Adaptive Façade Shading Systems inspired by Natural Elastic Kinematics

Simon Schleicher
University of Stuggart – ITKE

Biography

Simon Schleicher studied architecture at the University of Stuttgart and graduated from the Master of Architecture program at the Massachusetts Institute of Technology. Simon is currently working towards his PhD in the Institute of Building Structures and Structural Design (ITKE). Simon’s design approach explores elastic bending and folding kinematics found in plant movements and aims to transcend them to the design of lightweight constructions and adaptive cladding systems. His projects have won various awards including the DETAIL prize 2011 and the Ralph Adam Cram Award 2010.
Adaptive façade shading systems inspired by natural elastic kinematics

S. Schleicher\textsuperscript{1,3}, J. Lienhard\textsuperscript{1,3}, S. Poppinga\textsuperscript{2,3}, T. Masselter\textsuperscript{2,3}, T. Speck\textsuperscript{2,3} & J. Knippers\textsuperscript{1,3}

\textsuperscript{1} Institute of Building Structures and Structural Design (ITKE), University of Stuttgart, Germany.
\textsuperscript{2} Plant Biomechanics Group Freiburg, Botanic Garden, Faculty of Biology, University of Freiburg, Germany.
\textsuperscript{3} Competence Network Biomimetics, Baden-Württemberg, Germany, and Bionics Competence Network (BIOKON e.V.), Germany.

Contact: Simon Schleicher (s.schleicher@itke.uni-stuttgart.de)

Abstract

This paper aims to present a novel approach to conceptualize basic mechanics for exterior façade shading systems by investigating kinematics of complex plant movements that are based on reversible elastic deformations. In an interdisciplinary collaboration between architects, engineers, and biologists; autonomous and non-autonomous flower opening and leaf folding processes were tested for their potential to act as concept generators for deployable structures in architecture. By introducing two case studies, the paper will exemplify how kinematical relationships can be successfully derived from pliable structures in nature. While, for example, the Flectofin® façade is based on the valvular pollination mechanism of the Bird-Of Paradise flower, the curved-line folding kinematics in the second case study was informed by the rapid trap closure mechanism of the carnivorous waterwheel plant. Both systems couple surface deformations to a cascading movement such that a small and simple actuation in one part of the structure is translated into a large yet stable deflection of another. For a better understanding of the principles involved, the paper will firstly introduce the inspirational phenomenon and explain the plants' functional-morphological relationships. Secondly, the paper will present first abstractions of the underlying geometrical and structural features by using physical and digital models. Thirdly, FE-simulations will be used to validate the possibilities to scale and distort the kinematics and to transfer them into technical constructions. Finally, an outlook in which these adaptive façade shading systems are applied as parametric components to free-form geometries will close this paper.

Keywords: plant movements; biomimetics; deployable structures; pliable structures; bending-active structures; curved-line folding; flectofin®; adaptive façade shading; free-form geometry

1 Introduction

Adaptive architecture often refers to deployable structures which have the capacity to respond to changing environmental conditions (e.g. intensity/direction of solar radiation). Used for building envelopes, these technical systems (e.g. flaps, blinds, or louvers) gain their flexibility by combining multiple rigid elements with highly strained hinges. This concept, however, demands very accurate geometrical configurations and precise manufacturing processes. The aim of this paper is to find a different approach to tackle these mechanical challenges by focusing on hinge-less and bending-active structures. Moreover, elastic kinematics as found in complex plant movements act as role models for the development of new bio-inspired pliable systems that can be implemented architecturally. Plants typically have an all-in-one kinematical construction, in which a structure’s global flexibility is achieved by its local differentiation into regions of alternating material properties or special morphological and anatomical features. Since plants only have little building material diversity available (e.g. cellulose, lignin), local mechanical
adaptations are mostly due to variations in form and structure, not in material. Compared to technical systems, these pliable structures in nature replace local hinges by large elastic deformations of the entire structure and thus distribute the acting forces over a wider area in which bending takes place. Interestingly, latest developments in customizing glass-fibre reinforced plastics (GFRPs), which can combine high tensile strength with low bending stiffness, indicate that reproducing similar hinge-less kinematics for technical systems is becoming an increasingly reachable design goal. Finding an adequate methodology to analyse the biological role model, to abstract its kinematical principles, to test its geometrical and structural limitations, and finally to transfer it to a technical implementation is, however, unexplored ground that needs to be discovered in order to open up this novel design space. This paper aims to make a contribution to this discourse by briefly discussing the potential of pliable systems in general and the advantage of elastic kinematics in particular. Furthermore, the authors are going to present two exemplary case studies in which basic kinematical relationships were discovered and successfully informed the conceptualization of a technical pliable system with a similar adaptive behaviour.

2 Potential of elastic bending and folding principles for pliable systems

In order to discuss the potential of bending and folding principles for pliable systems as they could be used in adaptive façade shading systems, one has to look into the concept of bending-active structures. Bending-active structures are pliable constructions, which generate their geometrical form and their system rigidity by elastically deforming their members. Here, the basic design principle involved to generate a form is the global or local bending of zones within the structural component itself, rather than stringing multiple stiff components together. This alternative approach renders the possibility to form complex single- or double-curved beam, grid, or plate structures from straight or planar elements. Sufficiently thin component thickness thereby allows for small bending radii and thus results in low bending stresses. Structural rigidity can be either be increased by the combination of bending end tension pre-stress stored within individual elements or by the coupling of multiple elements to a combined system.

The use of bending and folding principles are not only helpful in the initial forming of complex geometries and in stabilizing them with additional pre-stress afterwards, but also in functionalizing the reversible deformation itself. Bending-active kinematics, therefore, define an object’s or systems’ deformation sequence by taking into consideration geometrical relationships as well as coupled internal forces that cause the motion or are responsible for the resulting transformation. In pliable systems the deformation behaviour of individual elements is constrained by their neighbouring elements. The linking of these elements allows the transmission of forces and torque. Thus the deformation of one element due to bending moments will, for example, subsequently result in the deformation of the adjacent element. This relationship can be used to build up a cascading deformation movement or to gear the transmission of acting forces and moments. The transmission ratio between constraint elements, thereby, is highly dependent on their geometry, material characteristics, and the properties of the hinge-zone between the components.

While the concept of pliable systems and bending-active kinematics is rather uncommon in the field of architecture and hardly been used in mechanics in general, it is commonly found in nature. The here presented plants demonstrate, for example, a fascinating bandwidth of hinge-less movements which all provide a high degree of flexibility while guaranteeing a sufficient structural stability.
3 Abstraction of the elastic kinematics of *Strelitzia reginae* and transfer to the Flectofin® principle for a hinge-less shading lamella

The first case study aims to exemplify a bottom-up research[1], in which the reversible deformation found in plant movements was analyzed from a biologically point of view at first, and then abstracted to a pliable structure[2,3] as well as transferred into the technical construction of a hinge-less, versatile flap named Flectofin®.

3.1 Phenomenon and functional-morphological relationships

The Bird-Of-Paradise (*Strelitzia reginae*, Strelitziaceae) shows a very fascinating non-autonomous reversible deformation movement. Actuating elements as well as kinematics are clearly defined by the plant’s functional-morphological relationships, which makes *Strelitzia reginae* an excellent role model to study biological bending kinematics. This flower is ornithophilous, which means that the transfer of pollen from one flower to another, leading to sexual reproduction, is maintained by birds. It features a perch of two adnate petals, which act as a landing platform. When the bird sits on this flower structure in order to reach the delectable nectar, its weight causes the perch to bend down (Fig.01). In a simultaneous movement - a sideways flapping of the petal lamina – the previously enclosed anthers (male sexual flower parts) and the style (female sexual flower part) get exposed and the pollen attached to the bird. When the bird flies away the open perch resets to the protective closed state again due to its elastic properties. A closer look at a cross-section through the perch reveals its monosymmetric set-up (Fig.02a). There are three reinforcing lateral ribs on both sides, which are loosely connected with a thin flexible lamina. Whereas the lower lateral ribs are merged together, the upper ribs are fused to a large flap-like lamina and close the cavity to cover the anthers. The schematic drawing in (Fig.02b) shows the perch in its open and closed position. From an engineering point of view, this flapping mechanism can be described as a hinge-less movement, in which an external mechanical force (weight of the bird) initiates a complex deformation cascade of multiple structural members in the upper lateral rib. They are linked in such a way that the kinematically stored elastic energy can reset the system. This mechanism is not only reversible but also highly repetitive. While the flower naturally gets visited by birds only a few times during its life span, the flexure mechanism itself is reliable enough to perform over 3000 cycles with only slowly increasing fatigue[4].

![Fig.01: Basic kinematics of the perch in closed and open position.](image)

![Fig.02a-b: Cross-section of the perch](image)

3.2 Abstraction of Kinematics

The structural effect that is responsible for the plant’s impressive kinematics is initiated by lateral torsional buckling and continues as an asymmetrical bending mode. It appears in the large flap-like lamina with its lateral rib when the perch is bent down. The interaction between lamina and rib can be demonstrated by building a simplified FE-model with a similar kinematical
behaviour. Here, a thin shell element is connected perpendicularly to a cantilevering beam (backbone) (Fig.03). Similar to the plant kinematics, the deformation of the two elements is constrained to each other. Hence, already small uniaxial bending of the backbone immediately triggers torsional buckling, which forces the shell element on its equilibrium path into an unsymmetrical bending motion. This deformation principle was named Flectofin®. The FE-model additionally enabled testing of various structural configurations, including the ones that not directly mimic the biological role model yet preserve the typical Flectofin® principle, for example a backbone on two supports (Fig.04).

3.3 Possibility to Up-Scale the Pliable System

A central question of this research is to determine whether biologically inspired kinematics like the Flectofin® principle can be scaled up significantly in order to reach a useful architectural dimension. The question of up-scaling a structural system in general is highly dependent on the ratio of geometrical to elastic stiffness. While the geometrical stiffness results from global curvature and the relationships of multiple constraint members within the system, the elastic stiffness of the system is defined by individual material and element characteristics. Hence, up-scaling a system’s geometry is usually possible, however, it requires the redefinition of material parameters and element profiles in order to preserve the functionality of the mechanism. The same is true for the Flectofin® principle and was validated for a height range from 0.2m to 14m [5]. Interestingly, up-scaling elastic kinematics is often much easier than down-scaling. This is due to the fact that occurring bending radii scale proportionally to the geometry of the entire system, thus causes smaller stresses when the elastic stiffness grows under proportional to the radii or even remains constant.

3.4 Transfer into a Technical Construction

The flexibility in scaling the Flectofin® principle allowed testing a prototypical mock-up of an adaptive façade shading system. Here, the Flectofin® principle was implemented in exterior fins made out of GFRP (glass-fibre reinforced plastic) with a height of 2m, a width of 0.25m, and a shell thickness of 2mm. Instead of having costly hinges, this set-up systematically uses the material’s natural elasticity to its advantage. Conceptualized as an all-in-one pliable system, this hinge-less fin unites backbone and shell element into one laminate with differentiated zones of stiffness. In the shown mock-up the hanging fins have pinned supports at the top and are connected to an electronic actuator at the bottom. The lower supports can be moved vertically in order to induce the initial bending of the backbones and thus to drive the deflection of the fins. Customized for an optimal transmission ratio, the system can guarantee the fins serviceability by keeping the tension and compression forces within predefined limits. Displacing the support by
only 30mm results in opening angles between -90° and +90°, which offers a marginally affected view outside or a complete covering of the façade. As a positive side effect, the fins’ double curved geometry provides additional stiffness helping to withstand stronger wind loads. In order to raise the fins stiffness also in the undeformed state, two fins are set on a common backbone. Hereby the torsion on the backbone is avoided and a larger shading area may be covered per backbone (Fig.05).

Fig.04: Multiple fins allow for adjustable shading  Fig.05: Double Flectofin with two supports.

4 Abstraction of biologically inspired elastic kinematics exemplified on curved-line folding principles in *Aldrovanda vesiculosa*

While the Flectofin® principle exemplifies a bottom-up research on bio-inspired elastic kinematics, the second case study is a top-down approach [1]. The intention is to gain a better understanding on the elastic kinematics of curved-line folding in general and to compare them with informative biological role models in particular.

4.1 Phenomenon and functional-morphological relationships

The biological role model chosen here is the fascinating snap-trapping mechanism of *Aldrovanda vesiculosa* (Droseraceae, Sundew Family), a free-floating aquatic plant that is commonly known as the waterwheel plant (Fig.06 [6]). Among biologists, *Aldrovanda*’s fascinating trapping mechanism has already been the subject of multiple studies [7,8]. Recent research mainly focused on the plant’s biochemical response to prey stimuli and aimed to quantify the propagation of action potentials in its leaves [9]. In our context, however, it is very interesting to analyze the post-stimulation mechanical aspects of the trapping mechanism in comparison to the Flectofin® principle. This trap is yet another example for kinematics that is based on the coupling of elastic and reversible surface deformation. This time, however, the plant’s kinematics additional curved-line folding feature – a hardly understood mechanical principle that may be very promising for conceptualizing technical pliable systems. Each of *Aldrovanda*’s whorly leaves terminates in a little clam-like trap of approximately 5mm in length. The schematic cross-section and upper view (Fig.07 [9]) reveals the trap’s monosymmetric morphology with two distinctive structural portions. In the middle of the trap there is a lens-shaped surface called central portion. It features a stiffer midrib, which distributes its linear structural impact by little wrinkles over a larger motor zone. The central portion is surrounded by sickle-shaped lobes, called marginal portion. An infolded rim frames the leaf-blades at the perimeter. From a structural point of view, it may be considered that both portions are zones of unequal stiffness. While the central portion has three cell layers, the marginal portion only has two. Both portions are linked together by a
curved-line rib, which is called enclosure boundary [7]. Finally, the trap features little trigger hairs that stand along the enclosure boundary and the midrib on the inner surface of the central portion.

When prey (e.g. water fleas) stimulates the trap mechanically by touching the sensory hairs, the trap-lobes close instantly. According to our measurements, Aldrovanda’s rapid closure only takes about 133ms. This fact becomes even more impressive when one takes into consideration that Aldrovanda lives underwater, which means that the trap-lobes have to push water aside as they close. The trapping mechanism itself has five distinctive stages: open, shutting, narrowing, closed, and reopening. During the open stage the trap is in its sensitive and structural metastable condition with the free margins of both lobes standing apart from each other in an opening angle of roughly 60°. The sickle-shaped trap-lobes in the marginal portion, thereby, already have a light convex curvature. A mechanical stimulus of the sensory hairs initiates the shutting stage. The following rapid closure movement is due to a sudden contraction of the midrib and the motor zone in the lens-shaped central portion, in which the elastically tensioned trap relaxes to a less strained configuration. This deformation of the trap’s central portion is likely to be coupled to the marginal portion in such a way that the bending of the centre surface triggers a successive bending of the adjacent sickle-shaped lobes. The sequential deflections of the coupled portions thus are a perfect example for bending-active kinematics within a pliable system. The shutting stage ends when the rims of the trap-lobes start to touch each other. In the successive narrowing stage the trap-lobes are in contact and during a complex deformation sequence the water in the trap gets exhausted. The resulting cohesion forces press the lobes tightly upon each other and the lens-shaped central portion forms a hollow space in which the caught animal is being trapped. While this rapid closure takes only a few milliseconds, the reopening stage of the trap takes up to half an hour.

4.2 Abstraction of Kinematics

The plant’s inspiring elastic kinematics in the various stages is highly complex. It is influenced by the curved-line folding pattern, specific material characteristics, and distinctive transition in stiffness where the ribs touch the surfaces. As a first step, in this paper, we have focused on the trap’s opening and shutting stages and investigated an abstracted structural pattern. Even though not related to this biological role model, versions of this pattern have already been presented [10] and found their way into a conceptual student project [11]. In our context, however, we aim for a set-up, which allows us to analyze multiple pattern configurations according to their transmission ratio and to compare them to the Flectofin® principle. This will give valuable insights about the relationships in the abstracted pliable system and thus might help gaining a better understanding of the much more complex kinematics in Aldrovanda’s trapping mechanism. The basic pattern
that was used in a first step of abstraction is a plane square with the corner points A,B,C,D (Fig.08a). Along the diagonal, two circular arcs cross point B and D. They divide the square surface into two distinct portions - a lens-shaped centre and two symmetrical lobes with a sickle-shaped edge. Similar to the Flectofin®, this surface partition creates a backbone in the middle and two adjacent shell elements that perform the aimed for flipping motion. Once again the goal is to conceptualize a kinematical component, which can be activated by a very small linear displacement of the support and to couple a rather complex deformation cascade of multiple surfaces to a pliable system.

4.3. Kinematics of the Basic Component

For a better understanding on how the proposed patterns can be deformed, we used the Rigid Origami Simulator software – a system for interactive simulation of origami patterns based on rigid origami models [12]. This tool generates a continuous process of transforming a surface into a folded shape by calculating the configuration with all its intermediate states from a given crease pattern. 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, we converted the developable surfaces to a quad-dominant mesh with planar faces, in which the surface rulings are parallel in the central portion and pass through the corner points in the marginal portions. Furthermore, we assigned a folding direction of the creases by defining whether they are mountain or valley folds (Fig.08b). Similar to the Flectofin®, we defined point B to be a pinned support while point D can translate linearly from D to D’. At this point we were able to simulate geometrically the kinematical behaviour of the curved folding and observed that the bending of the lens-shaped central portion triggers the flapping of marginal portions, lifting point A to A’ and C to C’ (Fig.08c). Typically for curved-line folding, this pliable system combines convex and concave surfaces that have surface normal curvatures in the direction of the fold line of equal magnitude. Similar to Aldrovanda, the surface deformation of the central and the marginal portions are constrained to each other and folding the pattern results in increasing curvature of the lobes. Finally, this pure geometrical simulation helped us to find the displacement needed in order for the lobes to touch and close the construction. In addition, it was therewith possible to calculate the displacement factor and the transmission ratio of different pattern configurations. Four patterns were tested, all with a diagonal length of 1500mm and changing radii for the arc lines between 1700mm, 2500mm, 3500mm, and 4500mm. The patterns’ deformation sequence was simulated iteratively (Fig.09) and the angle $\alpha$ between the central backbone and the lobes was determined in section (Fig.10). In the graph (Fig.11) you can see that the degree of geometrical efficiency (here referred to the closing angle $\alpha$) is highly dependent on the curvature of the curved-line. The less curvature the line has the more sensible the mechanism becomes towards stimulus (displacement of the support) and the quicker the pliable system performs a uniform movement. This sensitivity can be specified as ratio between the system’s global length and the local displacement needed at the support to fully open/close the device. The resulting displacement ratio for the pattern with a radius $r=3500mm$ is for example $(1500mm/16mm) = 94$. The Flectofin® mechanism in comparison has
(2000mm/30mm) = 67, which seems to be less sensible than two of the patterns. Since these studies were purely geometrically and neglect stresses and forces, additional FE-simulations were needed to validate whether or not these transmission ratios really occur when built with the targeted materials.

4.4 Validation through FE simulation

In the second step of abstraction, the pattern’s kinematics was analysed by using FEM. All four configurations were modelled as GFRP laminate with a thickness of 10mm in the central portion (Young’s modulus of elasticity $E = 15,000$ N/mm$^2$) and 5mm ($E=12,000$ N/mm$^2$) in the lobes of the marginal portion. In order to create a living hinge, the material of the curved line was given the thickness of 1mm ($E=12,000$ N/mm$^2$). The width of this zone, however, was adjustable and thus allowed for the creation of either sharp folding edges or rather smooth curved-bending zones. Similar to the geometrical simulation, the supports on one end of the structure were pinned while on the other end they enabled a linear displacement. As expected, the initial bending of the central portion results in a uniform lifting motion of the lobes as well as an increase of stresses in the bent surfaces (Fig.13). Once again the patterns with the less curved crease respond quicker to actuation and end up with less curvature. Analyzing the support reactions and displacements it can be concluded that within the range of tested arc line radii the actuation force rises proportional to the radius. Whereas the displacement needed to close the lobes sinks proportional to the radius. A difference to the geometrical simulation is the greater displacement needed in the FE-models need a greater displacement, which is partially due to compression in the soft zones. However, having soft zones instead of a sharp crease has the advantage that local stresses can spread over wider area and additionally results in larger bending radii (Fig.14). Interestingly, the flexibility in specifying the crease zone itself can also be used to remodel Aldrovanda’s enclosure boundary by assigning rib stiffenings along the curved-line bending zone as well as within the central portion (Fig.15). In this simulation, the ribs cause the central portion
to buckle locally, which shows that this is not yet the structural set-up of *Aldrovanda* and it would need further research to adjust better to the plant’s actual kinematics.

Nevertheless, the here presented studies exemplify successfully how to re-model material patterns with gradient zones of stiffness. Thereby, it is possible to quickly test and compare the interaction of semi-soft and semi-rigid elements in a pliable structure. This does not only help to understand the kinematics in a biological role model like *Aldrovanda*, but also renders the possibility to learn from the plant’s heterogeneous and anisotropic structural set-up, which might inform the way we conceptualize the use of fibre-reinforced materials in pliable structures.

![Fig 13: FE-simulation of curved-line folding pattern with sharp edges](image)

![Fig 14: Pattern with bending zone](image)

![Fig 15: Pattern with bending zone and rib stiffening](image)

### 4.5. Potential for Distortion and Arrangement of the Basic Component

While most of the currently used shading systems (e.g. blinds) are based on mechanics that require planar and rectangular façade elements, the curved-line folding kinematics presented here preserves its functionality even when being distorted. Thereby, this shading system can be applied to double curved free-form geometries, which until now have not easily been covered. This geometrical flexibility is the biggest difference to products currently on the market. Besides using the square patterns of the first abstraction step, it is also possible to distort the four-sided polygon irregularly. The pattern can be generated in any distorted polygon, as long as it stays convex, thus containing all the line segments that connect any pair of its points. Therefore, modular arrangements beyond the orthogonal grid are usually possible. Corner angles of 60° for example enable hexagonal configurations. The distortion of the pattern, however, affects the way each lobe reacts to the initial bending. As a result the symmetrical arc segments of the curved-line fold need to be replaced with specific spline curves to fine-tune the motion of each lobe.
Finally, by using an intermediate state of the folding process, in which two of the vertices have already lifted off the plane, it is also possible to generate a component that can address skew four-sided polygons, called skew quadrilaterals. Thereby, it is possible to populate synclastic as well as anticlastic surface geometries (Fig.16) with a parametric component that can open and close and thus provide more or less shading for exciting free-form façade designs (Fig.17).

Figure 16: Parametric curved-line folding component on synclastic and anticlastic geometries

5 Conclusion and Outlook

Even though these first studies already indicate how bio-inspired elastic kinematics could be used to conceptualize adaptive façade shading systems, further research is needed to fully tap the potential of hinge-less bending deformations as they are found in nature. The here presented Flectofin® as well as the curved-line folding principle already show that plants like Strelitzia reginae and Aldrovanda can act as concept generators for novel elastic kinematics. It would be interesting, however, to gain an even more profound understanding of the structural relationships in which the abstracted mechanisms increase distortion and scaling ability. Finally, actually implementing the shading kinematics for a real project would showcase their unique potential to address complex free-form geometries.

Fig.17: Exemplary implementation of the Flectofin® façade element as a parametric component
Acknowledgements

This research is part of the joint research project ‘Deployable structures in architecture - flexible surface structures on the basis of bionic principles’, which is supported within the funding directive BIONA by the German Federal Ministry of Education and Research. The authors are supervised and consulted by the Competence Network Biomimetics. In addition, the first author wants to express his gratitude to the German National Academic Foundation that supports his dissertation.

References


