b) × 2 mm (h) and stabilized in room condition for scanning and measure the average grain angle ($\text{Grain}_{\text{avg}}$) (Tab. 1). Then, the specimens were put inside the climatic chamber at 20 °C and relative humidity (RH) at 30% stabilized for 3 weeks and conducted the vibration test. The second time of vibration follow by another 3–week stabilization under 20 °C and RH=85%. Specimens' informations including density (ρ), specific modulus (E_s) were collected and calculated by the vibration tests results (Tab. 1). The 4–point bending test was performed in a climatic chamber at 20 °C and RH=85%. The length between the two supports was 110 mm and the distance between the two loading points was 60 mm. The average stress in this study is 10.52 (± 3.05) MPa. The strain was measured with the gauges of KYOWA KFGS-5-120-C1-11 and glued to the center of both sides of the specimen with cyanoacrylate glue. The strain gauge wires are connected to the TDS-120 data logger. The strain values for each channel are collected by the machine approximately every 5 seconds. The data logger is connected to a PC with a surface LabVIEW to collect the data and save it as a text file. In this text file, the time of the data logger, the time of the PC and the strain gauges values for each channel are recorded. The creep test duration was set to 10 days to achieve the relevant creep deformation and allow many tests.

Tab. 1 : The average of the physical and mechanical properties of the specimen.

	ρ (g/cm ³)	E_s (MPa)	$\text{Grain}_{\text{avg}}$
Douglas fir (<i>Pseudotsuga menziesii</i>)	0.54 (± 0.03)	19.73 (± 4.15)	2.1 (± 0.9)
Poplar (<i>Populus spp.</i>)	0.45 (± 0.02)	19.56 (± 1.61)	3.5 (± 2.7)
European Beech (<i>Fagus sylvatica</i>)	0.73 (± 0.02)	17.82 (± 2.21)	2.1 (± 0.8)
European Oak (<i>Quercus petraea</i>)	0.63 (± 0.02)	13.61 (± 2.18)	2.7 (± 1.2)

Results and Discussion

After 10–day creep test, there were 108 creep curves result have been used in modeling, including 29 Douglas fir samples, 34 Poplar samples, 33 Beech samples, and 12 Oak samples. In this study, we assumed that there are two possibilities for causing creep at the cellular level. The first one is the increased deformation of the cell wall. This means that creep behavior occurs at the microfibril scale or smaller. It could be a reorganization of microfibrils and/or a deformation of the amorphous regions of the cellulose or the amorphous matrix of hemicellulose and lignin. The second one is the creep deformation due to the sliding between the cells. In this case, the deformation of the specimen is caused by the movement between cells (Fig. 3). Based on this assumption, three models have been developed.

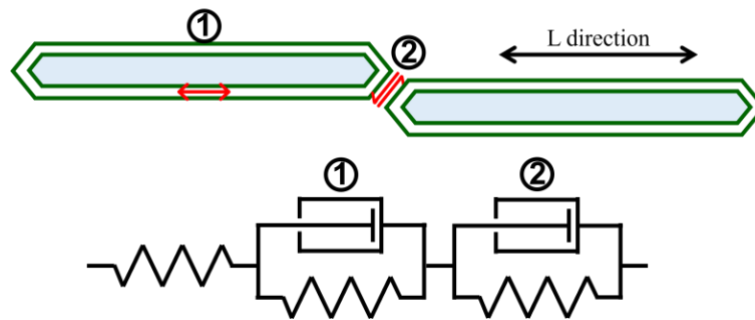


Fig. 3 : Assumptions of creep behavior in the cell scale: deformation of the cell wall (1) and sliding between cells (2), proposition of a model to represent both phenomena.

Linear model

The demarcation between primary and secondary creep is defined by previous studies (Matar, 2003) as when the loading for one day. By the results of linear regression between ρ , E_s , and delayed compliance ($J_{1d}-J_0$ for primary creep and $J_{7d}-J_{1d}$ for secondary creep), the creep factors can be defined as $1/(\rho \times (E_s)^{1.5})$ for primary creep and $1/(\rho \times (E_s)^3)$ for secondary creep. Fig. 4 and Fig. 5 show good linear correlation between the creep factors and delayed compliance.

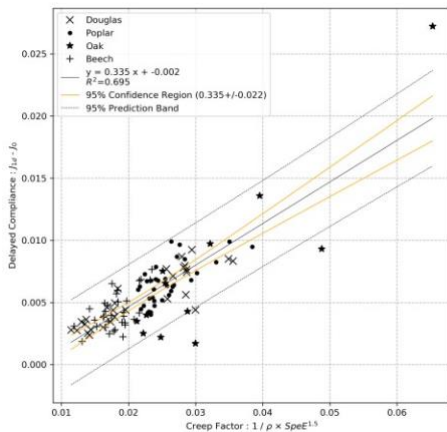


Fig. 4 : Linear model for primary creep behavior.

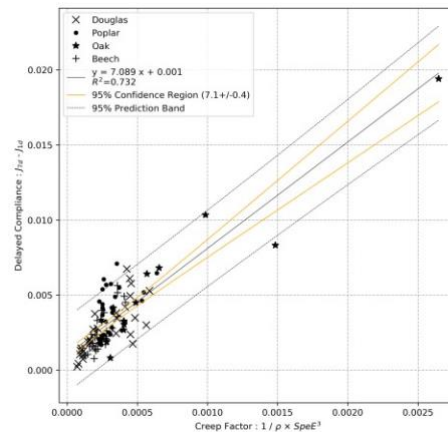


Fig. 5 : Linear model for secondary creep behavior.

Discrete compliance model

Considering the relationship between ρ , E_s , and delayed compliance changes with time, discrete compliance model was design to have the J^*i value at different characteristic time (τ) as the Fig. 6 and equation (1) show.

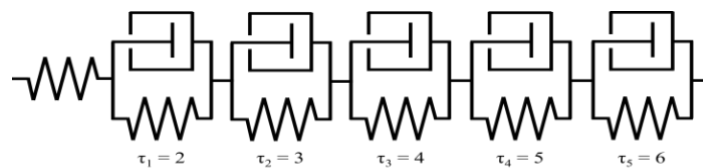


Fig. 6 : Discrete compliance model.

$$J(t) = J_0 + \sum J^*i(t) = J_0 + \sum J^*i(1 - e^{-(t/\tau)}) \quad (1)$$

Fig. 7 and Fig. 8 show the slope of linear regression between the J^*i and ρ , E_s . As the absolute value of slope between ρ and J^*i decrease, the absolute value of slope between E_s and J^*i tends to increase. It shows that creeping behavior starts from the cell wall and then shifts to intercellular sliding.

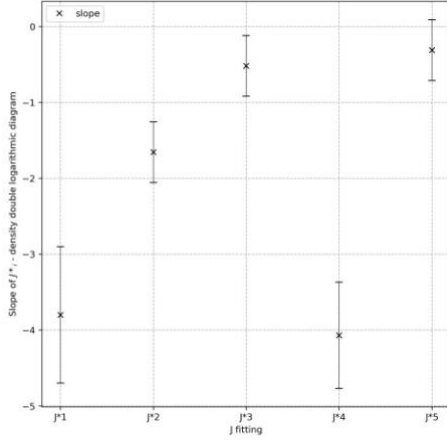


Fig. 7 : Correlation between the J^*i and the slope of regression result of J^*i and ρ at different τ .

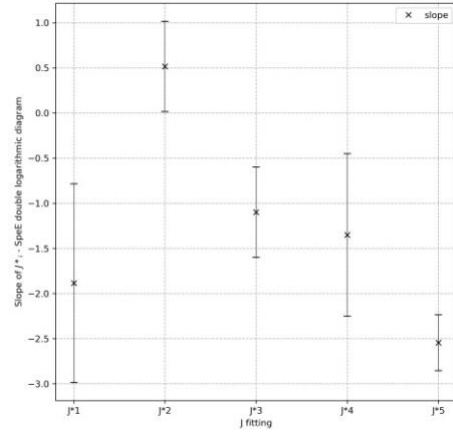


Fig. 8 : Correlation between the characteristic time (τ) and the slope of regression result of J^*i and E_s at different τ .

Multiple regression model

From the trends in Fig. 7 and Fig. 8, the relationship between τ and regression slope is not linear. We propose that the relationship between τ and regression slope can be present as polynomial as equation (4) to (6), which is the parameter to calculate J^*i (Eq.(3)). The 10 parameters in equation (4) to (6) was calculated from the 108 creep curves in this study.

$$J(t, \rho, E_s) = J_0 + \sum J^*i(t, \rho, E_s) \times (1 - e^{-(t/\tau)}) \quad (2)$$

$$J^*i(t, \rho, E_s) = a(\log \tau_i) \times \left(\frac{\rho}{\rho_0}\right)^b (\log \tau_i) \times \left(\frac{E}{E_{s0}}\right)^c (\log \tau_i) \quad (3)$$

$$a(\log \tau_i) = i_a + s_a \times \log \tau_i + q_a \times (\log \tau_i)^2 + c_a \times (\log \tau_i)^3 \quad (4)$$

$$b(\log \tau_i) = i_b + s_b \times \log \tau_i + q_b \times (\log \tau_i)^2 \quad (5)$$

$$c(\log \tau_i) = i_c + s_c \times \log \tau_i + q_c \times (\log \tau_i)^2 \quad (6)$$

The curve of $b(\tau_i)$ and $c(\tau_i)$ (Fig. 9) which represent the relationship between ρ and E_s show clearer trend than discrete compliance model. The effect of ρ decrease and E_s increase. This result shows again that wood creep behavior is a dynamic process that it starts from the

deformation of cell wall, then transfer to intercellular sliding. Fig. 10 shows one of the fitting results within 108 experimental creep curves.

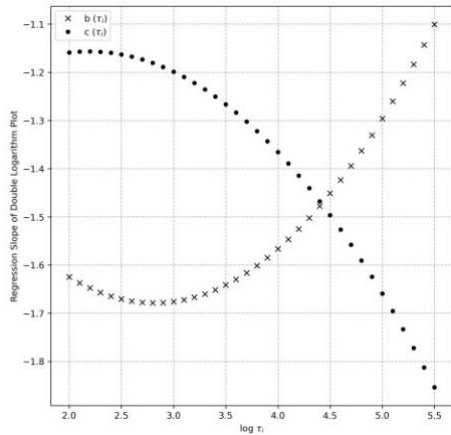


Fig. 9 : Fitting result of $b(\tau_i)$ and $c(\tau_i)$.

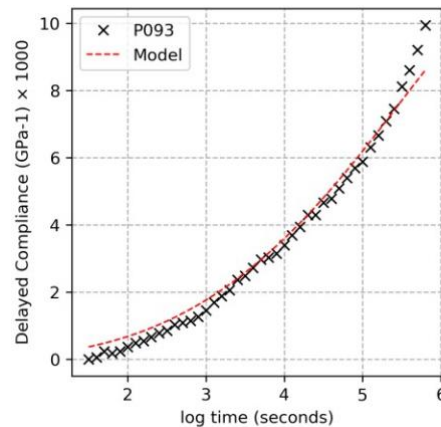


Fig. 10 : Multiple regression model fitting results of specimen P093.

Conclusions

In this study, the use of small clear wood was able to control the macroscopic material properties and reduce its variability. Density corresponds to material properties larger than cellular scale, and specific modulus corresponds to the property of the material that is smaller than the cellular scale, which is the microfibril angle or the grain angle. The most important assumption of the model in this study is that if delayed compliance is proportional to density, then creep behavior occurs only at the cell wall. It is proved in the linear model. However, we also observed that the magnitude of the effect of these factors on creep behaviors changed over time. Through the discrete compliance model, we found the compliance parameter values at characteristic time and the trend is not completely linear. Therefore, in the multiple regression model, we assume that the relationship between creep parameters and time is a polynomial function, which shows the degree of influence of material properties on the creep behavior change with time. The fitting results show that the effect of density decreases with time, while the effect of specific modulus increases. From this, we can infer that the creep behavior of wood starts with the deformation of the cell walls and then shifts to the intercellular space, which is related to the MFA and the grain angle and is presented by the specific modulus.

Remerciements

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