AN OBJECT-ORIENTED FINITE ELEMENT PROCESSING MODEL FOR ORIENTED STRAND BOARD WOOD COMPOSITES

Pascal Hubert [1] and Chunping Dai [1]

[1] *Composites and Treated Wood Products, Forintek Canada Corp., 2665 East Mall, Vancouver, B.C., Canada, V6T 1W5.*
http://www.forintek.ca

SUMMARY: In this work, a comprehensive 1-D object-oriented finite element processing model for oriented strand board (OSB) wood composites has been developed. The model consists of modules of heat and mass transfer, resin cure and wood compaction. Predicted transient temperature and internal steam pressure profiles for different mat initial moisture contents and densities are compared with measurements from instrumented mats. Furthermore, predicted vertical density profile is compared to results obtained from x-ray scans. In general, the model captures the trends observed in practice and therefore can be a valuable tool for the OSB producers to understand and improve manufacturing processes.

KEYWORDS: wood composites, oriented strand board, process modelling, object-oriented, hot pressing, finite element.

INTRODUCTION

Since its introduction in the early 80's, oriented strand board (OSB) has rapidly been recognized in the marketplace as an alternative to plywood in the residential building construction industry. OSB is an engineered wood product, which is made from small diameter logs of fast growing species like aspen, poplar or pine. To produce this wood composite, logs are first flaked into strands of dimensions varying from 70-150 mm in length, 5-30 mm in width and 0.5-1.0 mm in thickness. These strands are dried to a desired moisture content, blended with resin (normally less then 5% by weight) and formed into a mat. The mat formation process induces an in-plane or horizontal mat density variation due to random overlapping of the strands. Finally, pressure and temperature are applied to the mat to consolidate the wood elements and cure the resin.

During the hot pressing operation, heat and pressure are simultaneously applied from the press platens to the mat. With the platen temperature being as high as 220 °C, the mat surface layers are heated rapidly upon press closing. The elevated temperature then turns the moisture in the wood into steam, which flows into the inner layers causing convective heat flow. The change in local environmental conditions affects the wood consolidation characteristics and causes a non-uniform deformation distribution in the mat thickness direction. After the resin is cured, a small amount of springback is observed during the press opening, which leaves a noticeable vertical density profile across the panel thickness in the final product. Obviously, the density profile can have a substantial impact on bending and other properties of OSB panels.

To gain a better understanding of the complex pressing processes, models with different levels of complexity have been developed [1-6]. In most cases, the heat transfer and the moisture movement have been addressed [1-3], while the mat consolidation or deformation has been the focus of models presented in other studies [4-6]. However, no attempt has been made to integrate the solutions of all mentioned physical phenomena into a comprehensive model.

In this paper, an object-oriented finite element model is presented to simulate OSB mat behaviour during pressing. In the first part, an overview of the model assumptions and solution strategies is presented. Then, case studies are presented to demonstrate the merit of the model as a practical tool for the panel manufacturers.

MODEL DEVELOPMENT

The structure of the model is composed of three major components: a database, a user interface and a finite element method (FEM) solver (Fig. 1). The database contains all the inputs to run the model (i.e. solution options, press definition, press cycle, boundary conditions and material properties). The user interface allows the user to define a run and to monitor the evolution of key parameters during the run. The FEM solver, which is the heart of the model, contains all the calculation algorithms. To solve the complex problem, a modular approach [7] is used for the FEM solver as shown in Fig. 1. The mat and the press are described at any given time by a collection of state variables (e.g. temperature, moisture content, steam pressure, displacement and press opening). The pressing process is simulated by consecutive execution of modules describing various physical phenomena (i.e. heat and mass transfer, resin cure, stress and deformation). The modular nature of the proposed model allows for flexible incorporation of any changes that need to be implemented in the future.

The object-oriented method was applied in the design and implementation of the FEM solver. Application of object-oriented methods for the development of engineering software is relatively recent [8-10]. There are many advantages of using these methods. The most important one is that the programs are very modular which make them easier to maintain and to understand. More detailed description of the object-oriented approach can be found in [8]. For our application, the objects created and their relationship are presented in Fig. 2.

Model Description

In this model, the mat of wood strands is discretized into 1-D linear isoparametric elements in the mat thickness direction (out-of-plane) as depicted in Fig. 3. Performing the analysis on only a 1-D section is believed to be adequate, since most in-plane gradients are small compared to out-of-plane gradients and thus can safely be ignored. However, the in-plane steam flow has been included in the solution by using a 'leak term' at each node. We believe that the mat edge pressure condition has to be considered as a significant quantity of steam can escape from the mat edges. The mat is subdivided into a series of layers where different initial conditions, material properties and strand dimensions can be assigned (Fig. 3).

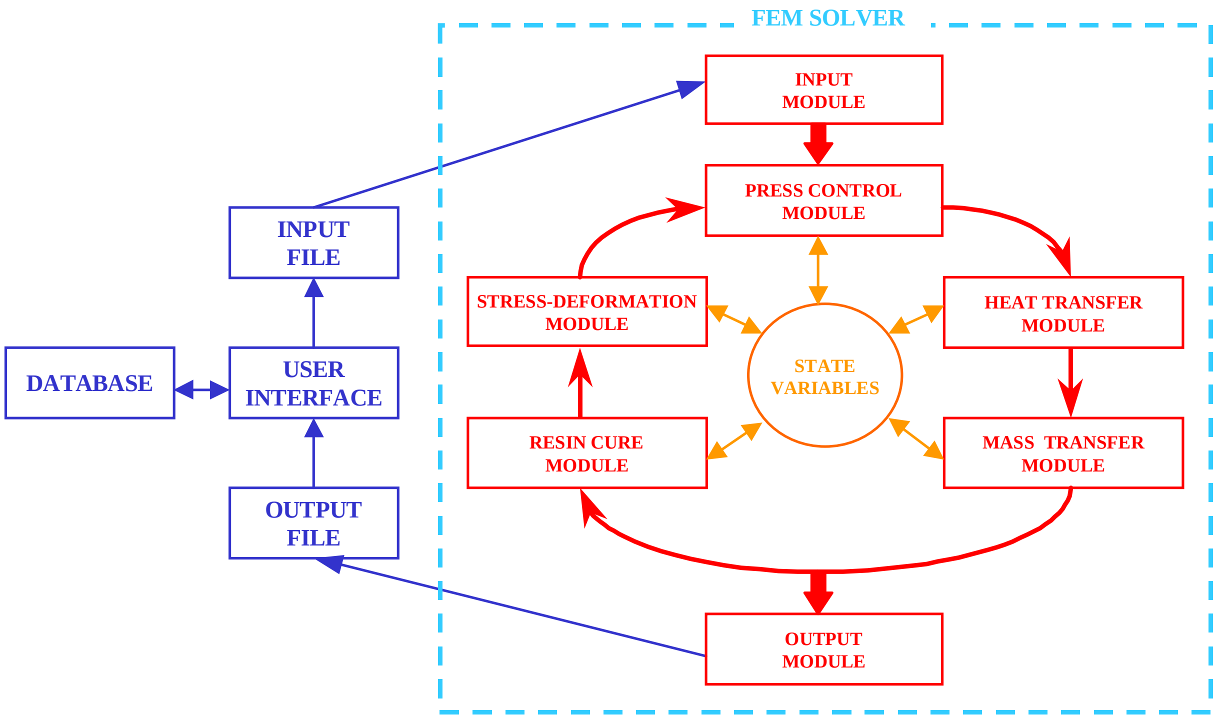


Fig. 1 Flow chart of the model components with the FEM solver architecture.

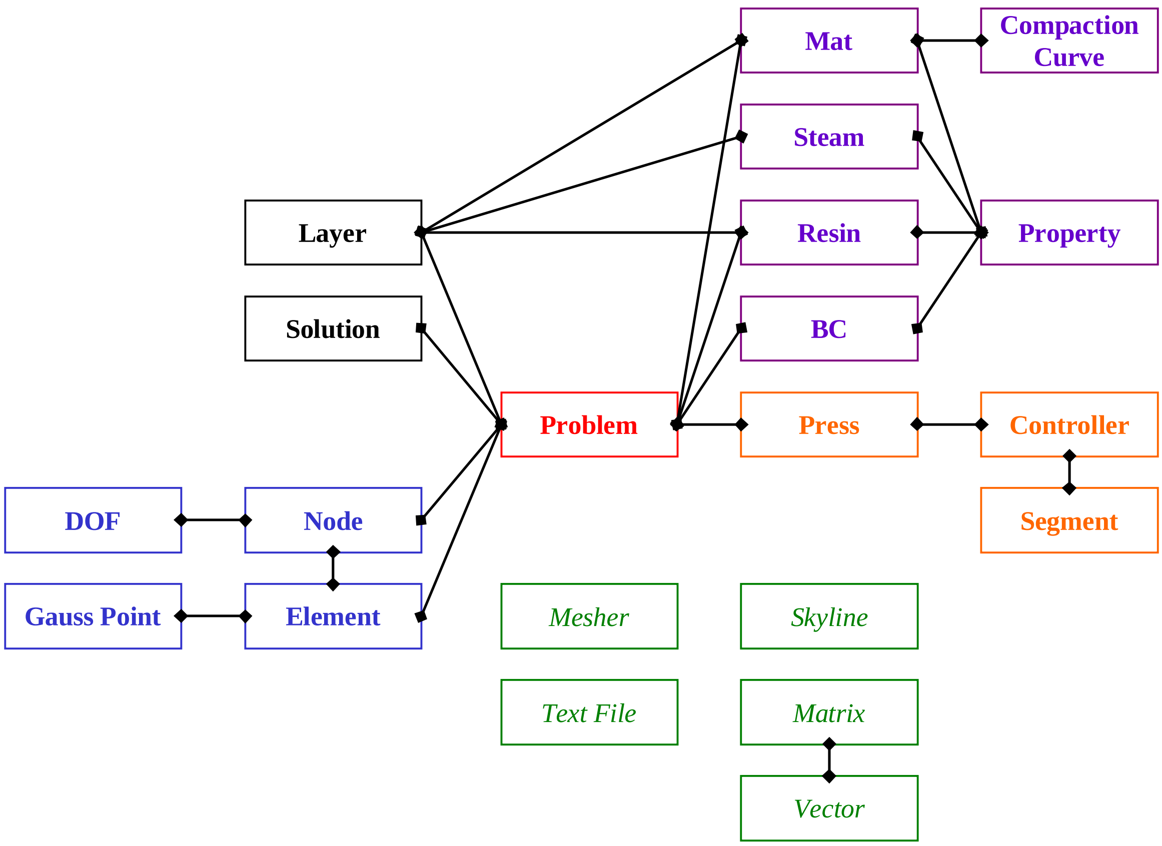


Fig. 2 Objects description and relationship, (italic objects are utility objects used by the main objects in bold).

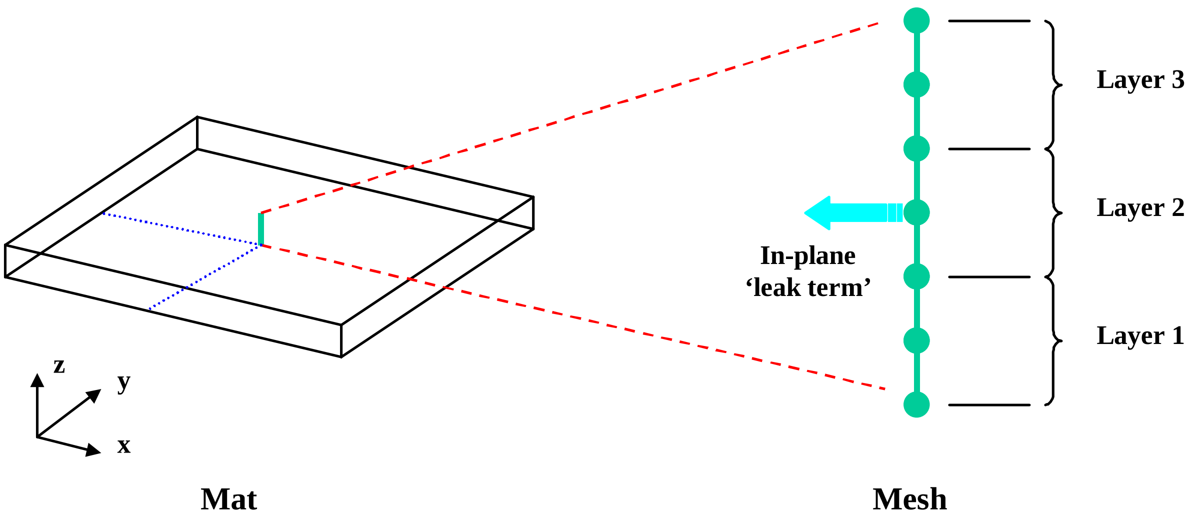


Fig. 3 Mat finite element discretization.

Heat transfer module

The heat transfer module calculates the distribution of temperature (T) during pressing by solving the heat transfer equation for conduction and convection in a porous medium:

$$\rho_m c_m \frac{\partial T}{\partial t} = k_m \frac{\partial^2 T}{\partial z^2} - \rho_s c_s v_z \frac{\partial T}{\partial z} + Q \tag{1}$$

where ρ_m, c_m and k_m are the mat density, specific heat and conductivity, ρ_s, c_s and v_s are the steam density, specific heat and velocity, and Q is a heat flux term which contains water phase change heat, resin cure heat generation and heat loss due to in-plane steam flow. A backward-Euler time stepping scheme is used to solve Eqn 1. The material properties and various heat fluxes are updated at each time step. The mat thermophysical properties (c_m and k_m) are calculated using the local mat density, temperature and moisture content, the steam properties (ρ_s and c_s) are computed from the steam tables based on local steam state, temperature and pressure. The heat fluxes caused by steam in-plane flow and water phases changes are obtained using the in-plane steam flow rate and the steam generation rate computed in the mass transfer module to be discussed in the next section. Convective conditions are applied at the boundaries to account for the contact thermal resistance between the press platens and the mat.

Mass transfer module

The mass transfer module calculates the distribution of vapor pressure (P) and moisture content (MC). Assuming that steam behaves like a perfect gas and flows in the mat according to Darcy's law, the steam pressure governing equation can be written as follows:

$$\frac{R_s T}{\varepsilon}\frac{\partial P}{\partial t} = \frac{\rho_s K_z}{\mu_s}\frac{\partial^2 P}{\partial z^2} + \frac{\partial m_L}{\partial t} + \frac{\partial m_{SG}}{\partial t} \tag{2}$$

where R_s, ρ_s, μ_s are the steam gas constant, density and viscosity, K_z and ε are the mat permeability and porosity, $\partial m_L / \partial t$ and $\partial m_{SG} / \partial t$ are the steam in-plane flow rate and steam generation rate (vaporization or condensation). A backward-Euler time stepping is used to solve Eqn 2. The material properties and steam fluxes are updated at each time step. The mat permeability (K_z) is calculated based on the mat local density. The steam properties (R_s, ρ_s and μ_s) are computed from the steam tables using local steam state, temperature and pressure. The moisture content is updated at each time step assuming that it corresponds to the steam generation rate:

$$\frac{\partial MC}{\partial t} \cong \frac{\partial m_{SG}}{\partial t} \tag{3}$$

An impermeable (no flow) condition is assumed at the platen-mat boundaries. The steam generation rate is calculated based on the steam state obtained from the local temperature and pressure. The state of steam can be liquid, boiling and condensing. During vaporization or condensation, the steam generation rate is obtained from the local heat flux and the steam latent heat of phase change. The steam in-plane flow rate is computed assuming that a pressure gradient is present from the mat center to the edges and is a function of the mat in-plane permeability and the mat in-plane dimensions.

Stress-deformation module

The stress-deformation module calculates the mat deformation and stresses during pressing by solving the stress equilibrium equation:

$$\frac{\partial(\sigma_z - P)}{\partial z} + F_z = 0 \qquad (4`$$

where σ_z, P and F_z are respectively the mat stress, steam pressure and body force. For the current model, the contribution of the steam pressure and the body force are neglected. The mat is treated as an elasto-plastic material with moisture and temperature dependencies of wood mechanical properties. To solve Eqn 4 with material non-linearities, a Newton-Raphson solution is used. Zero displacement condition is assumed at the bottom boundary, while prescribed displacement or pressure is assumed at the top boundary depending whether the press is in position or pressure control. At each time step, the mat compaction properties are updated based on the local deformation, temperature and moisture content. For this model, the viscoelastic behaviour of wood is neglected, this will mainly affect the accuracy of the prediction of the stress relaxation observed during the hold period [11]. The mat density is updated at each time step from the mat local strain. During the press opening phase, the mat springback behaviour is modeled assuming that the mat behaves as a linear elastic material where the elastic modulus or springback modulus is a function of the local resin degree of cure and mat density.

Resin cure module

The resin cure module calculates the resin degree of cure (α) assuming that the curing rate is a function of the degree of cure and the temperature:

$$\frac{\partial \alpha}{\partial t} = f(\alpha, T) \tag{5}$$

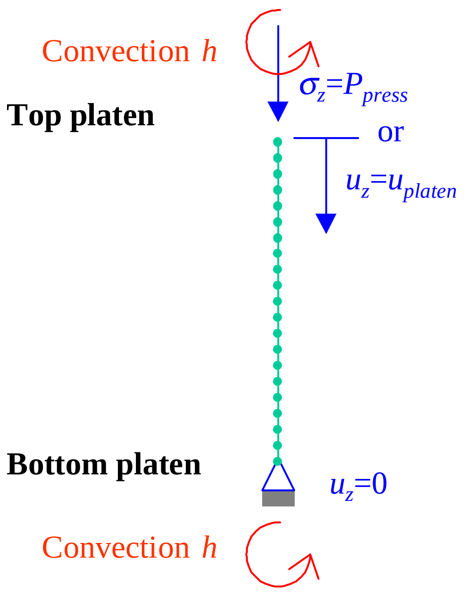
where $f(\alpha,T)$ can be an empirical or semi-empirical function proper to the type of resin used. A large number of functions have been developed for epoxy or polyester resin systems [12] and for a phenol-formaldehyde system [13]. In general, the function contains constants that have to be determined from resin curing tests. At each time step, the curing rate is calculated based on local temperature and degree of cure according to the curing function specified by the user.

Press controller module

The press controller module updates the press pressure or opening according to the press cycle specified. The temperature of the platens is assumed constant. The press cycle is defined by a series of segments similar to the procedure used for commercial presses. The press can be controlled in position or pressure and feedback from the measured pressure and position is obtained by the mat response calculated by the stress-deformation module.

CASE STUDY

To demonstrate the uses of the present model, a pressing simulation of OSB mat composed of commercial strands is presented. A 35x35 cm^2 mat with a target thickness of 11 mm and a target density of 650 kg/m^3 is meshed with 20 elements are shown in Fig. 4. A convection thermal boundary condition (h=400 $W/°Cm^2$) is used on top and bottom boundaries to account for the thermal resistance between the mat and the press platens maintained at a constant temperature (200 °C). Impermeable steam flow conditions are assumed on all boundaries. Fixed displacement (u_z=0) is assumed at the bottom platen and prescribed pressure ($\sigma_z = P_{press}$) or displacement ($u_z = u_{platen}$) is assumed at the top platen interface depending whether the press is in pressure or position control. Time steps of 0.05 seconds are used for the solution. The material properties are obtained from our characterization tests or from the literature. The press cycle used is generally composed of four segments as shown in Fig. 4. The simulation results are compared with experimental results obtained for similar mat specifications and pressing conditions.



Segment	Control mode	Target	Time	Criteria
1	Pressure	3.5 MPa	20 sec.	-
2	Pressure	3.5 MPa	-	Position<=11mm
3	Position	11 mm	300 sec	-
4	Pressure	0 MPa	20 sec	-

Press Cycle Definition

Fig. 4 Mesh and press cycle definition for the case study.

Results

One of the most important process variables controlled by OSB producers is the mat initial moisture content. The effect of the initial moisture content on mat consolidation behaviour and core temperature profile is investigated. The predicted mat consolidation is consistent in trend with experimental observations: an increase in initial moisture content leads to a reduction in time to reach the target thickness and time of pressure relaxation (Fig. 5). However, the predicted stress relaxation is significantly lower, particularly for the 9% moisture content case, which may be caused by viscoelastic effects ignored in the present model. The predicted core temperature profile follows the trend observed experimentally (Fig. 6): an increase in initial moisture content increases the heat transfer to the core and reduces the maximum core temperature. The extra amount of water generates steam which contributes to increase the convective flow, but consumes more energy. One important effect captured by the model is that the boiling temperature corresponding to the plateau observed in Fig. 6(a) is about 140 °C. This is attributed to the fact that the core internal pressure is significantly higher than the atmospheric condition. Such a coupling effect between the heat and mass transfer process seems well simulated in the present model.

One of the major issues during pressing is the development of internal steam pressure because it can potentially cause delaminations or 'blows' upon press opening. The mat density significantly affects the magnitude of the internal pressure. At high density, the mat is not as permeable and the flow of steam out of mat is thus reduced, which causes the internal pressure to build up. To demonstrate this effect, the model was used to simulate the pressing of a low density mat (600 kg/m^3) and a high density mat (700 kg/m^3). The predicted internal steam pressure in the core is compared to the experiment results in Fig. 7. Again, the model captures well the observed effect.

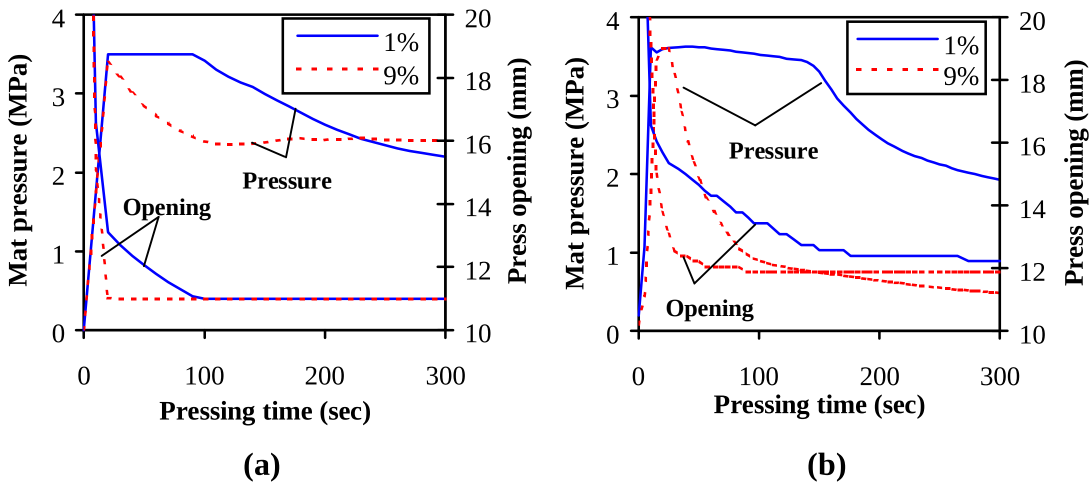
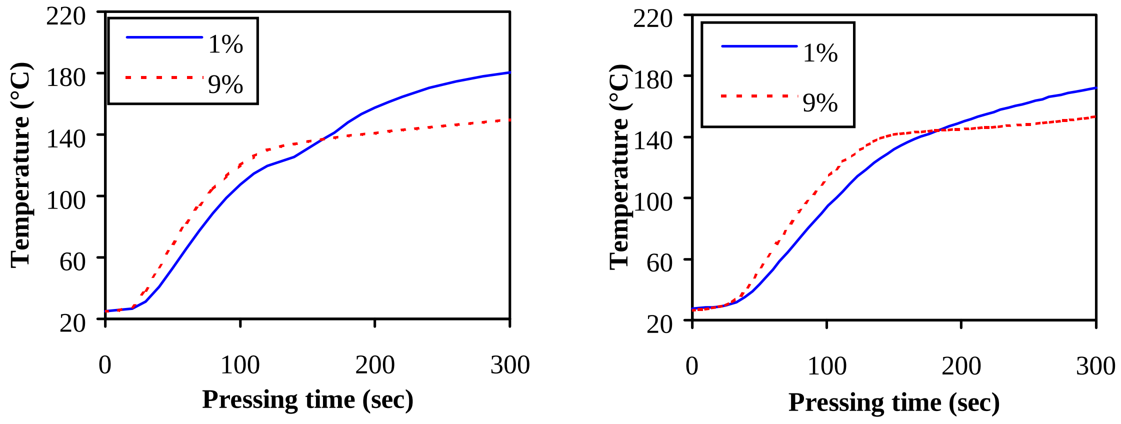
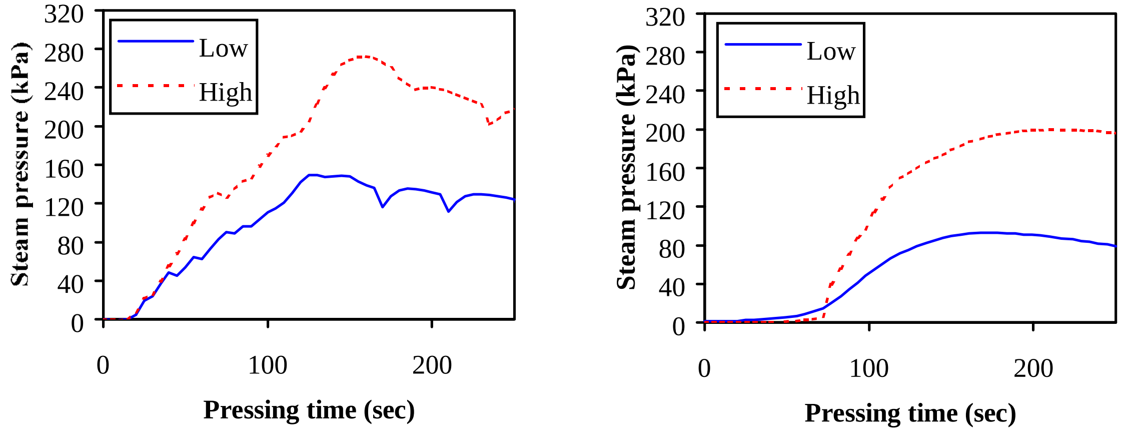


Fig. 5 Effect of initial mat moisture content on mat pressure and press opening profiles, (a) simulated, (b) measured.



(a) **(b)**

Fig. 6 Effect of initial mat moisture content on core temperature profiles, (a) predicted, (b) measured.



(a) **(b)**

Fig. 7 Effect of mat density on core steam pressure profiles, low and high correspond to a mat density of 600 kg/m^3 and 700 kg/m^3 respectively, (a) predicted, (b) measured.

Finally, the vertical density profile is an important characteristic of OSB panels. Among the factors affecting the shape and magnitude of the profile, the press closing rate is one of the most important. The density profiles obtained with a fast and slow press closing times (20 and 90 seconds) are shown in Fig. 8. The density profile shape is affected, particularly close to the panel surfaces. Similar result was found in refence [14] (Fig. 8(b)) and it is believed that pre-mature curing of resin in the surface layers is the main cause to this phenomenon. It occurs when the adhesive cures before the mat is plastically compressed. This condition which leads to higher local springback during press opening is more susceptible to occur in a slow closing rate pressing cycle.

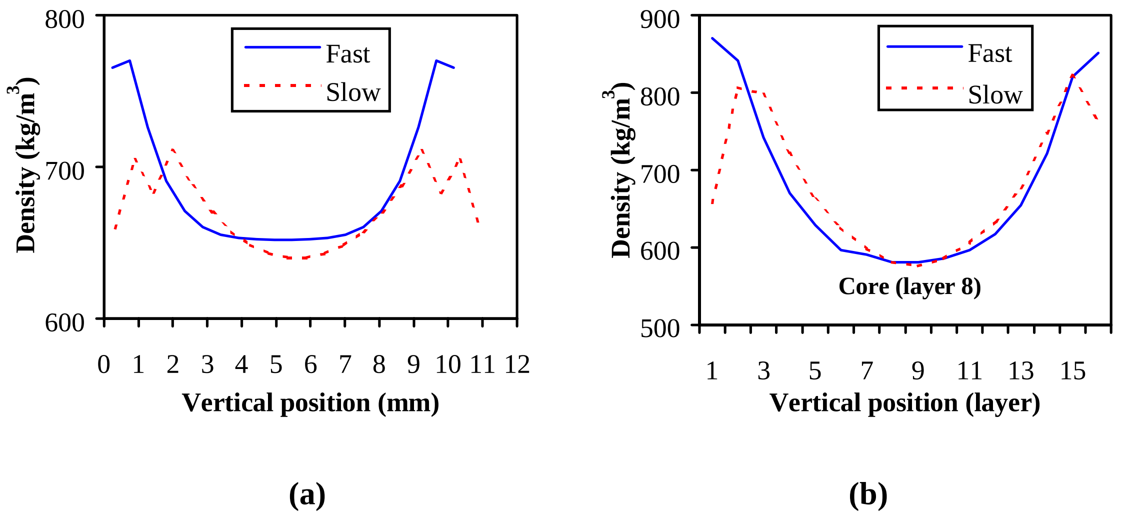


Fig. 8 Effect of press closing time on final panel density profile, fast and slow correspond to a press closing time of 20 and 90 seconds respectively, (a) predicted, (b) measured from [14].

SUMMARY AND CONCLUSION

A 1-D object-oriented finite element pressing model for oriented strand board wood composites has been developed. The model consists of several modules which simulate:

- heat and mass transfer, cure kinetics, wood compaction
- realistic boundary conditions and
- commercial pressing cycle.

A case study has been presented to demonstrate the usefulness of the current model. In general, the model captures well the complex interactions between all the main pressing variables, although some magnitude discrepancies exist between the model predictions and experimental observations. Variations in local material properties and pressing conditions can affect the results. Future model development will be possible by only adjusting specific modules without affecting the global structure.

ACKNOWLEDGMENTS

Financial support from the Structural Board Association (SBA), the Science Council of British Columbia (SCBC) and the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged. We would like to acknowledge the contribution of Mrs. Caroline Simon, Mr. Julien Ferriani, Mr. Maik Hirschberg and Mr. Craig Wilkinson for their work on the measurement of the mat pressing behaviour.

REFERENCES

1. Humphrey, P.E. and Bolton, A.J., “The Hot Pressing of Dry-formed Wood-based Composites Part II. A Simulation Model for Heat and Moisture Transfer, and Typical Results”, *Holzforschung*, Vol. 43, No, 3, 1989, pp. 199-206.

2. Kayihan, F. and Johnson, J.A., “Heat and Moisture Movement in Wood Composite Materials During the Pressing Operation - A Simplified Model”, *Numerical Methods in Heat Transfer*, Volume II, John Wiley & Sons Ltd, 1983, pp. 511-531.

3. Suo S. and Bowyer, J.L., “Simulation Modeling of Particleboard Density Profile”, *Wood and Fiber Science*, Vol. 26, No. 3, 1994, pp. 397-411.

4. Lang, E.M. and Wolcott, M.P., “A Model for Viscoelastic Consolidation of Wood-strand Mats, Part I. Structural Characterization of the Mat Via Monte Carlo Simulation”, *Wood and Fiber Scienc*e, Vol. 28, No. 1, 1996, pp. 100-109.

5. Lang, E.M. and Wolcott, M.P., “A Model for Viscoelastic Consolidation of Wood-strand Mats, Part II. Static Stress-Strain Behaviour of the Mat”, *Wood and Fiber Science*, Vol. 28, No. 3,: 1996, pp. 369-379.

6. Dai, C. and Steiner, P.R., “Compression Behaviour of Randomly Formed Wood Flake Mats”, *Wood and Fiber Science*, Vol. 25, No. 4, 1993, pp. 349-358.

7. Hubert, P., Johnston, A., Poursartip A. and Vaziri, R., “A Two-Dimensional Finite Element Processing Model for FRP Composite Components”, *Proceedings of the Tenth International Conference on Composite Materials*, Whistler, British Columbia, Canada, August 14-18, 1995, Vol. III: Processing and Manufacturing, pp.149-156.

8. Zimmermann, T., Dubois-Pèlerin, Y. and Bomme, P., “Object-oriented finite element programming: I. Governing principles”, *Computer Methods in Applied Mechanics and Engineering*, Vol. 98, 1992, pp. 291-303.

9. Besson, J. and Foerch, R., “Large scale object-oriented finite element code design”, *Computer Methods in Applied Mechanics and Engineering*, Vol. 142, 1997, pp. 165-187.

10. Mackie, R. I., “Using Objects to Handle Complexity in Finite Element Software”, *Engineering with Computer*, Vol. 13, 1997, pp. 99-111.

11. Wolcott, M.P., Kamke, F.A. and Dillard, D.A., “Fundamentals of flakeboard manufacture:Viscoelastic behavior of the wood composite”, W*ood Fiber Science*, Vol. 22, No. 4, 1990, pp. 345-361.

12. Yousefi, A. and Lafleur, P.G., “Kinetic Studies of Thermoset Cure Reactions: A Review”, *Polymer Composites*, Vol. 18, No. 2, 1997, pp. 157-168.

13. Barry, A. O., Peng, W. and Riedl, B., “The Effect of Lignin Content on the Cure Properties of Phenol-Formaldehyde Resin as Determined by Differential Scanning Calorimetry”, *Holzforschung*, Vol. 47, 1993, pp. 247-252.

14. Winistorfer, P.M., Young, T.M. and Walker, E., “Modeling and Comparing Vertical Density Profiles", *Wood and Fiber Science*, Vol. 28, No. 1, 1996, pp. 133-141.