

# SIMULATION MODELING OF PARTICLEBOARD DENSITY PROFILE

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## ABSTRACT

Particleboard properties are affected by the vertical density profile among other factors. To predict or model board properties, one needs to determine the density profile. A simulation model was developed in this study to model the vertical density profile by simulating the hot pressing process of a particleboard. Temperature and moisture content profiles during hot pressing in the thickness direction of a pressed mat and the influential factors affecting wood compressibility were modeled such that they can be determined at any moment of pressing. The models developed allow calculations of the profiles to be carried out by either the finite difference method or an alternative approximation method presented herein. The density profile was modeled based on the compressibility and the resulting strain of each layer of the board thickness due to pressing.

*Keywords:* Particleboard, simulation modeling, density profile, temperature profile, moisture content profile, finite difference method.

## INTRODUCTION

The vertical density profile of particleboard, or simply density profile, is one of the most influential factors affecting board properties. The density profile is usually determined by either a direct method such as a gravimetric method (Huang et al. 1976; Stevens 1978) or an indirect method such as X-ray or gamma-ray densitometric techniques (Steiner et al. 1978; Laufenberg 1986). Another method is to model density profile using simulation techniques. This paper, which is taken in part from Suo's doctoral dissertation (Suo 1991), presents a simulation modeling method that can be used to model the vertical density profile of a particleboard. A software package developed for Macintosh computers to predict structural particleboard properties includes the routines to determine the board density profiles.

A piece of particleboard may be modeled as a system of a number of thin and plane orthotropic layers in which each layer exhibits the same properties everywhere within the plane of the layer (Fig. 1). Elastic and physical properties of each layer are determined by the characteristics of the layer, the most important of which is the density of the layer. A denser layer is the result of more deformation or compression having occurred in that layer. The compressibility is associated with the stress-strain behavior of the layer. As for wood, a hygroscopic material, its stress-strain behavior is highly affected by temperature and moisture content (MC).

Strength and dimensional stability property models may be established once density, temperature, and moisture content profile models are formed (strength and dimensional stability

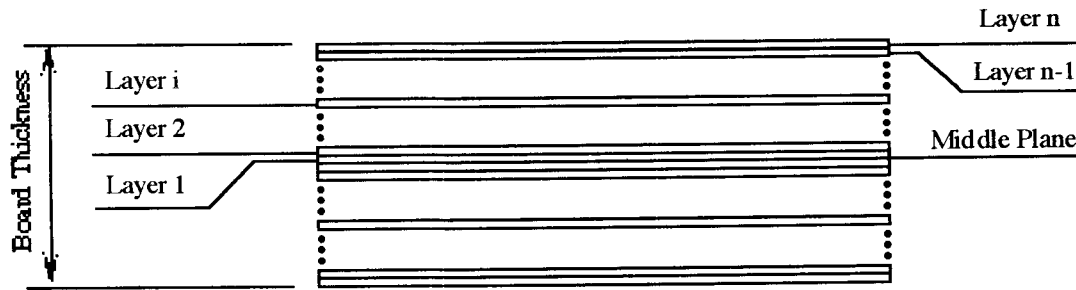


FIG. 1. A board consisting of 2n layers.

property models will be presented in future articles). Temperature and moisture content profile models were built based on heat and moisture diffusion theories.

#### TEMPERATURE PROFILE

During the pressing process, the mat in the hot press is compressed into a board while being heated. Heat from press platens travels through the mat surfaces into the inside. In the middle of the mat, the temperature increase lags behind that in the outside layers. As a result, a temperature distribution or profile through the mat thickness develops at each moment of the heating and pressing process.

The temperature profiles of the mat may be modeled based on heat transfer theory. For unsteady-state flow as in the case of hot-pressing of particleboard, heat transfer in terms of temperature changes inside the mat in the thickness direction can be expressed as (Siau 1984):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( D_h \frac{\partial T}{\partial x} \right) \quad (1)$$

where

$T$  = temperature at location  $x$  ( $^{\circ}\text{C}$ ),

$t$  = pressing time (sec),

$x$  = distance from one of board surfaces in the thickness direction (cm),

$D_h$  = thermal diffusivity ( $\text{cm}^2/\text{sec}$ ).

Define

$b$  = board thickness (cm),

$T_0$  = mat initial temperature before pressing ( $^{\circ}\text{C}$ ),

$T_1$  = platen temperature ( $^{\circ}\text{C}$ ).

Eq. (1) is bounded by the following conditions:

$$T = T_0 \quad \text{for } t = 0,$$

$$T = T_1 \quad \text{for } x = 0 \text{ and } t > 0,$$

$$T = T_1 \quad \text{for } x = b \text{ and } t > 0.$$

The thermal diffusivity,  $D_h$ , for transverse transport of heat in wood may be obtained by (Siau 1984)

$$D_h = \frac{G(4.80 + 0.090M) + 0.57}{G(0.268 + 0.0011C + 0.01M)\rho_w} \times 10^{-4} \quad (2)$$

where

- G = specific gravity of wood,
- M = moisture content of wood (%),
- $\rho_w$  = normal density of water (1 g/cm<sup>3</sup>),
- C = Celsius temperature (°C).

It is clear from Eq. (2) that the thermal diffusivity coefficient,  $D_h$ , is a function of temperature T because of the existence of the variable C in the equation, i.e.,

$$D_h = f(T) = D_h(T) \quad (3)$$

Eq. (1) can be solved by the finite difference method. The explicit scheme of the solution is as follows:

$$\frac{T_{j(t+1)} - T_{j(t)}}{\Delta t} = \frac{D_{j+1/2}^E(T_{j+1(t)} - T_{j(t)}) - D_{j-1/2}^E(T_{j(t)} - T_{j-1(t)})}{(\Delta x)^2} \quad (4)$$

where

$T_{j(t)}$ ,  $T_{j(t+1)}$  = temperatures of the jth layer at times t and t + 1, respectively,

$T_{j-1(t)}$ ,  $T_{j+1(t)}$  = temperatures of the (j - 1)th and (j + 1)th layers at time t, respectively,

$\Delta t$  = time increment or time interval,

$\Delta x$  = distance increment in the thickness direction, or layer thickness,

$$D_{j+1/2}^E = \frac{1}{2} [D_h(T_{j+1(t)}) + D_h(T_{j(t)})],$$

$$D_{j-1/2}^E = \frac{1}{2} [D_h(T_{j(t)}) + D_h(T_{j-1(t)})],$$

while the implicit scheme is:

$$\frac{T_{j(t+1)} - T_{j(t)}}{\Delta t} = \frac{D_{j+1/2}^I(T_{j+1(t+1)} - T_{j(t+1)}) - D_{j-1/2}^I(T_{j(t+1)} - T_{j-1(t+1)})}{(\Delta x)^2} \quad (5)$$

where

$T_{j+1(t+1)}$  = temperature of the (j + 1)th layer at time t + 1,

$T_{j-1(t+1)}$  = temperature of the (j - 1)th layer at time t + 1,

$$D_{j+1/2}^I = \frac{1}{2} [D_h(T_{j+1(t+1)}) + D_h(T_{j(t+1)})],$$

$$D_{j-1/2}^I = \frac{1}{2} [D_h(T_{j(t+1)}) + D_h(T_{j-1(t+1)})],$$

$$D_h(T_{j+1(t+1)}) = D_h(T_{j+1(t)}) + (T_{j+1(t+1)} - T_{j+1(t)}) \left. \frac{\partial D_h}{\partial T} \right|_{j+1,t},$$

$$D_h(T_{j(t+1)}) = D_h(T_{j(t)}) + (T_{j(t+1)} - T_{j(t)}) \left. \frac{\partial D_h}{\partial T} \right|_{j,t},$$

$$D_h(T_{j-1(t+1)}) = D_h(T_{j-1(t)}) + (T_{j-1(t+1)} - T_{j-1(t)}) \left. \frac{\partial D_h}{\partial T} \right|_{j-1,t}.$$

The partial derivative of  $D_h$  with respect to  $T$  can be obtained by differentiating Eq. (2):

$$\frac{\partial D_h}{\partial T} = -\frac{11D_h}{0.268 + 0.0011C + 0.01M} \times 10^{-8} \quad (6)$$

The Crank-Nicholson scheme of the solution that is preferred is a combination of the explicit and implicit solutions:

$$\frac{T_{j(t+1)} - T_{j(t)}}{\Delta t} = \frac{1}{2} \left[ \frac{D_{j+1/2}^E(T_{j+1(t)} - T_{j(t)}) - D_{j-1/2}^E(T_{j(t)} - T_{j-1(t)})}{(\Delta x)^2} + \frac{D_{j+1/2}^I(T_{j+1(t+1)} - T_{j(t+1)}) - D_{j-1/2}^I(T_{j(t+1)} - T_{j-1(t+1)})}{(\Delta x)^2} \right] \quad (7)$$

Temperature values of the layers may be obtained by implementing Eq. (7) in a computer program.

Alternatively, an approximate solution of Eq. (1) can be obtained by regarding  $D_h$  as a constant in relation to temperature. From Eq. (2), it can be shown that for a change in temperature  $C$ ,  $\Delta C$ , the relative change in  $D_h$ ,  $\Delta D_h/D_h$ , can be expressed as

$$\begin{aligned} \frac{\Delta D_h}{D_h} &= \frac{D_h(C + \Delta C) - D_h(C)}{D_h(C)} \times 100\% = \\ &= \frac{-0.11(\Delta C)}{0.286 + 0.0011(C + \Delta C) + 0.01M} \quad (\%) \end{aligned} \quad (8)$$

It is clear that the relative change in  $D_h$  is small even with a few degrees of change in temperature because of the small coefficient 0.0011 of the variable  $C$ . If temperature increases from 100 C to 110 C with moisture content held constant at  $M = 6\%$ , for instance, then the relative change in  $D_h$  is  $\Delta D_h/D_h \approx -2.45\%$ , i.e., an increase in temperature of 10 C results in only about a 2.45% decrease in the thermal diffusivity,  $D_h$ . The coefficient  $D_h$  can therefore be treated as a constant without losing much accuracy since within a short pressing time, temperature change is relatively small. For this purpose, Eq. (1) may be rewritten:

$$\frac{\partial T}{\partial t} = D_h \frac{\partial^2 T}{\partial x^2} \quad (9)$$

Let  $U = T - T_1$ . Then Eq. (9) becomes

$$\frac{\partial U}{\partial t} = D_h \frac{\partial^2 U}{\partial x^2} \quad (10)$$

The boundary conditions for this differential equation are:

$$\begin{aligned} T &= T_0 && \text{for } t = 0, \\ U &= T_0 - T_1 && \text{for } t = 0, \\ U &= 0 && \text{for } x = 0 \text{ and } t > 0, \\ U &= 0 && \text{for } x = b \text{ and } t > 0. \end{aligned}$$

A solution to Eq. (10) proposed by MacLean (1942), with  $U = T - T_1$  being substituted, is given below:

$$T = T_1 + (T_0 + T_1) \frac{4}{\pi} \left[ \sin \frac{\pi x}{b} \exp\left(-\frac{\pi^2 D_h t}{b^2}\right) + \frac{1}{3} \sin \frac{3\pi x}{b} \exp\left(-\frac{9\pi^2 D_h t}{b^2}\right) + \frac{1}{5} \sin \frac{5\pi x}{b} \exp\left(-\frac{25\pi^2 D_h t}{b^2}\right) + \dots \right] \quad (11)$$

The current layer temperatures calculated by the above equation are based on the diffusion coefficients of the layers at the previous time moment, which are in turn calculated using the temperature and moisture values at the time.

#### MOISTURE CONTENT PROFILE

Suppose that the initial mat moisture content is uniform throughout the thickness. When heat is applied, moisture starts moving inward and vaporizing at the moment the temperature reaches the boiling point. As in the case of temperature profiles, moisture content profiles are present throughout the pressing process.

By analogy to the treatment of temperature profiles, moisture content profiles may be modeled by (Siau 1984):

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_m \frac{\partial M}{\partial x} \right) \quad (12)$$

where

$M$  = moisture content (%),

$t$  = pressing time (sec),

$x$  = distance from one of board surfaces in the thickness direction (cm),

$D_m$  = transverse diffusion coefficient for moisture movement (cm<sup>2</sup>/sec).

This differential equation is restricted by the following boundary conditions:

$$\begin{aligned} M &= M_0 && \text{for } t = 0, \\ M &= 0 && \text{for } x = 0 \text{ and } t > 0, \\ M &= 0 && \text{for } x = b \text{ and } t > 0, \end{aligned}$$

where  $M_0$  is the initial moisture content of the mat.

The diffusion coefficient,  $D_m$ , may be obtained by the following formula (Siau 1984):

$$D_m = \frac{0.07}{(1 - a^2)(1 - a)} \exp\left(-\frac{9200 - 70M}{RT_k}\right) \quad (13)$$

where

$R$  = universal gas constant (1.987 cal/mol K),

$T_k$  = Kelvin temperature (K),

$a^2 = V =$  porosity of wood,

where  $V = 1 - G(0.667 + 0.01M)$ .

Comparing the effect of the term  $\exp\left(-\frac{9200 - 70M}{RT_k}\right)$  on  $D_m$  caused by moisture content,  $M$ ,

the effect of the factor  $\frac{0.07}{(1 - a^2)(1 - a)}$  on  $D_m$  is negligible. So  $V$  can be considered constant with respect to moisture content change in this situation.

Analogous to Eq. (1), Eq. (12) can be solved by the finite difference method. The explicit scheme of the solution is as follows:

$$\frac{M_{j(t+1)} - M_{j(t)}}{\Delta t} = \frac{D_{j+1/2}^E(M_{j+1(t)} - M_{j(t)}) - D_{j-1/2}^E(M_{j(t)} - M_{j-1(t)})}{(\Delta x)^2} \quad (14)$$

where

$M_{j(t)}$ ,  $M_{j(t+1)}$  = moisture contents of the  $j$ th layer at times  $t$  and  $t + 1$ , respectively,  
 $M_{j-1(t)}$ ,  $M_{j+1(t)}$  = moisture contents of the  $(j - 1)$ th and  $(j + 1)$ th layers at time  $t$ , respectively,

$$D_{j+1/2}^E = \frac{1}{2} [D_m(M_{j+1(t)} + D_m(M_{j(t)}))],$$

$$D_{j-1/2}^E = \frac{1}{2} [D_m(M_{j(t)} + D_m(M_{j-1(t)}))],$$

while the implicit scheme is:

$$\frac{M_{j(t+1)} - M_{j(t)}}{\Delta t} = \frac{D_{j+1/2}^I(M_{j+1(t+1)} - M_{j(t+1)}) - D_{j-1/2}^I(M_{j(t+1)} - M_{j-1(t+1)})}{(\Delta x)^2} \quad (15)$$

where

$M_{j+1(t+1)}$  = moisture content of the  $(j + 1)$ th layer at time  $t + 1$ ,  
 $M_{j-1(t+1)}$  = moisture content of the  $(j - 1)$ th layer at time  $t + 1$ ,

$$D_{j+1/2}^I = \frac{1}{2} [D_m(M_{j+1(t+1)}) + D_m(M_{j(t+1)})],$$

$$D_{j-1/2}^I = \frac{1}{2} [D_m(M_{j(t+1)}) + D_m(M_{j-1(t+1)})],$$

$$D_m(M_{j+1(t+1)}) = D_m(M_{j+1(t)}) + (M_{j+1(t+1)} - M_{j+1(t)}) \left. \frac{\partial D_m}{\partial M} \right|_{j+1,t},$$

$$D_m(M_{j(t+1)}) = D_m(M_{j(t)}) + (M_{j(t+1)} - M_{j(t)}) \left. \frac{\partial D_m}{\partial M} \right|_{j,t},$$

$$D_m(M_{j-1(t+1)}) = D_m(M_{j-1(t)}) + (M_{j-1(t+1)} - M_{j-1(t)}) \left. \frac{\partial D_m}{\partial M} \right|_{j-1,t}$$

The partial derivative of  $D_m$  with respect to  $M$  can be obtained by differentiating Eq. (13):

$$\frac{\partial D_m}{\partial M} = \frac{70D_m}{RT_k} \quad (16)$$

Combining the explicit and implicit solutions, the preferred Crank-Nicholson scheme of the solution is:

$$\frac{M_{j(t+1)} - M_{j(t)}}{\Delta t} = \frac{1}{2} \left[ \frac{D_{j+1/2}^E(M_{j+1(t)} - M_{j(t)}) - D_{j-1/2}^E(M_{j(t)} - M_{j-1(t)})}{(\Delta x)^2} + \frac{D_{j+1/2}^I(M_{j+1(t+1)} - M_{j(t+1)}) - D_{j-1/2}^I(M_{j(t+1)} - M_{j-1(t+1)})}{(\Delta x)^2} \right] \quad (17)$$

The same computer program routine for calculating the temperature values of the finite difference method can be used to obtain the moisture content values through Eq. (17).

Another alternative approach, which is simpler, is to calculate the average of  $D_m$ . If the average value of  $D_m$  can be determined, then Eq. (12) may be approximated by the following equation:

$$\frac{\partial M}{\partial t} = \bar{D}_m \frac{\partial^2 M}{\partial x^2} \quad (18)$$

where

$$\bar{D}_m = \text{mean of the diffusion coefficient } D_m$$

Eq. (18) is analogous to Eq. (10). A solution to Eq. (18) that is similar to Eq. (11) is also an infinite series:

$$M = \frac{4}{\pi} M_0 \left[ \sin \frac{\pi x}{b} \exp\left(-\frac{\pi^2 \bar{D}_m t}{b^2}\right) + \frac{1}{3} \sin \frac{3\pi x}{b} \exp\left(-\frac{9\pi^2 \bar{D}_m t}{b^2}\right) + \frac{1}{5} \sin \frac{5\pi x}{b} \exp\left(-\frac{25\pi^2 \bar{D}_m t}{b^2}\right) + \dots \right] \quad (19)$$

Once  $\bar{D}_m$  is known,  $M$  at time  $t$  and location  $x$  can be calculated using the above equation. So the moisture content profiles may be determined.

For a small moisture content change,  $\Delta M$ , within a small time increment as in the case of hot pressing, the mean value of  $D_m$ ,  $\bar{D}_m$ , may be computed by

$$\bar{D}_m = \frac{1}{\Delta M} \int_M^{M+\Delta M} D_m dM \quad (20)$$

or

$$\bar{D}_m = \frac{1}{\Delta M} \frac{0.07}{(1-a^2)(1-a)} \exp\left(-\frac{9200}{RT_k}\right) \int_M^{M+\Delta M} \exp\left(\frac{70}{RT_k} M\right) dM \quad (21)$$

or

$$\bar{D}_m = \frac{RT_k}{\Delta M} \frac{0.001}{(1-a^2)(1-a)} \exp\left(-\frac{9200-70M}{RT_k}\right) \left[ \exp\left(\frac{70}{RT_k} \Delta M\right) - 1 \right] \quad (22)$$

Substituting Eq. (22) into Eq. (19) yields the moisture content at any time and any location within the mat during pressing.

Both Eq. (11) and Eq. (19) converge rapidly. In fact, for practical use, a sum of the first few terms in the infinite series is accurate enough for approximation.

#### DENSITY PROFILE

Particleboard is distinguished from solid wood lumber and plywood by the presence of a vertical density profile. The density profile is usually "U" shaped, with high density in the surface layers and low density in the core. Particleboard properties are greatly affected by the shapes of the density profiles. Steep profiles enhance bending strength, for instance, while flat profiles improve internal bonding strength at the expense of bending strength. Certain desired properties can be obtained in designing particleboard by manipulating processing variables to adjust density profiles.

If a piece of particleboard is envisioned as composed of a number of layers as shown in Fig. 1, then the density of each layer is different. The magnitude of the layer density depends on layer compactness during pressing, which in turn is controlled by layer deformation or strain

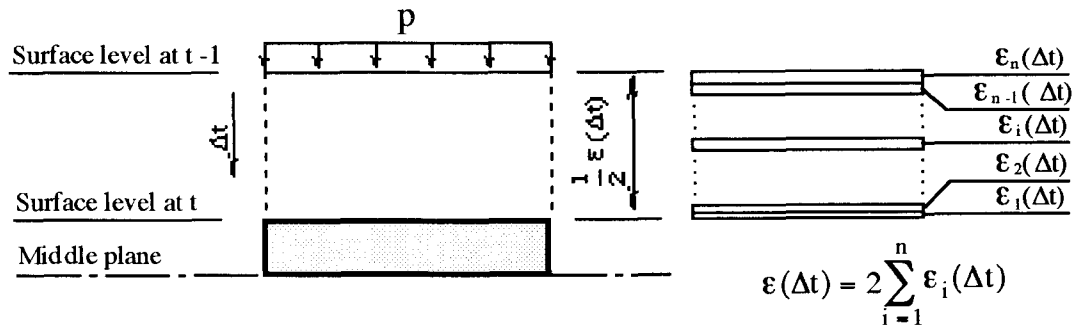


FIG. 2. Strain distribution along mat thickness (half thickness shown) during pressing from  $t - 1$  to  $t$ .

in the transverse direction of wood flakes. However, the wood stress-strain relation that dictates flake deformation is highly influenced by temperature and moisture content in the mat during pressing.

#### *Stress-strain behavior*

Stress-strain behavior of wood is to a large extent controlled by temperature and moisture content. At a constant strain level, stress decreases with temperature and/or moisture content (Kunesh 1961). In other words, compressing a mat will be easier under high temperature and moisture content than under low temperature and moisture content. Thanks to the temperature and moisture content profiles developed in the mat during pressing, the mat layer with high temperature and moisture content will deform or be compressed more than the layer with low temperature and moisture content.

#### *Layer density formation*

The density profile is mainly affected by press closing time, temperature, and moisture content distribution in the mat during pressing. Once the upper platen reaches the stops, the density profile is essentially formed.

During press closing, each decrement of the mat under pressure for a time increment is considered a strain that is distributed through the thickness of the mat. If the mat is divided into a number of layers with equal thicknesses, then each layer receives a portion of the total strain. The magnitude of the strain portion received by each layer depends on the temperature and moisture content of the layer. The higher the temperature and/or moisture content of the layer, the bigger strain or deformation it receives. The density of the layer is determined once the board total deformation is known.

One way to distribute a total strain during time interval  $\Delta t$  may be based on the current modulus of elasticity (MOE) of each layer,  $E_i$ , which is affected by its density, moisture content, and temperature.

#### *Strain distribution to each layer*

A mat is compressed successively into a board with a target thickness. If the mat thickness is assumed to be one unit at any moment, then after a period of pressing time, a certain amount of thickness is reduced. The amount of reduced thickness is the strain of the mat resulting from pressing during the time period. In other words, it is the sum of strains that occurred in all the layers during the period (Fig. 2).

What proportion of the total strain a layer receives is directly related to the compressibility



of the layer, or its MOE. Therefore, a total strain  $\epsilon_{(\Delta t)}$  occurring in the mat thickness direction during the pressing time interval  $\Delta t$  may be distributed to each layer subjected to the following rules:

$$\epsilon_{1(\Delta t)} : \epsilon_{2(\Delta t)} : \dots : \epsilon_{i(\Delta t)} : \dots : \epsilon_{n(\Delta t)} = \frac{1}{E_{1(t-1)}} : \frac{1}{E_{2(t-1)}} : \dots : \frac{1}{E_{i(t-1)}} : \dots : \frac{1}{E_{n(t-1)}} \quad (23)$$

and

$$2 \sum_{i=1}^n \epsilon_{i(\Delta t)} = \epsilon_{(\Delta t)} \quad (24)$$

where

$$\begin{aligned} \epsilon_{i(\Delta t)} &= \text{strain received by layer } i \text{ during time interval } \Delta t \text{ (} i = 1, 2, \dots, n \text{),} \\ E_{i(t-1)} &= \text{modulus of elasticity of layer } i \text{ at time } t - 1. \end{aligned}$$

The factor 2 in Eq. (24) takes care of the fact that  $n$  is the half number of layers in the board and that the board is symmetric in properties about its middle plane.

Let  $A = \sum_{i=1}^n \frac{1}{E_{i(t-1)}}$ ; then the above rules can be translated into the following equations:

$$\begin{aligned} \frac{2\epsilon_{1(\Delta t)}}{\epsilon_{(\Delta t)}} &= \frac{1}{A} \frac{1}{E_{1(t-1)}}, \\ \frac{2\epsilon_{2(\Delta t)}}{\epsilon_{(\Delta t)}} &= \frac{1}{A} \frac{1}{E_{2(t-1)}}, \\ &\dots \\ \frac{2\epsilon_{i(\Delta t)}}{\epsilon_{(\Delta t)}} &= \frac{1}{A} \frac{1}{E_{i(t-1)}}, \\ &\dots \\ \frac{2\epsilon_{n(\Delta t)}}{\epsilon_{(\Delta t)}} &= \frac{1}{A} \frac{1}{E_{n(t-1)}}. \end{aligned} \quad (25)$$

Once the MOE of each layer is determined, its strain can be calculated by the above set of equations since the total mat strain can be easily obtained as described later. It is noted that both sides of the equations sum to one.

#### *Factors affecting $E_i$*

Such factors as specific gravity, moisture content, and temperature affect wood elastic properties. Their interactions on the properties are complex and unknown. However, wood elastic properties can be adjusted for the factor effects in a proper sequence. Palka (1973) suggested the following sequence of adjustments for calculating the appropriate elastic properties in order of importance of the factors that affect board properties:

- (1) specific gravity adjustment,
- (2) moisture content adjustment,
- (3) temperature adjustment,

For the purpose of this study,  $E_i$  may be adjusted in this sequence.

Formulas used to adjust elasticity for moisture and temperature effects are those as proposed by Palka (1973). Comparisons of simulated and experimental results (described later) illustrate the usefulness of the formulas.

*Adjustment by specific gravity.*—The effect of specific gravity on MOE is adjusted by the formula given in the *Wood Handbook* (Forest Products Laboratory 1987). The formula is an empirical result from extensive research and tests. In the formula,  $p$  is a power factor that is an experimentally determined constant. Applied in this study, the formula takes the following form:

$$E_{i(t)} = E_{i(t-1)} \left( \frac{\rho_{i(t)}}{\rho_{i(t-1)}} \right)^p \quad (26)$$

where

- $E_{i(t)}$  = modulus of elasticity of the  $i$ th layer at pressing time  $t$ ,
- $\rho_{i(t)}$  = specific gravity of the  $i$ th layer at pressing time  $t$ ,
- $\rho_{i(t-1)}$  = specific gravity of the  $i$ th layer at pressing time  $t - 1$ ,
- $p$  = modification constant (from *Wood Handbook*).

The formula states that the MOE of a layer at a time moment is dependent on the MOE of the layer at the moment before. Therefore, once the initial values of MOE for all the layers are known, the MOE of each layer at time  $t$  can be computed according to this adjustment. The initial MOE values of the layers are the same at the beginning of the pressing and can be calculated based on input variables. The adjusted values then may be adjusted again for other effects.

*Adjustment by moisture content.*—Below the fiber saturation point, moisture content affects the elastic properties of wood. Once the relationship between the properties and moisture content is known, the properties can be adjusted using the relationship model. A model describing the relationship between modulus of elasticity and moisture content given by Palka (1973) is:

$$E_{i(t)} = E_{i(t-1)} [1 - \alpha_M (M_{i(t)} - M_{i(t-1)})] \quad (27)$$

where

- $M_{i(t)}, M_{i(t-1)}$  = moisture contents of the  $i$ th layer at pressing times  $t$  and  $t - 1$ , respectively (%).
- $\alpha_M$  = change of modulus of elasticity with 1% change in moisture content.

Thus, the MOE of each layer at time  $t$  may be adjusted by the difference of moisture contents at times  $t$  and  $t - 1$  based on the MOE of the layer at time  $t - 1$ . Increasing moisture content has an adverse effect on MOE.

*Adjustment by temperature.*—Temperature change affects MOE, but the influence of moisture content dominates the temperature response. Consequently, the effect of moisture content is incorporated into the equation for predicting the effect of temperature on MOE. An adjustment formula presented by Palka (1973) can be used:

$$E_{i(t)} = E_{i(t-1)} [1 - \alpha_T M_{i(t)} (T_{i(t)} - T_{i(t-1)})] \quad (28)$$

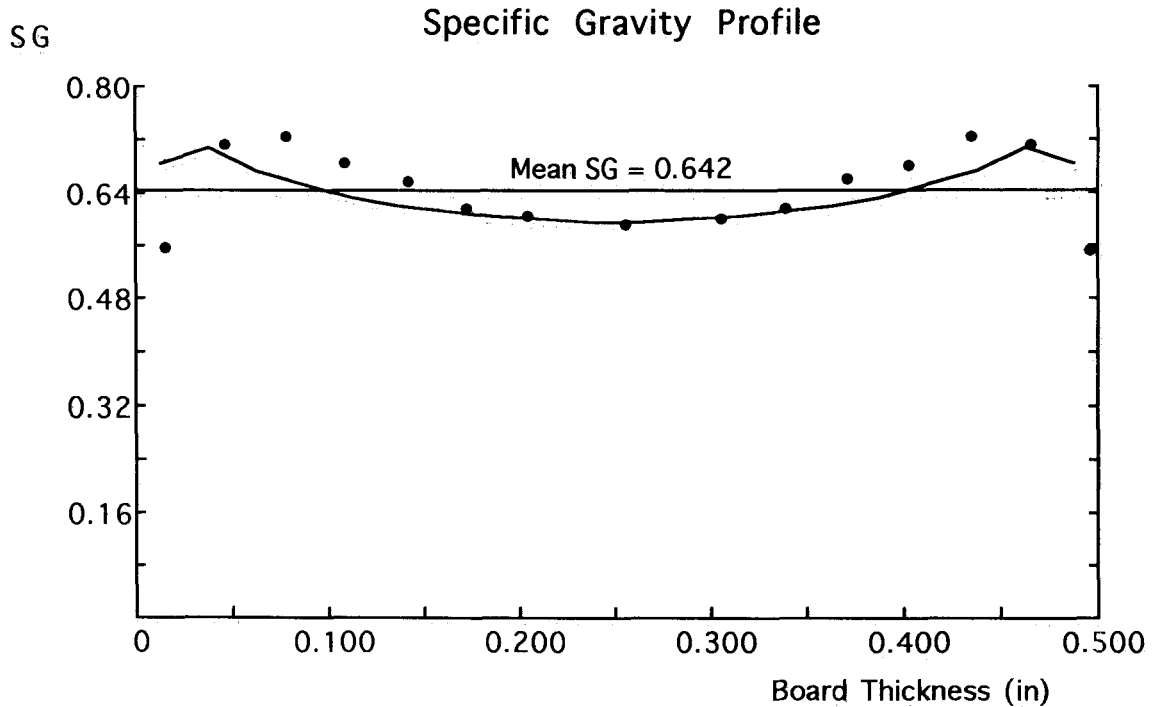


FIG. 3. Comparison of simulated and experimental density profile. The dots in the figure represent experimental data. The curve is the predicted result.

where

- $T_{i(t)}$ ,  $T_{i(t-1)}$  = temperatures of the  $i$ th layer at pressing times  $t$  and  $t - 1$ , respectively ( $^{\circ}\text{F}$ ),  
 $M_{i(t)}$  = moisture content of the  $i$ th layer at pressing time  $t$ .  
 $\alpha_T$  = change in modulus of elasticity with unit change in temperature.

It is clear from this model that moisture content plays an important role in predicting the temperature effect. As in the case of moisture change, a temperature increase results in decreasing MOE.

*Strain  $\epsilon_{(\Delta t)}$  during time interval  $\Delta t$*

The strain  $\epsilon_{(\Delta t)}$  is dependent on press closing time. Assuming that press closing rate is constant, as in most cases, then during the time interval  $\Delta t = t/m$ , where  $t$  is press closing time, and  $m$  is the number of time intervals within the press closing time, the strain of the mat  $\epsilon_{(\Delta t)}$  is

$$\epsilon_{(\Delta t)} = \frac{h_{t-1} - h_t}{h_t} \quad (29)$$

where

- $\epsilon_{(\Delta t)}$  = mat strain occurred during time interval  $\Delta t$ , which is the time from  $t - 1$  to  $t$ ,  
 $h_{t-1}$  = mat thickness at time  $t - 1$ ,  
 $h_t$  = mat thickness at time  $t$ .

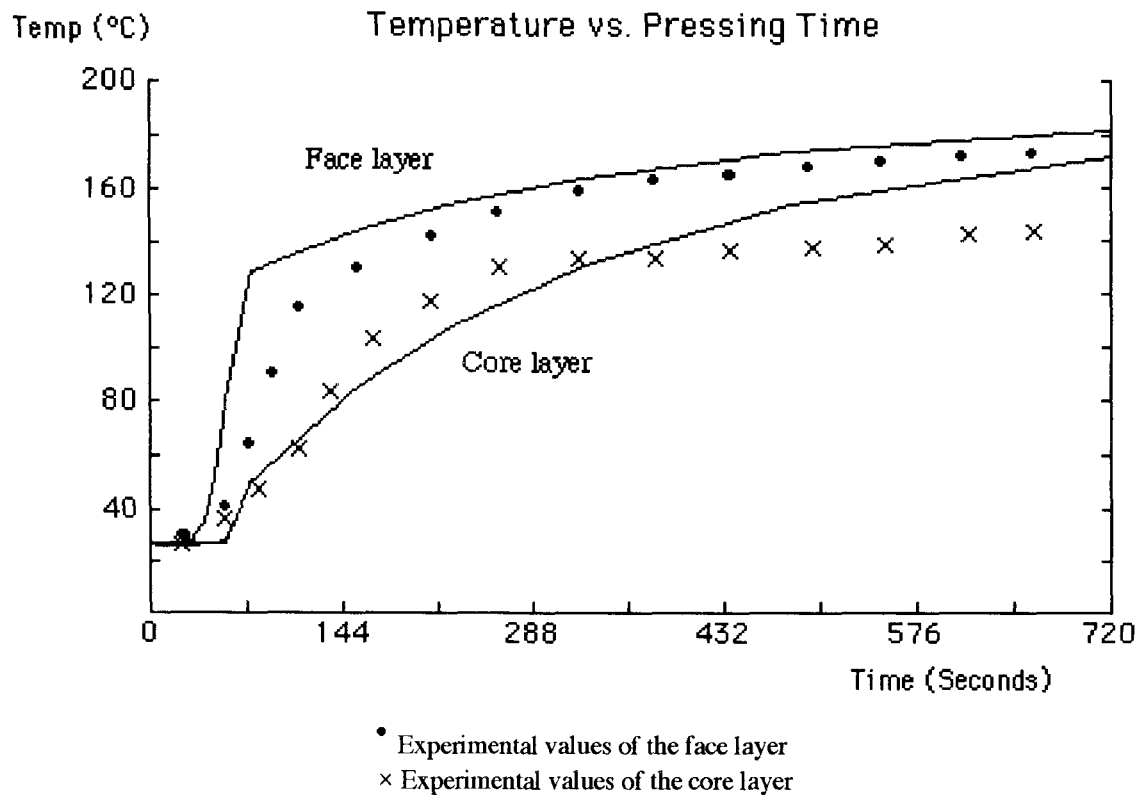


FIG. 4. Temperature profile with pressing time (platen temperature: 190 C, closing time: 1 minute, mat MC: 6.0%). The curves are the predicted results.

The strains for all the individual layers are calculated based on  $\epsilon_{(\Delta t)}$  by following the rules given above. The density for each layer can then be determined. Repeat this process for each time interval  $\Delta t$  until the upper platen reaches the stops. The final distribution of the layer density is therefore the vertical density profile of the board.

#### COMPARISONS OF SIMULATED AND EXPERIMENTAL RESULTS

The model was verified by plugging published experimental data into the simulation model and then comparing predictions with experimental results. The computer program routine built within the software package mentioned in the beginning of the article was run to simulate flakeboard density, temperature, and moisture content profiles. The simulated density and temperature profiles were compared with existing experimental data: a lack of appropriate experimental data prevented assessment of moisture content profiles. Correction factor values used in the simulation were  $\alpha_M = 0.016$  and  $\alpha_T = 0.000288$ . These values were among those proposed by Palka (1973) for compressive elastic properties.

#### *Case one*

The density profile through the thickness of a structural panel was simulated using data from Heebink et al. (1972) as input. Flakeboards from Douglas-fir were made with a density of  $0.641 \text{ g/cm}^3$  ( $40 \text{ lb/ft}^3$ ) and thickness of 12.7 mm (0.50 in.) under a press temperature of 177 C (350





