

MODELING OF STRENGTH PROPERTIES OF STRUCTURAL PARTICLEBOARD¹

Shuming Suo

Research Assistant

and

Jim L. Bowyer

Professor and Head

Department of Forest Products
University of Minnesota
St. Paul, MN 55108

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ABSTRACT

The strength properties of structural particleboard are critically important factors. In designing a particular particleboard, a series of experiments can be run to determine the effect of a particular combination of factors. Modeling could be used as an alternative approach. Simulation modeling is one of the modeling techniques that can be fast and cost-effective. Structural particleboard was modeled in this study as a multilayer system that consists of a number of thin and uniform layers that exhibit different strength properties between layers, but the same properties within each layer. The effective modulus of elasticity of a board is a resultant of the combined effect of the modulus of all the layers. The modulus of rupture was obtained by determining the ultimate force or maximum moment during the simulated bending test. Internal bond strength was modeled using a modified regression equation.

Keywords: Structural particleboard, wood composites, simulation modeling, modulus of elasticity, modulus of rupture, internal bond.

INTRODUCTION

In designing a structural particleboard for a particular application, strength properties such as the modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) are of concern. Evaluation of properties is usually carried out by experimental testing in a research laboratory setting where testing specimens are cut from a number of panels with the number and size of specimens dependent on property testing requirements. Process parameters are then changed based on test results. Since particleboard properties are related to a

great many factors, the business of designing a product for a particular application is difficult. The experimental approach using trial and error involves costly production and testing cycles. An alternative to trial and error product design is one that involves modeling of board properties using mathematical, statistical, and simulation techniques. Among the modeling methods, computer simulation modeling can be fast and cost-effective. Experience has shown that particleboard properties can be described reasonably well by simulation modeling techniques to such precision that the results are acceptable in research or production applications.

A simulation modeling method is presented in this paper. A structural particleboard is envisioned as a multilayer system as shown in Fig. 1. Board strength properties including ef-

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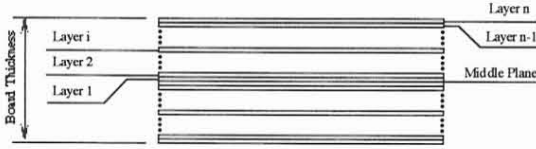


FIG. 1. A board consisting of $2n$ layers.

fective MOE, MOR, and IB are modeled. Effective MOE is modeled based on a board density profile (Suo 1991; Suo and Bowyer 1994), while MOR is based on MOE values of the board layers. Board IB is modeled according to a regression equation.

MODULUS OF ELASTICITY (MOE)

The effective MOE, or MOE for simplicity, of structural particleboard is related to the MOE of each layer (Bodig and Jayne 1982). As explained later, the MOE of each layer can be determined based on knowledge from wood science and technology. Because of the random orientation of flakes within each layer, the MOE of each layer is taken as the mean value of MOE of wood flakes over a full range of possible ring and grain angles of wood by applying Hankinson's formula. Board MOE is then determined based on the mechanics of composite materials by taking into account all the moduli of the layers.

Board MOE calculation

In particleboard, the MOE of a panel is a function of MOE values of the layers. Consequently, the effective MOE of a structural particleboard can be calculated by the function (assuming symmetry about the centroid and continuity between layers and between flakes):

$$\text{MOE}_{\text{eff}} = \frac{2}{I} \sum_{i=1}^n E^i [I_0^i + A^i (d^i)^2] \quad (1)$$

where

- MOE_{eff} = effective MOE of a panel,
- E^i = MOE of the i th layer of the panel,
- I_0^i = moment of inertia of the i th layer about its neutral plane,
- A^i = cross-sectional area of the i th layer,

- d^i = distance between the centroidal plane of the panel and the i th layer,
- I = moment of inertia of the entire panel,
- n = one-half the total number of layers.

If the thickness of each layer is the same and equal to t_0 , then I_0^i and A^i are constants. Let $I_0^i = I_0$, $A^i = A$, then

$$\begin{aligned} \text{MOE}_{\text{eff}} &= \frac{2}{I} \sum_{i=1}^n E^i (I_0 + A (d^i)^2) = \\ &= \frac{2}{I} \left(I_0 \sum_{i=1}^n E^i + A \sum_{i=1}^n E^i (d^i)^2 \right) \quad (2) \end{aligned}$$

Since

$$I = \frac{bh^3}{12}, \quad I_0 = \frac{bt_0^3}{12}, \quad \text{and} \quad A = bt_0 \quad (3)$$

where

- b = panel width,
- h = panel thickness,
- $h = 2nt_0$,
- t_0 = layer thickness,

substituting I and I_0 into Eq. (2), MOE_{eff} becomes

$$\text{MOE}_{\text{eff}} = \frac{3}{n^3 t_0^2} \left(\frac{t_0^2}{12} \sum_{i=1}^n E^i + \sum_{i=1}^n E^i (d^i)^2 \right) \quad (4)$$

MOE_{eff} is obtained once the MOE of each layer, E^i , is determined. It is apparent from Eq. (4) that the effective modulus of elasticity of a structural particleboard is a function of the moduli of elasticity of the layers, layer thickness, and number of layers. In the equation, d^i is a function of layer thickness, i.e.,

$$d^i = \left(i - \frac{1}{2} \right) t_0 \quad (5)$$

Thus d^i is the sum of i layer thicknesses less one half of the layer thickness.

E^i determination

In a nonoriented flakeboard, wood flakes are randomly formed into a mat, with the grain direction of each flake oriented randomly with

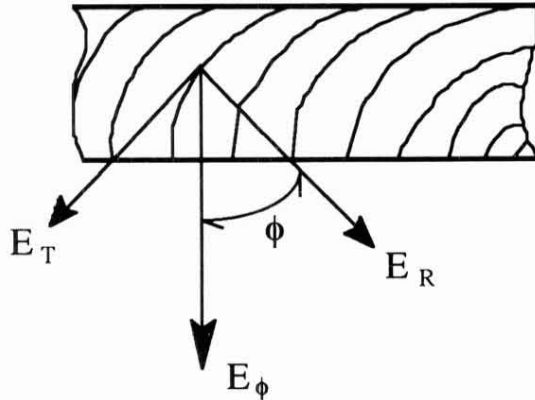


FIG. 2. Illustration of ring angle ϕ ($0 \leq \phi \leq \pi/2$).

respect to the length and width directions of the board. (Although randomness is not usually complete, randomness is assumed for approximation.) Also, the ring angles are different within flakes depending on the manner in which the flakes are cut and the part of the wood blocks from which they are cut. (The ring angle is illustrated in Fig. 2.) When attempting to determine probable E^i through modeling, average values of MOE over the full range of possible ring and grain angles should be used to reflect the randomness of the flake orientation in the board. Goodman and Bodig (1970) stated a three-dimensional Hankinson's formula to calculate wood compression strength at grain angle θ and ring angle ϕ . Since Hankinson's formula can be used to compute modulus of elasticity as well as compression strength, it follows that the three-dimensional Hankinson's formula can be used to predict the modulus of elasticity at grain angle θ and ring angle ϕ provided that corresponding parameters are used. The MOE of a flake at ring angle ϕ , E_ϕ , can be determined by

$$E_\phi = \frac{2\phi}{\pi}(E_R - E_T) + E_T - \frac{k}{2}(E_R + E_T)\sin 2\phi \quad (6)$$

where

E_R = flake MOE in the radial direction,
 E_T = flake MOE in the tangential direction,

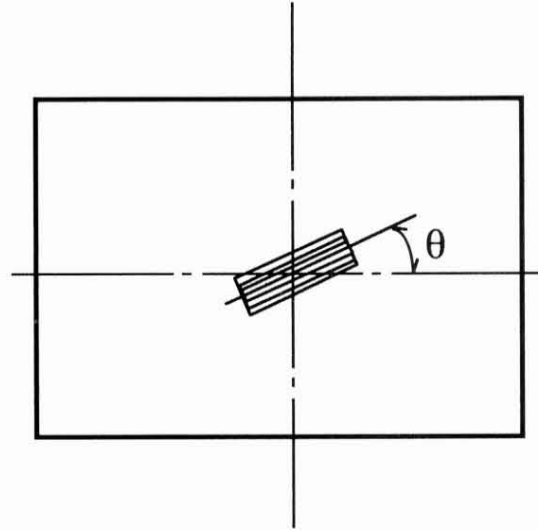


FIG. 3. Illustration of a longitudinally grained flake with a grain angle of θ ($0 \leq \theta \leq \pi/4$) with respect to board horizontal direction.

k = empirical adjusting constant, $k = 0.2$ for hardwoods, $k = 0.4$ for softwoods (Bodig and Jayne 1982).

Average values of E_ϕ , \bar{E}_ϕ , can be determined by integrating E_ϕ over $\phi \in [0, \pi/2]$ as follows:

$$\begin{aligned} \bar{E}_\phi &= \frac{2}{\pi} \int_0^{\pi/2} E_\phi \, d\phi = \\ &= \frac{2}{\pi} \int_0^{\pi/2} \left(\frac{2\phi}{\pi}(E_R - E_T) + E_T - \frac{k}{2}(E_R + E_T)\sin 2\phi \right) d\phi = \\ &= \left(\frac{1}{2} - \frac{k}{\pi} \right) (E_R + E_T) \end{aligned} \quad (7)$$

Hence the MOE of a flake at angle θ to the edge of a panel (Fig. 3) and at ring angle ϕ (Fig. 2) can be approximated by Hankinson's formula:

$$E_{(\theta\phi)} = \frac{E_L \bar{E}_\phi}{E_L \sin^2 \theta + \bar{E}_\phi \cos^2 \theta} \quad (8)$$

where E_L = flake longitudinal MOE.

The MOE of a panel layer, E_o^i , may be ap-

proximated by taking the average value of $E_{(\theta\phi)}$ over the grain angle range of $\theta \in [0, \pi/4]$ (assuming the layer of the panel is orthotropic in its properties).

$$\begin{aligned} E_0^i &= \bar{E}_{(\theta\phi)} = \\ &= \frac{4}{\pi} \int_0^{\pi/4} \frac{E_L \bar{E}_\phi}{E_L \sin^2\theta + \bar{E}_\phi \cos^2\theta} d\theta = \\ &= \frac{4E_L \bar{E}_\phi}{\pi} \int_0^{\pi/4} \frac{1 + \tan^2\theta}{E_L \tan^2\theta + \bar{E}_\phi} d\theta \quad (9) \end{aligned}$$

Solving the above equation gives the following result:

$$E_0^i = \frac{4}{\pi} \sqrt{E_L \bar{E}_\phi} \tan^{-1} \sqrt{\frac{E_L}{\bar{E}_\phi}} \quad (10)$$

Equation (7) indicates that layer MOE, which is the average value of MOE over the range of all possible grain angles, is independent of grain angle, but related to MOE in longitudinal direction and the average MOE over the ring angles.

Adjusted by layer specific gravity effect, the layer MOE, E^i , may be expressed as

$$E^i = E_0^i \left(\frac{\rho_i}{\rho_0} \right)^b \quad (11)$$

where

- ρ_i = specific gravity of the i th layer,
- ρ_0 = specific gravity of wood flakes,
- b = constant, $b = 0.90$ for softwoods, $b = 0.65$ for hardwoods (Wood Handbook 1987).

The specific gravity of each layer may be obtained through the determination of a board density profile such as that modeled by Suo and Bowyer (1994).

The moisture content (MC) effect on the MOE of each layer can be taken into account according to the relationship between MOE and MC of wood. For instance, a formula given by Palka (1973) may be used: $MOE(M) = MOE_0[1 + h(M - M_0)]$, where $MOE(M)$ is the MOE at MC of M , MOE_0 is the MOE at MC of M_0 , and h is the adjustment coefficient.

Board MOE modified by resin coverage

Resin coverage on flake surfaces is an important factor affecting particleboard properties. One way to take resin coverage into account is to consider the effect of resin spread (the amount of resin spread on one unit of flake surface area). For bonding between wafers of aspen waferboard without delamination, Suo (1985) reported phenol-formaldehyde (PF) resin levels of 1.22 to 2.38 grams per square meter of wafer surface area for board specific gravities ranging from 0.545 to 0.738. Maloney (1970) reported that adequate bonding in particleboard was achieved with resin spread levels of about 1 to 3.4 grams per square meter. From Lehmann's data (1974), MOE increased 9.95% or 14.03%, respectively, when resin spread was doubled or tripled (based on a resin content of 3%). Preliminary calculations indicated that the simulated panel MOE calculated by Eq. (3) corresponded to the panel MOE obtained by Lehmann at a resin spread level of 5 grams per square meter. Therefore, once resin spread is known, the panel MOE can be modified through the use of a straight-line interpolation method based on this information.

MODULUS OF RUPTURE (MOR)

When a specimen is tested for bending strength, the applied load is increased until the specimen fails. The maximum load that the specimen can bear is used for calculating the MOR of the panel. During testing, due to the changing load, stress is distributed along the panel thickness to each layer at every moment. The layer breaks when the stress exceeds its strength. Then stress is redistributed to the remaining layers. The load is increased to its maximum until all the layers are broken. The MOR can thereafter be computed.

Bending stress distribution

Under a standard bending test, an increasing load is applied to a specimen until it breaks. Then the maximum load that the specimen can bear is used in conjunction with the specimen dimensions to calculate the board MOR.

The formula used to calculate MOR is

$$\begin{aligned} \text{MOR} &= \frac{3P_u l}{2bh^2} = \\ &= \frac{6M_{\max}}{bh^2} \end{aligned} \quad (12)$$

where

- P_u = ultimate force,
 l = length of span,
 b = specimen width,
 h = specimen thickness,
 M_{\max} = maximum moment, $M_{\max} = P_u l/4$
 for a simply supported beam as in
 Fig. 4.

Each layer is under different stress due to its location along the thickness and elastic properties of the layers. For the laminar system, the cross section of each lamina needs to be transformed before calculation to compensate the difference among the moduli of the layers. Stress is distributed among the laminae according to the following function:

$$\sigma^i = \frac{Md^i}{I'} \cdot \frac{\omega^i}{\omega} \quad (13)$$

where

- σ^i = stress of the i th layer,
 ω = width of the top or bottom layer,

M = moment, $M = \frac{Pl}{4}$,

and

P = the load applied as in Fig. 4,

$$d^i = \sum_1^{i-1} t^{i-1} + \frac{t^i}{2},$$

and

- t^i = thickness of the i th layer,
 ω^i = transformed width of the i th layer,

$$\omega^i = \frac{E^i}{E^n} \omega,$$

and

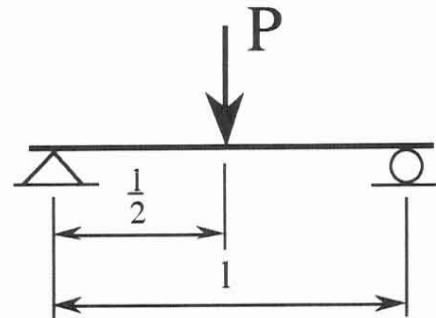


FIG. 4. A board is stressed under load P .

E^i = MOE of the i th layer,

E^n = MOE of the top (or bottom) layer,

$$I' = \frac{2\omega}{E^n} \sum_{i=1}^n \left(\frac{E^i (t^i)^3}{12} + E^i t^i \left(\sum_1^{i-1} t^{i-1} + \frac{t^i}{2} \right)^2 \right)$$

For constant layer thickness $t^i = t_0$,

$$d^i = \left(i - \frac{1}{2} \right) t_0, \quad (14)$$

and

$$I' = \frac{2\omega t_0^3}{E^n} \sum_{i=1}^n E^i \left(\frac{1}{12} + \left(i - \frac{1}{2} \right)^2 \right) \quad (15)$$

Therefore, Eq. (13) becomes

$$\begin{aligned} \sigma^i &= \frac{M \left(i - \frac{1}{2} \right) t_0}{I'} \cdot \frac{\omega^i}{\omega} = \\ &= \frac{M \left(i - \frac{1}{2} \right) t_0}{I'} \cdot \frac{E^i}{E^n} = \\ &= \frac{Pl \left(i - \frac{1}{2} \right) t_0}{4I'} \cdot \frac{E^i}{E^n} \end{aligned} \quad (16)$$

It is clear that the stress a lamina bears is related not only to the applied load and dimensions of the lamina, but also to the moduli of the lamina and the surface lamina.

Bending strength or MOR of the i th layer

Given the strength measures of a flake parallel and perpendicular to the grain, the bend-

ing strength of a flake at wood grain angle θ , $\sigma_{(u\theta)}^0$, can be determined by Hankinson's formula:

$$\begin{aligned}\sigma_{(u\theta)}^0 &= \frac{PQ}{P \sin^2\theta + Q \cos^2\theta} = \\ &= \frac{P}{\sin^2\theta + \frac{Q}{P} \cos^2\theta} \left(\frac{Q}{P}\right) \quad (17)\end{aligned}$$

where

$\sigma_{(u\theta)}^0$ = bending strength of a flake at grain angle θ (see Fig. 3),
 P = strength parallel to the grain,
 Q = strength perpendicular to the grain.

The average value of $\sigma_{(u\theta)}^0$ over angle $\theta \in [0, \pi/4]$ may be used as the bending strength of the layer. If the bending strength of the layer is σ_u^0 , then

$$\begin{aligned}\sigma_u^0 &= \frac{4}{\pi} \int_0^{\pi/4} \sigma_{(u\theta)}^0 d\theta = \\ &= \frac{4}{\pi} \int_0^{\pi/4} \frac{P}{\sin^2\theta + \frac{Q}{P} \cos^2\theta} \left(\frac{Q}{P}\right) d\theta = \\ &= \frac{4}{\pi} P \sqrt{\frac{Q}{P}} \tan^{-1} \frac{1}{\sqrt{\frac{Q}{P}}} \quad (18)\end{aligned}$$

Given the strength parallel to the grain and the ratio of the strength along and across the grain, the layer strength can be calculated by the above equation. The values of Q/P can be found in the Wood Handbook (1987).

Adjusted for layer specific gravity effect, the layer bending strength σ_u^i may be expressed as

$$\sigma_u^i = \sigma_u^0 \left(\frac{\rho_i}{\rho_0}\right)^b \quad (19)$$

where

ρ_i = specific gravity of the *i*th layer,
 ρ_0 = specific gravity of wood flakes,
 b = constant, b = 1.05 for softwoods, b = 1.10 for hardwoods (Wood Handbook 1987).

When the effect of moisture content is taken into consideration, layer bending strength, $\sigma_{u(M)}^i$, may be calculated by the following formula:

$$\sigma_{u(M)}^i = \sigma_{u(12)}^i \left(\frac{\sigma_{u(12)}^i}{\sigma_{u(g)}^i}\right)^{\frac{12-M}{M_p-12}} \quad (20)$$

where

$\sigma_{u(12)}^i$ = layer bending strength at 12% MC,
 $\sigma_{u(g)}^i$ = layer bending strength at green condition,
 M = moisture content (%),
 M_p = intersection moisture content as defined in Wood Handbook (1987).

Stress redistribution during bending

Equation (16) can be expressed in terms of M and P, respectively,

$$M = \frac{\sigma^i I'}{\left(i - \frac{1}{2}\right) t_0} \cdot \frac{E^n}{E^i},$$

and

$$P = \frac{4\sigma^i I'}{l \left(i - \frac{1}{2}\right) t_0} \cdot \frac{E^n}{E^i}$$

If σ^i is taken as strength of the *i*th layer, then M and P, respectively, are the maximum moment and force that the *i*th layer can bear. When the load force is increased beyond the bearing point, the *i*th layer breaks and the moment of inertia of the testing board is reduced to $(I')_i$, where

$$\begin{aligned}(I') &= I' - 2[I_0^i + A^i(d^i)^2] = \\ &= I' - 2 \omega^i t_0^3 \left(\frac{1}{12} + \left(i - \frac{1}{2}\right)^2\right) = \\ &= I' - \frac{2\omega E^i t_0^3}{E^n} \left(\frac{1}{12} + \left(i - \frac{1}{2}\right)^2\right) \quad (21)\end{aligned}$$

The stresses for all the layers are recalculated according to the new moment, with load P increased until all the layers break. Then the maximum load of P, P_u , is the ultimate load,

and can be used in calculating MOR of the board according to Eq. (12).

Board MOR modified by resin coverage

Again from Lehmann's data (1974), MOR increased 13.71% or 18.63%, respectively, when resin spread was doubled or tripled (based on a resin content of 3%). Preliminary calculations also indicated that the panel MOR calculated by Eq. (12) corresponded to the panel MOR obtained by Lehmann at a resin spread level of 5 grams per square meter. Thus, the panel MOR can be adjusted by a straight-line interpolation method similar to that used for adjustment of MOE.

INTERNAL BOND (IB)

The weakest tensile strength perpendicular to the plane of a board is assumed to be in the middle plane of the panel, where internal bond is evaluated. A regression equation, obtained by Lehmann (1974) and having a relatively high coefficient of determination of 0.885, was modified and used in this study to calculate IB. The equation takes the following forms in terms of the SI and English systems: for SI system,

$$(IB)_0 = 6,894.76 [-86.10 + 7.626(RC) - 3.99(FL) + 870.5(FT) + 130.5(SG)] \quad (22)$$

for English system,

$$(IB)_0 = -86.10 + 7.626(RC) - 10.14(FL) + 2,211(FT) + 130.5(SG) \quad (23)$$

where

- (IB)₀ = internal bond (Pa in SI, psi in English),
- RC = resin content (%),
- FL = flake length (cm in SI, in. in English),
- FT = flake thickness (cm in SI, in. in English),
- SG = board specific gravity.

Wax content was not considered in Lehmann's study. Based on Suo's data (1985), wax content in the range of 0 to 2.9%, which is the range

often used in production, is not a significant factor affecting board internal bond strength. Thus, wax content was not used as a factor in the modeling process.

Another important factor that was not included in the above regression equations is board compaction ratio, defined as the ratio of board density to wood density. The board compaction ratio is positively related to board IB strength (Rice and Carey 1978; Hse 1975). With board density and sizes being held constant, more flakes from low density wood can be included in a panel than from high density wood. In addition, higher pressure has to be used to make the panel when low density wood is used, which allows better contact between flakes. As a result, better bonding is formed. Because of the inclusion of more wood flakes and better bonding, IB is significantly increased. Rice and Carey (1978) reported a regression equation for flakeboard IB on compaction ratio:

$$IB = -50.0 + 157.3(CR) \quad (24)$$

where

IB = internal bond (psi),

CR = compaction ratio,

$$CR = \frac{\text{panel density}}{\text{wood density}}$$

Incorporating Eq. (24) into Eq. (22) or Eq. (23), the panel IB can then be obtained by the following equation:

$$IB = (IB)_0 \frac{-50 + 157.3(CR)}{-50 + 157.3(CR)_0} \quad (25)$$

where

- IB = simulated panel internal bond,
- (IB)₀ = panel internal bond obtained by Eq. (22) or Eq. (23),
- CR = compaction ratio of the desired panel,
- (CR)₀ = compaction ratio of the panel with respect to wood species used in the experiment to obtain Eq. (22) and Eq. (23).

Because the flakes used by Lehmann were Douglas-fir with a specific gravity of 0.48, Eq. (25) can be generalized to:

$$(IB)_1 = (IB)_0 \frac{-24 + 75.504 \frac{SG}{d_1}}{-24 + 157.3(SG)} \quad (26)$$

where

$(IB)_1$ = adjusted IB,
 SG = panel specific gravity,
 d_1 = wood specific gravity.

Resin spread is another factor that must be considered when computing IB. It is not sufficient to consider resin content alone since with the same resin content, thinner flakes receive less resin than thicker ones. The amount of wood needed to make a panel of given density is fixed, so there will be more flakes cut from wood if the flakes are thin than if they are thick. As a result, flake surface area in a panel is increased, and resin spread is therefore decreased when thin flakes are used. The coverage of resin on flake surfaces directly affects IB. The more the resin spread, the higher the IB. Resin spread can be calculated by (Suo 1985):

$$q = \frac{cd}{2\left(\frac{1}{t_1} + \frac{1}{t_2} + \frac{1}{t_3}\right)} \quad (27)$$

where

q = resin spread,
 c = resin content,
 d = wood specific gravity,
 t_1, t_2, t_3 = flake length, width, and thickness, respectively.

Based on Eq. (27), the panel IB can be adjusted by the following formula:

$$\begin{aligned} IB &= \frac{q_1}{q_0} (IB)_1 = \\ &= \frac{d_1}{d_0} (IB)_1 \end{aligned} \quad (28)$$

where

q_1 = resin spread of the simulated panel,
 q_0 = resin spread of the panel associated with Eq. (22) or Eq. (23),
 $(IB)_1$ = internal bond from Eq. (26),
 d_1 = wood specific gravity of the simulated panel,
 d_0 = wood specific gravity associated with Eq. (22) or Eq. (23) (0.48 of Douglas-fir).

Substituting $d_0 = 0.48$ into Eq. (28), the IB becomes

$$\begin{aligned} IB &= \frac{d_1}{0.48} (IB)_1 = \\ &= \frac{d_1}{0.48} \frac{-24 + 75.504 \frac{SG}{d_1}}{-24 + 157.3(SG)} (IB)_0 = \\ &= \frac{-24d_1 + 75.504(SG)}{-11.52 + 75.504(SG)} (IB)_0 \end{aligned} \quad (29)$$

COMPARISONS OF SIMULATED AND EXPERIMENTAL RESULTS

The model established in this paper was verified using experimental data. The comparisons of the simulated and experimental results are given in this section. The results show that MOE and MOR of structural particleboard are closely predicted by the model and IB is predicted with a wider range of discrepancy with respect to the experimental results.

Case one

Using data from Heebink et al. (1972) as input, the strength properties were predicted and density profile was simulated. The simulated results of MOR, MOE, and IB of Douglas-fir flakeboards are shown in Table 1.

The predicted MOR and IB were 85 and 70% of the experimental data, respectively. The predicted MOE was over the experimental value by about 18%.

Case two

The input data set consisted of the variables used in the research by Geimer et al. (1974).

TABLE 1. Comparison of predicted and experimental results for Case One.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	24.05 m Pa (3,488 psi)	28.41 m Pa (4,120 psi)	85
MOE	4,438 m Pa (644 k psi)	3,778 m Pa (548 k psi)	118
IB	458 k Pa (66.5 psi)	655 k Pa (95 psi)	70

Several types of boards were made for their study. For the purpose of this study, flakeboards made from disc-cut flakes were simulated by the simulation model. The predicted results are shown in Table 2 along with a comparison between predicted and experimental data.

Among the strength properties predicted, MOR and MOE were reasonably close to the experimental values, but the predicted IB was much higher than that of the experiment. One explanation for this is the variable nature of the IB property. The tested IB depends on many factors besides processing variables such as, which part of the board the test specimen is cut from, the density distribution vertically and horizontally in the board, and even the testing method used. IB values commonly range much more widely than those of MOR and MOE; in the study by Geimer et al. (1974), the coefficient of variation for IB was 72% compared to only 7 and 2% for MOR and MOE, respectively.

TABLE 2. Comparison of predicted and experimental results for Case Two.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	24.94 m Pa (3,620 psi)	29.72 m Pa (4,310 psi)	84
MOE	4,570 m Pa (663 k psi)	4,760 m Pa (691 k psi)	96
IB	429 k Pa (62 psi)	248 k Pa (36 psi)	172

TABLE 3. Comparison of predicted and experimental results for Case Three.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	33.76 m Pa (4,897 psi)	30.47 m Pa (4,420 psi)	110
MOE	4,979 m Pa (722 k psi)	5,137 m Pa (745 k psi)	97
IB	670 k Pa (97 psi)	248 k Pa (36 psi)	269

Case three

This set of input data was from the article by Kuklewski et al. (1985). The flakes used were from bigtooth aspen. The comparison of the predicted and experimental data is shown in Table 3.

The predicted MOR and MOE were very well within the ranges of 22.96–37.02 m Pa (3,330–5,370 psi) and 4,220–6,130 m Pa (612–889 k psi), respectively, obtained in the study by Kuklewski et al. (1985). Predicted IB, however, was far outside the experimental range of 117–303 k Pa (17–44 psi).

Case four

The input data were the same as in Case Three except that the flakes were from red maple. Table 4 shows the predicted and experimental data.

Experimental data ranged from 32.41–44.61 m Pa (4,700–6,470 psi) for MOR, 4,830–6,570 m Pa (700–953 k psi) for MOE, and 614–800

TABLE 4. Comparison of predicted and experimental results for Case Four.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	37.15 m Pa (5,388 psi)	38.33 m Pa (5,560 psi)	97
MOE	5,235 m Pa (759 k psi)	5,620 m Pa (815 k psi)	93
IB	644 k Pa (93 psi)	689 k Pa (100 psi)	93

TABLE 5. Comparison of predicted and experimental results for Case Five.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	22.34 m Pa (3,241 psi)	25.31 m Pa (3,670 psi)	88
MOE	3,523 m Pa (511 k psi)	3,960 m Pa (574 k psi)	89
IB	766 k Pa (111 psi)	718 k Pa (104 psi)	107

k Pa (89–116 psi) for IB. All strength properties were closely predicted with several percent under.

Case five

The input data set was from the study of aspen waferboard properties by Suo (1985). Wafer thickness, board specific gravity, resin content, and wax content used were 0.107 cm (0.042 in.), 0.609, 4.4%, and 1.92%, respectively. Strength properties were predicted by the simulation model. The predicted and experimental data are compared and shown in Table 5.

The predicted MOR and MOE were about 12 and 11% less than the experimentally obtained MOR and MOE, respectively. However, the predicted IB was about 7% greater than the experimentally obtained value.

Case six

The input variables were the same as in Case Five except that wafer thickness, board specific gravity, resin content, and wax content used were 0.0762 cm (0.03 in.), 0.545, 2.25%, and 1.92%, respectively. The predicted and experimental data on strength properties are compared in Table 6.

The predicted MOR was within 3% of experimental, with predicted MOE 12% less than the experimentally determined value. The predicted IB value was 21% higher than the value obtained through experimentation.

TABLE 6. Comparison of predicted and experimental results for Case Six.

Property	Predicted	Experimental	$\frac{\text{Predicted}}{\text{Experimental}}$ (%)
MOR	18.82 m Pa (2,730 psi)	18.28 m Pa (2,651 psi)	103
MOE	3,147 m Pa (456 k psi)	3,570 m Pa (518 k psi)	88
IB	390 k Pa (57 psi)	322 k Pa (47 psi)	121

SUMMARY

Nonoriented structural flakeboard was modeled as a multilayer system. Its bending properties (MOE and MOR) were modeled according to the mechanics of the system. Each layer of a panel was considered as a plane, orthotropic in its properties, to take into account the random orientation of flakes. The modeling process resulted in averaged layer properties over the ranges of the grain and ring angles of the flakes. Overall panel MOE and MOR were determined based on panel layer properties. The effective panel MOE was treated as a congregated effect of all the layers. The panel MOR was modeled as dependent on the ultimate force or maximum moment the system can bear, which is, in turn, equal to the strength of a layer that is able to resist the ultimate force in that particular setting.

The IB strength was modeled using a modified regression equation. Such variables as resin content and spread, board specific gravity, flake length and thickness, and board compaction ratio were accounted for in determining board IB.

Verification of the model by experimental results showed that the modulus of elasticity and modulus of rupture were predicted reasonably accurately. Internal bond strength as determined through simulation varied widely from experimental results.

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