CREEP AND CREEP-RECOVERY MODELS FOR WOOD UNDER HIGH STRESS LEVELS

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ABSTRACT

Forty small clear southern pine specimens were loaded under third-point bending to examine creep and creep-recovery behavior for wood under high stress levels. Stress levels of between 69% and 91% of the predicted static strength were applied for 23 h with 1 h allowed for recovery, and the resulting deflection vs. time behavior was studied. The experimental creep and creep-recovery behavior was modeled using modified power law functions. The results indicate that these functions provide the best fit to both primary and secondary experimental data. The empirical models can be used to simulate the viscoelastic behavior of wood under high stress levels. The simulation will provide a useful tool in future studies to examine duration-of-load (DOL) effect, which is one of the more important factors in wood structural design.

Keywords: Creep, recovery, duration-of-load, model, clear specimen, high stress level, southern pine.

INTRODUCTION

For purposes of stress analysis, wood may be considered a linearly elastic material under some conditions and as a linearly viscoelastic material under others (Schniewind and Barrett 1972). In the design of wood structures, the assumption is made that wood is an elastic material and that the deformation response to stresses is linear and completely reversible (Suchsland and Woodson 1990). For all practical purposes, at relatively low stress levels, this assumption is justified. In reality, how-

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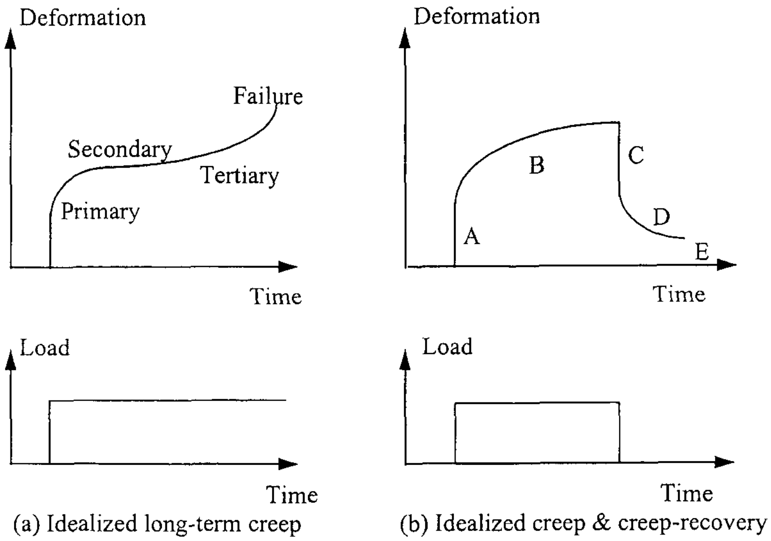

FIG. 1. Idealized (a) creep-rupture and (b) creep and creep-recovery.

ever, wood and wood-based composites include plastic response components that result in more complex behavior under stress, particularly high stress conditions. Materials that possess such time-sensitive plastic components are termed viscoelastic materials (Suchsland and Woodson 1990). Wood and wood-based composites are viscoelastic materials and their viscoelastic behavior dominates the overall response when they are under high stress. Creep rupture, also known in wood engineering as duration-of-load (DOL) effect, is exhibited by an apparent reduction in strength of a wood member under sustained load. Studies of creep and creep-recovery under high stress levels are essential to further understand the DOL effect, which is poorly understood yet is one of the more important adjustment factors in wood structural design.

There are two kinds of typical deformation response curves for viscoelastic materials: the first is creep rupture (failure) and the second is creep and creep-recovery (deformation) (Pentoney 1962). Both are illustrated in Fig. 1. Creep is usually defined as the time-dependent deformation resulting from a constant sustained load (Pentoney 1962). The long-term creep (Fig. 1a) is composed of four stages: (1) primary creep; (2) secondary creep; (3) tertiary creep; and (4) failure. Typically, deformation increases more rapidly in the primary and tertiary stages than in the secondary stage. Creep and creep-recovery (Fig. 1b) are divided into five stages (A, B, C, D, and E). Stage A is the initial and immediate elastic response to the applied load, and stage B demonstrates that a viscoelastic material continues to deform under constant load. When the load is removed, only the elastic deformation component is recovered immediately (stage C). The viscoelastic deformation component is recovered gradually and incompletely (stage D). Stage E shows permanent plastic deformation.

Elastic springs and viscous dashpots in various combinations are used oftentimes to represent the viscoelastic behavior of materials. Forms of the simplest viscoelastic models are the Maxwell, Kelvin, Linear, and Burger models (Gittus 1975), as shown in Fig. 2. Equations of creep behavior for the simplest viscoelastic models can be presented as follows: Equations (1) to (4) are produced according to Maxwell, Kelvin, Linear, and Burger models, respectively.

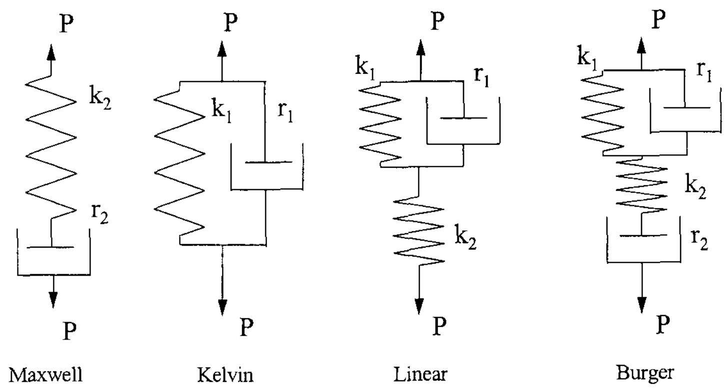

FIG. 2. Simplest models for viscoelastic material.

$$U = \frac{P}{k_2} + \frac{P}{r_2}t \tag{1}$$

$$U = \frac{P}{k_1}\left[1 - \exp\left(-\frac{k_1 t}{r_1}\right)\right] \tag{2}$$

$$U = \frac{P}{k_2} + \frac{P}{k_1}\left[1 - \exp\left(-\frac{k_1 t}{r_1}\right)\right] \tag{3}$$

$$U = \frac{P}{k_2} + \frac{Pt}{r_2} + \frac{P}{k_1}\left[1 - \exp\left(-\frac{k_1 t}{r_1}\right)\right] \tag{4}$$

where U is the creep deflection under constant load P for a period of time t; k_i is elastic constant for springs; and r_i is viscous constant for dashpots (i = 1 and 2). Equation (1) was modified as the power law creep model, which has another model constant n (Bodig and Jayne 1982):

$$U = \frac{P}{k_2} + \frac{P}{r_2}t^n \tag{5}$$

The power law creep model has been shown to effectively represent creep behavior of wood, especially for the primary creep range (Bodig and Jayne 1982; Gerhards 1991; Soltis et al. 1989). Gerhards (1985 and 1991) tested Douglas-fir 2 by 4 beams of different grades under various constant load levels. It was concluded that the bending creep of wood beams that did not have partial failure could be modeled using the power law function. Soltis et al. (1989) tested one hundred 2 by 4 specimens (12 ft (3.66 m) long) subjected to constant tensile and compressive loads. The average stress level (defined as applied stress divided by the predicted ultimate strength) was 71%. Overall creep (primary and secondary creep) was modeled by the power law function. However, Soltis et al. found that a linear function (i.e., n = 1) would provide a better fit for the secondary creep portion.

Senft and Suddarth (1971) tested small clear specimens of Sitka spruce under a compressive loading parallel-to-the-grain to examine the adequacy of the linear and Burger creep models. Stress levels of 10, 20, 40, and 60% were used, and it was concluded that the linear model fit the primary creep data accurately, while the Burger model fit the secondary creep data well.

There have been a number of empirical creep models that were developed to describe creep and recovery behavior of wood-based materials (Bodig and Jayne 1982; Gerhards 1985, 1991; Fridley et al. 1992). The power law term and exponential term are two fundamental forms used for empirical curve fitting. The techniques used to determine model constants include both graphical and formal statistical methods. The fitting of the power law and exponential equations to data are sensitive to the curve shape or data trend. The power law curve fitting works well for the primary creep whose slope changes more rapidly, while the exponential curve fitting works well for the secondary creep that is relatively flat (the change of its slope is small). Under high stress, the deflection-time curve includes both primary and secondary creeps and makes it difficult to fit using the power law and exponential curve fittings.

The objective of this paper is to present empirical creep and creep-recovery models that can accurately describe the primary and secondary creep and the recovery of small clear specimens subjected to relatively high stress levels. The empirical models under high stress will provide a numerical model for use in future (e.g., simulation based) studies of DOL effects on wood.

MATERIALS

Small clear test specimens were cut from southern pine 2 × 4s obtained from the Westvaco Mill, Summerville, SC. The specimens were conditioned in an environmental control chamber set to approximately 36% RH and 28°C (82°F) for approximately 17 months. Clear sections 660 mm (26 in.) in length were cross-cut from the 2 × 4 lumber. An edge-matched pair of the specimens was obtained by ripping the clear section lengthwise. The resulting edge-matched specimens (each approximately 38 × 38 × 660 mm) were randomly separated into two sets (A and B) with 60 specimens in each set. The density of the specimens was obtained by measuring the dimensions and weight at the current moisture content. Specimens were tested under third-point loading test with a support span of 610 mm (24 in.). All specimens were tested with the pith side down and under load control at a rate of 33.4 N/s (7.5 lb./s). Specimens in the control set (set A) were loaded to failure and modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated. The moisture content of each specimen was measured by cutting a small sample (about 38 mm (1.5 in.) long) approximately 50 mm (2 in.) from an end of the specimen. The average moisture content was 8.1% with a coefficient of variation of 2.4%.

TABLE 1. *Average mechanical properties of test specimens.*

	Number of specimens	Density (kg/m^3)[a]	MOE (10^9 N/m^2)[b]	Pre-MOR[c] 10^6 N/m^2
Max.	40	670.67	16.64	112.45
Min.	40	546.96	10.04	91.95
Average	40	598.71	14.27	100.78
COV %	0	4.9	11.9	5.4

[a] 1 kg/m^3 = 0.0624 pcf.
[b] 1 N/m^2 = 1.45 10^{-4} psi.
[c] Applied stress level is defined as applied stress divided by the predicted MOR.

Specimens in the second test set (set B) were loaded within their elastic ranges and MOE values were calculated from the slope of the load-deflection curve, dimensions, and the test configuration. MOR is known to correlate well with MOE and density (Cai et al. 1998), and the MOR of each specimen in the test set was predicted from the control set using the MOR relationship with MOE and density. The specimens were ranked-ordered with respect to their predicted MORs. The central 40 specimens were selected and divided into 10 groups of four so that MORs in each group were as close as possible. The average MOR in each group was used to determine the applied stress level. The average mechanical properties of the test set are given in Table 1.

EXPERIMENTAL PROCEDURE

The research reported herein was a part of a parent project focused on the experimental investigation of damage accumulation in wood. Therefore, the experimental program was designed to investigate creep rupture and creep behavior of wood at relatively high stress levels. The test procedures are briefly outlined in this paper. A schematic of the test setup is shown in Fig. 3. A hydraulic pump unit (not shown in the figure) was used to provide the necessary fluid pressure to a manifold. The manifold then equally transfers the pressure to five hydraulic cylinders, each with its own pressure meters. The cylinders then provide designated loads to test specimens. Four linear variable displacement transformers (LVDTs) were used to measure the midspan

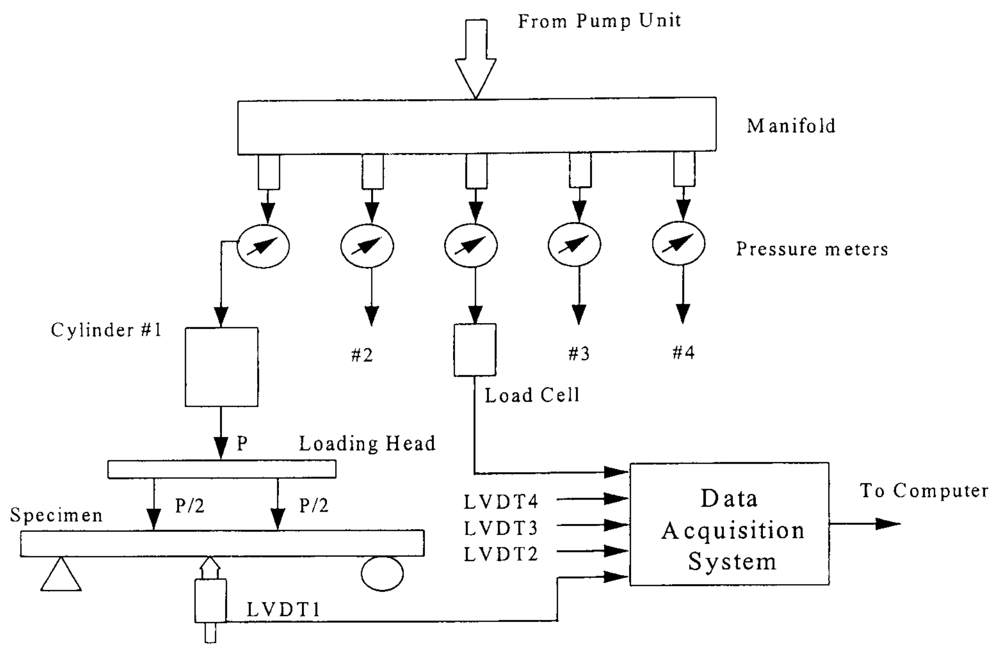

FIG. 3. Schematic of test setup.

deflections for the test specimens. One of the five cylinders (unnumbered in Fig. 3) was not used to test a sample; rather in its place a 22.2 kN (5000 lb.) load cell was used as a load indicator. A data acquisition system (DAS) was used to collect both load and deflection data automatically and simultaneously. To insure that the setup worked properly, the load cell, LVDTs, and the data acquisition system were carefully calibrated. This setup can be used to test four specimens simultaneously; however, Fig. 3 shows only a representative test specimen. Third-point loading with a simple support span of 559 mm (22 in.) was used in the five-day load test.

LOAD SEQUENCE AND DATA COLLECTION

Five one-day load pulses with the stress levels being the same for all pulses were used to investigate damage accumulation in the parent project. Thirteen specimens failed during the first day loading period. The individual failing stress level varies from 69% to 91%. In order to make the maximum use of samples and to compare the model parameters, only data from the first day loading are used herein to model creep and creep-recovery. The duration of the load pulse was 23 h with 1 h allowed for recovery. The applied stress level for each specimen with respect to the predicted MOR is provided in Table 2.

TABLE 2. *Average creep model parameters of test specimens.*

Specimen ID	Applied SL*	Creep model parameters				
		a	b	c	m	R^2
Max.	0.91	0.1979	−1.40E-06	0.1500	0.2150	0.99
Min.	0.69	0.0112	−1.23E-03	0.0150	−0.4786	0.76
Average	0.80	0.0718	−6.32E-05	0.0629	−0.1167	0.95
COV %	9.0	68.0	−371.8	50.8	−85.5	6.0

* Applied stress level is defined as applied stress divided by the predicted MOR.

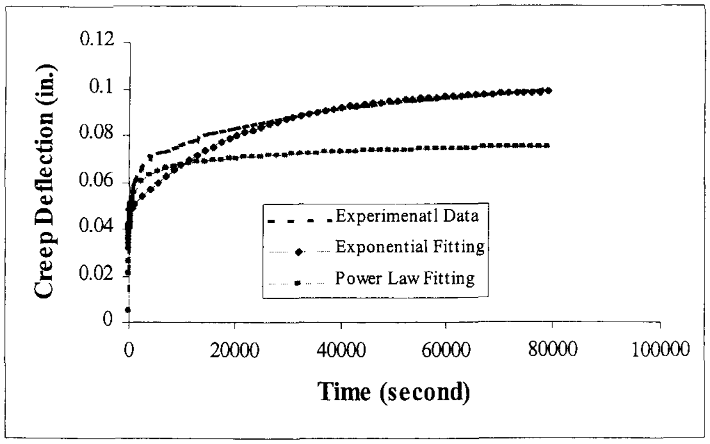

FIG. 4. Creep deflections predicted by existing creep models.

After the load reached the designated level, it remained constant with the DAS collecting the load/deflection data at a sampling rate of one reading every 2 s for about 15 min. This allowed the DAS to sample enough deflection data points to describe the initial elastic deformation and primary creep. The sampling rate was then reduced so as to collect data every 300 s in order to save data storage space. The rate of one reading every 300 s remained unchanged until unloading. Shortly before the specimens were unloaded, the sampling rate reverted back to one reading every 2 s so that more deflection readings could be taken. The DAS then collected the data at this rate for at least 20 min after the specimens were unloaded.

CREEP MODEL DEVELOPMENT

There are many creep models (with model parameters to be determined) that have been developed to describe creep behavior. Obviously, the fewer creep (or creep-recovery) parameters and the more accurate the relationship, the easier it will be to utilize the model.

Two of the simplest existing creep models examined in this paper were:

$$U = c - at^{m} \tag{6}$$

$$U = c - ae^{nt} \tag{7}$$

where U is creep deflection, defined as the difference between the total deflection and the instantaneous elastic deflection; c is the asymptotic creep deflection when time t approaches infinite; and a, m, and n are model parameters. Equation (6) is a power law fitting, while Eq. (7) is referred to as an exponential fitting. The two equations can be transformed to linear forms by taking the logarithm, thus allowing a linear regression with the experimental data to be used. The results of the regressions with a typical creep data set from this study are shown in Fig. 4. The power law curve fits in the primary creep range, while the exponential curve applies in the secondary creep range. However, none of the curves fits all of the experimental data very well.

A new creep model was created based on the power law creep model. Since there were large differences in predicting creep during the secondary creep range for the power law creep model, a modification term was added. The new creep model was:

$$U = c - at^{m+bt} \tag{8}$$

where b is another model constant. By reorganizing the above equation and taking the logarithm of both sides, the following equation was obtained:

$$\ln(c - U) = \ln a + m\ln t + bt\ln t \tag{9}$$

Equation (9) has a multiple linear form if ln(c

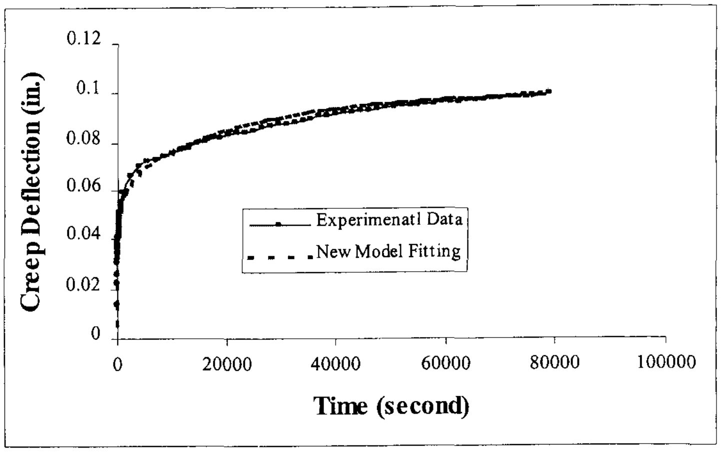

FIG. 5. Creep deflections predicted by the new creep model.

$- U$) is considered as a response variable and $\ln t$ and $t \ln t$ are considered as predictor variables. There is probably collinearity between the two predictor variables. However, "collinearity is a nonstatistical problem that is nevertheless of great importance to the efficacy of least-square estimation" (Belsley et al. 1980). The model constants of the new creep model can be obtained by performing multiple regression on the experimental data. A typical regression result of the new creep model is shown in Fig. 5. It is clear that the new model provides the best fitting curve not only for the primary creep but for the secondary creep as well. Creep is a related mechanism to the reduction in strength of a wood member under sustained stress, or creep rupture. Usually, when the creep increases, it indicates that there is more damage in the wood member or the strength reduces more. This is also known as duration-of-load effect in wood engineering. Although the new model is created empirically and it is difficult to relate the model constants to physical mechanisms, it predicts the creep very well. The model parameters that describe creep and creep increment may be at least empirically related to the duration-of-load effect. To confirm or create the relationship, however, further study is needed.

CREEP-RECOVERY MODEL DEVELOPMENT

The new creep-recovery model was created by using the same procedure as described above. The following three equations were fit to the experimental creep-recovery data.

$$\Psi = c + at^{m} \tag{10}$$

$$\Psi = c + ae^{nt} \tag{11}$$

$$\Psi = c + at^{m+bt} \tag{12}$$

where Ψ is the creep-recovery deflection, defined as the difference between the total recovery deflection and the instantaneous recovery deflection; and c, a, m, and n are model parameters. The results of curve fitting with a typical set of recovery data are shown in Fig. 6. The power law fitting curve (Eq. 10) fits best in the earlier stage of the delayed elastic recovery, while the exponential fitting curve (Eq. 11) fits best in the later stage of the delayed elastic recovery. The new creep-recovery model (Eq. 12) provided the best overall fit.

IMPLEMENTATION AND DISCUSSION

Forty small clear specimens of southern pine were loaded under third-point bending to examine creep and creep-recovery behaviors for wood. Applied stress levels varied between 69% and 91% of predicted strength. Two spec-

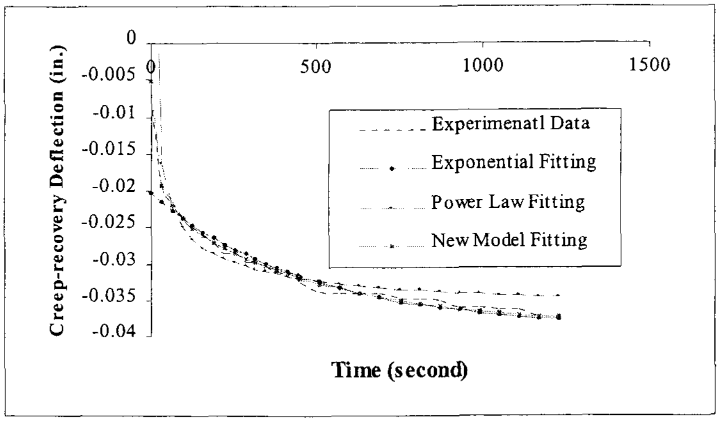

FIG. 6. Creep-recovery deflections predicted by existing models and the new model.

imens failed during the ramp loading, and thus no creep and creep-recovery data were collected. Eleven specimens failed during the constant loading, and thus no recovery data were available for these specimens as well. The remaining twenty-seven specimens survived the 23-h load pulse. Parameters of creep and creep-recovery were determined by performing the multiple linear regression for the new creep and creep-recovery models. Table 2 presents the average new creep model constants for the test specimens. Table 3 presents the average new creep-recovery model constants for the test specimens. A large difference exists among values of each model parameter, even for specimens under similar applied stress level. For example, two specimens are loaded under the same stress level, but their creep model parameter *a* varies between 0.0165 and 0.0656. This makes it difficult to relate the model constants to any physical factors. This observation is similar to that made by Soltis et al. (1989) when they used the power law model to fit their experimental data.

Five one-day load pulses with the stress levels being the same for all pulses were used to investigate damage accumulation in the parent project. Only data from the first day loading were used herein to model creep and creep-recovery. However, the new models were also used in the parent project to describe creep and creep-recovery behavior of test specimens under other load pulses (Cai 1997). The creep and creep-recovery model constants were obtained for each load pulse and plotted against the load sequence, respectively. Because of the variations of model constants during the five one-day load sequence, no useful trend was observed to relate changes of these model constants to the load sequence effect. In other words, there is no statistical difference in creep and creep-recovery behavior among each load pulse. However, high coefficients of determination (average R^2 = 0.95) demon-

TABLE 3. *Average creep-recovery model parameters of test specimens.*

Specimen ID	Applied SL*	Recovery model parameters				
		a	b	c	m	R^2
Max.	0.91	0.0505	−1.31E-04	−0.0099	−0.0983	0.99
Min.	0.69	0.0102	−3.10E-04	−0.0623	−0.2327	0.74
Average	0.80	0.0245	−2.47E-04	−0.0254	−0.1666	0.97
COV %	9.0	40.4	−14.9	−49.0	−18.8	5.6

* Applied stress level is defined as applied stress divided by the predicted MOR.

strate that the new models fit the experimental data very well, especially in both primary and secondary creeps. The model parameters that describe creep and creep increment may be related to the duration of load effect in a single load pulse. In the future, the research will be focused on the creep performances of the 11 specimens that failed during the first day loading. Hopefully, the creep model parameters along with some other properties (like MOE, density, and grain direction) could be used to simulate DOL behavior.

CONCLUSIONS

This paper presents new creep and creep-recovery models developed as part of a parent project that was focused on the experimental investigation of damage accumulation in wood. Creep and creep-recovery behavior of small clear specimens subjected to relatively high bending stresses were examined and modeled using a modified power law function. The new models were shown to provide the best fit to both primary and secondary experimental data. The new models were used in the parent project to describe creep and creep-recovery behavior of test specimens subject to five one-day constant-amplitude load sequences. The creep and creep-recovery model constants were obtained for each load pulse and plotted against the load sequence, respectively. No useful trend in the model constants during the load sequence was observed to relate changes of these model constants to load sequence effect on creep. Future studies will be focused on the creep behavior of specimens that failed during a single load pulse.

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