Hindwings of insects as concept generator for hingeless foldable shading systems

To cite this article: G Schieber et al 2018 Bioinspir. Biomim. 13 016012

View the article online for updates and enhancements.

Related content
- Flectofold—A biomimetic compliant shading device for complex free form facades
  A Körner, L Born, A Mader et al.
- Design and construction principles in nature and architecture
  Jan Knippers and Thomas Speck
- Functional adaptation of crustacean exoskeletal elements through structural and compositional diversity: a combined experimental and theoretical study
  Helge-Otto Fabritius, Andreas Ziegler, Martin Friák et al.
1. Introduction

The building envelope plays a key role in the design of sustainable buildings. In particular, external movable sun-shading systems can significantly increase the energy efficiency and quality of buildings (Barozzi et al 2016). Common shading systems with technical hinges tend to fail because of harsh weather conditions and the large number of load cycles. These cause frequent malfunction and expensive maintenance. In addition, traditional systems, such as blinds and shutters, often cannot be used during weather with high wind speeds and are restricted to planar facades with rectangular grids.

With the aim of a fundamentally different design approach, the latest research into deployable structures for architectural applications has focused on compliant mechanics found in plants (Knippers and Speck 2012, Schleicher et al 2015). The first prototypes have demonstrated that material-efficient plant-like mechanisms can be transferred to large-scale elastic kinetic sun-shading systems made of fibre-reinforced plastics (Lienhard et al 2011, Knippers et al 2013). In contrast to traditional shading devices, these less complex systems can easily tackle the geometrical challenges of modern complex facade geometries (Schleicher et al 2011, 2015).

However, this approach shows that our knowledge of compliant systems in architecture and our fabrication techniques and actuators are still rudimentary. Adaptive shading devices such as the Flectofin® (Lienhard et al 2011) gained their kinematic behaviour because of the principle of lateral torsional buckling. To perform the desired bending deformation, the element is designed as a mechanism with distributed compliance, whereby the deformation takes place over the whole element without a distinct hinge zone. Thus, a complex fibre lay-up is necessary to respond...
to the internal stress concentrations, leading to large actuation forces and an inherent conflict between the requirements of movement (low stiffness preferred) and the capacity to carry external loads, for example, wind (high stiffness preferred). This limits the potential of such systems for larger spans, which are only possible with additional load-bearing sub-structure. 

To develop new fibre-based systems for robust energy-efficient shading systems, we have examined the large potential in the compact foldable hindwings of insects.

Similar to previous biological role models found in plants (Schleicher et al 2011, 2015), insect wings consist of a compliant multifunctional fibre-composite structure (e.g. Vincent and Wegst (2004)). However, the insect cuticle, including the wing’s, is basically differentiated into two kinds of functional regions, i.e. rigid plates called sclerites and local pliable regions called membranes (e.g. Weber (1933)). Folding and unfolding are achieved along these defined pliable regions (folding zones). The wing cuticle can therefore deal with a large number of motion cycles under extreme environmental conditions such as wind and rain without losing shape (Byrne et al 1988, Ha et al 2013). The mechanical properties (elasticity, hardness) are achieved by the variation of only a few building materials, i.e. chitin nanofibres embedded in a protein matrix (e.g. Erko et al (2013)). From a technical point of view, this leads to highly material-efficient structures with an impressive range of Young’s modulus within one fibre-composite structure (Vincent and Wegst 2004).

In order to learn about means for gearing local flexibility by fine-tuning the composite structure and to develop new strategies for efficient robust sun-shading systems for complex facade geometries, we have formed an interdisciplinary group of engineers, architects and biologists. In this study, we have been principally interested in the insect wing with regard to its structural configuration, which permits repetitive folding-unfolding actions without becoming subject to severe wear and tear. Therefore, we have focused on folding principles and the ultrastructure of the insect wing cuticle in transition zones between neighbouring elements with different mechanical properties. As the natural folding patterns to be incorporated in the design have previously been studied (e.g. Haas and Wootton (1996), Forbes (1924), Dufour et al (2016) and Frantsevich (2011)), we first summarise the general folding principles of insect wings and present an overview of the principles of the Flexagon model abstracted by Haas (1994). In order to provide architects with a guideline for designing movable elements for irregular and doubly curved facades, we will highlight the geometrical rules for a simple Flexagon model. Whereas previous studies have neglected the natural compliant folding zones and focus on the geometric rules of a basic Flexagon, further kinetic studies will establish the functionality of several geometrical configurations in combination with pneumatic actuators and a local compliant hinge zone. The kinetic studies are devoted to the problems of the efficient actuation of these partial compliant systems for later use in architecture and possibilities for the variation of the geometries. In other words, our aim has been to ascertain the geometrical design freedom for movable elements that are based on the Flexagon model and that can be folded efficiently into a flat configuration.

In order to determine the way in which to translate the natural local compliant hinge zones (as explained by Haas and Wootton (1996)) into a technically robust composite structure, we have focused, in the next step, on the ultrastructure of the hindwing cuticle of the flexible joints along the folding zones of the wing in the minstrel bug, Graphosoma lineatum italicum (Müller 1766) (Insecta, Heteroptera) of the family Pentatomidae (shield bugs). In our biological investigations, we have analysed the anatomy of an insect wing by light and fluorescence microscopy and its ultrastructure (e.g. chitin fibre architecture) by transmission and scanning electron microscopy. We have focused on the pliable, stress-resistant (resilient) and elastic elements of the wing and on the material layout in transition zones between neighbouring elements of different mechanical properties.

The natural structure has been abstracted and six structural principles have been identified and partly transferred into new multi-layered fibre-reinforced plastic material with defined flexible hinge zones. A prototype of a combination of two abstracted Flexagon models with a bio-inspired hinge zone is presented, including the manufacture and first mechanical tests of this prototype. We also outline the initial concepts for technical implementation and provide a discussion of the results and proposals for further research.

2. Hindwings of insects as concept generators for foldable shading systems

2.1. Biological role model

Except for dragonflies (Odonata) and mayflies (Ephemeroptera), the representatives of all extant insect orders are able to fold their wings over their hind body at rest (Pringle 1957). The wings are thus tightly packed against a non-planar double-convex surface. When extended, they greatly enlarge their surface area and form lightweight aerofoils that withstand considerable perpendicular forces without losing shape (Byrne et al 1988, Ha et al 2013). Whereas most insect body parts are tubular, the insect wing represents a durable laminar fibrous structure. Folding and unfolding are achieved by controlled bending movements along folding zones. The coordination of these movements is structurally governed by the local differentiation of the mechanical properties of the cuticle. These mechanical properties (elasticity, hardness) are mainly achieved on the molecular level by the chitin/protein connection, the structural arrangement of the chitin nanofibres and the overall
most shield bugs, like the minstrel bug, are sturdy, comparably large insects with heavy bodies compared with their relatively small wing area, and thus putatively experience heavy wing loads and load shifts during flight.

Adult specimens were captured, anaesthetised with acetic aldehyde, killed by freezing at −20 °C and stored at −20 °C or in cold 70% ethanol at −22 °C. Preparations were made from this material and prepared wings were (1) mounted for fluorescence microscopy, (2) embedded in epoxy resin and sectioned or (3) processed for scanning electron microscopy (SEM). A detailed account of materials and methods used is available in the appendix.

2.2. Inspiration drawn from nature. I: folding

To ensure that the total wing surface is efficiently packed and adjusted to the double-convex surface of the abdomen in the resting position, insects apply a multitude of folding patterns, especially to their hindwings (e.g. Forbes (1924), Sharplin (1964), Haas (2000), Haas and Beutel (2001), Haas and Kuval-Peck (2001), Haas (2006) and Fedorenko (2009)). In this way, the total surface area of the wings can be reduced attenuating a folding ratio of up to 1:18 (Deiters et al 2016). Interestingly, all these different patterns make use of only two fundamental folding principles, i.e. (1) a zig-zag pattern consisting of alternating folding lines running in parallel or slightly fanning, and (2) the flexagon model (figure 2) in which intersecting folding lines subdivide the surface into triangular areas that are folded against each other (Haas and Wootton 1996).

As the wing lacks intrinsic muscles, unfolding and folding is achieved by extrinsic forces, which are indirectly transferred to the wing membrane.

The most straightforward source of movement is the action of direct flight muscles, i.e. thoracic muscles attached to the inner side of the wing base, and indirect flight muscles attached to thoracic regions adjacent to the wing base, from where forces are transferred into the wing plane by veins, elastic structures and sclerotised regions (e.g. Forbes (1924), Sharplin (1964), Haas (1996), Gorb (1999), Haas (2000), Dudley (2002), Nachtigall (2003), Chapman (2013) and Rajabi et al (2015)). Recent studies hint at the additional possibility of hydraulic forces aiding this mechanism in at least some cases (e.g. Sun et al (2014, 2016a, 2016b)). Other important mechanisms involved in wing deformation and folding include local energy storage by elasticity, passive deformation by aerodynamic forces or interference with other body parts such as cerci, abdomen or elytra (Haas 2006). An important factor with regard to the elasticity in the wing in various functions is the occurrence of the highly elastic cuticle protein resilin (e.g. Donouguhe et al (2011) and Michels et al (2016)).

During the process of the design of movable external sun shading systems for modern buildings, architects are often confronted with similar challenges. How can one design slender movable constructions with...
efficient actuators? How can one generate huge surfaces to provide shade for a façade (regular and irregular) during the day in summer? How can one fold these systems efficiently into a compact configuration, for example, in winter? Indirect movement by chains of coupled joints transferring forces from a remote power source reduces the necessity of actuators built into the device itself and hence reduces weight and maintenance. For this reason, we have assumed that a large biomimetic potential exists in the Flexagon. In contrast to the a zig-zag folding pattern, the Flexagon model enables in addition the design of sun shading systems, which can easily be adapted in various ways to doubly curved façades.

2.2.1. The Flexagon model
To describe the mathematics of the folding patterns of insect wings, the Flexagon model was proposed by Haas (1994). Based on recordings of wings of six species of Dermaptera and Coleoptera, he abstracted the general rules and created the base for a mathematical description by using vector calculation.

Figure 3 shows the simplest model with four flat panels and four creases (AO, BO, CO, DO) that merge to one central point (O). The four creases represent the local elastic joints in the insect cuticle and join the four panels with a single degree of rotational freedom. For the folding process, the crease pattern crucially always contains three convex (‘mountain’) creases and one concave (‘valley’) crease (or vice versa). Despite the arrangement of the crease pattern, the global geometry of the folded and unfolded system is defined by the angles (α, β, γ, δ) around the central point. To ensure, for example, a completely foldable and completely unfoldable flat model, the following constraints must be considered:

the sum of all four angles around the central point must equal 360° (α + β + γ + δ = 360°);
the non-adjacent angles must amount to exactly 180° (α + γ = β + δ = 180°).

Although the complex pattern in insect wings is designed to store the folded wing efficiently on the doubly curved abdomen under the elytra, the arrangement of the angles around the central point in the natural role model deviates from these two constraints (Haas 1994). In insect wings, the sum of all angles is therefore less than 360° (leading to a synclastic surface) or greater than 360° (leading to an anticlastic surface). This configuration further enables the wings to generate stiffening mechanisms. If the non-adjacent angles have half the sum (S) of all four angles (α + γ = β + δ = S/2) configurations with S > 360° and S < 360° can be completely foldable (Haas and Wootton 1996).

These geometrical rules can be used as a basis for designing movable sun shading systems that can easily adapt to doubly curved façades.

Whereas all insect wings make use of only two fundamental folding principles (Haas and Wootton 1996), various mechanisms can be found to actuate the wings (Forbes 1924, Haas 2006). These often highly complex mechanisms will not be discussed in this contribution. From a technical point of view, however, the most inspiring finding is that, by only rotating one crease, the whole model can be folded into a compact configuration (e.g. Haas (2006) and Frantsevich (2011)) and that intrinsic elasticity in the creases can be used to fold the system in one direction (e.g. Haas (2006)).

2.2.2. Bio-inspired mechanism
In order to gain a more profound understanding of the relationship between geometry and actuation, a kinetic model of the Flexagon was developed by using the commercial finite element model (FEM) software SOFiSTIK (SOFiSTIK AG, Oberschleißheim, Germany). To understand the behaviour of the general system, a completely foldable and completely unfoldable and symmetric Flexagon configuration was chosen (α + γ = β + δ = 180°, α + δ = β + γ = 180°, α = β and γ = δ) with a convex-concave-concave-concave crease pattern (figure 3).

Since we appreciate the huge potential in using pneumatic actuators for movable sun-shading systems based on fibre plastic, this investigation measures the pneumatic actuation forces that are applied in a
technical application in order to generate the folding and unfolding of the system. Therefore, the Flexagon is actuated by a pneumatic actuator in the concave crease line DO and the actuated foldline DO is fixed in place. A pneumatic cushion uniformly applies pressure onto plates connected perpendicularly to the faces adjacent to the hinge zone in line DO (figure 4(d)). Upon pressure increase, the faces adjacent to the actuated foldline rotate, leading to a complete folding of the whole Flexagon. During this folding process, the folding angles $\epsilon$ and $\zeta$ change from $180^\circ$ to $0^\circ$.

According to previous findings (e.g. Haas and Wootton (1996)), in this investigation, we have taken the local energy storage by elasticity in the biological role model into account. For this reason, the system is modelled with material properties of glass-fibre reinforced plastic (GFRP) and distinct hinge zones along the fold lines with reduced bending stiffness. The hinge zones act as compliant mechanisms with concentrated compliance and are able to store the elastic energy during the folding. As a result, it is only necessary to actuate the mechanism in one direction to close the elements, whereas the opening can be achieved by releasing the stored elastic energy. For the finite element analysis (FEA) model, the faces of the Flexagon are modelled with a thickness of 2.0 mm (the hinge zones with 0.2 mm).

To evaluate the influence of the angles between the foldlines on the folding behaviour and the actuation energy, models with varying angles $\alpha$ ($30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$) were tested and simulated. As shown in figure 4, the samples with $\alpha = 30^\circ$ and $\alpha = 60^\circ$ exhibit a highly linear relationship between the angle in the actuated fold line $\epsilon$ and the folding angle $\zeta$. By increasing the angle $\alpha$, a clear amplification of the actuated angle $\epsilon$ in the folding angle $\zeta$ becomes obvious, whereby a small change leads to a larger folding movement. A larger angle $\alpha$ also leads to a nonlinear actuation force, with a significant drop in the needed actuation energy after a certain folding angle ($\zeta = \text{ca. } 90^\circ$) is reached.

The most inspiring finding in these studies is that the pneumatically actuated Flexagon model allows for different geometries that can be folded into a flat compact configuration in a highly efficient manner. Figure 5 shows a combination of two abstracted Flexagon modules that can be actuated by only one fold line (here: OP). As in the simulation for the single Flexagon, here, the increase of angle $\alpha$ also leads to an increase of movement amplification. Even though elements with a large $\alpha$ cannot be folded into a complete closed and compact condition, a small change in $\beta$ leads to a large $\gamma$ and enables the opening and closing of roof or face surfaces.

The test element with $\alpha = 30^\circ$ could not be folded in the simulation. The prefolding of the element was not sufficient to prevent a snap-through of the attached faces.

### 2.3. Inspiration drawn from nature. II: structure

In shield bug species, both pairs of wings are folded at rest under the scutellum, i.e. a shield-like rearward-facing duplicate of the dorsal shield of the first thoracic segment, a shield that covers the greater part of the abdomen (Weber 1930). The hindwings are tightly packed under the forewings and undergo transverse folds at the wing base, plus two longitudinal and one oblique foldings through its membranous surface (Weber 1930, Betts 1986b) (figures 1 and 6). The mobility of the wing is ensured by differential sclerotisations into rigid, pliable and elastic regions.

In shield bugs, the vein pattern of the hindwing is reduced compared with the insect groundplan, with most veins represented only by a few solid lines of thickened cuticle, called false veins, that are either reduced veins or secondary structures. The main longitudinal foldings feature wing membrane of visibly reduced
thickness, appearing lighter in translucent light, and are bordered on either side by these false veins, resulting in a less complex system of motion and folding as compared with that of most other insect groups, (e.g. earwigs (Dermaptera) or beetles (Coleoptera) (Haas 1994, Haas and Kukalova-Peck 2001 and Fedorenko 2009). The foldable hindwing of G. lineatum constitutes triangular areas of wing membrane that fold against each other along visually discernible regions of thinned-out membrane bordered by thickened false veins (figure 6). In order to develop design guidelines for the manufacturing of compliant composite structures with high fatigue strength displaying locally large stiffness gradients, major points of interest were the spatial distribution of sclerotised and unsclerotised cuticular elements (including resilin-rich regions) across the wing surface and the directionality of chitin fibres. Regions of interest included false veins, the wing membrane between and within the folding lines and at the transition regions between false veins and the wing membrane.

Transmission electron microscopy (TEM) revealed differences in the chitin fibre arrangement in various layers across the transverse section of the wing membrane. In general, the wing membrane forms a sandwich structure, i.e. it consists of an exterior dorsal and an exterior ventral layer that enclose a central layer of proteinaceous material (figure 7(d)) where the original epidermis retracted during ontogeny (Weber 1933). The regular banding pattern apparent in the micrographs obtained by TEM is a result of the chitin fibres showing a helicoidal horizontal stacking pattern across the cross-section surface of the cuticle (Barth 1973) (figures 7(b), (d) and 8(a)). The ventral lamella has a thickness of 1–1.5 µm; it is composed of faintly discernible helicoidally stacked chitin fibre layers, whereby the chitin fibre arrangement takes a 180° turn over a thickness of approximately 150 nm (figure 7(d)). The dorsal lamella is much thinner (in the range of 100–200 nm). It is comparatively electron lucent and only occasionally shows a faintly discernible, diffuse structure (figures 7(d) and 8(a)). Fluorescence analysis has shown the remarkable differentiation of the cuticle composition. Whereas the ventral lamella exhibits a strong signal of sclerotin, the thin dorsal lamella lacks sclerotin fluorescence but shows strong fluorescence in the short wavelength range, a finding indicative of an enhanced resilin content (figure 7(c)).

False veins are primarily formed via a protrusion of the ventral lamella by about 2–3 µm of thickness. In addition, this area shows a greater number of more densely stacked fibre layers (180° over 80 nm of thickness) (figure 7(b)). The area of the false veins exhibits an enhanced autofluorescence at longer wavelength and reduced autofluorescence at short wavelength, indicative of stronger sclerotisation (figure 8(b)).
No abrupt change occurs in ultrastructure between the wing membrane and the false veins, as the cuticle properties seem to change gradually over a range of several micrometers (figure 7(a)).

In the longitudinal folding zones of the wing (figure 6), the involved membrane regions are thinned, accompanied by reduced sclerotin fluorescence and slightly enhanced resilin signals (figure 8(b)). Thin membrane regions along the longitudinal folds have no apparent modification of the dorsal lamella, whereas the ventral lamella consists of loosely stacked helicoidal chitin layers with only about three turns over a thickness of 600 nm (figure 8(a), compare with figures 7(b) and (d)).

2.3.1. Disclosed structural principles
Our structural analyses show that the hindwings of G. lineatum have a multi-layered structure of...
fibre-composite material, having regional differentiations that probably meet specific mechanical requirements. In all the analysed locations (i.e. the cross-sections of false veins, thinned membrane of folding zones and regular membrane at positions of approx 1/3 and 2/3 of the wing length), several horizontal fibre layers of different orientation are stacked to form the wing material. A schematic view of a cross section of the folding zone with accompanying structures and the principle layout of the wing cuticle are presented in figure 9.

Although the number of layers and the relative comparison of the fibre diameter to the total thickness of the wing structure are beyond the scope of technical
feasibility, six fundamental structural principles can be deduced from the general (ultra)structure of the insect wing (including our concrete example of the shield bug role model) that partly feed into the technical implementation:

1. Continuous layered structure: the principal setup of the wing as a layered structure is continuous throughout the wing: two layers of cuticle (ventral lamella, consisting primarily of exocuticle, and dorsal lamella, consisting primarily of mesocuticle) are bonded in the middle by a central lamella and are coated on either side by a layer of epicuticle, a thin chitin-free protective layer of proteins and water-resistant waxes.

2. Different constitution of proteinaceous matrix in mesocuticle and exocuticle: although the principal layered structure does not change throughout the wing, regional differentiations of different mechanical properties (e.g. sclerites, membranes, false veins) form on several levels. These regions differ in the constitution of the proteinaceous matrix of their chitin-containing cuticular layers (e.g. unsclerotised endocuticula, sclerotised exocuticula, resilin-enriched mesocuticula), as indicated by their autofluorescence. For instance, bending zones appear to have an enhanced proportion of elastic (resilin containing) material (figure 8(b)); further, the two layers of fibrous material (cuticular layers of the dorsal and ventral lamella, respectively) exhibit differentiated sclerotisation (figures 7(c), 8(a) and 9), forming a complex layer setup of varying proportions between the different regions (see next point).

3. Reduced material thickness of the exocuticle in the folding line: even further regional differentiation is accomplished on yet another level by varying the material thickness of the fibrous layers (endocuticle and exocuticle) in terms of both the gauge and number of the chitin fibre layers: false veins possess a thickened exocuticle (ventral lamella) (figures 7(a) and (b)), whereas the folding line exhibits a conspicuously reduced thickness of the exocuticle (ventral lamella) (figures 6(b) and 8(a), (b), compare 7(d)), leading to reduced overall thickness of the wing in these regions and a higher proportion of the putatively elastic mesocuticle (dorsal lamella) (see point above).

4. Transition zones: transition zones between rigid and pliable regions are not abrupt, but are always achieved as gradual changes in structure properties (figure 7(a)); this permits the realisation of rigid versus pliable regions without breaking the fibre architecture itself and the fibre layers are continuous between false veins and pliable membranes.

5. Fibre layout: multiple horizontal layers of different orientation (figures 7(b), (d) and 8(a)). Adjacent layers of chitin fibres are oriented at a small angle to each other; as a result, tension in any given direction can be taken up by some chitin fibre layers and, moreover, at any given direction of folding, only some fibre layers run perpendicularly to the direction of folding and experience minimal bending radii.

6. Accompanying structures along the folding zone: folding zones are accompanied by false veins (rigid materials) (figures 6 and 8(b)), possibly providing movement guidance and lead to thinner wing membranes and a material-efficient overall sclerite structure.

2.3.2. Biomimetic transfer and development of demonstrator

Fibre-reinforced polymers (FRP), which combine high tensile strength and low bending stiffness,

G Schieber et al

Figure 10. First mechanical tests of the bio-inspired composite structure. (a) Results of two-point-bending-test influence of prepreg numbers on the bending stresses in the test specimen, (b) Micro-section images of multilayer laminate. A: one prepreg, elastomer underneath (upper image), B: nine prepregs, elastomer underneath and PVC foil, C/F: PVC foil, D: prepregs, E: elastomer foil.

offer a huge potential for the development of bio-inspired compliant mechanism for architectural applications. This was previously demonstrated by plant-like, hingeless mechanisms, which rely on reversible deformation on the entire composite structure (Lienhard et al 2011). In order to enhance the performance of compliant composites current material research is focused on a highly pre-defined material distribution for the development of mechanisms with concentrated compliance and distinct hinge zones that connect rigid plates with high load-bearing capacity.

The biological role model of G. italicum exhibits, in its wing, exactly these characteristics, i.e. flexible hinges to connect rigid plates that are able to withstand the forces experienced during flight and that offer the possibility of folding compactly beneath the fore wings for protection when the wings are at rest. Microscopic images reveal that the layered structure in the highly articulated zones within the wing is continuous (structural principle 1) and consist mainly of two layers of fibrous material (cuticle) with differentiated sclerotisation (structural principle 2). To translate these principles into technical applications, a multi-layered fibre-reinforced plastic material is in development (Born et al 2017) and consists of a continuous elastomer foil, pre-impregnated woven glass fibre fabric (prepreg) and two PVC foils. The continuous elastomer foil resembles the less sclerotised, resilin-enriched regions (mesocuticle), whereas the GFRP consisting of the prepreg corresponds to high sclerotisation (exocuticle with highly organised chitin fibre content) (Born et al 2017). The laminates are produced in a vacuum-assisted hot press without the need for a closed pressing tool. A confining frame of multiple layers of elastomer surrounding the laminate prohibits the outflow of low-viscosity epoxy resin at high temperatures during the pressing process. The glass fibre weight fraction of the consolidated component is approximately 60% in the prepreg layers. To protect the composite structure from environmental influences such as UV light and to ensure certain visual and aesthetic qualities, a PVC foil (corresponding to the epicuticle) is applied on both sides of the laminate (structural principle 1). Micro-section images in figure 10(b) show the layered structure of the material.

In addition to the continuous layering of materials with distinct mechanical properties, the examination of the insect wings has also revealed a decrease of material thickness within the hinge zone (structural principle 3). This leads to reduced bending stiffness in areas of lower thickness, a character that is achieved in the technical application with fewer layers of glass fibre prepreg (corresponding to the exocuticle) within the hinges. The relationship between the number of prepreg layers within the laminate and bending stiffness has been examined in a modified two-point bending test, especially for FRP joints, based on DIN 53121 ‘Testing of paper and cardboard—Determination of flexural stiffness according to the bar method’. To evaluate the deformation behaviour regarding the application of the material in a compliant mechanism for facade-shading devices, the fibre composite is bent twice around a radius of 5 mm until a bending angle of 90° degree is reached. The actuation force during loading and off-loading is transferred into bending stress to evaluate the possible extent of elastic deformation of the material and to examine failures related to material thickness.

Figure 10(a) shows the maximum of the occurring bending stresses in test specimens having different numbers and orientations of prepreg layers. In all specimens, the elastomer is implemented at the compression side during the bending deformation. This laminate set-up is based on preliminary tests, which exhibited significantly lower bending stress in the case of integrated elastomer in the hinge zone. As shown in figure 10(a), bending stresses increase with an increasing number of prepreg layers.

The evaluation of the bending test for two load cycles shows a breakage of the laminates with 1° prepreg (±45°) + 8° prepreg (0/90°) elastomer underneath. Laminates of 1° prepreg (±45°) el. underneath have proven to be very flexible, whereas a laminate of 1° prepreg (±45°) + 4° prepreg (0/90°) elastomer underneath retains its flexibility by means of relatively
high bending stresses. The laminate also shows a plastic deformation after first bending; this is the reason for the reduced forces in the second load cycle.

An abrupt transition between the stiff plate-like element and the hinge zone leads to high local stress concentration and should be avoided. In the insect wing, this transition between stiff and flexible areas is accomplished by finely-graded zones at several hierarchical levels (structural principle 4 and 5); this can be abstracted into a step-wise graded structure with a different number of prepreg layers (corresponding to the exocuticle) as shown in figure 11(b). The graded transition leads to a reduction of bending stresses within the hinge zone of up to 18% in comparison with the test specimen with abrupt transition (figure 11(a)).

Similar to the examination of the different thicknesses, the decrease of the bending stress for the two different specimens from load cycle one to load cycle two can be explained by the plastic deformation of the material after first bending.

To ensure equally distributed pressure on areas with variable material thicknesses, removable metal inlays are applied on top of the laminate during the pressing process. The thickness of the inlays must correspond exactly to the thickness difference between the stiff plate region and the flexible hinge zone (difference of number of applied GFRP prepregs multiplied by thickness of pressed GFRP prepreg).

Based on the investigation of the different laminate parameters with regard to number and orientation of prepreg layers and the transition gradation, a laminate set-up for the first Flexagon demonstrator was determined (figure 12(a)). The entire element is covered with one layer of elastomer foil. Moreover, one layer of prepreg in a ±45° orientation orthogonal to the bending direction of the hinge zones passes through the whole component. The stiff plate-like regions are additionally reinforced with eight layers of prepreg in an orientation of 0/90° orthogonal to the hinge zone. To reduce the local stress concentrations attributable to the significant stiffness difference, the transition between stiff and flexible regions is achieved with a gradation in three steps. The metal inlays for the pressing process are produced accordingly. The finished demonstrator is shown in figure 12(b).

3. Concepts for technical implementation

The case study of insect wings has shown that their underlying structural principles can be transferred successfully into mechanisms with concentrated compliance. They offer the potential for upscaling to be made more relevant for architectural application in larger dimensions. In contrast to previous prototypes and projects (Lienhard et al 2011, Barozzi et al 2016) of deployable structures in architecture, the
bio-inspired system consists of compliant hinges with a locally reduced bending stiffness. Because of the local homogeneous stress concentration in the hinge zone, the bio-inspired mechanism is able to undergo cyclic loading and theoretically can resist wind loads, a feature that is especially relevant for the design of external shading applications on buildings.

In contrast to common rigid body hinges, the developed bio-inspired compliant hinge zone is able to store elastic energy during the folding actuation. Thus, it is only necessary to induce energy into the system to fold the components, the unfolding occurs by utilising the stored energy. Therefore, pneumatic actuators seem to be suitable, especially because of their comparatively high forces in one direction and low self-weight.

To actuate the one fold-line within the Flexagon component, plates can be mounted perpendicularly to the stiff plate-like regions on each side of the actuated hinge zone. Between these plates, pneumatic cushions can be placed that exert pressure onto these plates during inflation and therefore can initiate the folding movement (figure 13).

Because of the very low height of the pneumatic cushions in the uninflated condition, they can be integrated into the gap between the plates, given by the width of the compliant hinge zone (figure 13). Since the actuation force and folding behaviour of the Flexagon are dependent on the internal angles between all fold lines, the development of the folding pattern can be informed by the application of specific boundary conditions.

The differentiated pressure in the pneumatic actuator can be used to generate stable intermediate states between the open and the closed condition. Thus, the system can be tuned to create highly differentiated light conditions on a facade or to follow the sun angle during the day.

In addition to the functional aspects, various tessellation patterns can be translated for double-curved geometries into the Flexagon-based folding
pattern—offering large design freedom for potential architectural applications (figure 14).

Whereas the shown test pattern is based on a relatively homogeneous tessellation, various configurations are possible. By differentiating the module geometries, it is possible to react to aesthetic as well as functional aspects. Furthermore, differentiated material lay-ups within the composite laminates can be employed to create variable light transmission within a high-quality surface. By designing the degree of pre-folding in the closed condition of the component and therefore by controlling its structural height, the structure can react to external wind loads. Because the stiff plate-like regions exhibit no bending during the folding movement, additional sensitive elements such as photovoltaics can be integrated into the system.

4. Conclusion and outlook

Our study demonstrates that biomimetic research on arthropods can be an inspirational source for architects and engineers wishing to generate new strategies and innovative constructions for adaptive facade systems beyond traditional preconceptions. In an interdisciplinary team, promising motion principles exhibited in insect hindwings have been analyzed, abstracted and transferred into a new multi-layered fibre-reinforced plastic material with defined flexible hinge zones.

With this aim, the complex natural multi-layered natural system has been abstracted into a step-wise graded structure with different numbers of pre-impregnated woven glass fibre fabric layers (corresponding to the exocuticle), a continuous elastomer foil (corresponding to the mesocuticle) and two outer layers of PVC (corresponding to the epicuticle).

Whereas the proposed bio-inspired mechanism is still at an early design stage, the concept study of the shield bug _G. italicum_ demonstrates that technically graded materials with local flexibility are feasible by fine-tuning the composite structure. The application scenario illustrates the architectural potential for sustainable external elastic kinetic shading elements for doubly curved façades.

Initial bio-inspired prototypes have been successfully mechanically tested with permanent cyclic loading. Nevertheless, further studies and prototypes are required to optimise the compliant fibre-reinforced structure and to evaluate the scale limits of the shading device. In order to reduce the amount of material, we will, for instance, carry out further work on the differentiation of the plate structure next to the compliant hinge zone (corresponding to structural principle 6).

In combination with the integration of additional functions, technical hierarchical graded fibre composites have an enormous potential for innovative applications in architecture and in other fields such as the aircraft industry. Hence, we will further investigate the integration of internal pneumatic actuators in the next step of our work. Broader biomimetic research on arthropods together with integrated pneumatic actuators might help here to optimise the system further and to close gaps in our research.

Acknowledgments

The authors are grateful to the Baden-Württemberg foundation for funding our research work as part of the project BIAG ‘Bio-inspired adaptive façade shading systems’ as well as the German Research Foundation (DFG) for funding this work as part of the Transregional Collaborative Research Centre (SFB/Transregio) 141 ‘Biological Design and Integrative Structures’ (project A03). Furthermore, we would like to thank our industrial partners Transsolar Energietechnik GmbH, MHZ Hachtel GmbH & Co. KG, S-form Kunststofftechnik, Global Safety Textiles GmbH, Studio 2050, Knippers Helbig GmbH and all collaborating partners from Tübingen (EvE), namely Stefan Fischer, and York Steirhof, Lorenz Henneberg, Ulrike Meyer-Jürgens, Sandra Richter and Nina Glöckner of the ZMBF, and from the University of Stuttgart (ITKE and ITFT) and ITV Denkendorf. Theresa Jones corrected the English.

Appendix

Detailed description of the biological research on wing structures in _G. lineatum italicum_

In the course of this study, wings of the minstrel bug, _Graphosoma lineatum italicum_ (Müller 1766) (Insecta, Heteroptera) of the family Pentatomidae (shield bugs) were subjected to various investigations with regard to their structural composition.

Video-documented preparation

Live specimens were killed by freezing at $-20 \, ^\circ\text{C}$ in dry glass vials and kept at this temperature. Upon preparation, dental silicon-mounting medium (polyvinyl siloxane (4667 President light body 106 ml ENIVISI Odental Illertisen, Germany) was freshly prepared and a roughly bean-sized portion was placed on the bottom of a glass Petri-dish. The still-frozen specimen was placed on top of the medium and a toothpick was used to secure beak, legs and the ventral side of the abdomen in the medium firmly, without contaminating the dorsal side or the movable parts of the thorax and wings. A video camera (Sony Corporation, Tokyo, Japan) was mounted on a tripod $\sim 1\, \text{m}$ above the arena and lighting was provided with a Schott KL1500 double-crane fiberglass lighting device. A zoom lens was used to capture the animal with sufficient resolution without obscuring the view or access of the preparator. Video material was recorded at 1920 $\times$ 1080 pixels and 30 frames per second. No. 5 DuMont forceps, No. 11 scalpel blades, No. 2 and No. 0 steel insect needles and ophthalmological
scissors were used to demonstrate the mobility and coupled movements of wings and thoracic segments and of internal structures during the dissection of the specimen.

**SEM**

Fore- and hindwings were dehydrated in a graded ethanol series, critical-point dried in liquid carbon dioxide by using a Polaron CPD apparatus and then broken and/or cut into small segments, which were then placed on SEM stubs and sputtercoated with 6 nm gold/palladium. Digital images were recorded with a Zeiss EVO L15 scanning electron microscope.

**Light microscopy/TEM**

Whole wings were prepared on glass slides and embedded in either glycerol, purified water or Entellan for fluorescence microscopy.

Additionally, wings were fixed with modified Karnovsky’s solution, postfixed with osmium tetroxide, dehydrated in a graded ethanol series containing en-bloc staining with uranyl acetate and embedded in SPURR’s low viscosity epoxy resin. After polymerisation, semithin (500 nm) and ultrathin (50 nm) sections were cut perpendicularly to the wing plane, either at right angles to the longitudinal wing features or at an angle of 30° to the long axis of the wing. A detailed description of the protocols is given in the last paragraph ‘Histological protocols’. Additional specimens were fixed with the addition of picric acid to the fixative and the use of cacodylate buffer for enhanced contrast of fibrous features in TEM.

Ultrathin sections were placed on Formvar-coated copper grids and post-stained with uranyl acetate (20 min) and lead citrate (90 s) according to Venable and Coggeshall (1965). TEM images were recorded on MACO EMS plate negative films via a Siemens Elmiskop 1A and a Philips/FEI technai10 electron microscope. The developed negatives were digitalised by using an EPSON V750 scanner at 2400 dpi, 8 bit gray values, and digital images were processed in GIMP (brightness, contrast, tonal values) for maximum clarity of structural detail.

Semithin sections were placed on gelatine-coated glass slides and subjected to various staining regimes at regular intervals. The sections were either left unstained and mounted in Entellan for differential interference contrast or fluorescence analysis or stained with Stevenel’s blue for fast orientation. Stained slides were air-dried, treated with RotiHistol and mounted in Engelbrechts xylene-free embedding medium. Images were recorded by using a Zeiss Axioplan light microscope with a Nikon D7100 (Nikon Corporation, Tokyo, Japan) digital camera for conventional light microscopy, an Epi-fluorescence microscope Zeiss Imager M2 with Hamamatsu ORCA-flash 4.0 V.2 CMOS camera, or a Confocal Microscope Leica TCS SP8 (Laser lines: diode 405, pulsed 440, pulsed 470, Argon 488,496,514, DPSS 561, HeNe 594, HeNe 633) equipped with resonant scanner, HyD detectors and FLIM and FCS (CLSM). In the case of both fluorescence analysis methods, the autofluorescence of the cuticle was recorded in four wavelength channels, corresponding to the known autofluorescence properties of insect cuticle: the elastic protein resilin is characterised by light blue fluorescence after UV excitation, as can be conveniently demonstrated by using the DAPI-filter set. Unscerotised endo- and mesocuticle and chitin yield autofluorescence that can easily be demonstrated by using filters for Atto488, GFP and Cy3. Sclerotised exocuticle shows autofluorescence phenomena shifted towards a longer wavelength, as can be demonstrated with Cy5-filters.

As no quantitative analysis of the fluorescence signal was undertaken, because our interest was focused on qualitative (topological) analysis, and because the signal strength varied between channels, the respective representation was adjusted channel-wise for better anatomical clarity (spatial distribution of materials/properties) in the images (table A1).

**Histological protocols:**

<table>
<thead>
<tr>
<th>Fixative</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixative 1</td>
<td>1.67% glutaraldehyde (Serva, 25% TEM grade)</td>
</tr>
<tr>
<td></td>
<td>1.37% formaldehyde (freshly depolymerised from paraformaldehyde, Merck)</td>
</tr>
<tr>
<td></td>
<td>4% sucrose</td>
</tr>
<tr>
<td></td>
<td>1 ml 1 mM MgSO₄</td>
</tr>
</tbody>
</table>

**Table A1.** Wavelength windows used in this study.

<table>
<thead>
<tr>
<th>Material</th>
<th>Colour</th>
<th>WMF Excitation filter (nm)</th>
<th>WMF Emission filter (nm)</th>
<th>CLSM Excitation laser (nm)</th>
<th>CLSM Detectors (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resilin</td>
<td>Blue</td>
<td>DAPI 359–371</td>
<td>397–409</td>
<td>405</td>
<td>412–484</td>
</tr>
<tr>
<td>Endocuticle</td>
<td>Green</td>
<td>Atto488 450–490</td>
<td>500–550</td>
<td>488</td>
<td>496–568</td>
</tr>
<tr>
<td>Endo-/Mesocuticle</td>
<td>Amber</td>
<td>Cy3 538–562</td>
<td>570–640</td>
<td>561</td>
<td>569–636</td>
</tr>
<tr>
<td>Sclerotin</td>
<td>Red</td>
<td>Cy5 625–655</td>
<td>665–715</td>
<td>633</td>
<td>642–708</td>
</tr>
</tbody>
</table>
in 0.05 M HEPES-buffer, pH 7.56
fixation for 2 h at 0 °C
washes in 0.05 M HEPES, pH 7.56, 3 × 10 min
postfixation:
1% OsO₄ in 0.05 M HEPES buffer, 1.5 h at 0 °C
washes in 0.05 M HEPES, pH 7.56, 3 × 10 min

Fixative 2
2.5% glutaraldehyde (Serva, 25% TEM grade)
2.5% formaldehyde (freshly depolymerised from paraformaldehyde, Merck)
0.06% picric acid (Merck)
dissolved in 0.1 M cacodylate buffer, pH 7.4
fixation 2 h at 4 °C
washes
in 0.1 M cacodylate buffer, pH 7.4, 8 × 15 min
postfixation
1% OsO₄ in 0.1 M cacodylate buffer, pH 7.4, 1 h
at 4 °C
washes in
0.1 M cacodylate buffer, pH 7.4, 2 × 10 min
double-distilled water, 2 × 10 min

Embedding protocol 1
dehydration:
30% pure ethanol, 10 min, 0 ºC
50% pure ethanol, 10 min, 0 ºC
70% pure ethanol saturated with uranyl acetate, 8 h, 4 ºC
70% pure ethanol, 2 × 10 min, room temperature (RT)

85% pure ethanol, 3 × 10 min, RT
95% pure ethanol, 3 × 10 min, RT
100% pure ethanol, 3 × 10 min, RT
100% propylene oxide, 2 × 15 min, RT
embedding in SPURR’s resin/propylene oxide (PO) mixtures:
3:1 PO: resin, 1 h
1:1 PO: resin, 3 h
1:3 PO: resin, 6 h
pure resin for 13 h on a rotatory plate
polymerisation for 8 h at 70 ºC

Embedding protocol 2
dehydration:
50% pure ethanol, 15 min
70% pure ethanol, 15 min
70% pure ethanol with 1% uranyl acetate, 2 h
70% pure ethanol, 2 × 10 min
90% pure ethanol, 15 min
100% pure ethanol, 2 × 10 min
100% pure acetone, 3 × 10 min
embedding in SPURR’s resin/acetone according to protocol 1

Staining protocol
Stevenel’s blue (del Cerro, Cogen, and del Cerro 1980),
5 min at 55 ºC
rinses in distilled water, 5 min at 55 ºC
air-dry
mount in Engelbrecht’s xylene-free mounting medium.

Figure A1. G. italicum, four-channel and combined view of autofluorescence in WFM, performed on a 500 nm semithin section through the leading vein of the hindwing (Subcosta + Radius + media after Betts (1960b)). Channels adjusted for qualitative (topological) distinctness. Picture at the bottom right shows red (sclerotin) and blue (Resilin) channels only. Scale bar 50 µm.
References

Barth F G 1973 Microfiber reinforcement of an arthropod cuticle Z. Zellforsch 144 409–33
Bets CR 1986a Functioning of the wings and axillary sclerites of Heteroptera during flight J. Zool. 123–31
Bets CR 1986b The comparative morphology of the wings and axillary of selected Heteroptera J. Zool. 1 125–42
Born J et al 2017 Fiber-reinforced plastics with locally adapted stiffness for bio-inspired hingeless, deployable architectural systems Proc. of the 21th Symp. on Composites (21th Symp. on Composites) (Bremen, Germany)
Byrne DN, Buchmann SL and Spangler HG 1988 Relationship between wing loading, wingbeat frequency and body mass in homopterous insects J. Exp. Biol. 135 9–23
Deeters J, Kowalczyk W and Seidl T 2016 Simultaneous optimisation of earwig hindwings for flight and folding Biol. Open 5 638–44
Fedorenko DN 2009 Evolution of the Beetle Hind Wing, with Special Reference to Folding (Insecta, Coleoptera) (Soﬁa: Pensoft Publishers)
Forbes WT M 1924 How a beetle folds its wings Psyche 31 254–8
Frantsevich L 2011 Mechanisms modeling the double rotation of the elytra in beetles (Coleoptera) J. Biomech. Eng. 8 395–405
Gorb SN 1999 Serial elastic elements in the damselfly wing: mobile vein joints contain resilin Naturwissenschaften 86 552–5
Ha N S, Truong QT, Goo NS and Park HC 2013 Biomechanical properties of insect wings: the stress stiffening effects on the asymmetric bending of the alomyrina dichotoma beetle’s hind wing PLoS One 8 e80689
Haas F 1994 Geometry and Mechanics of Hind-Wing Folding in Dermaptera andColeoptera Master of Philosophy (Exeter: University of Exeter)
Haas F 2006 Evidence from folding and functional lines of wings on inter-ordinal relationships in Pterygota Arthropod Syst. Phylogeny 64 149–58
Haas F and Beutel RG 2001 Wing folding and the functional morphology of the wing base in Coleoptera Zoology 104 123–41
Haas F and Woottton RJ 1996 Two basic mechanisms in insect wing folding Proc. R. Soc. B 263 1651–8
Knippers J and Speck T 2012 Design and construction principles in nature and architecture Bioinsip. Biomim. 7 015002
Müller O F 1976 International Code of Zoological Nomenclature 11 51 (available online: http://www.nhm.ac.uk/hosted-sites/icn/code/index.jsp?article=51&nfv=)
Nachtigall W 2003 Insektenskelett (Berlin: Springer)
Pringle JW S 1957 Insect Flight (Cambridge University Press)
Sharplin J 1964 Wing folding in lepidoptera Can. Entomol. 96 168–9
Weber H 1933 Biologie der Hemipteren, eine Naturgeschichte der Schnabellerker (Berlin: Springer)
Weber H 1933 Lehrbuch der Entomologie (Jena: Verlag von Gustav Fischer)