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Hygro-mechanically coupled modelling of creep in wooden structures, Part II: Influence of moisture content

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ABSTRACT

In the first part of this publication, a modelling approach for the simulation of linear viscoelastic, non-linear viscoelastic–viscoplastic behaviour of wooden structures under consideration of creep failure is derived. In the framework of the paper at hand, which represents the second part, this formulation is enhanced by means of the consideration of hygro-mechanical coupling. With respect to the multiphysical characteristics of wood, mechano-sorptive effects due to simultaneous mechanical loading and moisture changes are captured in addition to the influence of the magnitude of MC on mechanically induced creep. In contrast to the majority of approaches, the separability of mechanically induced and mechano-sorptive deformation components is not presumed, which matches with recent experimental observations. The entire approach is applied for the investigation of the stress-level-dependent time to failure of beams subjected to different constant climates and climate changes basing on experimental investigations. Finally, the formulation is used to study the structural behaviour of a hygro-mechanically loaded face staggered joint.

1. Introduction

Wooden structures subjected to mechanical and hygro-mechanical long-term loading exhibit complex multiphysical features. Depending on the applied stress level (SL = ratio of applied mechanical loading and short-term strength), the long-term behaviour of wood may be characterised as linear viscoelastic, respectively non-linear viscoelastic–viscoplastic, already found for pure mechanical loading and constant moisture content MC. After a sufficiently long loading-time, respectively at a sufficiently high SL, creep failure occurs. Analogously to the short-term material behaviour (see e.g. Saft and Kaliske, 2011, 2013), the mechanically induced creep of wood is influenced by the magnitude m of MC. In addition, so-called mechano-sorptive effects are observed, when MC changes during a simultaneous mechanical loading, which leads to an overproportional increase of creep deformations.

With respect to modelling, a large variety of approaches is available, that describe particular features of the hygro-mechanical long-term characteristics of wood. Nevertheless, no formulation is known to the authors, which captures the entire spectrum of aspects. Thus, a modelling approach for the use within the framework of the Finite Element Method (FEM) is introduced in the scope of the work at hand, considering the

- cylindrically anisotropic material behaviour of wood,
- non-linear stress–strain-relationship, respectively strain–time-relationship depending on SL,
- occurrence of creep failure,
- influence of MC on the creep behaviour and
- mechano-sorptive effects.

For the sake of clarity, the different material features of wood as well as the state of the art with respect to modelling are presented in the particular sections.

The paper at hand is the second part of the entire work on the presented topic. Part I deals with the anisotropic structural behaviour of wood subjected to pure mechanical loading without consideration of MC (Reichel and Kaliske, submitted for publication). Using a standard-solid body-model in serial combination with a Bingham-element, linear viscoelastic and non-linear viscoelastic–vis coplastic behaviour are distinguished depending on SL (see Fig. 1). Creep failure is considered by means of the concept of strain-energy density.

The mechanical model introduced in Part I is improved in the framework of the paper at hand by the consideration of the

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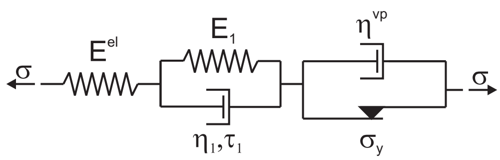

Fig. 1. Extended standard-solid body-model (one-dimensional).

influence of constant and varying MC by means of a hygro-mechanical coupling. Analogously to the short-term behaviour (see Saft and Kaliske, 2011), origin of loading (mechanical, hygrical, combined) and structural behaviour (linear and non-linear viscoelastic, viscoplastic) are distinguished with respect to the identification and determination of deformation components. That means, the additive combination of viscoelastic, viscoplastic, hygro-expansional and mechano-sorptive creep components, in contrast to the majority of modelling approaches (see e.g. Becker, 2002; Hanhijärvi and Mackenzie-Helnwein, 2003; Mackenzie-Helnwein and Hanhijärvi, 2003; Mohager and Toratti, 1993; Toratti, 1992; Chassagne et al., 2006, compare state of the art presented in Part I), is not a priori assumed. As it will be explained subsequently, this matches to experimental observations (see Section 2.4).

The approach introduced in Part I of the work and improved in the framework of the paper at hand may be characterised as phenomenological and pertains to the macroscopic scale. As extensively stated in Part I, the utilisation of as few as possible physically motivated input properties is aimed at. Rather than the exact approximation of few particular creep curves, the goal is the development of a general model with a wide spectrum of applications.

2. Creep-modell for hygro-mechanically loaded wooden structures

2.1. Basic constitutive equations

The approaches introduced subsequently are characterised as continuum-macro-mechanical models and are formulated for small strains. Due to the natural cylindrical anisotropy of wood, the material directions radial (r), tangential (t) and longitudinal (l) have to be distinguished (see Fig. 2). For use within the framework of the FEM, the displacements $\boldsymbol{u}$ for the three directions as well as the moisture content m are defined as degrees of freedom for each node. Since all aspects of mechanics and moisture transfer are solved at once, a monolithic solution procedure is applied in contrast to a staggered algorithm (compare Saft and Kaliske, 2011, 2013).

In addition to the weak form of the balance of momentum required for the description of the mechanical behaviour (see also Part I)

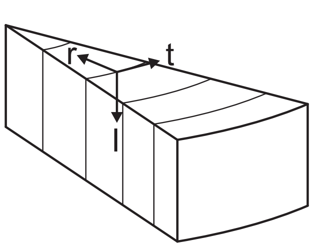

Fig. 2. Cylindrically anisotropic material directions of wood.

$$G_u = \int_B \delta \nabla \boldsymbol{u}\, \underline{\boldsymbol{\sigma}}\, dV - \int_B \delta \boldsymbol{u}\, \rho_0\, \boldsymbol{b}\, dV - \int_{\partial B} \delta \boldsymbol{u}\, \boldsymbol{t}\, dA = 0, \tag{1}$$

the weak form of the transient moisture transport problem is derived using the principle of virtual displacements with the test function δm

$$G_m = \int_B \delta m\, \rho_0\, \dot{m}\, dV - \int_B \delta \nabla m\, \boldsymbol{q}_m\, dV - \int_{\partial B} \delta m\, q_m^n\, dA = 0, \tag{2}$$

with $\underline{\boldsymbol{\sigma}}$: mechanical stresses, $\boldsymbol{b}$: body forces, $\boldsymbol{t}$: tractions at the boundaries ∂B of the studied body B, ρ_0: density in absolute dry conditions, $\dot{m}$: rate of MC, $\boldsymbol{q}_m$: body moisture flux, q_m^n: moisture flux across the surface.

Due to the non-linear characteristics of Eqs. (1) and (2), they are linearised for the use within the framework of the FEM

$$G_{u,lin} = G_u(\delta \boldsymbol{u}, \boldsymbol{u}, m) + \Delta G_u(\delta \boldsymbol{u}, \boldsymbol{u}, m; \Delta \boldsymbol{u}, \Delta m), \tag{3}$$

$$G_{m,lin} = G_m(\delta m, \boldsymbol{u}, m) + \Delta G_m(\delta m, \boldsymbol{u}, m; \Delta \boldsymbol{u}, \Delta m). \tag{4}$$

From the second terms of Eqs. (3) and (4), the components $\boldsymbol{K}_{i,j}$ of the tangent matrix for the spatially discretised body are achieved. One arrives at the system of equations

$$\begin{bmatrix} \boldsymbol{K}_{F,u} & \boldsymbol{K}_{F,m} \\ \boldsymbol{K}_{Q,u} & K_{Q,m} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{u} \\ m \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}^{apl} \\ 0 \end{bmatrix} - \begin{bmatrix} \boldsymbol{F}^{nr} \\ Q \end{bmatrix}, \tag{5}$$

with: $\boldsymbol{F}^{nr}$: vector of internal nodal forces, Q: nodal moisture flow, $\boldsymbol{F}^{apl}$: vector of external mechanical loadings (no equivalent in moisture transport). For each finite element, the required terms are defined as

$$\boldsymbol{F}^{nr} = \int_V \boldsymbol{B}_u^T : \underline{\boldsymbol{\sigma}}\, dV, \tag{6}$$

$$Q = \int_V \boldsymbol{B}_m^T \cdot \boldsymbol{q}_m\, dV \tag{7}$$

and

$$\boldsymbol{K}_{F,u} = \frac{\partial \boldsymbol{F}^{nr}}{\partial \boldsymbol{u}} = \int_V \boldsymbol{B}_u^T : \frac{\partial \underline{\boldsymbol{\sigma}}}{\partial \boldsymbol{u}}\, dV = \int_V \boldsymbol{B}_u^T : \underline{\underline{\boldsymbol{C}}} : \boldsymbol{B}_u\, dV, \tag{8}$$

$$K_{Q,m} = \frac{\partial Q}{\partial m} = \int_V \boldsymbol{B}_m^T \cdot \frac{\partial \boldsymbol{q}_m}{\partial m}\, dV, \tag{9}$$

$$\boldsymbol{K}_{F,m} = \frac{\partial \boldsymbol{F}^{nr}}{\partial m} = \int_V \boldsymbol{B}_u^T : \frac{\partial \underline{\boldsymbol{\sigma}}}{\partial m}\, dV, \tag{10}$$

with $\boldsymbol{B}_u, \boldsymbol{B}_m$: operator matrices for structural, respectively transport problem, $\underline{\underline{\boldsymbol{C}}}$: material tensor.

Due to the insufficient availability of experimental data and the comparatively low impact (e.g. hygro-elastic effect, see Simpson, 1971), the influence of the deformation state on moisture transfer is not considered. Thus, the remaining component of the tangent matrix is defined as

$$\boldsymbol{K}_{Q,u} = \frac{\partial Q}{\partial \boldsymbol{u}} = 0. \tag{11}$$

In the framework of the subsequent investigations, Voigt's notation is used for the representation of tensors.

2.2. Modelling of moisture transport

With respect to the numerical simulation of moisture transport in wood, a variety of publications is available. Nevertheless, for the sake of completeness, the applied model is briefly described in the following.