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Biomimetic Fiber-Reinforced Compound Materials

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1. Introduction

During the last years, many efforts have been made to transfer results of quantitative analyses of functional morphology and biomechanics in plants into technical applications. These attempts have been increasingly successful as is proven by the increasing number of biomimetic products on the market (e.g. paints based on the Lotuseffect® among many others, see Bar-Cohen (2006) and Masselter et al. (2010a)), of which the top 100 biomimetic products have generated about 1 billion Euros in 2005 to 2008 (Bushan, 2009). These successes are the result of the long period over which the form-structure-function relationships of the plants have been investigated and understood. Of the broad spectrum of biomimetic products, fiber-reinforced composites represent some of the most successful biomimetic technical applications. The potential of developing biomimetic fiber-reinforced compound materials is very high because 1) the fiber-matrix structure in plants is comparable to those in technical materials and 2) the complex fiber-matrix structures in plants are organized in at least five hierarchical levels (Masselter et al., 2009b, 2010a; Speck T. et al., 2007), from the molecular scale over the nanoscale and microscale to macroscale (Jeronimidis, 2000a). Quantitative analysis of this hierarchical structuring of plants is generally being increasingly recognized as one of the most important keys for understanding the form-structure-function relationships in plants (see Fratzl, 2007). This method allows interpreting and abstracting the interaction between the structural components in plants that possess different mechanical properties and in consequence, building a new generation of lightweight but stiff fiber-reinforced biomimetic compound materials (Masselter 2009b, 2010a,b; Speck, O. et al., 2005; Speck, T. et al., 2007; Speck, T. & Speck, O. 2008).

In a biomimetic project, dealing with the development of fiber-reinforced compound materials the most important assets are the biological concept generators, which can be linear (unbranched) or branched, thereby mirroring the structures that are present in technics. Branched structures as Y- and T-shaped branched components are very common in many fields of technical applications (Fig. 1). In plants, these branchings have to bear high static and dynamic loads that form a complex overlay of different loading modes: bending, compression-tension and torsion (Jeronimidis, 2000b). In technics, similar loads often drastically decrease the life time of a technical component causing wear and material fatigue

(Fig. 1C). This situation is further complicated by the need to join these technical structures together by welding or riveting. These joints represent potential failure regions as notch stresses are often very high in these regions (Mattheck, 2007). What's more, producing these joinings is time-consuming and costly. In plants, branchings are developed and shaped in a manner so that notch stresses present in 'joints' (i.e. stem-branch attachments) are diverted and distributed, so that similar zones of weakness do not develop (Mattheck, 1990, 2007; Mattheck & Tesari 2002; Schwager et al., 2010).

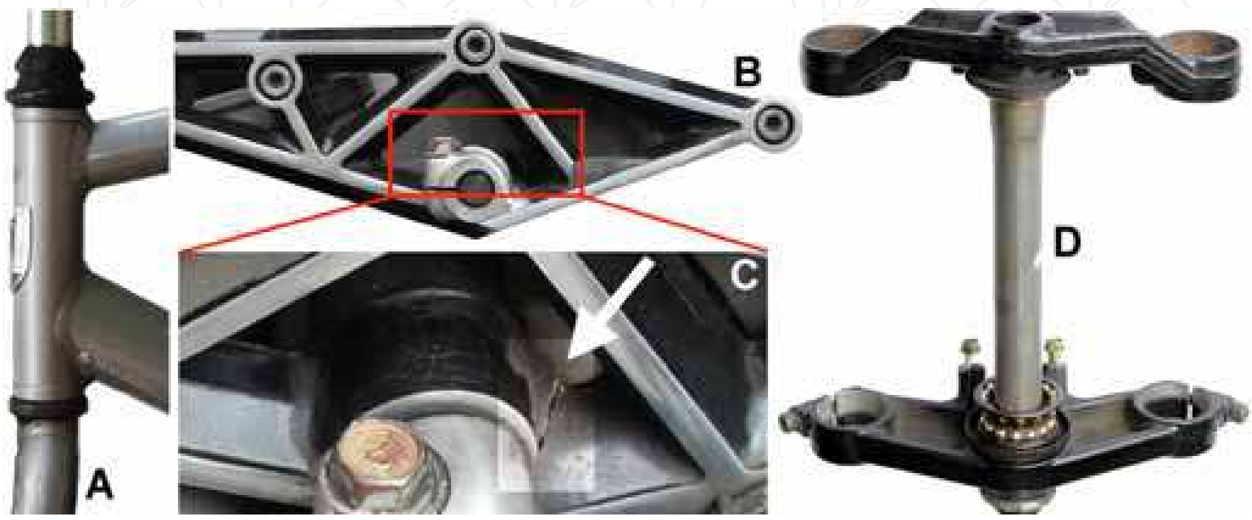

Fig. 1. Supporting structures in bicycle and motorbike engineering. (A) Headset of bicycle, (B),(C) subframe of motorbike with failure (arrow), (D) metal fork bridge of motorbike. © PBGF.

Generally speaking, plants are ‚ideal' concept generators for improving branched or unbranched technical structures since:

- Plants typically 'avoid' critical notch stresses
- Plants are lightweight structures
- Plants possess interesting mechanical properties like for example high stiffness and strength combined with a benign fracture behavior and good damping
- The laminated configuration of technical fiber-reinforced compound materials and the structure of some plant stems are highly comparable (Fig. 2, Ehrenstein, 2006; Speck T. et al., 2007)

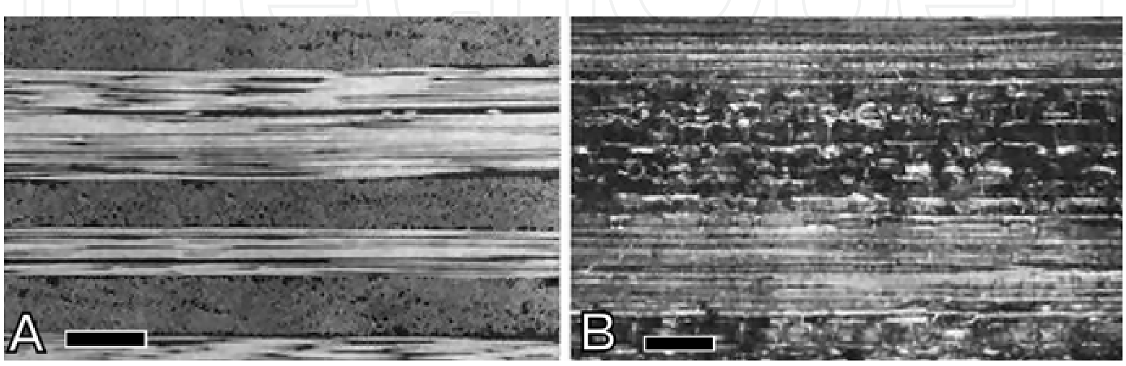

Fig. 2. Section of carbon-fiber-reinforced laminate (A) and bamboo stem wall (B) (from Ehrenstein, 2006). Scale bars = 200 µm.

2. Biomimetic fiber-reinforced compound materials and structures

2.1 Linear ‚unbranched' structures

2.1.1 Wood: Hierarchical structuring and microfibril angle

There exist numerous applications in which wood, wood pulp and natural fibers are used as components in the manufacturing of composites (e.g., Gindl & Jeronimidis 2004) for improving mechanical, thermal or other beneficial properties. Until now, the potential of using the hierarchical structure of wood as concept generator for developing innovative biomimetic fiber-reinforced compound materials has still been too little utilized (Fratzl, 2002b, 2007), even though wood is an excellent example for a complex structure that has led to several biomimetic applications (see below). The hierarchical structure of wood is well visible, including stem, tissue (Fig. 3A), cell (Fig. 3B,C) and ultrastructural level (Fig. 3D). Microfibril angles, i.e., the angles between the microfibrils and the longitudinal axis of wood tracheids, range typically between 0 and 30 degrees (Fig. 3D).

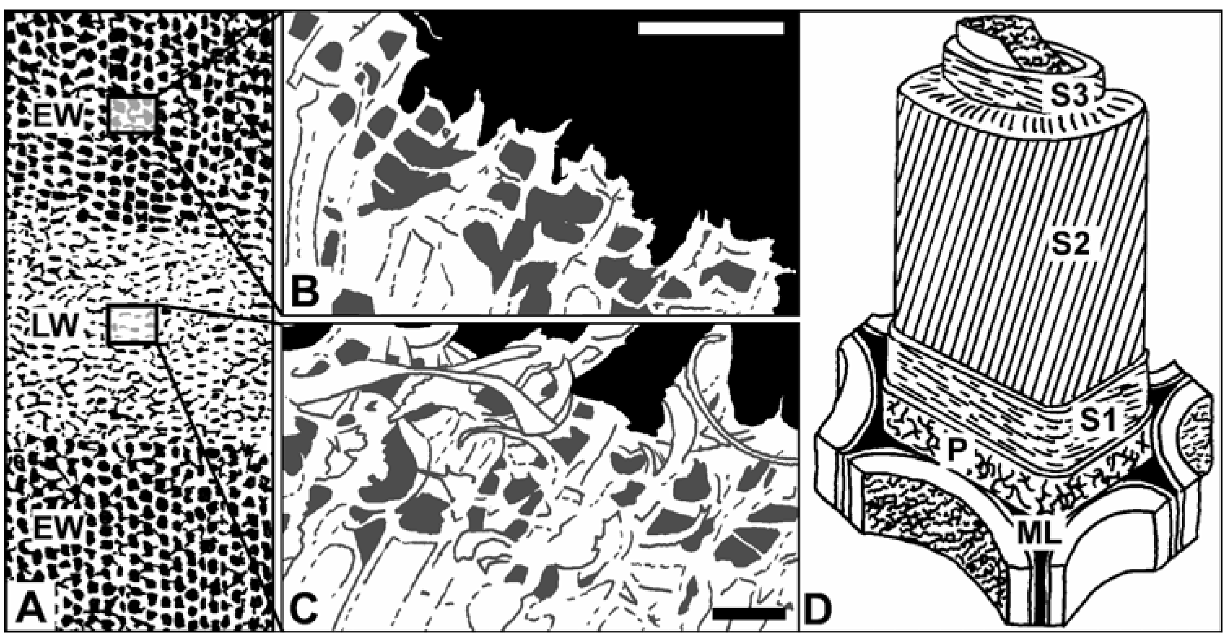

Fig. 3. Schematic drawing showing the hierarchical structure of spruce wood. (A) Tissue-level: cross-section of spruce wood; earlywood (EW) can be dinstiguished from the denser latewood (LW), (B, C) cell level: cellulose microfibril angle differs in (B) (0°) and (C) (50°) resulting in a plane fracture surface (B) or a highly structured fracture surface (C) in which tracheids and part of the tracheid wall are torn out, (D) ultrastructural level: different layers of a wood fiber tracheid can be distinguished: ML: middle lamella, P: pectin layer, S1-3: cell wall layers 1-3. The layer S2 represents approx. 80% of the overall thickness. Scale bars: (B) 100 µm; (C) 50 µm. Redrawn from Fratzl (2002a), Lichtenegger et al. (1999), Reiterer et al. (2001) and Vincent (2003). © PBGF.

When loaded under tension parallel to the longitudinal axis of the tracheids, spruce wood may show a markedly different fracture behavior (Fig. 3B, C) depending on the values of the fiber angle in the S2 wall of the fibers (Jeronimidis, 1979, 1980a,b, Fig. 3D). When the angles are well above 0°, the lignin between the helically arranged cellulose microfibers in the cell wall fractures (Fig. 3C) (Reiterer et al., 2001). This mechanism allows the tracheids to elongate, dissipates large amounts of energy and leaves the cellulose microfibers intact, so that they are still able to carry a load. Other interesting mechanical properties of wood for biomimetic applications are its low density, a high Young's modulus for resisting compressive forces, high fracture stress for resisting lateral forces and a large fracture strain to survive bending.

In a GFRP (glass-fiber reinforced plastic) with helically wound fibrous tubes, failure modes are very similar (Fig. 4A) to the failure modes of spruce wood (Gordon & Jeronimidis, 1980). There is a maximum of the work of fracture for a winding angle of 15° if subjected to three-point bending and tension. Initial failure is due to the resin between the fibers failing in shear (Fig. 4B). After that, the fibers rotate toward the longitudinal axis of the tubes, increasingly shearing the matrix and giving rise to further failures (Fig. 4B). This extends the strain before final failure and absorbs a large amount of energy. Both effects are of high interest for technical implementations. The findings of Gordon & Jeronimidis (1980) led to a patented composite material (Fig. 4C), which represents a different way of building a system of tubes with helically arranged fibers by using corrugation, with an optimal fiber angle α of about 15 degrees.

The potential fields of technical implementation are manifold, above all in the automotive industry and particularly in aerospace (Fig. 5) (Mangalgiri, 1999; Zhang et al., 2007). In new airplanes like the A380, compound materials contribute to 20-22% of the weight (Quilter, 2004). Carbon-fiber reinforced plastic, glass-fiber reinforced plastic and quartz-fiber reinforced plastic are used extensively in the wings, the fuselage sections, the tail and the doors (http://aero-defense.ihs.com).

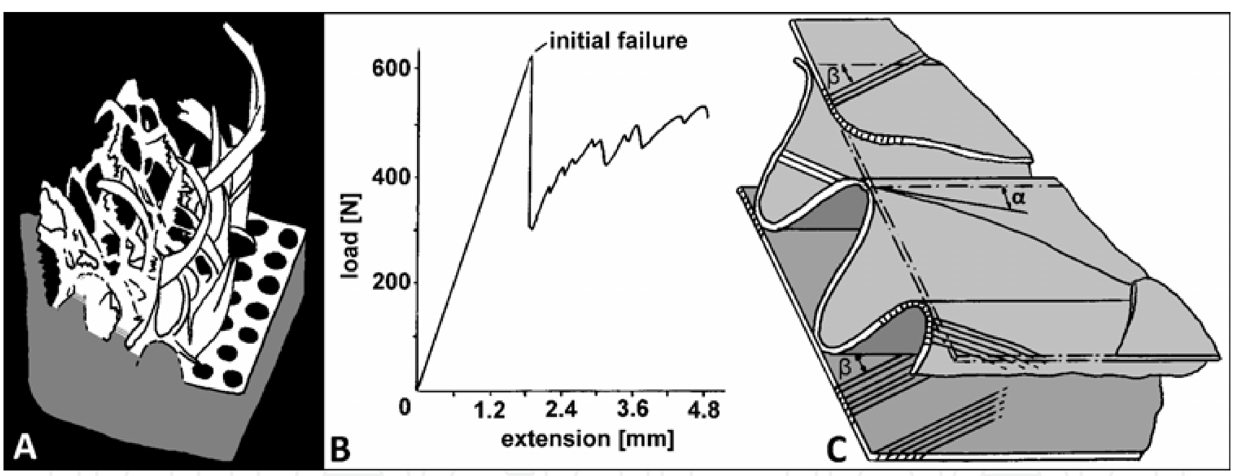

Fig. 4. Biomimetic glass-fiber reinforced plastics (GFRP). (A) Fracture morphology for GRFP with macrofibers, (B) force-displacement curve for GFRP, (C) patented composite material using optimized orientation of the reinforcing fibers to a corrugated medium. Redrawn from Caplin et al. (1983) and Gordon & Jeronimidis (1980). © PBGF.

2.1.2 Autonomous actuation and self-adaptation

Passive actuation systems in plants are of special interest for a biomimetic transfer as no active movements have to be abstracted and transferred into a technical application. Passive movements of plants or plant organs are mainly caused by changes in environmental conditions that act on dead tissues and cells (Dawson et al., 1997; Elbaum et al., 2007). Cell wall swelling or shrinking is effectuated by a combination of stiff cellulose fibrils that are embedded in different angles in a pliant and highly swellable matrix. Through this

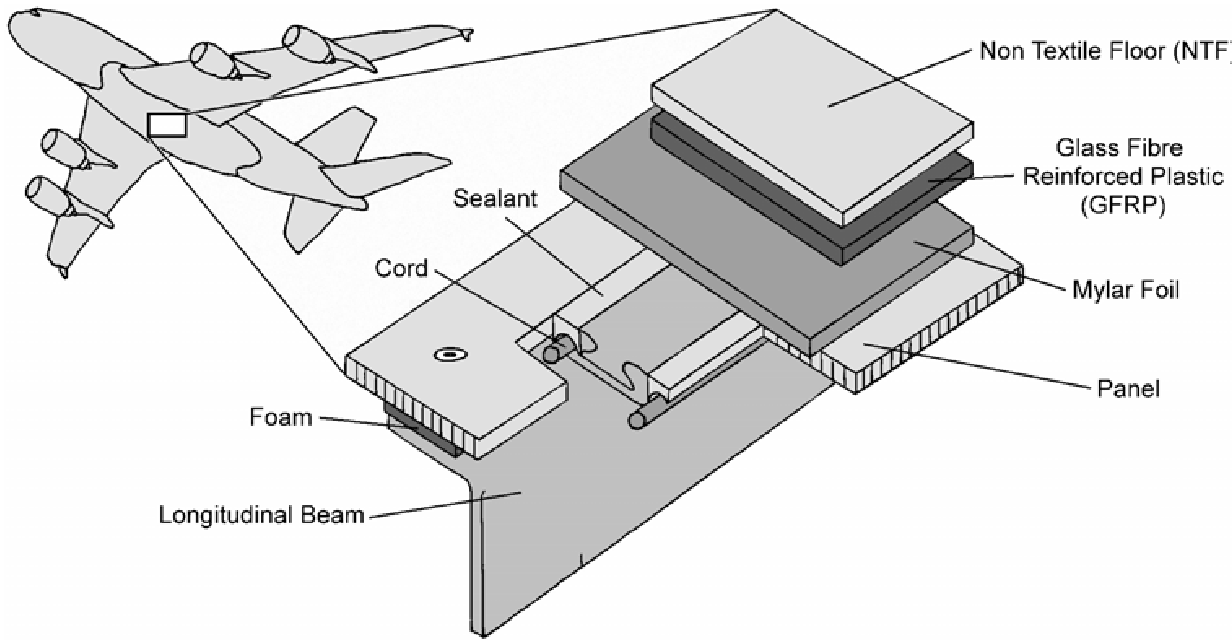

Fig. 5. Sandwich structure of the fuselage in a modern aircraft. Redrawn from http://www.airbus.com © PBGF.

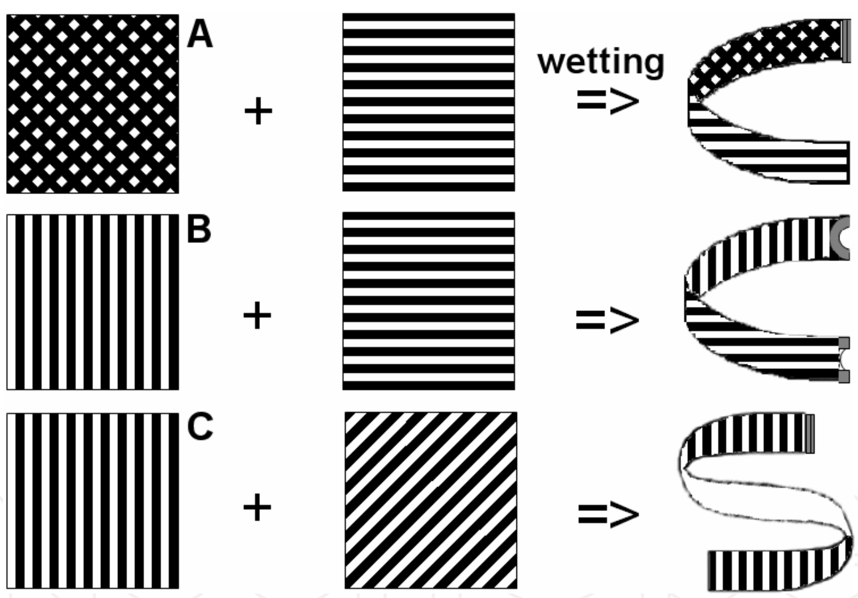

Fig. 6. Actuation principles of compound layer models. Different movements can be achieved by hydrating a swelling layer depending on its joining to a non-swelling layer. (A) Bending in a layer in which the fibers are parallel in one layer and in the other randomly organized, (B) rolling and bending in a bimorph layer with fibers and swelling direction of the two layers at an angle of 90°, (C) twisting and torsion in a similar bimorph layer with 45° angle. Redrawn from Stahlberg & Taya (2006). © PBGF.

structure, plants can generate various actuators by combining tissue layers consisting of cells with different swelling behavior and therefore elongation when wetted or dry. This actuator may cause bending, rolling and bending, twisting and torsion of plant organs (Fig. 6) and can cause large deformations. The modes of deformation depend on the relative

orientation of the cellulose microfibrils and the relative swelling direction of the two tissue layers (Fig. 6).
One of these actuation principles can be observed in wheat awns (Fig. 7A-C). These elongate structures are attached to the wheat fruit (Fig. 7A). By a passive movement, they assist in the dispersion and mobility of the fruit. In the adaxial side of the awn, the cap, the cellulose microfibrils are almost parallel to the longitudinal axis of the awn, on the abaxial side, the ridge, the microfibers are randomly organised (Fig. 7B). A change in humidity in the daily cycle causes differential swelling of the two sides and bending of the awns, by which the awned fruits dig themselves into the ground. As there are hooks on the abaxial side of the awns, preventing them from going upward (out of the soil) the fruits are pushed deeper in the ground (Fig. 7C) with every wetting-desiccation cycle (Burgert & Fratzl, 2009; Elbaum et al., 2007; Fratzl et al., 2008)

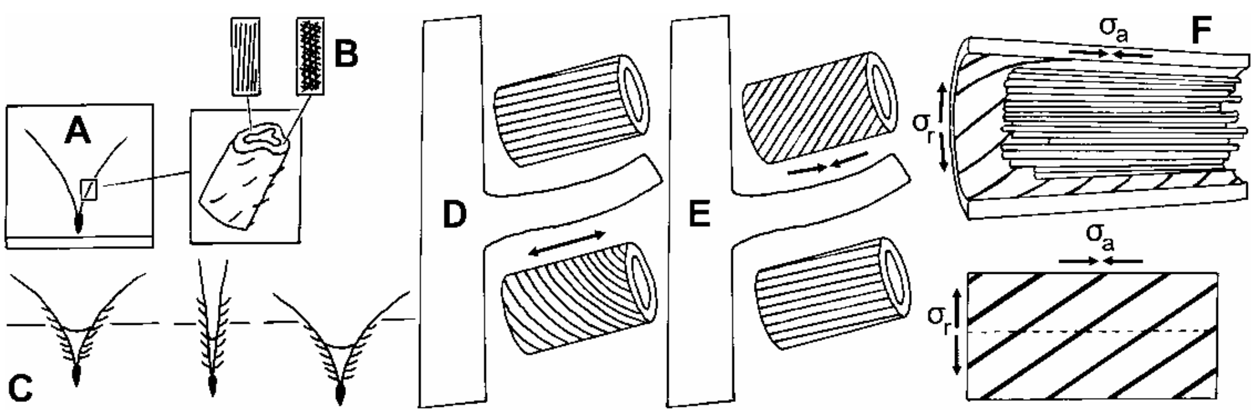

Fig. 7. Passive actuation systems in plants. (A) Dispersal unit of wheat with awns, (B) layers with axioparallel fibers (adaxial layer) and randomly organized fibers (abaxial layer) that cause bending (C) in daily cycles (open at day (dry) and closed by night (wet) due to a change in moisture. These cycles push the fruit in the ground. (D) Uprighting of a conifer branch by compression wood at the lower side of the branch. The angles in the microfibrils in normal wood (above) and compressive wood (below) are markedly different. Hygroscopic swelling increases the length of the compression wood tracheids causing an upright bending of the branch. (E) Uprighting of an angiosperm tree branch by tension wood in the upper side of the branch. (F) Model of the functioning principle of tension wood. Swelling of the gelatinous G-layer fibers (horizontal tubes at upper image) creates circumferential hoop stresses σ_r in the tracheid that are converted into axial tensile stresses σ_a shortening the length of the tracheid. The ratio between the axial tensile stresses σ_a and the radial stresses σ_r depends on the angle of the microfibrils. Redrawn from Burgert & Fratzl (2009), Elbaum et al. (2007) and Goswami et al. (2008). © PBGF.

Compression wood (Fig. 7D) as well as tension wood (Fig. 7E) can also act as actuators, by changing the curvature of the axis of a branch (Fig. 7D,E). In compression wood, swelling leads to an axial elongation of the wood (Fratzl et al., 2008). In tension wood, swelling leads to a reduction in axial length, depending in both cases on the angle of the cellulose microfibrils in the cell wall of the tracheid of wood fibers respectively. In tension wood, if the structure is exposed to humidity, the axioparallel G-layer fibers swell, leading to circumferential hoop stresses and inducing tensile stresses in and shortening of the cell wall, which causes actuation of a movement and a change of curvature of the branch (Burgert & Fratzl, 2009; Fratzl et al., 2008; Jeronimidis, 1980a).

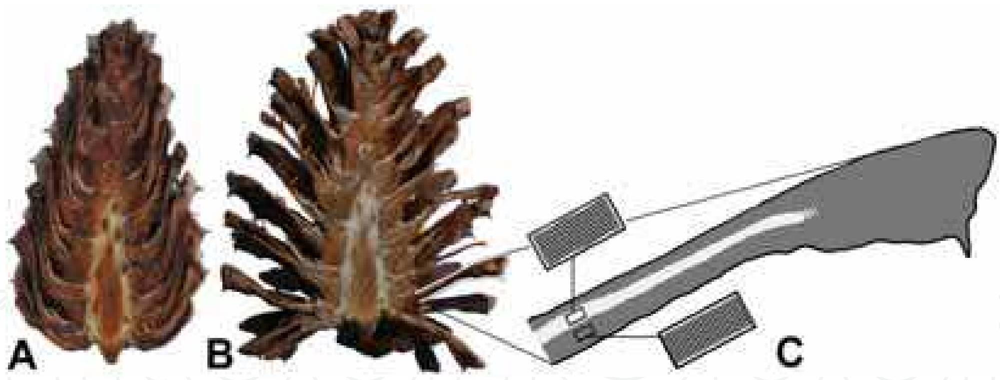

Fig. 8. Opening and closure of pine cones (*Pinus nigra*) due to changing moisture conditions. (A) Closed, wet state, (B) opened, dry state, (C) longitudinal schematic section displaying the differing directions of the fibers at the lower and the upper part of the seed scale leading to rolling and bending of the scale. © PBGF.

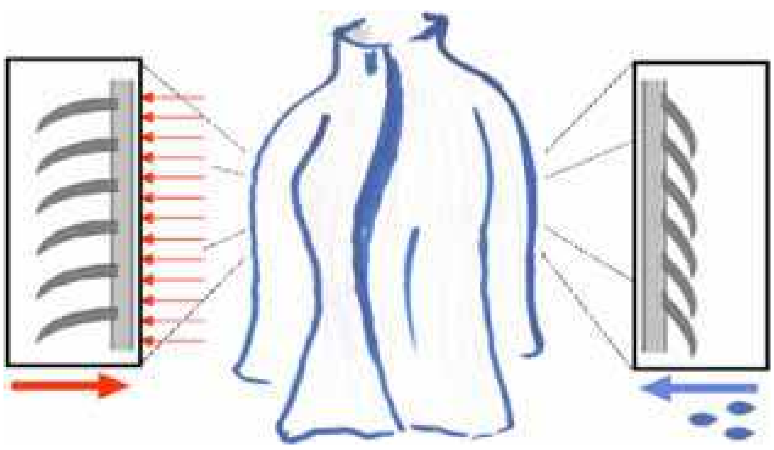

Fig. 9. Biomimetic clothing using an actuation principle similar to that of the pine cones to regulate ventilation and insulation. © PBGF.

In technical implementations, i.e. in fiber-reinforced compound materials, a wide range of potential movements and shape-shifts can be attained (Burgert & Fratzl 2009; Fratzl et al., 2008) using these actuation principles. One example of such a structure is the development of a biomimetic garment using the large displacement generated by moisture in pine cones (Fig. 8). These biological structures open up and close depending on the humidity of the environment (Fig. 8A,B). The orientation of the cellulose microfibrils in the cell walls of the upper side of the scale is almost parallel to the longitudinal axis of the scale; the microfibrils in the cell walls in the lower side of the scales are oriented almost perpendicular to the longitudinal axis of the scale (Burgert & Fratzl, 2009; Dawson et al., 1997, Fig. 8C). When the seeds are ripe, the cells in the scales die and desiccation causes a differential shrinking of the scale cells and an abaxial bending of the scales. This leads to an opening of the cone and allows the release of the anemochorous seeds.

Using the ‘pine cone effect’, an innovative self-adaptive clothing with small flaps that open and close depending on the moisture content of the environment (i.e., the sweatiness of the wearer) was developed by Julian Vincent from the University of Bath and Veronika Kapsali from the London College of Fashion (Fig. 9). Similar to its biological concept generator, the garment consists of two layers: one swellable layer with a dual structure, possibly wool combined with thin spikes each only 1/200th of a millimeter wide. This layer opens up when it is wetted and closes when it dries, thereby reducing its permeability and increasing the insulation. The wearer is protected against splash water and rain by an additional second layer.

Functioning has been demonstrated by developing a prototype using this relatively simple actuation principle which has the added advantage of being very failsafe and therefore highly reliable. Potential implementations are manifold because the novel biomimetic structural material is adequate for use in athletic performance, comfort wear, fabrics in the health sector, agriculture, building, packaging and upholstery.

2.1.3 External actuation and elastic architecture

Passive movements in plants are induced by external forces. This allows for movements of high complexity, including multiplanar simultaneous deformation. An excellent example is the fold-flap system present in the flower of the Bird-of-Paradise (*Strelitzia reginae*, Fig. 10, Lienhard et al., 2009, 2010; Poppinga et al., 2010a,b).

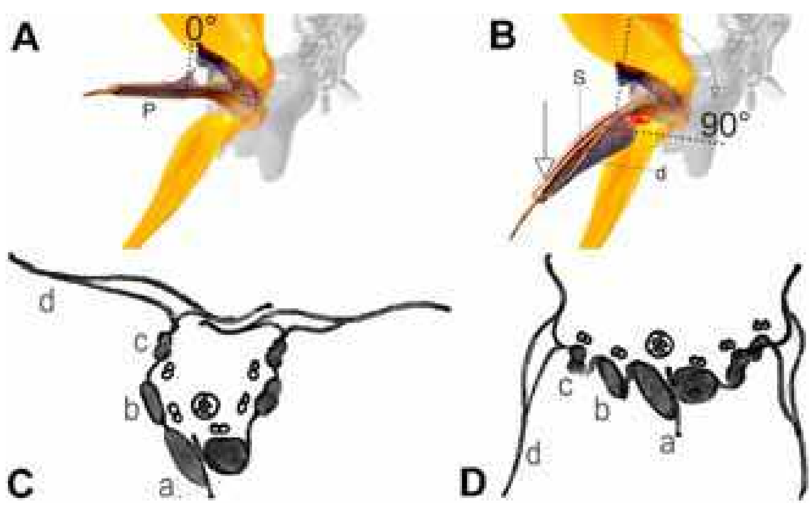

Fig. 10. Actuation principle of *Strelitzia reginae.* (A) Original (closed) position of the perch (p), (B) if the perch is bent down, the perch lamina (d) rotates and flaps sideways at an angle of approx. 90°, inducing opening of the flower and exposure of stamina and style (s), (C) schematic cross-section through the perch, with the closed lamina (d) and the top ribs (c), the middle ribs (b) and the compound lower rib at its bottom (a), (D) same cross-section as in C, in opened position. © PBGF and itke University of Stuttgart.

The flower of *S. reginae* has evolved a special landing platform –the perch- (Fig. 10A) for its pollinators, which are small birds. If a bird lands on the specially structured perch (p) to feed on nectar, the perch is bent down (Fig. 10B). The perch is composed of two petals and consists of stiff fibrous ribs (Fig. 10C, D) attached to a lamina (d) which is a thin and flexible parenchymatous tissue. When this composite structure is bent down, torsional buckling occurs, the lamina is simultaneously bent sideways, and the previously enclosed stamina (s) and style become exposed and pollen can be transferred to the bird's feet. When no force acts on the perch, i.e., the bird takes off, the deformation of the perch is reversed and the initial state is restored. This cycle can be repeated up to three thousand times with an almost identical force-displacement curve (Poppinga et al., 2010a,b). The mechanical behavior in bending is based on the interaction of the deforming fibrous ribs and the flexible lamina changing its curvature.

This can be abstracted in a first step by physical demonstrators consisting of a plastic rod with a rectangular plastic lamina glued vertically in longitudinal direction on top of the rod, forming a structure that shows similar torsional behavior when bent. In a next step computer simulations via Finite Element modeling are carried out (Fig. 11). These simulations allow for a detailed understanding of the abstracted systems, a mechanical analysis of developing stresses and strains under deformation and an evaluation of the potential technical applicability of the structures (Lienhard et al., 2009, 2010; Poppinga et al., 2010a).

The technical implementations of such systems are for example façade-shading systems (Fig. 12), which are patented under the name Flectofin™. The Flectofin™ principle uses the coupling of two main elements. A supporting rod acts as backbone element and has a rectangular cross-section. The rod can be easily bent in the direction of the smaller cross-section. The lamina or fin is a thin shell element that is attached perpendicular to the rectangular rod. The sideways bending and finally 90° flapping of the fin is a failure mode initiated by torsional buckling when bending the backbone (compare Figs. 10 and 11). As a result the curvature of the fin is changed to produce a double bent shell, which provides higher stiffness for the whole system (see Fig. 12).

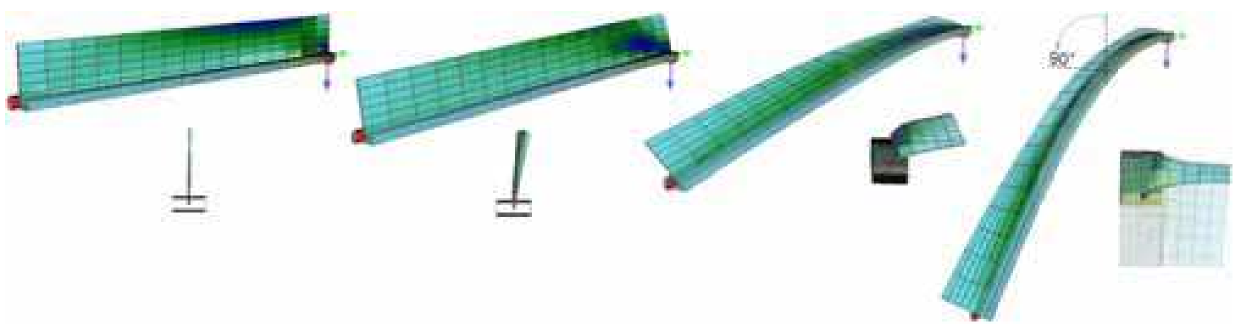

Fig. 11. Simulation of the abstracted kinetic structure in a finite element model. © itke University of Stuttgart.

Fig. 12. Demonstrator for a façade shading system able to bend sideways up to an angle of 90° inspired by the kinetic system found in the flower of *Strelitzia reginae*. Torsional buckling and displacement of the lamina are induced by slightly bending the supporting rod. © itke University of Stuttgart.

The Flectofin™ principle can be applied to various technical purposes. Possible application fields range from technical microflaps for functional coatings to large scale adaptive façade shading systems in architecture. It also can be used for prevention of or retaining of humidity, improving microclimates and working conditions for people and machines.

2.1.4 Morphological and mechanical gradients

Biological structures can incorporate a wide range of morphological gradients, e.g., in size of particles (coarse-fine), density of fibers, fiber angle, cell wall thickness, cell sizes, etc. Often these morphological gradients are complex and render the structural basis of mechanical gradients such as stiffness, hardness, breakage, damping and wear behavior. Understanding the morphological-mechanical relation of these gradients and their hierarchical arrangement in biological structures may help in improving the mechanical performance of biomimetic compound materials composite technical structures and avoid failure such as delamination.
Gradients at stem, tissue, cellular and subcellular level can be found in recent plants (e.g. *Washingtonia robusta*, Rüggeberg et al., 2008, 2009) or *Arundo donax* (Spatz et al., 1997, Rüggeberg et al., 2010) as well as in fossil species (e.g., *Medullosa* sp., see Speck, T. & Masselter, 2008).

2.1.4.1 Washingtonia robusta

Morphological-mechanical gradients are present on different hierarchical levels in the Mexican fanpalm, *Washingtonia robusta* (Fig. 13). At stem level to tissue level, the vascular bundles with their fiber caps are distributed unevenly in the cross-section of the cortex and of the central cylinder (Fig. 13). The number of vascular bundles and the size and structure of the fiber caps changes from the center to the periphery. The fiber caps are built of homogeneously thick-walled fibers and therefore are very stiff at the stem periphery, thus providing high flexural stiffness to the stem. The fiber caps located in the center of the trunk show morphological gradients that lead to a transition of stiffness from the center to the periphery of the fiber cap (Fig. 14). The fiber cap is stiffest near the phloem (ph) and the stiffness decreases toward the periphery of the fiber cap (f) as the ratio cell wall thickness to cell diameter decreases (Rüggeberg et al., 2008, 2009). These stiffness gradients could be beneficial for stem damping.
The mechanical gradients present in this plant are interesting for a technical implementation as they improve damping and may also prevent fracture due to delamination (Fig. 15) when the structure is submitted to cyclic or sudden loading.

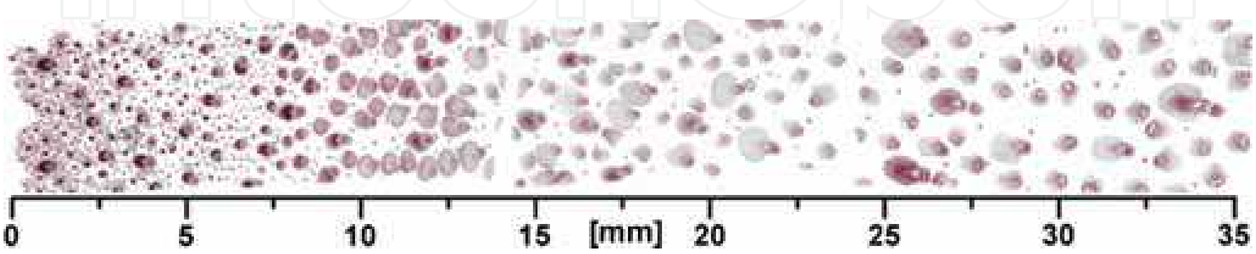

Fig. 13. Cross-section of cortex and outer central cylinder of the stem of the fanpalm *Washingtonia robusta*. Numbers indicate the distance from the outer edge of the trunk. The darker areas represent the vascular bundles with fiber caps embedded in a parenchymatous ground tissue. © Markus Rüggeberg. Source: Rüggeberg et al., 2009.

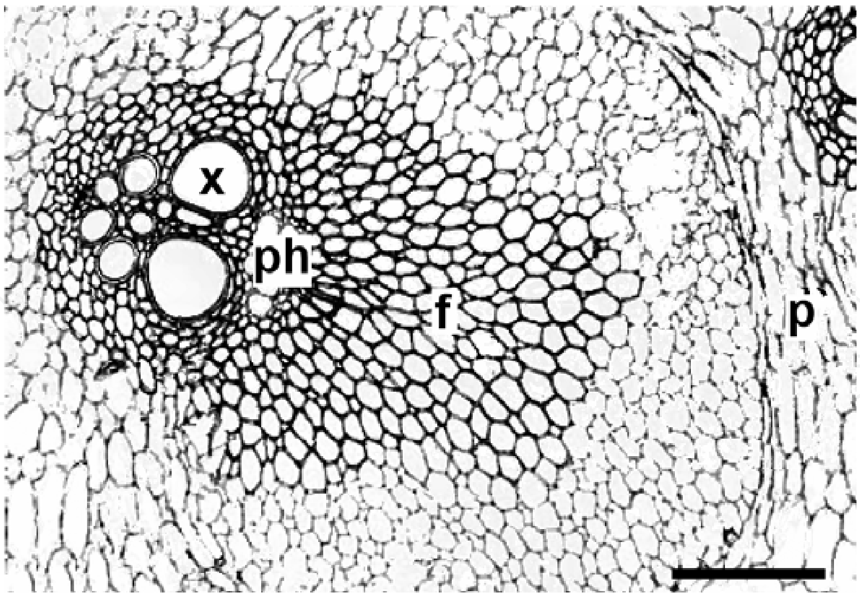

Fig. 14. Cross-section of vascular bundle with fiber cap in the stem cortex of the fan palm *Washingtonia robusta*. f: fiber cap, x: xylem, ph: phloem, p: parenchymatous cortex. Scale bar: 250 µm. © Markus Rüggeberg. Source: Rüggeberg et al., 2008.

Fig. 15. Delaminated technical composite structure © PBGF.

Prevention of delamination is an important issue for many technical structures because catastrophic failures can occur, as for example during the demolition of a windmill in Denmark in 2009. One of the blades of this windmill delaminated, leading to an unbalance in the wheel and to a delamination of the other blades, ultimately causing the destruction of both the wind wheel and the tower of the windmill (http://www.bt.dk).

2.1.4.2 Medullosa sp.

Fossil plants can have stem morphologies that are no longer existent and those can be quite different from extant stems. In well preserved fossil plants like the Carboniferous seed plant *Medullosa*, gradients at different hierarchical levels can be distinguished. At stem level, the number as well as the size and type of the fiber bundles change from the stem centre to the periphery (Fig. 16). At tissue level, the outer primary cortex shows two gradients from its inner side to its outer side: (1) a decrease of the cross-sectional area of the sclerenchymatous fiber bundles that are embedded in a parenchymatous ground tissue and (2) an increase of the lignification of the cell walls of the parenchymatous cells of the ground tissue (Fig. 17A).

At cellular level, resin ducts in the ground tissue of the inner cortex have two morphological gradients (Fig. 17 B,C). The first gradient is a decrease of the cell wall thickness from the resin duct to the parenchymatous ground tissue of the inner cortex. The second gradient consists of a decrease of the cellular lumen from the inner side of the duct toward its periphery followed by a subsequent increase of the cellular lumen in the inner cortex tissue surrounding the duct. In fossil plants that cannot be tested mechanically, the stem, tissue and cell structure on different hierarchical levels can be assumed to have mechanical implications. This is supported by numerous studies, e.g., Masselter et al., 2006, 2007, 2009a; Rowe & Speck, 1998; Speck & Rowe, 1994, 1998, 1999, 2003.

Gradients are already incorporated in some materials as, e.g., a functionally graded material consisting of a nickel-alumina joint (Bruck et al., 2002). Gradients in the microstructure link the very stiff alumina (Al_20_3) with a Young's modulus of about 300 GPa to the much more flexible nickel with a Young's modulus of about 2 GPa. This leads to different stress-strain relationships in the various parts of the graded microstructure and a customized gradient for optimal performance can be determined (Bruck et al., 2002). Natural concept generators can further improve the transition regions between stiff and flexible materials by 1) introducing continuous gradients instead of discrete transitions between different material layers and 2) by optimization at different hierarchical levels (Speck & Masselter, 2008).

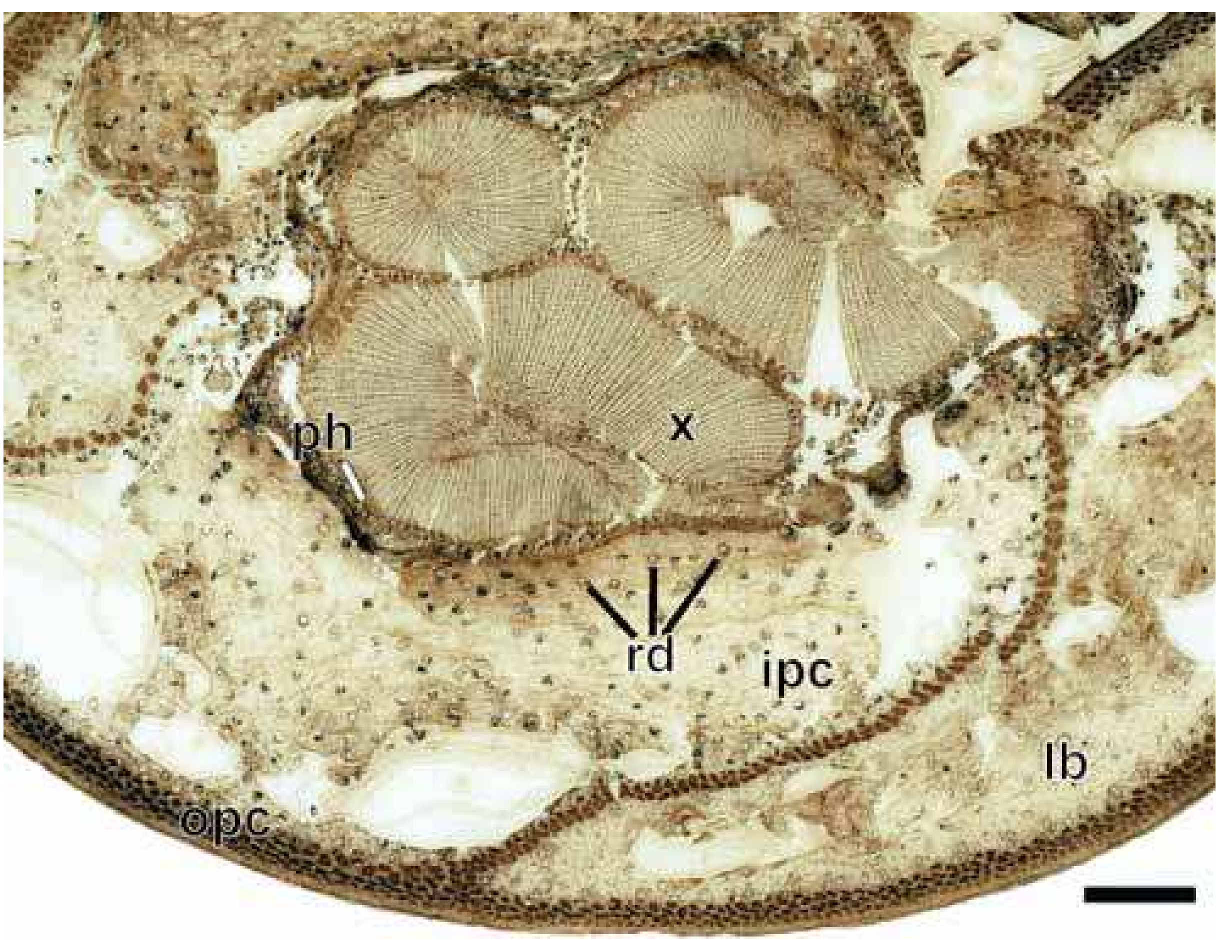

Fig. 16. Cross-section of a stem of *Medullosa* sp. with xylem (x), phloem (ph), inner primary cortex (ipc), leaf bases (lb), resin ducts (rd) and an outer primary cortex (opc). Scale bar: 5 mm. © PBGF.

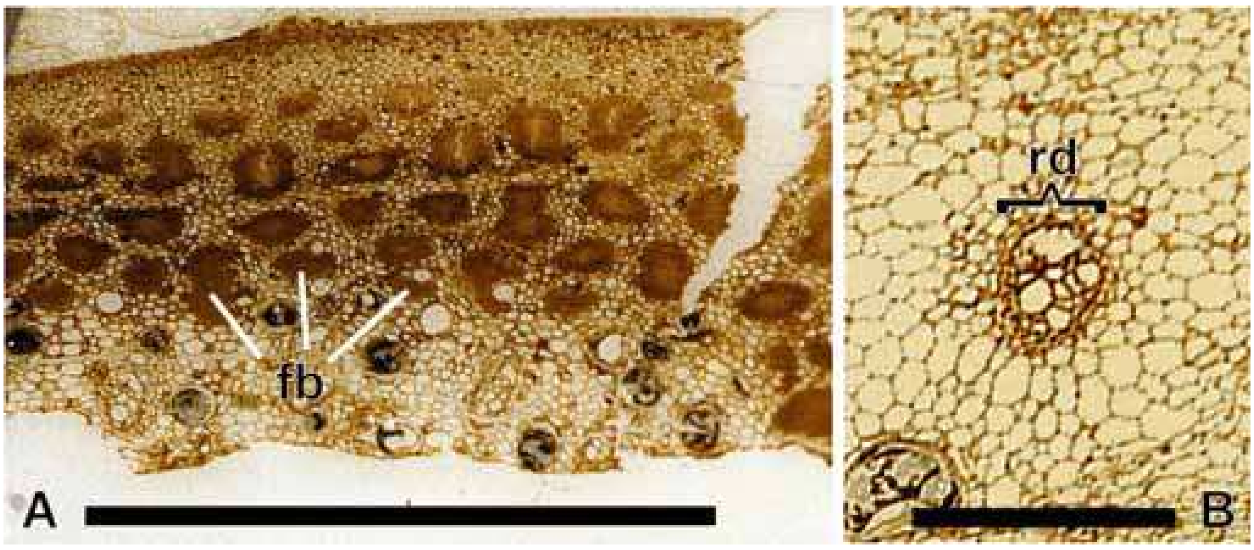

Fig. 17. Cross-section of a stem of *Medullosa* sp. (A) Detail of the outer primary cortex with densely arranged fiber bundles (fb), (B) detail of a resin duct (rd) with surrounding parenchymatous cortex tissue. Scale bars: A: 5 mm, B: 1 mm. © PBGF.

2.1.5 Heat insulation and flame retardancy

Heat insulation is an important issue when considering the high and increasing costs for energy and the ecological consequences of increasing energy consumption. Biological concept generators can be barks from trees (Fig. 18A), which can show a very good flame retardancy and heat insulation (Bauer et al., 2008, 2010). Increased flame retardancy and heat insulation is of interest for many technical applications. Recent investigations of the Plant Biomechanics Group in Freiburg suggested that in addition to the moisture content, the factors thickness, internal air cavities and surface structuring of the bark improve flame retardancy and heat insulation (Bauer et al., 2008, 2010). Potential technical implementations of these findings are the optimization of wood and bark panels (Fig. 18B), but also the development of new biomimetic insulation materials.

Fig. 18. Biological heat insulating structures. (A) Bark of the giant sequoia *Sequioadendron giganteum*, (B) Bark of the cork oak (*Quercus suber*) forming a 'wood panel'. © PBGF.

2.1.6 Impact damping

Many arborescent plants possess dual damping properties, e.g. vibration damping in their stems and leafs and impact damping in their fruits (Fig. 19). Impact damping is an important technical issue as many containers need protection from sudden shocks like crashes, drops or ballistic impacts. Some examples are the containments of hazardous goods, various types of protection helmets and hulls for electronic devices (e.g., mobiles) or car bodies. In order to optimize such technical structures, different biological concept generators with high energy dissipation upon impact are currently being investigated, such as petioles of the rhubarb (Huber et al., 2009) as well as fruits and nuts like the pumello, *Citrus maxima*, the coconut and the macadamia nut (Fischer et al., 2010; Seidel et al., 2009, 2010). When testing rhubarb petioles with an impact pendulum, the vascular bundles remain intact and are strained while the cortex structures and the parenchyma are destroyed, thereby dissipating a high amount of impact energy (Huber et al., 2009).

In the pumello (Fig. 19A) the deformation of the hierarchically structured thick spongy peel is mainly responsible for the energy dissipation upon impact (Fischer et al., 2010; Seidel et al., 2009, 2010). The tough outer layer of *Macadamia* nuts (Fig. 19C), the testa, is an example of a puncture material reinforced by densely packed stone cells (Seidel et al., 2009, 2010), while the *Coconut* (Fig. 19B) presents an interesting sandwich structure of a flexible middle layer of loosely interconnected fibers (mesocarp) and a stiff inner layer (endocarp) with densely arranged stone cells, thereby providing physiological and mechanical protection of the embryo by incorporating both good impact damping and puncture resistance (Speck T. et al., 2009).

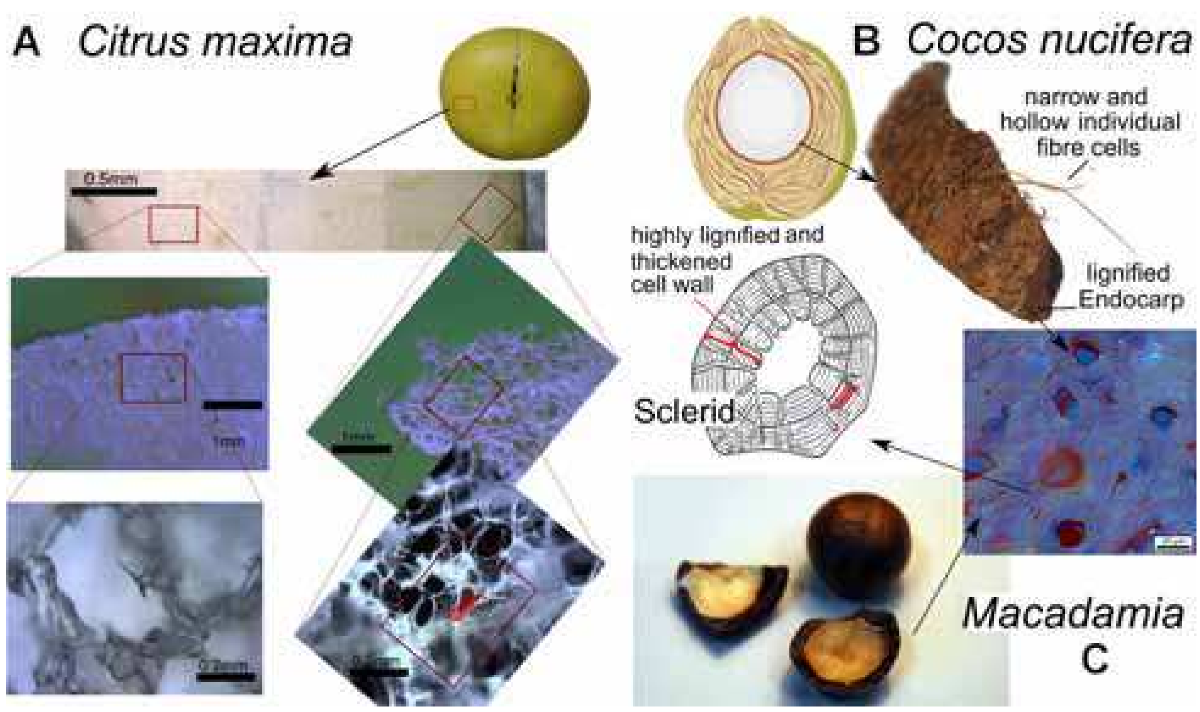

Fig. 19. Biological role models for shock-absorbing structures. (A) Highly damping spongy gradient structure in the peel of pumello (*Citrus maxima*), (B) combination of fibrous damping structure and tough shell in the fruit wall of coconut (*Cocos nucifera*), (C) entirely tough shell of fruits of *Macadamia* sp. © PBGF.

The hierarchical aspects of the organisation of these biological role models let them serve as concept generators for technical materials with a combination of solid layers with spongy fiber-reinforced structures, thereby ensuring good energy dissipation, shock-protection and puncture resistance (Fig. 20).

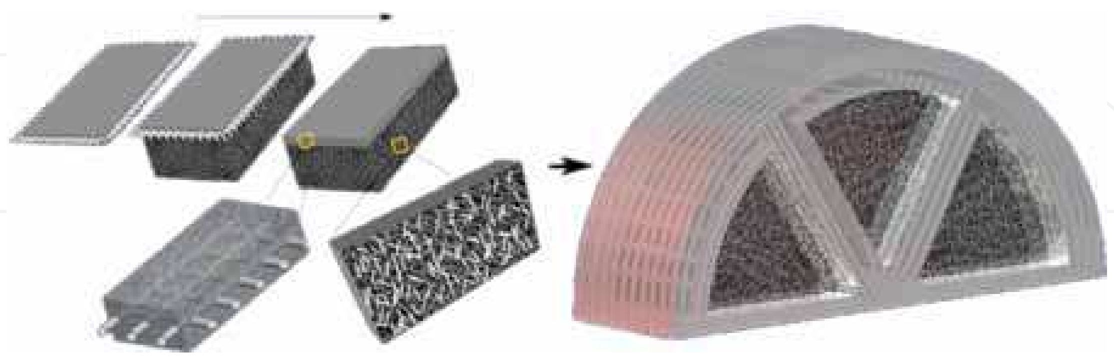

Fig. 20. Idea for biomimetic shock-absorbing structures developed on the basis of the biological concept generators (see Fig. 19). © Foundry Institute RWTH Aachen.

2.1.7 Vibration damping

Another important issue in many technical applications is vibration damping. This is the case for shock-absorbing pallets, which have to provide damping for the payloads, which often consist of delicate goods, like switch cabinets holding high-end computers. In a joint R&D project of the Plant Biomechanics Group Freiburg with the ITV Denkendorf and the company Rittal GmbH & Co. KG Herborn, a prototype of a shock-absorbing pallet with optimized mechanical characteristics was developed. At the beginning of the biomimetic project there was a technical problem: a shock-absorbing pallet with improvable damping properties and a material mix that makes it complicated or (nearly) impossible to recycle (Fig. 21). In order to solve these shortcomings, a screening for biological concept generators with excellent vibration damping was performed. The culms of bamboo, the spines of the

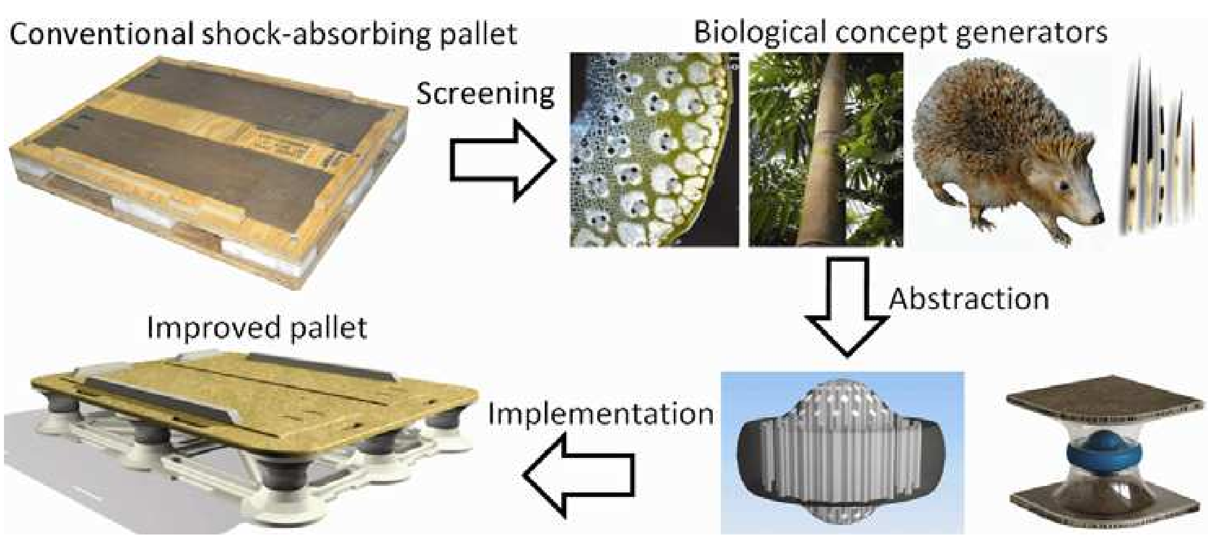

Fig. 21. Procedure of a biomimetic project in which an existing technical product is optimized by implementing the abstracted principles of biological concept generators (see text). © PBGF.

hedgehog and the quills of the porcupine were identified as potential concept generators. In a next step, the concept generators were tested as to their mechanical properties, the form-structure-function relationship was analyzed, and the principles were abstracted and implemented in a technical structure. Thereby, a shock-absorbing pallet with optimized damping properties and good recyclability was developed (Fig. 21, see Masselter et al. (2008) for a detailed description).

2.1.8 Flexible hulls

An additional approach for a transfer of concepts based on biological role models into technical applications consists of using structural changes in tissues that are induced by ontogenetic growth processes. In the Carboniferous seed plant *Lyginopteris oldhamia,* secondary growth leads to stresses and strains in the outer cortex, which becomes highly strained and is ultimately sloughed off (Fig. 22, Masselter et al., 2006, 2007). Of major

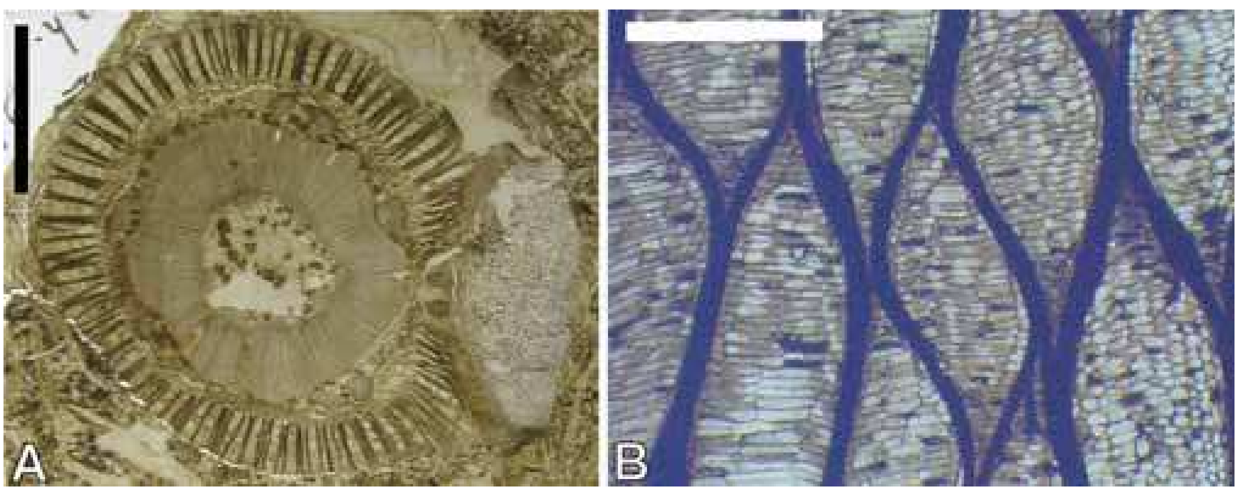

Fig. 22. *Lyginopteris oldhamia.* (A) Cross-section of the stem, (B) detail of strained outer primary cortex of the stem. Scale bars: (A) 5mm, (B) 1mm © PBGF.

Fig. 23. Potential technical implementation for flexible hull structures. (A, B) Demonstrators combining a cellular matrix consisting of closed-cell foams and inextensible fibers, (A) undeformed state, (B) deformed state, (C) conventional flexible tank as an example for a potential technical application. © PBGF.

interest are 1) the morphological-mechanical gradients, (2) the special organization of the parenchymatous/sclerenchymatous cortex and the fact that (3) the expansion of this cortical tissue is a gradual process while the sloughing is a more ‚abrupt‘ failure event. By integrating similarly arranged fiber-reinforced materials (Fig. 23A,B) into the hulls of conventional flexible tanks (Fig. 23C), an increase in extensibility could be achieved while the outer ‚overall‘ shape is retained. Other potential applications include structures with improved safety if exploding, as the tearing of the biomimetic hull structured according to the biological role model consumes a lot of energy and could therefore dampen the explosion impact.

2.1.9 The Technical Plant Stem

The ‚Technical Plant Stem‘ can be considered as a kind of 'summary' for the linear fiber-reinforced composites as this biomimetic product incorporates various mechanical optimizations discussed above, e.g., vibration damping, light weight, a benign fracture behavior, impact damping and high flexural stiffness.. Three of the five biological concept generators for the 'Technical Plant Stem' that are suitable for a transfer into biomimetic products are shown in figure 24. The cross-sections show the extreme lightweight construction of *Equisetum hyemale* as well as the morphological/mechanical gradients in *Arundo donax* and the interlocking of tissues in *Equisetum giganteum*. These morphological structures significantly influence the mechanical properties of these plants (Spatz & Emanns, 2004; Spatz et al., 1997, 1998). Biomechanical analyses by the Plant Biomechanics Group in Freiburg proved that the biological concept generators possess interesting mechanical characteristics (Spatz et al., 1997; Speck O. & Spatz, 2004; Speck O. et al., 2005).
After quantitatively analyzing, understanding and abstracting these principles, prototyping of a biomimetic structure took place and the ‚Technical Plant Stem‘ was developed (Milwich et al., 2006, 2007). Optimizations that were introduced into the 'Technical Plant Stem' are the following: gradients within the culm, optimized fiber orientation, gradual bonding of fibers and matrix, interlocking of tissues, lightweight construction and helical wall reinforcements (Fig. 25).

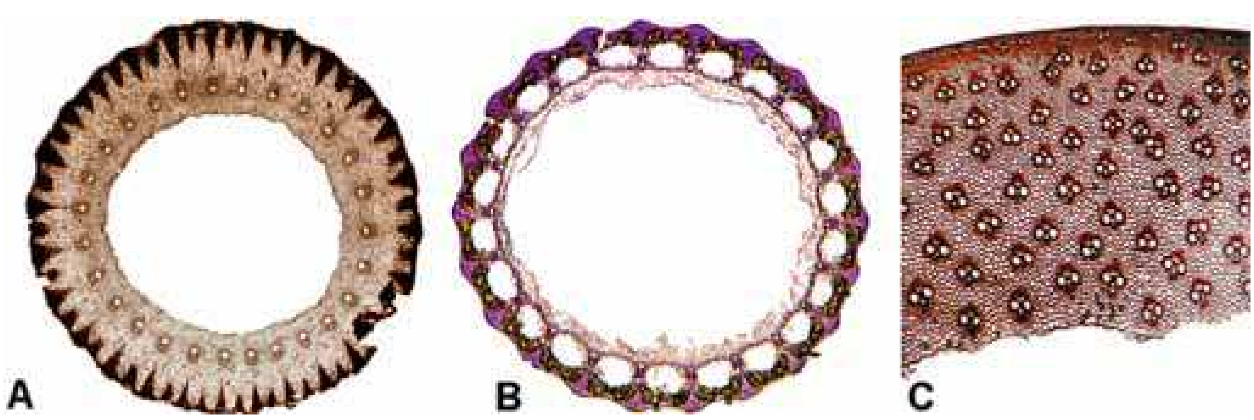

Fig. 24. Three of the five biological concept generators for the 'Technical Plant Stem'. (A) Cross-section of the stem (diam. 12 mm) of the Brazilian Giant Horsetail (*Equisetum giganteum*), (B) cross-section of the stem (diam. 6 mm) of the Dutch rush (*Equisetum hyemale*), (C) cross-section of the stem wall (width 4.3 mm) of the Giant Reed (*Arundo donax*). © PBGF.

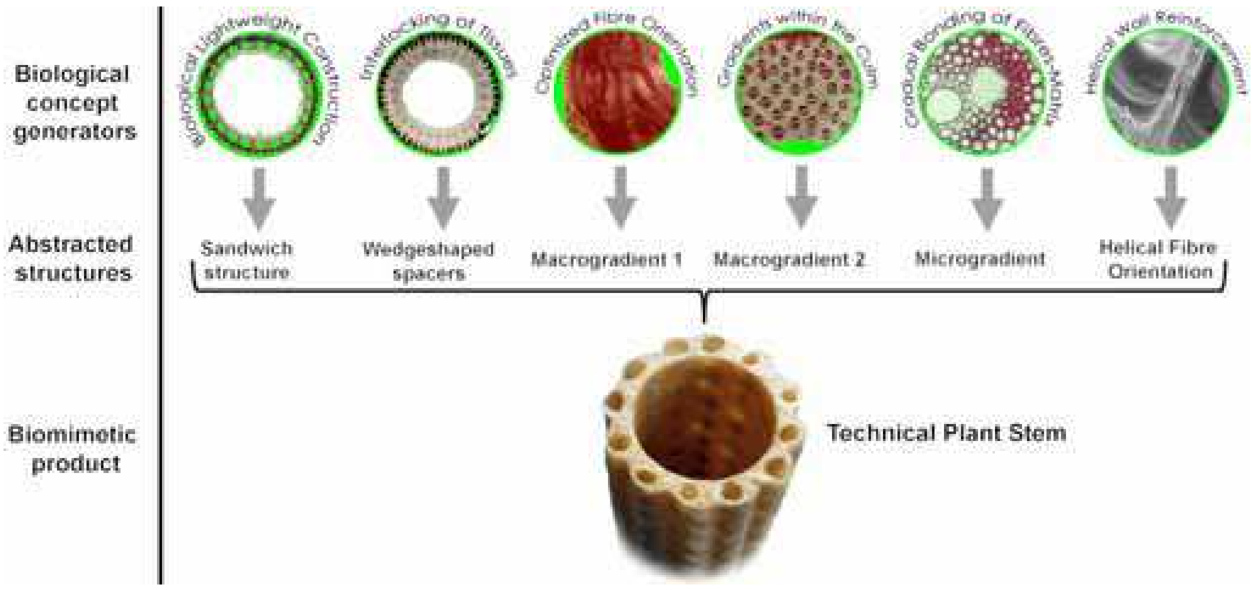

Fig. 25. Procedure of a biomimetic project in which a novel biomimetic product is developed by implementing the abstracted principles of several biological concept generators. © PBGF.

The potential fields of technical implementations range from the automotive industry (Fig. 1) to aerospace (Fig. 5) and also include architecture as well as sports equipment and special technical structures such as windmills or prostheses.

2.2 Branched fiber-reinforced structures

2.2.1 Biological concept generators

Y-shaped and T-shaped branchings that are present in technical structures are also found in branched arborescent plants. These branchings are optimized for fracture toughness (Jungnikl et al., 2009). Due to their special morphological organization, arborescent monocotyledons (Fig. 26A,B) and columnar cacti (Fig. 26C) hold a high potential for transfer into technical implementation. The stem-branch attachments of these plants are very different from those of gymnosperms and of most dicotyledon trees. A new biomimetic project for analysing the regions of stem-branch attachments of arborescent monocotyledons and columnar cacti and for transferring the results in technical applications has started in 2009 at the PBGF in cooperation with the Institute for Textile Technology and Process Engineering (ITV) Denkendorf, the Botanic Garden of the TU Dresden and the Institute for Lightweight Structures and Polymer Technology (ILK) of the TU Dresden.
The morphology of the stem-branch attachments found in arborescent monocotyledons and columnar cacti differs in its arrangement on several hierarchical levels. At stem level, the region of the stem-branch attachment is thickened by anomalous secondary growth in *Dracaena* (Fig. 26A) while the attachment is unthickened in *Freycinetia insignis* (Fig. 26B). In contrast, in the genus *Cereus*, the base of the branch is very small and the branch becomes thicker distally (Fig. 26C). At tissue level, the structure, the arrangement and the course of (groups of) fiber bundles (Fig. 26D,E) are of major influence on the biomechanical properties of the plant stems. These arrangements can be analyzed by using computer tomography, by maceration or by serial sectioning. At tissue and cellular level, the structure and course of individual fibers can be analyzed by using light microscopy and confocal laser microscopy. These methods allow to study the structure and gradients in the contact region between the fiber bundles and the cellular matrix of the parenchymatous ground tissue.

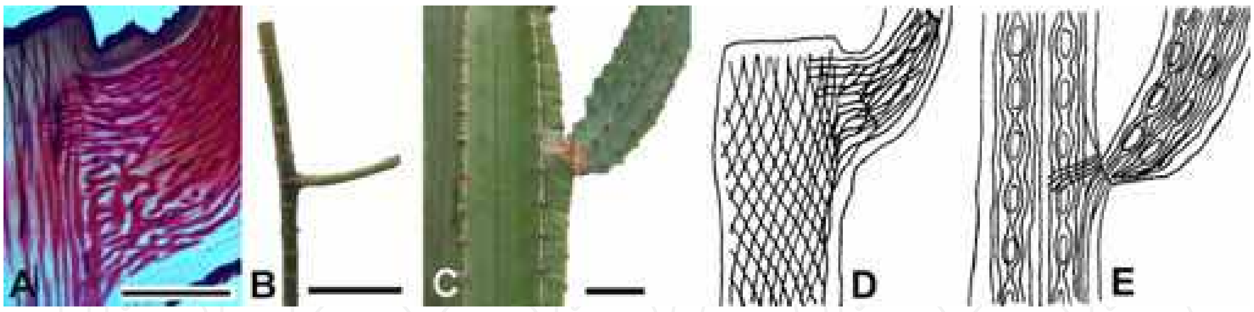

Fig. 26. Biological concept generators for branched technical structures. Longitudinal section of the stem-branch attachment region of *Dracaena marginata* (A) as well as an external view of the stem-branch attachment of *Freycinetia insignis* (B) and in *Cereus* sp. (C). Schematic drawing of the arrangement of fibrous bundles or wood strands, respectively, in the stem-branch attachment region of *Dracaena* sp. (D) and *Cereus* sp. (E). Scale bars: (A): 5mm; (B),(C):50 mm. © PBGF.

Biomechanical tests include breaking experiments in which a force is applied to a lateral twig until this twig breaks (Fig. 27A), using similar methods as described in detail in Beismann et al. (2000). This setup allows determining the force necessary to break the twig and the fracture toughness as well as the stress and strain at fracture. In many of the tested specimens, the resulting force displacement curve (Fig. 27B) shows a benign fracture behavior with a long plastic range, which is interesting for developing innovative branched technical structures. The structural analysis and the mechanical tests are complemented by FE-analyses (Fig. 28A) (Masselter et al., 2009, 2010a,b; Schwager et al., 2010).

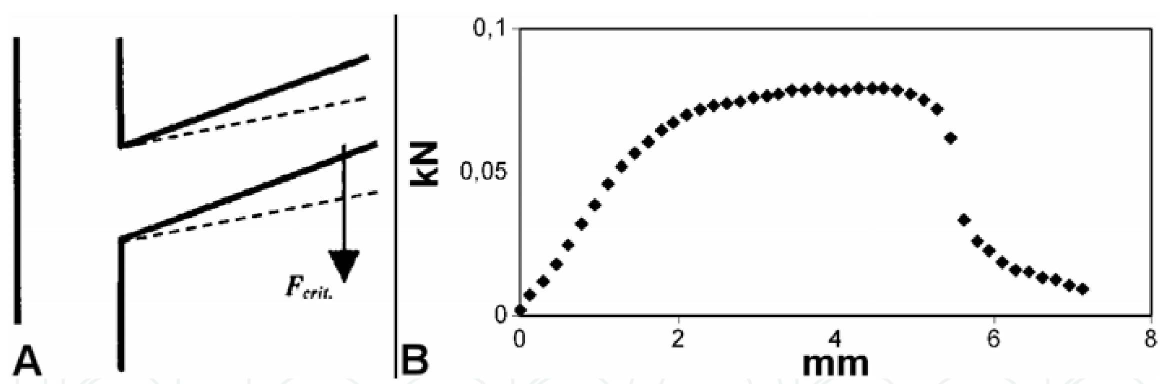

Fig. 27. Breaking experiment, schematic drawing of the geometry of a stem-branch attachment (A). The solid line represents a lateral twig before bending, the dashed line represents a lateral twig shortly before fracture, F_{crit} is the critical force necessary to break the twig. Exemplary force-displacement curve (B) measured for *Dracaena reflexa* using the setup shown in (A). © PBGF.

2.2.2 Technical implementation

Due to the fibrous composite structure of the biological concept generators, the braiding technique is predestined to transfer the branched biological role models into biomimetic products and to manufacture circular preforms (Fig. 28B). State-of-the-art braiding techniques such as the overbraiding technique or the 3D-rotary braiding technique are being further developed by the ITV Denkendorf and the ILK Dresden as they can be used for producing braided branchings (Cherif et al., 2007; Drechsler, 2001, Fig. 28C).

Fig. 28. (A) Simulated notch stresses in a stem-branch attachment region of a columnar cactus, (B) double braiding unit for producing branched braidings and (C) prototype of a braided Y-shaped preform. © (A) ILK Dresden, (B, C) ITV Denkendorf.

2.2.3 Technical applications for branched structures

A potential technical transfer is given for example in automotive engineering by developing optimized branched lightweight fiber-reinforced compound structures with minimized notch stresses following the studies of Claus Mattheck (Mattheck 1990, 2007, 2010, Mattheck & Tesari 2002, see Fig. 29)

Fig. 29. Supporting structures in cars (Opel). © Claus Mattheck, KIT, Karlsruhe.

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4. References

Bar-Cohen, Y. (2006). *Biomimetics: biologically inspired technologies*. Taylor and Francis, ISBN 978-0849331633, Boca Raton, Florida.

Bauer, G.; Speck, T.; Liehr, A.W. & Speck, O. (2008). Wärmeisolierung von Baumrinde: Neue Ansätze für bionische Dämmmaterialien. In: *Bionik: Patente aus der Natur*, Kesel, A.B. & Zehren, D. (Eds.), 48-56, GTBB, ISBN 9783000271939, Bremen.

Bauer, G.; Speck, T.; Blömer, J.; Bertling, J. & Speck, O. (2010). Insulation capability of the bark of trees with different fire adaptation. *J Mater. Sci.*, 45, 21, (Nov. 2010) 5950-5959, ISSN 0022-2461.

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, 344, (March 2000) 617-633, ISSN 0022-0957.

Bruck, H.A.; Evans, J.J. & Peterson, M.L. (2002). The role of mechanics in biological and biologically inspired materials. *Exp. Mech.*, 42, 4, (April 2006) 361-371, ISSN 1741-2765.

Burgert, I. & Fratzl, P. (2009): Actuation systems in plants as prototypes for bioinspired devices. *Phil. Trans. R. Soc. A*, 367, (April 2009) 1541-1557, ISSN 1471-2962.

Bushan, B. (2009). Biomimetics. *Phil. Trans. R. Soc. A*, 367, (April 2009) 1433-1444, ISSN 1471-2962.

Caplin, J.; Gordon, J.E. & Jeronimidis, G. (1983): Composite material, U.S. Patent No. 4409274.

Cherif, C.; Diestel, O. & Gries, T. (2007). *Textile Halbzeuge und Halbzeugfertigung," Textile Verbundbauweisen und Fertigungstechnologien für Leichtbaustrukturen des Fahrzeug- und Maschinenbaus*, Progress-media Verlag, Dresden.

Dawson, C.; Vincent, J.F.V. & Rocca, A.M. (1997). How pine cones open. *Nature*, 390, (Dec. 1997) 668, ISSN 1476-4687.

Drechsler, K. (2001). Composites im Flugzeug- und Automobilbau. *Conference proceedings of Denkendorfer Kolloquien, Technische Textilien*, Denkendorf, 2001.

Ehrenstein, G.W. (2006). *Faserverbund-Kunststoffe: Werkstoffe, Verarbeitung, Eigenschaften*. Hanser Fachbuchverlag, ISBN 978-3446227163, Muenchen.

Elbaum, R.; Zaltzman, L.; Burgert, I. & Fratzl, P. (2007). The role of wheat awns in the seed dispersal unit. *Science*, 316, (May 2007) 884-886, ISSN 1095-9203.

Fischer, S. F.; Thielen, M.; Loprang, R.R.; Seidel, R.; Speck, T.; Fleck, C. & Bührig-Polaczek, A. (2010). Pummelos as Concept Generators for Biomimetically-Inspired Low Weight Structures with Excellent Damping Properties. *Adv. Biomater.* (in press).

Fratzl, P. (2002a). Characterising natural fibre composites with hierarchical structure. *Fibre Diffr. Rev.*, 10, (April 2002) 31-39, ISSN 1463-8401.

Fratzl, P. (2002b). Von Knochen, Holz und Zähnen. *Physik Journal*, 1, 5, (May 2002) 49-55, ISSN 1617-9439.

Fratzl, P. (2007). Biomimetic materials research: what can we really learn from nature's structural materials? *J R. Soc. Interface*, 4, 15, (Aug. 2007) 637-642, ISSN 1742-5662.

Fratzl, P.; Elbaum, R. & Burgert, I. (2008). Cellulose fibrils direct plant organ movements. *Faraday Discuss.*, 139, 275-282, ISSN 1359-6640.

Gindl, W. & Jeronimidis, G. (2004). Wood pulp fiber reinforced melamime-formaldehyde composites. *J Mater. Sci.*, 39, 9, (Mai 2004) 3245-3247, ISSN 0022-2461.

Gordon, J.E. & Jeronimidis, G. (1980). Composites with high work of fracture. *Phil. Trans. R. Soc. A*, 282, 1411, (Jan. 1980) 545-550, ISSN 1471-2962.

Goswami, L.; Dunlop, J.W.C.; Jungnikl, K.; Eder, M.; Gierlinger, C.; Coutland, G.; Jeronimidis, G.; Fratzl, P. & Burgert, I. (2008). Stress generation in the tension wood of poplar is based on the lateral swelling power of the G-layer. *Plant J*, 56, 4, (Jul. 2008) 531-538, ISSN 1365-313X.

Huber, T.; Graupner, N. & Müssig, J. (2009). As tough as it is delicious? A mechanical and structural analysis of red rhubarb (*Rheum Rhabarbarum*). *J Mater. Sci.*, 44, 15, (Aug. 2009) 4195-4199, ISSN 1573-4803.

Jeronimidis, G. (1979). Morphological aspects of wood fracture. In: *Proc. ICM-3 Cambridge, Mechanical Behaviour of Materials, Vol. 3;* Miller, K.J. & Smith, R.F. (Eds.), 329-340, Cambridge.

Jeronimidis, G. (1980a). Wood, one of nature's challenging composites. In: *Mechanical Properties of Biological Materials, 34th Symposium of the Society for Experimental Biology* Vincent J.F.V. & Currey, J.D. (Eds.), 377-395, Cambridge University Press, Cambridge.

Jeronimidis, G. (1980b). The fracture behaviour of wood and the relations between toughness and morphology. *Proc. R. Soc. B*, 208, 1173, (Jul. 1980) 447-460, ISSN 1471-2954.

Jeronimidis, G. (2000a). Structure-property relationships in biological materials. In: *Structural biological materials*, Elices, M. (Ed.), 3-16, Elsevier Science, ISBN 0080434169, Oxford.

Jeronimidis, G. (2000b). Design and function of structural biological materials. In: *Structural biological materials*, Elices, M. (Ed.), 19-29, Elsevier Science, ISBN 0080434169, Oxford.

Jungnikl, K.; Goebbels, J.; Burgert, I. & Fratzl, P. (2009). The role of material properties for the mechanical adaptation at branch junctions. *Trees*, 23, 3, (Jun 2009) 605-610, ISSN 1432-2285.

Lichtenegger, H.C.; Reiterer, A.; Stanzl-Tschegg, S. & Fratzl, P. (1999). Variation of cellulose microfibril angles in softwoods and hardwoods - a possible strategy of mechanical optimization. *J Struct. Biol.*, 128, 3, (Dec. 1999) 257-269, ISSN 1047-8477.

Lienhard, J.; Poppinga, S.; Schleicher, S.; Masselter, T.; Knippers, J. & Speck, T. (2009). Abstraction of plant movements for deployable structures in architecture. In: *Proceedings of the 6th Plant Biomechanics Conference*, Thibaut, B. (Ed.), 389-397, Ecofog, Cayenne, French Guyana.

Lienhard, J.; Poppinga, S.; Schleicher, S.; Speck, T. & Knippers, J. (2010). Elastic architecture: nature inspired pliable strcutures. In: *Design and Nature V*, Brebbia, C.A. (Ed.), 469 – 477, WIT Press, ISBN 9781845644543, Southampton, Boston.

Mangalgiri, P.D. (1999). Composite materials for aerospace applications. *Bull. Mater. Sci.*, 22, 3, (May 1999) 657-664, ISSN 0250-4707

Masselter, T.; Barthlott, W.; Bauer, G.; Bertling, J.; Cichy, F.; Ditsche-Kuru, P.; Gallenmüller, F.; Gude, M.; Haushahn, T.; Hermann, M.; Immink, H.; Knippers, J.; Lienhard, J.; Luchsinger, R.; Lunz, K.; Mattheck, C.; Milwich, M.; Mölders, N.; Neinhuis, C.; Nellesen, A.; Poppinga, S.; Rechberger, M.; Schleicher, S.; Schmitt, C.; Schwager, H.; Seidel, R.; Speck, O.; Stegmaier, T.; Tesari, I.; Thielen, M. & Speck, T. (2010a). Biologically inspired products. In: Bar-Cohen, Y. (ed.), *Nature based Innovation*, CRC Press, Pasadena (in press), peer-reviewed.

Masselter, T.; Haushahn, H.; Schwager, M.; Milwich, M.; Nathanson, R.; Gude, M.; Cichy, F.; Hufenbach, W.; Neinhuis, C. & Speck, T. (2010b). Biomimetic fibre-reinforced composites inspired by branched plant stems. In: *Design and Nature V*, Brebbia, C.A. (Ed.), 411 – 420, WIT Press, ISBN 9781845644543, Southampton, Boston.

Masselter T.; Milwich, M.; Monnerat, H.; Scharf, U.; Hartel, M. & Speck, T. (2008). Bio-inspired solutions for technical problems: biomimetic cable entries and shock-absorbing pallets. In: *Design and Nature IV*, Brebbia, C.A. (Ed.), 51-58, WIT Press, ISBN 1746-448X, Southampton, Boston.

Masselter, T.; Rowe, N.P.; Galtier J. & Speck, T. (2009a). Secondary growth and deformation of stem tissues in the Lower Carboniferous seed fern *Calamopitys*. *Int. J Plant Sci.*, 170, 9 (Nov. 2009) 1228-1239, ISSN 1058-5893.

Masselter, T.; Rowe, N.P. & Speck, T. (2007). Biomechanical reconstruction of the Carboniferous seed fern *Lyginopteris oldhamia:* implications for growth form reconstruction and habit. *Int. J Plant Sci.*, 168, 8 (Oct. 2007) 1177-1189, ISSN 1058-5893.

Masselter, T. & Speck, T. (2009b). From stems to sticks - what can we learn for biomimetics from natural fibre-reinforced structures? In: *Proceedings of the 6th Plant Biomechanics Conference*, Thibaut, B. (Ed.), 375-366, Ecofog, Cayenne. French Guyana.

Masselter, T; Speck, T. & Rowe, N.P. (2006). Ontogenetic reconstruction of the Carboniferous seed plant *Lyginopteris oldhamia. Int. J Plant Sci.*, 167, 1 (Jan. 2006) 147-166, ISSN 1058-5893.

Mattheck, C. (1990). Engineering components grow like trees. *Materwiss. Werksttech.*, 21, 4 (Apr. 1990) 143-168, ISSN 0933-5137.

Mattheck, C. (2007). *Secret design rules of nature - Optimum shapes without computers*, Verlag Forschungszentrum Karlsruhe GmbH, ISBN 9783923704620, Karlsruhe.

Mattheck, C. (2010). *Denkwerkzeuge nach der Natur*, Verlag Karlsruher Institut für Technologie, ISBN 9783923704736, Karlsruhe.

Mattheck, C. & Tesari, I. (2002). Konstruieren wie die Natur. Bauteile wachsen wie Bäume und Knochen, *Konstruieren und Giessen*, 27, 2, 4-9.

Milwich, M.; Planck, H.; Speck, T. & Speck, O. (2007). Der technische Pflanzenhalm: ein bionisches Schmaltextil. *Melliand Textilberichte – Band- und Flechtindustrie*, 44, 34–38, ISSN 0005-4925.

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, 10, (Oct. 2006) 1455-1465, ISSN 1537-2197.

Poppinga, S.; Lienhard, J.; Masselter, T.; Schleicher, S.; Knippers, J. & Speck, T. (2010a). Biomimetic Deployable Systems in Architecture. In: *WCB 2010, IFMBE Proceedings 31*, Lim, C.T. & Goh, J.C.H. (Eds.), 40-43, Springer, ISBN 9783642145155, Heidelberg, Germany.

Poppinga, S.; Masselter, T.; Lienhard, J.; Schleicher, S.; Knippers, J. & Speck, T. (2010b). Plant movements as concept generators for deployable systems in architecture. In: *Design and Nature V*, Brebbia, C.A. (Ed.), 403 – 409, WIT Press, ISBN 9781845644543, Southampton, Boston.

Quilter, A. (2004). Composites in Aerospace applications. *Aircraft Maint. Technol.*, 16, 1, (Oct. 2004) 14-16, ISSN 1072-3145.

Reiterer, A.; Lichtenegger, H.C.; Fratzl, P. & Stanzl-Tschegg, S. (2001). Deformation and energy absorption of wood cell walls with different nanostructure under tensile loading. *J Mater. Sci.*, 36, 19, (Oct. 2001) 4681-4686, ISSN 0022-2461.

Rowe, N.P. & Speck, T. (1998). Biomechanics of plant growth forms: the trouble with fossil plants. *Rev. Palaeobot. Palynol.*, 102, 1-2, (Jul. 1998) 43-62, ISSN 0034-6667.

Rüggeberg, M.; Burgert, I. & Speck, T. (2010). Structural and mechanical design of tissue interfaces in the giant reed *Arundo donax*. *J R. Soc. Interface*, 7, 44, (Mar. 2010) 499-506, ISSN 1742-5662.

Rüggeberg, M.; Speck, T. & Burgert, I. (2009). Structure-function relationships of different vascular bundle types in the stem of the Mexican fanpalm (*Washingtonia robusta*). *New Phytol.*, 182, 2, (Jul. 2009) 443-450, ISSN 1469-8137.

Rüggeberg, M.; Speck, T.; Paris, O.; Lapierre, C.; Pollet, B.; Koch, G. & Burgert, I. (2008). Stiffness gradients in vascular bundles of the palm *Washingtonia robusta. Proc. R. Soc. B*, 275, 1648, (Oct. 2008) 2221-2229, ISSN 1471-2954.

Schwager, H.; Haushahn, T.; Neinhuis, C.; Speck, T. & Masselter, T. (2010). Principles of branching morphology and anatomy in arborescent monocotyledons and columnar cacti as concept generators for branched fibre-reinforced composites. *Adv. Biomater.* (in press)

Seidel, R.; Bührig-Polaczek, A.; Fleck, C. & Speck, T. (2009). Impact resistance of hierarchically structured fruit walls and nut shells in view of biomimetic applications. In: *Proceedings of the 6th Plant Biomechanics Conference*, Thibaut, B. (Ed.), 406-411, Ecofog, Cayenne, French Guyana..

Seidel, R.; Thielen, M.; Schmitt, C.; Bührig-Polaczek, A.; Fleck, C. & Speck, T. (2010). Fruit walls and nut shells as an inspiration for the design of bio-inspired impact resistant hierarchically structured materials. In: *Design and Nature V*, 421-430, Brebbia, C.A. (Ed.), WIT Press, ISBN 9781845644543, Southampton, Boston.

Spatz, H.-Ch.; Beismann, H.; Brüchert, F.; Emanns, A. & Speck, T. (1997). Biomechanics of the giant reed *Arundo donax*. *Phil. Trans. R. Soc. B*, 352, 1349, (Jan. 1997) 1–10, ISSN 1471-2954.

Spatz, H.-Ch. & Emanns, E. (2004). The mechanical role of the endodermis in *Equisetum* plant stems. *Am. J Bot.*, 91, 11, (Nov. 2004) 1936-1938, ISSN 1537-2197.

Spatz, H.-Ch.; Köhler, L. & Speck, T. (1998). Biomechanics and functional anatomy of hollow-stemmed sphenopsids. I. *Equisetum giganteum* (Equisetaceae). *Am. J Bot.*, 85, 3, (Mar. 1998) 305-314, ISSN 1537-2197.

Speck, O.; Milwich, M.; Harder, D. & Speck, T. (2005). Vom biologischen Vorbild zum technischen Produkt: der "Technische Pflanzenhalm". *Museo*, 22, 96-103.

Speck, O. & Spatz, H.-Ch. (2004). Damped oscillations of the giant reed *Arundo donax* (Poaceae). *Am. J Bot.*, 91, 6, (Jun. 2004) 789–796, ISSN 1537-2197.

Speck, T.; Harder, D. & Speck O. (2007). Gradient materials and self-repair: learning technology from biology. *VDI-Report*, B4284, 1-13.

Speck, T. & Masselter, T. (2008). Learning from the past for the future: fossil plants as concept generators for biomimetic materials and structures. In: *Bionik: Patente aus der Natur*, Kesel, A.B. & Zehren, D. (Eds.), 14-23, GTBB, ISBN 9783000271939, Bremen.

Speck, T. & Rowe, N.P. (1994). Biomechanical analysis of *Pitus dayi*: early seed plant vegetative morphology and its implications on growth habit. *J Plant Res.*, 107, 1088, (Dec 1994) 443-460, ISSN 0918-9440.

Speck, T. & Rowe, N.P. (1998). Modelling form and function in fossil plants. *Rev. Palaeobot. Palynol.*, 102 (special issue), 1-114, ISSN 0034-6667.

Speck, T. & Rowe, N.P. (1999). A quantitative approach for analitically defining size, growth for and habit in living and fossil plants. In: *The evolution of plant architecture*, Kurmann M.H. & Hemsley, A.R. (Eds.), 447-449, Kew: Royal Botanic Gardens, ISBN 9781900347723, Kew.

Speck, T. & Rowe, N.P. (2003). Modelling primary and secondary growth processes in plants: a summary of the methodology and new data from an early lignophyte. *Phil. Trans. R. Soc. B*, 358, 1437, (Sept. 2003) 1473-1485, ISSN 1471-2970.

Speck, T. & Speck, O. (2008). Process sequences in biomimetic research, In: *Design and Nature IV*, Brebbia, C.A. (Ed.), 3-11, WIT Press, ISBN 1746-448X, Southampton, Boston.

Speck, T.; Speck, O.; Masselter, T. & Seidel, R. (2009). Verpacken, Auspacken und Schützen nach dem Vorbild der Natur: Biologische Verpackungen und Behälter als Ideengeber für bionische Entwicklungen, In: *Blasformen 2009, VDI- Berichte Kunststofftechnik*, 4299, 1-19, VDI Verlag GmbH, ISBN 9783182342991, Düsseldorf, Germany.

Stahlberg, R. & Taya, M. (2006). What can we learn from nastic plant structures? The phytomimetic potentiality of nastic structures. *Proc. SPIE*, Vol. 6168, (Mar. 2006), 616802, ISSN 0277-786X.

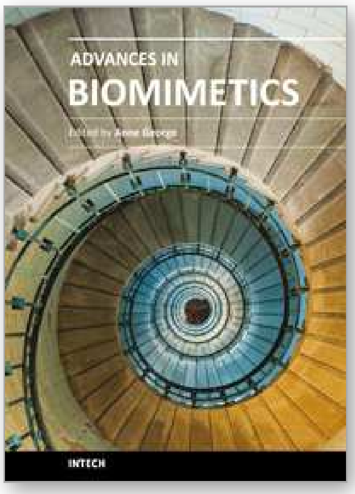
Vincent, J.F.V. (2003). Biomimetic modelling. *Phil. Trans. R. Soc. B*, 358, No. 1437 (Sept. 2003), 1597-1603, ISSN 1471-2970.

Zhang, Y.; Vassilopoulos, A.P. & Keller, T. (2007). Fatigue Behaviour of Adhesively Bonded Pultruded Gfrp. In: *Experimental Analysis of Nano and Engineering Materials and Structures*, Gdoutos, E.E. (Ed.), 203-204, Springer, ISBN 9781402062384, Dordrecht.

http://aero-defense.ihs.com/NR/rdonlyres/AEF9A38E-56C3-4264-980C-D8D6980A4C84/0/444.pdf 20.07.2010, 15:37

http://www.airbus.com/store/mm_repository/pdf/att00014197/media_object_file_fast_44_p2_p7.pdf 22.06.2010, 10:36

http://www.airbus.com/fileadmin/documents/Airbus_Technical_Data/AC/AC_A380_01NOV2008.pdf 22.11.2009, 10:43
http://www.bt.dk/nyheder/vindmoelle-eksploderet, 20.01.2010, 9:43



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The interaction between cells, tissues and biomaterial surfaces are the highlights of the book "Advances in Biomimetics". In this regard the effect of nanostructures and nanotopographies and their effect on the development of a new generation of biomaterials including advanced multifunctional scaffolds for tissue engineering are discussed. The 2 volumes contain articles that cover a wide spectrum of subject matter such as different aspects of the development of scaffolds and coatings with enhanced performance and bioactivity, including investigations of material surface-cell interactions.

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