Elastic architecture: nature inspired pliable structures

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Abstract

At the interfaces of our mostly stationary architecture and surrounding nature we need to make constructions adaptable to ambient changes. Adaptability as a structural response to changing climate conditions, such as the intensity and direction of sun radiation, can be realised with deployable systems. These systems are often based on the combination of stiff compression members and soft tension members connected with hinges and rollers. Deployable systems in nature are often based on flexibility. This can be observed especially in plant movements. New construction materials such as fibre-reinforced polymers (FRP) can combine high tensile strength with low bending stiffness, allowing large elastic deformations. This may enable a completely new interpretation of convertible structures which work on reversible deformation, here referred to as elastic or pliable structures. In a current research project the kinematics for such systems are derived from certain applicable plant movements.
This paper will focus on the biomimetic workflow used to develop elastic kinetic structures based on such movements. The abstraction and optimisation methods will be described from an engineering point of view, focusing on the technical approaches of converting the conceptual results of a first level abstraction into higher level abstractions and finally to physical design.
Keywords: pliable structures, deployable structures, plant movement, elastic deformation, variable stiffness, architecture, biomimetics.

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1 Introduction

In pliable structures the kinematics work on the basis of elastic deformation rather then rotation of stiff members around distinct hinges. Here the equilibrium paths which can be described for the deformation of linear and non-linear structures [1] are exploited to describe elastic kinematics. While the basis of such elastic kinematics may be bending and failure modes they can be used for complex pliable systems when several of the basic principles are coupled. Furthermore, the elastic deformation principles cannot only be applied to beam elements, but also to shell elements, opening a new range of possibilities for deployable surface structures, see also (Schleicher, this conference).

A transdisciplinary research collaboration amongst architects, engineers, and biologists led to an in-depth investigation of plant kinematics that can be used as concept generators for elastic kinematics in technical applications [2, 3]. An extensive screening process revealed various deformation principles found in plant movements, some of which are non-autonomous and generated by the application of mechanical force on the respective structure. Here the plants' kinetics and material set-up are often adapted during evolution to specific loading conditions, e.g. they are 'custom-fit' to be triggered only by the weight of specific pollinators. These movements show clearly defined mechanics and actuating elements with a coherence of form and kinematics, making them particularly adequate for an abstraction into structural technical systems. The findings presented in this paper will be based on the elastic kinematics inspired by the valvular pollination mechanism in the *Strelizia reginae* flowers (commonly known as Bird-Of-Paradise). These kinematics are taken as a given nature-inspired raw model. The abstraction steps that led to this system are described in detail by Poppinga et al. (this conference) and Lienhard et al. [4].

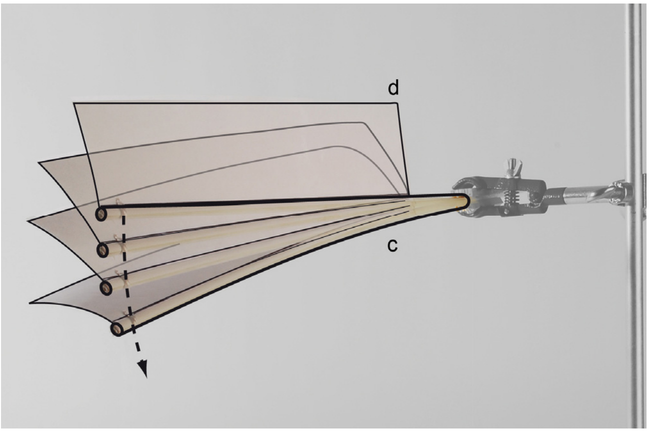

Figure 1: Physical model of the Flectofin®.

In-depth research on the plant's elastic kinematics led to the technical construction of a hinge-less, versatile flap named Flectofin®. The basic principle of the Flectofin® kinematics is shown in Fig 1. A thin shell element (d) is attached to a beam element (c). The equilibrium path of the shell element is a sideways bending motion, triggered by torsional buckling which is induced by uniaxial bending of the attached beam.

This presentation will show the steps that were undertaken for a successful scaling of the Flectofin® principle from the abstracted plant movement to the clarified kinematics and finally to the conceptualised implementation as an adaptive façade shading system.

2 Abstraction of biologically inspired elastic kinematics

In order to up-scale the pollination mechanism of the *Strelizia reginae* flower several abstraction steps were needed to disclose the physical principles behind the phenomenon. Firstly, the kinematics were analysed on the plant itself by cutting away all parts that are not essential to the performance of the plant's elastic kinematics. Thereafter the kinematical system was verified with a physical model that shows a similar adaptive behaviour; this being a very quick method to gain a first understanding and to prove the functionality of the disclosed mechanism (Poppinga, this conference). The structural system could then be abstracted into several possible configurations. In Fig. 2 some of the configurations for a structural system of the Flectofin® are shown. The beam element (c) can be supported as a cantilever or single span beam as well as any other configuration in which continuous bending can be induced. The beam element itself can also be a shell element, spanning perpendicular to the actuated shell (d). The bending of the beam or shell element (c) can be induced through displacement or rotation of a support, through thermal expansion or external forces.

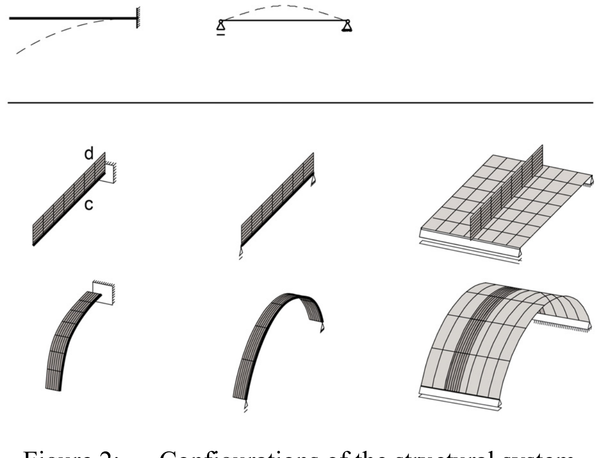

Figure 2: Configurations of the structural system.

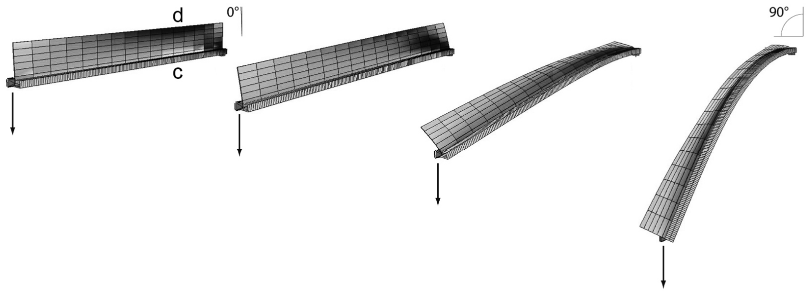

Figure 3: Simulation of the elastic kinematics in finite elements.

In order to gain a more profound understanding of the structural behaviour a finite element model of the cantilever system was developed, Fig. 3. The system is modelled with a 2m long beam (c) and a 0.25m high and 5mm thick shell element (d).The material properties of both members are standard glass fibre-reinforced plastic (GFRP) values. An analysis of the principal membrane forces at four vertical displacement steps shows the rearrangement of the tension and compression stresses. It could be shown that the sideways bending of the shell element actuated by bending of the attached beam is a failure mode initiated by lateral torsional buckling. Once buckling has started, the tension forces in the shell element (d) arrange in the formation of an arch between either end of the cantilever 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.

3 Scaling

The up-scaling of a structural system is highly dependent on the ratio of elastic to geometrical stiffness. While elastic stiffness results from material and element stiffness, geometrical stiffness is dependent on the curvature of the global geometry as well as the interrelations of multiple members in a system. A linear scaling of the geometrical system geometry is usually possible, while the material parameters and element sizes need to be redefined in order to preserve the functionality of the mechanism.

For elastic kinematics up-scaling is often easier than down-scaling. This is due to the fact that the bending radii are scaled proportionally to the geometry of the system, whereas the elastic stiffness may remain constant. Larger bending radii consequently cause smaller stresses. Systems of the Flectofin® in a height range of 1 to 14m have been simulated. GFRP laminate was used for all scales which showed that the maximum stress levels are in a similar range. In Fig. 4 14m and 2m high systems are shown, the geometrical scaling factor is 7, the thickness of the shell element only had to be scaled by a factor 3, with constant material parameters. 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 elastic kinematics.

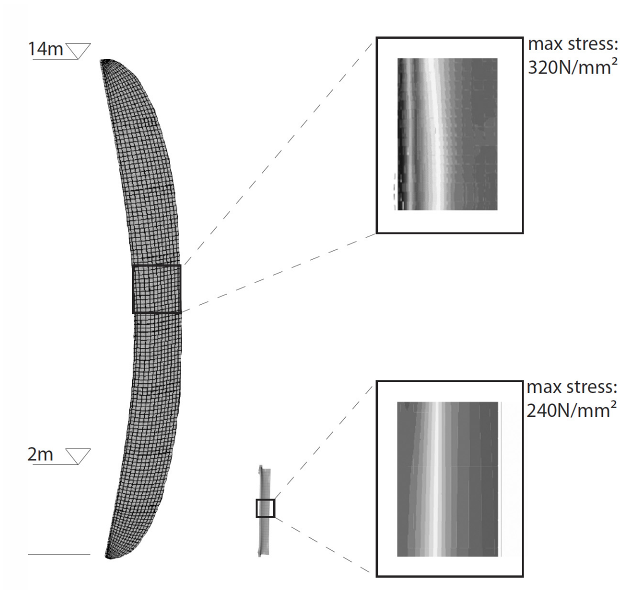

Figure 4: Scaling from 2m to 14m, max stress at 90° bending of the shell element.

On the other hand a linear up scaling may cause an exponential growth of external loads such as wind or snow. Therefore some pliable structures may have serviceability problems due to their high deformation under external loads. In the case of the Flectofin® the double curved surface which appears in the turned state can generate enough stiffness to withstand wind loads. In some other cases the architectural applications will work with variable stiffness; structures which can temporarily go into a flexible state at the moment of deformation and go back into a stiff state to withstand external loads.

4 Optimisation via reverse biomimetics

The precise and durable function of deployable systems that work on the basis of elastic deformation is dependent on the fine tuning of geometry and material parameters. Here, the optimisation of stiffness distributions and contour geometries is the key to the functionality of the deployable system. Once the basic principles of the elastic kinematics are clarified a process of optimisation must follow in order to achieve optimal system performance. Having completed an extensive screening the authors were able to catalogue nearly 100 distinguishable plant movements with a potential for abstraction. These may be distinguished according to their actuation principle (Poppinga, this conference) which may serve as an inspiration source for bottom up approaches in biomimetics [5, 6]. When distinguished according to their deformation behaviour they may serve for the optimisation of established elastic kinematics in top down approaches [5, 6]. Here, solutions may be found in several biological role models that show a similar deformation behaviour. This iteration step is also referred to as reverse bionics [6, 7]. As mentioned above, the Flectofin® principle is based on torsional buckling of the shell element actuated by uniaxial bending of the beam element. An important question here is the reduction of stress peaks at the transition of a semi-elastic shell element to a beam element. Biological adaptations to this may be found not only in the specific plant that served as a role model for the elastic kinematics. Being exposed to wind forces plant leaves have developed several strategies to avoid notch stresses in the transition areas from lamina to petiole. The most common solutions found in leaves are based on gradual transitions achieved through change in fibre orientation, variable thicknesses and optimised contour lines. In the Flectofin® the change of thickness and fibre orientation within the shell element enables a stress harmonisation throughout the entire surface. This was 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. Remaining notch stresses on either ends of the shell element can be reduced by an optimisation of the contour line. In Fig. 5 the contour geometry of *Strelizia reginae* petals and *Eucalyptus* spec. leaves were applied to the shell geometry. In both cases the stress peaks could be reduced considerably. The chamfered geometry of *Eucalyptus* spec. is based on shape optimisation realized via tension triangles as described by Mattheck and Burkhardt [8] and Mattheck [9]. The undercut geometry of *Strelizia reginae* shows a folded pocket with a thickened edge in the tip of the notch. This solution is difficult to implement into the production of a shell element and therefore was abstracted to a simple contour line with tension triangles leading both in

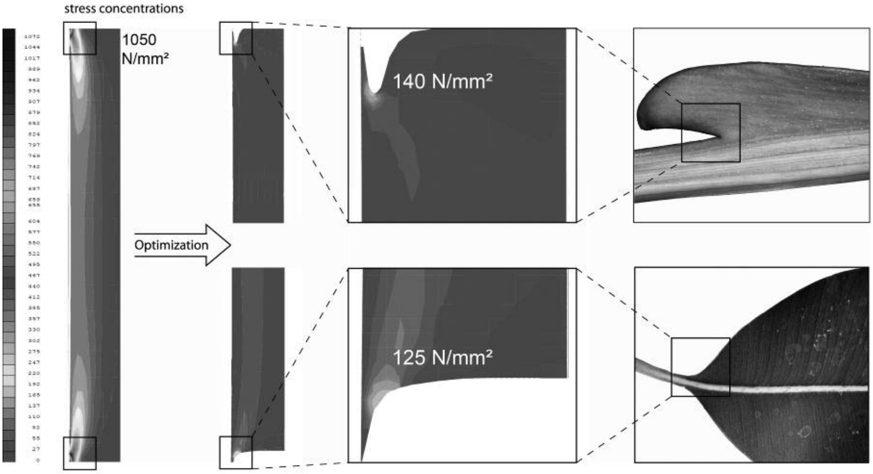

Figure 5: Reduction of stress concentrations using the countour geometry of a *Strelizia reginae* petal (above) and an *Eucalyptus spec.* leaf (below).

and out of the undercut. These geometrical optimisations reduced the maximum notch stress to approx. 60% of the permissible stresses for standard GFRP. At the transition of the semi-elastic shell element to the beam element max strain is less than 10% of the permissible stresses. It can therefore be assumed that fatigue may not occur. These findings will be verified with creep rupture tests.

5 Application for a faced shading system

The product's possible applications range from small-scale microsystems to large-scale architectural building components. The Flectofin® was used exemplary for conceptualisation of an adaptive façade shading system, which is currently being developed (Fig. 6). Here, the bending of the strand can be induced by displacement of a support, or through change of temperature in a laminate with different temperature expansion coefficients of its components.

The fins allow for opening angles between -90° and +90°, which provides a marginally affected view as well as complete façade covering. The smooth movement of the fins features a very strong visual effect and results in a deformation geometry with a harmoniously double curved surface. Moreover, multiple fins can be actuated slightly de-phased 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® in its open and closed state stays nearly the same. Thereby, the

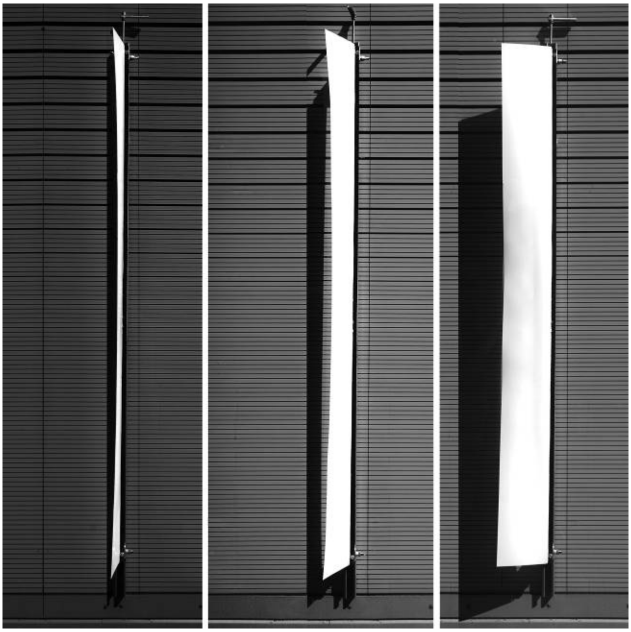

Figure 6: Prototype of a façade shading lamella based on the Flectofin®.

volumetric impression of the entire building can be preserved. Finally, the Flectofin® mechanism is not limited to straight façade sections but can be applied to curved surfaces as well.

6 Conclusion

Functional-morphological analyses of plant movements are a promising approach for concept generation and optimization in the field of architecture, building and construction. The respective structures of plants are optimised for similar boundary conditions as the architectural structures we inhabit. This study shows that even kinetic structures can be derived from some highly specialised plant systems, usually based on (visco-)elastic deformation. They serve as concept generators in an innovative biomimetic approach for deployable surface structures in architecture.

It was shown that the scaling of biologically inspired elastic kinematics can be easily accomplished. Furthermore, local stress concentrations in the scaled system could be reduced with the approach of reverse biomimetics. Here, solutions found in various plant species could serve as role models for a geometrical optimisation.

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