Adaptive FRP Structures for Exterior Applications

Larissa Born[1,*], Axel Körner[2], Anja Mader[2], Gundula Schieber[2], Markus Milwich[3], Jan Knippers[2], Götz T. Gresser[1, 3]

[1]*Institute for Textile and Fiber Technologies (ITFT), University of Stuttgart, Stuttgart, 70569, Germany*
[2]*Institute for Building Structures and Structural Design (ITKE), University of Stuttgart, Stuttgart, 70174, Germany*
[3]*German Institutes of Textile and Fiber Research Denkendorf (DITF), Denkendorf, 73770, Germany*

*Corresponding author: E-mail: larissa.born@itft.uni-stuttgart.de, Tel: (+49) 7119340530

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Abstract

Regarding modern, daylight-flooded buildings with large window façades, appropriate shading systems to improve the energy consumption of climate controlling systems are becoming more relevant. Building envelopes contribute largely to the temperature control and should be at best installed on the outside to prevent the interior from heating up. Preferably, those systems work with minimum maintenance and maximum robustness, covering as much of the window area as possible. Previous shading systems were mostly based on rigid-body mechanisms using error-prone joints. Components, whose movability is achieved by a local compliance of the material, offer a way to avoid the usage of mechanical joints. Within this paper, a new fiber-reinforced plastic (FRP) façade shading demonstrator called "Flexafold" is presented. Its opening and closing movement are controlled by pneumatic cushions which are integrated directly into the laminate set-up. The Flexafold shows thereby the possibility of producing self-supporting, adaptive FRP components whose actuators are integrated into the component and thus protected in exterior applications. The functional principles and components of Flexafold, e.g. the locally compliant FRP material, the folding pattern and the integrated actuator system, are explained within this paper. Furthermore, a comparison to existing adaptive façade shading systems "flectofin®" and "Flectofold" is given. Copyright © VBRI Press

Keywords: Fiber-reinforced plastic, façade shading, elastomer, hinge zone, compliant, pneumatic actuation.

Introduction

Current applications for fiber-reinforced plastics (FRPs) in civil engineering, besides textile reinforcement of concrete components, are limited to façade shading elements [**1**].

Façades with window surfaces are one of the main factors regarding the energy exchange of buildings with their surroundings. The development of new adaptive shading devices, which can be mounted on the outside of a façade, covering the whole surface of the building (**Fig. 1**), to ensure an energy-efficient climate control of a building, is of particular interest.

Although FRPs have a very high fatigue strength under dynamic loads, FRPs for movable, bendable parts are usually built up by individual components, inter-connected via mechanical joints. Their movement is based on rigid body mechanisms.

The motion of conventional shading devices is as well implemented by the utilization of rigid body mechanisms, which are guided by straight translation or rotation axis, which leads to geometric constraints. Applying those systems to doubly curved façades results in a high degree of mechanical complexity. In particular, the exterior application of rigid body mechanisms possesses high demands to the robustness of the material itself and the mechanical joints. Environmental influences due to the outside application increase the friction in the joints and mechanical abrasion causes failures in the overall system with a simultaneous increase of maintenance intensity.

Fig. 1. Scheme of a doubly curved window façade completely covered by Flectofold elements (detailed view of Flectofold element in **Fig. 3**).

One solution is to replace mechanical joints with compliant mechanisms [**2, 3**]. However, in the field of FRPs such mechanisms are mostly used for small-scale applications or systems, which do not have to withstand high loads.

Often those mechanisms are utilized by locally defined material gradients, which can be achieved i.e. by adjusting the thickness, in order to create thin, flexible hinge zones with an appropriate flexibility. This can be realized i.e. by subtractive fabrication methods such as milling or removing the stiffening matrix locally and thus exposing the fibers to environmental influences, which however results in limited load-bearing capacity [**4, 5**]. Furthermore, most large-scale compliant mechanisms based on FRPs, as i.e. the flectofin® (**Fig. 2**), are actuated by external mechanical devices with limited robustness.

Regarding the application as adaptive façade shading elements, foldable fiber-reinforced composite panels have been investigated, especially in terms of scalability, to increase the shading area of one component. To facilitate folding mechanisms with discrete compliant hinge zones, a fiber-reinforced, bendable hinge zone must not only be flexible, but also capable of bearing the weight of the moving component surfaces even under external loads (wind, snow). Therefore, the fiber-reinforced hinge zones developed so far [**4, 5**] cannot be applied in this scope.

Using compliant systems for external shading devices, the robustness of the actuation system, which initiates the motion, has to be considered as well. Mechanical, abrasive joints and external actuators lead to an increased maintenance intensity and should be avoided. A joint-free possibility of actuating a displacement motion is possible by volume change, e.g. by a pneumatic chamber via an air pressure change. However, such a system can only provide the necessary robustness against the dynamical loads and external influences if it is protected against the influences associated with use in areas accessible to public. This would be ensured by the integration of such chambers into the composite material, e.g. via integrating a pneumatic chamber directly into the material set-up. This also follows the idea of reduced mechanical complexity in the overall system. The positioning of pneumatic cushions inside the set-up of the FRP allows for a lightweight, slender, almost invisible actuation with no additional space or weight requirement at the location of motion actuation. As compressed air can be transported over large distances, the necessary compressor and the valves can be located centralized and easily accessible, allowing maintenance to happen independent from the place of installation of the kinetic elements.

The work presented within this article shows the development of such a self-weight load-bearing hinge zone with an integrated pneumatic actuation system. By integrating several of those hinge zones into a folding pattern, it was possible to produce a demonstrator with 10 hinge zones actuating a surface of 0,49 m² named “Flexafold” (**Fig. 10**).

Review of the façade shading systems flectofin® and Flectofold

As a result of interdisciplinary cooperation between institutes at the Universities of Freiburg (PBG) and Stuttgart (IBB, ITFT, ITKE) as well as the DITF Denkendorf, two adaptive façade shading elements, the flectofin® (**Fig. 2**) and the Flectofold (**Fig. 3**), have been developed at demonstrator level on the basis of FRPs. Both systems were inspired by kinetic principles found in plants.

The motion principle which is utilized in the flectofin® is lateral torsional buckling. While in structural engineering commonly known as a failure mode, the bird of paradise flower *Strelizia Reginae* exhibits the same motion principle during the pollination process: the pollination organs – previously enclosed by two lamellae – are uncovered by the deflection of the flower rod, which causes the opening motion of the petals [**9**].

Fig. 2. Three elements of the façade shading system flectofin®.

Due to the almost homogeneous stiffness distribution in the lamellae of the flectofin®, very high forces are required to actuate the motion, which leads to several disadvantages. First, the rigidity of the fiber-reinforced plastic is challenged and consequently the fatigue strength is relatively low. Second, the actuating forces are generated and transmitted mechanically, thus, the overall system is also susceptible to failure. In addition to those mechanical problems, the manufacturing process allows for very little tolerances regarding the symmetry of the lamellas. Therefore, the scalability is limited [**6-8**].

Based on the experience gained from the flectofin® demonstrator, it became obvious to investigate distinct hinge zones with locally adjusted bending stiffness to facilitate large deflections in compliant mechanisms made of fiber-reinforced plastics. For this purpose, the anisotropy of the mechanical properties of FRPs, influenced by the fiber orientation, was used. Drawing again inspiration from nature, the motion principle of the carnivorous underwater plant *Aldrovanda vesiculosa* was abstracted into a curved-line folding mechanism and implemented in a demonstrator, the Flectofold (**Fig. 3**), consisting of an elastomer-GFRP-hybrid composite, actuated by an external pneumatic cushion [**7, 10**].

Even though, the actuation forces, as well as the internal stresses could be reduced, cyclic load tests have shown that the fatigue strength of the bendable hinge zones is still limited and therefore not suitable for the envisioned architectural application. Another disadvantage of the Flectofold is the external actuation, which is still susceptible to cause malfunctions in the application due to external mounting, which exposes the cushion to the weathering conditions.

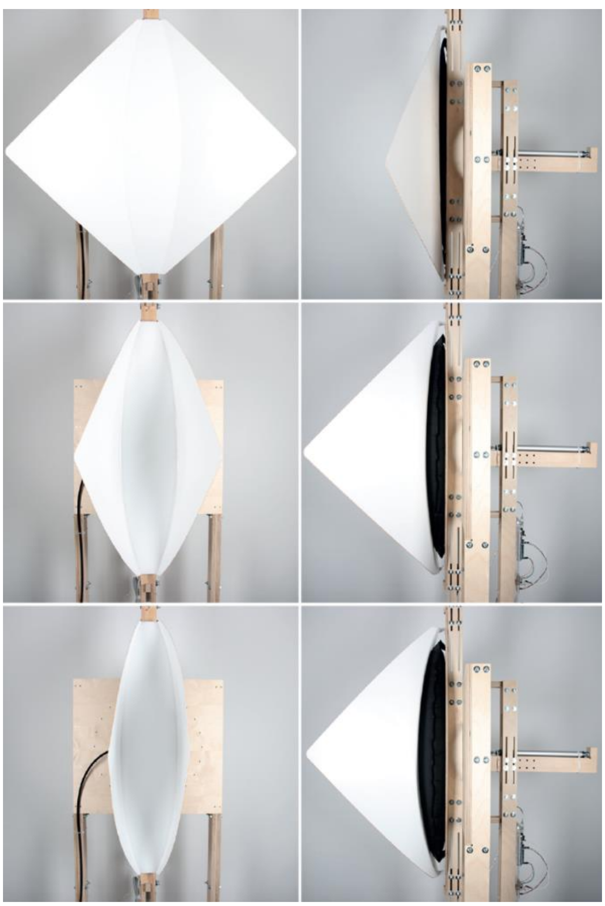

Fig. 3. Façade shading system Flectofold; from top to button image the underlying cushion is continuously pressurized up to an air pressure 2 bar.

Folding patterns with straight hinge zones

As described in the previous chapter, the kinematic principles of curved-line folding with distinct bendable hinge zones have been introduced to reduce the stress concentration in areas of large deflection. In addition to this, the kinematic behavior of the folding mechanism was used to amplify a comparatively small actuation impulse of the midrib of the Flectofold into a comparatively large resultant motion in the adjacent flaps (**Fig. 3**) [**10**].

Even though the stresses in areas of large deflection are highly reduced in comparison to the flectofin®, the stresses in the distinct hinge zones still lead to failure after 2.000 actuation cycles. A closer look into the hinge zone reveals, that not the whole width of the flexible zone is utilized for the bending movement. The transition of the convex midrib to the concave flap geometry within a discrete area would lead to double curvature in the hinge zone. That means, that the material needs to stretch or contract during folding, which is not possible with the used material combination. Therefore, the bending is concentrated into a thin line, taking the shortest path through the hinge zone. Thus, the width of the hinge zone is not fully utilized and the internal stresses lead to failure.

To overcome this geometrical problem, a possible solution might be the translation of the curved-line folding pattern into a straight-line folding pattern (**Fig. 4**). Explained in simplified terms, in curved-line folding patterns bent faces alternating in concave and convex directions are connected by curved fold lines, again alternating in mountain and valley directions. In many cases, the curved fold lines and the corresponding bent faces can be discretized into a series of straight fold lines with corresponding flat faces. Therefore, the curved fold line is discretized into a polyline – consisting of straight segments. The faces are split along lines which are originating from the end points of polyline segments. Thus, the bent faces are split into flat faces connected by straight fold lines.

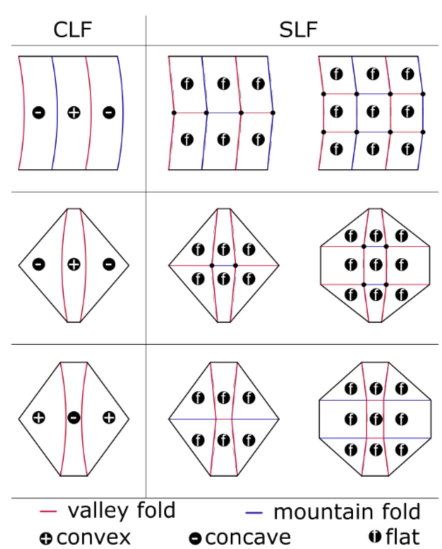

Fig. 4. Transformation from curved-line folding to straight-line folding patterns.

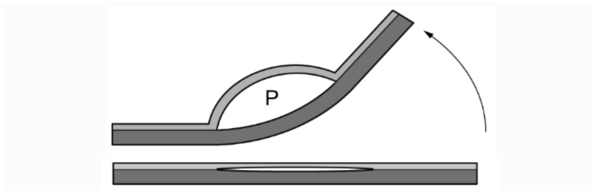

Fig. 5. Function principle of an integrated pneumatic cushion due to asymmetric placement within the laminate set-up.

Integrated actuation

The functional principle of an integrated pneumatic actuator is based on the asymmetric placement of an air chamber respectively a cushion within the material set-up (**Fig. 5**). To cause a rotational motion, one of the walls surrounding the air chamber needs to be of lower stiffness than the other. Upon pressurization and subsequent inflation of the air chamber, the side of lower stiffness exhibits higher deflection, resulting in a higher horizontal shortening and a rotational motion of the adjacent stiffer plate sections.

The actuator can be either an integrated cushion or a chamber created by the material itself, i.e. by placing a piece PTFE-foil into the laminate set-up. The connection between the surrounding layers is especially important, as the system is only functional as long as no delamination of these two layers occurs when the chamber inflates.

In addition to the protection of the cushion itself, the internal actuation determines, due to the asymmetric placement, the bending direction of the connected component surfaces. In contrast to external actuation, no pre-fold is necessary for the folding motion in a certain direction.

Material selection for movable FRPs

To increase both, the load-bearing capacity as well as the robustness of the actuation, a hybrid FRP hinge zone with an integrated pneumatic actuator has been developed. It consists of elastomer foil, thermoplastic polyurethane (TPU) foils as well as glass fiber-reinforced plastic (GFRP) addressing the requirements for exterior use in façade shading [**7, 10, 11**]. The weathering stability (UV radiation and water) is guaranteed by the TPU foils which enclose and seal the material on both sides. The load-bearing capacity of the foldable structure is ensured by the GFRP content in the hinge zone. Using these materials, a component with locally defined hinge zones can be manufactured in a single-step process. According to the required stiffness in the different component areas, the layers are stacked and pressed directly.

Fig. 6 shows the resulting bending stresses of an elastomer-GFRP compared to common GFRPs, mechanically tested in a two-point bending test in which the specimens were deformed with a test speed of 10 mm/min up to a bending angle of 90°. The specimens consist of either two layers woven glass fiber fabric (surface weight 80 g/m²) or four layers woven glass fiber fabric (surface weight 80 g/m²) with different matrices. The material set-up of each specimen set, including the used labeling, is shown in **Table 1**.

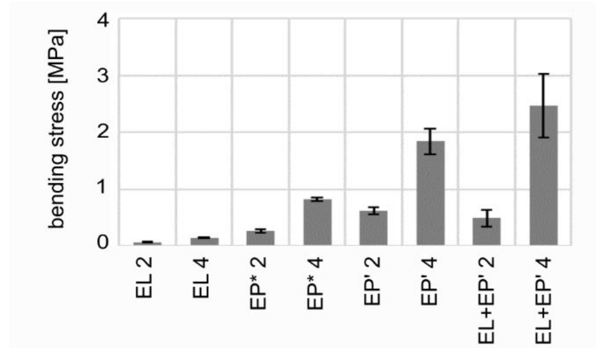

Fig. 6. Resulting bending stresses (two-point bending test) by using an elastomer-GFRP compared to common GFRP (labeling: EL − elastomer foil Kraibon AA6CFZ; EP* − Hexion RIMR135/ RIMH137; EP' – A.S.SET Powder 01) with two or four layers woven glass fiber fabric with a surface weight of 80 g/m².

Table 1. Material set-up of the test specimens in two-point bending test.

specimen (n=5)	material set-up
EL 2	2 layers elastomer foil Kraibon AA6CFZ
EL 4	4 layers elastomer foil Kraibon AA6CFZ
EP* 2	2 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with Hexion RIMR135/ RIMH137
EP* 4	4 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with Hexion RIMR135/ RIMH137
EP' 2	2 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with A.S.SET Powder 01
EP' 4	4 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with A.S.SET Powder 01
EL+EP' 2	2 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with A.S.SET Powder 01 enclosed by one layer elastomer foil Kraibon AA6CFZ on the bottom and top side
EL+EP' 4	4 layers woven glass fiber fabric (surface weight 80 g/m²) impreganted with A.S.SET Powder 01 enclosed by one layer elastomer foil Kraibon AA6CFZ on the bottom and top side

In order to compare the mechanical properties of the samples with one another, the resulting maximum bending stresses, which take into account the cross-sectional area of the 25*50 mm-sized specimens, were calculated. This is especially important as the specimens all have the same fiber weight content per square meter but different thicknesses as can be seen in **Table 2**.

Table 2. Thicknesses of the tested specimens in mm.

EL 2	EL 4	EP* 2	EP* 4	EP' 2	EP' 4	EL+EP' 2	EL+EP' 4
1.25	1.32	0.29	0.37	0.40	0.64	1.49	1.86

In addition to the cross-sectional area, the bending stress respectively the contained bending moment also considers the distance between the fixed bearing and the load application point, which was 11.5 mm in the presented two-point bending test. The calculation is based on the formula $\sigma_b = (6Fl)/(bh^2)$ with F (force in N), l (distance fixed bearing and load application point in mm), b (specimen width in mm) and h (specimen thickness in mm).

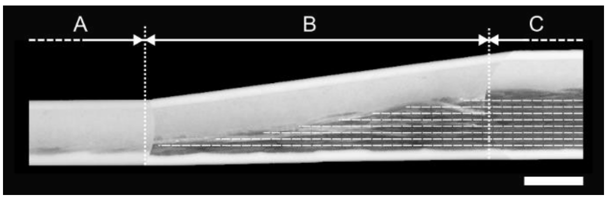

Fig. 7. Combined micro-section image of elastomer-GFRP hinge zone with (A) hinge zone (B) stepwise graded material transition (C) rigid component surface; scale bar 1 mm.

The variation between two and four layers of woven glass fiber fabric (80 g/m²) means in fact just a variation between 160 g/m² respectively 320 g/m² fiber weight content. However, the results in **Fig. 6** already show that with the combination of elastomer (EL) or elastomer and GFRP (EP'+EL) and pure GFRP (EP') in one composite component, a wider range of stiffnesses can be modeled, than it is possible with conventional GFRP (EP*).

In order to increase the fatigue strength of the hinge zone, the occurring bending stresses during the bending motion have to be as low as possible. Within mechanical studies, especially two-point bending tests up to a bending angle of 90°, it could be revealed, that the transition geometry between rigid component surface and hinge zone is one of the main influencing parameters and has to be stepwise graded to achieve (**Fig. 7**) the lowest possible bending stresses [**7, 10**].

Suitability of the material combination for integrated actuation

The combination of FRP with elastomer layers enables the integration of pneumatic cushions as actuators directly into the component. An airtight cushion is used as shown in **Fig. 8** and enclosed by two elastomer films, which flow into each other during the pressing process and cross-link, forming one single material layer.

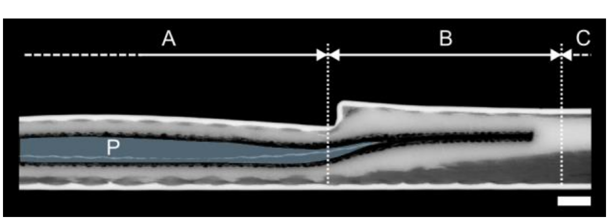

Fig. 8. Micro-section image of (P) an integrated pneumatic chamber in (A) hinge zone combined with (B) a stiffness gradient towards (C) the rigid component surface; scale bar 1 mm.

Due to the extension properties of the elastomer, this layer remains elastically deformable. As a result, the integrated actuator can be pneumatically actuated and the occurring shear forces are absorbed by the elastomer layers. At the same time, the actuator is firmly enclosed, embedded, and thus protected from environmental influences. The direction of movement and its grade of deflection depends on the stiffness distribution in the surrounding FRP, the number of cushion chambers and the pressure applied to the chamber(s). The result is a continuously adjustable, weather-resistant, adaptive system.

Technical implementation Flexafold

A physical prototype, the Flexafold, combines all aspects described in the previous chapters. It includes gradient material transitions between the compliant hinge zones and the rigid, movable component surfaces as well as integrated pneumatic chambers to create the folding motion. The stacking sequence of the Flexafold's laminate set-up is shown in **Fig. 9**. Depending on the direction of folding, the position of the air chambers and, due to this, the stacking sequence was adapted. In case of the Flexafold demonstrator the air chambers were formed by the elastomer-GFRP itself, placing a PTFE-foil in between two elastomeric layers to avoid their adhesion. The airtight TPU-coated nylon fabric was included only at the ends of the air chambers to allow for the attachment of the tubing. The prototype was stacked manually and pressed in a vacuum assisted hot press with a vacuum of 150 mbar and an effective pressing pressure of 3 bar.

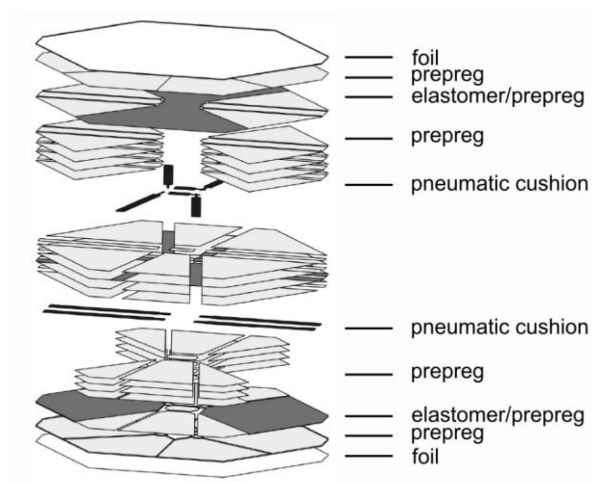

Fig. 9. Laminate set-up respectively stacking sequence of the Flexafold demonstrator.

Fig. 10 displays the motion created by the inflation of the air chambers with a maximum pressure of about 2 bars and proves the functionality of the Flexafold demonstrator. However, the demonstrator also revealed that the adhesion between the nylon fabric and the elastomer is comparably poor, so that leakage occurred after some pressure cycles. This long-term behavior did not occur in previous single hinge zone tests, using closed cushions out of the TPU-coated nylon fabric fully embedded into the FRP. Therefore, we recommend the usage of completely closed pneumatic cushions to avoid that issue in further tests.

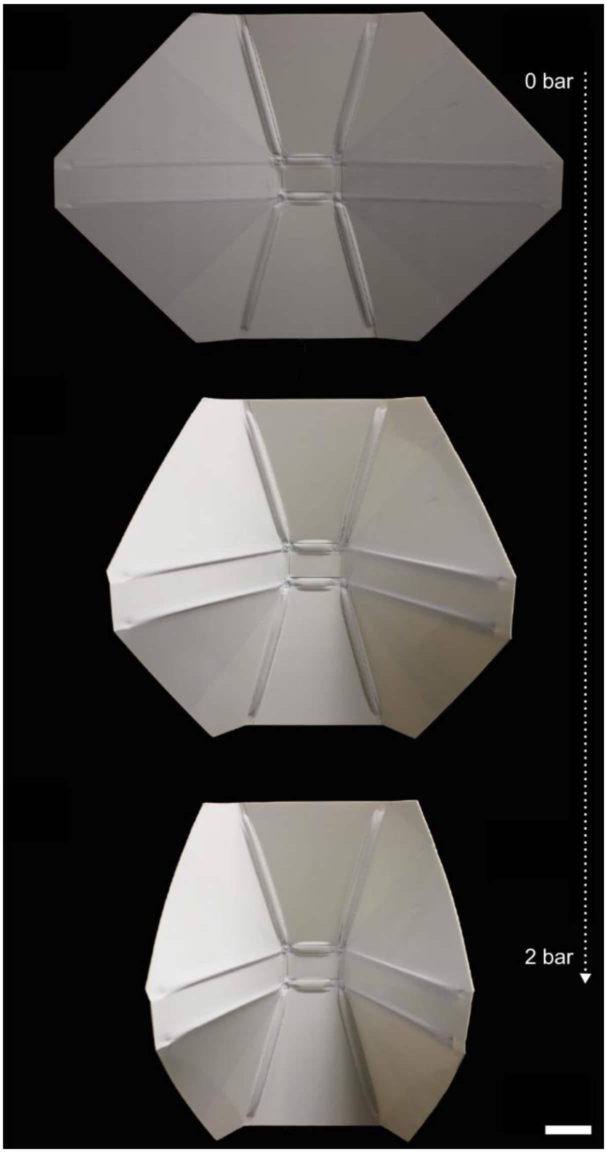

Fig. 10. Flexafold demonstrator with integrated pneumatic actuation; scale bar 10 cm.

Conclusion and future perspectives

The Flexafold demonstrator showed the chances by integrating the actuation of a movable component directly into the FRP structure by means of pneumatic cushions. The integrated pneumatic actuation in the hinge zones, as demonstrated here, offers the benefit of compliant systems to be actuated from a flat position without any pre-fold necessary. By using two opposing sets of cushions, theoretically, also the actuation in both folding directions is possible. However, the direct actuation of the hinge zones also requires a careful consideration of the actuation sequence for the folding pattern. Ideally, hinge zones undergoing a large angular change are actuated first to create the initial fold. Then a second set of actuated hinge zones that require smaller angular changes take over. By the folding pattern and the motion amplification associated with it, the distant folding lines can be folded further passively and exceed the actuation angles realizable by the pneumatic cushion.

However further research is necessary to make the system more robust and longer lasting. Complete pneumatic cushions fabricated out of reliable material with proven processes or different ways of attaching the tubing to the systems would need to be tested. Similarly, not all influencing criteria regarding the mechanical behavior of fiber-reinforced hinge zones are known. For the layout of such adaptive components, especially with regard to industrial feasibility, it is essential to know those criteria and their effect on the fatigue strength of such a moving component. In addition, the individual pressure control of the various hinge zones with differing necessary actuation angles, to better steer the motion, and also the monitoring of the achieved actuation angles are topics of further research on the path of bringing these systems closer to a to technical applications.

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