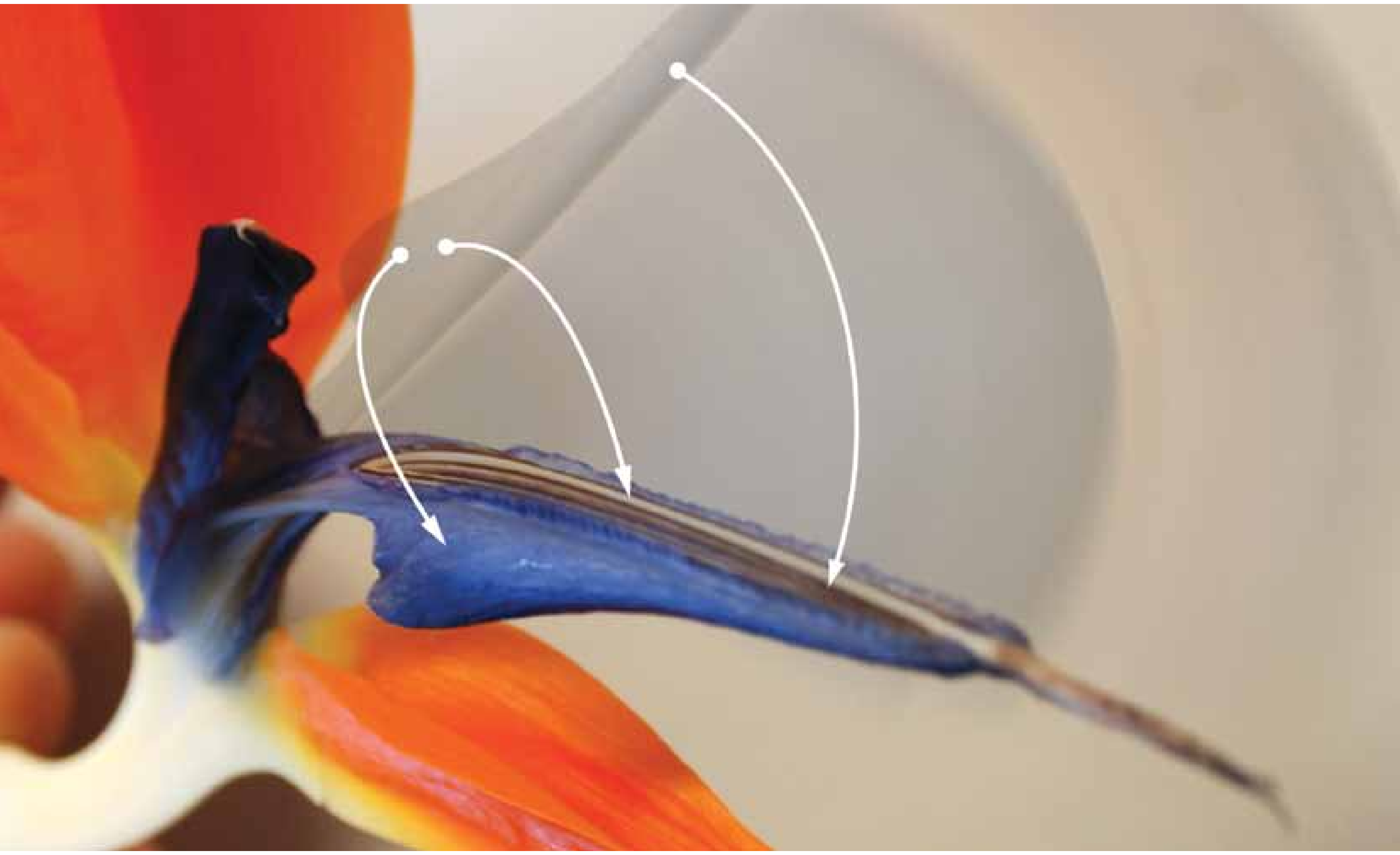
flectofin®



A Hinge-less Flapping Mechanism Inspired by Nature

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Flectofin®

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Flectofin®

The Flectofin® is a hinge-less flapping mechanism inspired by a deformation principle found in the Bird-Of-Paradise flower [1,2]. Its valvular pollination mechanism shows a fascinating non-autonomous plant movement which was analyzed to better understand the basic underlying principles that are responsible for the plant's mechanical performance. The abstracted model revealed a compliant mechanism at the basis of the deformation. By examining several plant movements, comparable elastic mechanisms were found with which it was possible to gain a deeper understanding of the interacting mechanical factors. With this knowledge it was possible to rearrange the mechanism's various structural, geometrical and material parameters, in order to develop new functional configurations. As a result, a patent for bio-inspired mechanisms was filed and registered as Flectofin® [3].
Unlike rigid-link mechanisms that are commonly used in technical applications, the adaptability of the Flectofin® is based on elastic deflection. The advantage of replacing local and susceptible hinges with elastic deformation is in the fusion of all mechanical elements within an all-in-one pliable component. Consequentially, fully functional mechanical systems can be constructed in one production step without the need for assembly. This technology renders the possibility for novel applications in various scales, ranging from architecture, aerospace technology, and medicine to mechanical engineering. The successful product development of the Flectofin® Lamella, for example, proves the feasibility of this approach and reflects the potential of advanced fabrication processes. Furthermore, using the lamella as part of a Flectofin® Facade shows the concept's adaptability to an architectural scale and taps into new market niches. First collaborations with engineers and architects exemplify how the techniques developed for the Flectofin® can inspire architectural projects and influence our designs already today.
Finally, by challenging our present mechanical understanding of biological and technical constructions, the Flectofin® clearly demonstrates an innovative paradigm shift towards an interdisciplinary knowledge transfer between biology, engineering, and architecture.

Fig.1: Cape Weaver bird on *Strelitzia reginae* (R.Koorts)

Introduction

In architectural constructions, such as shading systems like umbrellas or blinds, deployability is mainly provided by the use of rigid elements connected with technical hinges. Due to the high number of load cycles that act on gliding and rotating elements, however, hinges tend to gall over time which causes expensive maintenance or even periodical replacement. In contrast, some strong and flexible constructions in nature exemplify a different approach to solve this mechanical challenge. The deployability in plants, for instance, relies on the elastic properties of their flexible organs (e.g. leaves, petals). Even though the term 'hinge' is commonly used in literature to describe their flexible joints (e.g. pulvini), plants deform without technical hinge analogies [4]. In some constricted zones, they can be compared to the so-called pseudo-joints in compliant mechanisms that are formed by a local reduction of material thickness.

Implementing elastic deformation as a form-generating strategy is a rather new idea and has only been incorporated in a few building structures, predominantly in gridshells. While most of these projects used the elastic flexibility of timber to form a structure, some fibre-reinforced polymers (FRP), which combine high tensile strength with low bending stiffness, offer a larger range of calibrated elastic deformation set-ups for load-bearing structures [5]. The high strength-to-modulus ratio of FRP indicates that this material allows for large deflection before failure. By exploiting the material's special properties it becomes possible to reproduce plant-like, hinge-less mechanisms for architectural applications.

In the last decade, using nature as an inspirational source to solve technical problems has gained increasing importance. The 'Top-Down-Process' in biomimetics as defined by the Plant Biomechanics Group Freiburg [6] aims to find technical solutions by first defining a concise technical problem which may have already been solved by structures and principles found in nature.
In the context of the R&D-project presented here, the authors followed the 'Bottom-Up-Approach' in biomimetics; starting with a finding in biology and using it as a concept generator for technical innovation. In this case, the form-structure-function relationship of the Bird-Of-Paradise flower (*Strelitzia reginae*, Strelitziaceae) was analysed and compared to similar mechanisms of other plants. The flower's kinematical mechanism was abstracted and then transferred into new construction materials. This led to the invention of an advanced, deployable architectural system which operates with a complete absence of technical hinges and only relies on reversible material deformation.

Biological Role Model

The focus of this study is the optimisation of deployable systems in architecture using bio-inspired solutions. Aiming for an increase in adaptability and energy efficiency, as well as reducing weight and maintenance costs, the authors started a screening process, during which promising biological concept generators with high potential for translation into technical applications were identified and analysed [4,7-17]. Nastic plant

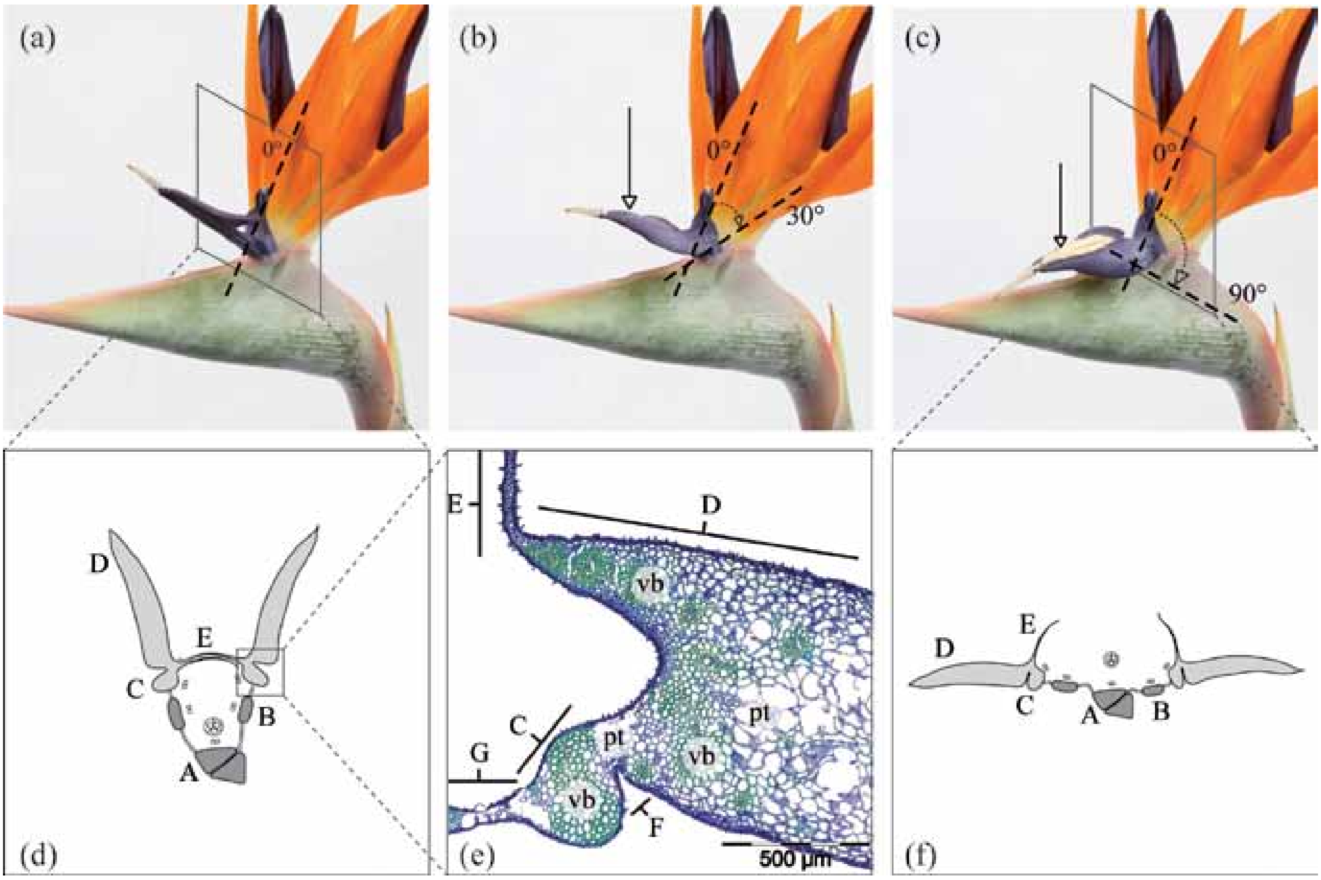

Fig.2a-c: The elastic deformation in the *Strelitzia reginae* flower. Bending of the *Strelitzia's* perch under the weight of the pollinator causes simultaneous bending of the lamina by 90 degrees.

movements, whose motion patterns are morphologically predetermined and show clearly defined actuating elements and mechanics, have been of special interest. Their potential for the development of biomimetic pliable technical structures was recently highlighted in "Actuation systems in plants as prototypes for bioinspired devices" by Ingo Burgert & Peter Fratzl [10].
In the research project presented here, a sophisticated pollination mechanism is described, which comprises a complex reversible deformation when an external mechanical force is applied. In contrast to typical autonomous plant movements that are internally actuated by e.g. changes in turgor pressure, cell wall shrinking, and swelling mechanisms, this non-autonomous deformation is actuated externally but yet follows specific morphological constraints.

Strelitzia reginae Banks ex Aiton (Strelitziaceae) is a South African perennial, ornithophilous plant, which means that the transfer of pollen from one flower to another, leading to sexual reproduction, is performed by birds (Fig. 1) [18,19]. The birds are rewarded with nectar in return. The flower-bird-interaction comprises a reversible deformation which enables a very fascinating valvular pollination mechanism. The flower features a protruding perch of two adnate, blue petals, which act as a landing platform (Fig.2 (a)-(c)). When the bird lands on this structure to reach the nectar at the base of the flower, its weight causes the perch to bend downwards (Fig.2 (b),(c)). In a simultaneous movement – a sideways flapping of the petal laminae – the previously enclosed anthers (male sexual flower parts) get exposed and the pollen can be attached to the bird, mainly to its feet (Fig.2 (c),(f)). When the bird flies away the open perch is unburdened and resets to the protective closed state again owing to its elastic properties.

In this valvular pollination mechanism, the actuating elements and kinematics are clearly defined by the plant's functional-morphological characteristics, making *Strelitzia reginae* an excellent model organism for the study of biological bending kinematics [1]. Former comprehensive morphological and anatomical studies can be found in [20,21]. Sections through the perch reveal its monosymmetric build-up (Fig.2 (d),(f)). There are three reinforcing lateral ribs on each side, which are loosely connected by thin petal laminae. The lower ribs are joined on a cellular level, thus forming a composite rib. The uppermost ribs carry the thick wings which cover the sheath cavity when it is closed. When the keel is bent down, the wings show a typical deformation behaviour which is based on anatomical features. The ribs mainly consist of fibrous tissue with vascular bundles, hence are relatively rigid and mainly serve to carry the bird's weight [21]. A constricted zone seen in a microscopic section between upper ribs and wings shows no fibrous tissue, which indicates higher flexibility in comparison to the surrounding zones, enabling the elastic sideways bending of the wings (F in Fig.2 (e)).

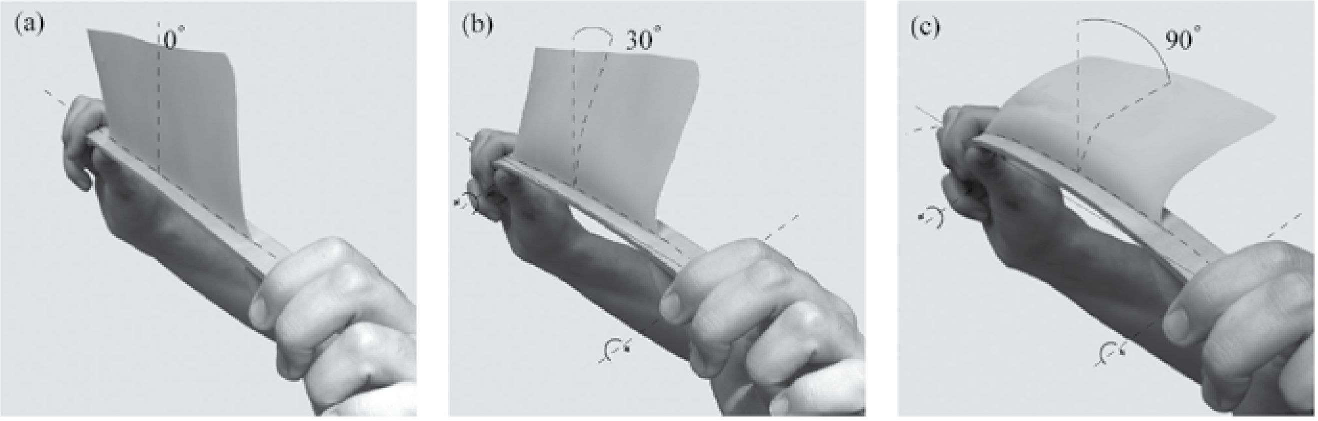

Fig.3: Physical model of the deformation principle of *Strelitzia reginae*. Bending the backbone causes the attached lamina to deflect up to 90° sideways, which is initiated by lateral-torsional buckling.

From an engineering perspective, the deformation of the Strelitzia's *flower* can be described as a hinge-less movement, during which an external mechanical force (the body weight of the bird) initiates a complex deformation of multiple structural members (ribs, laminae and wings). They are linked in such a way that the kinematically stored elastic energy can reset the system, accounting for its reversibility. *Strelitzia reginae* flowers bloom for a few days. It is conceivable that, during this time, pollination by birds and the associated execution of the flapping mechanisms leads to wear. Based on experimental tests of the flowers flapping mechanism the authors suppose that material fatigue does not exceed a critical level which would lead to malfunction, it is most presumably not an issue in the natural system as the flowers are too short-lived.

First Level of Abstraction

This kinematical system was verified by rebuilding it as a physical model which demonstrates similar adaptive behaviour (Fig.3), this being a very quick method to gain a basic understanding and to prove the functionality of the disclosed mechanism. Here, a thin shell element is attached orthogonally to a rib or beam element (here referred to as backbone). Uniaxial bending of the beam causes an unsymmetrical bending motion of the shell element which is enabled by torsional buckling. A simple physical model which shows this structural behaviour is displayed in Fig.3. This special form of lateral-torsional buckling is not unfamiliar to engineers but mainly perceived as an undesirable failure mode to be avoided when planning architectural constructions. Such instability is observed in beams with slender profiles exposed to in-plane bending. When the bending reaches a critical point the beam undergoes a combined deformation involving both out-of-plane bending and torsion [22]. While lateral-torsional buckling is usually initiated on the compression side of a beam, in the case of the observed system the compression side is reinforced by the backbone and held by the supports; consequentially it is the tension side that is deviating into out-of-plane bending due to its low lateral stiffness.
The mechanism in *Strelitzia reginae* seems to exploit the potential of this failure triggered unsymmetrical bending motion as an integrative part within a reversible deformable structure with multiple deflected equilibrium positions. The Flectofin® principle described here is an instrumentalisation of this failure mode. This highlights once more how nature and engineering differ in problem solving and shows that the structures and principles identified in biological concept generators can provide impulses and innovative means to achieve elastic mechanisms in technical structures in a previously unknown manner.

Second Level of Abstraction

In the second level of abstraction the Flectofin® principle was converted into several possible structural configurations, some of which are shown in Fig.4. The beam element, for example, can be supported as a cantilever or single span beam as well as any other structural system in which continuous bending can be induced. The beam element itself can also be a shell element, spanning perpendicular to the actuated wing. In the wing of the Flectofin® the stiffness near the backbone is increased. This is a major difference to *Strelitzia reginae* which shows a distinct localised area of high flexibility near the rib (the constricted area described above). By stiffening the region near the backbone the entire wing is forced into a bending deformation. Thereby the bending radius is largely increased which reduces bending stress and stabilises the wing in all positions against wind-caused deflections. The bending of the beam or shell element can be induced through displacement or rotation of a support, through thermal expansion, or other external forces. In order to gain a more profound understanding of the structural beha-viour, a finite element model of the Flectofin® principle was developed (Fig.5). Modern nonlinear finite element modelling (FEM) using Newton-Raphson algorithms makes the form-finding of complex equilibrium states of large elastic deformations possible. The system was modelled using shell elements for both backbone and wing. The dimensions are 2 m in length, 0.25 m in height, 5 mm thickness in the backbone and 2 mm thickness in the wing. The material properties of all elements are standard glass fibre-reinforced plastic (GFRP) values. Similar to the physical model, the deformation in this digital simulation is a response to the bending of the attached beam. The first deflection initiates a successive lateral

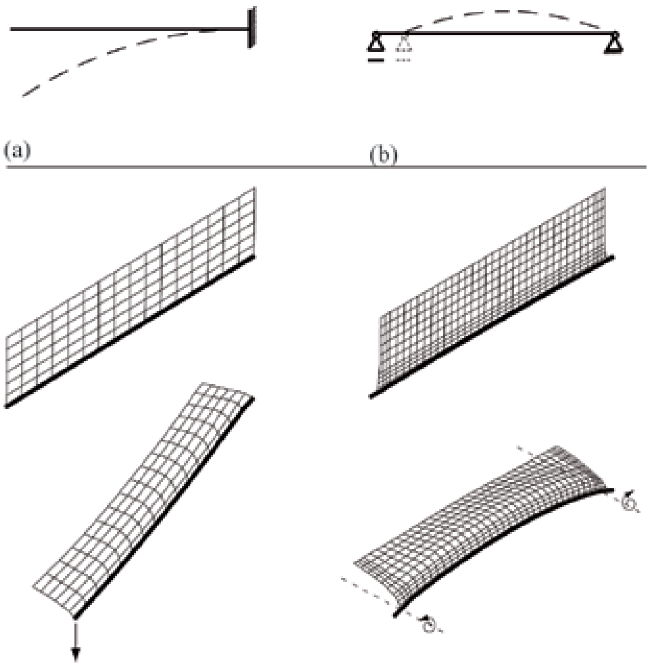

Fig.4: Configuration of the structural system.

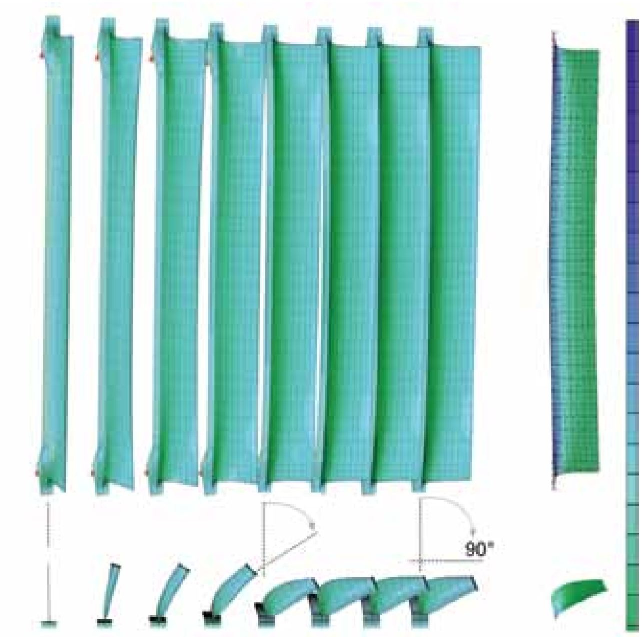

Fig.5: Simulation of the deformation in finite elements.

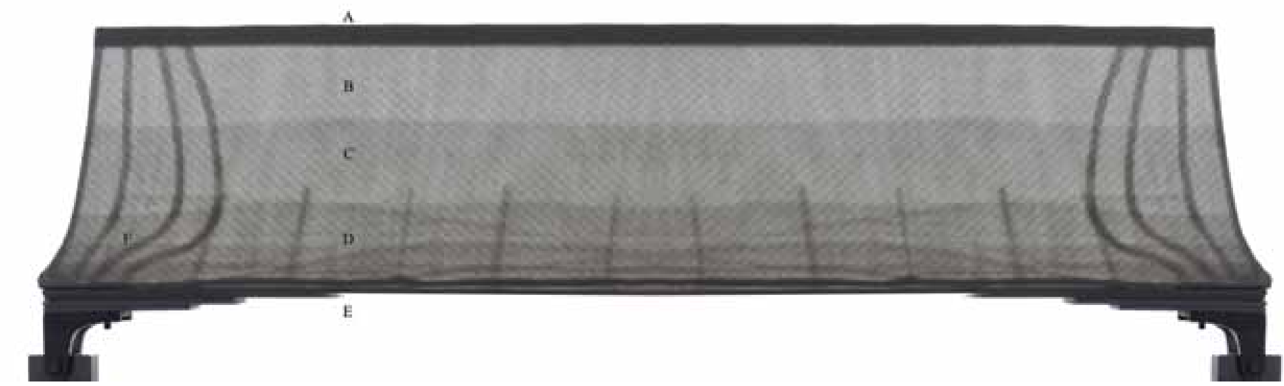

Fig.6: Thin walled laminate for a Flectofin®. A: edge reinforcement. B-D: stepped laminate with 4 to 8 layers. E: backbone made of a GFRP pultrusion profile. F: enclosed force distributing glass rovings. The lay-up of the Flectofin® Lamella was developed and produced by ITV-Denkendorf.

torsional buckling of the shell element and forces this element into an unsymmetrical bending mode. Once buckling has initiated the sideways bending, the tension forces in the wing cause the formation of an arch between either ends of the system which enhances the sideways bending up to 90° in relation to its initial position. Here, a new double curved surface is formed which provides higher stiffness in the shell element in each position during the buckling process.

Materialisation of the Flectofin® Lamella

The system inherent material requirements for high strength and low bending stiffness are most adequately fulfilled by fibre reinforced polymers (FRP). Comparing typical fibre composites with typical building materials like steel or aluminium clearly shows their advantage for large elastic deformation due to the composites' small stiffness-to-strength ratio. Since high modulus fibres can be sensitive to bending, the required elastic deformability cannot be accomplished by the fibre properties alone but has to be achieved by a suitable fibre lay-up. After a comparison of different high modulus fibres, glass fibres were selected because they are less costly than carbon fibres, more translucent, and have a better weather resistance than e.g. aramide fibres. Many different glass fibre woven fabrics and non crimp fabrics that differ in their fibre lay-up and area weight were tested for stiffness, resistance against wind-induced vibration, and the 90° bending properties near the base of the backbone.

Until now, the desired high strength and low stiffness properties were achieved by arranging 4-8 very thin plain-woven fabrics with an area weight of 80 g/m² in a set of layers (B-D in Fig.6). Due to a gradual decrease of the fabric layers from the stiff backbone to the edge of the wing, the Flectofin® Lamella is able to distribute act-

Fig.7: Full-scale prototype of the Flectofin® Facade, produced with the industrial partner clauss markisen. The lower support of the GFRP lamellas can be moved vertically and thus cause the eccentrically attached backbone to bend.

ing forces over a wider area while avoiding local stress concentrations. In order to further reduce tension forces at the edges of the fin, in particular at the meeting point of the wing and the backbone, glass fibre roving was spread out along the direction of forces (F in Fig.6).

For the matrix, an ultra-flexible epoxy resin was chosen that was treated additionally with several dyestuffs to satisfy diverse optical demands. In order to achieve the essential high quality in the laminate, the Flectofin® Lamella was fabricated by a manufacturing method called the Vacuum Assisted Process VAP®. A special layer of air-permeable foil is used to eliminate trapped air in the laminate thus enhancing the material's largely dynamic properties. The backbone profile itself was produced using a pultrusion process and is bonded to the wing to form an L-shape or a U-shape. The unidirectional fibres in the GFRP laminate of the backbone were oriented in order to optimally counteract the occurring longitudinal forces.

Technical Implementation in the Flectofin® Facade

The Flectofin® principle suits to a wide range of applications, from small-scale microsystems to large-scale architectural building components. Exemplarily it was used for the conceptualisation of an adaptive facade shading system, here referred to as Flectofin® Facade, which is currently being developed (Fig.7). Here, the bending of the fin can be induced by displacement of a support, or by temperature controlled bending. The fins allow for opening angles ranging from -90° to +90°, which provides a marginally affected view as well as complete facade covering. The smooth movement of the fins creates a very strong visual effect and results in deformation with a harmoniously double curved surface. Moreover, multiple fins can be actuated with a small time delay to increase a choreographic impression. Due to the fact that the outer edge of the fin performs a translation movement to the side while the surface itself is bending, the contour of the Flectofin® Facade in its open and closed state remains the same. Thereby, the volumetric impression of the entire building can be preserved. A significant expansion of possible future applications is given by the fact that the system functions without a straight turning axis, it can therefore be adapted to facades with curved geometries. The geometric adaptability of this concept will be explained in section 'Distortion and Modular Arrangement' (see below).

Contour Optimisation

While the first steps of abstraction represent a 'Bottom-Up-Approach' in biomimetics, in which a specific plant inspired the Flectofin® directly, it is also possible to follow a 'Top-Down-Approach' that starts with a technical question and screens the plant kingdom for promising solutions.

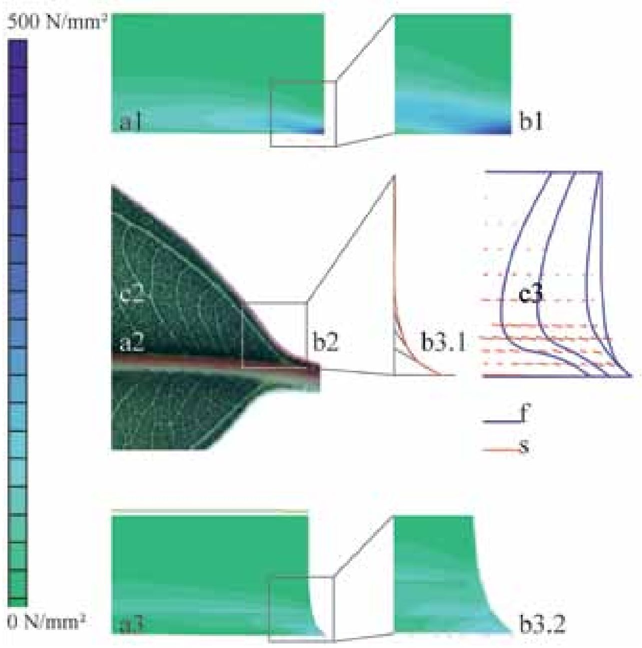

Fig.8: Reduction of stress concentrations up to 90% by using the contour geometry of a *Eucalyptus* leaf.

Fig.9: Laminate with reinforcements, accordingly placed to the tensile stress lines and leaf venation pattern.

The iteration step used here enabled further optimisation of the Flectofin® principle. Since the precision and durability of deployable structures that work on the basis of elastic deformation is dependent on the geometry and material parameters, an optimisation of the structure can be achieved by fine-tuning the element's inherent stiffness distribution as well as its contour geometry [24,25]. Interestingly, solutions to this specific technical problem may be found in several biological role models that show similar deformation behaviour. An important question, here, is the reduction of stress peaks at the transition of a flexible shell element to a beam element. 'Biological solutions' to this particular problem were found in plants which do not serve as model organisms for elastic kinematics. Being exposed to wind or other dynamic or static forces, plant leaves have developed multiple strategies to avoid notch stresses in the transition areas from leaf lamina to petiole. Some of these strategies are based on gradual transitions achieved through changes in fibre orientation, variable thicknesses and optimised contour lines. In the Flectofin® Lamella the change of thickness and fibre orientation within the shell element enables a stress harmonisation throughout the entire surface (Fig.8a and c). This is made possible by increasing the stiffness in the shell element at the transition to the beam element. Hereby, the bending was forced further into the surface, leading to larger bending radii and, consequentially, smaller stresses.

Furthermore, optimising the contour line can reduce remaining notch stresses on either ends of the shell element. Figure 8b shows how the contour geometry of *Eucalyptus* leaves was applied to the shell geometry. The stress peaks were considerably reduced by this application. The chamfered geometry of the *Eucalyptus* leaf is based on shape optimisation that can be reproduced via tension triangles as described by Mattheck [26]. The undercut geometry of *Strelizia reginae* shows a folded pocket with a thickened edge in the tip of the notch (Fig.8 a2). This solution is difficult to implement into the production of a shell element and therefore the contour geometry of *Eucalyptus* was applied. These geometrical optimisations reduced the maximum notch stress to approximately 60% of the permissible stresses for standard GFRP. Precise tests and estimation of the fatigue behaviour are yet to be done. Fatigue in composite materials is dependent on numerous factors including material choice for fibre and resin, fibre lay-up, element dimensions and environmental conditions. The wing of the Flectofin® Lamella is a comparatively thin composite that was tested for approximately 104 cycles under multiaxial stress, exposed to drastically changing environmental conditions, which makes analytical fatigue prediction very difficult. According to some general results shown in 'Fatigue Strength Prediction under Multiaxial Stress' [27], it can however be assumed that the given stress distribution and load cycles may not lead to fatigue problems if the maximum stress is lower than 60% of the permissible stresses.

Scaling and Geometrical Adaptation

A central question of this R&D-project was to determine whether bio-inspired compliant mechanisms like the Flectofin® can be scaled up significantly in order to fit an architectural dimension. The naturally occurring intraspecific and infragenetic variability of differently sized plant organs already indicates that scaling of structures in general is possible to a certain degree. In order to scale a technical system like the Flectofin®, however, one has to conciliate and balance the system's geometri-

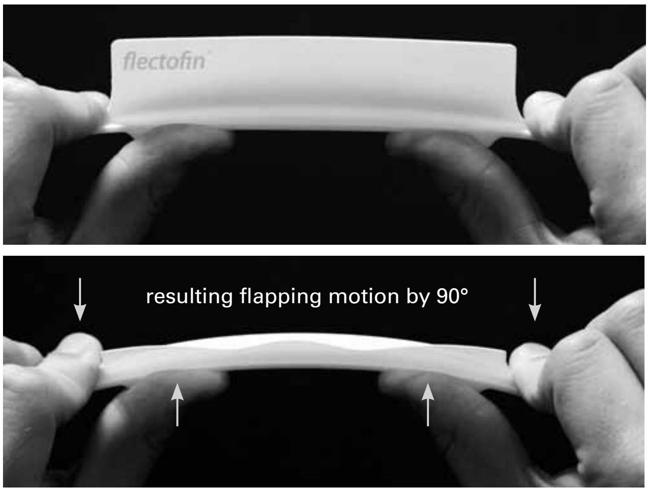

Fig.10: Fully functional model that was 3D-printed as 'one-piece mechanism' by Selective-Laser-Sintering (SLS).

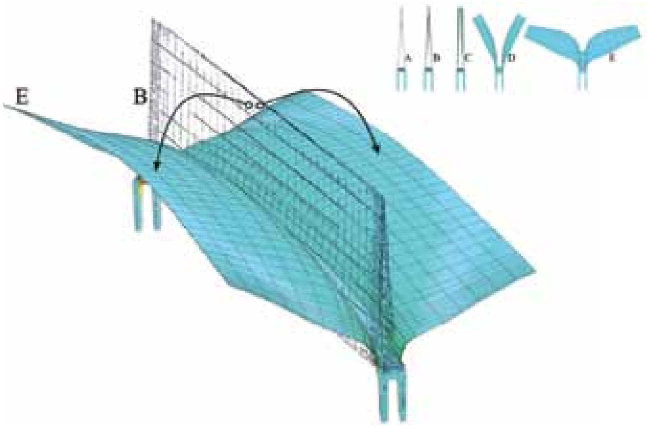

Fig.11: FE-simulation of the Double Flectofin® .

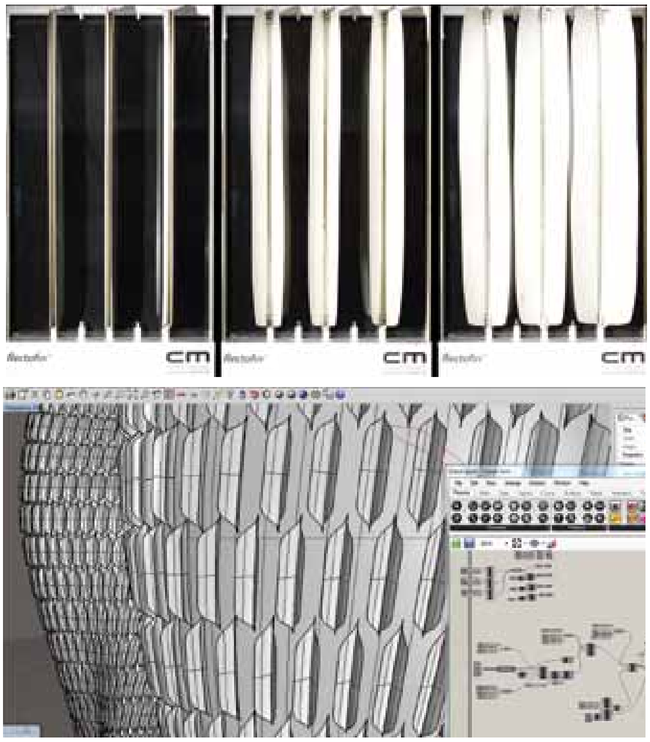

Fig.12-13: Facade mock-up with Double Flectofin® and digital control program simulating the motion.

cal and elastic stiffness. While the geometrical stiffness results from global curvature and the relationships of multiple constraint members, the elastic stiffness is defined by individual material and element characteristics. Since both are interdependent, up-scaling a system's geometry, for example, requires the adjustment of the system's elasticity by redefining its material or element profiles. Scaling the Flectofin® principle, for instance, was validated from small laser-sintered polyamide models of about 0.2 m length up to larger GFRP lamellas ranging in height between 2 m to 14 m (Fig.10,12). The geometrical scaling factor between the 2 m and the 14 m Flectofin® Lamella is 7. The thickness of the shell element, however, only had to be scaled by a factor 3, while the material parameters remained constant with standard GFRP values. Thus, maximum stress levels at the minimum bending radii rise only by a factor of 1.3. These findings may differ between various systems, yet they clearly demonstrate the scalability of compliant mechanisms out of fibre composites.

Interestingly, the up-scaling of a compliant mechanism is much easier than scaling it down, which is due to the fact that the bending radii scale proportionally to the geometry and consequently cause smaller local stresses. Furthermore, when using fibre composites for a Flectofin® Lamella, it is much less difficult to fine-tune its anisotropic material make-up and particular elastic stiffness in a macro-application than in comparable miniaturised micro-applications.

On the other hand, a linear up-scaling results in a quadratic growth of the exposed wing surface and hence an exponential growth of external loads such as wind or snow. Therefore, other pliable structures may have serviceability problems due to their high deformation under external loads. In the case of the Flectofin® Lamella, the double curved surface which appears in each position of the deflected (active) state can generate enough stiffness to withstand wind loads. The inactive state however remains rather unstable due to low elastic stiffness of the material. A further development to stabilise the inactive position is shown by the Double Flectofin® in Fig.11, with a configuration of two wings that theoretically interpenetrate (Fig.11A). Therefore, they rest in position figure 11B where they push against each other and share a large contact area which highly increases their stability. Due to their concave curvature in the inactive state the wings will bend outwards when the backbone is actuated as shown in figure 11C-F. As a positive side effect of the symmetrical deformation, the eccentric forces in the backbone that are induced by the bending of the wing counteract each other. This limits the torsion in the backbone and results in a more filigree profile.

This Double Flectofin® is a further development of the initially proposed facade component, which has an increased shading efficiency and higher wind stability. Having placed two wings on one slender profile, thereby, doubles the shaded area per backbone while hardly affecting the view (Fig.12).

Further Development of the Flectofin® by Comparison with the Trapping Mechanism of *Aldrovanda vesiculosa*

While the Flectofin® principle exemplifies a Bottom-Up research on bio-inspired compliant mechanisms, the second case study is a Top-Down approach [6]. The intention here is to refine the basic Flectofin® mechanism by comparing it with similar plant movements that have slightly different geometrical configurations and thus slightly different mechanical behaviour.

Secondary Biological Role Model

The plant movement chosen here is the fascinating snap-trapping mechanism of the aquatic carnivore *Aldrovanda vesiculosa* (Droseraceae), commonly known as the Waterwheel Plant (Fig.14). Among biologists, *Aldrovanda's* trapping mechanism has already been the subject of multiple studies which focused mainly on the physiological response to prey stimuli [28-30]. In the focus here, however, are the traps' post-stimulation mechanical aspects, which are yet another example for functionalized reversible deformations whose basic biophysical parameters have been published recently [31]. Interestingly, the plant's kinematics are influenced by curved-line folding - a hardly understood mechanical principle that may be a promising concept for designing compliant mechanisms. Each of *Aldrovanda's* leaves terminates in a little clam-like trap of approximately 5 mm in length (Fig.15). The trap has two distinctive structural regions, a lens-shaped central portion and two sickle-shaped lobes, called marginal portion. The central portion features a stiff midrib, which distributes its linear structural impact over the central portion. Both portions are of unequal stiffness. While the central portion has three cell layers, the marginal portion only has two. A curved fold and rib, called enclosure boundary [29], links both portions together and acts as living hinge. When a prey (mainly freshwater crustaceans) stimulates the trap by touching its sensory hairs, the trap-lobes close instantly. The movement, thereby, has five distinctive stages. The mechanism driving this closure movement is a deformation cascade, starting with a sudden contraction of the midrib that bends the central portion and thus triggers a successive bending of the adjacent sickle-shaped lobes. During the subsequent narrowing stage the touching lobes exhaust the water and close tightly upon each other, catching the prey in the hollow space within the trap. While this rapid closure takes only a about 100 milliseconds, the reopening stage of the trap takes up to half an hour.

Fig.14: Trap lobes of *Aldrovanda vesiculosa.*

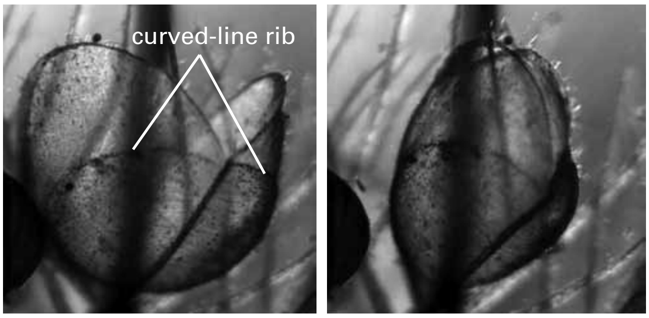

Fig.15: Trapping mechanism with curved-line ribs.

Abstraction of the Mechanism

As a first step of abstraction, we focused on the deformation happening during the opening and shutting stage. Here, the trap's elastic kinematics can be abstracted to a simplified pattern of interacting surfaces, folds, and ribs with different material characteristics (Fig.16). The abstracted pattern is a plane square with the corner points A,B,C,D. Along the diagonal, two circular arcs cross point B and D. They divide the square surface into two distinct portions - a lens-shaped centre (backbone) and two symmetrical lobes. Similar to the Flectofin® mechanism, the goal is to conceptualize a kinematical component that translates a small actuation to a rather complex motion when one of the supports gets displaced.

Kinematics of Basic Component

In order to analyse the patterns folding behaviour, the authors used the Rigid Origami Simulator [32]. This tool generates a continuous transformation process of a given crease pattern from its plane to its folded shape by calculating the configuration with all its intermediate states. The system thereby uses crease angles of all fold lines as variables to represent a constraint origami mechanism that performs a one-DOF (degree of freedom) finite rigid motion. In order to import the biologically inspired pattern to the software, it was converted to a quad-dominant planar mesh, in which the surface ru-lings are parallel in the central portion and pass through the corner points in the marginal portions. All creases were assigned a folding direction, which defines whether they are mountain or valley folds. Similar to the Flectofin® Lamella, one support is fixed and the other is linearly moveable. As expected, a translation of point D to D´ initiates not only the backbone to bend but triggers also a flapping motion of the lobes, lifting point A to A' and C to C'. Typically for curved-line folding, this pliable system couples the deformation of convex and concave surfaces that have normal curvatures in the direction of the fold line of equal magnitude and whose curvature increases the more the folding has progressed. This simulation method was not only used to determine the displacement needed to close one mechanism, but also to compare four slightly different patterns according to their displacement factor and the transmission ratio. All four configurations had the same diagonal length but varied in their arc radii. Measuring the angle α during the folding (closing of the structure) indicated that the coupling efficiency is highly dependent on the curvature of the fold (Fig.16,17). By decreasing the curvature of the fold (along the curve B-D in Fig.16), angle α is responding more sensitive and decreases quicker for a given deflection of the support.

Validation through FE-Simulation

Since the previous studies only took geometries into account and neglected stresses and forces, additional FE-simulations were needed to validate whether or not the relationship between angle α and the deflection of the support holds true when material effects are taken into account (Fig.18-19). All four patterns were simulated as GFRP laminate with a thickness of 10 mm (Young's Modulus of E = 15 kN/mm^2) in the central portion and 5 mm (E=12 kN/mm^2) in the lobes. Furthermore, a material thickness of 1 mm (E=12 kN/mm^2) along the curved line created a 'living hinge.' The width of this curved zone is adjustable, which allowed creating either sharp folding edges or smooth bending zones. Again, the supports on one end of the structure were fixed, while on the other end enabled linear displacement. As expected, the initial bending of the central portion results firstly in a uniform lifting motion of the lobes and secondly in increasing stresses within the bent surfaces. The highest stress concentrations, therein, were measured in the hinge itself. Once again the patterns with the less curved crease respond quicker to actuation and end up with less curvature.

Having analyzed the support reactions and displacement paths, it can be concluded that the actuation force increases proportionally to the radius of the arc line, whereas the displacement path needed to close the mechanism decreases proportionally. It is noteworthy that this path in the FE-models is much longer than predicted in the geometrical simulations, which may be partially due to compression in the soft zones. Interestingly, having soft folding zones instead of sharp creases has the advantage that local stresses can spread over wider area as well as they are smaller because of the larger bending radii (Fig.19). In addition, the FE-models can be used to remodel *Aldrovanda's* enclosure boundary by assigning stiffening ribs along the curved-line fold as well as driving the mechanism with an actuator rib in the middle of the central portion. However, due to local buckling effects the model is not yet suitable to describe the real mechanism in the plant which shows that further research is needed to find a closer match to the actual material set-up. Nevertheless, these studies give a first impression how to test and compare bio-inspired elastic kinematics with semi-soft and semi-rigid bending behaviour.

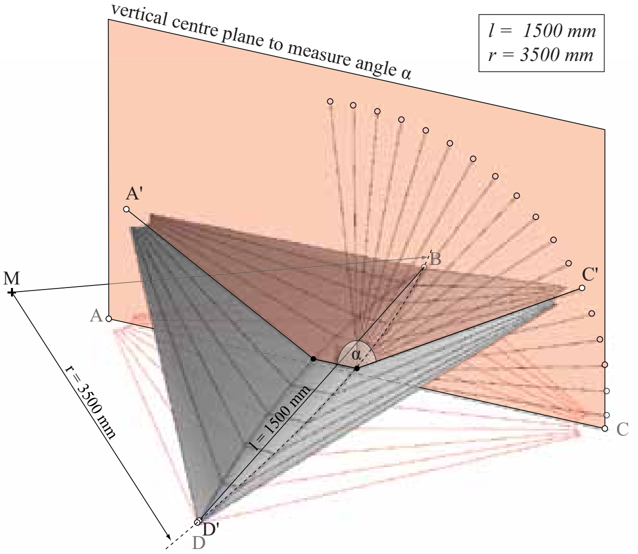

Fig.16: Kinematical simulation of the folding mechanism.

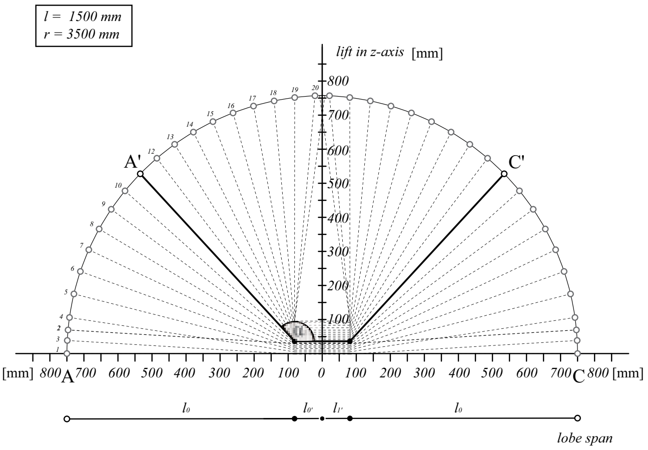

Fig.17: Cross-sectional study measuring folding angle α.

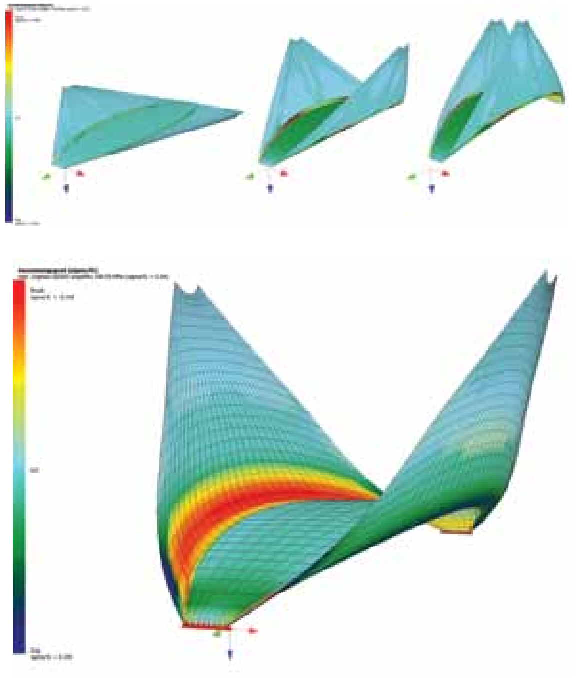

Fig.18-19: Simulation of the compliant mechanism in FE with creases of varying stiffness distribution.

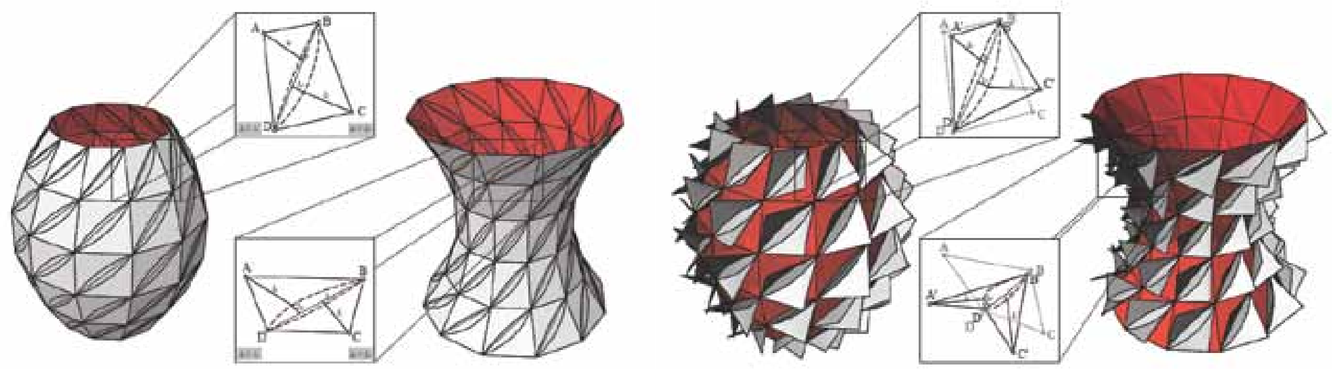

Fig.20: Parametric adaptation of curved-line folding component to surfaces with synclastic and anticlastic geometries.

Distortion and Modular Arrangement

Compared to most sun protections (e.g. blinds) whose mechanics are designed for planar and rectangular facades, the tested curved-line folding kinematics preserves its functionality even when being distorted. As mentioned in the introduction, this geometrical flexibility renders the unique possibility to enter the neglected market niche of shading double curved free form facades. Despite their smooth global appearance, their cladding strategy is highly rationalized. For reasons of constructability and economy, their shape is segmented into groups of planar or single curved panels, forming quad or triangle meshes. However, in these meshes most parts differ in size and proportion. Besides scaling, adapting a transformable shading system to this surface panelization therefore would also require individual distortion of each component. To exemplify this geometrical dependency, the curved-line folding component was applied to planar, synclastic, and anticlastic surfaces. While the first kinematical abstraction mapped the component on regular four-sided polygons, it is also possible to use any distorted polygon as a base, as long as it stays convex, which means that all line segments between two vertices remains inside or on the boundary of the polygon. Therefore, modular arrangements beyond the orthogonal grid are usually possible. Lobe contours with corner angles of 60°, for example, enable hexagonal configurations. Deforming the component, however, affects the way each lobe reacts to the initial bending of the backbone. As a result, the symmetrical arc segments of the curved-line fold need to be replaced with specific curves to fine-tune and synchronize the lobes' motion. The geometrical condition enables to populate synclastic and anticlastic surface geometries (Fig.20) with a parametric component that can open and close and thus provide shading for free form facade designs as can be seen in the design proposal in figure 21.

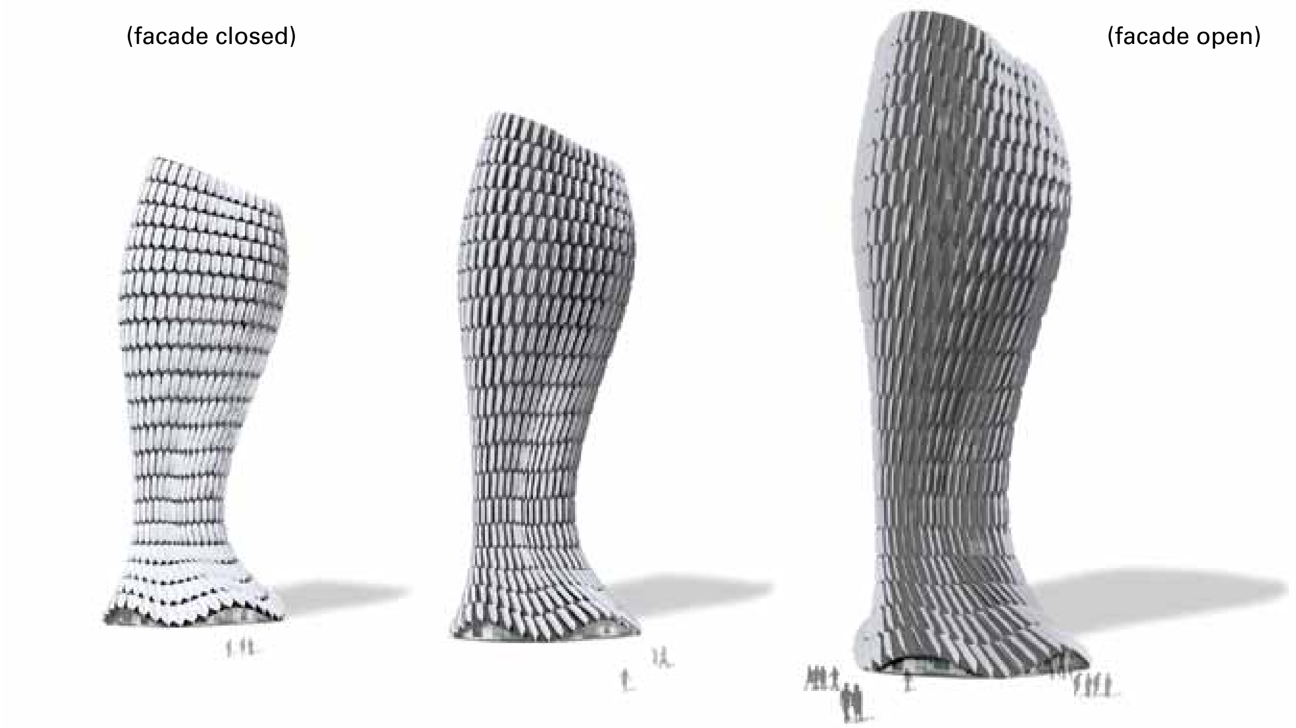

Fig.21: Exemplary free-form facade geometries with adaptable Double Flectofin® in open and closed configuration.

Design of the Thematic Pavilion EXPO 2012

Another opportunity for considering the here described mechanisms and inspire an architectural project has opened up during the design of the Thematic Pavilion at EXPO 2012 in Korea Yeosu (Fig.22-24). This pavilion was planned with a kinematic facade with 108 individually controllable fins. The design was done by Soma Architecture, the technical concept for the kinematic fins came from Knippers Helbig Advanced Engineering. The facade can adapt to light conditions and physical building conditions and allows the staging of special lighting effects. It has a total length of 140 m is designed to withstand the very high wind loads at the Korean coast. It was initially attempted to scale Flectofin® to the size of this facade. However, even though technically possible it did not met all structural and aesthetic requirements. Inspired by the research on plant movements another kinetic system was developed by Knippers Helbig, which is also based on elastic deformation triggered by a failure mode, here shell buckling. The final facade is made of slightly curved plates which are supported by two hinged corners at the top and the bottom. In the adjacent corners, a compressive force is applied in the plane of the fin, which leads to a controlled buckling. This principle shows locally smaller strains than the Flectofin®, but does not open completely. It perfectly matches the initial design intentions of the architects and offers a favorable ratio of structural stability and actuation energy. The elastically deformable fins are made of FRP and are between 3 m and 14 m high and 9 mm thick (Fig.24).

Conclusion

Both the Yeosu shading system and the Flectofin® movements are made possible via elastic deformations which in classical engineering represent non-desirable cases of stability failure and, therefore, are commonly avoided at all costs, by using sophisticated nonlinear analyses and bracing. Even though the Yeosu facade does not follow the abstraction of the plant movement directly, prior analyses of these biological concept generators led to a deeper understanding of the biomimetic potential and encouraged to look for solutions outside of traditional preconceptions, in this case exploiting deformations and stability failure modes for a translation into the Yeosu shading system. The two examples show that a linear understanding of biomimetics may only be sufficient if the focus is on the abstraction of single functions as is the case in technical products such as the Flectofin® Lamella. In architectural tasks, however, differing requirements between the aesthetics and functionality have to be met in a given set of defined boundary conditions. In the context of architecture a linear abstraction process is, therefore, difficult to maintain. Instead, an expanded definition of biomimetics is required: the analysis of natural form and function principles have the potential to inspire architects and engineers to use fundamentally new strategies in architectural design and technical implementation.

Fig.22-24: Kinematic facade of the Thematic Pavilion EXPO 2012 in Yeosu, South-Korea.
Architects: soma-architecture, Vienna; Engineer for Kinetic Facade: Knippers Helbig, Stuttgart, New York.

Market Potential

Current trends in architecture show increasing demand for intelligent, self regulating facade shading systems that adapt to changing light and weather conditions to save energy and to improve the building's microclimate. The increasing number of fully glazed facades with complex curved surface geometries, however, poses great challenges to the shading solutions currently available. The Flectofin® Facade opens new possibilities for adaptive exterior shading systems that are not restricted to regular planar facade geometries. Functional benefits are wind stability, variable dimensions, low maintenance costs (life cycle cost) and its adaptability to free form double curved surfaces. Since the facade of a building is an important architectural feature the design of a shading system cannot only be defined by its functions. The positive feedback from practicing architects that used Flectofin® Facades for competition entries already shows that the Flectofin® has the potential to fulfil great expectations not only due to its functional benefits but also because of its attractive aesthetics.

In 2011 the market for facades reached a total of 12 billion Euros world wide, 6% of which is accounted to shading systems. This may underline the huge market potentials for new facade shading systems that meet the upcoming demands in building technology, building physics and architectural quality.

In fact, buildings are the largest energy consumers in Europe; more than 40% of the primary energy consumption is attributable to the construction and use of buildings. There is an enormous energy saving potential in facade shading systems, particularly when applied on the exterior. This has finally been recognised by the European Union and the Federal Government, who will soon respond with regulations that make facade shadings compulsory. In Germany, for example, the EnEV has been in place since 2007, already ensuring greater energy efficiency in the building sector.

In terms of energy efficiency of a building the increasingly large glazed areas in modern facades are their weakest point. They may lead to extreme overheating in the summer and up to 40% heat loss in winter. As a consequence modern office buildings rarely function without air conditioning. Provided an efficient shading system is in place, office buildings in central Europe could, however, easily function without mechanical cooling. In addition the adaptability of a shading system allows the capturing of passive energy in winter. For Europe, this means a potential energy consumption reduction of approximately 41 million tons of oil (10%) and approximately 111 million tons CO^2 per year. Source: ES-SO trial 'ESCORP-EU 25' of the Physibel Institute in Maldegem / Belgium.

Fig.25: Full-scale prototype of the Flectofin® Facade, produced with the industrial partner clauss markisen. The Flectofin® Lamella was produced by ITV-Denkendorf.

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