TWO-DIMENSIONAL MATERIAL MODEL FOR STRUCTURAL ANALYSIS OF DRYING WOOD AS VISCOELASTIC-MECHANOSORPTIVE-PLASTIC MATERIAL

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ABSTRACT

The paper introduces a model for the stress analysis of drying wood in the transverse (RT) plane. The model is based on an earlier uniaxial development by Hanhijärvi in 1998–2000. The novel features are the two-dimensional extension, and the description of partially recoverable mechanosorptive strain by introducing a plastic element. Thus it defines the mechanical behavior of drying wood as a viscoelastic-mechanosorptive-plastic one. Moreover, the mechanical description of the constitutive equations has been consistently reformulated on a thermodynamic basis.

The model is applicable over a wide range of temperature as well as moisture content (20°C – 120°C; nearly 0% moisture content till fiber saturation), which is achieved through applying the time-temperature-moisture equivalence principle to the evolution laws for viscoelastic strain. This principle and a moisture-change-temperature equivalence principle is applied to mechanosorptive creep in order to take into account its dependence on temperature. Mechanosorptive creep is assumed to be absent in shear.

1 INTRODUCTION

The drying of wood involves several different and interdependent physical and chemical processes, which all occur simultaneously, and may have effects on the drying quality. Among these physical processes are temperature changes, moisture content changes, shrinkage, creep, cracking, to mention only the most important ones. These interdependent processes render the enhancement and optimization of the drying process a challenging task. However, the success in this early step of the manufacture of wood products is of foremost importance since drying defects such as cracking and unwanted deformations make the material sometimes useless and practically always cause a serious loss of value.

Numerical simulation is a potent tool for optimization of the wood drying process, since it allows to combine the effect of different physical phenomena and evaluate their collective impact on the drying quality. Without numerical tools the optimization of drying schedules would have to rely strongly on trial-and-error experiments. On the other hand, neither is numerical
simulation possible without experimental work, since it requires the knowledge of the physical and mechanical properties of the wood material, whose clarification calls for much experimental work. However, once these properties are known, the numerical simulation can be used to predict the resulting drying quality in an unlimited number of different conditions.

In order to optimize drying schedules, the constitutive models have to be very realistic. In the case of wood it has turned out that this requirement obliges the use of quite sophisticated models for various phenomena. The full simulation with prediction of drying defects requires the modeling and calculation of (a) moisture and temperature changes, (b) deformations due to shrinkage and other mechanisms, as well as stresses due to these deformations, and (c) cracking due to tensile stresses. Step (a) is a necessary prerequisite of step (b), and step (b) of step (c). Of these steps, step (a) has received most attention (among others, Perré and Degiovanni, 1990; Perré and Turner, 1997; Hukka, 1996). Apparently, among these works there are sufficiently realistic and accurate models available for step (a) at different drying conditions for the basis of a working optimization of drying. Step (b) has obtained some attention (Salin, 1992; Mårtensson and Svensson, 1997; Hanhijärvi, 2000b), but experimentally proven realistic models seem to exist only for one-dimensional problems. Step (c) has received very little consideration so far.

This paper introduces a model intended to cover step (b) for two-dimensional stress analysis in the transverse plane of drying wood. The model constitutes a two-dimensional extension of the uniaxial model presented earlier by Hanhijärvi (1998, 1999, 2000a,b). Concurrently, some of the features of the earlier model have been improved and its definition reformulated in a consistent thermodynamic framework. This includes the definition of total stress-strain relations based on the Helmholtz free energy function. In addition, the evolution laws for all internal variables have been expressed as functions of the corresponding thermodynamic stresses. As a major improvement, the condition for development of irrecoverable creep deformations has been reformulated on the basis of a yield criterion. Furthermore, it has been moved from strain space into stress space, thus making it fully compatible with the modern theory of plasticity. Altogether, the model defines the mechanical behavior of drying wood as a viscoelastic-mechanosorptive-plastic one.

The model can be applied in realistic calculations of changes in drying quality linked to deformation and stress. One such application is the calculation for the tendency to form distortions of the halves, if a dried piece of wood is split after drying. This defect hampering the subsequent usage is often referred to as casehardening and is caused by uneven development of irrecoverable deformation in the center and surface layers of the wood specimen. In practice, casehardening tendency is tested using the so-called casehardening split test (CEN, 2000). Due to limited space, this paper does not contain examples. Instead, all simulations given by Ranta-Maunus, Forsén, and Tarvainen (2001) in these workshop proceedings concerning the casehardening split test have been carried out using this model.

2 MODEL FORMULATION

Modeling the mechanical behavior of wood under drying conditions requires consideration of hygroexpansion, short-term elastic response, viscoelastic creep, and mechanosorptive creep. In addition, at least at elevated or high temperature levels, substantial irreversible deformation occurs. A model of this kind has been considered by Hanhijärvi (1998, 1999, 2000a,b). It is based on an additive decomposition of strain into individual portions directly related to each of the above mentioned phenomena, and on attaching irrecoverability to the mechanosorptive portion.

In the original formulation, the model was derived as a one-dimensional one. The evolution
laws for stress and partial strains were given as rate type formulations, i.e., in terms of hypo-elastic constitutive relations. Such a formulation cannot account for coupling effects between the radial and the tangential direction. Moreover, due to the hypo-elastic formulation energy dissipation may occur during elastic load cycles violating the second law of thermodynamics.

For improvement regarding these shortcomings, the mechanical model be reformulated and given in a fully two-dimensional thermodynamic consistent hyperelastic form. Figure 1 shows the schematic illustration associated with the constitutive model. Furthermore, it defines the decomposition of the total strain $\varepsilon$. The introduced strain tensors shall be explained in detail below. The irrecoverable deformation shall be taken into account by means of evolving plastic strain accompanying the mechano sorptive creep.

The stress response is uniquely defined by the Helmholtz free energy function. It is formulated as function of temperature $T$, moisture content $u$, the total strain $\varepsilon$, the viscoelastic strain tensors $\varepsilon_{i}^{ve}$, the mechanosorptive strain tensors $\varepsilon_{j}^{ms}$, the plastic strain tensors $\varepsilon_{j}^{p}$, the isotropic hardening strains $\alpha_{j}$, and the kinematic hardening strain tensors $\beta_{j}$. Based on these variables Helmholtz free energy is expressed as

$$
\psi(T,u,\varepsilon,\varepsilon_{i}^{ve},\varepsilon_{j}^{ms},\varepsilon_{j}^{p},\alpha_{j},\beta_{j}) = \phi(T,u) + \sum_{i=1}^{n} \frac{\gamma_{i}}{2} \varepsilon_{i}^{ve} : C_{0} : \varepsilon_{i}^{ve} + \frac{1}{2} \left( \varepsilon - \varepsilon_{u} - \sum_{i=1}^{n} \varepsilon_{i}^{ve} - \sum_{j=1}^{m} \varepsilon_{j}^{ms} \right) : C_{0} : \left( \varepsilon - \varepsilon_{u} - \sum_{i=1}^{n} \varepsilon_{i}^{ve} - \sum_{j=1}^{m} \varepsilon_{j}^{ms} \right) + \sum_{j=1}^{m} \frac{1}{2} \left( \varepsilon_{j}^{ms} - \varepsilon_{j}^{p} \right) : C_{j} : \left( \varepsilon_{j}^{ms} - \varepsilon_{j}^{p} \right) + \sum_{j=1}^{m} \frac{1}{2} K \alpha_{j}^{2} + \sum_{j=1}^{m} \frac{1}{2} \beta_{j} : \mathbb{H}_{j} : \beta_{j}. \tag{1}
$$

$\phi(T,u)$ is the internal or thermal energy not specified in detail here. The last term in the first line of (1) covers the energy stored in the viscoelastic elements. The second line describes the stored energy for the short-term elastic response of the model. The terms in the third line of (1) refer to the elastic energy, the isotropic hardening energy, and the kinematic hardening energy of the mechanosorptive-plastic element, respectively.
2.1 RATE INDEPENDENT DEFORMATIONS

The model contains two rate independent modes of deformation. A third may be considered by thermal expansion but due to its minor significance it will be neglected in the present context.

The first one to be considered is the stress-free hygroexpansion. It is considered proportional to the change of the moisture content \( u \) and computed as

\[
\varepsilon^u = \alpha_u (\min(u, u_{FS}) - u_0).
\]  

(2)

\( u_0 \) is the reference moisture content at which the stress-free material has its reference geometry. \( u_{FS} \) is the fiber saturation moisture content, above which no hygroexpansion occurs. In drying simulation this stress-free reference state is always above fiber saturation. Thus \( u_0 \) can be identified as \( u_{FS} \). The moisture content is considered to be known during the mechanical analysis. Hence the hygroexpansion strain \( \varepsilon^u \) is well defined during the analysis.

The second rate-independent deformation mode is due to the short-term elastic deformation. It is instantaneous and fully recoverable. The relevant constitutive relation is obtained from (1) as

\[
\sigma := \frac{\partial \psi}{\partial \varepsilon} = C_0 : (\varepsilon - \varepsilon^u - \sum_{i=1}^{n} \varepsilon^{ve}_i - \sum_{j=1}^{m} \varepsilon^{ms}_j).
\]  

(3)

Equation (3) states that the total stress \( \sigma \) is well defined by the actual values of the strain variables. Thus no rate equation and subsequent time integration is needed for the computation of the stress tensor.

Since (3) is linear, the elastic strain can be expressed in closed form as

\[
\varepsilon^{e}_0 = (\varepsilon - \varepsilon^u - \sum_{i=1}^{n} \varepsilon^{ve}_i - \sum_{j=1}^{m} \varepsilon^{ms}_j) = C_0^{-1} : \sigma.
\]  

(4)

\( C_0^{-1} \) is often referred to as elastic compliance \( J_0 \). However, we will keep the \( C_0^{-1} \) in order to distinguish between the previous one-dimensional formulation and the present fully two-dimensional one.

2.2 VISCOELASTIC CREEP

Over time wood exhibits additional deformations denoted as creep. Creep in general is considered to be a stress driven deformation rate. In wood one observes further acceleration of the strain rate due to changes of the moisture content referred to as mechanosorptive creep (see e.g. Ranta-Maunus, 1975; Hanhijärvi, 1995). Creep at constant moisture content is considered fully recoverable after sufficient time. Thus it is modeled as viscoelastic behavior. Figure 2 shows a characteristic viscoelastic element. It is the so-called Kelvin element as common in literature. The thermodynamic driving stress for the \( i \)th element can be obtained from (1) as

\[
\sigma_i^{ve} := - \frac{\partial \psi}{\partial \varepsilon_i^{ve}} = C_0 : (\varepsilon - \varepsilon^u - \sum_{i=1}^{n} \varepsilon^{ve}_i - \sum_{j=1}^{m} \varepsilon^{ms}_j) - \gamma_i C_0 : \varepsilon^{ve}_i = \sigma - \gamma_i C_0 : \varepsilon^{ve}_i.
\]  

(5)

\( \gamma_i \) is a dimensionless stiffness fraction associated with the \( i \)th Kelvin element. The rate equation for a linear viscoelastic damper can be expressed in terms of the driving stress given in (5) as

\[
\dot{\varepsilon}_i^{ve} = \frac{1}{\tau_i} (\gamma_i C_0)^{-1} : \sigma_i^{ve}.
\]  

(6)
Expressing $\sigma_{ve}^i$ by means of (5) yields the differential equation for $\varepsilon_{ve}^i$ as follows

$$\dot{\varepsilon}_{ve}^i + \frac{1}{\tau_i} \varepsilon_{ve}^i = \frac{1}{\tau_i^\prime} C_0^{-1} : \sigma. \tag{7}$$

The $n$ equations (7), $i = 1, \ldots, n$, together with (3) define a coupled system of first order differential equations for the viscoelastic strain tensors $\varepsilon_{ve}^i$.

### 2.3 MECHANOSORPTIVE CREEP WITH IRRECOVERABLE DEFORMATIONS

Changing moisture content increases the creep rate of wood, which is known as the mechanosorptive effect. At high temperatures as obtained in kiln drying, irrecoverable deformations also occur (Hanhijärvi, 2000a). The present model is based on a mechanosorptive Kelvin type element (Hunt, 1989; Salin, 1992; Toratti, 1992). In order to account for irrecoverable deformations, this element is altered by introducing a hardening type plasticity element. The related rheological model is shown in Figure 3. Consideration of irrecoverable strain in the

The original model based the evolution of irrecoverable strain on a one-dimensional relation between irrecoverable strain and the evolution of mechanosorptive strain. The same idea is reformulated utilizing modern multidimensional theory of plasticity based on an orthotropic yield condition. Plastic strain is used for the description of irrecoverable deformations. This enables the use of thermodynamic consistent hyperelastic laws even for mechanosorptive and plastic deformations. In harmony with the underlying uniaxial model, a combined linear isotropic and linear kinematic hardening law will be applied.
The thermodynamic driving stresses of the mechanosorptive-plastic part of the model are obtained as the stresses energetically conjugated to the involved partial strain tensors. Based on Helmholtz free energy function defined in (1) these thermodynamic stresses are obtained as follows

\[ \sigma^p_j := -\frac{\partial \psi}{\partial \varepsilon^p_j} = C_j : (\varepsilon^{ms}_j - \varepsilon^p_j), \]  

\[ \sigma^\alpha_j := -\frac{\partial \psi}{\partial \alpha_j} = K_j \alpha_j \]  

\[ \sigma^\beta_j := -\frac{\partial \psi}{\partial \beta_j} = \mathbb{H}_j : \beta_j. \]  

\[ \sigma^p_j \] is the driving stress for the plastic, i.e., irrecoverable deformations, \( \sigma^\alpha_j \) and \( \sigma^\beta_j \) are the isotropic and kinematic hardening stress, respectively. Finally, the driving stress for the mechanosorptive damper, \( \sigma^{ms}_j \), is obtained as

\[ \sigma^{ms}_j := -\frac{\partial \psi}{\partial \varepsilon^{ms}_j} = C_0 : (\varepsilon - \varepsilon^u - \sum_{i=1}^n \varepsilon_i^v - \sum_{j=1}^m \varepsilon^{ms}_j) - C_j : (\varepsilon^{ms}_j - \varepsilon^p_j) = \sigma - \sigma^p_j. \]

Evolution of plastic deformations is controlled by an orthotropic yield condition for each of the mechanosorptive-plastic elements. The considered yield functions \( f_j \) are formulated as

\[ f_j(\sigma^p_j, \sigma^\alpha_j, \sigma^\beta_j) = \frac{1}{2} (\sigma^p_j + \sigma^\beta_j) : A_j : (\sigma^p_j + \sigma^\beta_j) - \frac{1}{2} (\sigma_{Y,j} - \sigma^\alpha_j)^2. \]

The tensor \( A_j \) is considered to be independent of the state of stress and deformation. \( \sigma_{Y,j} \) is the initial equivalent yield stress. A positive definite tensor \( A_j \) defines an elliptic surface in stress space, a positive semi-definite \( A_j \) defines a cylindrical surface with an elliptical cross-section. The definition of \( A_j \) will be given in Appendix A.

The evolution equations for plastic loading are taken to be those for standard associative plasticity (see, e.g., Lubliner, 1990; Simo and Hughes, 1998). These rate equations are obtained as

\[ \dot{\varepsilon}^p_j := \dot{\gamma} \frac{\partial f_j}{\partial \sigma^p_j} = \dot{\gamma} \tilde{\varepsilon}_j, \]

\[ \dot{\alpha}_j := \dot{\gamma} \frac{\partial f_j}{\partial \sigma^\alpha_j} = \dot{\gamma} r^\alpha_j \text{ and} \]

\[ \dot{\beta}_j := \dot{\gamma} \frac{\partial f_j}{\partial \sigma^\beta_j} = \dot{\gamma} \tilde{\beta}_j, \]

where \( \dot{\gamma} \) is the consistency parameter and the flow directions \( \tilde{\varepsilon}_j \) and \( r^\alpha_j \) are defined by

\[ \tilde{\varepsilon}_j := A_j : (\sigma^p_j + \sigma^\beta_j) \quad \text{and} \quad r^\alpha_j := (\sigma_{Y,j} - \sigma^\alpha_j). \]

The set of governing equations is completed by means of the Kuhn-Tucker conditions

\[ f_j \leq 0, \quad \dot{\gamma} \geq 0, \quad \dot{\gamma} f_j = 0 \]

and the consistency condition

\[ \dot{\gamma} f_j = 0. \]
The Kuhn-Tucker conditions are also referred to as loading-unloading conditions. They state that for $f_j < 0$ the consistency parameter $\dot{\gamma}$ has to be zero. Alternatively, $f_j$ has to be zero for $\dot{\gamma} > 0$. This is identical to the following statement:

The plastic variables $\epsilon_p^j$, $\alpha_j$, and $\beta_j$ do not change in case of elastic loading or unloading ($f_j < 0$). In case of plastic loading ($f_j = 0$), the consistency parameter $\dot{\gamma}$ is a positive scalar to be determined from the consistency condition (18).

The multi-dimensional evolution equation for the mechanosorptive strain $\epsilon_{ms}^j$ can be defined as a function of the thermodynamic driving stress $\sigma_{ms}^j$. The functional relation is considered to be similar to that found for the viscoelastic damper given in (6) but scaled by the absolute value of the moisture content change rate $\dot{u}$ normalized by $u_{FS}$. It is obtained as

$$\epsilon_{ms}^j = \left( \frac{\dot{u}}{u_{FS}} \right) \left( \mu_j^{-1} \sigma_{ms}^j \right).$$

In (19), $\dot{u}$ is the moisture content change rate, $\mu_j$ is the characteristic moisture change (comparable to a characteristic creep time in viscoelasticity) and $\mu_j^{-1}$ is the tensor of mechanosorptive creep compliance.

The constitutive equations (8)–(11), the evolution equations (13)–(15) (flow rule and hardening rules) and (19) (mechanosorptive creep rate), the loading-unloading conditions (17), and the consistency condition (18) define a complete set of nonlinear partial differential equations. Their solution is obtained by means of a numerical time integration scheme.

2.4 TEMPERATURE AND MOISTURE DEPENDENCE OF THE EVOLUTION EQUATIONS

The effect of the actual temperature and the actual moisture content on the viscoelastic and mechanosorptive creep rates is of crucial importance in drying simulations. As utilized by Hanhijärvi (1999, 2000b), the time-temperature-moisture equivalence principle is applied to the described model. Moreover, a moisture change-temperature equivalence principle is considered for the mechanosorptive creep activating moisture change.

These principles are implemented by introduction of the shift factors

$$a = k_T(T - T_{ref}) + k_u(u - u_{ref})$$

and

$$b = k_{T,ms}(T - T_{ref}^{ms}).$$

$k_T$, $k_u$, and $k_{T,ms}$ are material parameters, $T_{ref}$, $T_{ref}^{ms}$, and $u_{ref}$ are the reference temperatures and the reference moisture content, respectively, at which the so-called master creep curves are defined (Hanhijärvi, 1999, 2000b).

Then, the time differentials in the evolution laws (6), (7), (13)–(15), and (19), as well as the moisture content differential in (19) have to be replaced by

$$dt \rightarrow e^a dt \quad \text{and} \quad du \rightarrow e^b du.$$
3 SUMMARY AND CONCLUSIONS

Within this paper we introduced a model for the stress analysis of drying wood in the transverse (RT) plane. The model is based on an earlier uniaxial development by Hanhijärvi (1998, 1999, 2000a,b). The limitations of the original work were the uniaxial formulation, and a hypoelastic incremental implementation.

The novel features or the presented model are the two-dimensional extension, the description of partially irrecoverable mechanosorptive strain by introducing a plastic element, and a hyperelastic formulation consistent with the laws of thermodynamics. Thus we described the mechanical behavior of drying wood as a viscoelastic-mechanosorptive-plastic one. The paper covers the derivation of all equations of state and evolution laws defining a complete set of partial differential equations forming the constitutive model. An efficient strategy based on a numerical time integration algorithm is required for the solution of these equations. This has not been given in this paper but will be presented in an upcoming publication.

The model is applicable over a wide range of temperature as well as moisture content. The given parameter set is intended to cover temperatures from 20° C to 120° C, and moisture contents from nearly 0% to fiber saturation. This has been achieved through application of the time-temperature-moisture equivalence principle to the evolution laws for viscoelastic strain and by applying this principle and a moisture change-temperature equivalence principle to mechanosorptive creep. Mechanosorptive creep is assumed to be absent in shear.

Applications for this constitutive model can be found in various practical problems, such as optimization of drying schedules or the simulation of the deformation behavior during post-drying quality control (e.g., casehardening split test) and manufacturing processes.

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APPENDIX

A PARAMETERS AND PARAMETER TENSORS (SCOTS PINE)

The inverse of the elastic stiffness tensor $C_0$ is defined as

$$C_0^{-1} = \begin{bmatrix}
\frac{1}{E_R} & -\frac{\nu_{RT}}{E_R} & 0 \\
-\frac{\nu_{RT}}{E_R} & \frac{1}{E_T} & 0 \\
0 & 0 & \frac{1}{G_{RT}}
\end{bmatrix} \quad (A.1)$$

where $E_R$ and $E_T$ are the Young’s moduli in $R$ and $T$ direction, respectively, $G_{RT}$ is the shear modulus and $\nu_{RT}$ the Poisson’s ratio in the $RT$-plane.

The stiffness fractions $\gamma_i$ for the viscoelastic elements are obtained from the fractional compliances $J_0$ and $J_i$, $i = 1, \ldots, 21$, as given in (Hanhijärvi, 1999) by means of the relation

$$\gamma_i := \frac{J_0}{J_i}. \quad (A.2)$$

The characteristic retardation times $\tau_i$ are identical to those published in that paper.
The mechanosorptive-plastic model requires the definition of the plastic interaction tensor $A_j$, the yield strengths $\sigma_{Y,j}$ (chosen to be $\sigma_{T,Y,j}$), the isotropic and the kinematic hardening moduli $K_j$ and $H_j$, respectively, the partial stiffness tensors $C_j$, the mechanosorptive compliances $E_{ms}^j$, and the characteristic moisture changes $\mu_j$. The scalar parameters are given in Table 1. In the second column if this table, $\varepsilon_{uT,\text{max}}$ is the maximal hygroexpansion strain in tangential direction which is caused by a moisture change from zero to the fiber saturation moisture content. The tensors $C_j$ and $E_{ms}^j$ are derived from a dimensionless reference tensor $E_{0}^{-1}$:

$$E_{0}^{-1} = \begin{bmatrix} k^2 & -k^2 & 0 \\ -k^2 & 1 & 0 \\ 0 & 0 & 10^{-6} \end{bmatrix}, \quad k^2 = 0.48. \quad (A.3)$$

The actual stiffness tensors are then obtained by scaling as

$$C_j = E_{ms}^j = \frac{1}{J_{0,j} + J_{1,j} \min(u,u_{FS}) - u_{FS}} E_0. \quad (A.4)$$

The compliances $J_{0,j}$ and $J_{1,j}$ are given in Table 1. The plastic hardening moduli are functions of the moisture content as well. They are defined as

$$K_j = \frac{\chi}{J_{0,j} + 3J_{1,j} \min(u,u_{FS}) - u_{FS}} \quad (A.5)$$

and

$$H_j = \frac{1 - \chi}{J_{0,j} + 3J_{1,j} \min(u,u_{FS}) - u_{FS}} E_0. \quad (A.6)$$

$\chi$ is the isotropic fraction of the total hardening. For the computations presented in (Ranta-Maunus et al., 2001), a value of $\chi = 1/2$ has been chosen. The compliances $J_{0,j}$ and $J_{1,j}$ are identical to those used in (A.4) and given in Table 1.

The plastic interaction tensors $A_j$ are defined as

$$A_j = \begin{bmatrix} k_j^2 & -k_j^2 & 0 \\ -k_j^2 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad k_j^2 := \left(\frac{\sigma_{T,Y,j}}{\sigma_{Y,j}}\right)^2 = 0.48. \quad (A.7)$$

Parameters for the time-temperature-moisture equivalence principle have been taken from (Hanhijärvi, 1999), those for the moisture change-temperature equivalence principle are newly introduced. Based on the exponential description (20)–(22) they are obtained as

$$k_T = 0.11 \cdot \ln(10) \quad k_u = 43 \cdot \ln(10) \quad k_{T,\text{ms}} = 0.05$$

$$T_{\text{ref}} = 373.15 \, \text{K} \quad u_{\text{ref}} = 0.15 \quad T_{\text{ms ref}} = 368.15 \, \text{K} \quad (A.8)$$