Wood and wood products – linking multiscale analysis and structural numerical simulations

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Summary:

Wood is one of the oldest construction materials known to man. Over thousands of years it has been mainly used in a craft framework, so that current design rules are often based on experience and tradition. The scientific knowledge about the material behavior is often surprisingly poor. In order to exploit the extraordinary ecological potential of the material and to enable its structural use also in an industrial framework, improved material models are required. Modern timber construction is characterized by increasing demand of two- and three dimensional bearing components. Dimensioning and design of such sophisticated structures require powerful material models for numerical simulation tools such as the finite element (FE) method. Moreover, the large variability of the macroscopic material properties has to be understood and suitably described to prevent exaggerated safety factors resulting in an uneconomic over-dimensioning of timber members.

In order to understand the variability of macroscopic properties of **solid wood** and the underlying phenomena and to suitably describe them in material models, the hierarchical microstructure of the material has to be considered. At sufficiently small length scales universal constituents common to all wood species and samples as well as universal building principles can be identified. Namely, lignin, hemicellulose, cellulose, and water are such tissue-independent universal constituents with common mechanical properties across the diverse wood species at the molecular level. They build up cell walls resembling fiber-reinforced composites, which are arranged according to a honeycomb pattern.
A mathematical formulation of the univeral building principles results in a multiscale micromechanical model for wood which links microstructural characteristics of individual wood samples to macroscopic mechanical characteristics of these samples. Homogenization techniques are employed for this purpose. In particular, the composite structure of the wood cell wall motivates application of continuum micromechanics for estimation of its elastic properties. At the cellular scale, plate-type bending and shear deformations dominate the mechanical behavior, which are more suitably represented by a unit cell approach.
Formulation of the localization problem corresponding to the multiscale homogenization scheme allows determination of strain estimates at smaller length scales for given macroscopic loading. Quadratic strain averages (so-called 'second-order estimates') over microstructural components turned out to suitably characterize strain peaks in these components. Combination of estimates for such averages with microscale failure criteria delivers predictions for macroscopic elastic limit states. As for solid wood, experimental investigations indicate that wood failure is initiated by shear failure of lignin in the wood cell wall. This can be suitably described mathematically by means of a von Mises-failure criterion.
The multiscale models for wood stiffness and elastic limit states are validated by comparison of model predictions for stiffness and strength properties with corresponding experimental results across a multitude of different wood species and different samples. The small errors of the model predictions underline the predictive capabilities of the micromechanical model. For example, the mean prediction errors for the elastic moduli and the shear moduli related to the three principal material directions *L*, *R*, and *T* are each below 10 %.

The capability of micromechanical approaches to link macroscopic properties to microstructural characteristics renders such approaches also very appealing for wood products. In this paper, models for a representative of strand-based products, namely the **Veneer Strand Board** (VSB), as well as for a representative of solid wood-based products, namely the DendroLight panel, are shown. VSB consists of large-area, flat and slender strands with uniform strand shape and dimensions and is typically built up of several layers with different strand orientations. The high-quality strand material results in increased stiffness and strength of the board compared to conventional strand and veneer-based panels. The multiscale model for VSB spans three scales of observations: the strand material, a homogeneous board layer, and the multi-layer board. Continuum micromechanics is applied first in order to estimate the elastic properties of a homogeneous board layer from the stiffness of the strands, their shapes, and their orientations. In the second step, effective stiffness properties of a multi-layer panel are determined by means of classical lamination theory. Thereby, the stacking sequence, the orientation of the principal material directions of the single layers, and the density variation across the board thickness are taken into account. Model validation is again based on independent experiments. Results of tests on specially produced homogeneous boards as well as inhomogeneous boards with a well defined vertical density distribution show a good agreement with corresponding model predictions. This underlines the capability of the model for estimation of the stiffness of strand-based engineered wood products from microstructural features and renders it a powerful tool for parameter studies and product optimization.

DendroLight is a three-layered lightweight panel consisting of thin outer layers of solid wood or particle board and a middle layer made up of small cells with webs inclined by an angle of 45° facing alternatively upwards and downwards. The periodic microstructure motivates application of the unit cell method for prediction of the mechanical behavior of this panel. As for plane periodic media, macroscopic unit curvature states are considered as loadings of the unit cell in addition to macroscopic unit strain states. In particular, effective in-plane stiffnesses and bending stiffnesses are obtained. For the purpose of model validation, several panel samples were produced by hand and tested in tension. The experimental results show a good agreement with corresponding stiffness predictions by the model. The multiscale model has already been successfully employed for product characterization and further product development.

Since wood is a naturally grown material, it shows growth irregularities, primarily knots and site-related defects. **Knots** result in a pronounced reduction of stiffness and strength of wooden boards. Due to the highly anisotropic material behavior of wood, the influence of the grain orientation on the mechanical properties of a board is very pronounced and results in high variability in strength and stiffness of structural timber. The latter is a major difficulty in solid wood utilization and brings about the need for wood grading. This motivates investigation of the effects of knots on the mechanical behavior of boards by means of physically-based numerical simulations. In particular, the FE method is combined with sophisticated models for the fiber course and the material behavior. For the description of the local fiber course around a knot, a mathematical algorithm based on a fluid flow approach and polynomial functions fitted to the annual ring course is employed. The algorithm is evaluated at every integration point of the FE model and yields the local three-dimensional fiber orientation there. With respect to the mechanical material behavior, the previously described micromechanical model for solid wood is used, enabling consideration of local variations of microfibril angles or chemical composition of the wood tissue in the vicinity of knots. First results obtained with the numerical simulation tool indicate its capability to estimate the stiffness and strength reduction of wood boards in consequence of knots.

On the whole, micromechanical models provide accurate estimates for the mechanical properties of wood and wood products in a fully three-dimensional and orthotropic framework. Also various couplings, e.g. between moisture transport and mechanical behavior, are suitably captured by these models. This makes these models highly valuable for **structural simulations**, whose predictive and also descriptive capabilities are often limited by the lack of suitable input data or the poor accuracy of available data. Hence, micromechanical modeling activities are expected to support structural analyses of wood structures, but also optimization of processes in wood drying technology.

Keywords:

wood and wood products, knots, mechanical characterization, stiffness, elastic limits, multiscale analysis, continuum micromechanics, unit cell model, experimental validation, finite element simulations

1 Introduction

The current deficiencies Wood is one of the oldest construction materials known to man. Over thousands of years it has been mainly used in a craft framework, so that current design rules are often based on experience and tradition. The scientific knowledge about the material behavior is often surprisingly poor.
As climate change becomes more of an issue, the pressure to build more ecologically results in a boom of wood constructions never seen before. Wood, a renewable and natural material, is capable to play an important role with respect to climate change policies and programs. Its use helps to reduce greenhouse gases by storing carbon dioxide and keeping it out of the atmosphere. A well-designed, well-kept timber building lasts hundreds of years and can be recycled and reused if it needs to be demolished. Moreover, the increased use of wood-based products results in partial substitution of energy-intensive raw materials contributing to a reduction of carbon dioxide sources.
In order to exploit the extraordinary ecological potential of the material and to enable its structural use also in an industrial framework, improved material models are required. Modern timber construction is characterized by increasing demand of two- and three dimensional bearing components (cf. Figure 1). Dimensioning and design of such sophisticated structures require powerful material models for numerical simulation tools such as the finite element (FE) method. Moreover, the large variability of the macroscopic material properties has to be understood and suitably described to prevent exaggerated safety factors resulting in an uneconomic over-dimensioning of timber members.


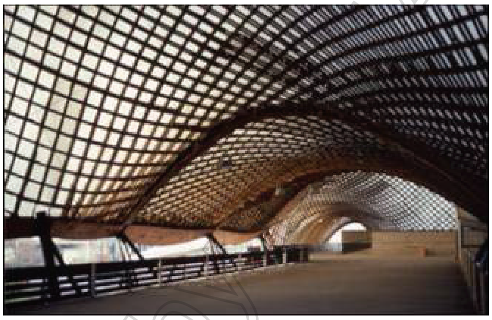

Figure 1: Wide-span timber constructions

Deficiencies with regard to suitable material models and lack of fundamental knowledge concerning the mechanical behavior of wood motivated the recent establishment of the research field ‘Mechanical Characterization of Wood’ at the Institute for Mechanics of Materials and Structures (IMWS) of Vienna University of Technology. Work in this field focuses on the development of micromechanically based material models and the application of these models to structural analysis. The research work is funded by the European Confederation of Woodworking Industries (CEI-Bois) in the framework of its strategic process ‘Building with Wood’.

2 Multiscale modeling of solid wood

The current deficiencies in the mechanical characterization of wood substantially result from the very complex behavior of this material: Wood is anisotropic and inhomogeneous due to growth irregularities. It shows large variations between individual tissues, different load carrying and failure mechanisms at different loading states, and pronounced interrelations with water because of the hygroscopicity of the material. This complexity is the result of the evolution of trees over more than hundred millions of years which has optimized the material microstrucuture across several length scales.

2.1 Hierarchical structure of wood

In order to understand the variability of macroscopic properties of wood and the underlying phenomena and to suitably describe them in material models, the hierarchical microstructure of the material has to be considered. Characteristic structural features vary at different scales of observation – from the nanometer scale up to the macroscale – and bring about the large variations of the macroscopic material properties of individual wood samples, both intra-species and inter-species. However, at sufficiently small length scales universal constituents common to all wood species and samples as well as universal building principles can be identified. Namely, lignin, hemicellulose, cellulose, and water are such tissue-independent universal constituents with common mechanical properties across the diverse wood species. The hierarchical structure of wood built up by these components is shown in Figure 2: Lignin, hemicellulose, and water are mixed in an amorphous polymer matrix at nanometer scale, in which partly crystalline, partly amorphous cellulose fibrils are embedded with typical diameters of about 50-200 nm. This cell wall material builds up a honeycomb structure with typical dimensions of 20-40 µm. In hardwood, this cellular material is in turn penetrated by pores with significantly larger diameters of up to 500 µm, so-called vessels, resulting in a two-scale porosity of hardwood material.

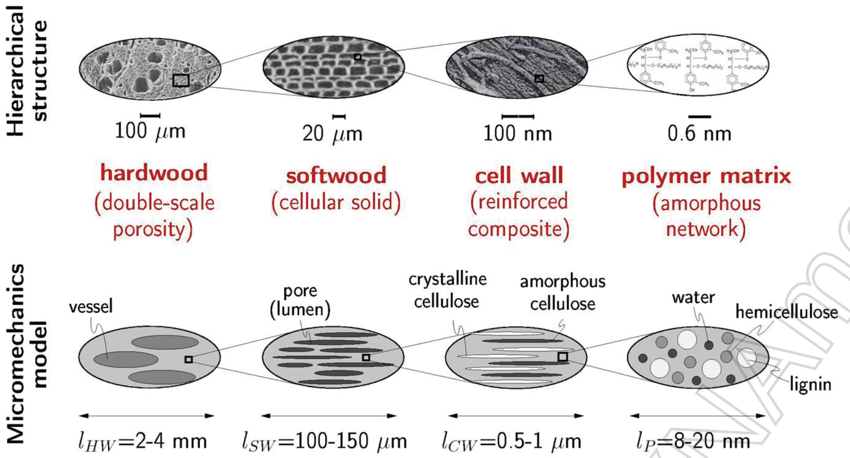

Figure 2: Hierarchical structure of wood and its representation in the micromechanics model [1]

2.2 Formulation of mathematical model

A mathematical formulation of the described building principle results in a multiscale micromechanical model for wood which links microstructural characteristics of individual wood samples to macroscopic mechanical characteristics of these samples. Continuum micromechanics and the unit cell method are employed as homogenization techniques.

The composite structure of the wood cell wall motivates application of continuum micromechanics for estimation of its elastic properties. In continuum micromechanics [2], a material is understood as a microheterogeneous body filling a representative volume element (RVE) of characteristic length *l*, *l* » *d*, *d* standing for the characteristic length of inhomogeneities within the RVE. The 'homogenized' mechanical behavior of the material, i.e. the relation between homogeneous deformations acting on the boundary of the RVE and resulting (average) stresses, can then be estimated from the mechanical behavior of different homogeneous phases, representing the inhomogeneities within the RVE, their dosages within the RVE, characteristic shapes, and interactions. Based on matrix-inclusion problems [3], [4], an estimate of the 'homogenized' stiffness of a material reads as [2]

$$\mathbb{C}^{\mathrm{hom}} = \sum_i f_i \cdot \mathbb{C}_i : \left[\mathbb{I} + \mathbb{P}_i^0 : \left(\mathbb{C}_i - \mathbb{C}^0\right)\right]^{-1} : \left\{\sum_j f_j \cdot \left[\mathbb{I} + \mathbb{P}_j^0 : \left(\mathbb{C}_j - \mathbb{C}^0\right)\right]^{-1}\right\}^{-1} \qquad (1)$$

where $\mathbb{C}_i$ and f_i denote the elastic stiffness and the volume fraction of phase *i*, respectively, and $\mathbb{I}$ is the fourth-order unity tensor. The two sums are taken over all phases of the heterogeneous material in the RVE. The fourth-order tensor $\mathbb{P}_i^0$ accounts for the characteristic shape of phase *i* in a matrix with stiffness $\mathbb{C}^0$. The choice of this stiffness describes the interactions between the phases. For $\mathbb{C}^0$ coinciding with one of the phase stiffnesses (Mori-Tanaka scheme), a composite material is represented (contiguous matrix with inclusions); for $\mathbb{C}^0 = \mathbb{C}^{\mathrm{hom}}$ (self-consistent scheme), a dispersed arrangement of the phases is considered which is typical for polycrystals.

A four-step homogenization scheme is formulated to represent the hierarchical microstructure of wood [5] (Figure 2): The first two steps are concerned with the mixture of hemicellulose, lignin, and water, lumped together with extractives, at a length scale of some nanometers in an amorphous material denoted as *polymer network*, and the embedding of inclined fiber-like aggregates of crystalline and amorphous cellulose in this polymer network, constituting the *cell wall material*. The 'homogenized' stiffnesses of the polymer network and of the cell wall material are determined by means of continuum micromechanics, namely though self-consistent and Mori-Tanaka homogenization steps, respectively,

as described in [5]. At a length scale of about one hundred microns, the material *softwood* is defined. In a simplified manner, the honeycomb structure can be approximated by cylindrical pores (lumens) penetrating the cell wall material of the preceding homogenization step, so that again the Mori-Tanaka scheme can be applied for stiffness estimation. Finally, at a length scale of several millimeters, *hardwood* comprises additional larger cylindrical pores denoted as vessels which are embedded in the softwood-type material homogenized before. Estimates of the stiffness of hardwood are derived in an analogous manner as estimates for softwood material in the third homogenization step [5].
The approximately periodic arrangement of the wood cells renders the unit cell method highly suitable for the third homogenization step. In this method, the real material microstructure is represented by a periodic arrangement of identical basic repetitive units (Figure 3) which are considered in a discrete manner. The unit cell is subjected to periodic, symmetric or antisymmetric boundary conditions for the displacements, such that the spatial averages of the corresponding strains are equal to the macroscopic strains related to the cellular material. Linking these macroscopic strains to the spatial average of the periodic microstresses they create, i.e. to the macroscopic stresses, yields the homogenized effective stiffness of the cellular material. In detail, six independent displacement configurations are imposed to the boundary of the unit cell so as to create unit values of macroscopic (normal and shear) strain components. The spatial averages of the corresponding periodic microstresses are equal to the components of the homogenized stiffness tensor of softwood then [6].

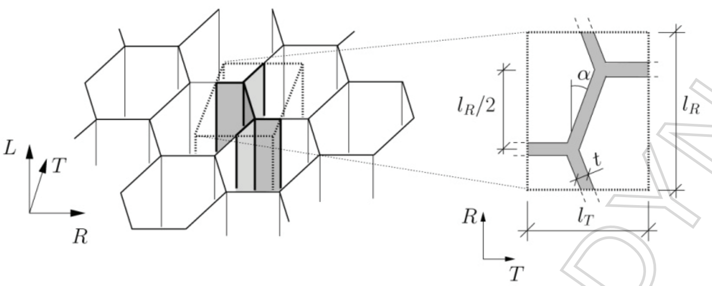

Figure 3: Unit cell for softwood material

At the cellular scale, plate-type bending and shear deformations dominate the mechanical behavior. Since such deformations are more suitably represented by a unit cell approach, the original version of the micromechanical model, exclusively based on continuum micromechanics, is improved by employing unit cell theory as homogenization technique at the cellular scale [7]. Consideration of a non-regular honeycomb structure also allows for representation of direction-dependent mechanical properties of wood in the cross-sectional plane perpendicular to the grain direction (*'longitudinal direction L'*). The elastic moduli in the two principal material directions in the cross-sectional plane, namely, the direction parallel to the growth rings (*'tangential direction T'*) and perpendicular to them (*'radial direction R'*), typically vary by a factor of two.

Formulation of the localization problem corresponding to the multiscale homogenization scheme allows determination of strain estimates at smaller length scales for given macroscopic loading. Quadratic strain averages (so-called 'second-order estimates') over microstructural components turned out to suitably characterize strain peaks in these components [8]. Combination of estimates for such averages with microscale failure criteria delivers predictions for macroscopic elastic limit states.
As for solid wood, experimental investigations indicate that wood failure is initiated by shear failure of lignin in the wood cell wall. This can be suitably described mathematically by means of a von Mises-failure criterion and results in estimates for macroscopic strength in the sense of elastic limit states [1].

2.3 Validation of multiscale model for wood

Validation of the presented continuum micromechanics model rests on statistically and physically independent experiments: the macroscopic material stiffness predicted by the micromechanical model on the basis of tissue-independent ('universal') phase stiffness properties of hemicellulose, amorphous cellulose, crystalline cellulose, lignin, and water (*experimental set Ia*) and of tissue-independent mean values of the morphological characteristics (*experimental set Ib*) for tissue-specific composition data (*experimental set IIb*) are compared to corresponding experimentally determined tissue-specific stiffness values (*experimental set IIa*) [5,7]. For the elastic moduli in the longitudinal direction (aligned with the stem axis), E_L, and in the transverse direction (in the cross-sectional plane of the stem), E_T, as well as for the shear modulus in the plane through the longitudinal axis, G_L, model estimates and experimental results show good agreement over a large variety of wood species (Figure 4).

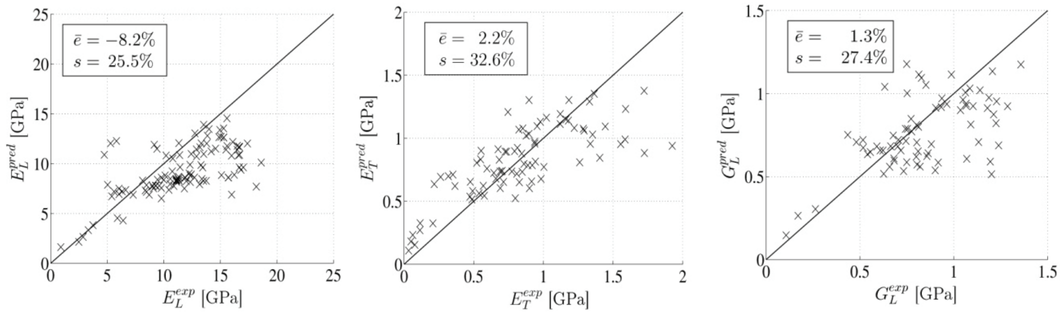

Figure 4: Comparison of predicted and measured elastic constants

In general, the mean prediction errors for the elastic moduli and the shear moduli related to the three principal material directions *L*, *R*, and *T* are each below 10 %. These small errors of the model predictions underline the predictive capabilities of the micromechanical model. Also macroscopic stress states estimated from local shear failure of lignin agree very well with elastic limit states observed in corresponding strength tests for a variety of macroscopic failure modes [1]. This underlines the paramount role of lignin as strength-determining component in wood.

3 Multiscale modeling of wood products

The capability of micromechanical approaches to link macroscopic properties to microstructural characteristics renders such approaches also very appealing for wood products. In the following, models for a representative of strand-based products, namely the Veneer Strand Board (VSB), as well as for a representative of solid wood-based products, namely the DendroLight panel, will be shown.

3.1 Veneer Strand Board

The innovative Veneer Strand Board (VSB) consists of large-area, flat and slender strands with uniform strand shape and dimensions (see Figure 5) and is typically built up of several layers with different strand orientations. The high-quality strand material results in increased stiffness and strength of the board compared to conventional strand and Veneer-based panels. The latter are typically used for sheeting and stiffening purposes, whereas the improved mechanical behavior of the VSB allows for an extension of the range of possible applications to the load-bearing sector. The development of a multiscale model for the analysis of the mechanical behavior of such boards has enabled identification of optimal strand dimensions and orientations as well as promising vertical build-ups in terms of the density profile and the layer structure [9,10].

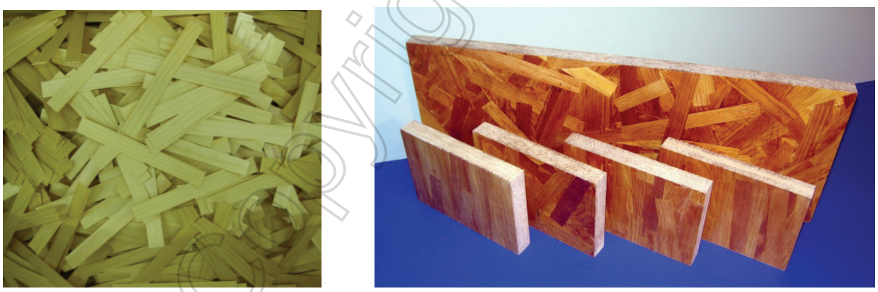

Figure 5: Veneer strands and finished board

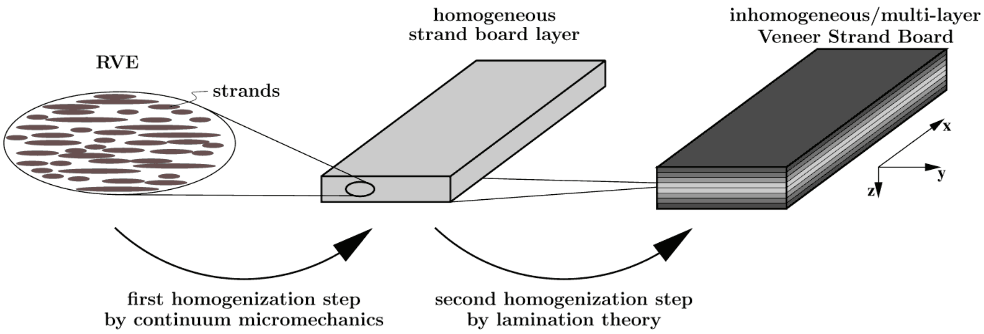

Figure 6: Hierarchical levels of strand boards and respective homogenization procedures

The multiscale model spans three scales of observations: the strand material, a homogeneous board layer, and the multi-layer board (Figure 6). At first, continuum micromechanics is applied to estimate the elastic properties of a homogeneous board layer from the stiffness of the strands, their shapes, and their orientations. The strands are connected by a synthetic adhesive which does not act as an own material phase but contributes to the mechanical behavior of the compound by two substantial effects: first, the adhesive penetrates the wood tissue of the strands and compensates for micro-damages in consequence of the strand production. Second, it establishes the crucial bonding between the strands, which is assumed to be perfect in the model. The absence of a contiguous matrix phase in the board motivates the use of the implicit self-consistent scheme. The strands constitute the only phase of the model, which is made up of inclusions with different orientations. The orientation distribution of the strands in the plane of the panel is described in terms of a normalized distribution function $g_s(\varphi)$, where the angle φ denotes the inclination of the principal axis of the strand to the main axis of the strand board. Considering the morphologically and mechanically justified periodicity of π, specification of Eq. (1) for the strand board layer reads as

$$\mathbb{C}^{\text{hom}} = \left\{ \int_{\varphi=-\frac{\pi}{2}}^{+\frac{\pi}{2}} \mathbb{C}_s(\varphi) : \left[\mathbb{I} + \mathbb{P}_s^{\text{hom}}(\varphi) : \left(\mathbb{C}_s(\varphi) - \mathbb{C}^{\text{hom}} \right) \right]^{-1} g_s(\varphi)\, d\varphi \right\} \left\{ \int_{\varphi=-\frac{\pi}{2}}^{+\frac{\pi}{2}} \left[\mathbb{I} + \mathbb{P}_s^{\text{hom}}(\varphi) : \left(\mathbb{C}_s(\varphi) - \mathbb{C}^{\text{hom}} \right) \right]^{-1} g_s(\varphi)\, d\varphi \right\}^{-1} \quad (3)$$

where $\mathbb{C}_s$ denotes the stiffness tensor of the compacted, adhesive-penetrated strands. The fourth-order Hill tensor $\mathbb{P}_s^{\text{hom}}$ is obtained by treating the strands as infinitely long cylinders with elliptic cross-sections [4,11] with an aspect ratio of 25; the longer extension is parallel to the panel plane.

In the second step, effective stiffness properties of a multi-layer panel are determined by means of classical lamination theory. Thereby, the stacking sequence, the orientation of the principal material directions of the single layers, and the density variation across the board thickness are taken into account.

Model validation is again based on independent experiments. For this purpose, homogeneous boards as well as inhomogeneous boards with a well defined vertical density distribution were produced. Three different distributions of the strand orientation [random (R), aligned (O), and crosswise (X)], three different wood qualities [good (G), medium, and poor (P)], and two different density levels [high and low (LD)] are considered. Inhomogeneous boards show either constant strand-orientation distribution across the board thickness or three distinct layers with alternating strand orientations in subsequent layers.
The mechanical testing of strands, homogeneous boards, and inhomogeneous/multi-layer boards allows for independent validation of both modeling steps based on continuum micromechanics and on lamination theory, respectively. Altogether, good agreement of experimental data and corresponding model predictions was observed. Correlation plots of experimental and numerical results for the two in-plane elastic moduli E_x and E_y as well as for the two shear moduli G_{yz} and G_{xz} of homogeneous boards are shown in Figure 7. Corresponding plots for inhomogeneous/multi-layer boards can be found in

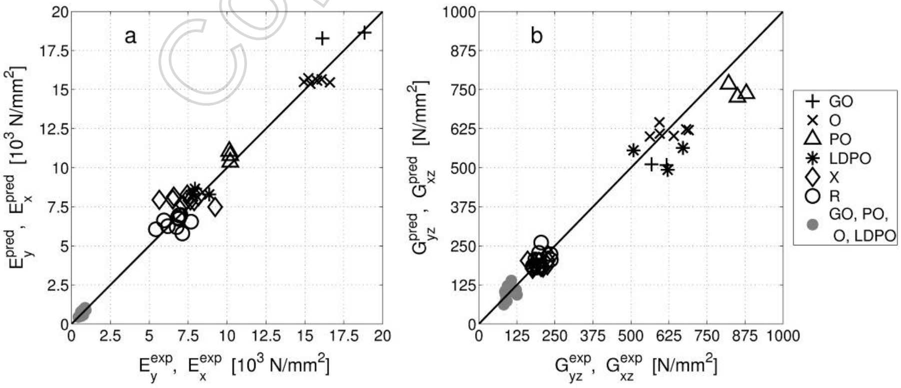

Figure 7: Comparison of experimental data and corresponding model predictions for the in-plane moduli of elasticity E_y and E_x and the shear moduli G_{yz} and G_{xz} of homogeneous strand boards

[10]. The good agreement underlines the capability of the model for estimation of the stiffness of strand- based engineered wood products by means of microstructural features and renders it a powerful tool for parameter studies and product optimization.

3.2 DendroLight panel

The needs for increased efficiency, the aim of reducing useless weight, and improvements in wood processing have led to the development of a new kind of wooden lightweight panel named DendroLight (Figure 8a). DendroLight is a three-layered panel: Thin outer layers consist of solid wood or particle board and provide basic stiffness to the panel. The middle layer is made up of small cells with webs inclined by an angle of 45°. The arrangement of the cells is such that they face upwards and downwards alternately, so that the webs cross each other at right angles. The mechanical characterization and optimization of the panel requires investigation of a multitude of panel designs with different materials, different overall thicknesses, and different ratios of the layer thicknesses. In order to reduce the numbers of prototype tests, numerical simulations were performed. These simulations were based on the unit cell method formulated for a plane medium [12,13]. As described in Section 2, the unit cell, which is the basic repetitive unit of the microstructure (see Figure 8b), is subjected to periodic boundary conditions. As for plane periodic media, macroscopic unit curvature states are considered as loadings of the unit cell in addition to macroscopic unit strain states. The local stress and strain fields resulting from these macroscopic loadings are determined by means of the FE method. The generalized stress resultants are equal to the homogenized stiffness

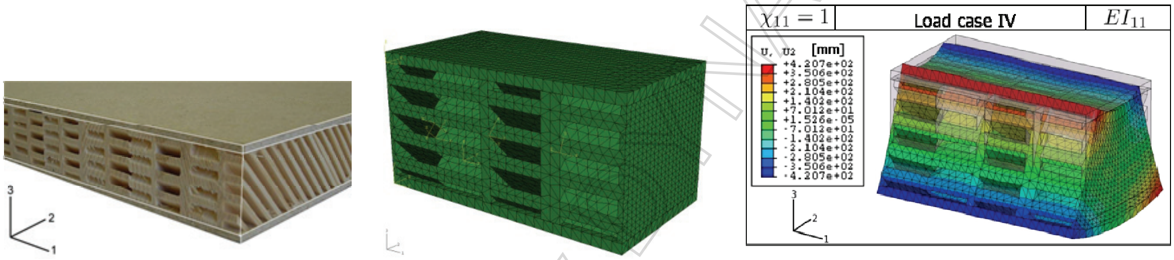

Figure 8: Modeling of DendroLight panel: (a) sample; (b) FE mesh of unit cell; (c) lateral displacement distribution in bending load case

properties of the panel. In particular, effective in-plane stiffnesses and bending stiffnesses are obtained. Under consideration of the panel thickness, six elastic constants can be derived therefrom: the in-plane moduli of elasticity in tension parallel and perpendicular to the principal orientation of the middle layer cells, the in-plane shear modulus, the moduli of elasticity in bending with respect to the latter orientations (cf. Figure 8c for exemplary results), and the shear modulus in torsion. The results of the computations show that the influence of the middle layer on the overall stiffness of the panel is mainly controlled by the orientation of the principal material directions of the two outer layers. If the load is acting in direction of higher stiffness within the outer panels, the middle layer contributes only a small part of the overall stiffness. If the load, on the other hand, is acting in direction of lower stiffness within the outer layers, the modulus of elasticity is mainly contributed by the middle layer.
For the purpose of model validation, several panel samples were produced by hand and tested in tension. The experimental results show a good agreement with corresponding stiffness predictions by the model.

4 Multiscale modeling of wood with knots

Since wood is a naturally grown material, it exhibits growth irregularities, primarily knots and site-related defects. Knots result in a pronounced reduction of stiffness and strength of wooden boards. Due to the highly anisotropic material behavior of wood, the influence of the grain orientation on the mechanical properties of a board is very pronounced. The fiber deviations in the vicinity of knots (cf. Figure 9) therefore cause a high variability in stiffness and strength. The latter is a major difficulty in solid wood utilization and brings about the need for wood grading.
This motivated investigation of the effects of growth irregularities on the mechanical behavior of boards by means of physically-based numerical simulations. Such simulations provide insight into the internal stress and strain fields and contribute to an enhanced understanding of the internal stress transfer in wood with growth defects. By analyzing various knot configurations, relations between the morphological knot characteristics and wood strength can be assessed.

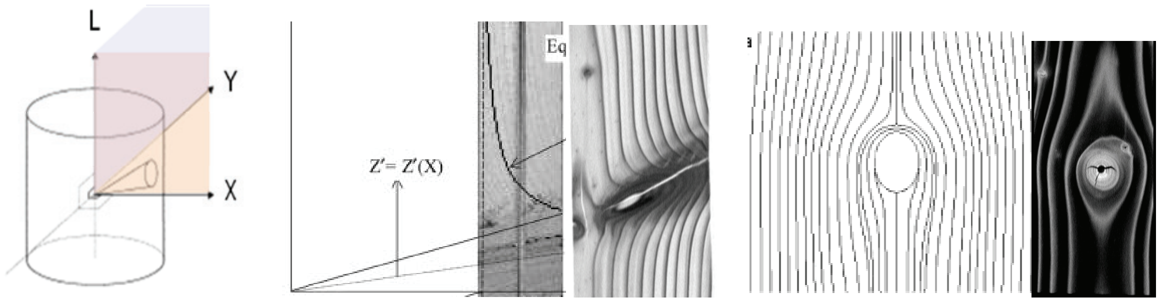

Figure 9: Fiber deviations around a knot: (a) local coordinate system; (b) polynomial equations in LX-plane (including knot axis); (c) flow-grain-analogy in LY-plane (perpendicular to knot axis)

The presented numerical model is based on the combination of the FE method with sophisticated models for the fiber course and the material behavior. The model takes into account the global fiber deviation caused by spiral grain and the local fiber deviation caused by the presence of a knot. For the latter a mathematical algorithm [14] based on a fluid flow approach and polynomial functions fitted to the annual ring course is implemented into the model. The algorithm is evaluated at every integration point of the FE model and provides the local three-dimensional fiber orientation there. With respect to the mechanical material behavior, the previously described micromechanical model is used [5,7], which allows to predict macroscopic mechanical properties of wood from the chemical composition and microstructural features. It is also evaluated at integration point level and permits consideration of local variations of tissue stiffness resulting from local variations of density and microscale properties in the vicinity of knots.
The developed numerical multiscale-model enables the virtual reconstruction of a timber board with knot inclusions and the estimation of the stiffness and strength reduction caused by the knots by means of FE simulations. The validation, which is done by comparison of model-predicted and experimental results for the mechanical behavior of boards with knot inclusions, confirms the practicability of the model. For example, the wood sample shown in Figure 10 was re-simulated. The computed effective elastic modulus (i.e. the relation between mean axial stress and mean axial strain in the longitudinal direction) amounts to 11100 N/mm², while the corresponding test result is 10500 N/mm².

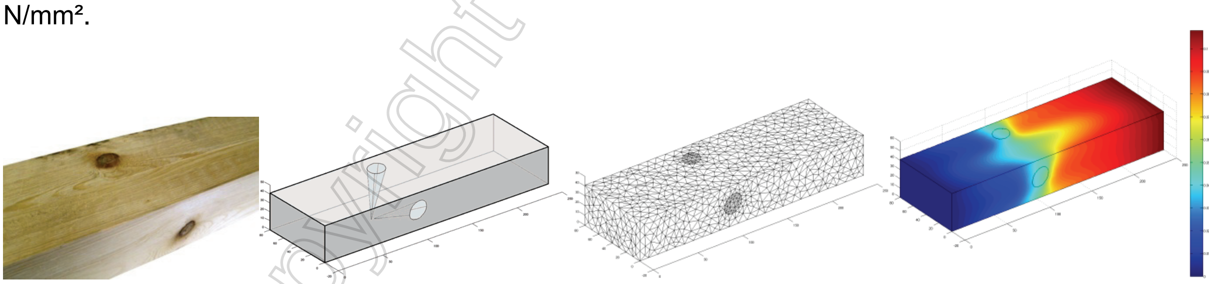

Figure 10: Modeling of wooden board with knots: (a) sample; (b) geometric model; (c) FE mesh; (d) longitudinal displacements under tensile load in this direction

5 Applications to structural simulations

Micromechanical models provide accurate estimates for the mechanical properties of wood and wood products in a fully three-dimensional and orthotropic framework. Also various couplings, e.g. between moisture transport and mechanical behavior, can be suitably captured by these models. This makes these models highly valuable for structural simulations, whose predictive and also descriptive capabilities are often limited by the lack of suitable input data or the poor accuracy of available data. Hence, micromechanical modeling activities are expected to support structural analyses of wood structures [15], such as, e.g., the elastoplastic numerical simulation of a barrel shell with a central opening (Figure 11a) or of a typical timber joint, a break joint (Figure 11b). Validation of such analyses is preferably done by structural testing as shown in Figure 11c for a glulam bending beam with a circular hole [16]. Moreover, multiscale models provide a valuable basis for optimization of wood processing, e.g. of wood drying technology

Figure 11: Experimental investigation and FE analyses of wooden structures (a) distribution of stress component perpendicular to the fiber direction, (b) distribution of in-plane component of shear stresses, and (c) experimental set-up of structural test [15], [16]

6 Literature

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