Design of Multilayered Spruce Laminates for Moisture-Sensitive Actuating Components

W. Hufenbach[1], M. Gude[1], F. Adam[1], V. Lustig[1], S. Spitzer[1]*, C. Kirvel[1], C. Neinhuis[2],
M. Horbens[2], A. Wagenführ[3], C. Siegel[3] and R. Kupfer[4]
[1] Institute of Lightweight Engineering and Polymer Technology,
Technische Universität Dresden, Dresden, Germany
[2] Institute of Botany, Technische Universität Dresden, Dresden, Germany
[3] Institute of Wood and Paper Technology, Technische Universität Dresden, Dresden, Germany
[4] Leichtbau-Zentrum Sachsen GmbH, Dresden, Germany
* Corresponding author (s.spitzer@ilk.mw.tu-dresden.de)

Keywords: *Residual stresses, Biological composite materials, Unsymmetrical laminates*

1 Introduction

Nature-originated materials from renewable resources gain increasing relevance for technical applications, especially due to the rising demand of biodegradable and carbon–dioxide-neutral materials. However, beyond the pure substitution of engineering plastics, biological materials offer the potential to create functionalized biomimetic multicomponent structures by taking advantage of the specific properties of natural materials. This also includes the analysis and technological transfer of the design principles of local plants and their structural arrangements and functions.

In flora, one principle of operation is the use of hygroscopic effects for humidity-sensitive integrated sensing/actuating components. For instance, the dispersal unit of wild wheat (*Triticum turgidum* L.) shows a specific composition of cellulose fibrils in their awns, which causes bending of the awns due to changes in humidity as shown in Fig. 1. This function enables the seed capsule to dig itself into the ground during several day and night cycles.

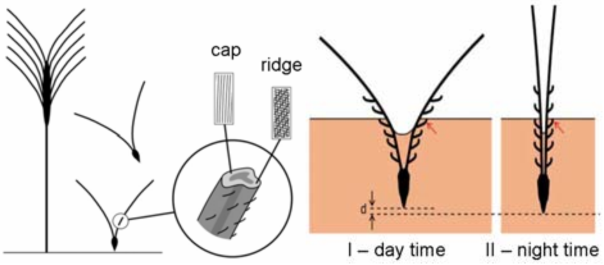

Fig. 1 Structure of the dispersal unit of wheat awn (left) [2] and movement in the day-night cycle (right) [1].

This reversible swelling effect can also be found in spores from field horsetail (*Equisetum arvense* L.) displayed in Fig. 2.

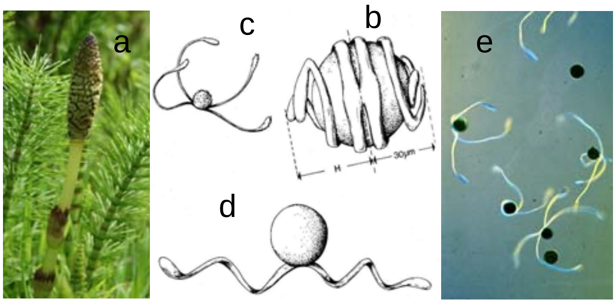

Fig. 2 Stalks of field horsetail (a), spore of horsetail with elaters in humid state (b) and in dry condition (c, d) [3] and spores with elaters in dry condition (e).

The moisture-sensitive actuating effect can be adapted for engineering applications using unsymmetrical multilayered wood laminates with different fibre orientations. For the design of such actuating structures made of plywood laminate, an analytical tool based on classical laminate theory was adapted to this specific application [4]. In comparison to the analytical method, a finite element analysis (FEA) has been used to calculate the moisture-induced bending. For the validation of the analytical and numerical studies, unbalanced laminate specimens made of spruce veneer (*Pecea abies* Karst.) were manufactured and afterwards conditioned to specified moisture. The resulting bending deformations of the laminates were measured and compared with the calculated values.

2 Multilayered Spruce Laminates for Actuating Components

In natural materials, the change of moisture often leads to a storage of water between the fibers, which causes a significant swelling of wood transverse to the fiber direction. In contrast, the swelling coefficient in longitudinal direction is negligible. Simultaneously, the moisture absorption causes decreasing stiffness perpendicular to the fibre direction, while the stiffness parallel to the fibre is almost constant (Fig. 3).

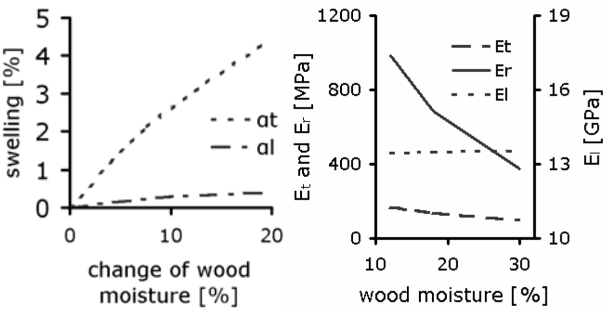

Fig. 3. Directional depending swelling (left) and stiffness of spruce depending on moisture.

This orthotropic elongation of the unidirectional single layers leads to a complex residual stress state in unbalanced laminates such as exemplarily shown in Fig. 4. These residual stresses can lead to large bending deformations of the laminate.
For experimental investigation of this effect, test specimes with unsymmetrical layup were made from spruce veneer.

length [mm]	100
width [mm]	100
layer thickness [mm]	1

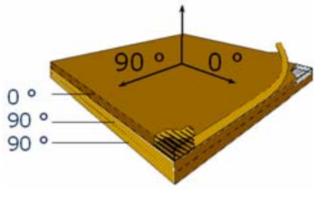

Fig. 4. Sample dimensions and lay-up.

For the calculation of the bending deformations, the required directional elastic properties and swelling coefficients longitudinal, radial and transversal to the fibre direction of the single layer were experimentally determined under different moisture contents *M*.

To minimize the influence of humidity fluctuation, the shear modulus was not determined conventionally on thin plates using a shear frame but on massive specimens using an adapted torsion test [5].

Tab. 1. Elastic stiffnesses of spruce depending on moisture (in MPa)

***M* [%]**	**12**	**18**	**30**
tangential stiffness E_t	168	140	99
radial stiffness E_r	985	683	376
longitudinal stiffness E_l	13432	13498	13551
shear modulus G_{lr}	459	392	296

3 Semi-analytical investigations

The analytical model is based upon the formulation of the elastic total potential energy

$$\Pi = \int_V \left(\tfrac{1}{2} \overline{Q}_{ij} \varepsilon_i \varepsilon_j - \overline{Q}_{ij} \beta_i \varepsilon_j \Delta M \right) \mathrm{d}V$$

which takes into account the reduced transformed stiffnesses of the spruce plies $\overline{Q}_{ij}$, their swelling coefficients β_i and the change of moisture ΔM. The strains ε_i are described by nonlinear terms of the midplane displacements $u_i^0 = \left(u^0 \quad v^0 \quad w \right)^T$ in the form of

$$\varepsilon_x = \frac{\partial u^0}{\partial x} + \left(\frac{\partial w}{\partial x} \right)^2 - z \frac{\partial^2 w}{\partial x^2},$$

$$\varepsilon_y = \frac{\partial v^0}{\partial y} + \left(\frac{\partial w}{\partial y} \right)^2 - z \frac{\partial^2 w}{\partial y^2},$$

$$\gamma_{xy} = \frac{\partial v^0}{\partial x} + \frac{\partial u^0}{\partial y} + \left(\frac{\partial w}{\partial x} \right) \left(\frac{\partial w}{\partial y} \right) - 2z \frac{\partial^2 w}{\partial x \partial y}.$$

The nonlinear theory is a necessisity considering the large expected deformation of the spruce laminate under moisture influence. Displacements of the midplane can be approximated by

$$u_i = \sum_k a_{ik} \varphi_k(x, y)$$

which are series of suitable shape functions with the unknown coefficients a_{ik} , here polynomials are chosen. According to the Rayleigh-Ritz technique the displacement functions are substituted in the energy equation leading to a function of the shape coefficients $\Pi = \Pi(a_{ik})$.

For calculating the laminate deformation as a result of humidity change, the variation calculus is used leading to the determination of the stationary value of the laminates total potential energy at a given moisture content**.** That extreme value problem yields a system of nonlinear equations for the unknown coefficients, namely

$$\delta\Pi = \frac{\partial \Pi}{\partial a_{ik}} \delta a_{ik} = 0$$

the solutions of which allow describing the deformation of the laminate at a distinct moistness mathematically. For a [0/90/90] spruce laminate with a size of 92x92x3 mm³ at moisture saturation (18%), the distortion shape is graphically exemplified in Fig.5.

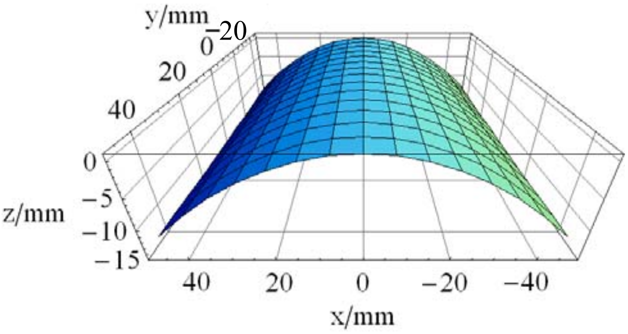

Fig. 5. Predicted distortion shape of spruce laminate at an assumed moisture of 18%

Though this semi-analytical method is limited to simple geometries, it enables time-efficient parameter studies for estimating the influence of different geometric and material properties allowing the target-oriented preliminary design of actuating elements, for instance. Fig. 6 shows the curvature dependence of a [0/90/90] quadratic wood laminate with an edge length of 100 mm depending on the layer thickness and the Young's moduli in fibre direction and perpendicular, respectively.

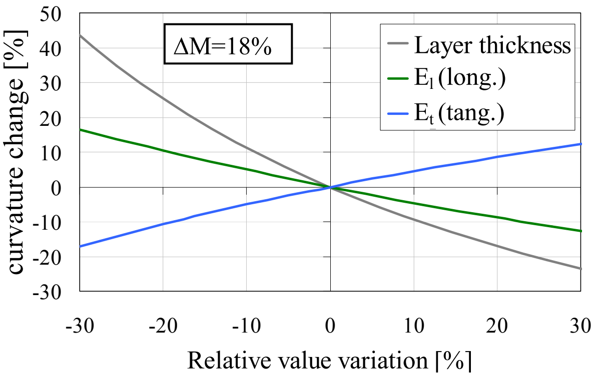

Fig. 6. Influence of variation in geometric and stiffness parameters towards laminate curvature

4 Numerical investigations

To predict the deformation behaviour of more complex moisture-active structures, an additional Finite Element Analysis (FEA) was performed using ANSYS V12.1. The specimens shown in Fig. 4 were analysed with 5 mm large Shell181 elements [6]. The change of moisture was implemented as a virtual temperature load simulation. Therefore, the directional depending swelling coefficient was defined in the material model of the spruce slice with orthotropic thermal expansion coefficient. The wood moisture was increased stepwise of spruce at a temperature of 23 °C.

As large deformations were expected, the numerical analysis was done with geometrically nonlinear behaviour (Fig. 5).

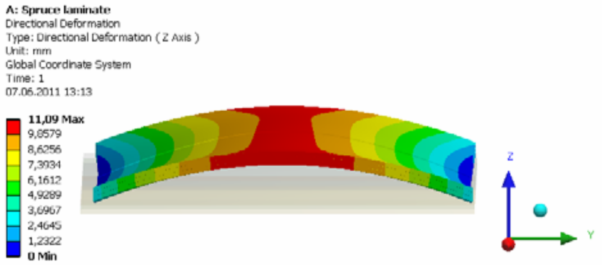

Fig. 7. Numerically calculated deformation of the spruce laminate with moisture saturation.

5 Experimental validations

For the experimental validation, the unbalanced laminates were conditioned at defined moistures from kiln-dried to 100 % humidity at a temperature of 24 °C. To adjust the humidity, the samples were placed in a special air conditioned and ventilated climatic case shown in Fig. 8

Fig. 8. Conditioning of spruce laminate in climatic case (left) and deformation with moisture saturation (right).

In comparison on the experiment, the semi-analytical and the numerical solution provide a good agreement. While the analytical solution is based on a simplified model which causes a linear correlation between deformation and change of moisture, the numerical model represents the real experimentally verified deformation behaviour (Fig. 9).

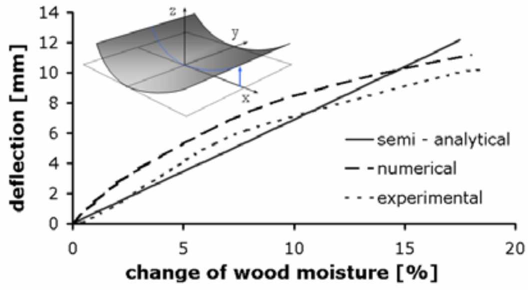

Fig. 9. Semi-analytical and numerically calculated deformation of spruce laminate depending on the change of moisture compared to the experimental determined values.

6 Conclusions

In addition to the renewability and carbon dioxide neutrality, nature-based materials offer the potential to create functionalised biomimetic multicomponent structures by using the specific material properties. Therefore, a multilayered spruce laminate for moisture sensitive actuating components was designed. Using the determined direction- and moisture-depending material properties, it was possible to calculate the deformation behavior of an unbalanced spruce laminate at changing moisture with conventional calculation methods.

Wherefore, a semi-analytical design tool based on classical laminate theory was adapted, which can primarily be used for extensive parameter studies. To predict the nonlinear deformation behaviour of complex structures in the future, a numerical FEA model was built up using ANSYS.

The results of both calculation models were experimentally verified. For this purpose, a laminate made out of spruce veneer was manufactured with an unbalanced stacking sequence [0/90/90]. These samples were conditioned in a special ventilated climatic case. The deformation was measured depending on the moisture and compared with the calculated values. It has been demonstrated, that the analytical and numerical models are suitable for predicting the deformation behaviour reliably.

Acknowledgment

The authors gratefully acknowledge the financial support of the research at Technische Universität Dresden. The project Biocomp 13855/2379 is funded by the European Union and the Free Sate of Saxony.

References

[1] R. Elbbaum “The Role of Wheat Awns in the Seed Dispersal Unit”. *Science*, Vol. 316, pp. 884-886, 2007.

[2] I. Burgert and P. Fratzl “Actuation systems in plants as prototypes for bioinspired devices”. *The Royal Society A*, 367, pp 1541-1557, 2009

[3] W. Haupt *“Bewegungsphysiologie der Pflanzen”*. 1st edition, Thieme, 1977.

[4] W. Hufenbach and M. Gude “Analysis and optimization of multistable composites under residual stresses”. *Composite Structures,* Vol. 55, pp. 319-327, 2002

[5] H.-J. Hardtke, W. Hufenbach, V. Lustig, M. Grimsel *“Eine neue Methode zur Identifizierung von Schubmoduln aus Torisonsversuchen an prismatischen Holzstäben. Roh- und Werkstoff Holz“*. Wissenschaftliche Zeitschrift der Technischen Universität Dresden, Y. 48, No. 2, pp. 13-16, 1999

[6] ANSYS® Academic Research, Release 12.1, Help System, Elements Reference, ANSYS, Inc., 2009.