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Upscaling of Self-actuated Wooden Bilayers

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Micro Abstract
The hygroscopic and rotational-orthotropic material wood can be used for generating bending motions of cross-ply structures in response to moisture content variations. We investigate the general behavior and the upscaling of such self-actuated wood bilayer structures by a combined experimental and simulation study using Finite element models, including the mechanical behavior of wood and the adhesive bonding. The aim is the manufacturing of complex curved wood parts by self-actuation.

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1 Introduction

As a hygroscopic material, wood is able to convert moisture content changes into changes of its dimensions, known as swelling and shrinkage. Its moisture content strives at equilibrating with the ambient relative air humidity. Further, wood represents a rotational-orthotropic material where three distinct anatomical directions can be distinguished. The longitudinal direction (L) represents the grain direction with strong mechanical properties and low swelling and shrinkage. The radial (R) and tangential (T) directions are perpendicular to the grain and generally show much lower mechanical properties but much higher swelling than along grain direction.

Using the natural anisotropy in mechanical properties and in hygroscopicity of wood, bilayered structures capable of actuation can be designed. Inspirations in nature, such as the opening of the pine cone by bending of the scales [2], or the opening of the Bauhinia seed pods by twisting [1] while drying, led the way to applications with wood. Different deformation patterns result from different orientation configurations of one layer to another. Bending, twist, or mixed-modes are possible. We will focus here on bending with bilayer structures composed of two cross-ply layers.

Wooden bilayers are well-suited for large-scale industrial applications, as demonstrated in [7]. The challenge is to the predict of the actuation given a specific configuration and moisture content change. Simple linear-elastic analytical models such as the Timoshenko formula [8], resulting from an equilibrium formulation on a system of two Euler-Bernoulli beams, show to be valid in the case of layer thicknesses smaller than 4 mm [7]. Considering thicker layers, we expect additional wood-specific deformation mechanisms such as plasticity, viscoelasticity, and mechanosorption to take place. In previous work from the authors in [5], a 3D constitutive material model for wood was developed, implemented in an Finite Element Method (FEM) framework, and verified. We use this model in the case of the hardwood species European beech (*Fagus sylvatica*) and the softwood species Norway spruce (*Picea abies*) to analyze upscaling-specific effects in wooden bilayer structures using FEM simulations.

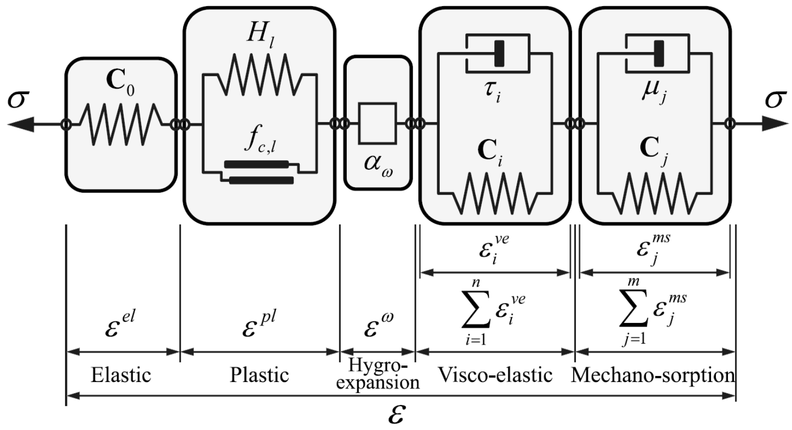

Figure 1. Constitutive material model for wood, a schematic illustration [5].

2 Materials and Methods

2.1 Wood-specific Material Model

The used constitutive material model for both beech and spruce was developed and presented in [5]. The 3D orthotropic material model for wood considers all wood-specific deformation mechanisms, i.e. elastic deformation, irrecoverable plastic deformation, swelling and shrinkage (also called hygro-expansion), viscoelastic creep, and mechanosorption. All material parameters were defined as moisture-dependent as wood generally shows strong moisture- and time-dependent behavior. In terms of numerical implementation, the approach of additive decomposition of the total strain was chosen and integrated as user material subroutine (UMAT) within a commercial Finite Element software-environment. Figure 1 schematically illustrates the principle of the used rheological model for wood. Generally, a total strain tensor $\boldsymbol{\varepsilon}$ is defined that can be decomposed into the single contributions:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{el} + \boldsymbol{\varepsilon}^{pl} + \boldsymbol{\varepsilon}^{\omega} + \sum_{i=1}^{n} \boldsymbol{\varepsilon}_i^{ve} + \sum_{j=1}^{m} \boldsymbol{\varepsilon}_j^{ms}.$$

The used material parameters and a detailed description of their experimental determination can be found in [6]. Additionally, a model for three common wood adhesives in timber industry, i.e. polyurethane (PUR), melamine resin (MUF), and phenol resorcinol (PRF) adhesives, was developed and implemented in the same UMAT as the softwood and hardwood model [4], [3].

2.2 Bilayer Model Setup

Two configurations of different layer-thicknesses were modeled with a constant ratio of 1:2. The thinner layer acting as passive (or resistive) layer, having its L-orientation in beam length-axis, was modeled as 5 mm thick in the first and 10 mm thick in the second configuration. The thicker active (or actuation-driving) layer was modeled such that its R-orientation was aligned with the beam length-axis. It is 10 mm thick for the first and 20 mm thick for the second configuration. The model length and width were chosen as 600 mm and 80 mm, respectively. The models were chosen as initially flat at 20% wood moisture content, corresponding to a storage at a 85% relative air humidity (r.h.) climate. A constant continuous drying to 14% wood moisture content ω was applied within a time-step of 500 hours, corresponding to a drying and reaching of mass-constancy in a 65% r.h. climate. A thin, 0.1 mm thick 1-component PUR layer was modeled as adhesive between the two wood layers and kept at 3% material moisture content. Figure 2 illustrates the described model setup, showing the initial flat state and the deformed state with curvature κ. The procedure was applied for the wood species beech and spruce. Each of the models was ran with all deformation modes active first, then respectively plasticity, mechanosorption, and viscoelasticity were switched off, until only a hygroelastic deformation mode was considered. This procedure allows for an analysis of relevance of the different deformation modes on the resulting bilayer curvature.

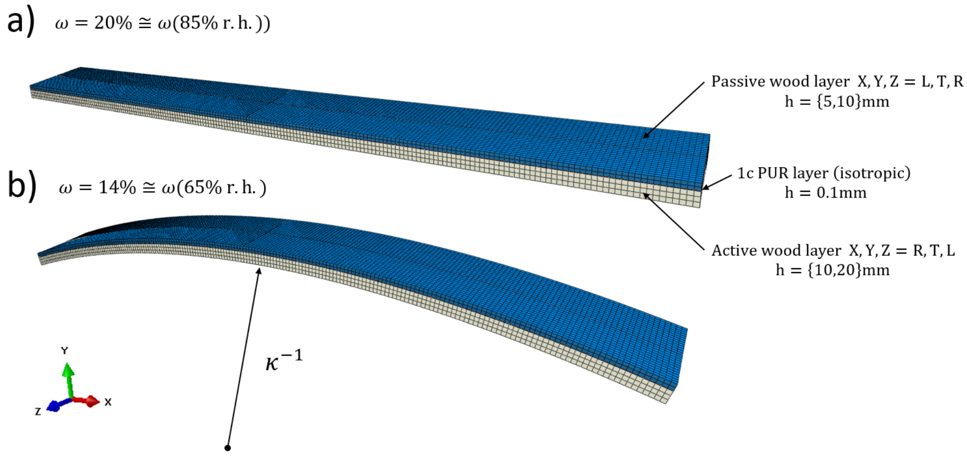

Figure 2. a) Modeled bilayer structure, adhesive layer between two wood layers, initial state at wood moisture content of $\omega = 20\%$. b) Deformed state after drying, reaching a curvature of κ at $\omega = 14\%$.

3 Results and Discussion

Figure 3 shows the calculated curvatures for the four different bilayer models for the applied 500 hour drying process. All curvatures develop nearly linear over moisture content. Surprisingly, it can be recognized that the hygroelastic-only calculations seem to perfectly match the calculations where all deformation modes were activated for all four models, disregarding of layer-thicknesses or wood species. A precise effect-study of the different deformation modes on the resulting end-curvatures of the bilayers is given in Table 1. Viscoelasticity seems to not affect κ at all, the possible explanation being that creep-relaxation in both layers cancel out. The stiffer but thinner passive layer being under high bending-stresses seems to creep in an equilibrated manner to the thicker but less stiff active layer under mostly tension. The same principle could also explain the weak influence of the other deformation modes, i.e. mechanosorption and plasticity. In the case of beech, mechanosorption seems to diminish curvature for both thickness-configurations (-0.50% for 05/10 mm and -2.32% for 10/20 mm), whereas it increases it for the thinner spruce model (1.04%). Plasticity effects on κ can not be observed for the spruce models and for the thin beech model, whereas in the case of the thicker beech model (10/20 mm), plasticity seems to increase the curvature (1.81%), corresponding to higher energy dissipation in the passive layer than in the active layer.

Mode	**Effect on κ** Beech 05/10	Beech 10/20	Spruce 05/10	Spruce 10/20
Hygroelasticity	100.52%	100.53%	98.91%	100.77%
Viscoelasticity	-0.02%	-0.02%	0.05%	0.06%
Mechanosorption	-0.50%	-2.32%	1.04%	-0.83%
Plasticity	0.00%	1.81%	0.00%	0.01%
Total	100%	100%	100%	100%

Table 1. Effect-study of deformation mechanisms on bilayer end-curvature.

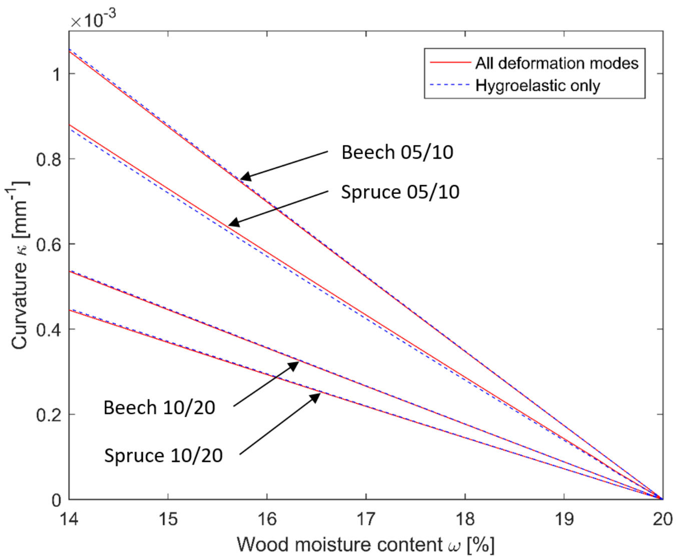

Figure 3. Model results. Calculated curvatures over 500 hour drying step for four models.

4 Conclusions

An effect-study of different wood-specific deformation contributions on resulting bilayer curvatures after drying was conducted on FE-models of beech and spruce with two different layer-thickness configurations. It was seen that in all cases, complex deformation modes such as plasticity, viscoelasticity, or mechanosorption had little to no effect on bilayer curvature between wood moisture contents of 20 to 14%. Dissipative effects in the single layers showed to overall cancel-out due to the thin and stronger passive layer (wood grain direction) being under higher stresses than the thicker but weak active layer (perpendicular to grain direction). For the accurate curvature prediction of thick bilayers (layer-thickness up to 20 mm) a hygroelastic-only model, as is e.g. the 2D Timoshenko function, may prove sufficient.

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