WOOD COMPOSITE WARPING: MODELING AND SIMULATION

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ABSTRACT

Warping, which is defined as the out-of-plane deformation of an initially flat panel, is a longstanding problem associated with secondary manufacturing processes in the wood panel industries. The mechanism of warping is still not fully understood. Unlike previous modeling, this study has developed a new two-dimensional warping model based on mechanics of layered composites. Wood composite panel is regarded as a multilayered composite material in which each layer has different properties, especially when they experience moisture gradient through their thickness. Detailed model development and computer simulation results are presented. Panel parameters such as thickness, MOE, LE, Poisson's ratio, shear modulus, density, and orientation of layer were simulated; and quantitative relationships between these parameters and warp were presented. The results should provide a better understanding of wood composite warp.

Keywords: MOE, Poisson's ratio, density, warp, wood composite, layered, simulation.

INTRODUCTION

Warping is defined as the out-of-plane deformation of a panel from an initially flat condition (Suchsland and McNatt 1986). Warping of wood-based composites is a long-standing problem associated with secondary manufacturing processes in the wood panel industries. Severe warping of finished products has the potential to significantly increase the cost of manufacturing and lower the consumer's confidence in using wood composites. The Composite Panel Association (previously called the National Particleboard Association) considers warp to be the leading technical problem requiring further investigation (National Particleboard Association 1996).

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Heebink et al. (1964) developed a one-dimensional mathematical model by equating the strain (due to the changes in moisture content and temperature) to the strain (determined by the geometry of the panel). Many researchers (Norris 1964; Suchsland and McNatt 1986; Suchsland 1990; Suchsland et al. 1993 and 1995; Wu 1999) have used the one-dimensional warping model to investigate warping problems in a number of wood-based composites including particleboard, laminated wood panels, veneered furniture panels, plywood, and medium density fiberboard (MDF). While this model has evolved and found continued use, it does not include the effect of lateral strain. Lateral strain is usually determined through Poisson's ratio and needs to be considered for a two-dimensional (plane) panel. To model warping in two dimensions, the

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finite element method (FEM) was introduced (Tong and Suchsland 1993; Cloutier et al. 2001). The more recent work by Cloutier et al. (2001) used FEM to model an MDF panel based on unsteady-state moisture transfer and mechanical equilibrium. Differing wood composites require the selection of different elements.

Composite wood panels can be regarded as a multilayered composite material, where each layer has a unique set of physical properties. Individual layers can be approximated as an orthotropic material having two principal directions. Sun (1994) showed that the behavior of wood composites can be modeled using the mechanics of layered composites. Nevertheless, the mechanical relations that govern the behavior of layered composites have not been applied to the warping problem. The goal of this study is to investigate and model the warping mechanism of wood composites using the theory of mechanics in layered composites and thus provide insight into understanding the structure and physical properties of wood and wood composites. A better means to model warp will provide new knowledge to help minimize warp in wood composites.

MECHANICS OF LAYERED COMPOSITES

The mechanical behavior of layered composite materials is quite different from that of most common engineering materials that are homogeneous and isotropic. The makeup and physical properties of layered composites vary with location and orientation of the principal axes. Wood has unique and independent mechanical properties in the directions of three mutually perpendicular axes, so it may be described as an orthotropic material (Wood Handbook 1999). Figure 1 shows a typical thin wood veneer with two principal directions that are perpendicular to each other. For thin layers, a state of plane stress parallel to the laminate can be assumed with reasonable accuracy. The two-dimensional stress-strain equation is (Sun 1994):

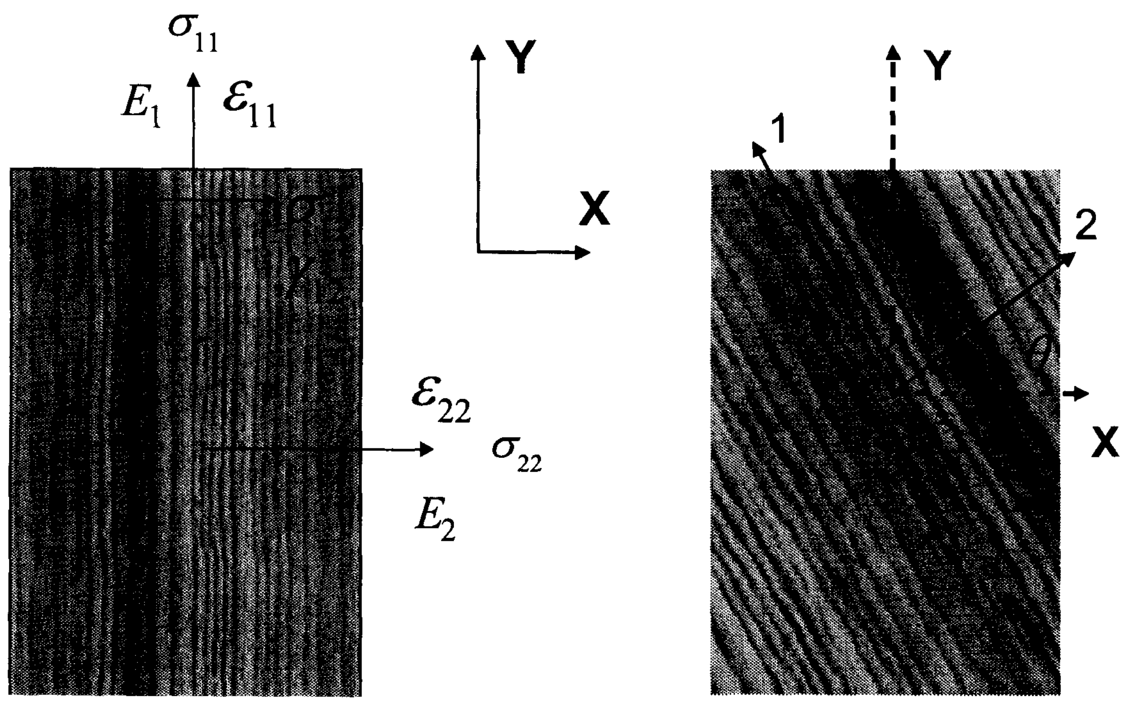

FIG. 1. Orthotropic characteristics of thin layer and its coordinates.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{Bmatrix} \begin{bmatrix} \frac{E_1}{1-\upsilon_{12}\upsilon_{21}} & \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} & 0 \\ \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} & \frac{E_2}{1-\upsilon_{12}\upsilon_{12}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (1)$$

where *1* and *2* represent the two principal coordinate directions; E_1 and E_2 are the moduli of elasticity along the two directions; σ_{11} and σ_{22} are stresses along the two principal coordinates; σ_{12} is the in-plane shear stress; G_{12} is the in-plane shear modulus; υ_{12} is Poisson's ratio measuring contraction in the *1*-direction due to uniaxial loading in the *2*-direction; υ_{21} is Poisson's ratio measuring contraction in the *2*-direction due to uniaxial loading in the *1*-direction; ε_{11} and ε_{12} are strains along the two principal coordinates; and is the shear strain. The 3×3 matrix of elastic constants is usually denoted by:

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (2)$$

Usually, during the construction of plywood, the grain orientation of each layer may be different. Figure 2 shows an example of 5-layer plywood. The principal grain directions of the second and fourth layers from the top ±45° are from the overall coordinate *x-y*, respectively. The product is called [0/45/90/-45/0] balanced construction. Therefore, in stress analysis, if a coordinate system *x-y* is set up that does not coincide with the material principal axes *1–2* (the right side of Fig. 1), the two sets of stress-strain components must be transformed to the two coordinates system. The two-dimensional stress-strain equation in x-y system is then

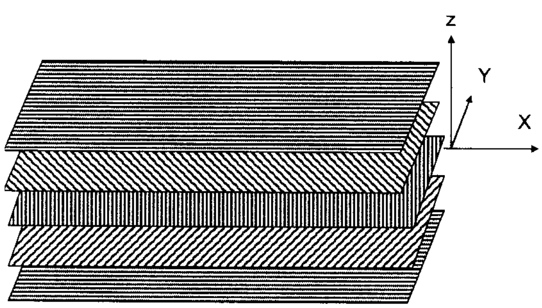

FIG. 2. An example of 5-layer composite with different grain orientations.

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = [\bar{Q}] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (3)$$

where:

$$[\bar{Q}] = \begin{bmatrix} \cos^2\theta & \sin^2 & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix}^{-1}$$
$$[Q] \begin{bmatrix} \cos^2\theta & \sin^2\theta & \sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -\sin\theta\cos\theta \\ -2\sin\theta\cos\theta & 2\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \quad (4)$$

A layered composite consists of a number of laminae with different orintations in the thickness direction (Fig. 2). To establish a constitutive equation for the composite, the stress and strain components of each layer must be transformed to the global x-y coordinates. For a uniform composite plate with thickness of *h*, the plate resultant forces $\{N\}$ and moments $\{M\}$ are defined by

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xx} \end{Bmatrix} = \int_{h/2}^{h/2} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} dz \quad (5)$$

and

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xx} \end{Bmatrix} = \int_{h/2}^{h/2} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} z dz \quad (6)$$

where z is in the thickness direction. When a composite plate consists of n thin layers where each layer has different properties, the plate resultant forces and moments will be summations of resultant forces and moments of each layer, respectively. Assuming the ith layer located at thickness region from $z = z_{i-1}$ to $z = z_i$, the plate resultant forces and moments of a composite with n layers will become:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xx} \end{Bmatrix} = \sum_{i=1}^{n} \int_{z_{i-1}}^{z_i} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} dz \tag{7}$$

and

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xx} \end{Bmatrix} = \sum_{i=1}^{n} \int_{z_{i-1}}^{z_i} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} z dz \tag{8}$$

Equation (3) describes the relationship between stresses and strains in the global x-y coordinate for a laminate. Because of the plate resultant forces and moments, the strains in the laminate include two major components. One is the in-plane strains including ε_x^0, ε_y^0 and γ_{xy}^0. The other is out-plane strain due to the bending with the curvatures of κ_x, κ_y and κ_{xy} (Beer and Johnston 1992). Equation (3) is then

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = \left[\bar{Q}\right] \left(\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \right) \tag{9}$$

Substituting Eq. (9) to Eqs. (7) and (8), we obtain

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xx} \end{Bmatrix} = \sum_{i=1}^{n} \left[\bar{Q}\right]_i \left(\int_{z_{i-1}}^{z_i} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{Bmatrix}_i dz + \int_{z_{i-1}}^{z_i} \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} z dz \right) \tag{10}$$

and

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xx} \end{Bmatrix} = \sum_{i=1}^{n} \left[\bar{Q}\right]_i \left(\int_{z_{i-1}}^{z_i} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{Bmatrix}_i z dz + \int_{z_{i-1}}^{z_i} \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} z^2 dz \right) \tag{11}$$

Since both in-plane and out-of-plane strains are independent of z, the integration in Eqs. (10) and (11) can be performed. The results can be combined into the following form, which is the constitutive equation for the composite.

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{11} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{Bmatrix} \tag{12}$$

In addition to the external stresses (i.e., self-weight or restraint), wood composites sometimes have experienced significant internal stresses due to thermal changes and moisture movements. Including the internal stresses, Eq. (12) becomes

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} + \begin{Bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_y^T \\ M_{xy}^T \end{Bmatrix} + \begin{Bmatrix} N_x^H \\ N_y^H \\ N_{xy}^H \\ M_x^H \\ M_y^H \\ M_{xy}^H \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{11} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{Bmatrix} \tag{13}$$

Symbolically, Eq. (13) is expressed in the following form:

$$\begin{Bmatrix} N \\ M \end{Bmatrix} + \begin{Bmatrix} N^T \\ M^T \end{Bmatrix} + \begin{Bmatrix} N^H \\ M^H \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ \kappa^0 \end{Bmatrix} \quad (14)$$

where $\{N\}$ are the plate resultant external forces; $\{M\}$ are the plate resultant external moments; $\{\varepsilon^0\}$ are the in-plane strains; $\{\kappa^0\}$ are the curvatures of the mid-surface, and

$$A_{jk} = \sum_{i=1}^{n} \overline{Q}_{jk}^{(i)} t_i \quad (15)$$

$$B_{jk} = \sum_{i=1}^{n} \overline{Q}_{jk}^{(i)} t_i z_i \quad (16)$$

$$D_{jk} = \sum_{i=1}^{n} \overline{Q}_{jk}^{(i)} \left(t_i z_i^2 + \frac{t_i^3}{12} \right) \quad (17)$$

$$\{N^T\} = \Delta T \sum_{i=1}^{n} [\overline{Q}]_i \{\alpha^T\}_i t_i \quad (18)$$

$$\{M^T\} = \Delta T \sum_{i=1}^{n} [\overline{Q}]_i \{\alpha^T\}_i t_i z_i \quad (19)$$

$$\{N^H\} = \Delta H \sum_{i=1}^{n} [\overline{Q}]_i \{\alpha^H\}_i t_i \quad (20)$$

$$\{M^H\} = \Delta H \sum_{i=1}^{n} [\overline{Q}]_k \{\alpha^H\}_i t_i z_i \quad (21)$$

where t_i is the thickness of the ith layer; z_i is the centroid of the ith layer; $\{N^T\}$ and $\{M^T\}$ are the plate internal forces and moments due to change of temperature (ΔT) at thermal expansion coefficient of $\{\alpha^T\}$; $\{N^H\}$ and $\{M^H\}$ are the plate internal forces and moments due to change of moisture content (ΔH) at linear expansion coefficient of $\{\alpha^H\}$.

If both external and internal stresses and moments are determined, the composite plate deformations can be obtained from:

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa^0 \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{Bmatrix} N + N^T + N^H \\ M + M^T + M^H \end{Bmatrix} \quad (22)$$

For most wood composite panels, deformation or dimensional changes are mainly caused by the moisture movements. For free hygroscopical expansion where there are no external stresses and thermal stresses ($\{N\}=\{M\}=\{N^T\}=\{N^T\}=\{0\}$), Eq. (22) then becomes:

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa^0 \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{Bmatrix} N^H \\ M^H \end{Bmatrix} \quad (23)$$

Again, $\{\varepsilon^0\}$ are the in-plane strains, which determine the plate elongation; $\{\kappa^0\}$ are the curvatures of the mid-surface, which determines the out-plane deformation (warping). The shear deformations are in-plane and very small comparing to the plate elongations, so it is usually neglected. For a panel with dimension shown in Fig. 3, the mid-span deflection along the y-axis (D_y) and the mid-span deflection along the x-axis (D_x) can be easily calculated based on the mathematic relationship (the right side of Fig. 3). The center deflection (CD) of the panel, commonly used for determining the warping, is then the summation of D_x and D_y.

$$D_x = \frac{(W + \Delta W)^2}{8R_x} = \frac{(W + W \times \varepsilon_x^0)^2}{8} \times \kappa_x^0 \quad (24)$$

$$D_y = \frac{(L + \Delta L)^2}{8R_y} = \frac{(L + L \times \varepsilon_y^0)^2}{8} \times \kappa_y^0 \quad (25)$$

$$CD = D_x + D_y \quad (26)$$

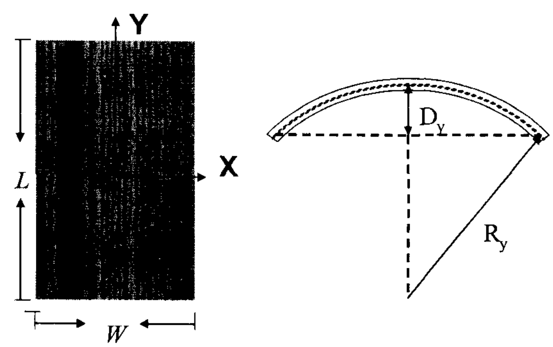

FIG. 3. Dimensions and mid-span deflection of a lamina.

where: W is the width and L is the length of the panel, and R is the radius of curvature (Fig. 3).

COMPUTER PROGRAM AND MODELING

Using Microsoft Excel, a computer program has been developed based on the theory and mechanism described above. Wood-based panels are modeled as composites consisting of ten layers with different orientations and properties. Ten layers are probably a reasonable and feasible number to model a wood composite. Once the model has been given input parameters (Table 1), it will calculate and plot the overall linear expansion and out-of-plane warping of the wood-based panel (shown in Fig. 4) at free boundary condition. The input parameters include the following information for each layer: MOE in the two principal coordinate directions; layer orientation (θ); Poisson's ratios; thickness; linear expansion coefficient due to MC changes; thermal expansion coefficients; change in MC; change in temperature; shear modulus. In addition to the information of each layer, a density of the panel is needed to calculate the self-weight effect.

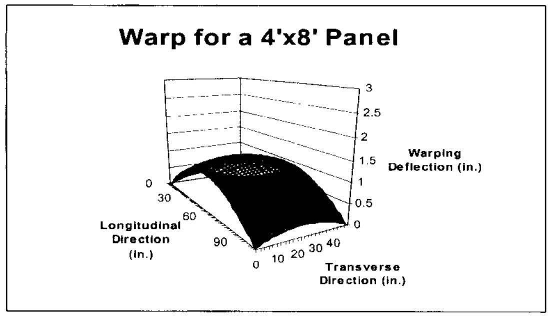

FIG. 4. A typical plate warping for a 4′ × 8′ panel from the computer program.

COMPUTER SIMULATION

Many researchers (Norris 1964; Suchsland and McNatt 1986; Suchsland 1990; Suchsland et al. 1993, 1995; Wu 1999) have used the one-dimensional warping model to investigate warping problems in a number of wood-based composites including particleboard, laminated wood panels, veneered furniture panels, plywood, and MDF. Given the many parameters that affect warp, most researchers focus on the effects of moisture gradient and linear expansion. It is impossible for researchers to design an experiment to investigate all possible parameter effects on warp, since these parameters are interactive. Therefore, to provide a better understanding of warp, it is necessary to simulate all possible parameter effects on warp based on the newly developed two-dimensional warp model.

Thickness effect

Empirical observations point toward a tendency for thinner panels to be more susceptible

TABLE 1. *Typical properties of each layer during simulation.*

Layers	Thickness (in.)	E_1[1] (psi)	E_2[1] (psi)	θ[2] (degree)	G_{12}[3] (psi)	V_{12}[3]	ΔMC[4] %	LEC[4] in./in. %MC
1	0.050	400,000	280,000	0	80,000	0.30	1.0	9.7E-04
2	0.050	380,000	266,000	0	80,000	0.30	0.8	9.7E-04
3	0.050	350,000	245,000	0	80,000	0.30	0.6	9.7E-04
4	0.050	320,000	224,000	0	80,000	0.30	0.6	9.7E-04
5	0.050	300,000	210,000	0	80,000	0.30	0.6	9.7E-04
6	0.050	300,000	210,000	0	80,000	0.30	0.6	9.7E-04
7	0.050	320,000	224,000	0	80,000	0.30	0.6	9.7E-04
8	0.050	350,000	245,000	0	80,000	0.30	0.6	9.7E-04
9	0.050	380,000	266,000	0	80,000	0.30	0.6	9.7E-04
10	0.050	400,000	280,000	0	80,000	0.30	0.6	9.7E-04

[1] E_1 is MOE value in grain direction and E_2 is MOE value perpendicular to the grain direction.
[2] Grain orientation between layers.
[3] G_{12} = In-plane shear modolus; V_{12} = Poisson ratio.
[4] ΔMC = Change of moisture content; LEC = linear expansion coefficient.

to warp than thicker panels. While this may typically be the case, a theoretical explanation has not been fully developed. To investigate this warping tendency, computer simulation was performed on a 4 × 8 ft board having ten layers. With the exception of thickness, all board characteristics (Table 1) were held constant during repeated simulations. Since the moisture change was so small, the properties were considered as unchanged during the simulation process. The center deflection (*CD*) of the board was recorded as panel thickness varied between 0.10 in. and 1.00 in. (Fig. 5). The results show a hyperbolic relationship with rapidly increasing deflection below about 0.25 in. panel thickness. The hyperbolic relationship reveals that the product of thickness (t) and *CD* is constant (Eq. 27).

$$CD \times t = const. \tag{27}$$

Under the same condition, if warping of a panel with a certain thickness is known, then the warping of a panel (with the same properties except the thickness) with any thickness can be calculated using Eq. (27).

MOE effect

MOE is widely believed to have a significant effect on warp, namely, that a panel having higher MOE will be more resistant to warp. However, this may not necessarily be the case. Computer simulations were performed to determine the effect of MOE on warping in a 10-layer board having dimensions of 4 × 8 ft. Initial conditions included an MC gradient through the thickness to induce some warp that might be typical in a particleboard panel (Table 1). This is a balanced construction that exhibits symmetric properties. When MOE values (both E_1 and E_2) of each layer change at the same percentage rate, the CD of the panel remains unchanged (Fig. 6). However, if MOE values of each layer change unevenly due to sanding or laminating, the warping behavior would be different. Again, it is still assumed that a panel has the initial conditions shown in Table 1. When only MOE values of the top layer (which has prevailing MC changes) increase, the simulation result shown in Fig. 7 indicates that warping will increase too. When MOE values of the bottom layer (which has fewer MC changes) increase, the simulation result shown in Fig. 8 indicates that warping will decrease. Therefore, it is observed that the MOE effect on warp depends on the location and magnitude of MOE changes. Generally, when MOE values of each layer change uniformly, there is no effect on warp; when MOE values of the layer that has prevailing MC changes increase, it also increases the internal out-of-plane moment that causes warping; but when MOE values of the layer that has fewer MC changes increase, it increases the stiffness and compensates for warping.

Linear expansion (LE) effect

Linear expansion of wood composites usually includes thermal expansion and hygroscopic ex-

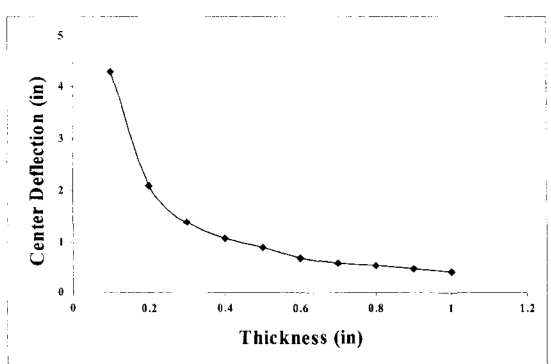

FIG. 5. Thickness effect on warp.

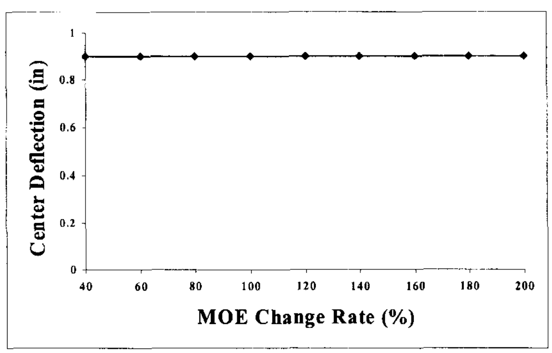

FIG. 6. Warping performance when MOE values change uniformly for layers.

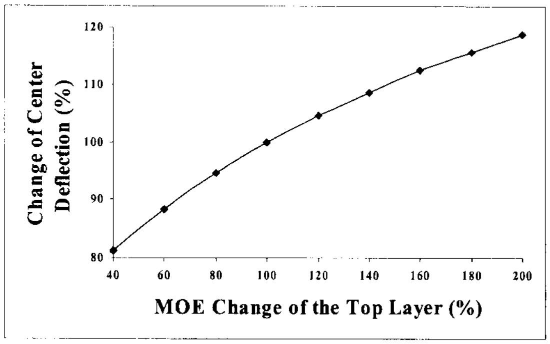

FIG. 7. Warping performance when only MOE values of the top layer change.

pansion as discussed previously. Both LEs perform about the same way, and since hygroscopic expansion is more common and thermal expansion is relatively very small, only the effect of hygroscopic LE was simulated in this study. Hygroscopic LE can be calculated using Eq. (28) (Wood Handbook 1999).

$$LE = D \times C \times \Delta MC \tag{28}$$

where D is the sample length; C is LE coefficient; and ΔMC is the change of MC. It is difficult to determine practically the LE coefficient for each layer and investigate LE effect on warping experimentally. Kelly (1977) did an extensive literature search on the relationship between board density and LE coefficients. He concluded that there was no statistically valid relationship between LE coefficient and overall density in particleboard. On the other hand, linear expansion coefficient is known to be related to particle geometry and alignment.

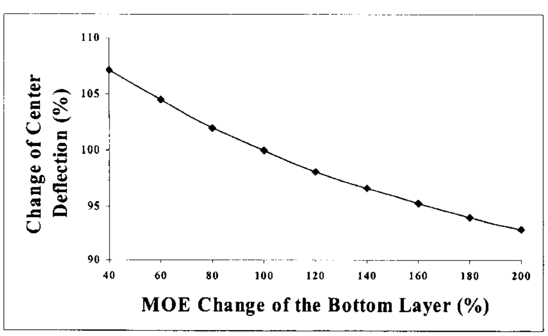

FIG. 8. Warping performance when MOE values of the bottom layer change.

Computer simulations were performed to examine LE effect on warp. Table 2 shows the simulation results of LE coefficient effect on warp performance under the same MC gradient. An approximately liner MC gradient from top to bottom layers was assumed. Three cases were studied. Case A assumed that the ten layers had the same LE coefficient. Case B assumed that there was an LE coefficient gradient through the thickness; LE coefficients of the face layers were higher than that of the center layers. Case C assumed that LE coefficients of the center layers were higher than that of the face layers. The rest of the properties remained the same as shown in Table 1. The thickness of board was 0.5 in. in all three cases. CD differences among the three cases indicate that LE coefficient had a major effect on the warp performance. Decreasing LE coefficient, or using materials with low LE coefficient on the faces, will reduce the warp. Therefore, it is desirable to place material with low LE coefficients on the faces when making wood composites.

MC change is the key parameter to determine the linear expansion once a panel is produced. Generally speaking, minimizing the MC change is the best way to keep panels from warping. For a panel with balanced construction, if the MC changes through its thickness are constant, there

TABLE 2. *Simulation results on different LE coefficients.*

Layers	LEC[1] A	in./in. B	%MC C	ΔMC[2] %
1	0.00100	0.00100	0.00033	1.0
2	0.00100	0.00083	0.00050	0.8
3	0.00100	0.00067	0.00067	0.7
4	0.00100	0.00050	0.00083	0.6
5	0.00100	0.00033	0.00100	0.5
6	0.00100	0.00033	0.00100	0.4
7	0.00100	0.00050	0.00083	0.3
8	0.00100	0.00067	0.00067	0.2
9	0.00100	0.00083	0.00050	0.1
10	0.00100	0.00100	0.00033	0.0
Center Deflection (in.)	3.06	2.85	1.23	

[1] LEC = linear expansion coefficient.
[2] ΔMC = Change of moisture content.

will be no induced out-of-plane stress. Therefore, there will be no warp. But for a panel with unbalanced construction, even if MC through the thickness changes uniformly, it is still possible to have out-of-plane deformation and warping problems.

Balanced-construction composites are not necessarily free from warping. For a balanced panel, if there is an MC gradient through the thickness, the panel will still have a warping tendency. In the process of MC change, there is usually an MC gradient through the thickness. Computer simulation based on the new warp model was performed to investigate the effect of MC gradient on warp. It assumed that the panel has initial MC changes as follows: 2% increment for layer 1, 1.5% for layer 2, 1% for layer 3, 0.8% for layer 4, 0.6% for layer 5, 0.5% for layer 6, 0.4% for layer 7, and no MC change for the last three layers. The panel thickness was 0.5 in., and the rest of the layer properties were the same as shown in Table 1. The model predicted a CD of 5.9 in. When MC gradients increase or decrease by an increment of 20%, the CD changes accordingly. Table 3 and Fig. 9 show the simulation results indicating that increasing the MC gradient will increase warp proportionally.

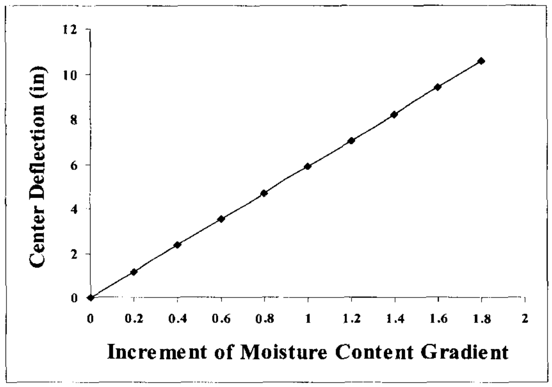

FIG. 9. MC gradient effect on warp.

Effect of Poisson's ratio

Poisson's ratio is a constant that determines the deformation caused by stress in the direction perpendicular to the applied stress. It is an important parameter in simulating plane stress for layered wood composites. Poisson's ratios for wood products have a broad range from 0.01 to 0.7 (Wood Handbook 1999). They vary between species and even within species (with different directions). The previous one-dimensional warp model (Heebink et al. 1964) neglects Poisson's ratio and assumes that the two principal directions within each layer are independent. To simulate the effect of Poisson's ratio on warp, the new warp model was applied to a panel with properties shown in Table 1. It was assumed that only layer 1 changes its Poisson's ratio and the rest of the layers remain the same. Figure 10 shows that warp increases when the Poisson's ratio of layer 1 increases. If comparing the warp

TABLE 3. *Effect of MC gradient on warp.*

	Gradients of Moisture Contents throughout the Thickness								
Layer	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8
1	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
2	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7
3	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
4	0.2	0.3	0.5	0.6	0.7	1.0	1.1	1.3	1.4
5	0.1	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.1
6	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
7	0.1	0.2	0.2	0.3	0.0	0.5	0.6	0.6	0.7
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CD[1] (in.)	1.2	2.3	3.5	4.7	5.9	7.0	8.2	9.4	10.6

[1] CD = center deflection.

when Poisson's ratio in layer 1 equals 0.3 (which is common for wood) to warp when Poisson's ratio is zero (one–dimensional model), the difference is 13%. This result indicates that Poisson's ratio has a significant effect on warp that cannot be neglected during warp modeling.

Effect of shear modulus

Shear modulus is a constant that relates shear strain and shear stress. In the mechanics of layered composites, shear is assumed to be in-plane only and the composite only has in-plane shear strain. Since there is no out-of-plane shear strain involved during the linear expansion, the value of shear modulus does not affect the overall warp calculation. There are some in-plane shear deformations that might affect measurements of in-plane dimensions (length and width), but the amount of shear deformations are negligible compared to thermal and hygroscopic expansions.

Density effect

Density is not listed as an input parameter in the new warp model. For a panel, the density will determine its self-weight which will, in fact, provide external stresses or moments depending upon the boundary conditions of the panel. If the panel is placed flat, the self weight will provide an external moment that will compensate for warping. Computer simulation was performed on a panel with layer properties shown in Table 1. Initially, MC gradient was adjusted so that CD would be 10 in. Panel density was allowed to vary and the results were observed. Figure 11 shows the density effect on warp, which indicates that the heavier panel has more resistance to warping. The self-weight had less effect on warp in a stiffer panel, because the same moment creates less deflection to offset warping.

Density is believed to have a strong correlation with MOE and might also be related to LE coefficient (Wood Handbook 1999 and Kelly 1977). Due to its availability, vertical density profile (VDP) of a composite panel is commonly used to judge whether the panel construction is balanced or not. It is practically accepted that if the VDP is symmetric, then the panel is regarded as having balanced construction.

Effect of layer orientation

During construction of plywood or laminated wood products, the orientation of each layer may be different. Computer simulations based on the new two-dimensional model were performed to determine the predicted effect of layer orientation on warping in a 10-layer board having dimensions of 4 × 8 ft. Initial conditions included an MC gradient through the thickness in order to induce some warp in the panel (Table 1). It was assumed that values of transverse MOE were

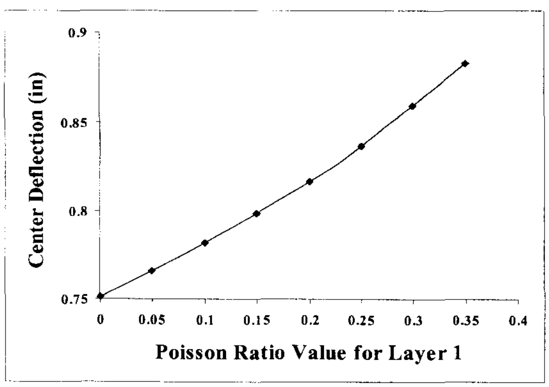

FIG. 10. Effect of Poisson's ratio on warp.

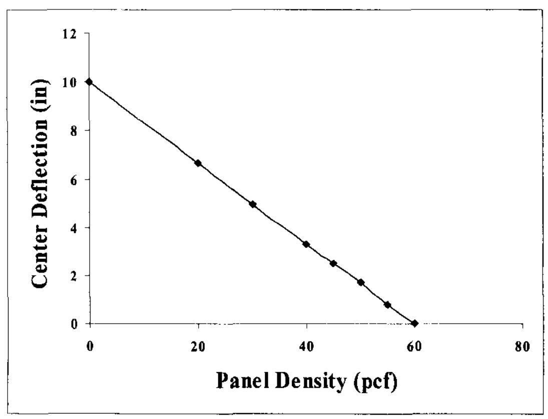

FIG. 11. Density effect on warp.

70% of longitudinal MOE in each layer, and the longitudinal direction was in the direction of zero degrees. When the orientation of the top layer rotates from 0 to 180 degrees, Fig. 12 shows the warping acts in a sine wave form accordingly. The result indicates that when the top layer is oriented perpendicularly, the panel exhibits the minimum warping.

SUMMARY

Wood composites under the influence of a moisture gradient are modeled as a layered composite material. Mechanics of layered composites was used to investigate warping of wood composite panels, and a new two-dimensional warping model was developed. After providing information about each layer regarding its properties and moisture movement, the new model can determine panel warping. Computer simulations based on the model were performed to investigate warping behavior. Parameters of thickness, MOE, LE, Poisson's ratio, shear modulus, density, and orientation of layer were simulated to develop quantitative relationships with warp. The simulation results indicated:

- Thickness has a hyperbolic relationship with warp.
- MOE and LE have a complicated relationship with warp. Their effects on warp depend on construction and location within the panel.
- Increasing Poisson's ratio has the potential to increase warp.
- Shear modulus has no effect on warp.
- If the panel is placed flat, the self weight will provide an external moment which compensates for warping. The negative linear relationship between density and warp indicates that higher density panels have a higher resistance to warp.
- Layer orientation has a sinusoidal effect on warping as the layer rotates.

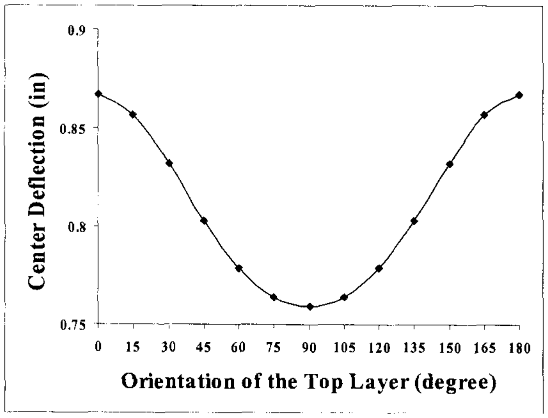

FIG. 12. Effect of the top layer orientation on warp.

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