Experimental and Numerical Investigation on Compression Creep Behavior of Wood

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Abstract

This article provides an efficient and intuitive way to predict the long-term (12-h) compression creep behavior of wood by a finite element method (FEM). In this study, oriental beech (*Fagus orientalis* L.) was used as an example. First, a short-term (3-h) compression creep experiment was conducted to obtain the original creep data of beech, and then a Kelvin model (KM) with two elements in series was applied to fit the curve of creep strain and time to calculate parameters used in FEM. Second, long-term compression creep behavior was numerically analyzed by the FEM based on the short-term creep data. Finally, the results of the FEM and the KM were compared with that of the long-term creep experiment. The results showed that the creep deformations increased in the order of longitudinal (L), radial (R), and tangential (T) directions under the same loading level, and the creep behavior of beech in the L direction stopped after a short time and stayed constant. Additionally, in the same orientation, the creep deformation increased with the growth of loading levels below the ultimate creep strength. In addition, the KM did not work well for predicting the long-term creep behavior of beech. By contrast, the results of FEM were highly consistent with those of the experiment, and errors in L, R, and T directions were all less than the standard deviation. As a result, the numerical method provided acceptable accuracy to predict the long-term creep behavior of wood construction and wood products.

Wood, as a biomass material, has complicated physical and mechanical properties, which combine the characteristics of solids and fluids. It is extensively used in constructing structures and manufacturing products because it is environmentally friendly. However, the creep behavior of wood is the main factor that decreases the stiffness of wood construction under long-term loading and influences the quality of wood products.

There are many factors that influence creep behavior, such as temperature, humidity, loading level, and time. This study aims to establish a relationship between these factors and creep behavior. Currently, experience models and mechanical models are the two main research methods of predicting creep behavior (Holzer et al. 1989). Experience models evaluate long-term creep behavior with equations that are derived by fitting curves of the short-term creep experiment data and time. Nakano (1999) mathematically analyzed the creep behavior of wood during water adsorption based on the excitation response theory and derived a function of creep compliance with moisture content and time.

The mechanical model combines the characteristics of the spring and damper to simulate creep behaviors of wood. These models were able to predict the creep behavior more accurately than the experience model by using different combinations of springs and dampers, such as the Maxwell model, the Kelvin model (KM), and combinations of models, such as the Burgers model (Ma et al. 2008) and a modified KM (Chen et al. 2006). Mechanical model studies that were mainly focused on how to combine springs and dampers were more efficient in evaluating long-term creep behaviors in different conditions. Wang et al. (2012) developed a probabilistic model called the creep-rupture model that was capable of predicting the time-dependent deflection and time-to-failure data at different stress levels of wood composites. Chang et al. (2013a) used the time–temperature superposition principle to verify the master curves for wood–plastic composites. The results showed that the effect of naturally elevated temperatures during the summer months caused additional increases in creep strain. Comparisons between long-term data and the master curves showed that the master curves tended to overestimate the real creep strain of large specimens and that the deviation increased with time. In general, the master curves cannot

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Forest Prod. J. 68(2):138–146.
doi:10.13073/FPJ-D-17-00030

precisely predict the long-term creep strain but merely provide conservative estimates. In the same year, Chang et al. (2013b) introduced the time–temperature–stress superposition principle, which was able to involve the effects of both temperature and stress simultaneously.

The viscoelastic behavior of wood at stress levels corresponding to linear and nonlinear behavior has been studied since 1977. Mukudai et al. (1978) studied the bending deflection of wood; the results showed that the creep strain resulting from load change with time, in the linear stress level range, could be predicted by the numerical calculation method. Mukudai (1983) studied the nonlinear viscoelastic bending deflection of wood and reported that the viscoelastic deflection resulting from loads increasing continuously from the 30 to 60 percent stress level, i.e., within the proportional limit, was measured over a period of 10 hours. Foudjet and Bremond (1989) investigated the creep of four tropical hardwoods (Azobe, Tali, Sapell, and Movingui) from Cameroon. The results showed that the total relative creep was not more than 35 percent. Ranta-Maunus (1993) studied the rheological behavior of wood in directions perpendicular to the grain, including tension and bending tests. The results showed that the mechanical model was more capable in directions perpendicular to the grain than in the longitudinal direction.

In recent years, some researchers have paid much attention to the method of putting the creep theories into practice. The finite element method (FEM) was a highlight among many methods for its generality and systematicity. Chassagne et al. (2005) presented a qualitative explanation of the creep phenomenon based on the physical and chemical mechanisms that occur at microstructural and ultrastructural levels of wood during moisture diffusion and constructed a formulation of a three-dimensional (3D) nonlinear hydro-viscoelastic model. The model was then implemented in the FEM program, and the validity of the 3D approach for moderate stress levels (up to around 30%) was proved. Vidal-Sallé and Chassagne (2007) put forward a nonlinear viscoelastic orthotropic constitutive equation applied to wood material, which was based on a rheological generalized Maxwell model with two elements in parallel, in addition to a single linear spring taking into account the long-term response. The proposed model was implemented in the finite element code ABAQUS/Standard via a user subroutine UMAT, and a simple example was shown to demonstrate the capability of the proposed model. Fortino et al. (2009) proposed a 3D moisture–stress numerical analysis for timber structures under variable humidity and load conditions. Both the constitutive model and the equations needed to describe the moisture flow across the structure were incorporated into user subroutines of the ABAQUS finite element code. The presented computational approach was validated by analyzing some wood tests described in the literature and comparing the computational results with the reported experimental data.

Much attention has been paid to theories of creep behaviors, but that attention rarely focused on methods of predicting the long-term creep behavior more simply and efficiently. The aim of this article is to introduce a new method of predicting the compression creep behavior of wood by FEM. The compression creep behavior of beech in different directions was studied as an example. The long-term (12-h) compression creep behavior of beech was evaluated by FEM with commercial software ABAQUS 6.14-1 based on short-term (3-h) compression creep experimental data. In addition, the physical and mechanical properties of wood were taken into consideration, which were measured by experiments, including the density, elastic moduli, Poisson ratios, and shear moduli. The research on long-term creep behavior of wood is an important and difficult subject, because many experiments were required to be conducted and the mechanical models are not usually effective for evaluating the long-term creep behavior. Thus, it is vitally important to research evaluation of long-term creep using the numerical method.

Materials and Methods

Physical and mechanical properties of beech

All specimens were made with oriental beech (*Fagus orientalis* L.) bought from a local commercial supplier. All physical and mechanical parameters of the beech were measured carefully by conducting experiments in according to ASTM D4442-92 (ASTM International 2001) and ASTM D143-94 (ASTM 2000), respectively. The average specific gravity was 0.69 g/cm^3, and the moisture content of beech was conditioned to and held at 12 percent before and during the experiment. The mechanical properties of beech were determined using a TDS-530 static data acquisition instrument (TML, Japan) referring to former studies (Aira et al. 2014; Hu and Guan 2017a, 2017b). The dimensions of specimens and positions of sensor gauges are shown in Figure 1. Specimen a was used to test E_L, V_{LR}, and V_{LT}; specimen b was used to measure E_R, V_{RT}, and V_{RL}; and specimen c was used to measure E_T, V_{TR}, and V_{TL}. The shear moduli G_{LT}, G_{LR}, and G_{RT} were determined based on specimens d, e, and f, respectively. Testing for each property measurement was repeated 10 times with the testing method shown in Figure 2. In addition, the load was controlled by a universal mechanical test machine, and the strains were recorded by a TDS-530 static data acquisition instrument.

Specimens and test methods

The experiments were carried out by a compression test with beech blocks. The specimens measured 30 mm long by 20 mm wide by 20 mm thick, and the length direction of specimens were longitudinal (L), radial (R), and tangential (T), respectively, as shown by specimen a, specimen b, and specimen c in Figure 1. In addition, all specimens were sanded by fine sandpaper, and then the true dimensions of every specimen were measured, and the specimens were stored in a vacuum bag waiting for testing.

The creep behaviors of beech in L, R, and T directions were measured by the compression test with three loading levels of 800, 1,000, and 1,200 N, respectively. The loads selected in test must ensure all directions of specimens in elastic range when loading. Because the proportional limit stress of the T direction of beech was the smallest, which was 4.49 N/mm^2, and the area of cross section of the specimen was 400 mm^2, the maximum load must be smaller than 1,796 N. As a result, the selected loads were 800, 1,000, and 1,200 N, respectively, which were relatively safe. The universal test machine was used to monitor the process of testing. First, the load increased gradually at a rate of 1 mm/min until reaching the loading level specified before, and then the load was held for 3 hours to obtain the creep data. Second, 12 hours of the compression test were numerically analyzed by FEM with the 3 hours of experimental data. Finally, in the verification stage, long-term (12-h) compression creep experiments in three

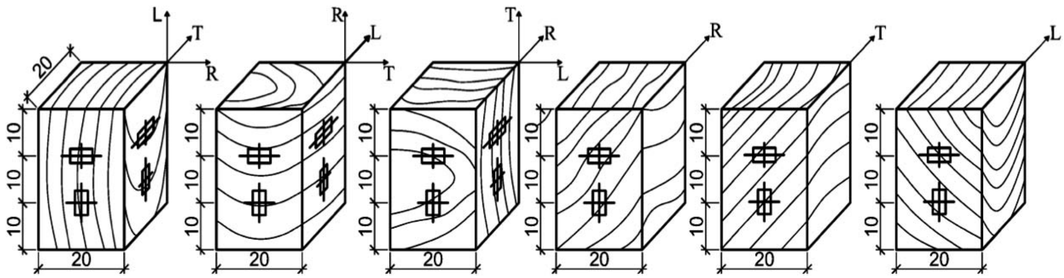

Figure 1.—Specimens (left to right: a through f) to measure elastic constants of beech. L = longitudinal; T = tangential; R = radial.

orientations were conducted with the 1,000 N loading level, and each grain orientation was repeated 10 times.

Calculation of parameters used in FEM

A power law function was used in FEM to define the creep behavior of beech, which is shown in Equation 1.

$$\dot{\varepsilon}^{cr} = A\sigma^n t^m \quad (1)$$

where $\dot{\varepsilon}^{cr}$ is uniaxial equivalent strain rate; σ is uniaxial equivalent deviatoric stress; t is total creep time (s); and A, m, and n are all parameters in ABAQUS, which is defined by the user.

As Equation 1 shows, the parameters A, m, and n were needed in FEM, and they were determined by using the short-term experimental creep data in different conditions, such as the temperature, humidity, and loading levels. In this study, the temperature was controlled in 25°C, and the relative humidity was 48 percent. The creep behaviors under different loading levels were used as an example to introduce the method of obtaining the parameters A, m, and n.

Equation 2 can be derived by the integral of Equation 1 for time (t), and Equation 3 gives the logarithmic linearization regression of the power function (Eq. 2). Furthermore, experimental data are linearly fitted by Equation 3.

$$\varepsilon^{cr} = \frac{A}{m+1}\sigma^n t^{m+1} \quad (2)$$

$$\log(\varepsilon^{cr}) = \log\left(\frac{A}{m+1}\right) + n\log(\sigma) + (m+1)\log(t) \quad (3)$$

First, with Equation 3 as the function of $\log(\varepsilon^{cr})$ and $\log(t)$, the three fitting lines of L, R, and T directions are obtained. The value of the line's slope was equal to $(m+1)$, and the intercept of the line was equal to $\log(A/(m+1)) + n\log(\sigma)$. Because the values of m and σ were already known, an equation of A and n can be derived.

Second, set Equation 3 as the function of $\log(\varepsilon^{cr})$ and $\log(\sigma)$. In this study, the loading levels were 800, 1,000, and 1,200 N, and the corresponding creep strains at the end of 3 hours were also known; therefore, a linear regression equation of $\log(\varepsilon^{cr})$ and $\log(\sigma)$ can be calculated. The intercept of the line was $\log(A/(m+1)) + (m+1)\log(t)$, so the value of A can be obtained. Meanwhile, the value of n was also determined.

Results and Discussion

Mechanical properties of beech

Table 1 shows the mechanical properties of beech used in the FEM.

The influences of loading levels on creep strains in three orientations of beech were calculated and compared. The creep strain can be expressed as Equation 4. The displacement was recorded as C_0 at the beginning of creep, and then the displacement at the end of loading was recorded as C_t.

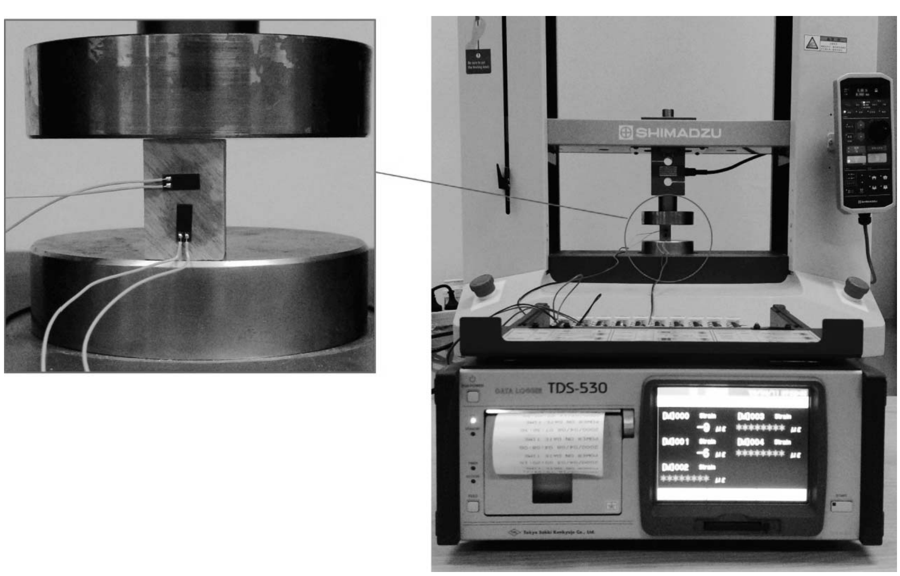

Figure 2.—Methods of measuring mechanical properties and creep behavior of beech.

Table 1.—Mechanical properties of beech.

Mechanical properties								
Elastic modulus (N/mm^2)			Poisson ratio			Tangential modulus (N/mm^2)		
E_L	E_R	E_T	V_{LR}	V_{LT}	V_{RT}	G_{LR}	G_{LT}	G_{RT}
1,2567	1,374	579	0.450	0.554	0.841	899	595	195
Yield strength								
Longitudinal (N/mm^2)			Radial (N/mm^2)			Tangential (N/mm^2)		
42.51			9.83			4.49		

$$\varepsilon^{cr} = (C_t - C_0)/L \tag{4}$$

where C_0 refers to the initial creep displacement (mm), C_t refers to displacement at the end of loading (mm), and L refers to the initial length of the specimen (mm).

Creep strains at 800 N

The curves of creep strain and time at a loading level of 800 N are shown in Figure 3, where the fine dotted lines are results of 10 individual tests, and the solid lines are the averages of them. The comparisons of creep strains between three orientations of beech are shown in Figure 3d. Meanwhile, the fitting functions of L, R, and T directions are shown as Equations 5, 6, and 7, respectively, and correlation coefficients (R^2) of them were all bigger than 0.9.

$$\varepsilon_L^{cr} = 6.36E^{-6} + 7.6E^{-5} \times (1 - e^{-t/740.69})$$
$$R^2 = 0.9132 \tag{5}$$

$$\varepsilon_R^{cr} = 4.38E^{-5} + 9.05E^{-4} \times (1 - e^{-t/9,908.22}) + 2.37E^{-4} \times (1 - e^{-t/497.53})$$
$$R^2 = 0.9997 \tag{6}$$

$$\varepsilon_T^{cr} = 7.92E^{-5} + 0.00335 \times (1 - e^{-t/19,882.24}) + 4.09 \times (1 - e^{-t/562.70})$$
$$R^2 = 0.9998 \tag{7}$$

Creep strains at 1,000 N

The curves of creep strain and time at a loading level of 1,000 N in three directions of beech are shown in Figure 4, and Figure 4d shows the averages of them. In addition, Equations 8, 9, and 10 are equations of three orientations of beech fitted by Origin software.

$$\varepsilon_L^{cr} = 7.69E^{-6} + 9.68E^{-5} \times (1 - e^{-t/8,064.24}) + 4.96E^{-5} \times (1 - e^{-t/568.34})$$
$$R^2 = 0.9991 \tag{8}$$

$$\varepsilon_R^{cr} = 4.85E^{-5} + 2.4E^{-3} \times (1 - e^{-t/13,475.02}) + 2.465E^{-4} \times (1 - e^{-t/631})$$
$$R^2 = 0.9999 \tag{9}$$

$$\varepsilon_T^{cr} = 4.66E^{-5} + 8.1E^{-3} \times (1 - e^{-t/37,128}) + 5.15E^{-4} \times (1 - e^{-t/652.67})$$
$$R^2 = 0.99809 \tag{10}$$

Creep strains at 1,200 N

Figure 5 shows the curves of creep strain and time at a loading level 1,200 N; therein, the fine dotted lines are results of 10 individual tests and the solid lines are the averages of them. Figure 5d presents the comparison of the three directions of beech under the loading level 1,200 N, and Equations 11, 12, and 13 are fitting equations of them.

$$\varepsilon_L^{cr} = 1.15E^{-5} + 1.89E^{-4} \times (1 - e^{-t/22,123.30}) + 5.8E^{-5} \times (1 - e^{-t/775.13})$$
$$R^2 = 0.9972 \tag{11}$$

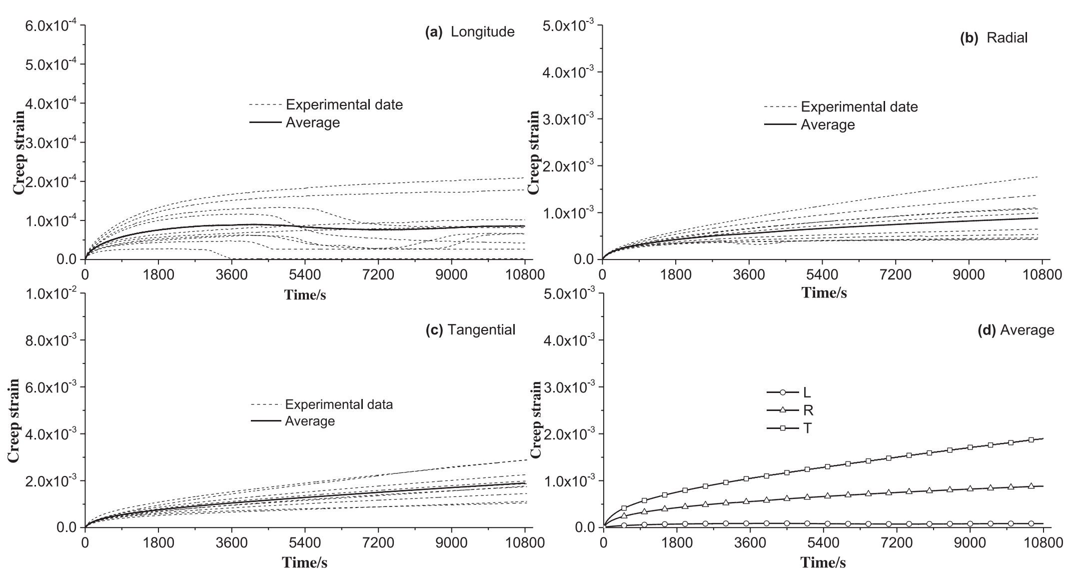

Figure 3.—Strain and time curves of creep behavior under 800 N loading level.

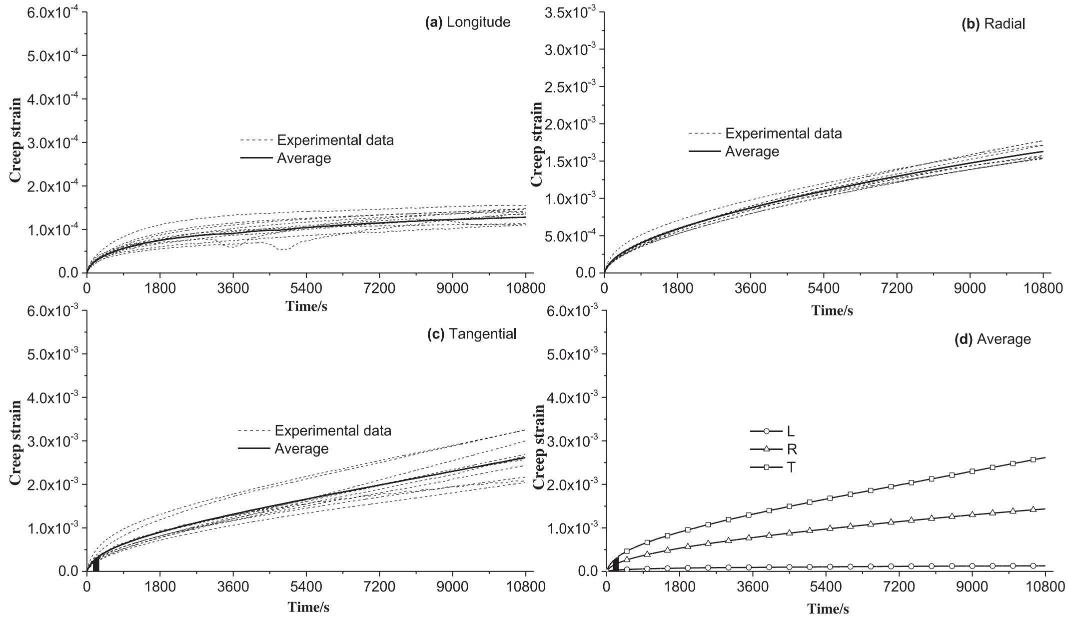

Figure 4.—Strain and time curves of creep behavior under 1,000 N loading level.

$$\varepsilon_R^{cr} = 6.78E^{-5} + 3.25E^{-4} \times (1 - e^{-t/603.48}) + 3.8E^{-3} \times (1 - e^{-t/19{,}379.85})$$
$$R^2 = 0.9998 \quad (12)$$

$$\varepsilon_T^{cr} = 2.59E^{-4} + 1.93E^{-3} \times (1 - e^{-t/10{,}766.11}) + 1.93E^{-3} \times (1 - e^{-t/10{,}766.64})$$
$$R^2 = 0.99767 \quad (13)$$

Comparison and analysis

The results of creep strains with three kinds of loading levels showed that the KM with two elements in series was able to predict the short-term (3-h) creep behavior, and the correlation coefficients were all above 0.9. At the same loading level, the creep strains from high to low successively were L, R, and T. In addition, the creep strain of the L direction tended to stop and keep constant in the short term, which was different from the other two grain orientations; the creep behaviors of the R and T directions were very similar to each other. This conclusion was consistent with the result of Taniguchi et al. (2010), which can be taken into consideration for design of wood structures. Figure 6 shows the results of the three directions at different loading levels; it indicates that the creep strains increased with loading levels, growing within ultimate creep strength. In addition, Kutnar (2010) also confirmed this point that compression creep was not able to predict the creep during the densification process at high stress levels.

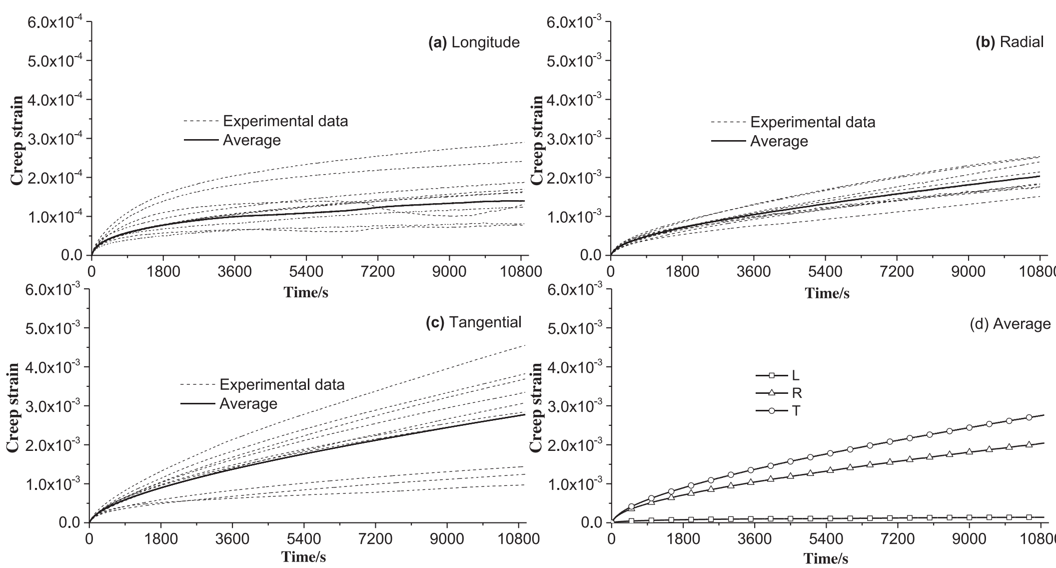

Figure 5.—Strain and time curves of creep behavior under 1,200 N loading level.

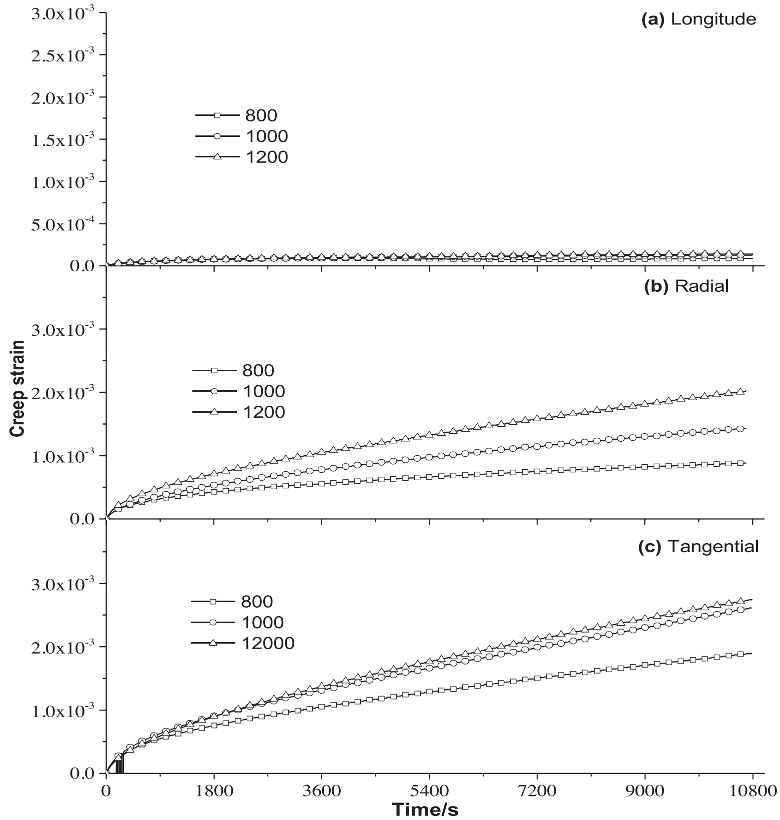

Figure 6.—Creep strain and time curves of beech in three directions under different loading levels.

Results of parameters used in FEM

The logarithmic linearization regression fitting curves of L, R, and T are shown in Figures 7a, 7b, and 7c, respectively. Meanwhile, with Equation 3 as the function of $\log(\varepsilon^{cr})$ and $\log(t)$, the corresponding functions of them are shown in Equations 14, 15, and 16, respectively.

$$\log(\varepsilon_L) = 0.39309\log(t) - 5.44731 \quad R^2 = 0.95465 \quad (14)$$

$$\log(\varepsilon_R) = 0.54988\log(t) - 5.04083 \quad R^2 = 0.99532 \quad (15)$$

$$\log(\varepsilon_T) = 0.55881\log(t) - 4.93093 \quad R^2 = 0.99413 \quad (16)$$

Then set Equation 3 as the function of $\log(\varepsilon^{cr})$ and $\log(\sigma)$; the results are shown in Figure 7d, and the corresponding functions are Equations 17, 18, and 19 for each orientation of beech. The values of parameters A, m, and n for three directions of beech were calculated according to the method above, and the results are shown in Table 2.

$$\log(\varepsilon_L) = 1.89183\log(\sigma) - 4.63230 \quad R^2 = 0.99598 \quad (17)$$

$$\log(\varepsilon_R) = 2.08594\log(\sigma) - 3.66278 \quad R^2 = 0.91724 \quad (18)$$

$$\log(\varepsilon_T) = 1.34155\log(\sigma) - 3.11475 \quad R^2 = 0.93876 \quad (19)$$

Results of FEM

The 12-hour compression creep behavior of beech was analyzed by FEM under 1,000 N loading level with parameters calculated using 3 hours of experimental data. Figure 8 shows the results of creep deformations of beech based on FEM. Figure 8a shows the initial state of the compression test without applying load, and Figure 8b shows the state that the load just reached at 1,000 N. In addition, the creep deformation increased with the growth of time, which is shown in Figure 8c, and Figure 8d shows the state at the end of the 12 hours. In addition, Figure 9 shows curves of creep strain and time analyzed by FEM in three directions of beech.

Comparison and verification

In order to verify the validity of the FEM, an experiment was carried out using 12 hours of creep tests, and the results were compared with those of FEM and the KM. Figure 10 shows the comparison of them in three directions of beech, which suggests the curves of FEM, KM, and the experiment were similar to each other in the L direction of beech, and creep deformations stopped after a short time and stayed constant. However, for the R and T directions, accuracies of FEM and KM were all acceptable within the short-term

Table 2.—The parameters used in finite element method (FEM) for three directions of beech.

Direction[a]	FEM parameters		
	A	n	m
L	2.38064E−07	1.936193	−0.63691
R	5.73546E−07	2.424092	−0.45012
T	2.05684E−06	1.302724	−0.44119

[a] L = longitudinal; R = radial; T = tangential.

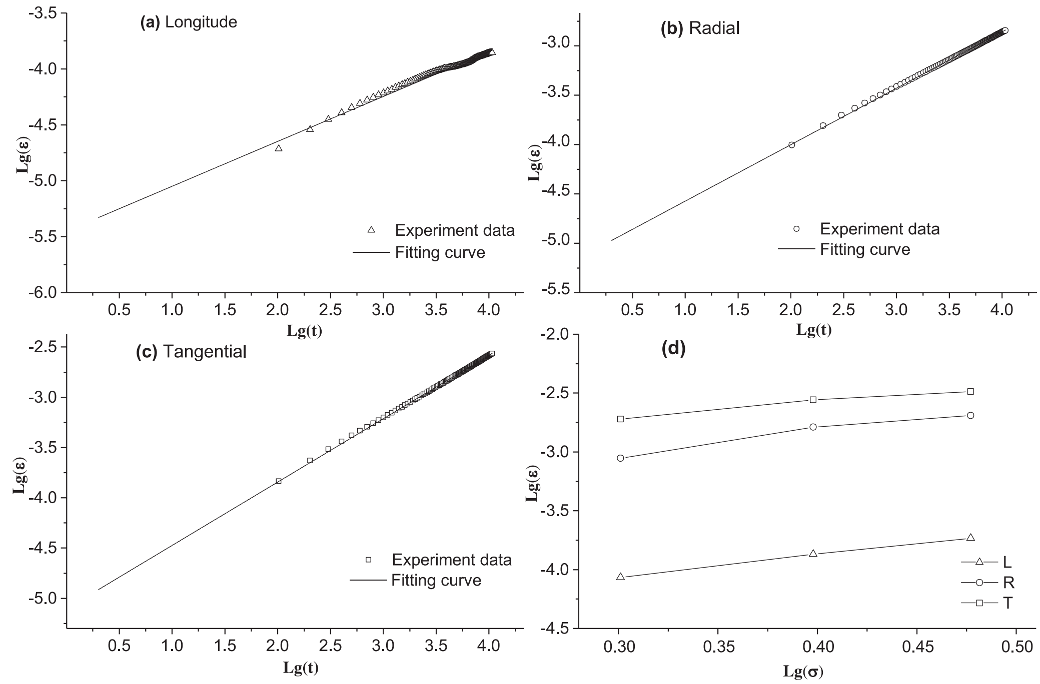

Figure 7.—Curves of log(ε) – log(t) and log(σ) – log(t) under 1,000 N in three directions.

creep, but the differences were significant when the time was beyond 12 hours. In addition, the creep deformation of the three methods after 12 hours are listed and compared in Table 3.

Table 3 shows that the result of FEM was more accurate than that of KM except for the L grain orientation, because the creep deformation of the L direction was so small that the deviation of the experiment was relatively larger. In addition, the error between FEM and the experiment was within a standard deviation of the experiment in R and T orientations. Meanwhile, the error between FEM and the experiment was acceptable, so the FEM was accurate enough for the purpose of engineered design. Compared with other studies, most of them were concentrated on creep of timber under bending force (Mackerle 2005, Fortino et al. 2009), and few reports had been made about compression creep analyzed by FEM.

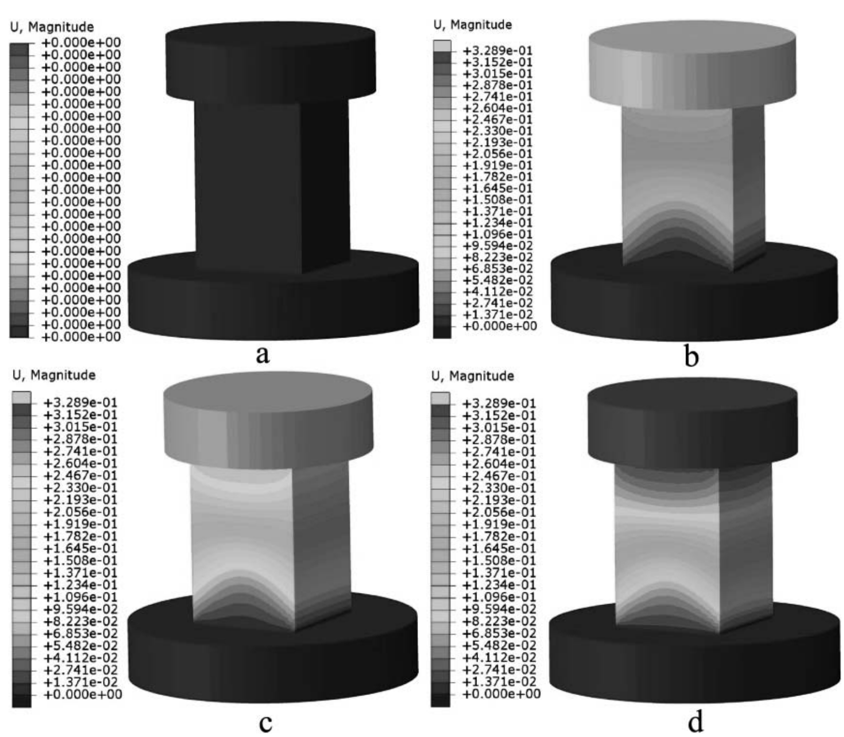

Figure 8.—Process of creep deformation based on finite element method.

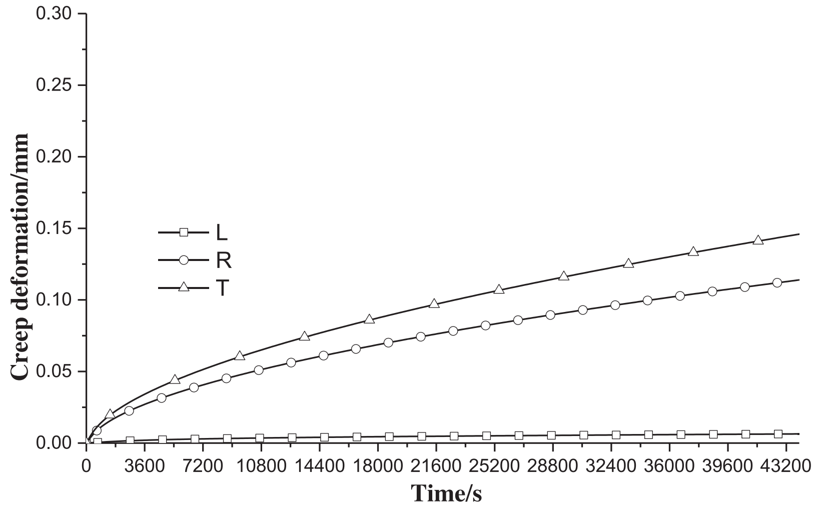

Figure 9.—Results of finite element method in three directions of beech: longitudinal (L), radial (R), and tangential (T).

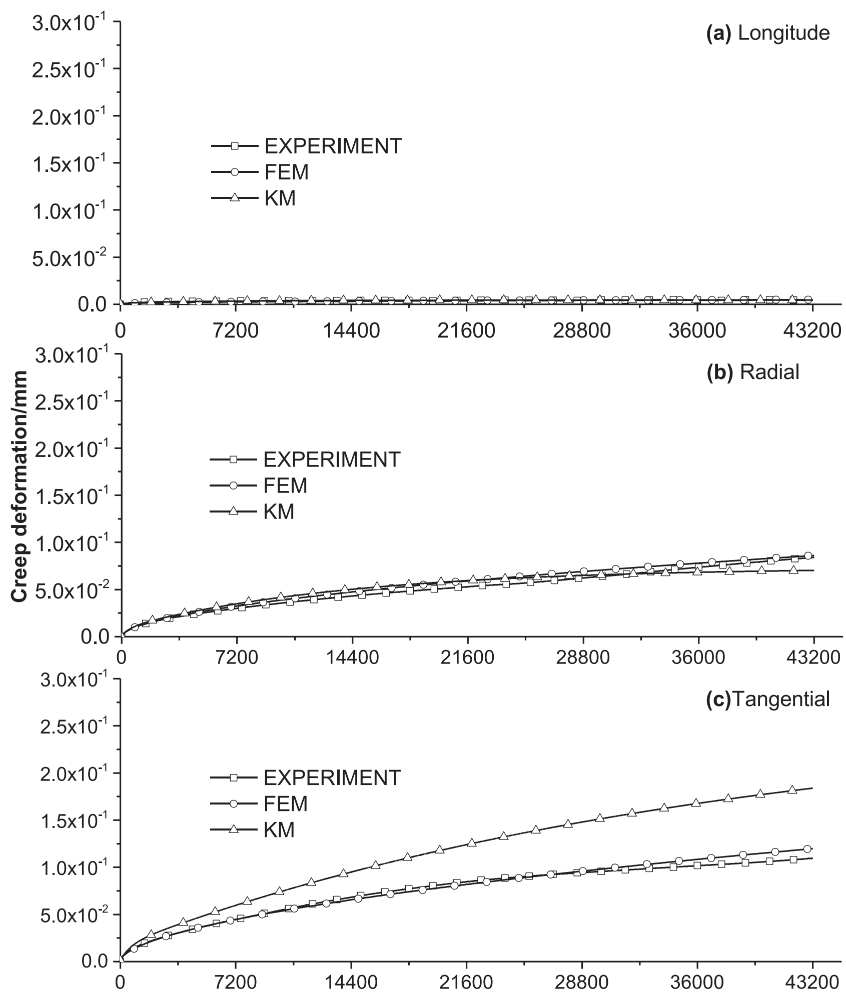

Figure 10.—Comparison of experiment, finite element method (FEM), and Kelvin model (KM) under 1,000 N.

Table 3.—The results of creep deformation and comparison of three methods.[a]

Direction	Creep deformation/mm				Error %	
	Experiment	KM	FEM	SD	KM	FEM
L	0.00423	0.00461	0.00481	0.00067	8.98	13.7
R	0.08405	0.07029	0.08608	0.0101	16.4	2.42
T	0.10965	0.18394	0.11980	0.0112	68.8	9.23

[a] KM = Kelvin model; FEM = finite element method; SD = standard deviation of the experiment; L = longitudinal; R = radial; T = tangential.

Conclusions

The method of evaluating the long-term (12-h) compression creep behavior of beech by FEM was introduced in detail. First, the parameters needed in FEM were obtained by short-term (3-h) compression experiments, and then a long-term (12-h) compression test was analyzed by FEM. Finally, the results of FEM were compared with those of the experiment and KM with two elements in series. The conclusions drawn were as follows.

1. The creep deformation increased in three orientations of beech in the order of longitudinal (L), radial (R), and tangential (T) directions successfully under the same loading level.
2. The creep deformation of the L direction stopped after a short time and stayed constant, but the other two orientations did not. The creep deformation in the same orientation increased proportional to loading levels from 800 to 1,200 N.
3. The KM with two elements in series can predict the short-term (3-h) creep behavior in three directions of beech, and the correlation coefficients were all above 0.9. However, this model could not predict the long-term (12-h) creep behavior.
4. The results of FEM in three orientations were consistent with that of the experiment, and the errors in the L, R, and T directions were all within the standard deviation of the experiment, which satisfied the request of engineered design. However, results of the KM were significantly different from the experiment after 9 hours of creep.

In conclusion, the method introduced in this study was capable of predicting the long-term (12-h) creep behavior of beech, and a further study will be focused on the long-term creep behavior of wood structures and products. In addition, it is of interest to study the relaxation behavior of wood by FEM.

Acknowledgments

This study was supported by the National Forestry Public Welfare Industry Research, Special project no. 201204700202l, and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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