Ramifications in Plant Stems as Concept Generators for Branched Technical Fiber-Reinforced Composites

T. Masselter[1,3], T. Haushahn[1], F. Cichy[2], M. Gude[2], and T. Speck[1,3]

[1] Plant Biomechanics Group Freiburg, Botanic Garden, Faculty of Biology, University of Freiburg, Germany
[2] Institute of Lightweight Structures and Polymer Technology, Technical University, Dresden, Germany
[3] Competence Network Biomimetics, Baden-Wuerttemberg, Germany, and BIOKON International-The Biomimetics Association

Abstract— **Fiber-reinforced composites are constantly optimized to meet high standards such as lightweight, a good load-bearing capacity and the ability to withstand high torsion and bending forces and moments. These mechanical loads are especially high in nodal elements and manufacturing of ramifications with an optimized force flow is one of the major challenges in many areas of fiber-reinforced composite technology, e.g. branching points of framework constructions in building industry, aerospace, ramified vein prostheses in medical technology or the connecting nodes of axel carriers. A biomimetic 'Top-Down-Process' is currently applied to address this problem via an adaptation of innovative manufacturing techniques and the implementation of novel bio-inspired mechanically optimized fiber-arrangements and fiber-matrix-transitions. Hierarchically structured plant ramifications serve as concept generators for innovative, biomimetic branched fiber-reinforced composites. Promising biological role models are tree-like monocotyledons, including *Dracaena* and *Freycinetia* species. The ramifications in these plants show a pronounced fiber matrix structure and a special hierarchical stem organization, which markedly differs from that of other woody plants by consisting of isolated fiber-bundles running in a partially lignified ground tissue matrix. Our preliminary morphological and biomechanical analyses confirm that these lightweight ramifications possess mechanical properties interesting for a transfer into bio-inspired technical applications, such as a benign fracture behavior and good dynamic energy absorption. The results from the biological role models are currently transferred in the development of concepts for producing demonstrators and first prototypes in lab-bench scale of biomimetic branched fiber-reinforced composites.**

Keywords— **biomimetics, branched fiber-reinforced composites, monocotyledons, lightweight.**

I. INTRODUCTION

Modern technical applications and structures are often subject to extreme loads in terms of tension, torsion and bending forces and moments. For dynamically loaded mechanical parts, i.e. subjected to vibration and impact loads in general, e.g. in planes or cars, local failures (micro-cracks) can develop, that often entail disastrous consequences as they can lead to the collapse of the entire structure.

Providing excellent mechanical performance as well as the structural integrity of individual components is one of today's major challenges in research and development of innovative materials and composites. Holding the potential to meet these high performance standards, fiber-reinforced composites additionally satisfy the increasing demand for lightweight materials. Due to the complex shape of many components, e.g. axel-carriers in automotives (Fig. 1), production of such branched structures often proves to be very difficult and complicated. Here, classic engineering optimization techniques have reached their limit.

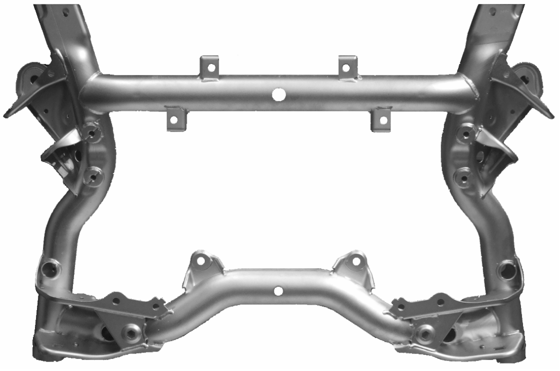

Fig. 1 Axel-carrier from the company Ilsenburger Grobblech

A very promising approach to deal with these challenges constitutes of a biomimetic optimization of the inner and outer structure of fiber-reinforced composites and the development of new production techniques. Adding up and combining different optimized substructures into a highly optimized superordinate structure is a common principle for enhancing the mechanical properties in plants. What's more, the high structural comparability of the laminated configuration of technical products, e.g. carbon-fiber reinforced epoxy resin with the layered structure of some plant stems [1, 2], predestinate plants to serve as excellent concept generators for designing innovative fiber-reinforced composites.

C.T. Lim and J.C.H. Goh (Eds.): WCB 2010, IFMBE Proceedings 31, pp. 36–39, 2010.
www.springerlink.com

The methodological approach for the development of ‘branched’ biomimetic composite structures can be described as a ‘Top-Down-Process’ as defined by the Plant Biomechanics Group Freiburg [2, 3].

II. MATERIAL AND METHODS

A. Top-Down-Process

Within a Top-Down-Process a R&D project in biomimetics is initiated by a concrete technical problem. A solution is not constrained to one specific application, but can influence a large number of products or may even lead to the development of new applications. The second step consists of the search for adequate biological role models with a high potential of solving the technical problem. Following this screening, the form-structure-function-relationship of the identified concept generators is then quantitatively analyzed by means of biomechanical testing as well as anatomical investigations. In the next crucial step, the underlying principles found in the biological concept generators are then abstracted into a fundamental model and thereby completely detached from their original biologic background. The next step covers the implementation into technical components and the production of lab-scale prototypes as well as feasibility tests. As a last step of a project the biomimetically optimized structures are introduced onto the market. For the present study, this process has been described in more detail in [4].

B. Anatomical Investigations

The stem-branch-junctions of *Dracaena reflexa* and *Dracaena marginata* were investigated morphologically and anatomically by producing serial thin and semi-thin sections. In addition micro-tomography scans were used for analyzing the external and internal structure of the ramifications. These methods allow to analyze quantitatively the organization and arrangement of fiber-bundles within the branching region and a transfer into a three-dimensional model by using modern imaging software (Fig. 2).

C. Mechanical Investigations

The biological concept generators were tested biomechanically, using a similar experimental setup as described by Beismann et al [5]. In these breaking experiments a force is applied to the lateral twig at stem-branch-junctions until fracture. This setup allows the determination of the critical force necessary to break off a side branch and subsequently the calculation of fracture toughness as well as stress and strain at fracture.

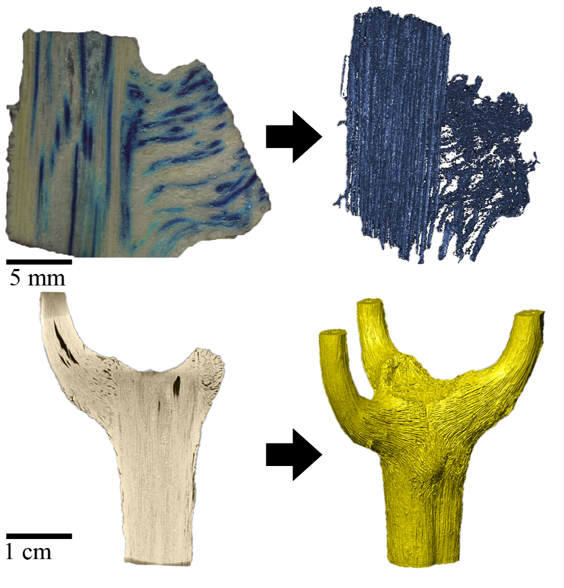

Fig. 2 Three-dimensional visualization (top right) of toluidin-dyed vascular bundles from serial sections (top left), surface-model of ramification (bottom right) based on µ-tomography images (bottom left)

III. RESULTS

The Y- and T-shaped ramifications of arborescent monocotyledons such as *Dracaena reflexa* and *Dracaena marginata* show angles that are very similar to angles found in technical components (Fig. 3)

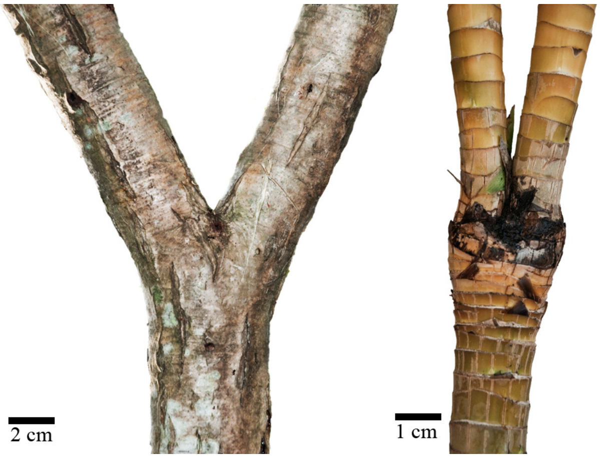

Fig. 3 Y-shaped branching in *Dracaena* sp

These biological role models form per se natural fiber-reinforced composites, since their isolated fiber-bundles run in a partially lignified parenchymatous ground tissue matrix. The ramifications of monocotyledons are hierarchically structured on at least five levels (Fig. 4):

1. Form of the branching, i.e. Y- or T-shaped (Fig. 4A) and an enlarged diameter at the interconnecting region (Fig. 4B)
2. 3D-arrangement of the fiber-bundles (Fig. 4C)
3. Course of the individual fiber-bundles (Fig. 4C)
4. Anatomy and ultra-structure of the fiber-bundles (Fig. 4D)
5. Gradients between fibers and fiber-bundles and the ground tissue matrix (Fig. 4E)

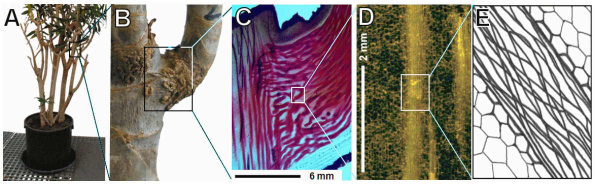

Fig. 4 Hierarchical organization of the biological role models (*Dracaena* sp.)

In the course of evolution a network of partially helical but mostly paraxial fiber-bundles had developed in the stems of arborescent monocotyledons as an adaption to complex loading conditions. In the regions of stem-branch-junctions evolution resulted in a complex interwoven arrangement of fiber-bundles/fibers. Stem-branch-junctions can therefore be described as solid tubes with a thickened diameter at the interconnecting region which are internally interconnected by fiber-bundles/fibers being arranged in a complex 3D-pattern [4].

As result of the fracture tests, different failure modes could be discerned. Especially for sickle-shaped detachment the force-displacement curves show a benign breaking behavior with a long plastic range (Fig. 5).

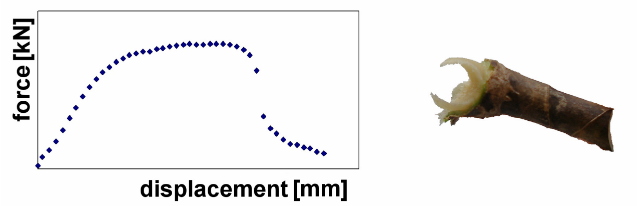

Fig. 5 Force-displacement curve for a sickle-shaped detachment of a branch of *Dracaena* sp

The use of modern techniques and methods is required for the transfer of ideas inspired by the branched biological role models into bio-inspired technical products. Given the analogy of biological fiber bundles to technical fibers or fiber bundles, braiding techniques are predestined for the transfer of the optimized structures of plants into technical products and for the manufacturing of tubular preforms. More specifically, braids of elementary shapes, which can be used as reinforcement of lightweight structures, can be manufactured by the overbraiding technique or the 3D-rotary braiding technique [6-9]. The producibility of braided branching has been proven in principle and will be used for the technical implementation [6, 8].

IV. OUTLOOK

The potential fields of implementation of fiber reinforced composites produced by braided branching not only cover those of the 'technical plant stem', a 'linear' biomimetically optimized fiber-reinforced structure [10-12], but have the additional advantage of connecting tubular shaped composite components at joint regions. Following the example of the biological role models, these joints shall be designed with continuing fibers from a tubular structure through the joint and to the next tubular structure. By adjusting the amount, the diameter and the arrangement pattern of the fibers or fiber bundles the load bearing capacity of the technical structure can be adapted to meet the mechanical requirements. Furthermore it is our intention to incorporate these bio-inspired adjustments on several hierarchical levels. Excessive notch stresses in the branchings shall thereby be reduced to a minimum. Thus life-span and safety of components for automotive engineering, aerospace and many other areas of lightweight engineering will be improved.

ACKNOWLEDGEMENTS

We gratefully acknowledge the DFG Priority Programme 1420 for funding of this project. We thank our project partners Christoph Neinhuis, Hannes Schwager, Rhiain Nathanson and Markus Milwich for many helpful discussions.

In this study the free software from the NIH/NCRR Center for Integrative Biomedical Computing, P41-RR12553-10 was used.

REFERENCES

1. Ehrenstein, G.W. (2006) Faserverbund-Kunststoffe: Werkstoffe, Verarbeitung, Eigenschaften. Hanser Fachbuchverlag, Muenchen, 2006
2. Speck, T., Harder, D. & Speck O. (2007) Gradient materials and self-repair: learning technology from biology. VDI-Report B4284: 1-13
3. Speck, T. & Speck, O. (2008) Process sequences in biomimetic research. Design and Nature IV, ed. C.A. Brebbia, WIT Press, Southampton, 2008, pp. 3-11

4. Masselter, T. & Speck, T. (2009) From stems to sticks - what can we learn for biomimetics from natural fibre-reinforced structures? Proceedings of the 6th Plant Biomechanics Conference, Cayenne, 2009, pp. 357-366
5. Beismann, H., Wilhelmi, H., Baillères, H., Spatz, H.-C., Bogenrieder, A. & Speck, T. (2000) Brittleness of twig bases in the genus Salix: fracture mechanics and ecological relevance. J Exp Bot 51: 617-633
6. Drechsler, K. (2001) Composites im Flugzeug- und Automobilbau. Conference Proceedings of Denkendorfer Kolloquien, Technische Textilien, Denkendorf, 2001
7. Hufenbach, W., Blazejewski, W., Kroll, L., Böhm, R., Gude, M. & Czulak, A.(2005) Manufacture and multi-axial test of composite tube specimen with braided glass fibre reinforcement. J Mater Process Tech 162/163: 65-70
8. Cherif, C., Diestel, O. & Gries, T. (2007) Textile Halbzeuge und Halbzeugfertigung. Textile Verbundbauweisen und Fertigungstechnologien für Leichtbaustrukturen des Fahrzeug- und Maschinenbaus, ed. W. Hufenbach, Progress-media Verlag: Dresden, 2007.
9. Hufenbach, W. (2007) Textile Verbundbauweisen und Fertigungstechnologien für Leichtbaustrukturen des Maschinen- und Fahrzeugbaus. Sächsisches Druck- und Verlaghaus: Dresden, 2007
10. Speck, O., Milwich, M., Harder, D. & Speck, T. (2005) Vom biologischen Vorbild zum technischen Produkt: der "technische Pflanzenhalm". Museo 22: 96-103, 2005.
11. Milwich, M., Speck, T., Speck, O., Stegmaier, T. & Planck, H. (2006) Biomimetics and technical textiles: solving engineering problems with the help of nature's wisdom. Am J Bot 93: 1455-1465
12. Milwich, M., Planck, H., Speck, T. & Speck, O. (2007) Der technische Pflanzenhalm: ein bionisches Schmaltextil. Melliand Textilberichte – Band- und Flechtindustrie 44: 34–38

Communicating author: Tom Masselter
Institute: Plant Biomechanics Group, Botanic Garden, University of Freiburg
Street: Schaenzlestraße 1
City: Freiburg
Country: Germany
Email: tom.masselter@biologie.uni-freiburg.de