

**DEVELOPMENT OF AN INTERACTIVE COMPUTER  
SIMULATION MODEL FOR DESIGNING  
LAMINATED COMPOSITE PANELS**

**by**

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## ABSTRACT

Application of computer science in the analysis of industrial data has become increasingly important in today's society due to increased complexity of the industrial processes and high product quality standards required. In particular, computer simulation of industrial processes has led to improvement in both production efficiency and product quality.

In this study, an interactive computer software was developed to provide a design tool for the manufacture of warp-resistant laminated wood composite panels. The program was based on combining several mathematical theories in predicting material properties, equilibrium moisture content, transient moisture distribution, and panel warping. Numerical techniques were used to solve the unsteady state moisture diffusion equation. The program was capable of creating new panels, searching existing panels in the database, performing equilibrium and transient warp analysis, and displaying the results graphically. Four example panels were created and their warping behaviors were simulated using the program. The program predicted well-expected trends on panel's warpage as influenced by layer thickness, orientation, moisture content change, panel width, and moisture gradient. The software could be a very useful tool for wood composite laminate manufacturers to produce high quality laminates.

*Keywords:* database, design, laminated panels, simulation, warping, VB programming

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## CHAPTER 1

### Introduction

#### Background

Application of computer science in the analysis of industrial data has become increasingly important in today's society due to increased complexity of the industrial processes and high product quality standards required. In particular, computer simulation of industrial processes has led to improvement in both production efficiency and product quality.

In the field of wood science and technology, many scientists have attempted to accurately model the performance behavior of laminated wood composite panels, in order to provide some design guidelines for manufacturing high quality products [Tong and Suchsland 1993, Xu 1993]. However, the efforts have often been met with frustrations because of the complexity involved. A large amount of information about the performance behavior can be obtained by modern computer simulation techniques, providing valuable information for equipment and process modification and developments. These assumptions and ideas are the motivation for this study.

#### Significance

Each year, a tremendous number of wood-based composite panels are produced in the world to meet the market demand for wood-based furniture [Suchsland and McNatt 1985]. The lamination, which combines different materials in a layered structure as one solid panel, has been done on a trial-and-error basis. This practice often leads to wastes in resources and poor product quality. The use of the modern computer simulation



technology as outlined in this study allows a quicker and more accurate selection of the laminated materials. The software developed will provide a training tool for industrial personnel to better control of the lamination process. This work will lead to increased production speed and product quality in the furniture industry, and will also advance the current knowledge in computer simulation technologies.

### Statement of the Problem

The wood material industry uses overlaid panels as flat, straight elements in furniture and cabinet construction [Suchsland and McNatt 1985]. The panels are often in 3-ply or 5-ply construction with a thick core and thin overlays. Occasionally, two-ply overlaid panels (e.g., particleboard or medium density fiberboard overlaid on the visible face only) are used for economical reasons. These types of panels sometimes warp unexpectedly and severely after being assembled, having left the manufacturing plant in a perfectly flat condition. Such warping cannot be easily corrected by the application of cleats or other reinforcing members because the forces that cause the warping are of considerable magnitude. Often the entire panel or the entire product must be replaced with no real guarantee that the replacement will perform better than the original. Severe warping of finished products may well damage a company's reputation and even lead to lawsuits against the manufacturer.

There is a sound technological basis for such warping to occur. The potential to warp is often built into the panel during manufacture [Norris 1964]. This potential may be triggered by changes in the moisture content of the panel components in response to long-term variations in relative humidity (RH) of the air. There is a need for a scientific

understanding of the mechanism of panel warping under service conditions. The reasons are twofold: (a) to see whether existing lamination practice is as efficient as possible and (b) to enable the technology to be extended to new products. The efficiency of the lamination process depends on two opposing economies: (a) the need to reduce operating costs by keeping production time to a minimum; and (b) the need to prevent wastage costs being incurred if the product is damaged. An optimum lamination process must be found which minimizes operating costs without damaging the product.

Determining the optimum lamination design for a given product application is a matter of significant complexity, requiring fundamental information on how the material behaves under a dynamic environment. The use of computer simulation technology is a feasible way to study the complex interaction among many variables that control the warping process. However, none of the existing simulation models has displayed all merits in the process analysis. Therefore, the purpose of this study was to develop and implement a new computational model based on the lamination concepts. The model was capable of finding the best combination of various materials in terms of their performance behavior and was implemented into an interactive computer program to provide a design and training tool for industrial personnel.

#### Objectives of Project

The following objectives will be achieved in this study:

1. To develop database tables using MS Access for storing physical and mechanical properties of common lamination materials including wood veneer, plastic laminates, and wood-based composites;

2. To develop a mathematical simulation model for predicting warping behavior of multi-layer laminated panels;
3. To implement the model in a user-friendly design software using Visual Basic with graphical interface and MS Access database for dynamic data storage and exchange; and
4. To apply the software as a design and training tool for the industrial personnel.

#### Definition of Terms

Diffusion – The process of moisture movement within a piece of wood-based materials.

Equilibrium Moisture Content (EMC) – Moisture content in wood-based material reached at a given relative humidity and temperature.

Lamination – Process of combining two or more pieces of sheet materials together under heat and pressure to form a solid panel.

Linear Expansion (LE) – In-plane swelling of wood-based material over a given moisture content change expressed as a percentage of the original dimension.

Moisture Content (MC) – The amount of water in wood-based material expressed as a percentage of dry wood weight.

Modulus of Elasticity – Elastic constant of a wood-based material determined in bending.

## CHAPTER 2

### Review of Related Literature

Model analysis has been the underlying approach of choice for selecting and combining various materials to form a solid and warp-resistant panel in composite design [Norris 1964, Springer 1976, Xu 1993]. In wood science field, several studies have been conducted to measure and model warping behavior of wood-based laminates.

Heebink and Haskell [1962] measured properties of high pressure laminate (HPL) materials. This information was later utilized in a follow-up study [Norris 1964] on the warping of three-ply laminates consisting of HPL face, particleboard, and HPL backer sheet. There was a fairly good agreement between calculated and measured warping.

Suchsland and McNatt [1985] conducted a comprehensive study on the warping of laminated panels. Emphasis in this study was on the theoretical evaluations of the effect of the variability of panel component properties, particularly of those of the face and back layers of multi-layered laminates on the warping of structurally balanced and unbalanced panels.

The warping of a veneered cabinet door was analyzed by Suchsland [1990]. By applying an elastic warping model to the exact construction of the warped door, the effects of such variables as grain deviation in the veneer layers, species differences, and veneer thickness differences were investigated. The results showed warping of the same order of magnitude as that exhibited by the real door. It was also found that warping caused by imbalances in the panel is an essential prerequisite to the elimination of large moisture content differences among layers and to the manufacture of stable panels.

A study of wood-based composite sheathing materials exposed to fluctuating moisture conditions was conducted by Hiziroglu and Suchsland [1991]. Elastic analysis indicated that even moderate moisture content changes in the materials could lead to bending stresses exceeding the ultimate bending strength. However, the experimental investigation revealed that these materials are not elastic and that relaxation at high relative humidity reduces the maximal bending stresses to about 40 to 50 percent of the bending strength. A buckled oriented Strandboard (OSB) beam does not return to its original straight configuration upon regaining its initial moisture content, and at the initial moisture content, the axial stress does not disappear but turns from compression into a sizable tensile stress.

A study of the warping of overlaid particleboard was conducted by Suchsland et al. [1993]. These laminates, consisting of different particleboard substrates and of various types of plastic overlays, both in 2-ply and 3-ply constructions, were exposed to one moisture cycle, and the warp was measured and also calculated based on elastic assumptions. Residual warping at the end of the cycle indicated viscoelastic behavior, at least on the part of the particleboard substrates.

Xu [1993] developed a visco-elastic plate theory, taking into account the effects of changing moisture contents over time, and applied this theory with good results to the prediction of the warp of a two-ply yellow-poplar laminate. Tong and Suchsland [1993] developed a finite element model to predict warping in wood-based products.

Warp may also occur as a consequence of a transient imbalance such as the development of an unbalanced moisture content gradient (Wu and Suchsland 1996). A

study by Suchsland et al. (1993) showed that if overlays are rigid, the transient warp may not be recovered after eliminating the moisture gradient, and may contribute to permanent deformation of the panel. Therefore, analysis of the warping problem requires knowledge not only of the equilibrium moisture content (EMC) corresponding to a given relative humidity, but also of the time-dependent moisture distribution within the laminate.

In summary, it can be seen that various approaches have been taken to study the warping behavior of laminated wood panels. However, the models are often complicated in nature and are difficult to apply by industrial personnel. Thus, development of user-friendly computer software implementing various mathematical theories will provide a useful and convenient tool for designing the products. At the same time, it will help advance current knowledge on the warping behavior of laminated wood panels.

## CHAPTER 3

### Methodology

The magnitude of warping of a laminated panel is a relatively complex function of moisture distribution across panel thickness, layer thickness, modulus of elasticity (or Young's modulus), moisture expansion, and relative position of the layer in the panel. Under swelling or shrinking conditions, these variables interact and result in a complex pattern of warping for a given panel. Thus, simulation of the warping behavior requires a detailed knowledge of internal moisture distribution and its effect on strength properties of the material.

#### Moisture Distribution Model

##### 1. Equilibrium Moisture Content

Layer equilibrium moisture content (EMC) is calculated using the Nelson's sorption isotherm [Wu and Suchsland 1996]:

$$EMC = M_V \left\{ 1.0 - \frac{1}{A} \text{LN} \left[ \left( -\frac{RT}{W_w} \right) \text{LN}(RH) \right] \right\} \quad [1]$$

where  $W_w$  = molecular weight of water (18 g/mole);  
 $R$  = universal gas constant (1.9858 cal/mole/°K);  
 $T$  = absolute temperature (°K);  
 $A$  = natural logarithm of the Gibbs free energy per gram of sorbed water as RH approaches zero ( $\Delta G_o$ , cal/g), i.e.  $A = \text{LN}(\Delta G_o)$ ;  
 $M_V$  = material constant which approximates the fiber saturation point for desorption (%). For a given temperature, the term  $(-RT/W_w)$  becomes a constant and

parameters  $A$  and  $M_V$  define the sorption isotherm. Wu and Suchsland [1996] measured material constants defining the sorption isotherm (i.e.,  $A$  and  $M_V$ ).

## 2. Transient Moisture Distribution

Fick's second law was used to describe the MC distribution inside a multi-ply laminate (Fig. 1). The laminate consists of the materials that have different sorption and diffusion characteristics. The one-dimensional form of the equation states:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left[ D ( x, M ) \frac{\partial M}{\partial x} \right] \quad [2]$$

where,  $M$  = moisture content (%);  $t$  = time (hr);  $x$  = spatial coordinate starting from one surface of the laminate (mm) (Fig. 1), and  $D$  = diffusion coefficient ( $\text{mm}^2/\text{hr}$ ), which may vary with MC and  $x$ . The initial and boundary conditions for Equation 2 are:

$$M ( x, t ) = EMC_0 ( x, t < 0 ) \quad 0 \leq x \leq H \quad t < 0$$

$$M ( x, t ) = EMC ( x, t ) \quad x = 0 \quad t \geq 0 \quad [3]$$

$$M ( x, t ) = EMC ( x, t ) \quad x = H \quad t \geq 0$$

where,  $H$  is the panel thickness (mm), and  $EMC_0(x, t < 0)$  represents the initial EMCs across panel's thickness.

At each interface between two adjacent layers of different materials, two additional conditions must be specified [Springer 1976]. The first is that the rates of moisture crossing the surfaces of two materials per unit area are equal

$$\left[ -D_{I-1} \rho_{I-1} \frac{\partial M}{\partial x} \right]_{I-1} = \left[ -D_I \rho_I \frac{\partial M}{\partial x} \right]_I \quad [4]$$



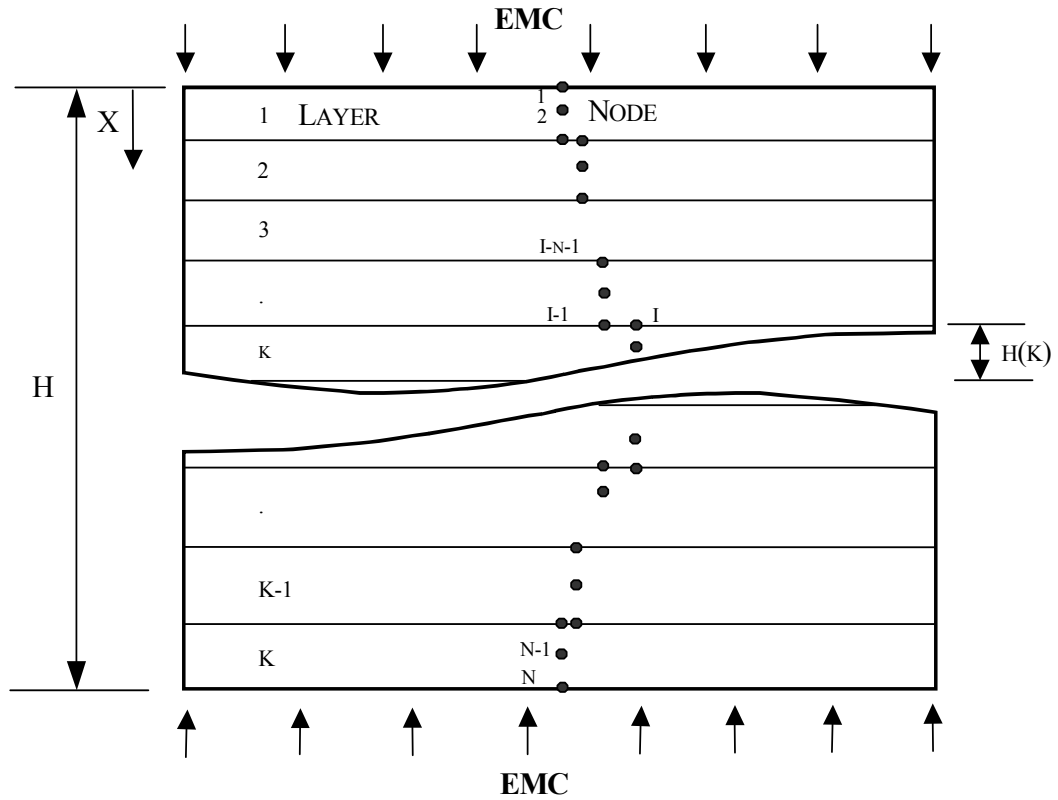


Figure 1. Moisture Distribution Model

where  $\rho$  is the density at the oven-dry condition ( $\text{g}/\text{mm}^3$ ), and subscripts I-1 and I refer to the adjoining regions at the interface (Fig. 1). The second condition is that MCs at the surfaces of two interfacing materials correspond to the same relative humidity:

$$F_{I-1}(M|_{I-1}) = RH = F_I(M|_I) \quad [5]$$

where F represents the function defined by the right-hand side of Equation 1.

It is noted that at the interface RH is continuous, but MC is discontinuous. For an isotherm condition, Equation 5 after substituting Equation 5a and replacing EMC with M becomes:

$$M|_{I-I} = M_V|_{I-I} \left[ 1.0 - \left( \frac{A|_I}{A|_{I-I}} \right) \right] + \left[ \left( \frac{A}{M_V} \right)_I \left( \frac{M_V}{A} \right)_{I-I} \right] M|_I \quad [6]$$

which provides an additional equation for the MCs of two materials at each interface.

Equations 1 to 6 define the entire moisture distribution problem. The Crank-Nicholson's finite difference method [Crank 1965] was used to transform the differential equations into a set of algebraic equations, which were solved through matrix operation. The presence of the interface discontinuity in MC makes the coefficient matrix asymmetric. A matrix solver based on the LU decomposition procedure [Press et al. 1989] was used to perform the matrix inversion and multiplication.

#### Warping Model

The equation that predicts the warping (i.e., radius of curvature – Figures 2 and 3) of a laminated panel upon changes of moisture content and attendant expansion or shrinkage of the various layers is:

$$R = \frac{\frac{2 \sum_1^n E_i (S_i^3 - S_{i-1}^3)}{3 \sum_1^n E_i (S_i^2 - S_{i-1}^2)} - \frac{\sum_1^n E_i (S_i^2 - S_{i-1}^2)}{2 \sum_1^n E_i T_i}}{\frac{\sum_1^n \alpha_i E_i (S_i^2 - S_{i-1}^2)}{\sum_1^n E_i (S_i^2 - S_{i-1}^2)} - \frac{\sum_1^n \alpha_i E_i T_i}{\sum_1^n E_i T_i}} \quad [7]$$

where  $S_i = \sum_1^n T_i$  (Figure 2),  $\alpha_i$  = expansion value of layer i (in/in), and  $E_i$  = modulus of

elasticity of layer i (Psi). The equation reduces the warp of a plate to a one-dimensional

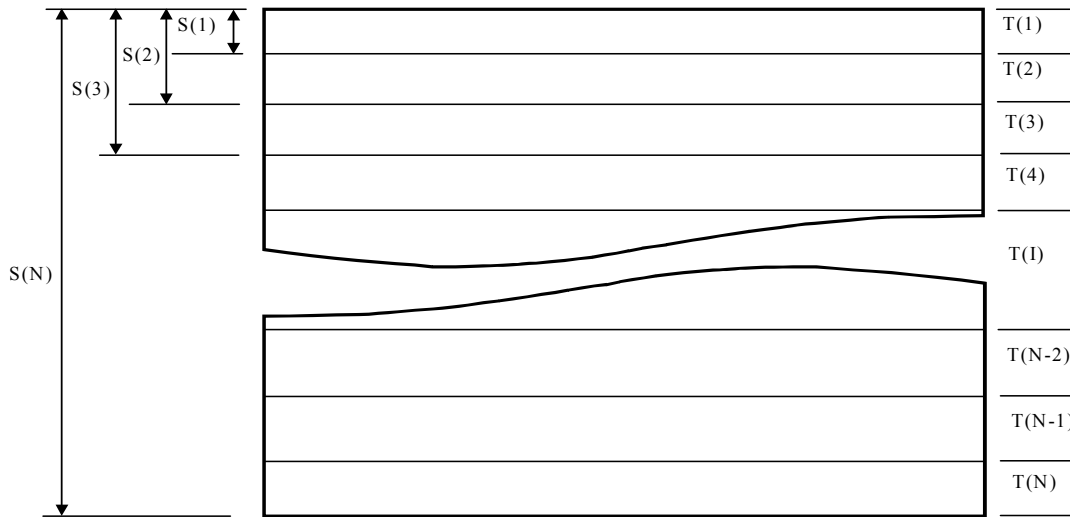


Figure 2. Definition of Terms Used in the Warp Equation

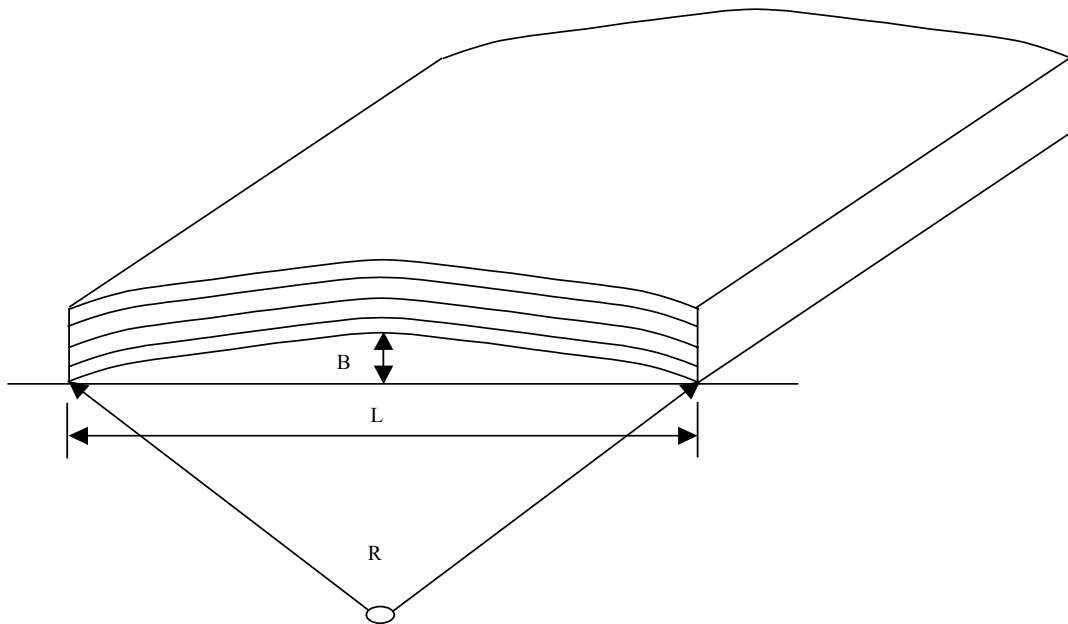


Figure 3. Definition of Center Deflection ( $B$ ) and Radius of Curvature ( $R$ ) over a given Span ( $L$ ) for a Warped Panel

situation. It gives the radius of curvature of a laminated beam. To obtain the radius for the other dimension of a plate, the equation must be applied again with appropriate changes in the inputs. From the radius of curvature, the center deflection over a given span is calculated as:

$$B = \frac{L^2}{8R} \quad [8]$$

where B = center deflection over length L(in) and R = radius of curvature (in).

There are three input variables to the warping equation (Equation 7 or 8): ply thickness, expansion value, and modulus. Ply thickness is straight forward and strictly a matter of measurement. The change in thickness with changing moisture content can be disregarded.

The expansion value is the unrestrained expansion or shrinkage of each layer when its moisture content changes. This expansion or shrinkage depends on the extent of the moisture content change and on the sensitivity of each kind of material to such moisture content changes. The Wood Handbook (1987) list only solid wood shrinkage values measured in the radial and tangential directions when wood is dried from the green condition to 0% moisture content. The moisture content range during which shrinkage occurs is from 30% to 0%. Above 30% (fiber saturation point –FSP), no dimensional changes take place. The shrinkage is a linear function of the moisture content change so that the shrinkage value for any given moisture content interval can be calculated as

$$\alpha = \frac{a \Delta MC}{FSP 100} \quad [9]$$

where,  $\alpha$  = expansion value (in/in),  $a$  = total shrinkage value (in/in),  $\Delta MC$  = moisture content change (%), and FSP = fiber saturation point (%).

The modulus of elasticity is a material constant that indicates its resistance to deformation under load. The higher the modulus of elasticity, the less the material will deform under a given load. It has dimension PSI (lb/in<sup>2</sup>) and is listed for the grain or longitudinal direction ( $E_L$ ) for a large variety of species in the Wood Handbook [Wood Handbook 1987]. The moduli of elasticity in the tangential ( $E_T$ ) and radial ( $E_R$ ) directions are listed for several species (as fractions of the longitudinal moduli). For other species, these averages suggested  $E_T = 0.05 E_L$  and  $E_R = 0.09 E_L$ .

### Material Property Models

#### 1. Modulus of Elasticity in Relation with Moisture Content

As moisture content increases, the modulus decreases. Moisture contents in excess of the fiber saturation point do not result in further reduction of modulus. The Wood Handbook lists modulus of elasticity values for two moisture contents: 12 percent and green. The value at the green condition is equivalent to the minimal value that the modulus reaches near the fiber saturation point (FSP). The modulus for any moisture content between zero and fiber saturation can be obtained as follows:

$$E_M = E_{12} [1 + C_M (M - 12)] \quad [10]$$

Where

$E_M$  = modulus of elasticity at moisture content  $M$  (psi);

$E_{12}$  = modulus of elasticity at 12 percentage moisture content (psi); and

$C_M$  = Correction coefficient for moisture effect on modulus (1/%MC).

## 2. Expansion and Modulus of Elasticity In relation with Grain Deviation

Input for both expansion value and modulus of elasticity must be corrected when the direction of the grain deviates from the direction in which the warping is calculated. The deviation from the perfect grain alignment is defined by the angle  $\theta$ . It is clear that the expansion value for a given moisture content change in the given direction is larger than the minimal value associated with the grain direction (longitudinal). Similarly, the expansion value in the transverse direction is less than the maximum value found in the direction perpendicular to the grain (radial or tangential). The values for the given directions must be determined and used as inputs.

The same adjustments must be made for the modulus of elasticity values. In a given direction the modulus of elasticity is less than the maximum value in the grain direction and larger than it is in the direction perpendicular to the grain direction (radial or tangential). The necessary modifications of the input values are obtained by the use of a Hankinson-type equation for the modulus of elasticity (Wood Handbook 1987) and by a similar formula for the expansion value:

$$E_{\theta} = \frac{E_L \cdot E_P}{E_L \cdot \sin^2 \theta + E_P \cdot \cos^2 \theta} \quad [11]$$

$$\alpha_{\theta} = \sqrt{[(1 + \alpha_P) \sin \theta]^2 + [(1 + \alpha_L) \cos \theta]^2} - 1 \quad [12]$$

where  $E_L$  = Longitudinal modulus,  $\alpha_L$  = Longitudinal expansion,  $E_P$  = Perpendicular modulus, and  $\alpha_P$  = Perpendicular expansion.

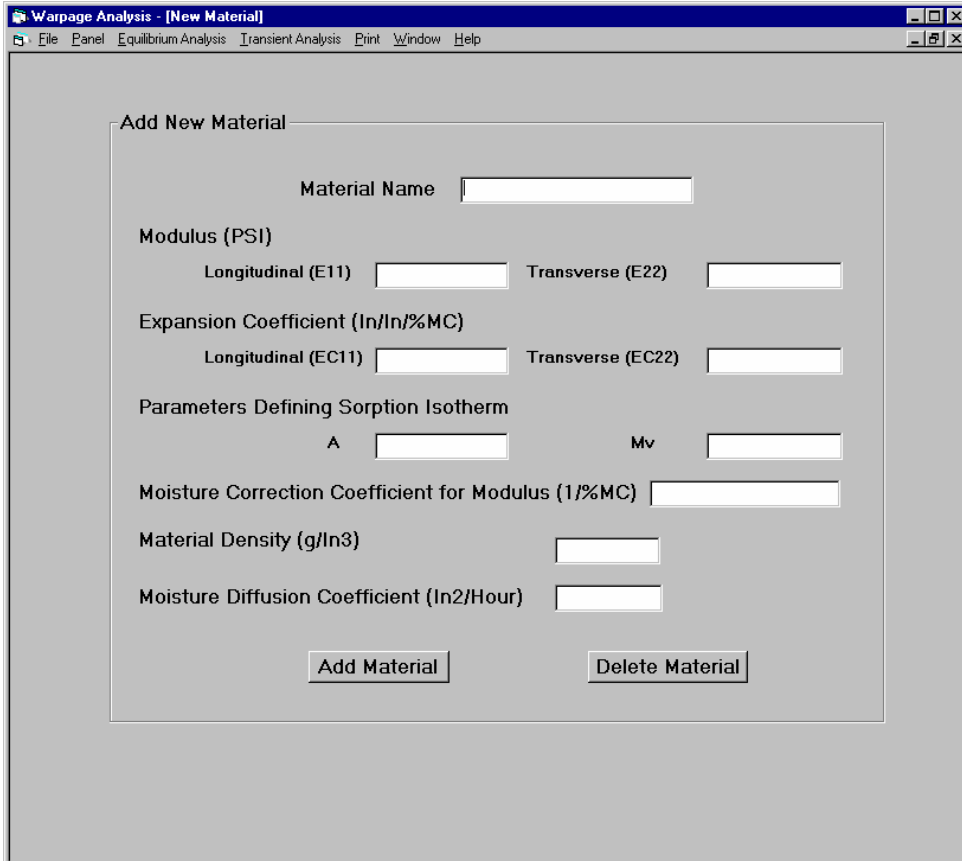
## Program Design

This program uses Visual Basic 6.0 as front end for graphical interface and MS Access database for storing panel details and layer properties and for accessing them when required. The main MDI form acts as a container and is also used for navigation to other forms. This program contains the following VB forms and database tables.

### 1. VB Program Forms

#### Material Property Form

This form defines material properties to be used for panel design. New material can be added to and existing materials can be deleted from database.



The screenshot shows a Windows-style window titled "Warpage Analysis - [New Material]". The menu bar includes "File", "Panel", "Equilibrium Analysis", "Transient Analysis", "Print", "Window", and "Help". The main area is a form titled "Add New Material" with the following fields and buttons:

- Material Name:
- Modulus (PSI):
  - Longitudinal (E11):
  - Transverse (E22):
- Expansion Coefficient (In/In/%MC):
  - Longitudinal (EC11):
  - Transverse (EC22):
- Parameters Defining Sorption Isotherm:
  - A:
  - Mv:
- Moisture Correction Coefficient for Modulus (1/%MC):
- Material Density (g/In3):
- Moisture Diffusion Coefficient (In2/Hour):

At the bottom of the form are two buttons: "Add Material" and "Delete Material".

Figure 4. Screen-shot of the Material Property Form

## Panel Structure

This form defines panel structure and basic layer properties including material, thickness, and grain orientation. For a new panel, panel name, width, and number of layers are first requested and the data are stored in the database tables. Material, thickness and grain orientation of each layer are then added to the database table. For an existing panel, panel name is used to search for the available information in the database. Panel structure and layer properties can be added, updated, and deleted. Validations (with warning messages) are performed before entering any data to the database.

The screenshot shows a software window titled "Warpage Analysis - [Panel Details]". The window has a menu bar with "File", "Panel", "Equilibrium Analysis", "Transient Analysis", "Print", "Window", and "Help". The main content area is divided into two sections: "Panel Structure" and "Layer Properties".

**Panel Structure Section:**

- Panel Name:
- Panel Width (Inch):
- Number of Layers:

**Layer Properties Section:**

- Layer ID:
- Material:
- Thickness (Inch):
- Grain Orientation:

**Layer List:**

Layer ID, Material

1.	Mahogany
2.	Yellow Poplar
3.	ParticleBoard
4.	Yellow Poplar
5.	Yellow Poplar

Figure 5. Screen-shot of the Panel Structure Form



## Equilibrium Layer Properties

This form defines layer properties for an existing panel in the database under the equilibrium RH and temperature conditions given. Thus, it is not allowed to change panel structure (i.e., name, width, and number of layers) in this form. An existing panel in the database is searched through panel name. Given the layer ID number, existing layer properties for the layer in the database is listed in the corresponding text boxes. Two pop-up forms (EMC Lookup – Figure 7 and MOE/EC Lookup – Figure 8) are provided to update layer EMC, modulus, and expansion coefficient. A summary popup form (Summary – Figure 9) is used to provide a summary of the updated panel properties. Layer properties can be added, updated, and deleted.

The screenshot shows a software window titled "Warpage Analysis - [Equilibrium Layer Properties]". The window has a menu bar with "File", "Panel", "Equilibrium Analysis", "Transient Analysis", "Print", "Window", and "Help". The main content area is divided into three main sections:

- Panel:** Contains "Panel Name" (WPB5) and "Panel Width (Inch)" (48) input fields, a "Find" button, and a "Layer ID, Material" list box showing:
  - 1, Mahogany
  - 2, Yellow Poplar
  - 3, ParticleBoard
  - 4, Yellow Poplar
  - 5, Yellow Poplar
- Conditions:** Contains "RHI (%)" (50), "RHF (%)" (70), and "Temperature (F)" (70) input fields.
- Equilibrium Layer Properties:** Contains input fields for "Layer ID" (1), "Material" (Mahogany), "Orientation" (0), "Initial EMC (%)" (8.613794), "Final EMC (%)" (11.65551), "Layer Modulus (PSI)" (422199.7), and "Layer EC (1/%MC)" (5.300045E-04). To the right of these fields are buttons for "Add", "Update", "Delete", "Clear", "EMC Lookup", "MODULUS/EC Lookup", and "Summary".

At the bottom center of the form is a "Clear All" button.

Figure 6. Screen-shot of the Equilibrium Layer Properties Form

### EMC Lookup

Given the material type, which defines the material constants  $A$  and  $M_V$  in Equation 1 for the layer in the database, initial and final RH, and temperature, Equation 1 is used to calculate layer EMC values. The calculated initial and final EMC values are returned to the Equilibrium Layer Properties form (Figure 6) through clicking OK button. The calculated values will not be returned if Quit button is clicked.

Layer Property	
Material	Mahogany
Initial RH (%)	50
Final RH (%)	70
Temperature (F)	70
<b>Calculate</b>	
EMCI (%)	9.735225
EMCF (%)	13.3256
<b>Ok</b> <b>Quit</b>	

Figure 7. Screen-shot of EMC Lookup Form

### MOE/EC Lookup

Given the material type, which defines the modulus (MOE) and expansion coefficient (EC) values in the parallel (i.e., 0 degree grain orientation) and perpendicular

Layer Property	
Material	MAHOGANY
Orientation	0
EMCI (%)	8.613794
EMCF (%)	11.65551
Temperature (F)	70
<b>Calculate</b>	
<b>Modulus (E, PSI)</b>	<b>Expansion Coefficient (EC, 1/%MC)</b>
1490116	2.699971E-03
<b>Ok</b> <b>Quit</b>	

Figure 8. Screen-shot of MOE/EC Lookup Form

(i.e., 90 degree grain orientation) directions for the layer in the database, initial and final moisture contents, and temperature, the current layer modulus is calculated using Equations 10 and 11 and EC is calculated using Equation 12. The calculated MOE and EC values are returned to the Equilibrium Layer Properties form (Figure 6) through clicking OK button. The calculated values will not be returned if the Quit button is clicked.

Summary

The completed panel properties are summarized in this form (Figure 9). This allows the user to check if all the information is correct before performing warp analysis. A return button is provided for the user to return to the Equilibrium Layer Properties form (Figure 6) after validating the data.

LayerID	Material Name	Thickness	Orientation	EMCi	EMCF	Modulus	Expansion Coefficient
1	Mahogany	0.016	0	8.613794	11.65551	422199.7	5.300045E-04
2	Yellow Poplar	0.031	90	8.960755	11.91316	211647.9	5.300045E-04
3	ParticleBoard	0.50	0	8.613794	11.65551	422199.7	5.300045E-04
4	Yellow Poplar	0.031	90	8.791922	16.29405	459906.3	5.300045E-04
5	Yellow Poplar	0.031	0	5.533014	9.181065	2160852	5.500317E-04

Figure 9. Screen-shot of Equilibrium Analysis Summary Form

## Warpage VS Width Analysis

This form allows analyzing panel warpage as a function of panel width for an existing panel with valid layer properties in the database. Given a panel name, a search is made in the database. If found, panel width, layer ID, and material are listed. An initial panel shape showing layer arrangements is drawn. The Initial Panel Frame is then disabled and Warped Panel Frame is enabled. Given a panel width, panel warpage is calculated using Equation 7 and returned to the textbox. The warped shape is then drawn showing warping direction. The calculated warpage can be added to a database table (Add to Table) and plotted as a function of panel width (Summary).

The screenshot displays a software window titled "Warpage Analysis - [Warpage Vs Width]". The interface is divided into two main sections: "Initial Panel" and "Warped Panel".

**Initial Panel Section:**

- Panel Name:
- Panel Width (Inch):
- Initial Shape: A diagram showing a rectangular panel with multiple horizontal layers.
- Layer ID, Material list:
  - 1. Mahogany
  - 2. Yellow Poplar
  - 3. ParticleBoard
  - 4. Yellow Poplar
  - 5. Yellow Poplar
- Find button

**Warped Panel Section:**

- Panel Width (Inch):
- Warpage (Inch):
- Radius Of Curvature (Inch):
- Warped Shape: A diagram showing the panel with a downward curvature.
- Calculate/Draw Shape button
- Add to Table button
- Clear button

At the bottom of the window, there are two buttons: Summary and Clear All.

Figure 10. Screen-Shot of Warpage VS Width Analysis Form

## Warpage VS Width Summary

This form allows listing and plotting calculated panel warpage values as a function of panel width. The form can be printed. The user can navigate between Warpage VS Width Analysis Form (Figure 10) and Warpage VS Width Summary Form (Current) using the Back Button.

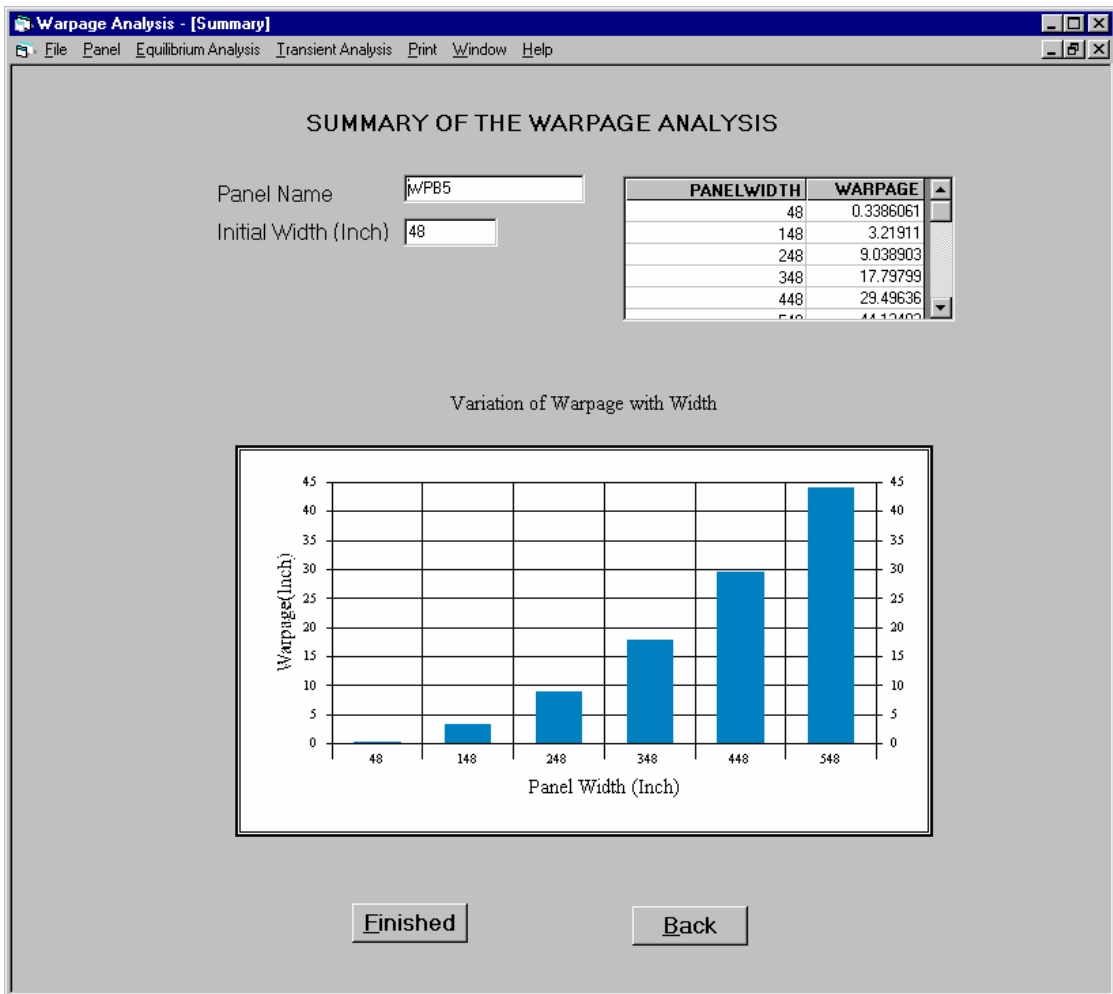


Figure 11. Screen-shot of Warpage VS Width Summary Form.

## Warpage VS Thickness Analysis

This form allows analyzing panel warpage as a function of layer thickness for an existing panel in the database. Given a panel name, a search is made in the database. If found, panel width, layer ID, and material are listed. An initial panel shape showing layer arrangements is drawn. Once a layer is selected from the listbox, the Initial Panel Frame is then disabled and Warped Panel Frame is enabled. Given a layer thickness, panel warpage is calculated using Equation 7 and returned to the textbox. The warped shape is then drawn showing warping direction. The calculated warpage can be added to a database table (Add to Table) and plotted as a function of layer thickness (Summary).

Warpage Analysis - [Warpage vs Thickness]

File Panel Equilibrium Analysis Transient Analysis Print Window Help

Panel

Panel Name: wPB5

Panel Width (Inch): 48

Initial Shape

Layer ID, Material

- 1. Mahogany
- 2. Yellow Poplar
- 3. ParticleBoard
- 4. Yellow Poplar
- 5. Yellow Poplar

Find

Warped Panel

Material: Mahogany

Layer ID: 1

Layer Thickness (Inch): 0.016

Warpage (Inch): 0.3386061

Radius of Curvature (Inch): 850.5457

Warped Shape

Calculate/Draw Shape

Add to Table Clear

Summary Clear All

Figure 12. Screen-Shot of Warpage VS Thickness Analysis Form

## Warpage VS Thickness Summary

This form allows listing and plotting calculated panel warpage values as a function of layer thickness. The form can be printed. The user can navigate between Warpage VS Thickness Analysis Form (Figure 12) and Warpage VS Thickness Summary Form (Current) using the Back Button.

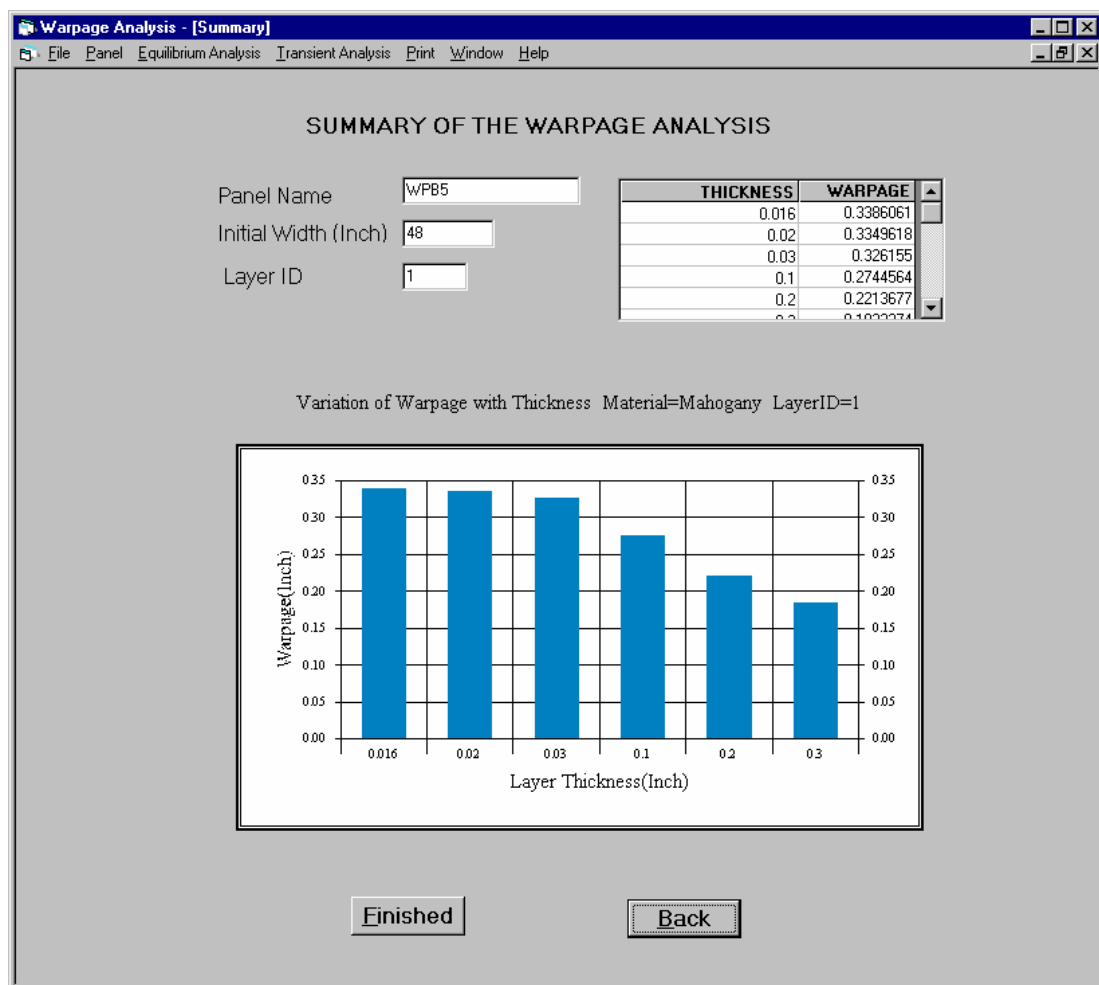


Figure 13. Screen-Shot of Warpage VS Thickness Summary Form

## Warpage VS Orientation Analysis

This form allows analyzing panel warpage as a function of layer orientation for an existing panel in the database. Given a panel name, a search is made in the database. If found, panel width, layer ID, and material are listed. An initial panel shape showing layer arrangements is drawn. Once a layer is selected from the listbox, the Initial Panel Frame is then disabled and Warped Panel Frame is enabled. Given a grain angle, panel warpage is calculated using Equation 7 and returned to the textbox. The warped shape is then drawn showing warping direction. The calculated warpage can be added to a database table (Add to Table) and plotted as a function of layer orientation (Summary).

Warpage Analysis - [Warpage Vs Orientation]

File Panel Equilibrium Analysis Transient Analysis Print Window Help

Panel

Panel Name wpB5

Panel Width (Inch) 48

Initial Shape

Layer ID, Material

- 1. Mahogany
- 2. Yellow Poplar
- 3. ParticleBoard
- 4. Yellow Poplar
- 5. Yellow Poplar

Find

Warpped Panel

Material Mahogany

Layer ID 1

Layer Orientation 0

Warpage (Inch) -0.8541522

Radius of Curvature (Inch) -337.1765

Warpped Shape

Calculate/Draw Shape

Add to Table Clear

Summary Clear All

Figure 14. Screen-Shot of Warpage VS Orientation Analysis Form



## Warpage VS Orientation Summary

This form allows listing and plotting calculated panel warpage values as a function of layer orientation. The form can be printed. The user can navigate between Warpage VS Orientation Analysis Form (Figure 14) and Warpage VS Orientation Summary Form (Current) using the Back Button.

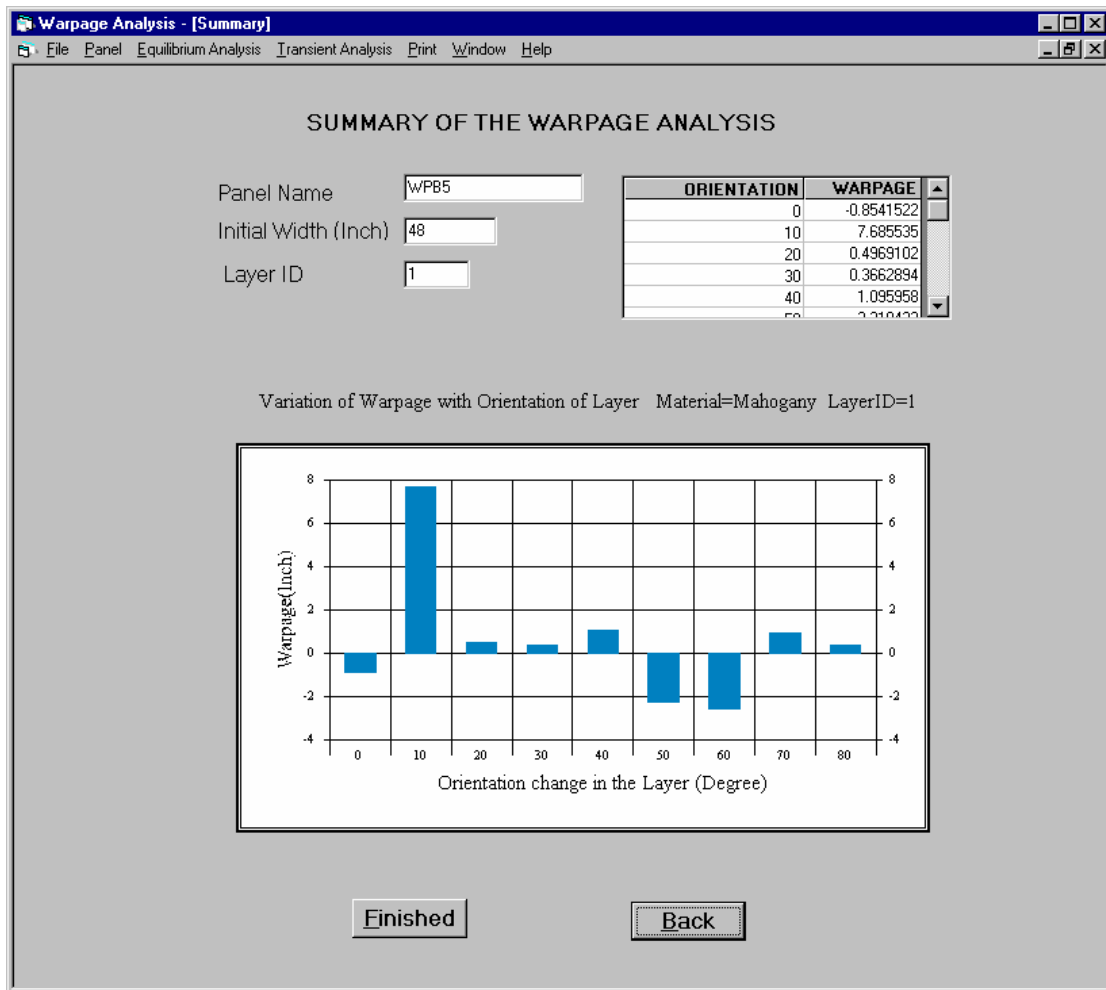


Figure 15. Screen-Shot of Warpage VS Orientation Summary Form

## Warpage VS Moisture Content Analysis

This form allows analyzing panel warpage as a function of layer moisture content for an existing panel in the database. Given a panel name, a search is made in the database. If found, panel width, layer ID, and material are listed. An initial panel shape showing layer arrangements is drawn. Once a layer is selected from the listbox, the Initial Panel Frame is then disabled and Warped Panel Frame is enabled. Given new initial and final MCs, panel warpage is calculated using Equation 7. The warped shape is then drawn showing warping direction. The calculated warpage can be added to a database table (Add to Table) and plotted as a function of layer orientation (Summary).

The screenshot displays the 'Warpage Analysis - [Warpage Vs Moisture Change]' software window. The interface is divided into two main sections: 'Panel' and 'Warped Panel'.

**Panel Section:**

- Panel Name: WPB5
- Panel Width (Inch): 48
- Initial Shape: A diagram showing a rectangular panel with multiple horizontal layers.
- Layer ID, Material Listbox:
  - 1. Mahogany
  - 2. Yellow Poplar
  - 3. ParticleBoard
  - 4. Yellow Poplar
  - 5. Yellow Poplar
- Find button

**Warped Panel Section:**

- Material: Mahogany
- Layer ID: 1
- Initial MC (%): 8.613794
- Final MC (%): 11.65551
- Warpage (Inch): 0.3386061
- Radius of Curvature (Inch): 850.5457
- Warped Shape: A diagram showing the panel with a downward curve, indicating warpage.
- Buttons: Calculate/Draw Shape, Add to Table, Clear

At the bottom of the window, there are buttons for 'Summary' and 'Clear All'.

Figure 16. Screen-Shot of Warpage VS Moisture Content Analysis Form

## Warpage VS Moisture Content Summary

This form allows listing and plotting calculated panel warpage values as a function of layer moisture content change. The form can be printed. The user can navigate between Warpage VS Orientation Analysis Form (Figure 16) and Warpage VS Orientation Summary Form (Current) using the Back Button.

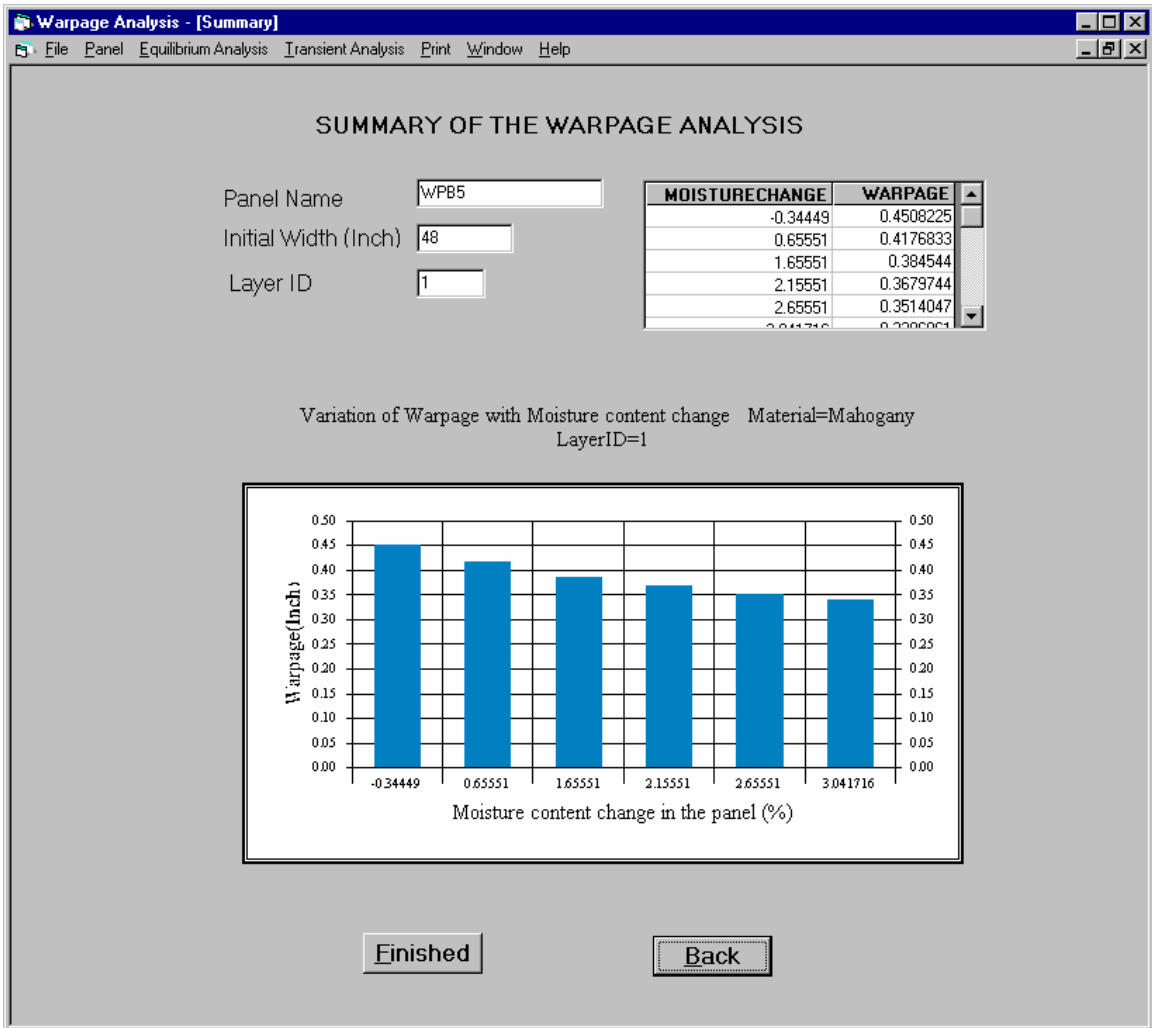


Figure 17. Screen-Shot of Warpage VS Moisture Content Summary Form

## Transient Layer Properties

This form allows performing transient moisture and warp analysis for an existing panel in the database. Given a panel name, a search is made in the database. If found, panel width, layer ID, and material are listed. The panel frame is disabled. Initial Equilibrium Conditions, Final Conditions, and Transient Layer Properties Frames are enabled. Initial and final RH and temperature conditions are then requested. Note that it is

Warpage Analysis - [Transient Layer Properties]

File Panel Equilibrium Analysis Transient Analysis Print Window Help

Panel

Panel Name

Panel Width (Inch)

Find

Layer ID, Material

- 1, HPL Face
- 2, Particleboard Face
- 3, Particleboard Core
- 4, Particleboard Face

Initial Equilibrium Conditions

RH (%)  Temperature (F)

Final Conditions

RHL (%)  RHR (%)  TempL (F)  TempR (F)

Transient Layer Properties

Time To Perform Analysis (Hrs)

Layer ID	Modulus E	Expansion EC	Initial MC	Final MC
Layer 1	1982147	1.250022E-03	3.997	6.251701
Layer 2	399898.9	5.299833E-04	7.978463	8.912143
Layer 3	200096	5.299833E-04	8.344079	9.064301
Layer 4	426029.5	5.299833E-04	7.978463	12.12664

Calculate MC/E/EC

Warp Analysis

Summary Clear All

Figure 18. Screen-shot of Transient Layer Properties Form

allowed using different final exposure conditions for the two panel surfaces. Given a time to perform analysis, internal moisture distribution is calculated based on theories outlined under Moisture Distribution Model. Database tables defining various material parameters for each layer are used in the calculation. The layer mean moisture content, modulus, and expansion coefficient are then calculated and returned to the listbox.

### Transient Warp Analysis

A popup form (Figure 19 – Transient Warp Analysis) is used to perform warp analysis. Panel name, width, number of layers, and layer properties are listed in the form

The screenshot shows a software window titled "Warpage Analysis - [Transient Analysis]". The window contains the following elements:

- Initial Panel Section:**
  - Panel Name: PBHPL4
  - Panel Width (Inch): 48
  - Initial Shape: A diagram of a flat rectangular panel with four horizontal layers. The top layer is labeled '1' and the bottom layer is labeled '4'.
  - Layer ID, Material: A listbox containing:
    - 1, HPL Face
    - 2, Particleboard Face
    - 3, Particleboard Core
    - 4, Particleboard Face
- Warped Panel Section:**
  - Time (Hrs): 60
  - Warped Shape: A diagram of the panel after 60 hours, showing a concave-up curvature across all layers.
  - Warpage (Inch): 0.7174996
  - Radius of Curvature (Inch): 401.394
- Return Button:** A button labeled "Return" is located at the bottom center of the form.

Figure 19. Screen-shot of The Transient Warp Analysis Form

for validation purpose. The time at which analysis is done and actual warpage values are listed, which can be added to a database table for plotting. The user can return to the transient layer properties form by clicking the Return button.

### Transient Warp Summary

This form is used to plot transient warp as a function of time for the given panel.

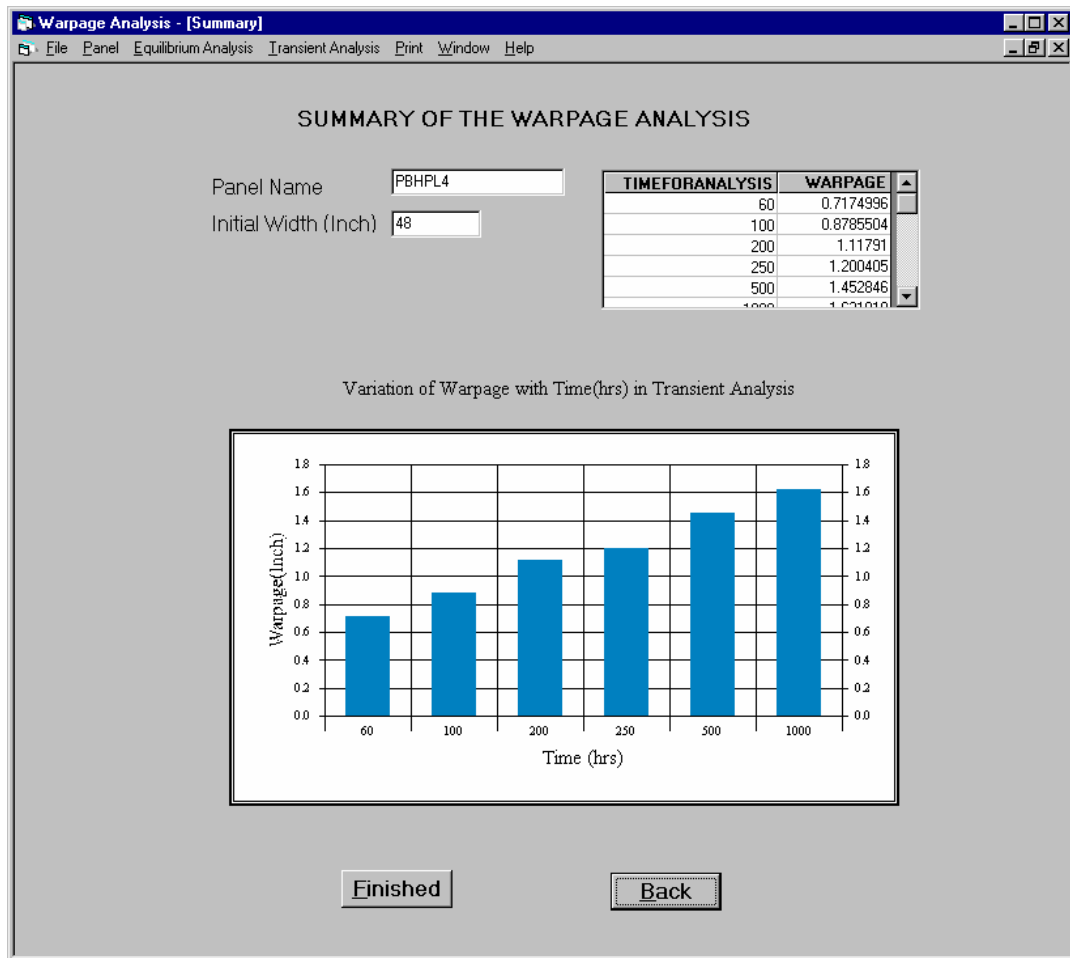


Figure 20. Screen-shot of The Transient Warp Analysis Summary Form

## 2. Relational Database for Data Access and Data Storage

Relation database used for Warpage analysis is shown in Figure 21. Most of the tables have one-to-many relationships maintaining referential integrity. Panel name has one-to-many relationship (i.e., modifying the panel name in the Panel Structure Form changes the panel name in all the other forms). The same applies for deletion of a panel. This database employs referential integrity. In some tables, two fields are taken as the primary key.

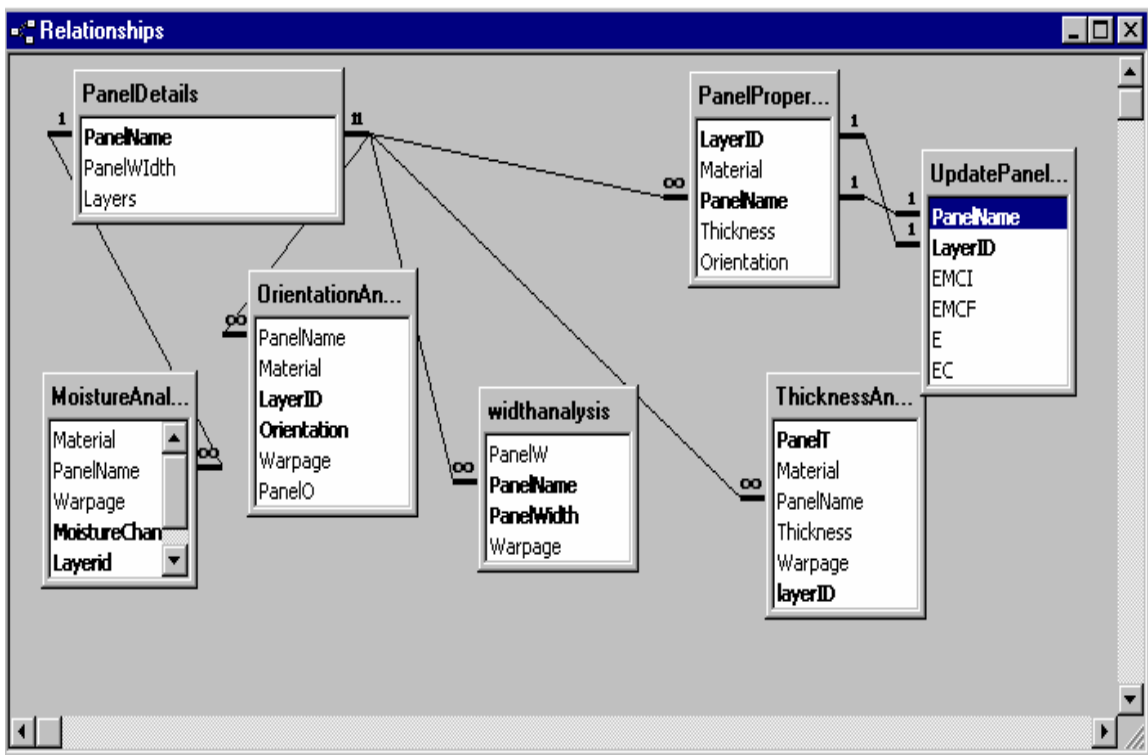


Figure 21. Screen-shot of the Database Relationship

### 3. Access Database Tables

There are 8 MS Access tables for storing material properties, panel name and structure, and calculated results.

#### Material Properties

This table contains layer material properties. New material can be added to the table and existing material can be deleted from the table.

MaterialID	MOE11	MOE22	EC11	EC22	Density	DiffusionCoefficient	Absorption	MVA	Cm
HPL Back	2284000	1514000	0.0004	0.00055	19.67	0.0000341	5.66	12.6	0.019127
HPL Face	2227000	1560000	0.00075	0.00125	24.59	0.0000233	5.17	11.368	0.019127
Mahogany	1500000	65000	0.00007	0.0027	8.9	0.00279	5.015	27.1	0.019127
ParticleBoard	300000	300000	0.00053	0.00053	10.49	0.000465	5.15	22.95	0.019127
ParticleBoard Core	212000	212000	0.00053	0.00053	8.69	0.000775	5.23	23.24	0.019127
ParticleBoard Face	425000	425000	0.00053	0.00053	12.29	0.000155	5.095	23.325	0.019127
Yellow Poplar	1580000	69000	0.00007	0.0027	6.88	0.00279	5.015	27.1	0.019127
*	0	0	0	0	0	0	0	0	0

Figure 22. Screen-shot of the Material Properties Table

#### Panel Details

This table contains panel name, width, and number of layers.

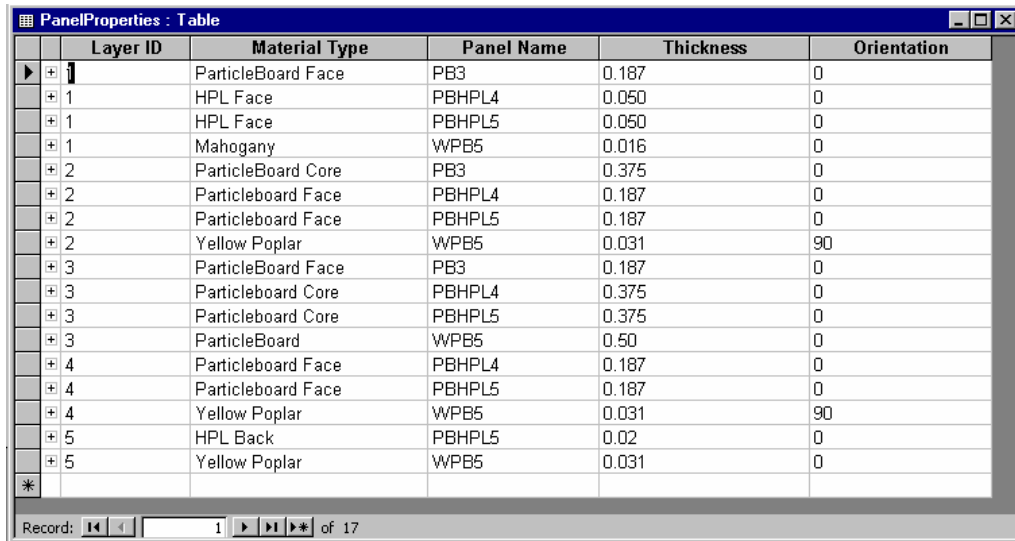
PanelName	PanelWidth	Layers
PB3	48	3
PBHPL4	48	4
PBHPL5	48	5
WPB5	48	5
*		

Figure 23. Screen-shot of the Panel Details Table



### Layer Properties Table

This table contains layer ID, material type, panel name, thickness, and orientation for all existing panels in the database.

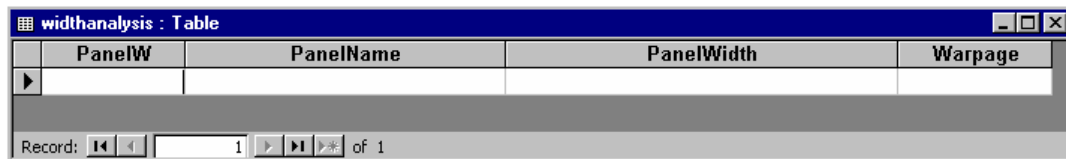


Layer ID	Material Type	Panel Name	Thickness	Orientation
1	ParticleBoard Face	PB3	0.187	0
1	HPL Face	PBHPL4	0.050	0
1	HPL Face	PBHPL5	0.050	0
1	Mahogany	WPB5	0.016	0
2	ParticleBoard Core	PB3	0.375	0
2	Particleboard Face	PBHPL4	0.187	0
2	Particleboard Face	PBHPL5	0.187	0
2	Yellow Poplar	WPB5	0.031	90
3	ParticleBoard Face	PB3	0.187	0
3	Particleboard Core	PBHPL4	0.375	0
3	Particleboard Core	PBHPL5	0.375	0
3	ParticleBoard	WPB5	0.50	0
4	Particleboard Face	PBHPL4	0.187	0
4	Particleboard Face	PBHPL5	0.187	0
4	Yellow Poplar	WPB5	0.031	90
5	HPL Back	PBHPL5	0.02	0
5	Yellow Poplar	WPB5	0.031	0

Figure 24. Screen-shot of the Layer Properties Table

### Width Analysis Summary Table

This table contains information from panel width analysis. The data are used for run-time plotting. After exiting the program, the data are deleted.

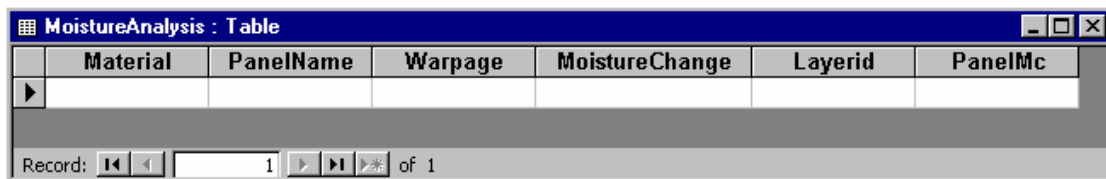


PanelW	PanelName	PanelWidth	Warpage

Figure 25. Screen-shot of the Width Analysis Summary Table

### Layer Moisture Analysis Summary Table

This table contains information from layer moisture content change analysis. The data are used for run-time plotting. After exiting the program, the data are deleted.

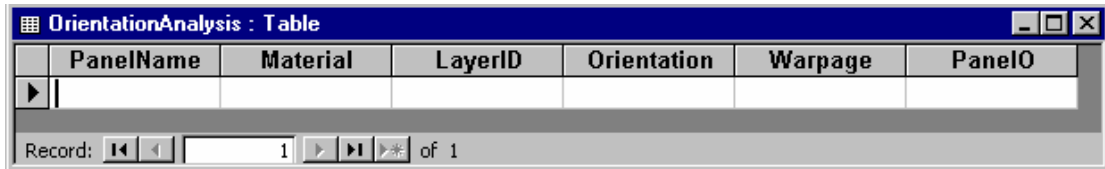


Material	PanelName	Warpage	MoistureChange	Layerid	PanelMc

Figure 26. Screen-shot of the Layer Moisture Analysis Summary Table

### Layer Orientation Analysis Summary Table

This table contains information from layer orientation change analysis. The data are used for run-time plotting. After exiting the program, the data are deleted.

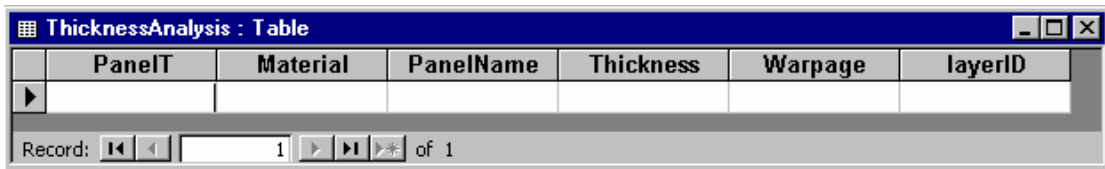


The screenshot shows a window titled "OrientationAnalysis : Table". It contains a table with the following columns: PanelName, Material, LayerID, Orientation, Warpage, and PanelO. The table is currently empty. Below the table, there is a record navigation bar showing "Record: 1 of 1".

Figure 27. Screen-shot of the Layer Orientation Analysis Summary Table

### Layer Thickness Analysis Summary Table

This table contains information from layer thickness change analysis. The data are used for run-time plotting. After exiting the program, the data are deleted.

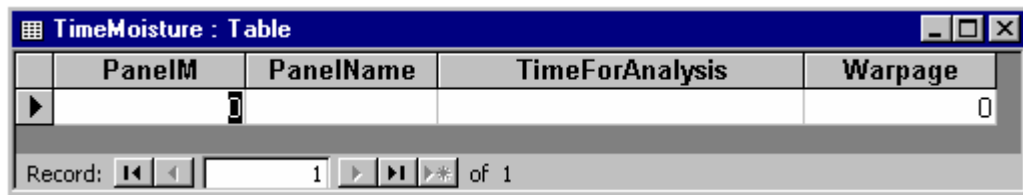


The screenshot shows a window titled "ThicknessAnalysis : Table". It contains a table with the following columns: PanelT, Material, PanelName, Thickness, Warpage, and layerID. The table is currently empty. Below the table, there is a record navigation bar showing "Record: 1 of 1".

Figure 28. Screen-shot of the Layer Thickness Analysis Summary Table

### Transient Warp Analysis Summary Table

This table contains information from transient warp analysis. The data are used for run-time plotting. After exiting the program, the data are deleted.



The screenshot shows a window titled "TimeMoisture : Table". It contains a table with the following columns: PanelM, PanelName, TimeForAnalysis, and Warpage. The table has one row with the following values: PanelM is empty, PanelName is empty, TimeForAnalysis is empty, and Warpage is 0. Below the table, there is a record navigation bar showing "Record: 1 of 1".

Figure 29. Screen-shot of the Transient Warp Analysis Summary Table

## CHAPTER 4

### Program Testing and Results

#### 1. Material Properties

Layer material properties for the selected laminating materials are summarized in Table 1. The properties are included in the database tables so that they can be accessed during program running.

Table 1. Material Properties of Selected Laminating Materials.

Material Type	Density (g/In <sup>3</sup> )	Modulus (1000 PSI)		Expansion Coefficient (In/In/%MC)		Sorpton Isotherm Parameters		Diffusion Coefficient (In <sup>2</sup> /hr)
		Par <sup>1</sup>	Per <sup>2</sup>	Par <sup>1</sup>	Per <sup>2</sup>	A	Mv	
Mahogany	8.19	1,500	65	0.00007	0.0027	5.02	27.1	0.00279
Yellow Poplar	6.88	1,580	69	0.00007	0.0027	5.02	27.1	0.00279
Particleboard	10.49	300	300	0.00053	0.00053	5.15	22.9	0.000465
Particleboard Face	12.29	425	425	0.00053	0.00053	5.11	23.1	0.000155
Particleboard Core	8.69	212	212	0.00053	0.00053	5.23	23.2	0.000775
HPL Face	24.59	2,227	1,560	0.00075	0.00125	5.17	11.4	0.0000233
HPL Back	19.67	2,284	1,514	0.00040	0.00055	5.66	12.6	0.0000341

<sup>1</sup> Parallel Direction

<sup>2</sup> Perpendicular Direction

#### 2. Example Panels

Four example panels were created using the materials listed in Table 1 to test the program (Table 2). These panels represent real commercial laminated wood-based panels used by the furniture manufacturers.

Table 2. A Summary of Panel Structure, Layer Material, Thickness, and Orientation of the Example Panels.

Panel Type	Layer ID	Layer Material	Layer Thickness (Inch)	Layer Orientation (degree)	
				Parallel	Perpendicular
1) Five-Layer Particleboard Wood Laminate (WPB5)	1	Mahogany	0.016	0	90
	2	Yellow Poplar	0.031	90	0
	3	Particleboard	0.500	0	90
	4	Yellow Poplar	0.031	90	0
	5	Yellow Poplar	0.031	0	90
2) Three-Layer Particleboard (PB3)	1	Particleboard Face	0.187	0	90
	2	Particleboard Core	0.375	0	90
	3	Particleboard Face	0.187	0	90
3) Four-Layer Particleboard HPL Laminate (PBHPL4)	1	HPL Face	0.050	0	90
	2	Particleboard Face	0.187	0	90
	3	Particleboard Core	0.375	0	90
	4	Particleboard Face	0.187	0	90
4) Five-Layer Particleboard HPL Laminate (PBHPL5)	1	HPL Face	0.050	0	90
	2	Particleboard Face	0.187	0	90
	3	Particleboard Core	0.375	0	90
	4	Particleboard Face	0.187	0	90
	5	HPL Back	0.020	0	90

### 3. Typical Results

Typical results showing panel warpage as function of panel width, layer thickness, layer orientation, and layer moisture content change under equilibrium conditions are shown in Figures 11, 13, 15, and 17 respectively. Typical results showing panel warpage as a function of time under transient moisture conditions are shown in Figure 19. The predicted trends compared well with results from other related studies. Thus, the software could be a very useful tool for wood composite laminate manufacturers to produce high quality laminates.

## CHAPTER 5

### Conclusions and Recommendations

In this study, an interactive computer software was developed to provide a design tool for the manufacture of warp-resistant laminated wood composite panels. The program was based on combining several mathematical theories in predicting material properties, equilibrium moisture content, transient moisture distribution, and panel warping. Numerical techniques were used to solve the unsteady state moisture diffusion equation. The program was capable of creating new panels, searching existing panels in the database, performing equilibrium and transient warp analysis, and displaying the results graphically. Four example panels were created and their warping behaviors were simulated with the program. The program predicted well-expected trend on panel's warpage as influenced by layer thickness, orientation, moisture content change, panel width, and moisture gradient. The software could be a very useful tool for wood composite laminate manufacturers to produce high quality laminates.

Testing and verification of the program with additional laminates will be the next step for improving the capability of the software. Immediate goals will be set to develop additional panels with different materials for the analysis.

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