FIBRES IN BIOLOGY AND TECHNOLOGY: SMART FIBRE-REINFORCED MATERIALS AND STRUCTURES INSPIRED BY PLANTS AND ANIMALS

T. Speck[1,2,3,4], T. Masselter[1,2,3,4], S. Poppinga[1,4], M. Thielen[1,4], G. Bauer[1,2], K. Bunk[1,2], L. Hesse[1,2], S. Schmier[1,2] and A. Westermeier[1,2]

[1]Plant Biomechanics Group and Botanic Garden, University of Freiburg, Schänzlestr. 1, 79104 Freiburg, Germany, Web Page: https://www.botanischer-garten.uni-freiburg.de/
[2]Freiburg Centre for Interactive Materials and Bioinspired Technologies (FIT), Georges-Köhler-Allee 105, 79110 Freiburg, Germany, Web Page: http://www.fit.uni-freiburg.de/
[3]Competence Network Biomimetics, Schänzlestr. 1, 79104 Freiburg, Germany, Web Page: http://www.kompetenznetz-biomimetik.de/
[4]Freiburg Materials Research Center (FMF), Stefan-Meier-Straße 21
D-79104 Freiburg, Germany, Web Page: http://www.fmf.uni-freiburg.de/
Email: thomas.speck@biologie.uni-freiburg.de, Email: tom.masselter@biologie.uni-freiburg.de, Email: simon.poppinga@biologie.uni-freiburg.de, Email: marc.thielen@biologie.uni-freiburg.de, Email: georg.bauer@biologie.uni-freiburg.de, Email: katharina.bunk@biologie.uni-freiburg.de, Email: linnea.hesse@biologie.uni-freiburg.de, Email: stefanie.schmier@biologie.uni-freiburg.de, Email: anna.westermeier@biologie.uni-freiburg.de

Keywords: biomimetics, fibre-reinforced materials, damping materials, bioinspired elastic architecture

Abstract

During the last decade biomimetics has attracted increasing attention as well from basic and applied research as from various fields of industry and building construction. Biomimetics has a high innovation potential and allows for the development of sustainable technical products and production chains. Fibre-reinforced structural materials found in plants and animals share many structural and functional properties with fibre-reinforced compound materials and technical textiles. Therefore they can be used in various ways as role models for novel biomimetic materials and structures. Interesting properties that can be transferred from biological concept generators to bioinspired technical products include high-loadbearing and vibration damping in (ultra-)lightweight branching regions, energy dissipation and puncture resistance as well as elastic deformability without joints and hinges. Selected approaches are exemplified by using actual developments in interdisciplinary R&D-projects of the Plant Biomechanics Group Freiburg in collaboration with engineers, materials scientists and architects.

1. Introduction

Biomimetics is characterized by a high innovation potential and offers the possibility for the development of sustainable technical products and production chains. For these reasons, biomimetics has attracted increasing attention as well from basic and applied research as from various fields of industry and building construction. The basis for all biomimetic R&D-projects is the huge number of organisms with their specific structures and functions that have developed during evolution. Over the last decades new fascinating insights into multi-scale mechanics and other functions of biological materials became possible due to novel sophisticated methods for quantitatively analysing and simulating the form-structure-functions-relationship on various hierarchical levels. On the other hand, new production methods allow for the first time the transfer of many outstanding properties of the biological role models into biomimetic products at reasonable costs [1, 2]. Within the framework of the Collaborative Research

Excerpt from ISBN 978-3-00-053387-7

Centre TRR 141 “Biological Design and Integrative Structures”, interdisciplinary teams aim to explore the potential of biomimetic materials and structures for a new smart kind of bioinspired architecture [3].

Fibres, polymers and minerals are the basis of most structural materials found in plants and animals. Vertebrate bone, for example, consists of collagen molecules and fibrils embedded in a hydroxyapatite matrix, and the cuticle of arthropods is mainly built up from chitin molecules in a more or less sclerotinised protein matrix and sometimes additionally strengthened by calcite. The cell wall of higher plants (embryophyta) consists of cellulose molecules and microfibrils in a complex matrix of hemicellulose, pectin and lignin [4]. Therefore (most) biological structural materials are built of complex polymer fibrils and fibres embedded in polymer or mineral matrices. This structure gives these materials a unique combination of stiffness and toughness, often leading to a benign fracture behaviour as well as inhomogeneous and anisotropic material properties which render the basis for the evolution of manifold structural and functional evolutionary and ecological adaptations found in the different lineages of plants and animals. Furthermore, fibre based anisotropic materials are the basis for the various types of motion found in plants and animals. The interconnected woody vascular system found in cacti which serves for water transport and stabilization [5] exemplifies the complexity and functionality of the fibrous skeleton found in plants (Fig. 1).

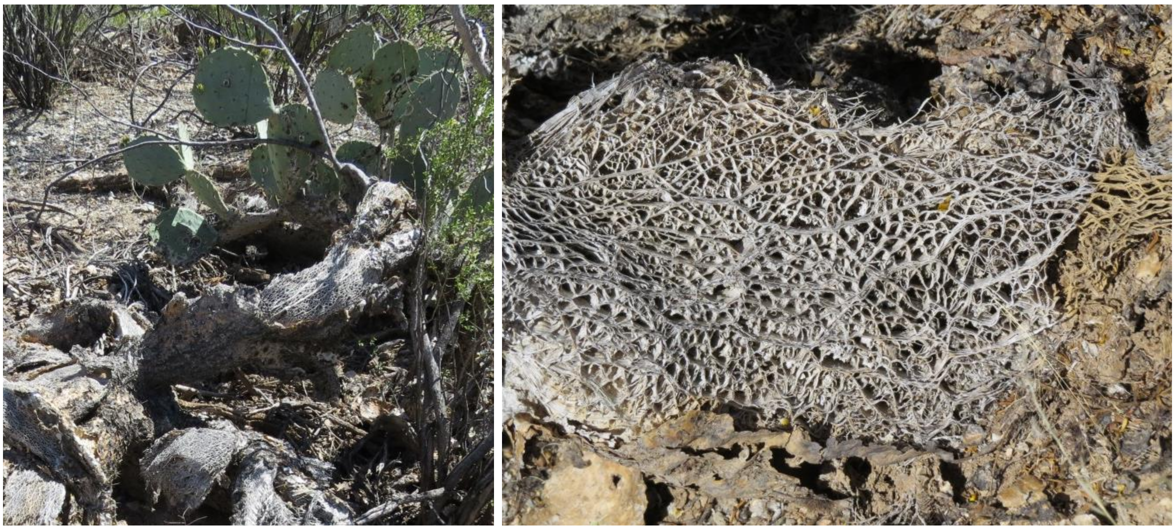

Figure 1. Complex system of lignified vascular bundles in a flat rounded shoot (cladode) of a prickly pear cactus (*Opuntia* sp.) visible after decay of the water storing parenchymatous matrix tissue (Saguaro National Park, Arizona, USA), © Plant Biomechanics Group Freiburg.

2. Results

2.1. Un-branched and branched fibrous composite materials

Fibre-reinforced compound materials and technical textiles share many structural and functional properties with their biological counter parts and proved to be very suitable for the fabrication of innovative biomimetic products [6-8]. Examples for light-weight materials with excellent mechanical properties include biomimetically optimized un-branched and branched fibrous composite materials with gradient structure, high stiffness, good vibration damping and benign fracture behaviour which are developed in collaboration with colleagues from the University of Stuttgart, ITV Denkendorf and TU Dresden. A patented example for a biomimetic un-branched fibrous composite material is the “technical plant stem” which is inspired by structural and functional properties of bamboo, giant reed and horsetails

Excerpt from ISBN 978-3-00-053387-7

[6,9]. This example shows that for biomimimetic products inspiration is taken often from more than one biological concept generator.

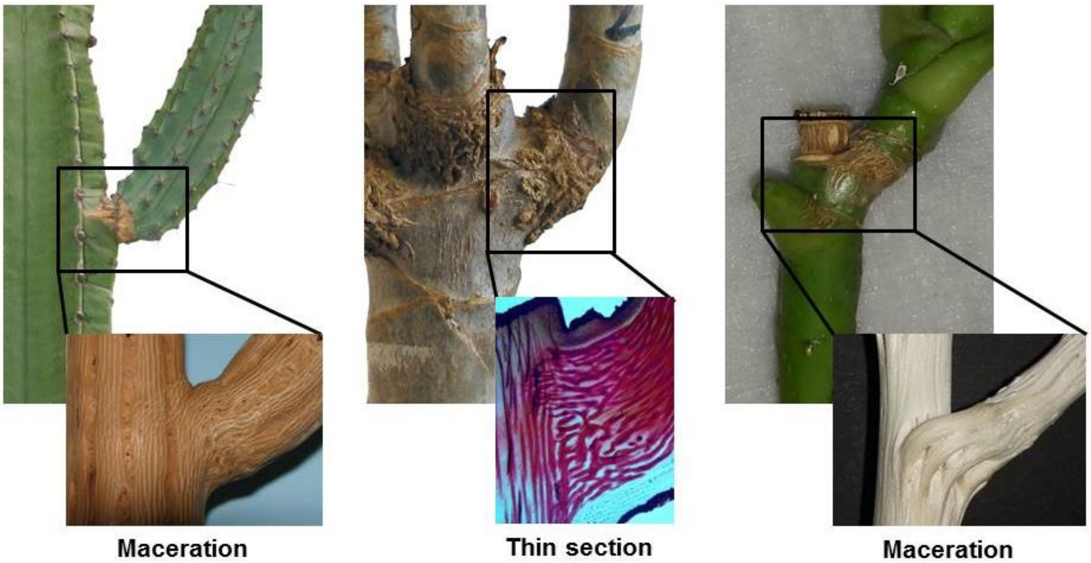

Figure 2. Branching regions of columnar cactus (*Pachycereus* sp.), dragon tree (*Dracaena marginata*) and dwarf umbrella tree (*Schefflera arboricola*) which serve as concept generators for the development of bioinspired branched fibrous composite structures, © Plant Biomechanics Group Freiburg & TU Dresden.

Actual R&D-projects deal with the development of branched fibrous composite structures for which the branching regions of dragon trees, columnar cacti and selected arborescent dicotyledons (e.g. dwarf umbrella tree, *Schefflera arboricola*) serve as concept generators (Fig. 2) [7,8,10,11]. These branched structures can be either realized by using glass fibre-reinforced polymers (GFRP) or carbon fibre-reinforced polymers (CFRP) (Fig. 3). The field of potential applications is large and ranges from frames (e.g. for motorbikes or bicycles) over bearing structures in machines, automobiles and in aerospace (e.g. stringers) to highly load-bearing constructions in architecture, where especially carbon fibre-reinforced polymers (CFRP) filled with light-weight free-floating concrete are of interest [11].

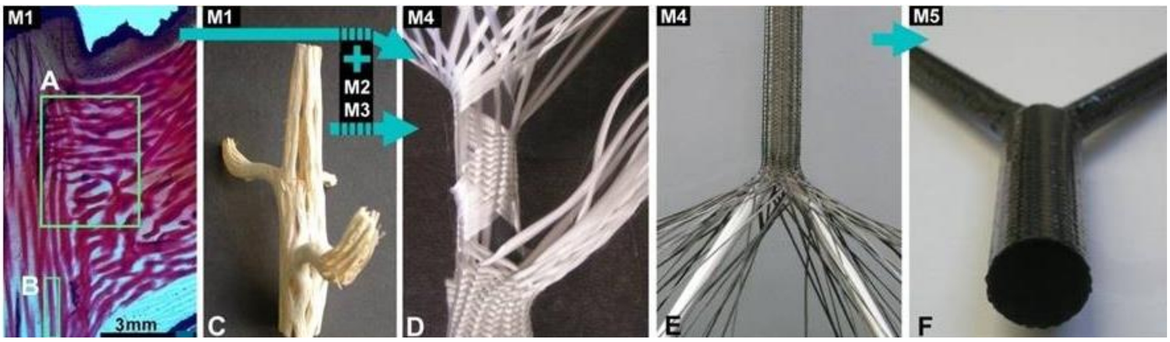

Figure 3. From the biological role model (branching region of dragon tree and columnar cactus) to the bioinspired branched fibrous composite structure, © Plant Biomechanics Group Freiburg, TU Dresden, ITV Denkendorf & ILK Dresden.

Excerpt from ISBN 978-3-00-053387-7

2.2. Structural materials with a high energy dissipation capacity and puncture resistance

Other examples for which fibrous plant materials are used as concept generators are bioinspired fibre-reinforced graded foams and ultra-thin-layer materials. They are inspired by fruit peels (pomelo, coconut) and seed coats (macadamia) and represent examples for structural materials with a high energy dissipation capacity and/or puncture resistance [12-14]. In the peel of pomelo (*Citrus maxima*), a large citrus fruit, a graded foam-like structure consisting of individual cells which constitute the struts of the foam is embedded in a three-dimensional network of lignified vascular bundles. This “construction” enables the fruit to survive impacts from up to 15 m high without splitting open or suffering from any other visible damage. The complex arrangement of graded foam and 3D-bundle network (Fig. 4) allows for a very efficient transfer of local impacts (small contact area of impacting fruit with the surface) to a global answer (involvement of a huge part of the peel/fruit volume in energy dissipation), and by this enables the pomelo (peel) to dissipate more than 90% of the impact energy [12,14,15]. Seed coats and fruit walls often represent very tough and puncture resistant protection layers sheltering the embryo and nutrients from desiccation, mechanical damage (e.g. by frugivorous animals) and other harmful influences (e.g. UV-radiation).

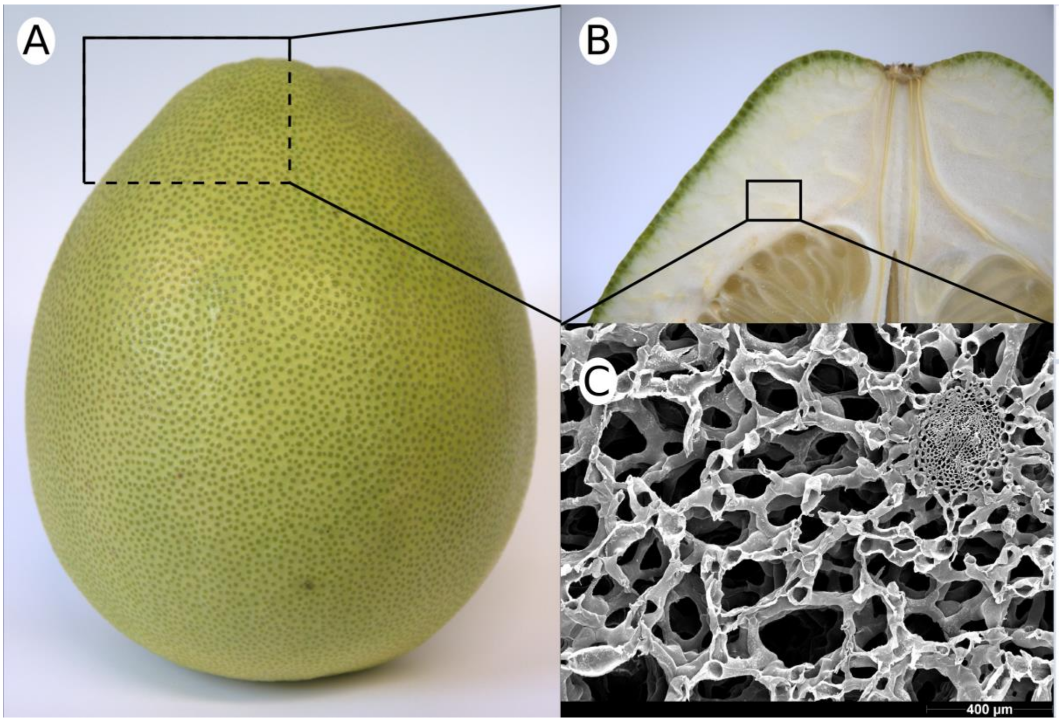

Figure 4. Pomelo fruit (A) showing the white peel (B) with foam struts (biological cells) embedded in a three-dimensional network of (lignified) vascular bundles (C), © Plant Biomechanics Group Freiburg.

Puncture resistant fruit walls and seed coats typically represent complex micro-laminated structures consisting of consecutive layers of (highly) lignified fibres/fibre bundles and (round) sclereid cells causing a combination of high toughness and stiffness which is fascinating as well from a technical as from a biological point of view. Interesting examples for such puncture resistant protection layers include the seed coat of macadamia (*Macadamia integrifolia*), which outcompetes other seed coats and nut shells by a factor of three regarding the ratio of fracture force over wall thickness [13], and the endocarp (inner layer of the fruit wall) of the coconut (*Cocos nucifera*) [14]. In collaboration with physicists, engineers, material scientists and architects from the RWTH Aachen, TU Berlin, the Universities of Stuttgart und Tübingen as well as with industrial partners, these plant structures were used as concept generators for

Excerpt from ISBN 978-3-00-053387-7

diverse applications. The applications range from highly energy dissipating and puncture resistant bioinspired materials for crash-boxes in cars or sheltering layers for transportation vessels of hazardous goods over helmets and other kinds of (sports-)protectors to novel types of impact and earthquake resistant building materials. These bioinspired materials can be produced on the basis of various classes of technical materials ranging from metals and minerals/concrete to polymers [16, 17, 18]. Other examples for innovative bioinspired fibre-based damping products include a shock-absorbing transportation pallet with dampers that were inspired by bamboo culms and the kind of embedding of hedgehog and porcupine spines in the tough skin of the respective animals [19].

2.3. Elastic architecture – the biomimetic façade-shading systems flectofin® and flectofold

Hinges and joints are regions of stress concentration in all technical moveable systems which often fail and typically need a considerable amount of maintenance making them often to the "week and costs expensive points" in technical constructions. Within the framework of elastic architecture we aim for transferring structural and functional solutions found in deployable and/or moving plant organs which move and alter shape without any localized hinge or joint into applications for a novel bioinspired architecture. The role models include motions of various plants organs including flower opening, deformation processes of fern false indusia shielding the sporangia, and trap movements of carnivorous plants [20-26]. As a first type of application bioinspired façade-shading systems were developed by a consortium of biologists, engineers and material scientists from the Universities of Freiburg and Stuttgart and the ITV Denkendorf. The biomimetic façade-shading systems flectofin® is inspired by the movement of the violet perch of the bird-of-paradise flower (*Strelitzia reginae*) which opens due to the weight of a pollinating bird landing on it in order to feed on the nectar at the base of the flower. The opening movement represents a torsional buckling process of a cylinder open on one side and can be repeated more than 3000 times without any material fatigue (Fig. 5).

Figure 5. Flower stand of the bird-of paradise flower with a violet perch acting as role model for the hingeless biomimetic façade-shading system flectofin®. Demonstrator of the biomimetic façade-shading system flectofin® actuated by bending of the backbone with hydraulic pistons at the base of each module in various states of closing, © Plant Biomechanics Group Freiburg, ITV Denkendorf & ITKE University of Stuttgart.

This biological concept generator was analysed and abstracted by the interdisciplinary team and rendered the basis for the development of the the hingeless façade-shading systems flectofin® which was patented in 2012 [25, 27-30]. Based on the mode of functioning of the flectofin® further bioinspired façade-shading systems were developed and for example used by SOMA architecture (Vienna) and Knippers Helbig Engineers (Stuttgart) in the One Ocean thematic pavilion at the Expo 2012 in Yeosu, South Korea [29]. A recent development was inspired by the motion of the snap trap of the water wheel plant

Excerpt from ISBN 978-3-00-053387-7

(*Aldrovanda vesiculosa*) in which the two leaf halfs, representing the two "cups" of the snap trap, are closed by a slight bending of the midrib due to motion amplification [25, 30]. Both biomimetic façade-shading systems were constructed using glass fibre-reinforced polymers (GFRP) and make use of the anisotropy of the fibre reinforced compound material [30].

3. Conclusions

Fibre-reinforced structural materials found in plants and animals share many structural and functional properties with fibre-reinforced compound materials and technical textiles and therefore can be used in various ways as inspiration for novel biomimetic materials. Interesting properties that can be transferred from biological role models to bioinspired technical products include high-loadbearing and vibration damping in (ultra-)lightweight branching regions, energy dissipation and puncture resistance as well as elastic deformability without joints and hinges [2]. New production methods (additive methods, 3D-braiding pultrusion to name just a few) developed during the last decade(s) allow for the first time to transfer many of the outstanding (mechanical) properties of biological role models into biomimetic products at reasonable costs and will markedly widen the field of application and the market chances of biomimetic products in the coming years. As a very interesting field of application, biomimetic architecture became of considerably increasing interest during the last decade as it allows to test biomimetic innovations already in a prototype state in future-bound buildings [3, 29]. Architecture furthermore allows for combining functional efficiency of the biomimetic solutions with the aesthetics of the biological role models. In both cases we succeeded not only in abstracting and transferring the mode of function of the biological role models into technical façade-shading systems but also in retaining the aesthetics of motion of the biological concept generators [29-31].

Acknowledgments

We thank the German Federal Ministry of Education and Research (BMBF), the MWK Baden-Württemberg and the Baden-Württemberg Stiftung for long-lasting financial support. The current projects have been funded by the German Research Foundation as part of the Transregional Collaborative Research Centre 141 'Biological Design and Integrative Structures' and of the Priority Programme SPP 1420 'Biomimetic Materials Research: Functionality by Hierarchical Structuring of Materials'.

References

[1] T. Speck and O. Speck. Process sequences in biomimetic research. In: Brebbia, C.A. (ed.), *Design and Nature IV*, 3-11. WIT Press, Southampton, 2008.

[2] T. Speck and O. Speck. Von der Klette zum Klettverschluss - Bionik oder wie wir von der Natur die Technik der Zukunft abschauen. *Naturwissenschaftliche Rundschau*, 68/10: 510-523, 2015.

[3] J. Knippers and T. Speck. Design and construction principles in nature and architecture. *Bioinspiration and Biomimetics*, 7, 2012. DOI:10.1088/1748-3182/7/1/015002

[4] U.G.K. Wegst, H. Bai, E. Saiz, A.P. Tomsia and R.O. Ritchie. Bioinspired structural materials. *Nature Materials*, 14: 23-36, 2015.

[5] H. Schwager, T. Masselter T. Speck, and C. Neinhuis. Functional morphology and biomechanics of branch-stem junctions in columnar cacti. *Proceedings of the Royal Society London B*, 280: 0132244. 2013. http://dx.doi.org/10.1098/rspb.2013.2244

[6] M. Milwich, T. Speck, O. Speck, T. Stegmaier and H. Planck. Biomimetics and technical textiles: solving engineering problems with the help of nature's wisdom. *American Journal of Botany*, 93: 1455-1465, 2006.

[7] H. Schwager, T. Haushahn, C. Neinhuis, T. Speck and T. Masselter: Principles of branching morphology and anatomy in arborescent monocotyledons and columnar cacti as concept

Excerpt from ISBN 978-3-00-053387-7

generators for branched fibre-reinforced composites. *Advanced Engineering Materials/Advanced Biomaterials*, 12: B695-B698, 2010.

[8] L. Müller, M. Milwich, A. Gruhl, H. Böhm, M. Gude, T. Haushahn, T. Masselter, H. Schwager, T. Neinhuis and T. Speck. Biomimetically optimized branched fiber composites as technical components of high load capacity. *Technical Textiles*, 56/5: 231-235, 2013.

[9] M. Milwich, H. Planck, T. Speck and O. Speck. The technical plant stem: a biomimetically inspired narrow fabric. *Melliand – Narrow Fabric and Braiding Industry*, 44/2: 34-38, 2007.

[10] T. Haushahn, T. Speck and T. Masselter. Branching morphology of decapitated arborescent monocotyledons with secondary growth. *American Journal of Botany*, 101: 754-763, 2014.

[11] L. Born, F.A. Jonas, K. Bunk, T. Masselter, T. Speck, J. Knippers and G. Gresser. Branched structures in plants and architecture. In: Knippers, J., Speck, T. and Nickel, K. (eds.), *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*. Biologically-Inspired Systems, Springer, Heidelberg, Berlin, in press, 2016.

[12] M. Thielen, C.N.Z. Schmitt, S. Eckert, T. Speck and R. Seidel Structure-function relationship of the foam-like pomelo peel (Citrus maxima) - an inspiration for the development of biomimetic damping materials with high energy dissipation. *Bioinspiration and Biomimetics*, 8, 2013. DOI:10.1088/1748-3182/8/2/025001

[13] P. Schüler, T. Speck, A. Bührig-Polaczek and C. Fleck. Structure-function relationship in *Macadamia integrifolia* seed coats – Fundamentals of the hierarchical microstructure. *PLoS ONE*, 9(8): e102913, 2014. DOI:10.1371/journal.pone.0102913

[14] S. Schmier, C. Lauer, I. Schäfer, K. Klang, G. Bauer1, M. Thielen, K. Termin, C. Berthold, S. Schmauder, T. Speck and K.G. Nickel: Developing the experimental basis for an evaluation of scaling properties of brittle and 'quasibrittle' biological materials. In: Knippers, J., Speck, T. and Nickel, K. (eds.), *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*. Biologically-Inspired Systems, Springer, Heidelberg, Berlin, in press, 2016.

[15] M. Thielen, T. Speck and R. Seidel. Impact behaviour of freeze-dried and fresh pomelo (*Citrus maxima*) peel – Influence of the hydration state. *Royal Society Open Science*, 2:140322, 2015. DOI.org/10.1098/rsos.140322.

[16] S.F. Fischer, M. Thielen, R.R. Loprang, R. Seidel, C. Fleck, T. Speck and A. Bührig-Polaczek. Pummelos as concept generators for biomimetically inspired low weight structures with excellent damping properties. *Advanced Engineering Materials/Advanced Biomaterials*, 12: B658-B663, 2010.

[17] S.F. Fischer, M. Thielen, P. Weiß, R. Seidel, T. Speck, A. Bührig-Polaczek and M. Bünck. Production and properties of a precision-cast bio-inspired composite. *Journal of Materials Science*, 49: 43-51, 2014.

[18] K. Klang, G. Bauer, N. Toader, C. Lauer, K. Termin, S. Schmier, W. Haase, C. Berthold, K.G. Nickel, T. Speck and W. Sobek. Plants and animals as source of inspiration for energy dissipation in load bearing systems and facades. In: Knippers, J., Speck, T. and Nickel, K. (eds.), *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*. Biologically-Inspired Systems, Springer, Heidelberg, Berlin, in press, 2016.

[19] T. Masselter, M. Milwich, H. Monnerat, U. Scharf, M. Hartel and T. Speck. Bio-inspired solutions for technical problems: biomimetic cable entries and schock-absorbing pallets. In: Brebbia, C.A. (ed.), *Design and Nature IV*, 51-58. WIT Press, Southampton, 2008.

[20] S. Poppinga, T. Masselter, J. Lienhard, S. Schleicher, J. Knippers and T. Speck. Plant movements as concept generators for deployable systems in architecture. In: Brebbia, C.A. & Carpi, A. (eds.), *Design and Nature V*, 403-410. WIT Press, Southampton, 2010.

[21] O. Vincent, C. Weißkopf, S. Poppinga, T. Masselter, T. Speck, M. Joyeux, C. Quilliet and P. Marmottant. Ultra-fast underwater suction traps. *Proceedings of the Royal Society London, B*, 278: 2909-2914, 2011.

[22] S. Poppinga, S.R.H. Hartmeyer, R. Seidel, T. Masselter, I. Hartmeyer and T. Speck. Catapulting tentacles in a sticky carnivorous plant. *PLoS ONE* 7(9): e45735, 2012. DOI: 10.1371/journal.pone.0045735.

Excerpt from ISBN 978-3-00-053387-7

[23] S. Poppinga, T. Masselter and T. Speck. Faster than their prey: new insights into the rapid movements of active carnivorous plants traps. *Bioessays*, 35: 649-657, 2013.

[24] S. Poppinga, T. Haushahn, M. Warnke, T. Masselter and T. Speck. Sporangium exposure and spore release in the polypod fern *Adiantum peruvianum* (Pteridaceae). *PLoS ONE*, 10(10): e0138495, 2015. DOI:10.1371/journal.pone.0138495

[25] S. Schleicher, J. Lienhard, S. Poppinga, T. Speck and J. Knippers A methodology for transferring principles in plant movements to elastic systems in architecture. *Computer-Aided Design*, 60: 105-117, 2015. DOI.org/10.1016/j.cad.2014.01.005

[26] S. Poppinga, C. Weisskopf, A. Westermeier, T. Masselter and T. Speck. Fastest predators in plant kingdom: Functional morphology and biomechanics of suction traps found in *Utricularia*, the largest genus of carnivorous plants. *Annals of Botany PLANTS*, 8, 2016. DOI: 10.1093/aobpla/plv140.

[27] J. Lienhard, S. Schleicher, S. Poppinga, T. Masselter, M. Milwich, T. Speck and J. Knippers. Flectofin: a nature based hinge-less flapping mechanism. *Bioinspiration and Biomimetics*, 6, 2011. DOI:10.1088/1748-3182/6/4/045001

[28] S. Schleicher, J. Lienhard, S. Poppinga, T. Speck and J. Knippers. Abstraction of bio-inspired curved-line folding patterns for elastic foils and membranes in architecture. In: Brebbia, C.A. & Carpi, A. (eds.), *Design and Nature V*, 479-490. WIT Press, Southampton, 2010.

[29] T. Speck, J. Knippers and O. Speck. Self-x-materials and -structures in nature and technology: Bio-inspiration as driving force for technical innovation. *AD Architectural Design*, 85(5): 34-39, 2015.

[30] S. Poppinga, A. Körner, R. Sachse, L. Born, A. Westermeier, L. Hesse, J. Knippers, M. Bischoff, G. Gresser, M. Milwich and T. Speck. Compliant mechanisms in plants and architecture.. In: Knippers, J., Speck, T. and Nickel, K. (eds.), *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*. Biologically-Inspired Systems, Springer, Heidelberg, Berlin, in press, 2016.

[31] T. Speck. Approaches to Bio-inspiration in Novel Architecture. In: B. Imhof & P. Gruber (eds.), *Built to Grow - Blending architecture and biology*, 145-149. Birkhäuser Verlag, Basel, 2015.

Excerpt from ISBN 978-3-00-053387-7