PREDICTION OF CREEP IN PLYWOOD PART I. PREDICTION MODELS FOR CREEP IN PLYWOOD[1,2]

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ABSTRACT

Three models for predicting creep in plywood from measured constituent properties were formulated using phenomenological linear viscoelastic theory. The three models represent a one-dimensional, quasi-elastic solution, a two-dimensional, quasi-elastic solution, and a two-dimensional, viscoelastic solution. In part II of this study, the models will be used to compute the principal components of the two-dimensional creep compliance tensor for plywood and will show that predictions of creep behavior based on all three solutions give similar results. The most accurate prediction of parallel and perpendicular creep was made with the one-dimensional model.

Keywords: Plywood, creep, viscoelasticity, orthotropic elasticity, two-dimensional stress analysis, modeling, predicting.

INTRODUCTION

Solid wood, when subjected to low stress levels in tension parallel-to-grain at a sufficiently low temperature and moisture content, behaves as a linear elastic material (Bach 1965). Because of the simplicity of the linear elastic constitutive relationship, this model has been used almost exclusively for stress analysis and structural design problems for wood. At load levels actually encountered in structures, however, wood exhibits both elastic and viscous behavior. Proper material constitutive relations should describe the evaluation of the state variables (stress, strain) in both space and time. Therefore, for certain applications wood should be classified as a viscoelastic solid.

A great deal of experimental work has been published on the response of wood to constant and varying conditions of stress, temperature, and moisture content (Schniewind 1968). By contrast, much less work has been reported on the viscoelastic behavior of plywood and other wood composites.

The objective of this study was to develop analytical models to relate creep deformation of plywood to constituent (veneer) behavior. This was done for the two-dimensional creep compliance tensor, assuming a state of plane stress. The models were developed using a linear viscoelastic theory, treating plywood as a layered orthotropic composite material.

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LITERATURE REVIEW

A number of studies have been performed to characterize the functional form of the creep curve for plywood and other wood-based materials and to compare relative time-dependent deflections (Norris and Kommers 1943; Campredon 1947; Halligan 1965; Narayanamurti and Aswathnarayana 1970; Perkitny and Steller 1972; Kalina 1972; and Gressel 1972a,b,c). These studies indicate that relative creep is greatest in fiberboard, followed by particleboard, plywood, laminated wood, and solid wood. Work at the Technical Research Center of Finland has been of a more fundamental nature. Ranta-Maunus (1972) studied creep and stress relaxation in bending and observed linear viscoelastic behavior under steady-state climatic conditions at allowable stress levels for spruce plywood. Weak nonlinearity was observed for birch plywood. The shear deformation in bending was weakly nonlinear for plywood made from both species of wood. Increasing moisture content increased the degree of nonlinearity. This work has been extended to include nonsteady-state environments (Ranta-Maunus 1973) for the case of periodic variations in moisture content.

The theory of elasticity for laminated composites made from anisotropic lamina is well developed. A review of the theory has been published by Stavsky and Hoff (1969). Considerable success has been achieved in predicting elastic behavior of plywood from properties of its constituents. The U.S. Forest Products Laboratory has done much work in this area (Anon. 1964).

Significant contributions have also been made by Hearman (1948), Sawada et al. (1959), Steller (1967), Masuda et al. (1969), Rautakorpi (1969, 1971) and many others. These studies are based primarily on the two-dimensional theory of elasticity for anisotropic composite materials. Various simplifying assumptions have been made in each analysis. The most common simplification is the use of the rule of mixtures. This rule states that each constituent of the mixture is a separate continuum that may be acted on by external forces and by other constituents, with the mixture mass, momentum, and energy being conserved. Thus, the contribution of each constituent to mixture behavior is in proportion to its mass weighted average.

The contribution of the glue line to total elastic behavior is small when veneers have a thickness greater than 0.05 inches (Curry 1957; Preston 1954), and most investigators have ignored the effect of the glue line in the mathematical analysis. Okuma (1966) was the only one to treat the glue line as a separate layer. In other studies, the effect of the glue line was determined indirectly by measuring constituent properties on parallel laminated specimens matched to the plywood specimens. This method has been shown by Preston (1954) to be more effective than using properties of solid wood for predicting elastic behavior of plywood. Predictions of modulus of elasticity of plywood in tension parallel-to-grain of the face veneers, based on properties of parallel laminated specimens, are usually within 10% of experimental values. Larger errors result when solid wood is used for controls. This difference is attributable, in part, to the presence of lathe checks in the veneer, which have an adverse effect on bending stiffness (Yagishita and Egusa 1965).

Only Ranta-Maunus (1972) has dealt with the prediction of the viscoelastic behavior of plywood from constituent properties. Plywood was assumed to act as an orthotropic multilayer sandwich plate, following the analysis Rautakorpi

(1971) used for the elastic case. Pure bending deflection was determined from creep tests on strips subjected to third-point loading. Total deflection, due to the combined effect of shear and bending, was then determined on strips subjected to a concentrated load. From these tests the constitutive equations of an individual veneer sheet based on axial stress and rolling shear were determined. This enabled time-dependent deflection to be calculated for plywood using linear viscoelastic theory.

PREDICTING CREEP OF PLYWOOD

Three analytical models, representing different degrees of refinement, will be formulated to determine effective creep compliance functions for plywood based on experimentally measured, time-dependent constituent properties. The first is a one-dimensional, quasi-elastic analysis that ignores Poisson's effects and makes some simplifying assumptions concerning the dependency of stress at any point in time on the previous stress history of the body under consideration. The second is a two-dimensional, quasi-elastic analysis, where the Poisson's effect is considered. The third is a two-dimensional, viscoelastic analysis where previous stress history is also taken into account. All three solutions employ linear viscoelastic theory as developed for anisotropic composite materials. The quasi-elastic solutions will be discussed first, beginning with the two-dimensional analysis as a matter of convenience.

Two-dimensional, quasi-elastic analysis

The analysis begins with the properties of the plywood constituent, either the veneer or the laminated material shown in Fig. 1. The elastic constitutive relation for this orthotropic material, relating stresses σ_{kl} and strains ϵ_{ij} is

$$\epsilon_{ij} = S_{ijkl}\sigma_{kl}, \tag{1}$$

where:

S_{ijkl} are components of the compliance tensor,
i,j,k,l are equal to 1,2,3.

The subscripts are related to the axis of veneer or parallel laminated veneer as follows:

1 is the longitudinal axis
2 is the tangential axis
3 is the radial axis.

The linear viscoelastic constitutive equation may be determined directly from the elastic equation through use of the well-known elastic-viscoelastic correspondence principle. This principle may be defined as:

> Replace in the elastic equations the stress and strain by their Laplace transforms and the material properties by their associated transforms multiplied by the transform parameter "p" to obtain the transform of the viscoelastic equations.

Applying correspondence to Equation 1 yields for the viscoelastic case:

$$\bar{\epsilon}_{ij} = p\bar{S}_{ijkl}\sigma_{kl}, \tag{2}$$

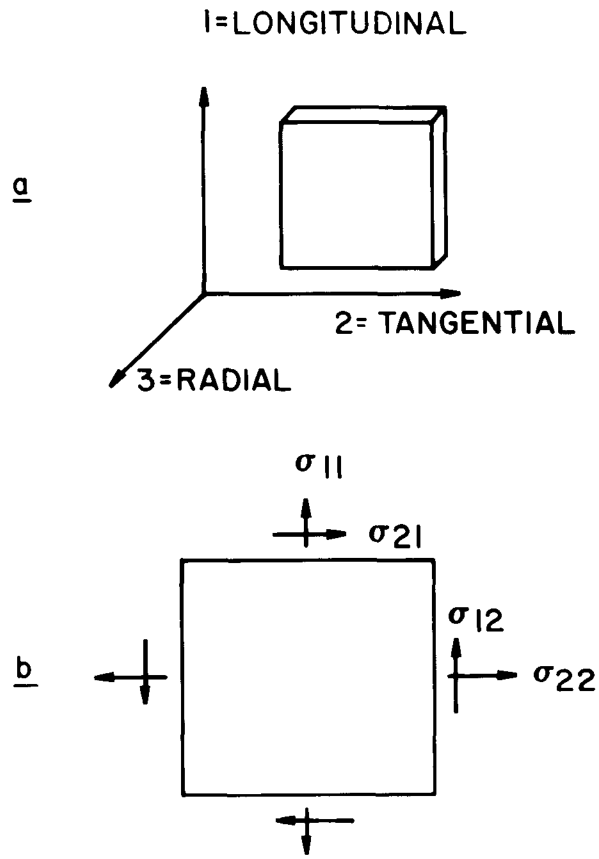

FIG. 1. a) Orientation of plywood constituent in space. b) Plywood constituent in a state of plane stress.

where the bar signifies that the tensor has been transformed into Laplace space. Equation 2 may be expressed in terms of the Boltzman superposition integral (Schapery 1967; Halpin and Pagano 1968):

$$\epsilon_{ij}(t) = \int_{t_0^-}^{t} S_{ijkl}(t - \tau)\frac{d\sigma_{kl}}{d\tau}\, d\tau. \tag{3}$$

The lower limit indicates that the problem is quiescent before, or that the problem begins at time t_0. Now, if the veneer in question is stress free prior to t_0 and then experiences an instantaneous stress, a discontinuity occurs a time t_0. This discontinuity can be taken outside the integral:

$$\epsilon_{ij}(t) = \sigma^{o}{}_{kl}S_{ijkl}(t - t_o) + \int_{t_0^+}^{t} S_{ijkl}(t - \tau)\frac{d\sigma_{kl}}{d\tau}\, d\tau. \tag{4}$$

$S_{ijkl}(t)$ is a fourth rank tensor containing, in the most general case, 81 components. Symmetry of the stress and strain tensors reduces the number of independent components to 36, with further reduction to 21 because of relations analogous to the Maxwell relations in elastic theory.

Plywood may be considered as a cross-laminated composite made up of thin layers of orthotropic plates bonded together. When this plate is subjected to in-plane stresses, it is reasonable to assume a state of plane stress, such that $\sigma_{33} = \sigma_{23} = \sigma_{31} = 0$. Figure 1 defines the state of plane stress for a thin plate such as plywood. For this two-dimensional problem, the creep-compliance tensor is

$$S_{ijkl}(t) = \begin{bmatrix} S_{1111}(t) & S_{1122}(t) & 0 \\ S_{2211}(t) & S_{2222}(t) & 0 \\ 0 & 0 & 4S_{1212}(t) \end{bmatrix}. \tag{5}$$

Of the five creep compliance components shown, four are independent. This study will be concerned with tensile creep specimens that are free of shear stresses. Therefore, only three components will be evaluated, namely $S_{1111}(t)$, $S_{2222}(t)$, and $S_{1122}(t)$.

These three material functions may be determined for veneer and veneer laminates from uniaxial tension tests using the step-function stress input:

$$\sigma_{kl} = \sigma^{o}_{kl}H(t), \tag{6}$$

where:

H(t) is the Heaviside unit step function. Substitution of Equation 6 into Equation 4 yields:

$$\epsilon_{ij}(t) = S_{ijkl}(t)\sigma^{o}_{kl}, \tag{7}$$

where the components of $S_{ijkl}(t)$, defined by Equation 3, are represented by experimental data fit to an equation such as

$$J(t) = J_o + mt^n, \tag{8}$$

where: J(t) is the creep compliance at time "t," and
J_o, m and n are constants determined experimentally for each test.

Equation 7 is a linear elastic constitutive relation for a single lamina or layer since the strain at any time (t) depends only on the value of the creep compliance tensor at that time. In other words, previous stress history has been ignored in deriving Equation 7.

Mathematical derivation of effective creep compliance components for plywood, expressed in terms of constituent behavior is analogous to Schniewind's (1972) analysis of the elastic behavior of the single wood fiber in terms of its distinct layers. To obtain the effective creep compliance tensor for plywood, Equation 7 is rewritten to express the stresses as functions of the strains:

$$\sigma^{o}_{kl} = C_{ijkl}(t)\epsilon_{ij}(t), \tag{9}$$

where:

$$C_{ijkl}(t) = C(t) = \begin{bmatrix} C_{1111}(t) & C_{1122}(t) \\ C_{2211}(t) & C_{2222}(t) \end{bmatrix}, \tag{10}$$

and the matrix of components of time-dependent stiffness is obtained by inversion of the creep compliance matrix:

$$\Big[C(t)\Big] = \Big[S(t)\Big]^{-1}. \tag{11}$$

Since in plywood the stiffness components $C_{ijkl}(t)$ will generally vary from layer to layer, but all layers are required to deform together, the stresses will also generally vary. Equilibrium dictates that the externally applied stress σ^o_{kl} be equal to the sum of the stress in the nth layer times the area ratio of that layer, A_n:

$$\boldsymbol{\sigma}^o_{kl} = \sum [A_n(\sigma^o_{kl})_n]. \quad (12)$$

Substituting Equation 9 into the right hand side of Equation 12 yields:

$$\boldsymbol{\sigma}^o_{kl} = \sum \{A_n[C_{ijkl}(t)]_n[\boldsymbol{\epsilon}_{ij}(t)]_n\}. \quad (13)$$

All layers of the plywood will deform in an amount equal to the overall deformation $\epsilon_{ij}(t) = \epsilon_{ij}(t)_n$ so that Equation 12 becomes:

$$\boldsymbol{\sigma}^o_{kl} = \sum [A_n C_{ijkl}(t)]_n[\boldsymbol{\epsilon}_{ij}(t)]. \quad (14)$$

From Equation 14 we see that the effective stiffness matrix is defined as:

$$\mathbf{C}_{ijkl}(t) = \sum \{A_n[C_{ijkl}(t)]_n\} \quad (15)$$

and the effective creep compliance tensor for plywood is finally obtained by inverting the effective stiffness matrix

$$\left[\mathbf{S}(t)\right] = \left[\mathbf{C}(t)\right]^{-1}. \quad (16)$$

One-dimensional, quasi-elastic analysis

It is common in practical calculations of the elastic stiffnesses of plywood to ignore Poisson's effect in order to simplify calculations. The consequence of ignoring Poisson's effect in conventional cross-laminated plywood is to reduce the predicted elastic stiffness parallel-to-the-face grain by a small amount, from 1 to 3% (Stavsky and Hoff 1969). The lower predicted stiffness from the one-dimensional solution is explained by restraints that are present in the plywood panel. An individual ply, if it were free to do so, would expand in the direction of the tensile stress and contract in the direction normal to the stress in response to stress parallel to one material axis. In plywood, however, the adjacent ply partly restrains the contraction unless all layers have identical Poisson's ratios. The one-dimensional solution, of course, ignores this restraint.

The one-dimensional solution for effective parallel and perpendicular creep compliance for plywood is determined by the simple relation:

$$\frac{T_{a+b}}{\mathbf{S}(t)} = \frac{T_a}{S_a(t)} + \frac{T_b}{S_b(t)}, \quad (17)$$

where:

T is the layer thickness,
$\mathbf{S}(t)$ is an effective plywood stiffness component,
$S(t)$ is a veneer stiffness component, and
a,b refer to parallel and cross plies, respectively.

Equation 17 can be derived in a manner analogous to the two-dimensional case.

For the effective parallel-to-face-grain, creep compliance component, Equation 17 becomes:

$$S_{1111}(t) = \frac{TS_{1111}(t)S_{2222}(t)}{T_aS_{2222}(t) + T_bS_{1111}(1)}, \tag{18}$$

and for the effective perpendicular-to-face-grain, creep compliance component,

$$S_{2222}(t) = \frac{TS_{1111}(t)S_{2222}(t)}{T_aS_{1111}(t) + T_bS_{2222}(t)}, \tag{19}$$

where, as before, the creep compliance components $S_{1111}(t)$ and $S_{2222}(t)$ are experimentally determined values obtained from tests on veneer or laminates fitted to Equation 8. Since Poisson's effects are ignored, the transverse compliance $S_{1122}(t)$ is not obtained in this analysis.

Two-dimensional viscoelastic analysis

The linear viscoelastic constitutive relation has been presented in Equation 2 as a direct result of the correspondence principle. The difficulty of this solution is in performing the inverse Laplace transform to obtain the effective creep compliance matrix in real space. The problem is made more tenable when the experimental data are fitted to a creep function other than Equation 8. A more convenient representation of the data, applicable to linear materials, is by a series of exponentials. The simplest relation, containing one exponential term is:

$$J(t) = J_1 - J_2e^{-t/\lambda}. \tag{20}$$

The parameters necessary to characterize Equation 20 are defined in Fig. 2. The parameters J_1 and J_2 are read off experimental curves for each compliance component. The assumption is made that the creep curves have zero slope at the end of the test. The parameter λ will, in general, be different for each creep compliance component. However, to facilitate transformation, it is best to stipulate that λ is the same for all creep compliance components. The parameter λ can be determined by finding the intercept of the line $J(t) = J_1$ with the curve tangent to the creep curve at t_0 and subtracting the value of t_0.

Once the exponential relation of the form shown in Equation 20 is fitted to the experimentally determined data for plywood constituents, the effective creep compliance components for plywood may be calculated. Equation 20 is substituted into Equation 5 to give:

$$S_{ijkl}(t) = \begin{bmatrix} J_1 - J_2e^{-t/\lambda} & J_3 - J_4e^{-t/\lambda} \\ & J_5 - J_6e^{-t/\lambda} \end{bmatrix}. \tag{21}$$

The creep compliance matrix for the plywood constituents may then be transformed into Laplace space using a table of transforms (Flugge 1967):

$$L\{S_{ijkl}(t)\} = \begin{bmatrix} \frac{J_1}{p} + \frac{J_2}{p + 1/\lambda} & \frac{J_3}{p} + \frac{J_4}{p + 1/\lambda} \\ & \frac{J_5}{p} + \frac{J_6}{p + 1/\lambda} \end{bmatrix}, \tag{22}$$

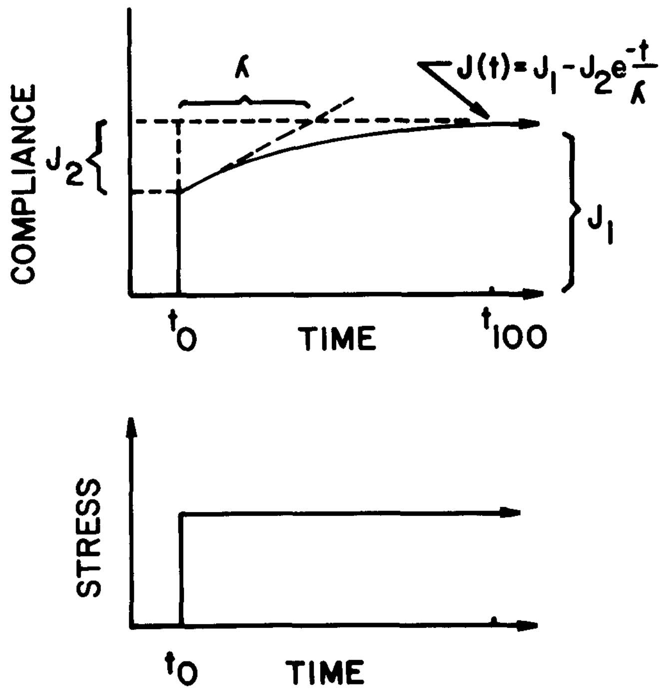

FIG. 2. Exponential creep function to which experimental data was fitted for use in viscoelastic analysis of plywood creep behavior. The parameters are defined for an idealized creep curve generated by a step function stress input.

where:
p is the transform parameter.

The remaining steps in computing effective creep compliances for plywood are completely analogous to the two-dimensional, quasi-elastic solution, except that they are carried out in Laplace space. The matrix of Equation 22 is inverted to obtain the stiffness components for each constituent lamina:

$$\left[\bar{C}(p)\right] = \left[\bar{S}(p)\right]^{-1}. \tag{23}$$

Then, as before, effective stiffness components for the plywood may be obtained by weighting each lamina by its area ratio:

$$\bar{C}_{ijkl}(p) = \sum\{A_n[\bar{C}_{ijkl}(p)]_n\}. \tag{24}$$

Next, the effective creep compliance components for the plywood composite are obtained by inverting the effective stiffness matrix.

$$\left[\bar{S}(p)\right] = \left[\bar{C}(p)\right]^{-1}. \tag{25}$$

We now have an algebraic expression for each creep compliance component containing powers of the transform variable (p). Several methods for performing the transform inversion have been proposed to obtain the desired solution in real space (Schapery 1961, 1962; Cost 1964). The method of partial fractions (Hildebrand 1960) is suggested to perform the transform inversion. After algebraic manipulation, an expression must be obtained for each component $S_{ijkl}(p)$ of the form:

$$Y(p) = \frac{G(p)}{H(p)}, \tag{26}$$

where: G(p) and H(p) are polynomials of p, and the degree of G(p) is lower than that of H(p). Through further algebraic manipulation, Equation 26 must be expressed as the sum of a number of partial fractions containing both repeated and unrepeated factors in the denominators. Techniques that may be used to transform these partial fractions are described in some detail by Kreyszig (1967).

SUMMARY

This paper has developed prediction models for creep of plywood based on linear viscoelastic theory. Plywood was considered to be a cross-laminated composite made from orthotropic laminae. Three types of solutions were presented: a one-dimensional, quasi-elastic solution that ignores Poisson's effects and stress history; a two-dimensional, quasi-elastic solution that includes Poisson's effects, and a two-dimensional, viscoelastic solution that also incorporates the effects of previous stress history.

In the second part of this study, the time-dependent properties of veneer and veneer laminates will be used to calculate components of the two-dimensional, creep compliance tensor for plywood using the three analytical models described in this paper.

The effects of lathe checks will be evaluated through a comparison of plywood made from both conventional rotary peeled veneer and sawn veneer devoid of lathe checks. Glue line effects will be evaluated through comparison of creep properties of single-ply and parallel laminated sawn veneer, and by the ability of each type of constituent to predict the time-dependent behavior of plywood made from matched veneer. The appropriateness of using linear viscoelastic theory will be determined through creep tests on plywood, carried out over a wide range of stress levels.

SUMMARY OF EXPERIMENTAL RESULTS

Results of the experimental phase of this research, to be published at a later date, are summarized here for convenience. Plywood was shown experimentally to behave as a linear viscoelastic material for stress levels as high as 59% of maximum static strength. Predictions of creep behavior based on all three solutions gave similar results. Questions remain concerning the prediction of transverse creep since positive creep was observed experimentally, while negative creep was predicted with both two-dimensional solutions. The most accurate prediction of parallel and perpendicular creep was made with the one-dimensional solution using measured creep properties of parallel laminates, with maximum difference between predicted and experimental total creep compliance of 10.6%. The presence of lathe checks influenced both elastic and creep behavior, tending to increase deformation relative to predicted results. The presence of glue lines and the laminating process has an effect on the creep of plywood which is greater than the direct effect of wood compression. However, this work has demonstrated that creep behavior of plywood parallel and perpendicular-to-face grain may be predicted with a high degree of accuracy from measured properties of parallel laminates, made of the same veneer type and thickness.

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