Computers and Structures 89 (2011) 2460–2470

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Numerical simulation of the ductile failure of mechanically and moisture loaded wooden structures

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ARTICLE INFO

Article history:
Received 18 October 2010
Accepted 15 June 2011
Available online 19 July 2011

Keywords:
Wood mechanics
Plasticity
Moisture diffusion
Hygro-mechanical coupling

ABSTRACT

Wooden structures are always exposed to climate changes. Since all its mechanical properties are moisture-dependent, the influence of moisture content on the mechanical behavior has to be considered for a realistic simulation. A hygro-mechanically coupled macroscopic material model for use within the framework of the FEM is introduced. Thereby, moisture diffusion, hygro-expansion and moisture-dependent linear elastic behavior and ductile failure are covered. The tangent matrix required for the Newton procedure is derived completely. The model is applied to the simulation of experiments for the determination of the swelling pressure of spruce.

1. Introduction

Besides mechanical loads, wooden constructions are always exposed to changes of the ambient atmosphere, such as relative humidity (RH) and temperature. The natural biopolymer wood responds to this by means of changes of moisture content and wood temperature. Both of these quantities obviously influence the mechanical behavior of wooden structures, since phenomena like swelling, shrinkage and thermal expansion exist. Within the limits of natural room temperature, the influence of moisture content strongly prevails. Since this temperature range is sufficient for the object of research described subsequently, the model that is presented in this paper focuses on the coupling of mechanical behavior and moisture transport. Furthermore, time-dependent long-term effects like visco-elastic creep, relaxation and mechano-sorptive creep are not considered within this work. Since the model is aimed to be applicable to wooden engineering structures, continuum macro-mechanical models are used.

Due to its specific structure, wood follows the physical laws of capillary porous bodies. The macro- as well as the micro-system are able to absorb moisture when the structure is exposed to water. This is caused by the huge inner surface. Thus, the material behaves hygroscopic, since moisture is absorbed at increasing RH (adsorption) and emitted at decreasing RH (desorption). The wood moisture content that arises at one RH is called equilibrium moisture content (ECM) and depends on whether the equilibrium is reached by adsorption or by desorption (sorption-hysteresis). When relative humidity is equal to 100%, the resulting wood moisture content is denoted as fiber saturation area (FSA). Depending on the wood species, FSA lies between 22% and 35% for middle European wood [1]. The FSA is characterised by the complete saturation of the cell walls' micro-capillaries. Besides RH, which is the main factor, amongst others temperature, density, mechanical loading and pretreatment influence ECM and FSA. A multitude of models has been developed and published that aim to describe the sorption behavior of wood. Not all of those models are physically motivated, in fact, many of them are purely empirical equations that approximate experimental results (e.g. [2,3]). An overview on typical sorption models as well as further information on the sorption behavior of wood can amongst others be found in [4,5].

All material properties that describe the mechanical behavior of wooden structures are more or less dependent on moisture content. Since the content of this paper focuses on the modeling of ductile failure, the influence of moisture content on the stiffness and strength properties is of interest. When moisture content increases, the quantities of stiffness and strength properties initially slightly increase and then decrease with different magnitude until FSA is reached. Though, the influence of moisture content on strength properties is much more distinctive then on stiffness properties. In many studies, experimental investigations on the moisture dependency of particular mechanical properties are published. Often, the measured data is additionally approximated by regression functions. Nevertheless, a significant lack of knowledge is found in this field, since no publication is providing a complete

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doi:10.1016/j.compstruc.2011.06.004

set of moisture dependent mechanical properties, not even for one wood species. A complete set of moisture dependent stiffness properties of spruce wood has been published by Neuhaus [6] by means of a moisture dependent compliance matrix. In many publications, the moisture dependency of mechanical properties is simplified as being linear (e.g. [1,7,8]). When the moisture content exceeds FSA, the dependence of mechanical properties on moisture content vanishes. Thus, the change of the slope of the moisture content-mechanical parameter-dependency is another means to define the FSA. Since the slope does not change suddenly but gradually decreases, the traditional denotation "fiber saturation point" is more and more replaced by "fiber saturation area" [4,5].

Besides the moisture dependency of the mechanical properties, moisture-induced volume changes have to be considered for the realistic simulation of the short-term hygro-mechanical behavior of wood. Due to the absorption of moisture into the micro-capillaries, the cell walls expand until FSA is reached. This leads to swelling of the wood structure. When FSA is exceeded, no more swelling is observed. The amount of length-change (or strain) due to swelling and shrinkage significantly depends on the material direction and the wood species. In [9], the mean shrinkage value for European wood species, which means the amount of length-change due to change of moisture content from 0% to FSA, is given for the longitudinal direction at 0.4%, the radial direction at 4.3% and the tangential direction at 8.2%. Although the moisture content-swelling strain-relationship is nonlinear, for practical reasons it is mostly taken as linear for moisture contents below FSA. This assumption is sufficiently right, since the nonlinearity is caused by the changes of sorption behavior when FSA is reached. For this reason, it is possible to specify differential shrinkage values which represent the percentage of length-change caused by one percent change of moisture content. Studies on free swelling and shrinkage can e.g. be found in [10,12]. When free length-change is restrained, considerable swelling stresses occur, which can form a large part of the overall mechanical stresses. In e.g. [11,13,14,35], experimental investigations on the swelling pressure of wood can be found.

Within the scope of hygro-mechanical wood behavior, merely the influence of the moisture content on the mechanical characteristics of wood is introduced so far. To realistically gather all wood-water-relationships, the influence of the loading state on moisture sorption has to be considered as well. The ECM decreases at constant RH and temperature, when a structure is pressure loaded at the same time. If tensile loading occurs, ECM increases. This effect is caused by the change of pore volume and is especially distinctive in tangential direction, because of the large shrinkage value [1,4,5]. In [4], this phenomenon is denoted as hygro-elastic effect. Furthermore, an approach for the quantification of the effect is deduced. That has been developed by Barkas in 1949 (cited in [4]). Compared to the experimental results of Simpson [15], the theoretical values are always too large so that the influence of the loading state is overestimated. Simpson also discovered, that the influence of tensile loading on ECM is larger then the influence of compressive loading. Nevertheless, since the influence of loading state on the sorption behavior is small within the range of small strains and nearly no quantitative information is available, hygro-elastic effects are neglected for the following considerations.

Compared to other construction materials like for example steel, concrete or rubber, the number of publications on material models for the simulation of wood is small. Especially hygro-mechanically coupled models for the simulation of the short-term behavior are rare. Within some investigations, the influence of moisture content on the elastic behavior is considered by means of moisture-depended stiffness-properties and the consideration of shrinkage strains [16–18]. However, all of those publications are aimed at the simulation of the long-term behavior of wood. In some papers, irreversible deformations due to creep effects are considered by the introduction of a plastic strain part [19,20]. In [21], a hygro-mechanically coupled nonlinear-elastic material model is published which considers moisture hysteresis and stress- and moisture-dependency of the stiffness properties as well as the stress-dependency of shrinkage and sorption. Mechanical behavior and moisture transfer are coupled by means of different coupling coefficients that have to be fitted with the help of experiments. At least, the definition of shrinkage as a stress-dependent property has to be reconsidered, since compressive loading acts as a restraint for swelling and the resulting hygro-expansional strains are a combination of free swelling and the "mechanical response" to the partly restraint. Publications on coupled numerical models for the simulation of the short-term ductile failure of mechanically and moisture loaded wooden structures are not known. The material models used as basis for the coupled formulation are introduced in the subsequent sections.

The goal of the paper at hand is the introduction of a macroscopic three-dimensional constitutive model for the simulation of ductile failure of mechanically and moisture loaded wooden structures. This offers the possibility to more realistically simulate the characteristics of wood and with that to understand better the processes within a wooden structure since experimental investigations do not allow to look inside. In the subsequent sections, the constitutive models that are used for the simulations of purely mechanical behavior, moisture transfer and hygro-mechanical coupling are introduced, at which the focus lies on the detailed description of the hygro-mechanical coupling. Thereafter, the presented model is applied to the simulation of longitudinal swelling stresses according to the experimental investigations of Krauss [35].

2. Constitutive hygro-mechanical model for wood

In the following, material models for the realistic simulation of the material behavior of wood are introduced. All of them can be classified as continuum-macro-mechanical models and are formulated for small strains. This assumption is sufficient for the bulk of applications in structural engineering of wood. Furthermore, the models were developed for the simulation of spruce wood (picea abies) but can easily be adapted to the simulation of other wood types. For all models, the material directions radial (r), tangential (t) and longitudinal (l) are defined (see Fig. 1). These result from the cylindrical anisotropy of wood. The transformation from global to local material directions is published in detail in [22].

The material models that will be introduced below are developed for the use within the framework of the Finite Element Method (FEM). As degrees of freedom of every node, the displacements ($\boldsymbol{u}$) for the three directions as well as the moisture content (m) are defined. All subproblems of mechanics and moisture transfer are solved at once in one system of equations. Thus, we have a mono-

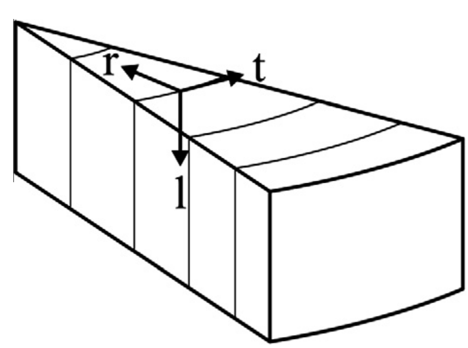

Fig. 1. Cylindrical anisotropic material directions of wood.