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Hygro-mechanically coupled modelling of creep in wooden structures, Part I: Mechanics

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ABSTRACT

In the paper at hand, a modelling approach for the simulation of the anisotropic long-term behaviour of wooden structures subjected to mechanical loading at constant moisture content for the use within the framework of the Finite Element Method is presented. Using a standard-solid body-model in serial combination with a Bingham-element allows for the differentiation between linear viscoelastic and non-linear viscoelastic–viscoplastic behaviour with respect to the applied stress level. Creep failure is considered by means of the concept of strain-energy density. Due to the cylindrical anisotropy of wood, the four material properties required for the description of the creep behaviour are determined depending on material direction and loading type (tension, compression, shear) by means of the re-calculation of experimental results. Finally the approach is applied to the re-calculation of two test-series in bending and to the analysis of a face staggered joint.

The paper at hand is the first part of a more complex model and deals with the mechanical long-term behaviour of wood. In the second part, the hygro-mechanical coupling is covered with respect to the consideration of the influence of moisture content on mechanically induced creep and mechano-sorptive effects caused by simultaneous mechanical loading and moisture changes.

1. Introduction

The time-dependent behaviour of wooden structures subjected to mechanical and hygro-mechanical long-term loading is characterised by complex physical processes. Even at constant moisture content (MC), wood exhibits a non-linear stress–strain-relationship depending on the stress level (SL), the ratio of applied load and short-term strength. Furthermore, the stress–strain-relationship is influenced by the amount of (constant) MC. In terms of simultaneous mechanical loading and moisture changes, in addition to the hygro-expansion (swelling and shrinkage), mechano-sorptive effects are observed, which significantly scale up the creep deformations.

Although there exists a large variety of approaches for the simulation of particular features of the complex multi-physical behaviour, no model is known to the authors, which entirely captures the mentioned phenomena. Hence, a novel modelling approach under consideration of 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 constant MC on the creep behaviour and
- mechano-sorptive effects

for the use within the framework of the Finite Element Method (FEM) is developed. The model may be characterised as phenomenological and refers to the macroscopic scale. A basic idea in the course of model development is the use of as few as possible physically motivated input properties (in contrast to pure model parameters) to describe the long-term behaviour of wood under consideration of failure processes. The fitting of the model to particular experimental creep curves is explicitly not aspired. Rather, the development of a general model with wide spectrum of application is aimed at.

The achievement of the final goal requires a structured proceeding with respect to model development. To capture the before mentioned features, several modelling steps are necessary, which build upon each other. Thus, step n is the precondition for step $n+1$ with respect to modelling and algorithmic implementation as well as with respect to the material properties to be identified

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Table 1
Steps of development with respect to modelling of the long-term behaviour of hygro-mechanically loaded wooden structures.

	Additionally captured material characteristic	SL	MC
1.	Linear viscoelastic creep	$< LL$	Constant
2.	Non-linear viscoelastic-viscoplastic creep	$> LL$	Constant
3.	Creep failure	$> LL$	Constant
4.	Influence of constant MC	All	Constant
5.	Mechano-sorptive effect	All	Changing

by means of recalculating experimental results. In Table 1, the steps in development are shown. In the framework of the paper at hand, the numerical modelling of the purely mechanical behaviour is dealt with. The influence of MC as well as mechano-sorptive effects are described in the second part of this publication. 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.

2. Creep-model for wooden structures

2.1. Material characterisation

Viscoelastic creep of wood may be defined as the time-dependent increase of deformations at constant mechanical and hygrical loading. At this, as mentioned above, a non-linear relationship with respect to SL is observed. Nevertheless, in literature, wood is often characterised as linear viscoelastic (e.g. Schniewind and Barrett, 1972) with constant ratio of stress and time-dependent strain. Thus, the principle of superposition is valid and the order of the application of particular loading steps is insignificant for the final result.

However, the assumption of linear viscoelasticity is only valid for wood, as long as SL stays below a specific value, the so-called limit of linearity (LL). When the applied SL exceeds LL, a disproportional increase of creep deformations is observed in comparison to the linear viscoelastic range. Furthermore, the principle of superposition is not longer valid. At high values of SL, creep failure occurs. Following the majority of references (e.g. Becker, 2002; Hunt, 1989), no permanent deformations develop for loadings below LL – creep deformations are entirely reversible. In contrast, when SL exceeds LL, irreversible deformations arise. For this reason, LL is sometimes denoted as yield limit and defined as the maximum SL with a creep velocity tending to zero and the deformations tending to a final state (Gressel, 1983). Thus, the existence of a creep limit is assumed in this case, which is also confirmed in other publications (e.g. Becker, 2002; Hunt, 1989).

Considering the creep velocity, three phases of wood creep may be distinguished (see Fig. 1)

- primary creep: linear viscoelastic with decreasing creep velocity,
- secondary creep: non-linear viscoelastic with constant creep velocity,
- tertiary creep: non-linear viscoelastic with increasing creep velocity followed by creep failure.

At this, as to be seen in Fig. 1, occurrence and temporal extent of the creep phases depend on SL.

So far, the qualitative characteristics of wood creep at constant MC are roughly described. With respect to quantification, creep deformations are influenced by several factors. Except SL, the type and direction of loading significantly influences the amount of creep deformations. In this respect, creep deformations due to compressive loading at the same SL are considerably larger than those due to tensile loading. Creep resulting from shear and torsional loading, again, is more pronounced than compressive creep. Concerning the direction of loading, creep due to loading perpendicular to the grain of wood is much more distinctive than creep due to loading parallel to the grain, when the same SL is applied. More information on this topic can e.g. be found in Becker (2002), Gressel (1983) and Ranta-Maunus (1993).

With respect to modelling and description of the time-dependent behaviour of wood, in addition to the phenomenological approaches introduced subsequently, several structurally based models have been developed. In contrast to the phenomenological models, which merely characterise the reaction of the material to a particular loading, structural models are based on microscopic, sub-microscopic, respectively molecular features of the material's structure. Since those approaches are not of further interest for the following investigations, they will not be explained in the framework of the paper at hand, but rather, for the sake of completeness, mentioned giving related references:

- theory of hydrogen bond breaking and remaking, e.g. Bodig and Jayne (1993) and Hanhijärvi (1997),
- theory of polymer reaction, e.g. Gressel (1983), Hanhijärvi (1997) and van der Put (1989),
- theory of physical aging, e.g. Hunt and Gril (1996),
- lenticular trellis model, e.g. Hanhijärvi (1997), Boyd (1982) and
- theory of slip plane formation in compression, e.g. Hanhijärvi (1997) and Hoffmeyer and Davidson (1989).

2.2. Basic constitutive equations

The modelling approach introduced subsequently can be classified as continuum-macro-mechanical model and is formulated for small strains, since this assumption is sufficient with respect to the majority of applications in wood structural engineering. Resulting from the natural structure of wood, the cylindrically anisotropic material directions radial (r), tangential (t) and longitudinal (l) have to be distinguished (see Fig. 2). The transformation from global coordinates to local material directions is explained in detail in Resch and Kaliske (2005).

The material model is developed for use within the framework of the FEM. Since, in this first part of the entire work, the influence of MC is disregarded, the displacements $\boldsymbol{u}$ for the three directions are used as degrees of freedom for each node. On the basis of the static balance of momentum, the weak form of equilibrium is derived utilising the principle of virtual displacements with the test function $\delta\boldsymbol{u}$

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

with $\underline{\boldsymbol{\sigma}}$: mechanical stresses, $\boldsymbol{b}$: body forces and $\boldsymbol{t}$: tractions at the boundaries ∂B of the investigated body B. Since Eq. (1) is a non-linear function of the field variable $\boldsymbol{u}$, it has to be consistently linearised for the use within the FEM

$$G_{u,lin} = G_u(\delta\boldsymbol{u},\boldsymbol{u}) + \Delta G_u(\delta\boldsymbol{u},\boldsymbol{u};\Delta\boldsymbol{u}). \tag{2}$$

After subsequent spatial discretisation into particular elements, one arrives at

$$\boldsymbol{K}_{F,u}\cdot\boldsymbol{u} = \boldsymbol{F}^{apl} - \boldsymbol{F}^{nr}. \tag{3}$$

At this, $\boldsymbol{K}_{F,u}$ is the tangent matrix obtained from the second term of Eq. (2), $\boldsymbol{F}^{nr}$ are the internal nodal forces and $\boldsymbol{F}^{apl}$ the applied external mechanical loading

$$\boldsymbol{F}^{nr} = \int_V \boldsymbol{B}_u^T : \underline{\boldsymbol{\sigma}}\,dV, \tag{4}$$