A REVIEW OF CREEP IN WOOD: CONCEPTS RELEVANT TO DEVELOP LONG-TERM BEHAVIOR PREDICTIONS FOR WOOD STRUCTURES

Siegfried M. Holzer, Joseph R. Loferski, and *David A. Dillard*

Professor of Civil Engineering, Assistant Professor of Forest Products,
and Associate Professor of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

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ABSTRACT

A review is presented of the effects of constant and transient moisture and temperature conditions on the time-dependent behavior of wood as a material and as a structural element. A rational approach towards the identification of long-term behavior of wooden structures is proposed. Utilizing the fact that wood is a combination of several polymers, polymer viscoelasticity concepts are suggested to enhance the predictive capabilities. A finite element procedure is outlined to indicate how design predictions can be made. Some attention is given to structures such as domes where creep of the wood could lead to structural instabilities.

Keywords: Creep, creep models, time-dependent modeling, creep buckling, finite element, long-term predictions.

NOTATION

The following symbols are used in this paper:

A_1, A_2, m, n = material parameters
E_o, E_i = spring constants
$J(t)$ = compliance at time t
J_o = initial compliance
t = time
$\epsilon(t)$ = strain at time t
ϵ_c = creep strain
$\dot{\epsilon}_c$ = creep strain rate
ϵ_o = initial strain
η = viscosity
$\sigma(t)$ = stress at time t
τ = retardation time

INTRODUCTION

The time-dependent behavior of wood has been widely observed, and the following measures of time-dependent response are commonly used in experimental investigations: creep, the time-dependent deformation under constant load; relaxation, the stress decay under constant deformation; stiffness variation in dynamic mechanical analysis (Ferry 1980); and rate of loading (or straining) effects (Bodig and Jayne 1982). These basic techniques can also be generalized to include recovery (the recovery of strain once a creep load is removed) and more general

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loading histories (Barrett 1982). At least within the linear range of viscoelastic response, all of the above tests are interrelated by mathematical expressions, which, although simple in form, are often difficult to perform exactly (Ferry 1980). For measuring long-term behavior of materials, the transient tests are normally preferred over rate of loading or dynamic techniques. For relatively stiff materials, creep is normally selected over relaxation. Creep is also more consistent with the loading conditions imposed by dead and live loads on structures. A detailed discussion of rheological properties of wood is presented by Bodig and Jayne (1982).

Creep in wood has undergone extensive research, and valuable insight into the phenomenological behavior under a variety of environmental conditions has been gained. However, there exist no long-term creep laws (50 year) or practical methods to investigate the effect of creep on the safety and serviceability of wood structures over their design life.

In current wood design codes (NDS (1986), AITC (1985)), the consideration of creep is confined to a serviceability criterion: The creep deflection is defined as a multiple of the dead load deflection. However, creep can have a significant effect on the integrity of a structure. For example, long-term creep can magnify the short-term deflections in columns, compression panels, shallow arches, and shells through geometric coupling of axial (membrane) and bending actions (the P-Δ effect). This can lead to the reduction of stiffness and buckling failures (Hayman 1981). A recent study in this direction (Itani et al. 1986; Zahn 1987) was concerned with the effect of creep on initially crooked columns; however, it was confined to short-term creep (400 hours). The investigation of long-term creep is particularly important for glulam lattice domes (Triax Domes 1975; Varax Domes) because global elastic instability in the form of snap-through buckling is a dominant failure mode for shallow single layer domes (Holzer and Loferski 1987).

This failure mechanism was illustrated experimentally by Hayman (1981) in the creep-induced snap-through buckling of shallow 3-hinged concrete arches: Three arches were subjected to constant loads equal to 85%, 65%, and 35% of the short-term buckling load. All three arches collapsed suddenly after a period of time. Only a fourth arch with a load equal to 16.5% of the short-term buckling load did not collapse during the 10-month test period.

The purpose of this paper is to report on the status of long-term creep modeling of wood and the application of the finite element method to predict the long-term creep behavior of wood structures. The paper reviews the rheological properties of wood under constant and variable environmental conditions and presents guildelines for time-dependent modeling of creep and the analysis of creep problems by the finite element method.

CREEP IN WOOD

Analogous to concrete, wood is a special structural material that interacts with the environment to undergo complex changes in its properties. Accordingly, it is useful to organize the review relative to constant and variable environmental conditions. It was pointed out by Bodig and Jayne (1982) for wood and by Dillard et al. (1989) for composites that creep is often much more sensitive to temperature, moisture content, and physical aging than elastic properties. A similar sensitivity is evident in the loss versus storage moduli of a material.

Effects of environment

Many rheological studies of wood were concerned with identifying conditions under which wood may be modeled as a linear viscoelastic material. This is reflected in a review of creep experiments by Schniewind (1968). The experiments indicate that within certain limits of stress and at constant moisture content and temperature wood can be treated as a linear viscoelastic material. This finding has been confirmed by other studies (Bach 1965; Bazant 1985; Grossman et al. 1969; Nakai and Grossman 1983; Pentoney and Davidson 1962; Schaffer 1982). For example, Schaffer (1982) draws the following conclusion from evidence in the literature: "Wood behaves nonlinearly over the whole stress-level range, with linear behavior being a good approximation at low stresses. Because of this nearly linear response at low levels of stress, Boltzmann's superposition principle applies to stress-strain behavior for stresses up to 40% of short time strength."

Under variable temperature and moisture content, the time-dependent behavior of wood is very complex, especially when cyclic variations occur, and our knowledge is still fragmented. The results of phenomenological studies of environmental effects are presented, analogous to Schniewind (1968), for constant and variable conditions during a specific experiment.

Effects of temperature.—Creep tests at constant temperatures, over a wide range of temperature levels, were conducted on small specimens in bending, compression and tension parallel and perpendicular to the grain, shear, and torsion at various moisture contents, from green to oven-dry (Schniewind 1968). The overall effect of temperature was an acceleration of creep with increasing temperature (Davidson 1962). Specifically, Bach (1965) reported that the tensile creep parallel to grain of hard maple was proportional to the square of the temperature in the range of 30 C to 70 C. Similarly, Kingston and Budgen (1972) and Kingston and Clarke (1961) found from bending and compression tests in the range of 20 C to 50 C that temperature had a significant effect on creep.

The interaction of creep with variable temperature results in a complex behavior that may be difficult to predict from constant temperature creep tests (Schniewind 1968). For example, an increase in temperature in the range of 20 C to 50 C during a bending test resulted in a creep that was larger than the creep caused by constant temperature at the highest level (Kitahara and Yukawa 1964). Similar results have been reported by Arima (1972) and Urakami and Nakato (1966).

Effects of moisture.—Moisture in wood acts as a plasticizer; that is, creep increases with moisture content (Bodig and Jayne 1982; Schniewind 1968). This was observed in experiments with bending, torsion, tension and compression parallel and perpendicular to grain. For example, Bach (1965) deduced from tensile tests, with moisture contents in the range of 4% to 12%, that the creep compliance is proportional to the square of the moisture content. Moreover, the effect of moisture adsorbed below the fiber saturation point tends to be much greater on creep than on the initial deformation (Bodig and Jayne 1982).

Reviews on the effects of the interaction of moisture movement (drying and wetting) with the mechanical behavior of wood, called mechano-sorptive behavior (Grossman 1976), are provided by Schniewind (1968), Grossman et al. (1969), Grossman (1978), Johnson (1978), Bodig and Jayne (1982), and Bodig (1982). Early key papers on the subject were presented by Armstrong and Christensen (1961) and Hearmon and Paton (1964).

Experiments have demonstrated that changes in moisture content of the loaded specimen have a marked effect on the creep rate and the total creep. For example, Armstrong and Kingston (1960) observed that the relative creep of a loaded beam allowed to dry was at least twice that occurring in the loaded beam at constant moisture content.

The acceleration in creep of a loaded beam is even more pronounced under cyclic moisture changes (Armstrong and Christensen 1961; Hearmon and Paton 1964). This was illustrated, for example, in an experiment by Hearmon and Paton (1964): A small beech beam (2 × 2 × 60 mm) under ⅜ of the maximum short-time load was subjected to moisture cycling, each cycle ranging from completely dry conditions to 93% relative humidity. The beam broke in 28 days after undergoing 14 complete moisture cycles and having deflected 25 times the initial deflection.

Mechano-sorptive behavior of structures.—An important question for the designer is: to what extent can the mechano-sorptive behavior observed in the laboratory on very small specimens be realized by large structural members in the actual environment? Specifically, what is the effect of the range and period of the moisture content cycle and the size of the cross section on mechano-sorptive behavior? The following researchers addressed this issue to some extent.

Hearmon and Paton (1964) were interested in the relation between the increased deflection caused by moisture cycling and the range, the percent change, of the moisture content. They concluded that this relation appears to be linear. This suggests that a narrow range will result in a small increase in creep due to moisture cycling.

Armstrong and Christensen (1961) compared the behavior of two beams, 1 × 1 × 60 mm and 20 × 20 × 900 mm, to provide some indication of the size effect on the interaction of cycling moisture content changes with mechanical behavior. They observed that the behavior of the two beams was similar. However, while the time of the sorption process for the small beam was 2 to 3 hours, it took approximately 50 hours for the large beam. Thus, the slow rate of moisture migration in large structural members will reduce at least the rate of mechano-sorptive creep acceleration.

Schniewind and Lyon (1973) conclude from their experiments on the effect of specimen size: "As specimen size increases and severity of environmental changes decreases, creep-rupture life approaches that obtained with specimens at constant moisture content." Barrett (1982) compares trend lines obtained from the results of Schniewind (1967) and Schniewind and Lyon (1973) with the trend line for constant environmental tests from Wood (1951) and concludes: Environmental cycling would have "probably little or no effect on the behavior of large timbers and glued-laminated members."

Bodig (1982) states that large wooden members are less sensitive to moisture cycling than small pieces of wood; however, "The effect of moisture cycling can be quite significant and should be taken in account in design when structural wood members are exposed to cyclic moisture conditions."

Information about the moisture content in laminated timbers, classified according to geographical and seasonal variations and types of exposure, is provided by the U.S.D.A. Forest Service (Hann et al. 1970; Oviatt 1968). It was obtained from a 3-year study of representative laminated timber structures. The results show that there "was remarkably little geographical or seasonal variation in the moisture content of laminated timbers in interior normal exposure. Also the variation in readings [of moisture probes] within and between timbers was quite small" (Hann et al. 1970). Similarly, the range in moisture contents observed in protected exterior exposure was also quite narrow. However, moisture content in all geographical areas except the Rocky Mountain region in unprotected exterior exposure was extremely variable (Hann et al. 1970).

In light of the work by Arima (1972), one wonders if the more critical case of transient environmental conditions may be that of changing temperature. The higher values of thermal diffusivity than moisture diffusivity may result in more significant temperature changes in service.

Creep in connections

The structural performance of a wood building is closely related to the behavior of the joints or connections between the members. Analytical models that predict joint behavior are extremely complex due to the large number of influencing variables such as fastener characteristics, joint geometry, and material variability. Also, because of the large number of proprietary fasteners in the market place, no unified design method for connections has been developed, even for short-term loadings. Consequently, because of the complexity of the problem, few models have been developed to predict the long-term performance of timber connections. Most joint creep models are based on phenomenological studies of lateral-slip stiffness. For example, the reduction of lateral-slip stiffness over time has been studied and models were developed for dowel-type joints, including nails and bolts (Mack 1962, 1965; Brock 1968; Noren 1968; Kuipers 1977; Polensek 1982; Feldborg and Johansen 1987; Whale 1988), split ring connectors (Kuipers 1977), and toothed plate connectors (Kuipers 1977; Leicester et al. 1980).

In the most comprehensive study to date, Whale (1988) developed six models based on hereditary integrals for predicting lateral displacements in dowel-type joints subjected to varying load histories. Whale (1988) indicates that "At working load levels creep in the metal connector is almost negligible and the majority of joint creep is attributed to bearing creep of the wood in the immediate vicinity of the connection." This suggests that models based on polymer theories have potential for predicting creep in joints. However, because of the complex mechanisms of load transfer such models may be difficult to develop.

MATHEMATICAL MODELS OF CREEP IN WOOD

In order to represent creep in finite element models of wood structures, it is necessary to formulate constitutive equations that define the time-dependent material behavior rather than element behavior. Consequently, creep functions should be based on uniaxial tension or compression tests in which the response is not influenced by other factors such as the variable stress distribution in bending tests. The review of creep models is organized relative to constant and variable environmental conditions.

Constant environment

Available creep models can be divided into empirical models and mechanical models, also called rheological models (Bodig and Jayne 1982; Pentoney and

Davidson 1962; Schniewind 1968). Empirical analogs are obtained by fitting a mathematical function to experimental data. Mechanical models, composed of springs and dashpots, are used to simulate the viscoelastic behavior of materials. The analog representation of viscoelastic constitutive equations by spring and dashpot models has been justified by thermodynamics (Schapery 1966).

Details of representative experiments and creep equations are presented in Tables 1 and 2 for empirical and mechanical models, respectively. Commonly used empirical equations for creep compliance functions include:

$$J(t) = J_o + A_1 \log(t + 1) \tag{1}$$

$$J(t) = J_o + A_1 \log(t + 1) + A_2 \log^2(t + 1) \tag{2}$$

$$J(t) = J_o + mt^n \tag{3}$$

where A_1, A_2, J_o, m, n are material parameters. If these parameters are functions of stress, the material is nonlinear. Creep compliance for the mechanical analog in the form of a generalized Kelvin element is given by

$$J(t) = \frac{1}{E_o} + \sum_{i=1}^{n} \frac{1}{E_i}(1 - e^{-t/\tau_i}) + \frac{1}{\eta} \tag{4}$$

where E_o, E_i, τ_i, η are material parameters.

The choice of the appropriate compliance model depends on the researcher's preferences, the length of time being modeled, the degree of accuracy required, and the intended use of the model. The phenomenological models (Eqs. 1–3) can work well over limited time domains. The power law form (Eq. 3) is widely used in the polymer field (Dillard and Hiel 1985), and, as will be discussed later, may have some predictive capability. For varying load histories, each of these models needs some type of superposition integral. Although computationally inefficient, this is straightforward for linear materials. Simple forms are not readily available for most nonlinear situations. The mechanical analog model is only valid over the time span for which the parameters are calculated. Computationally efficient recursive relationships are available for linear and nonlinear systems (Zienkiewicz and Cormeau 1974; Henricksen 1984).

Variable environment

Several investigators have been concerned with the development of models to simulate mechano-sorptive behavior in wood: Leicester (1971) devised rheological models that include "mechano-sorptive elements" to fit experimental data. He proposed a first approximation model for beam deflection, which was tested by Grossman (1971) who concluded it had value. Schaffer (1972) introduced a model to explain the change of creep response with changing moisture content by considering the effect of diffusion of moisture within the loaded specimen. Ranta-Maunus (1975) expressed the creep strain arising from variations in moisture content in integral (hereditary) form on the basis of hydroviscoelasticity theory. The model was applied to published experimental results. Bazant (1985) proposed a speculative model of the effects of variations in moisture content and temperature on creep based on thermodynamics of the process of diffusion of water in wood. The model reflects qualitatively some experimental results. Quantitative fitting of test data was not attempted. Mukudai and Yata (1986, 1987) proposed

TABLE 1. *Creep tests in constant environments: empirical models.*

Specimen	Load test	Stress level	Test period	Moisture content	Temperature	Creep equations	Reference
Douglas-fir (1 × 1 × 22 in.)	bending	60 to 95%*	10 years	6 and 12%	75 and 80 F	Equation 3	Clauser (1959)
Domestic and tropical species	tensile parallel to grain	6 to 86%*	30 minutes	12%	75 to 80 F	Equation 1	King (1961)
Hard maple (3.5 × 4.5 × 47 mm)	tensile parallel to grain	20 to 80%*	1,000 minutes	4 to 12%	30 to 70 C	Equation 2	Bach and Pentoney (1968)
Douglas-fir	twisting and tensile	linear	1,000 minutes	10%	72 F	Equation 3	Schniewind and Barrett (1972)
Douglas-fir (89 × 89 × 4,900 mm)	bending	linear	400 hours	12%	70 F	Equation 3	Hoyle et al. (1985)
Spruce, pine, beech	bending	linear	10 years	12%	20 C	Equation 3	Gressel (1984)

* Of ultimate short-term strength.

TABLE 2. *Creep tests in constant environments: mechanical models.*

Specimen	Load test	Stress level	Test period	Moisture content	Temperature	Creep equations	Reference
Hoop pine (0.8 × 0.8 × 36 in.)	bending	linear and nonlinear	50 days	green and air dry	21 C	Equation 4 with n = 3, 4	Grossman and Kingston (1954)
White pine, red cedar, sugar maple (10 × 20 × 300 mm)	bending	linear	6–10 hours	15.8–20.5%	20–60 C	Equation 4 with n = 40 without flow term	Davidson (1962)
Teak (3.2 × 9.5 × 64 mm)	tensile parallel to grain	linear and nonlinear	8 days	12.5%	30 C	Equation 4 with n = 2 without flow term	Bhatnagar (1964)
Finland	compression parallel to grain	linear and nonlinear		15%		Equation 4 with n = 1 without flow term	Ylinen (1965)
Sitka, spruce	compression parallel to grain	10–60%*	20 days	93%	31C	Equation 4 with n = 1	Senft and Suddarth (1971)
Hinoki (5 × 15 × 350 mm)	bending	linear and nonlinear	10 hours	11%	25C	Equation 4 with n = 3	Mukudai (1983)
Spruce, pine, beech	bending	linear	10 years	12%	20C	Equation 4 with n = 1	Gressel (1984)

* Of ultimate short-term strength.

a model for viscoelastic behavior of wood under moisture change. Good agreement was observed between the model response and published experimental results.

Schaffer (1982) was also concerned with the design of structural timber members to sustain loading during fire exposure. He developed a nonlinear (in stress) viscoelastic-plastic model based on thermodynamic constitutive theory (Schapery 1966). The model was correlated with experimental creep data, and Schaffer concluded that the resultant qualitative model sufficiently characterizes the viscoelastic-plastic response of dry wood parallel to the grain. Viscoelastic behavior of wood in changing environments is considered by Tang (1980).

TIME-DEPENDENT MODELING

The preceding review reflects the extensive research effort that has been expended to study time-dependent properties of wood. Although some studies have been quite comprehensive, much of the work provides only fragmented insights into the overall problem of viscoelasticity of wood. Many of the studies have been empirical and their validity is limited to a specific species, specimen geometry, and environmental condition. In an effort to glean information from these past studies and extend the scope to develop a rational design approach that can account for time-dependent behavior of wooden structures, the following guiding concepts are presented. They are drawn from the wealth of polymer time-dependent theories and may be used in a specialized finite element approach to model time-dependent behavior of wooden structures.

The time-dependent behavior of wooden structures can be examined at several levels, which include 1) polymer, 2) microstructure, 3) continuum (material properties), 4) structural element, and 5) structure levels. Failure to consider any one of these levels is likely to leave an imperfect understanding of how to predict long-term behavior. These levels are important building blocks for developing a rational approach to structural design with wood.

The wood cell contains three polymers: cellulose, hemicellulose, and lignin. Cellulose, the primary constituent, is arranged in microfibrils. Lignin and hemicellulose serve as the matrix to bind the fibrils together. Although the polymer composite is complex, it obeys general polymer physics principles. Thus we anticipate that to a certain extent, concepts such as time-temperature superposition will be applicable, if only in a thermorheologically complex sense. Although one can conduct phenomenological rheology studies to curve fit rather arbitrary mathematical models to experimental data, the insights gained into long-term prediction capabilities and justification cannot be as great as could be derived from a molecular rheology approach (Pentoney and Davidson 1962).

The unique cellular microstructure of wood suggests reasons for observed behavior. For example, the creep of wood in shear is less than the creep perpendicular to the grain (Schniewind and Barrett 1972). This is exactly opposite the measured behavior in man-made fiber reinforced plastics, but it can be explained by the cellular honeycomb-like microstructure of wood. An understanding of the microstructure and its variability can provide valuable insight into wood behavior.

Although polymeric and microstructural aspects are essential guiding concepts, constitutive relations at the continuum level are the essential building blocks for modeling the behavior of a structural element. Of particular interest for skeletal structures are the tensile and compressive properties in the longitudinal direction and the shear behavior.

Using the continuum constitutive relations, the behavior of structural elements can be predicted. These include the behavior of wood beams in bending, transverse shear, and torsion. In addition, beam column effects and viscoelastic stability can be investigated.

Finally, at the structure level, numerical solutions to complex combinations of structural elements are required to understand the interactions among the elements. Of particular interest is how the time-dependent behavior of the individual structural components affect the global stability and long-term integrity of the structure.

Time-temperature superposition and accelerated testing

Accurate prediction of long-term behavior of any material exposed to various environmental conditions is a difficult task, but it is necessary if some confidence in the long-term behavior is desired. In most cases, designers do not have the luxury of waiting for the results of long-term tests (on the order of the service life) before designing a desired structure. The methodology for accelerated characterization of man-made polymers is highly developed and may be useful for predicting the creep response of wood. Confidence for predicting long-term behavior of wood structures from short-term data is predicated on understanding how accelerated characterization techniques can be applied to wood.

An important question, addressed in several experiments, is whether and under what conditions the time-temperature superposition principle of thermorheologically simple materials applies to wood. The time-temperature superposition principle (TTSP) is widely used to extend the range of measurement when viscoelastic parameters are studied in polymers as a function of time and temperature (Ferry 1980; Povolo and Fontelos 1987). Specifically, portions of the material response are measured at different temperatures and then shifted along the log time axis to construct a composite (master) curve. This permits the prediction of material behavior over many decades of time for low temperatures from relatively short-time tests at high temperatures.

The concept of time-temperature superposition is firmly grounded in polymer theory (Ferry 1980), especially throughout the glass transition region of a homopolymer. Extensions of these concepts become more difficult, however, within the glassy region of polymer response which is of interest for structural applications. Reasons for these difficulties include: breakdown of the almost universally applicable Williams-Landel-Ferry equation (Ferry 1980) below the glass transition temperature, flat slope of the compliance curves which complicates shifting procedures, and physical reasons arising because the molecular motions are no longer of the type (Ferry 1980), which gives rise to the expected time-temperature interrelationship. Nevertheless, accelerated characterization procedures based on Arrhenius models (Sperling 1986) are commonly employed in regions well below the glass transition region. These techniques have been applied not only to mechanical modulus (Sperling 1986) and delayed failures of wood (Caulfield 1985) and other materials (Zhurkov 1965), but even to the accelerated aging of electronic components.

In order for time-temperature correspondence to rigorously hold and be easily implemented, certain requirements must be met:

1) The material must be thermorheologically simple, i.e., all retardation times must shift by equivalent amounts.
2) The mechanisms which occur in the service environment must be the same mechanisms which are accelerated in the testing program. These include, but are not limited to:
   a) no chemical changes in the material; i.e., aging, bond scission and formation, oxidation, etc. do not depend on the conditions imposed by the service environment or by the accelerated test environment.
   b) failure mechanisms and damage accumulation ideally do not exist, but if they are present, they must be identical to the tests at the different time frames.
3) The shift factors must be the same for all the viscoelastic functions, they must match over an extensive range of the polymer response, and they must be consistent with polymer experience (Ferry 1980).

When any of these conditions are relaxed, application of TTSP becomes more difficult and reliability of the predictions becomes suspect.

Time-temperature superposition has been applied to wood by several investigators, but it has not always provided the desired results. The experimental results on the validity of the time-temperature superposition principle are not conclusive, which is reflected in the following statements: "Short term tests at higher temperatures cannot replace long-term tests at normal temperatures" (Goldsmith and Grossman 1967); "Superposition of time and temperature must be used with caution" because changes in temperature may result in structural changes in the material (Davidson 1962). However, on the basis of available strain-time data at several temperatures, for oven-dry wood and at various moisture contents, Schaffer (1982) concludes that "the viscoelastic response of wood is thermorheologically simple over narrow temperature ranges." Because the temperature range required to accelerate the response for realistic service lives is expected to be reasonably small, this last conclusion is quite encouraging.

If practical techniques for predicting long-term behavior are to be developed, confidence in extending short-term test results to long-term predictions is required. Also, if prediction errors exist, they should err toward the conservative side. Findley and Peterson (1958) showed reasonable agreement between predicted creep (based on the power law model) using 2,000 h data and long-term 92,000 h data, a 45-fold projection. These results were reported for canvas, paper, and asbestos laminates. Although agreement was quite good, the predictions were nonconservative in several cases. Gressel (1984) applied several creep laws to bending of spruce, pine, and beech and found that the power law predictions provided the best agreement with the actual long-term data. Here 2,000 h data was sufficient to give a reasonable estimate of 80,000 h behavior. These interpolations suggest that 1 yr data could be used to give some estimate of 50 yr behavior, although the agreement would not be exact. A disturbing trend in Gressel's work is that predictions fit to moderate-term data were significantly different from those estimates based on short-term results. Failure of the models to approach a limiting value as subsequent data is utilized leaves concern about the validity of the models for long extrapolation. One factor is that Gressel used creep data to fit his power law models. Hiel et al. (1984) have shown on fiber-reinforced composites that power law coefficients are more accurately determined from recovery data than from creep data. It is possible that such information could improve the consistency at longer times.

Constitutive models for time dependence

Creep of materials is commonly broken into three stages: primary, secondary (quasi-steady flow), and tertiary (failure imminent). If the creep remains within the secondary region, some confidence in predicting long-term behavior seems justified.

The tertiary stage of creep is always to be avoided in design because damage and deflections accelerate quickly and precipitate failure (Humphries and Schniewind 1982). Unfortunately, it is often not possible to predict when this tertiary response will begin. Because tertiary creep leads to failure, great care is needed in the accelerated characterization procedure to insure that the onset of unexpected tertiary response in the actual structure will not occur.

Within the primary and secondary regions of creep, a variety of equations has been used to model the response (Tables 1 and 2). Several researchers have concluded, based on short-term tests, that wood may be modeled as a three parameter solid (a spring and Kelvin element in series) or a four parameter fluid (a spring, dashpot, and Kelvin element in series). Such models are inappropriate for extrapolation to long-term behavior. Since the response of a single Kelvin element is only active over 2 decades in time, a three parameter solid or any generalized Kelvin model in which the longest relaxation time is not on the order of the maximum time being modeled will give nonconservative predictions. The addition of a free dashpot results in overly conservative predictions as demonstrated by Gressel (1984). On the other hand, the use of the power law, although empirical, appears to have some predictive capabilities. Gressel has found it to be the most appropriate for predicting long-term behavior of wood.

Orthotropic property determination

Most creep studies on wood have been conducted in bending. Bending tests have been preferred to tension and compression tests because they are easier to implement and load, and because the deformations are much larger and easier to measure. Unfortunately, bending tests give *structural element properties* rather than *material properties*. Since stresses vary from tension to compression through the beam, the response is only a spatially averaged behavior. Kingston and Clarke (1961) pointed out that the nonlinearity in uniaxial compression occurs at a much higher percentage of ultimate load, and is much more distinct than observed for bending of equivalent beams. It is certainly disconcerting to know that the time-dependent response and delayed failures, in particular, are being masked by the transfer of load to interior regions of the beam. Another problem is that most bending tests in the literature are based on three-point loading such that shearing forces are also present. Since the stiffness in shear is much less than the stiffness in the longitudinal direction, shear creep deformations may not be negligible even for slender beams.

Although little work on the shear creep response of wood has been reported, it has potential impact on the modeling effort. Schniewind and Barrett (1972) report that the relative creep in shear is only 60% of that perpendicular to the grain for Douglas-fir specimens loaded for 1,000 minutes. They show, however, that this relative shear creep is 5 times larger than relative creep parallel to the grain. Because the shear stiffness is considerably lower than the longitudinal stiffness, and because the relative shear creep is much greater than the relative longitudinal creep, shear behavior can potentially have a large effect on wood beam performance. It should be further noted that shear deformation leads to beam-column type eccentricities which can enhance the likelihood of viscoelastic instabilities.

FINITE ELEMENT ANALYSIS OF CREEP PROBLEMS

In statically indeterminate structures, such as space frames and lattice domes, the creep differences within the structure can cause extensive long-term stress redistributions, even under constant loads. Accordingly, creep laws must be formulated for variable stresses; the creep models in Tables 1 and 2 are limited to constant stress response. Moreover, any creep analysis must proceed in an incremental manner with suitable time steps, and iteration within time steps is frequently required to satisfy the creep law and assure convergence.

This section provides a brief review of variable stress creep laws and the development of finite element programs for the analysis of creep problems.

Creep laws

There are two choices for formulating variable stress creep models. They are based on the following assumptions (Kraus 1980):

1. The material response depends on the present state explicitly.
2. The material response depends on the past history explicitly.

The resulting creep models are called the equation of state, or rate-type, formulation and the hereditary, or integral-type, formulation, respectively.

The equation of state can be expressed in the form

$$\dot{\epsilon}_c = f(\sigma, \epsilon_c) \tag{5}$$

where the dot denotes differentiation with respect to time. Equation 5, a strain hardening model, defines the creep strain rate as a function of the current stress and the current strain, which reflect the effect of the history of the material. The hereditary creep law can be expressed as

$$\epsilon_c(t) = \int_0^t J(t - \tau)\frac{d\sigma(\tau)}{d\tau}\,d\tau \tag{6}$$

where J is the creep compliance function. Equation 6, which is based on Boltzmann's superposition principle, defines the creep strain at any time t in terms of the entire stress history, $\sigma(\tau)$. Viscoelastic solutions may also be obtained in the Laplace domain (Hackett 1971).

The equation of state approach has been applied extensively, and it is easy to incorporate into existing computer programs. The need to store the complete stress history in the hereditary approach tends to overtax the storage facilities for large structures. To overcome this limitation, procedures have been developed to convert the hereditary integral into a state equation (Chan 1983; Kabir 1976; Nilson et al. 1982). This has been accomplished, for example, by expanding the compliance function in a Dirichlet series (Kabir 1976), as given by Eq. 4.

Computer programs

With few exceptions (Sharifi and Yates 1974), finite element computer programs for the analysis of creep problems are based on the initial strain method (Boyle and Spence 1983; Bushnell 1977; Kraus 1980; Nickell 1974; Zienkiewicz and Watson 1966). The initial strain method was motivated by the similarity of creep problems to thermal stress problems (Greenbaum and Rubinstein 1968; Mendelson et al. 1959; Zienkiewicz and Cormeau 1974), where the method was first proposed. A shortcoming of early applications, the requirement of small time steps to achieve convergence (Nickell 1974), has been overcome by the subincrementation of time steps and effective time integration algorithms (Bushnell 1977; Snyder and Bathe 1981; Zienkiewicz and Cormeau 1974).

For example, Snyder and Bathe (1981) developed a solution procedure for the finite element analysis of creep problems that is based on a one-parameter integration method (the α-method) for a system of ordinary differential equations. The α-method, which contains the well-known Euler forward and backward methods, was shown to be an effective algorithm for complex thermo-elastic-plastic and creep problems. For a range of values for α, this integration method is unconditionally stable. The solution procedure uses one time step size for the calculation of nodal displacements and a smaller one for integration of creep strains.

SUMMARY AND CONCLUSIONS

The current status of modeling long-term creep in wood is reviewed for application to the analysis of wood structures. Creep in wood is an extremely complex phenomenon and is affected by many variables including temperature, moisture, species, grain direction, loading conditions, and wood's natural variability. Extensive creep data have been collected by researchers for numerous wood species. However, because of conflicting experimental objectives, not all of these are directly applicable to modeling the long-term behavior of wood structures. Data have been collected for species that are not widely used for structural applications, while other species, such as the southern pines, have not been adequately characterized. Researchers have devoted considerable effort to studying the mechano-sorptive creep behavior in small specimens. However, experimental evidence suggests that large wood members used for interior applications do not undergo large moisture fluctuations and therefore mechano-sorptive creep effects are minimal. However, for members exposed to large cyclic moisture conditions, such as exterior exposure, mechano-sorptive creep effects should be considered.

Structural instability in the form of snap-through buckling is a potential failure mode in some innovative wood structures such as shallow domes and arches. To preclude such failures, designers should conduct stability investigations that account for creep. The finite element method is ideally suited for such analysis if material constitutive laws for creep in tension, compression, and shear are available. Unfortunately, the preponderance of available data is from short-term tests and is not suitable to permit extrapolating the results to long times. Much of the existing data was collected from bending tests and therefore represents member and structural behavior rather than material behavior. Bending tests tend to mask the true time-dependent material behavior because stresses and strains vary throughout the cross section. Also, shear creep deformations in beams may contribute to the time-dependent deflections, but this possibility has not been adequately analyzed.

Several fundamental forms of mathematical models have been used in the literature for creep in wood under constant stress. For linear materials, these models may be used in hereditary integrals or converted to recursive relationships to model variable load histories. The rate-type or equation-of-state formulation is preferred for finite element analysis of wood structures because it does not require storage of the entire stress history.

An integrated approach that considers the material behavior at several levels including polymers, microstructure, continuum (physical material properties), structural element, and the structure itself must be used to develop rational creep models for use in design. Accelerated testing using the time-temperature superposition principle may provide a method for developing long-term data from relatively short-term tests. However, this concept has not been rigorously tested on wood products.

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