VISCOELASTICITY OF WOOD COMPOSITE MATS DURING CONSOLIDATION

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ABSTRACT

To improve our understanding of the wood composite hot-pressing process, viscoelastic consolidation of wood flake mats was investigated in terms of constituent flake properties and mat formation. A fundamental model of mat stress relaxation was developed based on the compressive stress relaxation of wood flakes and Poisson distribution of flake overlaps formed in the mat. Both stress relaxation and creep of wood flakes and flake mats at ambient condition were experimentally tested and analyzed. The results showed that the stress relaxation of wood flakes at different levels of compression follows linear double logarithmic relationships with varying slopes or rates of stress relaxation. The mat stress relaxation model was validated by comparing the model predictions with the experimental data. Like stress relaxation, creep of flakes also varies with the level of compression. Due to porosity difference, creep of flake mats is not quantitatively comparable to creep of flakes in terms of relative creep strain. Instead, relative creep compaction ratio of mats is comparable to that of wood flakes.

Keywords: Wood composites, modeling, mat consolidation, viscoelasticity, pressing.

INTRODUCTION

Hot-pressing is a key operation in wood-based composite manufacture. During such an operation, mats of resinated wood fibers, particles, or flakes are consolidated under heat and pressure to create close contact and form bonds between the wood constituents. Due to limited amount of resin usage, effective bonds rely on a high degree of mat densification. Increasing mat density, on the other hand, causes negative effects such as heavier products, more wood consumption, and more importantly excessive thickness swell in service when the product is subjected to high humidity conditions (Kelly 1977). The necessity and detrimental effects of mat densification suggest the importance of process optimization, which requires a solid understanding of the mechanism of mat consolidation.

The pressing of a wood composite mat involves physical, mechanical, and chemical interactions. Once the press closes, moisture and heat transfer takes place between the hot platens and the mat. During the course of pressing, temperature and moisture content inside the mat are both spatially and temporally dependent (Humphrey and Bolton 1989). At the same time, the platens exert compressive forces onto the mat, causing reduction of voids and compression deformation in wood constituents (Dai and Steiner 1993). The mat deformation is usually not uniform across the mat thickness due to the variations of heat and moisture content from the surface to the core layers. Elevated temperature accelerates resin polymerization, which combines with mat deformation to form permanent bonds between wood constituents. With little springback, the glue bonds also freeze the overall and layered mat deformation upon press opening. This leads to formation of the well-known vertical density profile in pressed wood composite panels, which in turn has a significant effect on the physical and mechanical properties of the final products (Suchsland 1959; Kelly 1977; Harless et al. 1987; Wolcott et al. 1990; Winstorfor et al. 1994).

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If mat consolidation is defined as the compression deformation of randomly arranged wood constituents, the overall mat stress-strain relationship is governed by the initial mat structure and mechanical properties of wood constituents (Dai and Steiner 1993; Lang and Wolcott 1996). Due to viscoelasticity of wood, a mat of wood elements exhibits the time-dependent behavior of deformation (creep) and stress relaxation. The compression viscoelasticity of wood and wood composite mats has received limited attention and therefore forms the main subject of this paper.

BACKGROUND

Compressive viscoelasticity of wood and other cellular materials

Viscoelasticity of wood influences the long-term performance of wooden structures in service. Viscoelasticity also influences wood densification during wood products processing such as in press-drying where wood is under a static pressure and subjected to changes in temperature and moisture content. In these situations, wood can be adequately treated as a linear viscoelastic material, because the applied load is under certain limits within the linear range. The linear viscoelasticity thus became a subject of many studies, which were cited in several review papers (Schniewind 1968; Pentoney and Davidson 1962; Bodig and Jayne 1982; Holzer et al. 1989).

During the manufacture of wood composites, however, high pressure is required in order to consolidate mats of wood constituents into integrated panels. The high pressure, coupled with the random mat structure, results in a highly nonlinear and nonuniform mechanical response of the wood constituents (Dai and Steiner 1993). Youngs (1957) and Kunesh (1961) are two of the earlier researchers who investigated the nonlinear viscoelastic behavior of wood under perpendicular-to-grain compression. Fundamental viscoelastic phenomena such as the time-dependent stress-strain relationship, instantaneous and delayed strain recovery, permanent deformation, and temperature- and moisture-dependent stress relaxation were observed. The global behavior was attributed to the destruction of cellular structure of wood. Bolton and Breese (1987) attempted to interpret viscoelastic behavior wood loaded at right angles to the grain by relating strain development to microstructure change in cell-wall material. They concluded that the majority of strain development involved bond breakage and reformation in regions containing less ordered cellulose, hemicellulose, and lignin.

The effects of cellular structure on nonlinear viscoelasticity was also observed in other natural and synthetic cellular materials (e.g., Gibson and Ashby 1988; Meinecke and Clark 1973; Rusch 1969). The nonlinearity was attributed to the interaction between linear viscoelastic response of cell-wall polymers and geometric nonlinearities of cellular deformation (Meinecke and Clark 1973; Rusch 1969). This interpretation and the relevant nonlinear viscoelasticity models were adopted by Wolcott (1990) to explain response of wood flakes during the pressing of wood composites.

According to these researchers, the nonlinear stress relaxation modulus E(t) of synthetic cellular polymers and wood could be adequately predicted by multiplying the linear response E′(t) by the nonlinear strain function $\varphi(\epsilon)$, or:

$$E(t) = \varphi(\epsilon)E'(t) = \varphi(\epsilon)Kt^{-\xi} \qquad (1)$$

where the strain function $\varphi(\epsilon)$ depends only on strain ϵ and is independent of time t. The constant K is the relaxed modulus of the material at a certain time (usually 1 s). The constant ξ is the slope in the double logarithmic plot of modulus E(t) versus time elapsed t, which is indicative of the rate of stress relaxation; it depends only on the cell-wall polymer.

The usefulness of Eq. (1) implied a possibility of extending the linear Boltzmann superposition principle to modeling the response of nonlinear cellular material to successive loads, provided that the stress relaxation rate ξ was not too large (Meinecke and Clark 1973). The stress at any time t was then given by:

$$\sigma(t) = \epsilon_0 E_0 + \varphi(\epsilon) \int_0^t E(t - t') \frac{d\epsilon(t')}{dt'} dt' \quad (2)$$

where ϵ_0 and $\epsilon(t)$ are the initial strain and the strain at time t, respectively.

Compared with stress relaxation, nonlinear creep response of cellular materials seems much more complicated. According to the available literature, there has been very limited success in developing a compression creep model for wood and other cellular materials (Meinecke and Clark 1973; Gibson and Ashby 1988; Wolcott 1990). As such, the focus of model development in this study was on stress relaxation, whereas the creep response of wood flakes and mats was experimentally measured and compared.

Rheological behavior of wood composite mats

Despite its critical importance, the rheological behavior of wood-furnish mats in compression has been investigated only to a limited extent. Wolcott (1990) used theories of the viscoelastic behavior of amorphous polymers (Ferry 1980) to explain the formation of vertical density profile in flakeboard. The glass transition temperature of the lignin component in wood was estimated from experimentally measured temperature and vapor gas pressure at different locations inside the flake mat during hot-pressing. Mat strain development was related to the external pressure profile through the difference between the actual flake temperature and the calculated glass transition temperature. The information provided from this analysis contributes to general understanding of density gradient formation. A quantitative prediction certainly requires a more comprehensive treatment of wood viscoelasticity.

The thermo-hydro rheological behavior of randomly formed wood fiber mats was experimentally investigated by Ren (1991). Samples were measured under a wide range of temperature and moisture content conditions encountered in a typical wood composite hot-pressing process. The data were then fitted to a five-element "spring and dashpot" model. The model parameters were determined as functions of the temperature, moisture content conditions inside the mat, and the mat density. Such a model has an immediate application to predicting compression strain development in fiber mats of structure and constituents similar to the tested samples. In order to predict mats of other wood furnish such as wood strands, the model needs to incorporate effects of such factors as wood element geometry, orientation, and species. Like other materials, the global viscoelastic properties of a wood composite mat should be determined by viscoelasticity of its constituent elements and the element organization in the mat.

OBJECTIVES

The overall objective of this study was to improve our fundamental understanding of the mat consolidation process; specific objectives were:

1). To develop a model for prediction of mat stress relaxation based on the compressive viscoelastic properties of wood and the random mat structure;
2). To experimentally study stress relaxation and creep response of wood flakes and flake mats; and
3). To validate the stress relaxation model by comparing the viscoelastic properties between wood flakes and flake mats.

A MODEL FOR PREDICTING FLAKE-MAT STRESS RELAXATION

Random formation of flake mats

If a mat of flakes is divided into columns of very small area, then the number of flake overlaps in individual columns i varies (Suchsland 1959). While effort is made during mat forming to disperse flakes as uniformly as possible, the actual deposition of individual flakes may well be random. Assuming random flake positioning, the mathematical model for characterizing the flake overlaps in the imaginary columns follows the well-known Poisson distribution (Dai 1994):

$$p(i) = \frac{a_i}{A} = \frac{e^{-n}n^i}{i!} \quad (3)$$

where $p(i)$ = fraction of mat areas that have i flake overlaps, a_i = mat areas in which flake overlap is i, A = total mat areas, and n = average number of flake overlaps.

Assume a total of N_f flakes with dimensions of λ in length and ω in width. Regardless of flake positions, the average flake overlap always equals the ratio of total flake projection area $\lambda\omega N_f$ to total mat area A, or,

$$n = \frac{\lambda\omega N_f}{A} \quad (4)$$

Relationship between local and global mat stresses

The concept of imaginary columns allows for calculation of overall mat compression stresses based on local flake overlaps. It is assumed that when a load is applied to a mat with thickness T, it is supported by only those columns with flake overlaps i being greater than T/τ (τ: flake thickness). The relationship between the normalized mat stresses at any given time t, $\sigma_n(t)$, and the stresses shared by local flake columns, $\sigma_i(t)$, is:

$$\sigma_n(t) = \sum_{i=T/\tau}^{Nf} \frac{\sigma_i(t)a_i}{A} \quad (5)$$

In the above relationship, the term a_i/A represents the characteristics of random mat formation as described in Eqs. (3) and (4).

Stress relaxation under instantaneous loading

For a standard stress relaxation test in which compression deformation is suddenly applied to a flake mat, the mechanical responses of supporting flake columns take place simultaneously, i.e., the column stress $\sigma_i(t) = 0$, for $t < 0$ and $\sigma_i(t) = \sigma_{i,max}$ for $t > 0$. The stress relaxation in individual flake columns is then given by Eq. (1). Thus the mat stress relaxation can be further defined by substituting a_i/A and $\sigma_i(t)$ in Eq. (5) with Eqs. (3) and (1), respectively, i.e.,

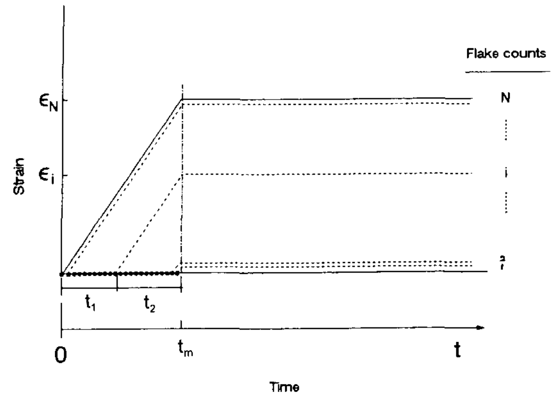

FIG. 1. Linear loading strain histories of flake columns in a mat. t_1 = time elapsed before i-flake columns become under compression; t_2 = time taken for i-flake columns to reach maximum strain ϵ_i.

$$\sigma_n(t) = Ke^{-n} \sum_{i=T/\tau}^{N_f} \frac{\varphi(\epsilon_i)\epsilon_i n^i}{i!} t^{-\xi_i} \quad (6)$$

where ϵ_i = strain in an i-flake overlap columns, given by $(i\tau - T)/i\tau$, and the average flake overlap n is given by Eq. (4).

Stress relaxation under linear press closing

During hot-pressing, platens close at a given rate. Therefore, the overall mat strain is applied in a successive manner. The strain histories of individual flake columns in a mat vary in accordance with their flake overlaps. The more the flake overlaps, the sooner the column areas become compressed. Assume linear loading strain histories (Fig. 1). The compression stresses in flake columns can then be calculated using the extended Boltzmann superposition principle (Eq. 2). But first, the strain and time parameters pertaining to the loading histories need to be determined.

Loading histories.—The maximum strain in the highest flake overlap columns, ϵ_N, is given by:

$$\epsilon_N = \frac{N\tau - T}{N\tau} \quad (7)$$

where N is the maximum number of overlaps contained in flake columns. It can be estimated by designating p(i) = 0.001 in Eq. (3) and solving the equation for i (=N). It should be noted that ϵ_N is 0 when $T > N\tau$.

Likewise, the maximum compression strain in i-flake columns, ϵ_i, is given by:

$$\epsilon_i = \frac{i\tau - T}{i\tau} \tag{8}$$

If a flake mat is compressed with a constant platen speed V during press closing, the time required for all supporting flake columns to reach their maximum strain, t_m, is determined by:

$$t_m = \frac{N\tau - T}{V} \tag{9}$$

The time elapsed from the moment of the external load being applied onto the mat to the moment of i-flake columns start compression, t_1, is given by:

$$t_1 = \frac{N\tau - i\tau}{V} \tag{10}$$

The time needed for i-flake columns to reach their maximum strain, t_2, is obtained by:

$$t_2 = \frac{i\tau - T}{V} \tag{11}$$

Thus the strain history in i-flake columns can be described by the following expression:

$$\epsilon_i(t) = \begin{cases} 0 & (t < t_1) \\ \dfrac{t - t_1}{t_2}\epsilon_i & (t_1 \le t < t_m) \\ \epsilon_i & (t \ge t_m) \end{cases} \tag{12}$$

Taking derivative of $\epsilon_i(t)$ with respect to t in Eq. (12) and substituting ϵ_i and t_2 with Eqs. (8) and (11) yields:

$$\frac{d\epsilon_i(t)}{dt} = \begin{cases} \dfrac{V}{i\tau} & (t_1 \le t < t_m) \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

Modified Boltzmann integral.—The above equation (13) enables the use of the extended Boltzmann superposition integral to calculate stress relaxation in flake columns under successive loading. For $t < t_m$, the integral (Eq. 2) can be rewritten as follows:

$$\sigma_i(t) = 0 + \varphi(\epsilon_i)\int_{t_1}^{t} K(t - t')^{-\xi_i}\frac{V}{i\tau}\,dt' = \frac{KV\varphi(\epsilon_i)}{i\tau(1 - \xi_i)}(t - t_1)^{1-\xi_i} \tag{14}$$

For $t \ge t_m$, the integral becomes:

$$\sigma_i(t) = 0 + \varphi(\epsilon_i)\int_{t_1}^{t_m} K(t - t')^{-\xi_i}\frac{V}{i\tau}\,dt' = \frac{KV\varphi(\epsilon_i)}{i\tau(1 - \xi_i)}[(t - t_1)^{1-\xi_i} - (t - t_m)^{1-\xi_i}] \tag{15}$$

Mat stress relaxation model.—Finally, the mat stress relaxation can be calculated by substituting $\sigma_i(t)$ in Eq. (5) with Eqs. (14) and (15), and a_i/A with Eq. (3), i.e.,

$$\sigma_n(t) = \frac{KVe^{-n}}{\tau}\sum_{i=T/\tau}^{N_f}\frac{\varphi(\epsilon_i)n^i}{i(1 - \xi_i)i!}(t - t_1)^{1-\xi_i} \quad (t < t_m)$$

$$\sigma_n(t) = \frac{KVe^{-n}}{\tau}\sum_{i=T/\tau}^{N_f}\frac{\varphi(\epsilon_i)n^i}{i(1 - \xi_i)i!} \times [(t - t_1)^{1-\xi_i} - (t - t_m)^{1-\xi_i}] \quad (t \ge t_m) \tag{16}$$

The significance of the above equation (16) is that it allows the global mat stress relaxation to be calculated based on viscoelastic properties of local strand columns, which can be determined by testing a stack of flakes or single flakes. Also it has established a quantitative relationship between the mat stress relaxation and such fundamental parameters as press closing rate V, flake relaxation modulus K, flake relaxation rate ξ_i, flake thickness τ and average flake overlaps n.

MATERIALS AND EXPERIMENTAL PROCEDURE

The objectives of this experiment were: 1) to test the viscoelasticity of wood flakes under transverse compression to develop a database needed for predicting mat stress relaxation; 2) to measure the stress relaxation of flake mats and compare with model prediction; and 3) to correlate the creep of flake mats to that of wood flakes.

All mat samples were hand-formed and made of aspen (*Populus tremuloides*) flakes with average length 37.51 mm, width 6.09 mm, and thickness 0.79 mm. Each sample weighed 72 g and was 152-mm by 152-mm square. For testing the viscoelastic properties of wood, 25-mm by 25-mm square flakes with thickness 0.79 mm were hand-cut. To reduce the effect of wood variation, the samples were prepared by randomly selecting six flakes and stacking them together. A more detailed description of sample preparation procedures was presented elsewhere (Dai and Steiner 1993).

All samples were conditioned to 9.1% moisture content at 20°C before being tested on an MTS testing system at room temperature and humidity conditions. Stress and strain were measured and acquired in real time through a computer data acquisition system.

The stress relaxation tests on wood flakes were conducted by suddenly imposing strain on a 6-flake stack and then maintaining this strain for 10 min. Several strain levels were chosen to represent different stress-strain characteristics. During the mat stress relaxation tests, a loading speed of 5 mm/s was used.

To test the creep response of wood flakes, different loading levels representative of the full range of a stress-strain curve were applied in an instantaneous fashion to stacks of 6 flakes and maintained for 10 min. The flake mat creep tests were carried out by first imposing predefined stresses at a constant rate of 5 MPa/s and then maintaining the stress levels for 10 min.

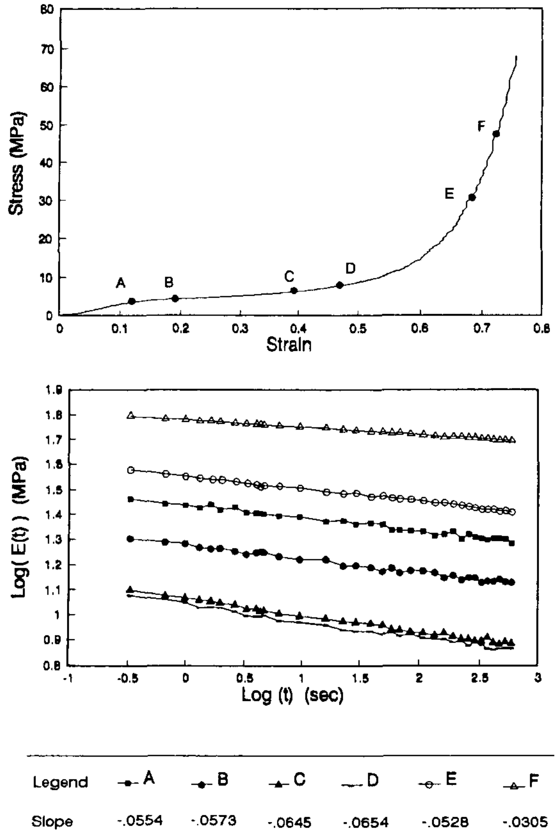

FIG. 2. (a) The strain levels imposed during flake stress relaxation tests, as indicated in a typical stress-strain curve. (b) Double logarithm plots of stress relaxation in 6-layer flake columns in compression.

RESULTS AND DISCUSSION

Flake stress relaxation

A full stress-strain curve of wood in perpendicular-to-grain compression is highly nonlinear. Thus the stress relaxation modulus E(t) is not only time-dependent but also strain-dependent. Such nonlinear stress relaxation behavior was evaluated by testing the relaxed modulus E(t) at different strain levels, as shown in Fig. 2a. The double logarithmic plots of modulus E(t) versus time are straight lines with varying slopes (Fig. 2b). Therefore, the modulus E(t) model as given by Eq. (1) is validated, and the stress relaxation rates as indicated by the slopes of the lines in Fig. 2 vary with the strain levels. The finding on double logarithmic linearity agrees with what was reported by many other researchers (Youngs 1957; Kunesh 1961; Rosa and Fortes 1988; Wolcott 1990). However, the variable slopes