INVESTIGATIONS OF FLAKEBOARD MAT CONSOLIDATION PART II. MODELING MAT CONSOLIDATION USING THEORIES OF CELLULAR MATERIALS

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ABSTRACT

This work tested the applicability of theories designed to predict the compressive stress-strain behavior of cellular materials for modeling the consolidation of a wood flake mat. Model mats designed to simulate narrow sections of randomly aligned and preferentially oriented flake mats were compressed at ambient temperature and moisture conditions in a specially designed apparatus fitted to a servo-hydraulic testing machine. Load and deflection data were collected in real time, and theoretical equations designed to predict the compression of cellular materials were fit to the experimental data. Wood flake mats are cellular-cellular materials, exhibiting two overlapping phases of densification and a highly nonlinear stress-strain response. No differences in the observed stress-strain responses of mats resulted from variations in flake orientation. Theoretical models developed for the stress-strain relationships of cellular foams were fairly effective in predicting the stress-strain relationships of wood flake mats at strains less than 70%. At higher strain levels, the relative density surpassed the initial flake density, causing a violation of model assumptions and forcing the predicted stress levels to increase asymptotically. Combining one cellular material model for the densification of the mat with another for the densification of the wood flakes may be an effective way to model the complex mechanical behavior occurring during consolidation of a wood flake mat.

Keywords: Oriented strandboard, cellular materials, modeling, stress-strain behavior.

INTRODUCTION

Mathematical models can help to elucidate the complexities of intricate systems such as the hot-pressing of wood-based composites. A model with the ability to predict the stress-strain behavior of a wood flake mat in compression, based on mat structure and raw material properties, would be useful for improving the processing and performance of nonveneered structural panels. This work assumes that the structure of a wood flake mat is similar to a cellular material. In such an analogy, the cell walls of the material are composed of the flakes, and the voids are the spaces between the flakes. The mechanical properties of such cellular materials are governed by the cellular geometry, or arrangement of cells, and the properties of the solid cell-wall substance. The influence of environmental variables is restricted to the cell-wall substance; and the effects of time, temperature, and moisture are combined in the viscoelastic response of the cell-wall material (Wolcott 1989). The cellular geometric structure gives rise to the nonlinear response that is characteristic of cellular materials when loaded in compression. Separating the nonlinear response of the cellular structure from the viscoelastic behavior of the cell-wall material has been demonstrated to be an effective route in simplifying the understanding of the complex mechanical behavior of cellular materials (Wolcott 1989; Gibson and Ashby 1988; Meinecke and Clark 1973; Rusch 1969). Theories based on this principle have been shown to effectively model the compressive stress-strain behavior of many natural and synthetic cellular materials based on cell geometry and mechanical properties of the cell-wall substance (Gibson 1989a; Wolcott 1989; Gibson and Ashby 1988; Warren and Kraynik 1987; Gibson and Ashby 1982; Meinecke and Clark 1973).

In terms of this project, the consolidation process is defined as a one-stage compression of the wood flake mat to the final thickness, simulating the press closing phase in wood-based panel manufacture. During consolidation, the temperature of a flakeboard mat is well below that required by commonly used adhesive systems for resin cure. Therefore, the presence of resin on the wood furnish does not affect the mechanical behavior of the mat during consolidation.

In the interest of modeling the consolidation of wood flake mats using theories of cellular materials, the goals of this research were to demonstrate that wood flake mats behave mechanically as cellular materials and to evaluate the effectiveness of using theories developed for modeling the compressive stress-strain behavior of cellular materials to model the consolidation of wood flake mats.

Compression behavior of cellular materials

Natural and synthetic cellular materials, such as wood, foams, and honeycombs, are widely used in applications requiring structural performance. The stress-strain curve provides perhaps the most comprehensive collection of information regarding the mechanical behavior of cellular materials loaded in compression. The stress-strain behavior of cellular materials in compression is highly nonlinear, resulting from the cellular structure (Wolcott 1989). All cellular materials exhibit similarities in mechanical behavior (Gibson and Ashby 1988), and their compressive stress and strain curves have the same characteristic shape. Three distinct regimes exist, corresponding to three different mechanisms of cell deformation (Gibson 1989b; Wolcott et al. 1989a; Shutler 1993). The initial linear elastic regime corresponds to cell-wall bending; the stress plateau to cellular collapse; and the final sharp increase in stress is due to densification of the cell wall after the majority of cell walls have collapsed. Cellular collapse occurs by either elastic buckling, plastic yielding, or brittle crushing, depending on test conditions and the nature of the cell-wall material.

Modeling the compression of cellular materials

Gent and Thomas (1959) were among the first to develop quantitative theories to predict mechanical properties of foams, relating the stress-strain behavior in compression to the structure of the foam and the properties of the matrix material. Rusch (1969) suggested factoring the compressive stress of cellular materials into two terms, a nonlinear strain function reflecting the buckling of the cellular matrix and the Young's modulus, which is a function of the properties of the cell-wall material. Rusch's modified Hooke's Law is:

$$\sigma = E\psi(\epsilon) \tag{1}$$

where σ = compressive stress, ϵ = compressive strain, E = Young's modulus of cellular material, and $\psi(\epsilon)$ = nonlinear strain function.

Stemming from this original work, several theories describing the linear elastic and yielding behavior of cellular materials based on cell geometry and cell-wall properties have been developed (Gibson and Ashby 1988; Warren and Kraynik 1987; Maiti et al. 1984; Ashby 1983; Gibson and Ashby 1982; Easterling et al. 1982; Meinecke and Clark 1973). Gibson and Ashby (1982, 1988) and Maiti et al. (1984) have demonstrated that the Young's modulus of a cellular material can be expressed as a function of the Young's modulus of the cell-wall material and the relative density of the cellular material, which is the density of the cellular material divided by the density of the cell-wall material.

$$E = C_1 E_s \left(\frac{\rho}{\rho_s}\right)^x \quad (2)$$

where E_s = Young's modulus of the cell-wall material, C_1 = constant, ρ = density of cellular material, ρ_s = density of cell-wall material, ρ/ρ_s = relative density of cellular material, x = power (1.5–3.0) reflecting the type of cellular structure.

This modeling approach has been applied to a number of natural and synthetic cellular materials including wood (Wolcott 1989; Wolcott et al. 1989a; Gibson and Ashby 1988; Gibson et al. 1989b; Maiti et al. 1984; Easterling et al. 1982). Maiti et al. (1984) developed equations to predict the Young's modulus, plateau stress, and stress-strain relationships of both flexible and plastic foams. Equations (3) and (4) were shown to effectively predict the stress-strain relationships for flexible and plastic open-celled foams, respectively.

$$\frac{\sigma}{E_s} = C_2\left(\frac{\rho}{\rho_s}\right)^2 \left[\frac{1 - \left(\frac{\rho}{\rho_s}\right)^{1/3}}{1 - \left[\frac{\rho}{\rho_s}\frac{1}{(1-\epsilon)}\right]^{1/3}}\right]^2 \quad (3)$$

$$\frac{\sigma}{\sigma_y} = C_3\left(\frac{\rho}{\rho_s}\right)^{3/2} \left[\frac{1 - \left(\frac{\rho}{\rho_s}\right)^{1/3}}{1 - \left[\frac{\rho}{\rho_s}\frac{1}{(1-\epsilon)}\right]^{1/3}}\right] \quad (4)$$

where: C_2 = linear elastic constant, C_3 = constant, and σ_y = yield stress of cellular material. Maiti et al. (1984) determined that values of 0.05 and 0.3, respectively, for the constants C_2 and C_3 provided the best fit to experimental data for foams with relative densities less than 0.3. Wolcott (1989) used a similar relationship (Eq. 5), originally developed by Gibson and Ashby (1982) for the elastic compression of a closed cell foam, to model the stress-strain behavior of wood in transverse compression, finding good agreement for low density woods (less than 500 kg/m^3) and fair agreement for medium density woods (500–700 kg/m^3).

$$\frac{\sigma}{E_s} = C_2\left(\frac{\rho}{\rho_s}\right)^3 \left[\frac{1 - \left(\frac{\rho}{\rho_s}\right)^{1/3}}{1 - \left[\frac{\rho}{\rho_s}\frac{1}{(1-\epsilon)}\right]^{1/3}}\right]^3 \quad (5)$$

Kunesh (1961) investigated the inelastic behavior of solid wood in transverse compression under conditions similar to those encountered in the hot-pressing of wood-based composites. Whittaker (1971) demonstrated that the structural theories developed for honeycombs and closed cell foams can be applied to wood. These theories relate the E and σ_y of the wood to the E and σ_y of the cell wall through experimentally derived constants and relative density (a ratio of wood density to cell-wall density. Easterling et al. (1982) and Maiti et al. (1984) modeled the compression of wood using theories developed for rigid plastic foams.

Modeling the compression of wood flake mats

Suchsland (1959, 1962) was among the first to investigate the relationship between the structure and properties of a wood composite mat. Suschland and Xu (1989, 1991) later expanded this original work to investigate the horizontal density distribution in a panel and its effect on the particle bonding process.

In the interest of establishing a relationship between individual properties of wood constituents, spatial arrangement of raw material elements, and overall mat response, thus enabling quantitative analysis of the wood composite manufacturing process, a random mat structural model was developed (Steiner and Dai 1994; Dai and Steiner 1994a). In this model, a randomly formed flake mat was divided into columns of infinitely small cross-sectional area. The total and average number of flakes in each column were then determined from a Poisson distribution (Dai and Steiner 1994b). Based on this mat structural model and Rusch's (1969) modified Hooke's law (Eq. 1), a theoretical relationship that predicts compressive force necessary for the consolidation of random flake mats based on mat structure and compression properties of solid flakes was developed:

$$\sigma_n = \frac{F}{A} = \sum_{i=T/\tau}^{\infty} \sigma_i \frac{a_i}{A} = Ee^{-n} \sum_{i=T/\tau}^{\infty} \psi(\epsilon_1)\epsilon_i \frac{n^i}{i!} \quad (6)$$

where: σ_n = nominal overall compression stress, i = number of flakes in an arbitrarily chosen column, T = mat thickness, τ = average flake thickness, a_i = total area of flake columns with i flakes, n = mean flake number of all columns, ϵ_i = flake strain in columns with i flakes. The nonlinear strain function $\psi(\epsilon_1)$ was obtained empirically by determining the constants in the following equation (Dai and Steiner 1994b):

$$\psi(\epsilon) = \sum_{i=0}^{10} b_i \epsilon^i \quad (7)$$

Dai and Steiner expressed the stress-strain relationships of their mats with plots of compaction pressure verses mat thickness. The relationships predicted by their model appear to be in good agreement with experimental data for thin mats formed randomly from very small aspen flakes. Parameters from the mat structural model were also used to quantify changes in void volume and flake-to-flake bonded area during compression. A closer evaluation of this model by Lang and Wolcott (1995b) reveals that it tends to underpredict stress in the plateau region. This underprediction is due to the occurrence of stresses necessary to induce flake bending during consolidation. These flake bending stresses cause compressive stress to arise in the mat prior to the onset of flake densification, and were not accounted for in the Dai and Steiner model.

Lang and Wolcott (1995a, b) employed a similar approach to that used by Dai and Steiner (1994b) to model the static stress-strain behavior of yellow-poplar strand mats. Lang and Wolcott's model, however, differs in the fact that the stress required to compress the mat up to the point where wood densification begins is determined by the cumulative effect of flake bending stresses. Parameters relevant to calculating the flake bending stresses developed in the early stages of mat consolidation were measured from images of mat cross sections. Monte Carlo simulation was used to predict these geometric characteristics and replicate the structure of the mat based on Lognormal and Poisson probability distributions (Lang and Wolcott 1995a). Hooke's law, modified by an experimentally determined nonlinear strain function $\psi(\epsilon)$ for the compression of cellular materials (Eq.1), was used to predict the stress required to compress solid columns of flake layers. In this model, two parameters generally control the shape of the predicted response. The average number of overlapping flakes per column determines the strain level at which the inflection point, corresponding to the rapid increase in stress at the onset of densification, occurs. The flake compression modulus determines the slope at which the stress increases during densification (Lang and Wolcott 1995b). The stress-strain responses predicted by this model were more accurate than those of Dai and Steiner and in fairly good agreement with experimentally obtained stress-strain curves for small yellow-poplar flake mats; however, the model tended to overestimate compaction stress in the plateau region.

EXPERIMENTAL METHODS

Consolidation of wood flake mats

Narrow wood flake mats, hence referred to as model mats, were created to simulate thin cross sections of random and preferentially oriented flakeboard mats. Details of the methodology used in the design and formation of these model mats have been described previously (Lenth 1994; Lenth and Kamke 1995).

The apparatus designed to hold the model mat and maintain the integrity of mat edges during consolidation was a rigidly reinforced rectangular frame with a glass front, which could be removed to facilitate insertion and removal of narrow model mats. The model mat compression apparatus was fixed to a servohydraulic testing machine, and load was applied to the model mats via a vertical aluminum plate attached to the crosshead of the testing machine.

Model mats were placed into the consolidation apparatus, and compression was carried out at ambient conditions. The average furnish moisture content prior to consolidation was 9%. The thickness of uncompressed mats varied considerably due to the randomness of formation. Prior to consolidation, mats were precompressed to a 70-mm thickness to reduce variability in initial mat density. Precompression is a common industrial practice to reduce mat thickness prior to consolidation. The 70-mm thickness was chosen to satisfy requirements of the concurrent project for quantifying mat structure. No stress could be detected when the model mats were compressed from the initial "uncompressed" thickness to the testing "precompressed" thickness. Thus, the precompression was determined not to affect the load-deflection behavior of the model mats because of their loose "fluffy" structure. Once the mat was prepared for consolidation, the time-date generator and data acquisition system for recording load deflection information were started simultaneously. Subsequently, the ramp cycle on the testing machine was initiated. Model mats were compressed at a ramp speed of 0.42 mm per second (1 inch per minute) to a target thickness of 28.5 mm. In most cases, the consolidation was terminated shortly before the target thickness had been reached due to the compressive force exceeding the upper limit of the load cell. While a larger capacity load cell would have prevented this situation, the increased accuracy provided by the smaller load cell was more important to the results of this study. During mat consolidation, load and deformation data were acquired in real time and stored for later analysis.

Modeling mat consolidation

The models developed by Maiti et al. (1984) for the compressive stress-strain behavior of flexible and plastic foams (Eqs. 3 and 4, respectively) as well as the model for the elastic collapse of a closed cell foam (Eq. 5) used by Wolcott (1989) were fit to the data acquired during consolidation of the model mats. The empirical mat consolidation model developed by Lang and Wolcott (1995b) was also fit to the experimental data from the compression of two of the randomly oriented model mats.

The model for the compression of a flexible foam (Eq. 3) requires input of E_s, the Young's modulus of the cell-wall material. Lang and Wolcott (1995b) determined a modulus of 4.2 MPa for yellow-poplar flake columns from the slope of the linear elastic portion of a stress-strain curve obtained from the ambient compression of columns of vertically stacked flakes. The justification for using values from the compression of flake columns as opposed to the compression modulus of solid wood lies in the effects of surface roughness on compression modulus. Surface irregularities and nonparallelism effectively reduce the compression modulus of thin material (Wolcott 1989; Kasal 1989; Dai and Steiner 1994b). This effect becomes more pronounced as specimen thickness is reduced (Wolcott 1989; Kasal 1989). This surface roughness effect is likely to be significant in the compression of a column of flakes, where the relative proportion of surface irregularities to thickness is high.

Equation 4, the model for the compression of a plastic foam, required input of the yield stress of the mats. For most materials, yield stress is obtained from the inflection point on the stress-strain curve where linear elastic behavior ceases and the stress plateau begins. The absence of observable linear elastic behavior in the compressive stress-strain response of wood flake mats makes this quantity impossible to determine in the traditional manner. This problem was dealt with by combining the yield stress and the constant C_3 into a new constant, C_3'. Thus Eq. 4 was rewritten as:

$$\sigma = C_3'\left(\frac{\rho}{\rho_s}\right)^{3/2}\left[\frac{1-\left(\dfrac{\rho}{\rho_s}\right)^{1/3}}{1-\left[\dfrac{\rho}{\rho_s}\dfrac{1}{(1-\epsilon)}\right]^{1/3}}\right] \quad (8)$$

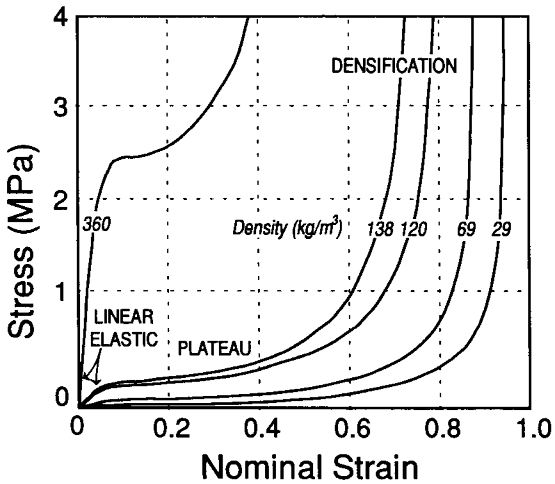

FIG. 1. Stress-strain response of a polyethylene foam, illustrating typical compressive stress-strain behavior for cellular materials.

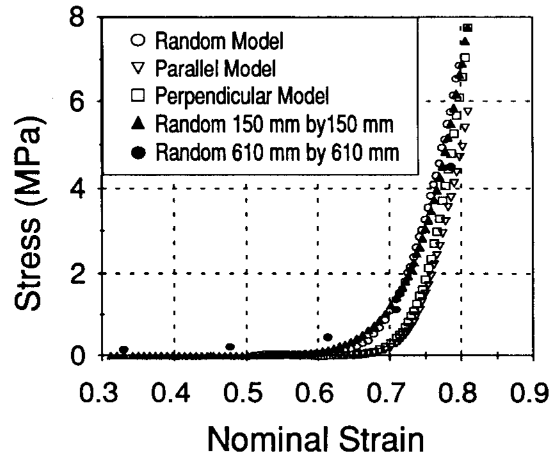

FIG. 2. Stress-strain curves for the consolidation of three model mats, a laboratory size (150 mm by 150 mm) mat, and a flakeboard panel (610 mm by 610 mm).

The elastic and plastic foam models were applied to data obtained from consolidating random and oriented model mats. The mat consolidation model developed by Lang and Wolcott was applied to model mats formed with randomly oriented flakes.

RESULTS AND DISCUSSION

Compressive stress-strain behavior of mats

A compressive stress-strain response for a polyethylene foam, illustrating mechanical behavior typical of cellular materials, is shown in Fig. 1. Figure 2 illustrates the compressive stress-strain relationships for model mats formed with three different directions of flake orientation. The designation parallel model refers to a model mat with flakes oriented parallel to the mat cross section. Total mat strain was computed using the initial mat thicknesses. No data are shown for model mats at strain levels less than 0.5 because the mats were precompressed prior to consolidation. For comparison, stress-strain curves for the compression of a 150-mm by 150-mm laboratory mat and the consolidation of a 610-mm by 610-mm flakeboard panel, formed from commercial OSB furnish, are also included in Fig. 2.

The longer stress plateau exhibited by the oriented model mats is likely a result of the more organized cellular structure obtained when flakes are aligned during mat formation. A mat formed with aligned flakes will tend to be less "fluffy" than a randomly oriented mat, thus requiring less compressive stress in the early stages of consolidation and achieving a higher strain before densification begins. The slightly higher stress plateau in the response shown for the 610-by 610-mm flakeboard mat is the result of a greater rate of consolidation. Obvious similarities in the shapes of stress-strain curves of the three mat types indicate that the model mats were effective in simulating the compressive stress-strain behavior encountered during the consolidation of a flakeboard mat.

When comparing the stress-strain responses of the flake mats to those of other cellular materials (Fig. 1), the stress-strain response of the mats most closely resembles that of low density polyethylene foams. However, the absence of a visible linear elastic region is evident. This lack of observable linear elastic behavior was also shown for the aspen flake mats modeled by Dai and Steiner (1994b), and the yellow-poplar flake mats modeled by Lang and Wolcott (1995b). The exponential increase in stress in the densification region of the stress-strain response of the wood flake mats is, however, characteristic of cellular material behavior in compression.

There are several possible explanations as to why wood flake mats exhibit no noticeable linear elastic behavior in compression. The yield point could possibly occur at such a low stress level that the transducer used to measure the applied load does not have sufficient resolution to detect it. Furthermore, since a wood flake mat obviously has a very low compression modulus, the slope of the linear elastic region, should it exist, would be very flat. Thus it would be impossible to visibly discern the transition between linear elastic behavior and the stress plateau. On a cellular level, traditional honeycombs and foams respond to a compressive force initially by elastic bending of the cell walls until some maximum moment is reached and plastic hinges are formed (Gibson and Ashby 1988). However, during consolidation of a flake mat, no connections exist between adjacent cell edges (flakes), reducing the resistance of flakes to bending forces and the associated rotation and bending moment created at the cell corners. This would then reduce the ability of the cellular material to respond elastically to an applied load. As an analogy, the individual cell edges of a traditional cellular material can be viewed as beams rigidly fixed at both edges, whereas the flakes in a mat are like simply supported beams, with the ends allowed to rotate in response to a bending moment.

Another consequence of the lack of connections between adjacent cell edges in a flake mat is that a minor compressive force can cause permanent changes in the cellular structure, and thus the mechanical properties, of the mat. In a loose flake network, individual flakes can shift their position in response to a compressive force, altering the cellular geometry. This suggests that a flake mat undergoing compression is essentially a transient material, with properties that are continuously changing as the mat is being consolidated.

Theoretically, densification of a wood flake mat would be complete only if the mat were compressed to a density equal to that of the wood cell wall. A wood flake mat can be viewed as a cellular-cellular material, in which mat consolidation causes two phases of densification. In the first phase, the between-flake void volume is reduced through aligning, flattening, and bending of the flakes. In the second phase, the flakes themselves are compressed, eliminating any remaining between-flake void volume and reducing the within-flake void volume. Kasal (1989), Wolcott (1989), Gibson and Ashby (1988), Easterling et al. (1982) and others have shown that the response to transverse compression of small wood specimens is characteristic of cellular material behavior, and can be modelled effectively using cellular material theories. Ideally under this cellular-cellular approach, consolidation could be predicted by combining a model for the mat consolidation with one for flake consolidation. The difficulty in modeling this cellular-cellular approach lies in the fact that both modes of densification occur simultaneously during the latter stages of consolidation. Also, the localized strains responsible for the flake densification are not represented by the total mat strain, and would be difficult or impossible to measure.

Modeling results

The models for the compressive stress-strain response of foams developed by Gibson and Ashby (1982) (5) and Maiti et al. (1984) (3 and 8) were fit to the data from the consolidation of the yellow-poplar model mats. The models were fit to the load deflection data of each mat. The actual response and model prediction for mats formed with flakes oriented both parallel and perpendicular to the mat cross section were very similar to those shown for the randomly oriented mats. Hence only the responses for the randomly oriented mats are presented. Generally, the models were in slightly better agreement with the actual data from the randomly oriented mats than they were with the data from the oriented ones. The initial relative density of the model mats was approximately 0.24 for all three flake orientations, corresponding to an uncompressed mat density of 100 kg/m^3. Figure 3 shows the three cellular material models fit to the compression of a randomly oriented model mat.

All three of the cellular material models appeared to follow the actual stress-strain responses in the plateau region, to a strain level of approximately 0.675. At this point, the predicted responses increase rapidly, approaching a vertical asymptote. This rapid increase corresponds to $\rho/\rho_s\,[1/(1-\epsilon)]$, the relative density of the mat as a function of strain, approaching unity. This indicates that the mat has been compressed to a point where the mat density is equal to the initial flake density. At this point, the denominators in the cellular material equations approach zero, causing the predicted stress to increase asymptotically, deviating sharply from the actual stress.

The asymptotic increase in stress suggests a violation of the models used. The cellular material models assume a constant density of the cell-wall material. Under the assumptions of the model, densification is complete, and the stress-strain curve becomes nearly vertical when the relative density as a function of strain is equal to one (Maiti et al. 1994). Because of the relatively low density of the cell-wall material (flakes), the final mat density is generally considerably higher than the initial flake density. Foams and other traditional cellular materials are generally made from denser materials, thus having much higher cell-wall densities. If the relative density of the mat were to be calculated using the flake density as a function of strain, the mat relative density could never be greater than one. That is, the density of the mat could never be greater than the average density of the flakes, because, as the relative density approaches one, the average flake density must increase together with the mat density until the density of the wood cell wall is reached and densification is indeed complete. While this violation of assumptions invalidates the use of these models for the prediction of stresses at relative densities greater than one, the results should still be valid for relative densities less than one.

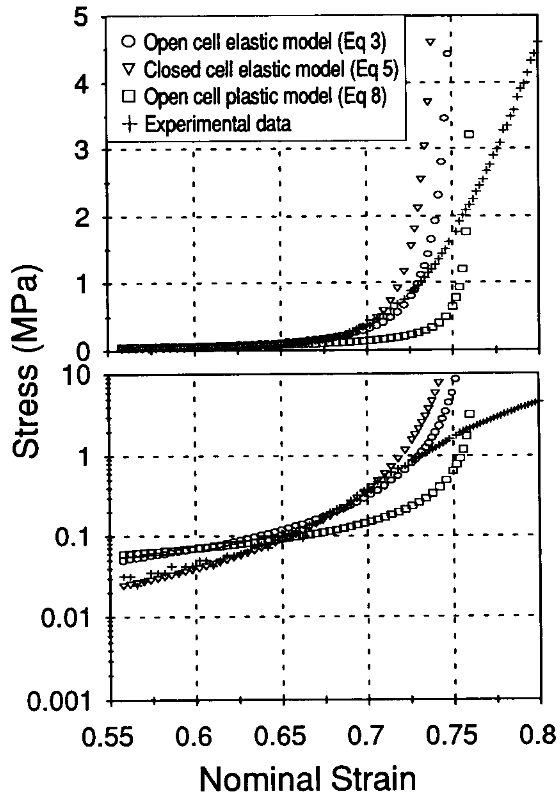

FIG. 3. Stress-strain response of a randomly oriented model mat with predicted responses from three cellular material models. $C_2 = 0.05$, $C_3' = 0.25$.

Equation 8, the model for plastic compression of an open celled-foam, had the poorest agreement with the experimental data for all three flake orientations. This model yielded a considerable underestimation of the stress at the onset of densification. Equation 3, the model for elastic compression of an open-celled foam, predicted the actual stress quite closely in the plateau region; however, it slightly underestimated the stress at the onset of densification. Equation 5, the model for elastic compression of a closed-cell foam, produced the best fit with the experimental data, especially when observing stress plotted on a log axis. The compressive stress predicted by Eq. 5 traced the experimental value closely through the plateau region to a strain of 0.7. Comparing the quality of the fit by the elastic vs, the plastic models may provide some insight as to the

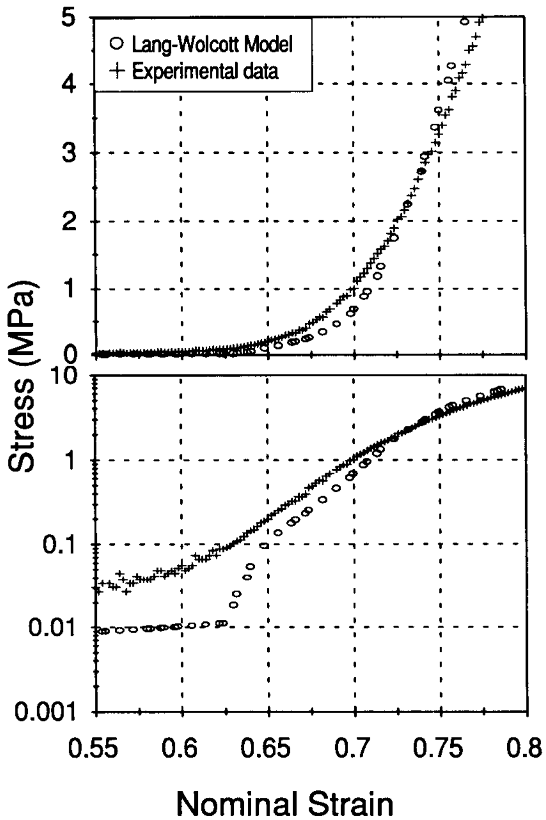

FIG. 4. Stress-strain response of a randomly oriented model mat with the predicted response from the mat consolidation model developed by Lang and Wolcott.

type of deformation occurring during mat consolidation. While both elastic and plastic yielding are sure to occur during consolidation, the closer predictions by the elastic models suggest that elastic deformation may be more prevalent during initial mat compression, while the plastic deformation necessary for the development of panel properties occurs later in the pressing cycle.

The model developed by Lang and Wolcott (1995b) was applied to data from the compression of two of the random model mats. The model prediction is based on a simulation of 44 columns, with an average of 53 flakes per column. As can be seen from Fig. 4, the predicted data fit the experimental results quite well, especially in the densification region. However, when stress is plotted on a log axis, it is evident that this model does considerably underestimate the compressive stress in the plateau region where the strain is less than 0.75. This empirical model predicts the entire stress-strain response of the random mats much more thoroughly than any of the theoretical models for cellular materials applied. The improved prediction exhibited by the Lang-Wolcott model is due in part to the empirical nature of the nonlinear strain function used, and is also a function of the calculated compressive stress being numerically independent of the relative density of the mat.

CONCLUSIONS

Wood flake mats behave like cellular materials in which the cell-wall material, the wood flakes, is also a cellular material. Densification of mats during consolidation occurs in two overlapping phases: the reduction of between-flake void volume and the reduction of within-flake void volume.

The observed stress-strain responses of narrow wood flake mats in compression were highly nonlinear, characterized by a long stress plateau resulting from collapse of between-flake voids followed by a rapid increase in stress corresponding to densification of the wood component. No differences in the compressive stress-strain responses of mats were observed due to differences in the direction of flake orientation.

The loose structure of wood flake mats leads them to exhibit an absence of observable linear elastic behavior at the onset of compression. This initial linear elastic behavior is inherent to the stress-strain behavior of foams and other cellular materials.

Theoretical models developed to predict the stress-strain response of cellular materials in compression were effective in predicting the stress required to compress wood flake mats to 70%. The fact that flake mats can be compressed to densities greater than the initial flake density violates the assumption of the models that the cell-wall density is constant. This limits the validity of these models to conditions where the relative density of the mat as a function of strain is less than one.

The best single prediction of the compressive stress-strain response was provided by the mat consolidation model developed by Lang and Wolcott (1995b). This empirical model provided a poorer prediction of the stress-strain response of a random flake mat in the plateau region and a better prediction in the densification region than the theoretical cellular material models. A combination of the model for the elastic compression of a closed cell foam at strains less than 0.65 and the Lang-Wolcott model at higher strains may be the best recommendation for predicting the entire stress strain response of wood flake mats in compression. Combining one cellular material model for the densification of the mat with another for the densification of the wood flakes may also be an effective way to model mat consolidation.

The results of the modeling investigations in this study provide a framework for understanding the nature of the mechanical behavior of a wood-flake mat during consolidation. The models evaluated herein could be used as a component in a comprehensive model to simulate the consolidation of a wood-based composite. Such a comprehensive model would be useful in the design and optimization of new and existing wood-based composite products and processes.

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