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Transient multi-Fickian hygro-mechanical analysis of wood

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ABSTRACT

A new hygro-mechanically coupled material model to simulate the structural behaviour of wooden objects below the fibre saturation area is introduced. A multi-Fickian moisture transport model is coupled to a moisture-dependent, orthotropic, elasto-plastic, mechanical material model. It is applied to wooden specimens at simulated climate changes of the ambient air and analysed by the finite element method with respect to internal stresses due to swelling and shrinkage. A simulation of the ductile failure of a swelling pressure experiment is presented. The results are compared to different, widely used moisture transport models. The importance of capturing water vapour diffusion inside the object and its emissivity at the objects' surface are discussed.

1. Introduction

The performance and durability of wooden structures are strongly influenced by the exposition to the surrounding climate conditions, since a change in moisture content m in wood could lead to cracking, plastic deformations or other irreversible damages. Especially fast humidity changes and large m-gradients over the cross-section lead to large internal stresses. Furthermore, the material behaviour changes dramatically with changing m, e.g. in hygro-expansion (swelling and shrinkage), compliance, strength and mechano-sorptive creeping [23,29,30]. Modelling of m-dependent mechanical characteristics and transport of moisture beneath the fibre saturation area (FSA) are necessary for a suitable numerical simulation of e.g. stresses by means of the finite element method (FEM). Within this paper, a new hygro-mechanically coupled material model is presented, which combines recent material models in both, mechanical and moisture transport characterisation. The goal of this paper is the comparison of different transient moisture transport models and the assessment of their reliability within hygro-mechanical structural analyses. An objective recommendation for the application range of the considered moisture transfer models for hygro-mechanical investigations is targeted.

The transport of moisture below FSA is described by three different phenomena, which are water vapour emissivity at the surface to the ambient air, and diffusion and sorption inside the porous material (see Figs. 1 and 2). Diffusion is modelled, in analogy to Fourier's law of heat conduction, by Fick's law (e.g. [7,17]). The assumption of modelling the moisture transport by only one diffusion equation based on Fick's law is suitable for the simulation of steady-state transport processes.

Moisture flux $\boldsymbol{J}_m$ is proportional to the gradient of m. The diffusion coefficient $\boldsymbol{D}$ and the density in absolute dry conditions $\varrho_0 = \varrho(m=0)$ serve as constants of proportionality

$$\boldsymbol{J}_m = -\varrho_0\,\boldsymbol{D}\,\nabla m. \tag{1}$$

Using the transient form of Fick's law

$$\frac{\partial m}{\partial t} = \nabla(\boldsymbol{D}\nabla m) \tag{2}$$

leads to discrepancies of the simulations compared to experimental results, often denoted as "non-Fickian" behaviour, e.g. [2,51]. The larger the gradient $\partial m/\partial t$ and the larger m, the more pronounced are the deviations. By applying Fick's law to the driving potential of m, moisture transport is homogenised to only one global, smeared phase. However, beneath the FSA (standard application range), moisture diffusion in the porous medium wood has to be divided into the two parallel processes of water vapour diffusion in wood pores with its concentration c_v and the bound water diffusion in cell walls corresponding to c_b

$$\frac{\partial c_b}{\partial t} = \nabla(\boldsymbol{D}_b\nabla c_b) + \dot{c}, \tag{3}$$

$$\frac{\partial c_v}{\partial t} = \nabla(\boldsymbol{D}_v\nabla c_v) - \dot{c}. \tag{4}$$

Both processes interact via the sorption term as sorption rate $\dot{c} = \partial c/\partial t$, which is the velocity of the increase of bound water concentration, e.g. [15,51] (Fig. 1). The velocity of bound water diffusion is much slower than vapour transport and, thus, neglected in

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Nomenclature

$\boldsymbol{J}$	flux	σ, f	stress, strength
ϱ_0, ϱ_m	density in absolute dry conditions, density at moisture content m	ε	strain
D	diffusion coefficient	E, G, ν	Young's modulus, shear modulus, Poisson's ratio
m	moisture content	r, t, l	local material directions: radial, tangential, longitudinal
c	moisture concentration	β	differential shrinkage coefficient
RH	relative humidity of air	$\boldsymbol{B_u}, \boldsymbol{B_m}$	operator matrix
p, p_v	pressure, pressure of water vapour	$\boldsymbol{K}$	tangent matrix
T	temperature	$\underline{\underline{\boldsymbol{C}}}$	material tensor
R	gas constant	$\boldsymbol{x}$	global coordinates
M_{H_2O}	molar mass of water	N	shape function
t	time	MC, EMC	moisture content (global), equilibrium moisture content
$\boldsymbol{n}$	surface normal vector	ξ	reduction factor of D_v
k_v	surface emission coefficient of water vapour	H	reaction rate
φ	pore volume fraction (porosity)	$(\,)_b$	bound water
V, A	volume, area	$(\,)_v$	water vapour
u	displacement	$\dot{(\,)}$	derivative with respect to time
F	force	$\nabla(\,)$	gradient, derivative with respect to space

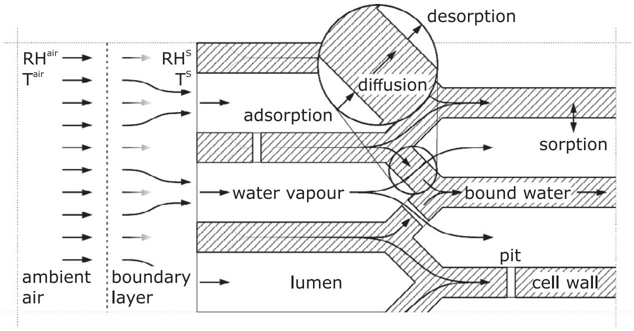

Fig. 1. Moisture transport from ambient air over boundary layer to the surface and inside the wood as parallel water vapour transfer in the lumens and bound water diffusion in the cell wall, coupled by sorption.

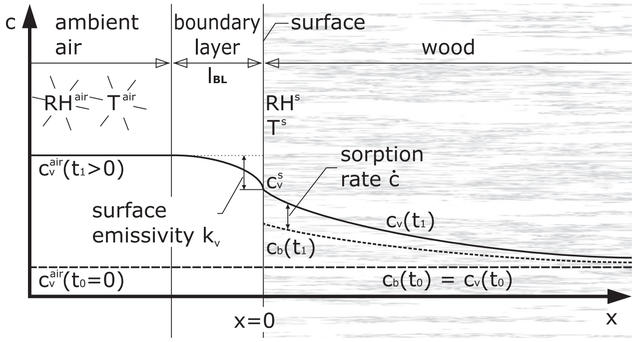

Fig. 2. Distribution of equivalent water vapour concentration c_v, corresponding to p_v in the lumens (cf. Eq. (6)) and current c_b in the cell wall during increase of ambient relative humidity RH^{air}.

[20]. A comprehensive approach regarding the coupled multi-phase diffusion and energy conservation law in terms of heat flux is presented in [9]. The sorption function, describing the dependence of equilibrium moisture content (EMC) on the ambient air's RH and temperature T, yields a hysteresis, with the condensed process of humidity increase entitled as adsorption, laying under the declining path of desorption [23]. To consider the water vapour exchange with the ambient air, denoted as surface emissivity (SE), the moisture flux perpendicular to the surface is defined as

$$\boldsymbol{n}\boldsymbol{J}_b = 0, \quad \boldsymbol{n}\boldsymbol{J}_v = k_v\left(p_v^s - p_v^{air}\right) \tag{5}$$

with the surface normal vector $\boldsymbol{n}$, the SE coefficient (SEC) k_v and the potential of water vapour pressures of the body's surface minus those of the ambient air. Several models for the description of emission of water vapour on the surface with respect to clear and varnished wood are discussed in [30].

The transient and hygro-mechanical modelling by a multi-Fick'ian diffusion approach is still not state of the art. The most general and comprehensive model for moisture-dependent elastic and failure characteristics, that is known to the authors, is developed by Saft/Reichel and Kaliske [30–32,36,37], considering moisture-dependent, three-dimensional orthotropic material characteristics, coupled to a single-Fick'ian diffusion approach. Both, mechanical and diffusion equations are solved at the same time in an economical way by a monolithic solution algorithm in a fully coupled hygro-mechanical numerical analysis. The alternative is a sequential or staggered solution. An implementation in a commercial FE-software is presented, e.g. by Fortino et al. in [11]. Most recent developments in multi-Fick'ian moisture transport modelling are published by Frandsen [14], Hozjan and Svensson [20] and Eitelberger [9]. The only known publications on multi-Fick'ian hygro-mechanical analysis are presented by Fortino et al. in [12] accompanied by an analysis of a beam cross-section by Hradil et al. in [21]. The models are implemented into user subroutines, including also models for mechanical long-term behaviour and temperature-dependency, but excluding failure, and they are based on a sequential thermo-hygro-mechanical coupling. Since it is not a fully coupled approach and only the mechanical quantities are updated after the calculation of the diffusion equation system, the paper at hand presents new opportunities for the structural analysis of wooden objects. The model in the paper at hand is based on the comprehensive former work of Saft/reichel and Kaliske for the mechanical part and extended to multi-Fick'ian diffusion by a monolithic solution algorithm.

2. Constitutive hygro-mechanical model for wood

Within this section, the material models for a realistic simulation of the material behaviour are introduced. They can be