FINITE ELEMENT MODELING OF LAMINATE WOOD COMPOSITES HYGROMECHANICAL BEHAVIOR CONSIDERING DIFFUSION EFFECTS IN THE ADHESIVE LAYERS

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ABSTRACT

The performance and quality of appearance layered wood composite products depend largely on their dimensional stability. Layers of various wood species and orientation and the presence of adhesive layers in such products may induce deformation following moisture content changes and reduce product value. In this context, research on the design and hygromechanical behavior of layered wood composites is of primary importance. More specifically, the impact of the adhesive layers on moisture movement and dimensional stability is not known. The main objective of this paper is to demonstrate the impact of the adhesive layer on the dimensional stability of layered wood composites and how it should be modeled by the finite element method. The impacts of mesh density, degree of interpolation of the elements and linear interpolation of the adhesive properties in the wood-adhesive interface of an engineered wood flooring strip were studied to determine the role of an adhesive layer in the cupping process. The results show that when the effective diffusion coefficient of the adhesive layer decreases, the gap between the linear and quadratic interpolation increases. It is however relatively small and when the number of element layers used in the adhesive increases, the gap between the linear and quadratic interpolation increases. The

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degree of interpolation used for the mechanical component of the model has a minor effect on cupping. Therefore, the choice of a higher degree of interpolation than linear is not necessary. The use of a mesh with a single layer of elements in the adhesive layer can lead to important approximation errors. Therefore, the utilization of more than one layer of elements in the adhesive is necessary.

Keywords: Layered wood composites, moisture diffusion, adhesive, wood flooring, deformation, simulation, mesh density.

INTRODUCTION

In wood products design, dimensional stability is of primary importance especially for layered wood composites where a small deformation in service can result in important value losses. This is particularly true for appearance products such as parquetry, flooring, cabinetry, and furniture components. Non-homogeneous adsorption and desorption of water vapor by the composite may induce cupping, and consequently decrease product value. In this context, the design of a stable product is fundamental since it determines the end value of the composite. Numerical simulations of the deformation of the composite under various ambient relative humidity conditions can be very useful to improve the design of wood products. For example, the finite element method has been successfully used in engineered wood flooring (EWF) design by Blanchet et al. (2005).

A common feature of many composite wood products is the presence of an adhesive layer between the layered components. These adhesive layers are very thin with respect to the whole product and are often overlooked, and in some cases completely neglected in the modeling process. Indeed, it is generally believed that they have little influence on the solution behavior. Consequently, in most numerical simulations, the mesh used in the adhesive layers is very coarse with only one layer of elements. Previous work has shown the significant impact of the adhesive layer in modeling EWF dimensional stability (Blanchet et al. 2005) even with a single layer of elements in the adhesive layer. It was concluded from that study that the modeling of the adhesive layer needs to be investigated more thoroughly. Therefore, the main objective of this paper is to demonstrate the impact of the strategy used to model the dimensional stability of layered wood composites by the finite element method considering the effect of the adhesive layer. Mesh density, interpolation level, and the approach used to define the properties of the wood-adhesive interface were considered in a EWF finite element model to demonstrate the critical role of the adhesive.

PROBLEM STATEMENT

The flooring strip considered in this study is the same as the one described in Blanchet et al. (2005). Its construction details are briefly recalled here. The EWF is a free- standing three layer strip as shown in Fig. 1. It is 65 mm wide, 14 mm thick, and 1000 mm long. The construction considered is a 4-mm-thick sugar maple surface layer (SL), a 8-mm-thick white birch core layer (CL), and a 2-mm-thick yellow birch veneer backing layer (BL). The core layer is made of 22-mm-wide sticks with a 2-mm spacing. The adhesive used to bind the layers together is a urea-formaldehyde (UF) resin.

The deformation is induced by water vapor desorption from 6.3 to 5.0% moisture content occurring by free convection at the top surface. This corresponds to a decrease from 30 to 20% relative humidity (RH) at 20ºC. All the other

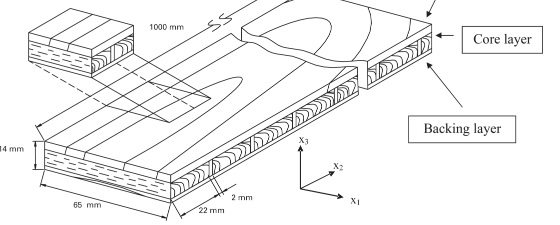


FIG. 1. Engineered wood flooring strip construction and geometry used in the model.

edges and the bottom surface of the EWF are assumed impervious. Each wood layer of the composite is assumed to be orthotropic and elastic; no mechanosorptive effects were taken into account as previous work demonstrated that the behavior is elastic under the conditions considered in this study (Blanchet et al. 2003). Since the components were conditioned before and after assembly, the EWF is assumed to be initially free of stress.

The modeling of the behavior of EWF requires the knowledge of the physical and mechanical properties of the wood species used for each layer as well as for the adhesive. The material properties used in the current study were taken from Blanchet et al. (2005) and are recalled in Table 1.

MODELING APPROACH

Mathematical model

The governing equation used for the description of the mechanical aspect of the problem is the 3-dimensional equation of equilibrium:

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0 \qquad (1)$$

where body forces are assumed to be negligible. σ_{ij} are the normal and shear stress components, expressed in a rectangular coordinate system. We used a quasi-static stress analysis, therefore, we did not include an inertia term in Eq. 1. This is justified since the phenomenon is slow. Because the wood material and the adhesive are

TABLE 1. *Finite element model parameters.*

	Material			
	Surface	Core	Backing	Adhesive
Parameters	Sugar maple	White birch	Yellow birch	UF resin
d_b (kg m^{-3})	[1]597	[1]559	[1]506	[4]1500
D (m^2 s^{-1})				[5]1.0×10^{-14}
D_L (m^2 s^{-1})	[2]2.2×10^{-9}	[2]2.2×10^{-9}	[2]2.2×10^{-9}	
D_R (m^2 s^{-1})	[5]1.8×10^{-11}	[2]4×10^{-11}	[2]4×10^{-11}	
D_T (m^2 s^{-1})	[5]1.8×10^{-11}	[2]4×10^{-11}	[2]4×10^{-11}	
M_0 (%)	6.3	6.3	6.3	6.3
M_∞ (%)	5.0	5.0	5.0	5.0
h (kg m^{-2} s^{-1}%$^{-1}$)	[2]3.2×10^{-4}	[2]3.2×10^{-4}	[2]3.2×10^{-4}	[2]3.2×10^{-4}
β (m m^{-1}%$^{-1}$)				[5]1.9×10^{-2}
β_L (m m^{-1} %$^{-1}$)	[6]1.5×10^{-4}	[1]1.5×10^{-4}	[1]1.5×10^{-4}	
β_R (m m^{-1} %$^{-1}$)	[6]2.1×10^{-3}	[1]1.7×10^{-3}	[1]1.9×10^{-3}	
β_T (m m^{-1} %$^{-1}$)	[6]3.3×10^{-3}	[1]2.4×10^{-3}	[1]2.3×10^{-3}	
α_L (m m^{-1} %$^{-1}$)	[6]1.8×10^{-4}			
α_R (m m^{-1} %$^{-1}$)	[6]1.9×10^{-3}			
α_T (m m^{-1} %$^{-1}$)	[6]2.8×10^{-3}			
E (GPa)				[4]9.0
E_L (GPa)	[3]13.810	[3]12.045	[3]15.251	
E_R (GPa)	[3]1.311	[3]1.069	[3]1.251	
E_T (GPa)	[3]0.678	[3]0.516	[3]0.641	
G_{LR} (GPa)	[3]1.013	[3]0.829	[3]0.971	
G_{RT} (GPa)	[3]0.255	[3]0.200	[3]0.242	
G_{LT} (GPa)	[3]0.753	[3]0.607	[3]0.721	
v				[4]0.35
v_{LT}	[3]0.50	[3]0.43	[3]0.45	
v_{RT}	[3]0.82	[3]30.78	[3]0.70	
v_{TL}	[3]0.025	[3]0.018	[3]0.018	
v_{RL}	[3]0.044	[3]0.043	[3]0.035	
v_{TR}	[3]0.42	[3]0.38	[3]0.36	
v_{LR}	[3]0.46	[3]0.49	[3]0.43	

[1]Jessome (2000), [2]Siau (1995), [3]Bodig and Jayne (1993), [4]Dorlot et al. (1986), [5]Blanchet et al. (2005), [6]Goulet and Fortin (1975)
L: longitudinal; R: radial; T: tangential

assumed elastic, Hooke's law can be used to relate stresses to strains:

$$\sigma_{ij} = C_{ijkl}(\varepsilon_{kl} - \beta_{kl}\Delta M) \tag{2}$$

where C_{ijkl}: stiffness tensor; ε_{kl}: normal and shear strain components; β_{kl}: moisture shrinkage/ swelling coefficients ($\%^{-1}$); ΔM: moisture content change between two time steps (%). Because the UF adhesive is assumed isotropic, Hooke's law can be simplified for that component of the composite by assuming: $E_1 = E_2 = E_3 = E$, $\nu_{23} = \nu_{32} = \nu_{13} = \nu_{31} = \nu_{12} = \nu_{21} = \nu$, $G_{23} = G_{13} = G_{12} = E/2(1+\nu)$, and $\beta_1 = \beta_2 = \beta_3 = \beta$.

The normal and shear strains are related to the displacements u_1, u_2, and u_3 measured along the x_1, x_2, and x_3 directions, respectively:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

The transient moisture movement through the model is described by the three-dimensional moisture conservation equation.

$$\frac{d_b}{100}\frac{\partial M}{\partial t} + \vec{\nabla} \cdot (-K_M \vec{\nabla} M) = 0 \text{ with } K_M = \frac{D\, d_b}{100} \tag{4}$$

where K_M: tensor of effective water conductivity (kg m^{-1} s^{-1} $\%^{-1}$); D: tensor of effective moisture diffusion (m^2 s^{-1}); d_b : density (kg m^{-3}); and M: moisture content (%).

Discretization of the mathematical model

The finite element modeling of hygromechanical deformation of EWF was performed using the finite element code MEF++. The finite element discretization of the Galerkin weak form of the mechanical equilibrium Eq. (1) and moisture conservation Eq. (4) was performed using standard isoparametric and linear or quadratic interpolation of the unknown displacements u_1, u_2, u_3, and moisture content, M. Essential boundary conditions correspond to specified values of the displacements u_1, u_2, and u_3, or moisture content, M. Natural boundary conditions correspond to specified values of the normal stress vector ($\vec{\sigma} \cdot \vec{n}$) or moisture flux vector ($K_M\vec{\nabla}M \cdot \vec{n}$) where $\vec{n}$ is the unit normal vector to the boundary. The time discretization of the equation was performed by the standard Euler implicit time marching scheme. The predicted values of M, u_1, u_2, and u_3 depend on position and time. A single coupled system of discrete equations was solved for the displacement components and M at each time step. A user-specified initial time increment of 0.5 s was used. The following time increments were automatically adjusted between 0.1 and 100000 s by the MEF++ software based on the convergence rate.

Application of the discretized model to engineered wood flooring

The problem considered is the central part of an EWF strip as shown in Fig. 1. The computational domain considered corresponds to half the width of the strip and a length of 24 mm as presented in Fig. 2. The principal material directions of wood are assumed to be perfectly oriented with the strip and the wood growth rings perfectly flat. As a result, a Cartesian coordinate system can be used. The tangential, longitudinal, and radial properties of wood are specified for both surface and backing layers in the x_1-, x_2-, and x_3-directions, respectively. In the core layer, the x_1-, x_2-, and x_3-directions correspond to the longitudinal, radial and tangential wood principal directions respectively as this layer is cross

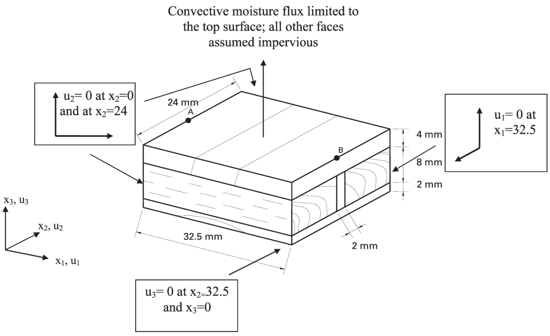


FIG. 2. Computational domain considered and boundary conditions applied to the geometry of the model domain considered.

grain oriented compared to the surface and backing layers. A perfect adhesion between wood and the adhesive was assumed.

Initial and boundary conditions

Initial and boundary conditions must be specified for moisture transfer and for the mechanical components of the model. The initial condition for moisture content was as follows:

$$M(x_1, x_2, x_3, t_0) = M_0 = 6.3\% \qquad \forall(x_1, x_2, x_3) \quad (5)$$

The moisture transfer boundary conditions specify no moisture flux ($K_M\vec{\nabla}M \cdot \vec{n} = 0$) through any surface except the top one through which desorption is assumed to occur. On that surface, the moisture flux is given as follows:

$$K_M \vec{\nabla}M \cdot \vec{n} = q = h(M - M_\infty) \qquad (6)$$

where h is the convective mass transfer coefficient (kg m^{-2} s^{-1} $\%^{-1}$) and M_∞ is the equilibrium moisture content (%).

The following boundary conditions were used for the mechanical part of the model. The essential boundary conditions are illustrated in Fig. 2. They are defined as follows:

$$u_1 = 0 \qquad \text{at } (32.5, x_2, x_3) \qquad (7)$$

$$u_2 = 0 \qquad \text{at } (x_1, 0, x_3) \text{ and } (x_1, 24.0, x_3) \qquad (8)$$

$$u_3 = 0 \qquad \text{at } (32.5, x_2, 0) \qquad (9)$$

Equation (7) defines a symmetry axis along the centerline of the strip. Equation (8) specifies that the domain considered cannot swell along the x_2 axis since it is part of a longer strip. This corresponds to the restraint that would be provided longitudinally by the remaining part of the strip. Finally the strip is considered as freestanding which adds an inequality boundary condition also called contact condition, to the model. However, using the symmetry of the mechanical component of the problem we can circumvent the contact condition by using Eq.(9) which states that the bottom part of the strip cannot move vertically along the x_2 axis. As initial condition we assumed that the flooring strip is initially free of stress and without deformation. This model was also used in a previous study by Blanchet et al. (2005).

Wood adhesive interface

The adhesive considered in this model has low effective water conductivity. Therefore, the adhesive layer behaves as a moisture barrier between the different wood layers. The adhesive layer is an important component of the desorption phenomenon in the product. Using only one layer of elements in the adhesive is a rather crude approach. It is especially true taking into account the important difference in the moisture diffusion coefficient and the mechanical properties between wood and the adhesive considered in this work.

Our purpose is to illustrate the importance of a good physical and geometrical description of the adhesive layer and how it should be modeled by the finite element method considering its low effective water conductivity. For this reason, we used a series of decreasing values of adhesive effective moisture diffusion coefficients: 1.0×10^{-14}, 1.0×10^{-15}, 5.0×10^{-16}, 3.0×10^{-16}, 1.0×10^{-16} m^2 s^{-1} and four finite

TABLE 2. *Number of elements and nodes of the various meshes used.*

Mesh	Number of layers of elements: Sugar maple surface	Top adhesive layer	White birch-core	Bottom adhesive layer	Yellow birch backing	Total number of elements/nodes
Mesh_1	4	1	8	1	1	2328/3029
Mesh_2	4	2	8	1	1	2496/3224
Mesh_3	4	3	8	1	1	2664/3419
Mesh_ref	12	6	24	6	6	33984/38150

element meshes (see Table 2). A coarse finite element mesh (Mesh_1) used one-mm-thick elements for the surface and core layers and 2-mm-thick elements for the backing layer. The 0.1-mm-thick superior adhesive layer located between the surface and core layers was meshed with one (Mesh_1), two (Mesh_2), three (Mesh_3), and six layers of elements (Mesh_ref). For each set of physical properties and geometrical arrangement considered, a new reference solution was computed using the finer mesh (Mesh_ref, 33984 elements). These reference solutions were then used to evaluate the accuracy of the solutions obtained with the other meshes.

The assumption that the interface between wood and the adhesive is a perfect plane also seems to be unrealistic. In practice, the adhesive penetrates into wood creating a transition zone containing a mixture of wood and adhesive. A more realistic approach is proposed to take this transition zone into account. Using the finite element mesh containing six layers of elements in the adhesive layer (Mesh_ref), the physical and mechanical properties were linearly interpolated from pure wood to pure adhesive in the first two layers of elements to represent the properties of the wood-adhesive interface. Pure adhesive properties were used in the central layers of elements of the adhesive. Finally, the properties were linearly interpolated from pure adhesive to pure wood properties in the last two layers of elements. This approach is graphically described in Fig. 3 and leads to the following interpolation in the case of the effective diffusion coefficient.

Let D_0, D_1 and D_A be the effective diffusion for wood species 0, 1 and for the adhesive layer between them respectively. Let us denote by z_0, z_1, z_2, and z_3 the heights of different parts of the adhesive layer (see Fig. 3). The following functions can be introduced:

$$\lambda_0(x_3) = \begin{cases} 0 & x_3 \le z_0 \\ \dfrac{(x_3 - z_0)}{(z_1 - z_0)} & x_3 \in [z_0, z_1] \\ 1 & x_3 \ge z_1 \end{cases}$$
$$\lambda_2(x_3) = \begin{cases} 1 & x_3 \le z_2 \\ \dfrac{(x_3 - z_3)}{(z_2 - z_3)} & x_3 \in [z_2, z_3] \\ 0 & x_3 \ge z_3 \end{cases} \tag{10}$$

These functions can be used to build the linear interpolation $\hat{D}_{0,\mathrm{A},1}$ for the effective diffusion of the adhesive:

$$\hat{D}_{0,\mathrm{A},1}(\mathrm{x}_3) = \begin{cases} \lambda_0(\mathrm{x}_3)D_\mathrm{A} + (1 - \lambda_0(\mathrm{x}_3))D_0 & \mathrm{x}_3 \le \mathrm{z}_2 \\ \lambda_2(\mathrm{x}_3)D_\mathrm{A} + (1 - \lambda_2(\mathrm{x}_3))D_1 & \mathrm{x}_3 \ge \mathrm{z}_2 \end{cases} \tag{11}$$

As a first crude approximation, the effective diffusion for the adhesive layer was considered to be a linear combination of the diffusion coefficient of white birch (at z_0) to the adhesive diffusion coefficient (at z_1). Then from z_1 to z_2 the diffusion coefficient will correspond to the adhesive diffusion coefficient. Finally, from z_2 to

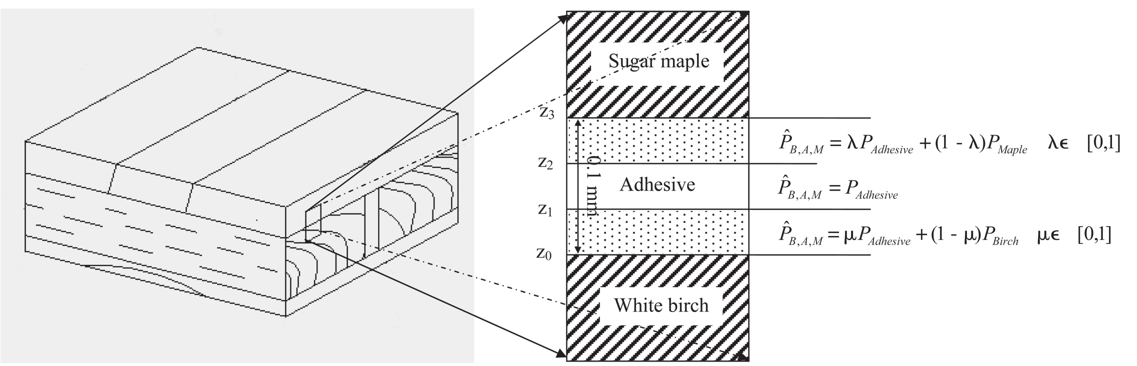


FIG. 3. Schematic representation of the linear interpolation of a property P in the upper adhesive layer.

z_3 we will have a linear combination of the adhesive diffusion coefficient (at z_2) to sugar maple diffusion coefficient (at z_3).

Determination of strip cupping

The determination of strip cupping was used as a comparative tool for the different solutions. We introduced points A and B (see Fig. 2) and defined cupping C(t,A,B) as the evolution with time of the difference in vertical displacement (u_3) of points A and B:

$$C(t,A,B) = u_3(t,A) - u_3(t,B) \tag{12}$$

where $A = (0,12,14.2)$ and $B = (32.5, 12, 14.2)$.

Introducing U_{Ref} the linear displacements obtained with Mesh_ref and $C_{Ref}(t,A,B)$ the corresponding cupping, we define the relative error (%) with respect to cupping as follows:

$$\text{error} = \frac{100*(C(t,A,B) - C_{Ref}(t,A,B))}{C_{Ref}(t,A,B)} \tag{13}$$

If we have C_1 and C_2, two different cupping values obtained from two displacements U^1 and U^2 we define the variation of cupping $\Delta C_{1,2}$ (%) as

$$\Delta C_{1,2} = \frac{100*(U^1(t,A,B) - U^2(t,A,B))}{U^2(t,A,B)} \tag{14}$$

Simulation time interval

Finally, since we have an unsteady state phenomenon, we have to set a time interval for our purposes. In this case, we chose to study the phenomenon for 82 days (da), which corresponds approximately to the duration of the fall season where wood typically desorbs water in North American conditions.

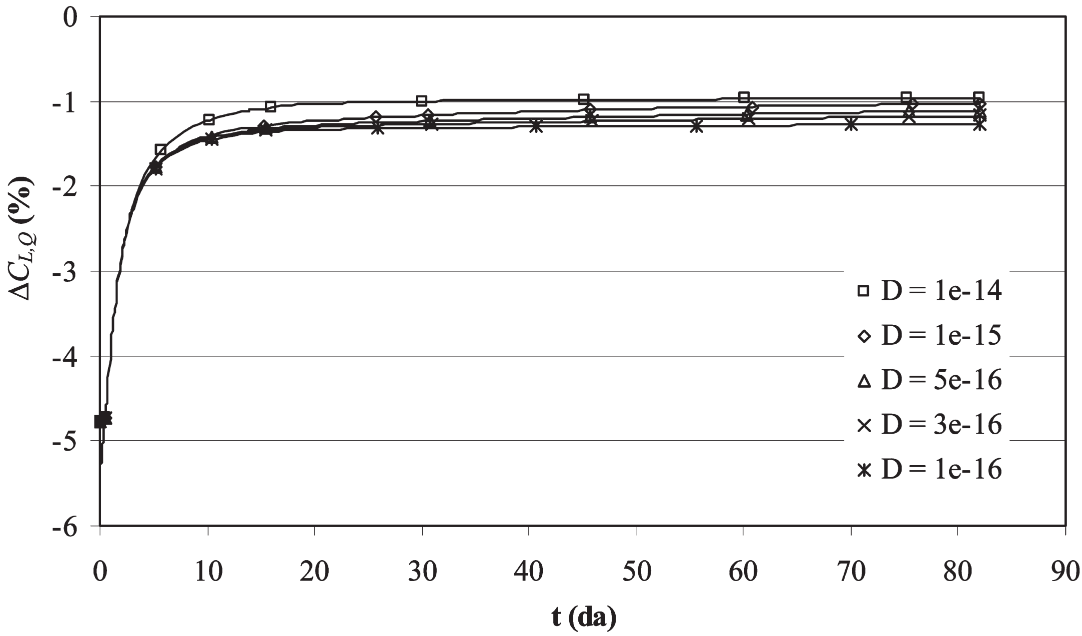
RESULTS AND DISCUSSION

Influence of the degree of interpolation of the elements in the adhesive layer

In the following numerical results, moisture content is always linearly interpolated. The interpolation of the displacements can be either linear or quadratic. Figure 4 presents the effect of the degree of interpolation of the displacements on cupping for different values of the effective diffusion coefficient. The linear and quadratic interpolations of the displacement for two meshes are compared: one with a single layer of elements in the adhesive and the other with three layers of elements. As can be seen in Figs. 4a and 4b, there is little difference between the cupping calculated by linear and quadratic interpolation ($\Delta C_{L,Q}$ defined by Eq. 14) for all the diffusion coefficients considered. There is a variation of less than 5% between the results obtained for one-layer and three-layer meshes, which indicates that in either case a linear interpolation of the displacements is sufficient. A higher degree of interpolation would not give an important gain in accuracy in the calculation of cupping.

Influence of the number of layers of elements in the adhesive layer

We have already shown that the degree of interpolation of the elements used for the calculation of the displacements plays a small role in the calculation of cupping. Therefore, we used only linear interpolation of the displacements for the results that follow. Figure 5 presents the cupping calculated for constant values of effective diffusion coefficient between 1.0×10^{-14} and 1.0×10^{-16} m^2 s^{-1} using two meshes: a coarse one with one layer of hexahedral elements in the adhesive layer and a finer one with three layers of elements (Mesh_1 and Mesh_3). The graphs presented in Fig. 6 were obtained by comparing cupping calculated using a linear interpolation of the displacements for the various meshes to cupping calculated for the reference displacements U_{Ref}, computed for each value of effective diffusion coefficient with the finer mesh (Mesh_ref). Figures 6a and b present the error in cupping calculated from Eq. 13 for one- and three-layer mesh respectively for effective diffusion coefficients varying from 1.0×10^{-16} to 1.0×10^{-14} m^2 s^{-1}. In Fig. 6c, we have plotted the error for an effective diffusion coefficient of a)



b)

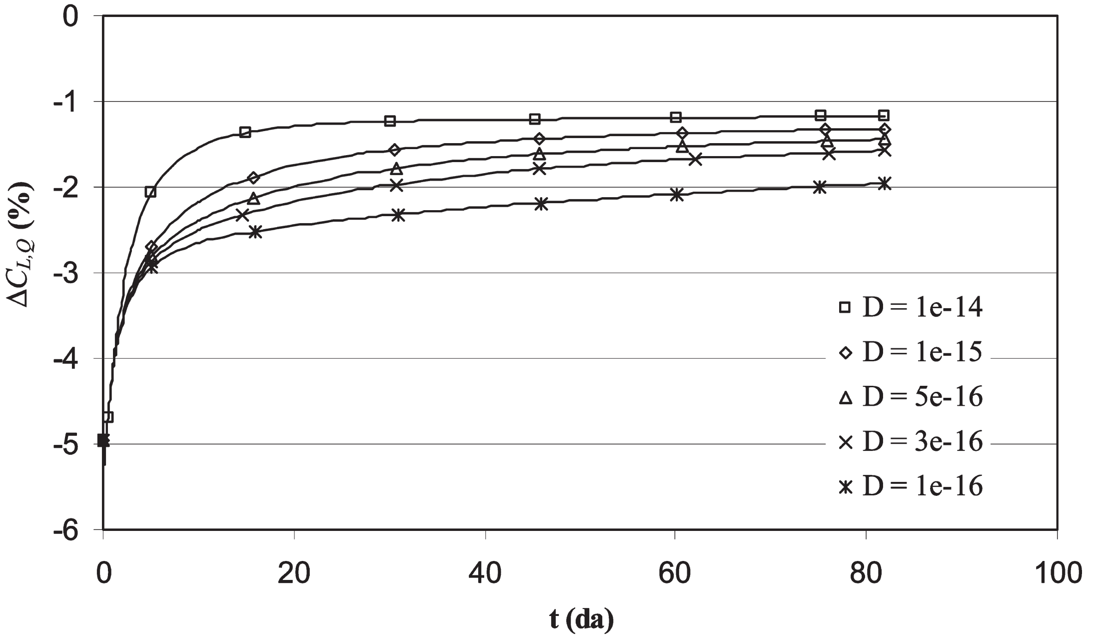


FIG. 4. Effects of the degree of interpolation of the displacements on cupping; a) variation of cupping for linear and quadratic interpolation of the displacements, one-layer mesh; b) variation in cupping for linear and quadratic interpolation of the displacements, three-layer mesh.

5.0×10^{-16} m^2 s^{-1} for three meshes: Mesh_1, Mesh_2, and Mesh_3 (see Table 2).

Figure 5 shows the important difference between the solutions obtained with a one-layer and a three-layer mesh, and the effect of small effective diffusion coefficient on cupping. Even though the problem is simplified since we assume constant value for all properties, we ob-

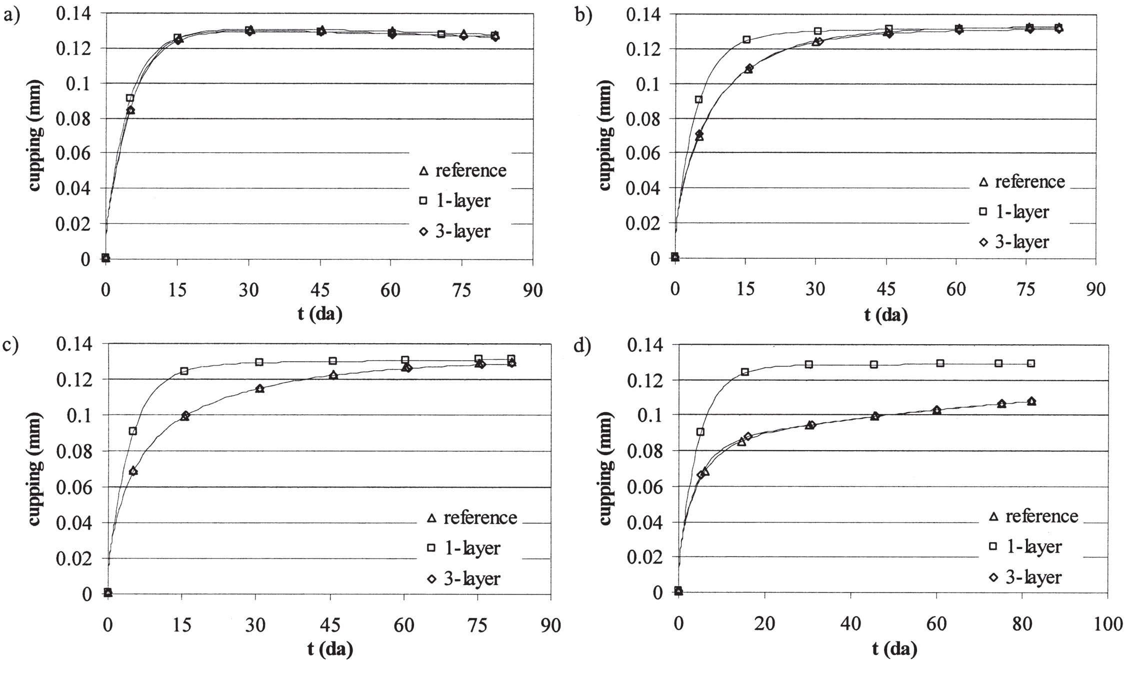


FIG. 5. Effect of the diffusion coefficient and the number of layers of elements in the adhesive on cupping for effective diffusion of a) 1×10^{-14} m^2 s^{-1}; b) 1×10^{-15} m^2 s^{-1}; c) 5×10^{-16} m^2 s^{-1}; and d) 1×10^{-16} m^2 s^{-1}.

tained important differences between the two solutions for diminishing values of the effective diffusion coefficient. As Fig. 6a shows, an important loss of accuracy was observed as the effective diffusion coefficient decreases, going from an error of less than 15% for an effective diffusion coefficient of 1.0×10^{-14} m^2 s^{-1} to an error of more than 25% for the first 20 da for an effective diffusion coefficient of 5.0×10^{-16} m^2 s^{-1}. As the effective diffusion coefficient increases, the error decreases. However, even for relatively high values of effective diffusion coefficient, we have an important gap of up to 10% (see Figs. 6a and b) between the one-layer and the three-layer solution in the first 15 da of cupping. The discrepancy between the two solutions for each value of diffusion can be explained by the poor approximation of the mechanical phenomenon in the adhesive layer in the one-layer mesh. Therefore, a fine mesh should be used in the adhesive layer for a problem with such complex physical properties.

Figures 6a, b, and c clearly show the importance of mesh density in the adhesive layer when the moisture diffusion coefficient is small. It is obvious that a mesh with three layers of elements in the adhesive layer between the surface and core layers is preferable. From the error calculated for two- and three-layer meshes in the adhesive layer (Fig. 6c) it appears that a single layer of elements oversimplifies the geometry and neglects important effects due to the mechanical properties of the adhesive layer and the drastic difference in diffusion coefficient between the adhesive layer and the wood substrate. Moreover, Fig. 6b shows that a linear interpolation has a tendency to slightly underestimate the displacements after the transition period corresponding to 30 da in all cases studied.

Linearly interpolated properties

Even though we had small values of effective diffusion coefficient in the adhesive layer, we obtained relatively different solutions which we expected to be identical for such small diffusion coefficient values. This raises questions on the

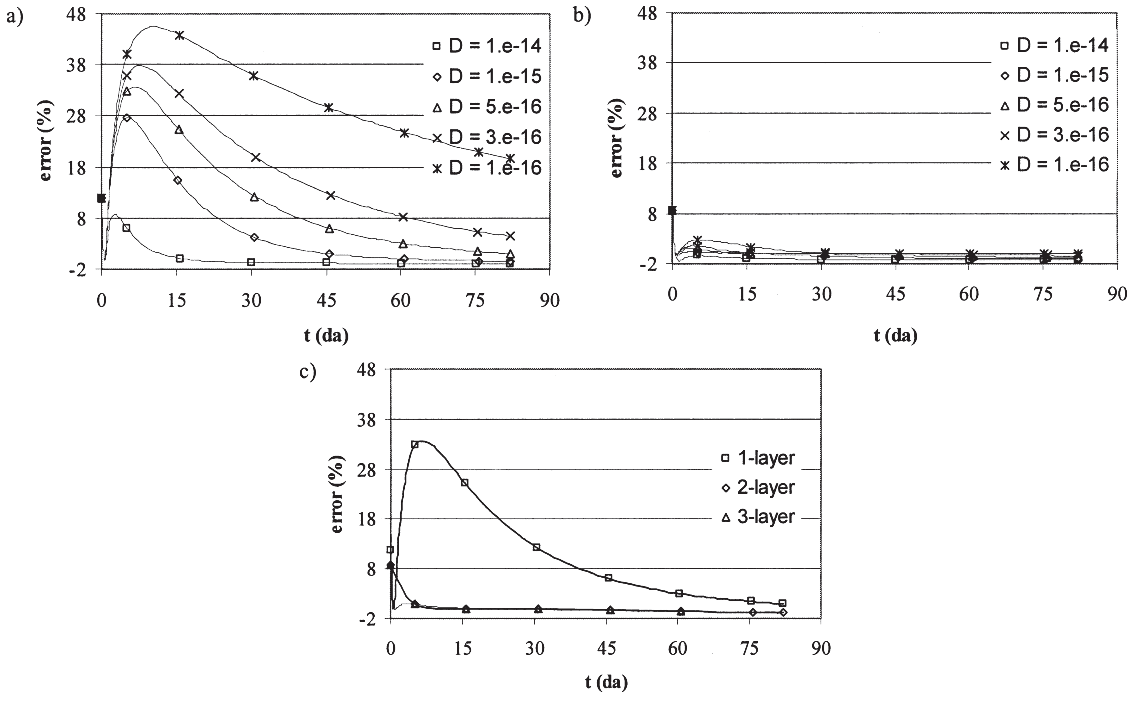


FIG. 6. Relative error based on cupping with linear interpolation of the displacements; a) for 1-layer mesh in the adhesive layer with various diffusion coefficients of the adhesive; b) for 3-layer mesh in the adhesive layer with various diffusion of the adhesive; and c) for 1-2-3 layer meshes in the adhesive layer and adhesive diffusion of 5×10^{-16} m^2 s^{-1}.

hypothesis regarding the description of the adhesive layer and lead to a more refined model for the adhesive layer. More specifically we introduced two interfaces for each adhesive layer. Those four interfaces can be viewed as transition zones between the wood and the adhesive.

Until now, only numerical aspects of the model were considered: effects of the degree of interpolation of the displacements and mesh refinement on the approximation of the cupping deformation. It was then reasonable to assume that the solution obtained with a very fine mesh corresponded to the exact solution of the original problem. In that sense the introduction of an "interpolated effective diffusion coefficient" for the adhesive layer is not a numerical consideration but a refinement of the physical model of the phenomenon. The only measure of quality of each of those models will be their ability to reproduce experimental results. For this reason validity cannot be established without a comparison with the "discrete effective diffusion coefficient" (model without a transition zone; a pure adhesive layer) and experimental results. For this, experimental results from Blanchet et al. (2005) that presents a series of data collected over a 42-da period was used.

Figure 7 presents the experimental results, the cupping obtained by Blanchet et al. (2005) using the constant diffusion model on Mesh_1 with the finite element code ABAQUS and our results obtained with Mesh_ref for the constant diffusion model and for the interpolated diffusion model. In this case the interpolated diffusion model can be easily described: For each adhesive layer we introduced layer thicknesses and effective diffusion coefficients of wood and the adhesive. A linear interpolation of the effective diffusion coefficient was then calculated for the interface layers with Eqs. (11) to (14) as described in Fig. 3. For the upper adhesive layer (Fig. 3), the effective diffusion coefficient will vary from that of white birch to that of urea-formaldehyde resin in the lower wood-adhesive interface. The UF resin effective diffusion coefficient will be used in the middle layer and then it will vary from that of UF resin to that of sugar maple in the upper wood-adhesive interface. For the lower adhesive layer a similar approach is used but the diffusion coefficient of yellow birch, UF resin and white birch are used for the interpolation of the wood-adhesive interface diffusion coefficient.

In the transient phase corresponding to the first 14 da, the ABAQUS solution obtained using a constant diffusion model with a one-layer mesh in the adhesive layer shows the most important gap with the experimental results (Fig. 7). The constant diffusion model used with Mesh_ref leads to cupping values that behave more appropriately on the first 4 da but rapidly shows the same behavior as the ABAQUS solution. The interpolated diffusion model is the best solution obtained in this transient phase. Nevertheless, it is during this phase that this solution departs the most from the experimental results. In the stabilization phase (after the first 14 da) the constant diffusion model overestimates the results by almost 20% on the last day (Fig. 7). Recalling that for this physical model, the Mesh_ref solution can be assumed to be the best for the constant diffusion model, it is clear that this model oversimplifies the physical and geometrical complexity of the adhesive layer. On the other hand, the interpolated diffusion model is accurate and shows almost no difference with the cupping experimental results as can be seen in Fig. 7. This demonstrates that the interpolated diffusion model provides a satisfactory calibration of the finite element model.

CONCLUSIONS

The main objective of this paper was to demonstrate the impact of the strategy used to model the dimensional stability of layered wood composites by the finite element method considering the effect of the adhesive layer. Mesh density, degree of interpolation of the elements and linear interpolation of the adhesive properties were considered with application to engineered wood flooring to demonstrate the critical role of the adhesive layer in the composite. The results show that the degree of interpolation of the elements used in the model has a minor effect on the calculated cupping. Therefore, the choice of a linear interpolation of the displacements is sufficient and quadratic interpolation can be avoided.

The results also show that the use of a finite element mesh with a single layer of elements in the adhesive layer can lead to significant errors.

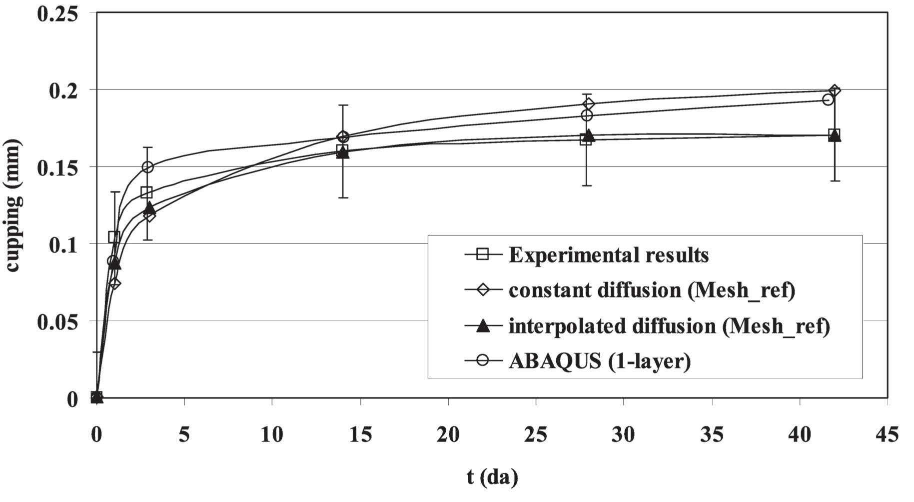


FIG. 7. Assessment of cupping obtained by various calculation approaches compared to experimental results. Error bars correspond to the standard deviation of the experimental data.

This is particularly true for low values of the adhesive effective diffusion coefficient. An important gain in accuracy is obtained when the model includes more than one layer of elements. The maximum amplitude of the calculated cupping was approximated adequately for all values of effective diffusion coefficient considered when two or three layers of elements were used in the adhesive layer with an error of less than 3%.

The work performed on the interpolation of the adhesive properties has shown that the assumption of a constant effective diffusion coefficient across the adhesive layer leads to an important gap with the experimental results for large time values corresponding to more than 14 da in our case. The interpolation of the effective diffusion coefficient based on the assumption of a linear combination of wood and adhesive effective diffusion coefficients in part of the adhesive layer model gives a good solution for the entire time interval.

From the results presented in this paper, it is clear that an accurate finite element model of the cupping of an engineering wood flooring strip must be based on a dense finite element mesh discretization of the adhesive layers and must take into consideration the presence of transition zones in the adhesive layers characterized by a combination of the wood and adhesive properties.

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