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Beetle Elytra as Role Models for Lightweight Building Construction

Käferelytren als Vorbilder für Leichtbaukonstruktionen

Thomas van de Kamp, Moritz Dörstelmann, Tomy dos Santos Rolo,
Tilo Baumbach, Achim Menges & Jan Knippers

Summary: Being natural lightweight constructions, elytra of beetles constitute promising role models for biomimetic development. In 2014, a multi-disciplinary team led by scientists from the University of Stuttgart constructed a research pavilion in order to evaluate fiber composites for architecture and to develop fabrication methods for fiber-reinforced polymer structures. Functional principles of the elytra of the Colorado potato beetle (*Leptinotarsa decemlineata*) and the Green tortoise beetle (*Cassida viridis*) were analyzed, abstracted and transferred into a modular pavilion. Two collaborating industrial robots were employed to wind 36 individual glass and carbon fiber-reinforced elements, which were assembled into the final prototype.

Keywords: Elytra, biomimetics, research pavilion, architecture, robotic fabrication

Zusammenfassung: Als natürliche Leichtbaukonstruktionen stellen Käferelytren interessante Vorbilder für biomimetische Entwicklungen dar. Im Jahr 2014 konstruierte ein multidisziplinäres Team unter der Leitung der Universität Stuttgart einen Forschungspavillon, um den Wert von Faserverbundstoffen für die Architektur zu untersuchen und neue Fertigungsmethoden für faserverstärkte Polymere zu entwickeln. Funktionsprinzipien der Elytren des Kartoffelkäfers (*Leptinotarsa decemlineata*) und des Grünen Schildkäfers (*Cassida viridis*) wurden analysiert, abstrahiert und auf einen modularen Pavillon übertragen. Zwei kooperierende Industrieroboter wurden verwendet, um 36 individuelle glas- und karbonfaserverstärkte Bauelemente zu wickeln, die dann zum fertigen Prototypen zusammengesetzt wurden.

Schlüsselwörter: Elytren, Biomimetik, Forschungspavillon, Architektur, Roboter-Fertigung

Introduction

Biomimetic engineering is an emerging discipline aiming at the transfer of structures and processes found in nature into technical applications (Bhushan 2009). Insects are considered interesting role models for biomimetics (Gorb 2011) and for example have inspired the development of adhesive pads (Daltorio et al. 2009), flying machines (Conn et al. 2007) and six-legged walking robots (Pfeiffer 2007).

Being a complex fibrous composite material, insect cuticle is of particular interests for biomimetic development (Chen & Fan 2004). It primarily consists of layered chitin microfibrils, which are embedded in a protein matrix (e.g. Neville 1975, 1993, 1998; Andersen et al. 1996; Andersen 2010). Due to its multiple functions, however, cuticle architecture is highly variable. Specialized cuticular structures found in insects include efficient adhesive microsculptures (Gorb 2008), biophotonic surfaces (Burresi et al. 2014) and complex articulations, e.g. resembling screw-and-nut systems (van de Kamp et al. 2011, 2014; dos Santos Rolo et al. 2014), gimbals (Frantsevich & Wang 2009) and gears (Burrows & Sutton 2013).

Beetle elytra are duplications of the integument and possess a thick dorsal and a thinner ventral cuticle connected by columns (trabeculae) and the hemolymph space between them (Chapman 1998; van de Kamp & Greven 2010). They serve as protective shields for the membranous hindwings and the abdomen. In most flying species, they are lifted during flight and may produce significant aerodynamic forces (e.g. Nachtigall 1964; Schneider & Hermes 1976; Neville 1993; de Souza & Alexander 1997). In these species, an efficient lightweight construction of the elytra is crucial to provide sufficient protection without impeding flying ability by adding too much weight. Material may be saved by reducing the overall thickness, the ventral cuticle or by the enlargement of the hemolymph space (van de Kamp & Greven 2010). Stability may be achieved by an efficient distribution of the trabeculae and specific strengthening of the load-bearing regions. The mechanical properties make elytra promising role models for material-efficient lightweight construction (Chen et al. 2007a, b, 2015a, b). Biomimetic transfer of these superior structural characteristics into technical applications requires an abstraction of the underlying functional principles and their technical implementation. Material efficiency in biological structures is often based on locally adapted morphologies and material organizations (Knippers & Speck 2012). Industrial production processes for fiber composites however are predominantly designed for mass production of identical components and thus unsuitable to differentiate geometry and fiber orientation of individual parts.

Therefore exploration of novel form generation and fabrication processes is required to open up a transfer potential for fiber based biological lightweight construction principles into individualized locally adapted fiber composite constructions (Menges & Knippers 2015). These are particularly suitable for the individual demands of architectural constructions, as each building is usually a one-off that adapts to its unique internal requirements and external context. The Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart develop computational design, simulation and robotic fabrication methods for innovative lightweight constructions, which are regularly tested in 1:1 scale prototypes (Knippers et al. 2015; Dörstelmann et al. 2015a, b). Architectural pavilions have reduced programmatic and functional requirements and therefore are ideal test constructions that allow foregrounding research aspects e.g. novel design paradigms, materials and construction methods.

In March 2014 the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart constructed a biomimetic research pavilion by adapting basic functional principles of beetle elytra. The project was planned and constructed within one and a half years by students and researchers within a multidisciplinary team of architects, engineers and biologists. The focus of the project was a parallel bottom-up design strategy for the biomimetic investigation of natural fiber composites and the development of novel robotic fabrication methods for fiber reinforced polymer structures. The aim was the development of a winding technique for modular, double layered fiber composite structures, which reduces the required formwork to a minimum while maintaining a large degree of geometric freedom. Functional principles of elytra were analyzed and abstracted. Through the development of a custom robotic fabrication method, these principles were transferred into a modular prototype pavilion (Parascho et al. 2015).

2. Production process

2.1. Species examined

Two chrysomelid beetle species were selected for a comparative examination: the Colorado potato beetle *Leptinotarsa decemlineata* (Fig. 1A) and the Green tortoise beetle *Cassida viridis* (Fig. 1B). While *L. decemlineata* represents a "common" type of rounded elytra (Fig. 1C) as observed in many beetles, *C. viridis* exhibits flat elytra (Fig. 1D) with bifurcating epipleurae (arrow).

2.2. Synchrotron X-ray microtomography

The global 3D morphology of the elytra, i.e. the distribution of trabeculae and local reinforcements, was analyzed by employing synchrotron X-ray microtomography. Scans were performed at the TOPO-TOMO beamline of the ANKA Synchrotron Radiation Facility (van de Kamp et al. 2013) at Karlsruhe Institute of Technology (KIT). The measurements consisted of the acquisition of 2,500 radiographic projections of in a range of 180°. The parallel polychromatic X-ray beam, spectrally filtered to obtain a peak at about 15 keV, was detected by a custom-designed indirect X-ray area detector. It consists of a thin, plan-parallel lutetium aluminum garnet single crystal scintillator doped with cerium (LuAG:Ce), optically coupled via a Nikon Nikkor 85/1.4 photo-lens to a pco.dimax camera with a pixel matrix of 2008 x 2008 pixels. The magnification of the optical system was adjusted to 3 x, yielding an effective X-ray pixel size of 3.66 µm (see dos Santos Rolo et al. 2014 for data acquisition protocol). The frames were processed with the ImageJ plugin ANKAphase (Weitkamp et al. 2011); volumes were reconstructed using the PyHST software developed at the European Synchrotron Radiation Facility in Grenoble, France, and KIT (Chilingaryan et al. 2011).

2.3. Abstraction and transfer

The complex morphology of beetle elytra integrates various functional features. The described investigation methods and comparative studies allowed to identify and to abstract the underlying structural principles which are of interest for architectural lightweight construction. The hollow beetle elytron with its internal trabeculae can be abstracted as a double layered shell with internal bracing connections. Several parameters of the trabecular morphology as well as their global arrangement affect the structural capacity of the shell. Thin hemolymph space with sparse trabeculae can be found in less loaded areas while closely packed and long trabeculae increase the structural depth of the shell and the capacity to transfer horizontal forces between the upper and lower shell layer.

Based on the differentiated trabeculae morphology and the individual fiber arrangements, a double layered modular system was generated for implementation in an architectural prototype. Through the development of computational design and simulation tools, both the robotic fabrication innovation characteristics and the abstracted biomimetic principles could be simultaneously integrated in the design process (Dörstelmann et al. 2014).

Glass and carbon fiber reinforced polymers were chosen as building material, due to their high performance qualities (high strength to weight ratio) and the potential to generate differentiated material properties through fiber placement variation. Together with their unrestrained moldability, fiber reinforced polymers are suitable to implement the complex geometries and material organizations of the abstracted natural construction principles. Conventional fabrication methods for fiber composite elements require a mold to define form. However, this method proves to be unsuitable to transfer natural construction principles into architectural applications since

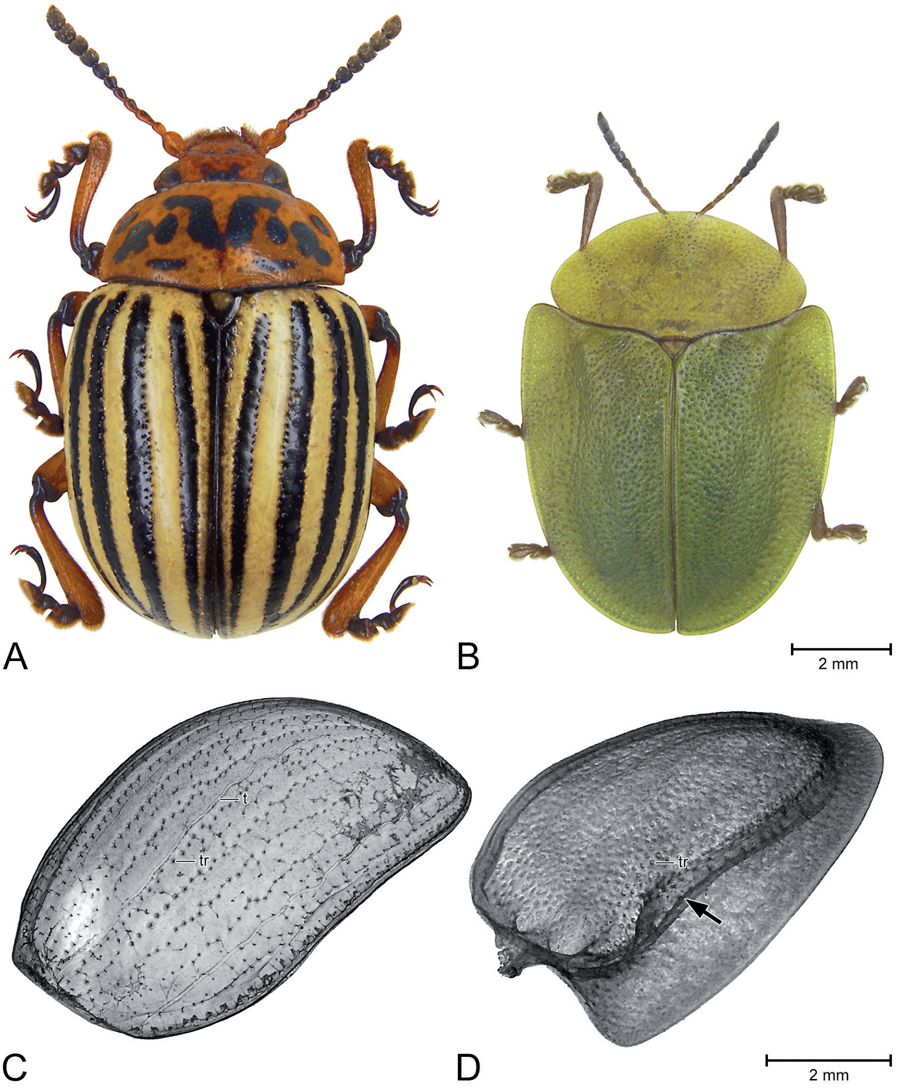

Fig. 1: Beetles and isolated elytra. **A** Colorado potato beetle (*Leptinotarsa decemlineata*). **B** Green tortoise beetle (*Cassida viridis*). **C, D** Volume renderings of elytra based on synchrotron X-ray tomography data (C: *L. decemlineata*; D: *C. viridis*; note the bifurcated epipleurae (arrow)).
Abb. 1: Käfer und isolierte Elytren. **A** Kartoffelkäfer (*Leptinotarsa decemlineata*). **B** Grüner Schildkäfer (*Cassida viridis*). **C, D** Volumenrenderings von Elytren basierend auf Synchrotron-Röntgenmikrotomographie-Daten (C: *L. decemlineata*; D: *C. viridis*; man beachte die gabelförmig geteiltenr Epipleuren (Pfeil)).

Fig. 2: Development and construction of the research pavilion. **A** Finite element analysis of global force flows and their transfer into structural carbon fiber reinforcements. **B** Filament winding by synchronized robots. **C** Detail of fiber winding process. **D** Assembling of the elements.
Abb. 2: Entwicklung und Konstruktion des Forschungspavillons. **A** Finite-Elemente-Analyse der globalen Kräfteflüsse und ihr Transfer zu Karbonfaser-Verstärkungen. **B** Wickeln der Filamente durch synchronisierte Roboter. **C** Detail des Wickelprozesses. **D** Zusammensetzen der Elemente.

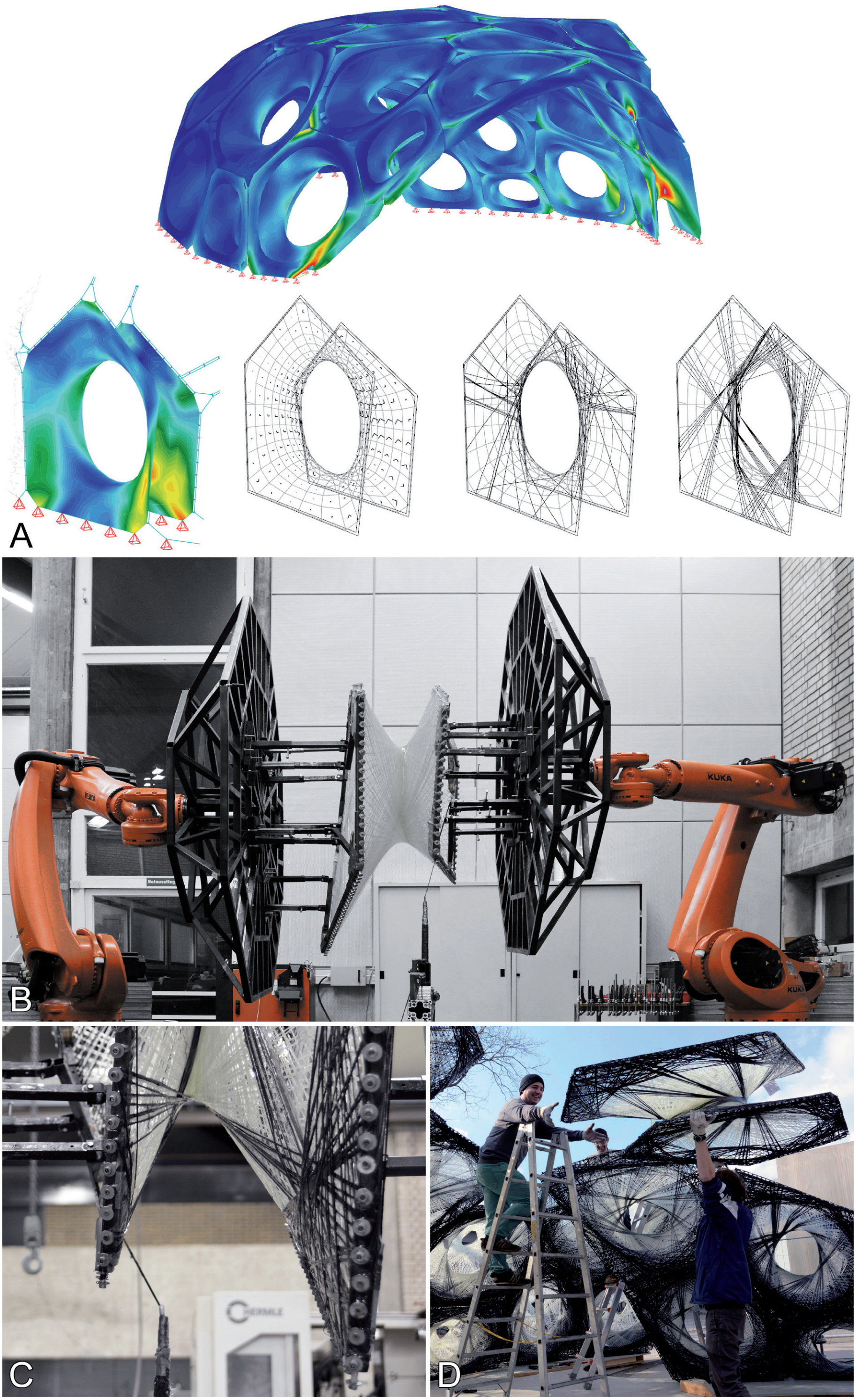
A
B
KUKA
C
D

Fig. 3: Completed research pavilion at the campus of the University of Stuttgart. **A** Front view. **B** View from inside; note the fiber construction and the two walls. **C** Top view.
Abb. 3: Fertiger Forschungspavillon am Campus der Universität Stuttgart. **A** Vorderansicht. **B** Blick von innen; man beachte die Fiberkonstruktion und die beiden Wände. **C** Aufsicht.

they usually involve unique elements that would require an individual mold-extensive formwork and prohibitively complex molds (Reichert et al. 2014).

2.4. Fabrication and construction

For the fabrication of the geometrically unique, double curved modules a robotic coreless winding method was developed (Prado et al. 2014), which uses two collaborating 6-axis industrial robots to wind fibers between two custom-made steel frame effectors held by the robots. While the effectors define the edges of each component, the final geometry is emerging through the interaction of the subsequently laid fibers. The fibers are at first linearly tensioned between the two effector frames. The subsequently wound fibers lie on and tension each other which results in a reciprocal deformation. This fiber-fiber interaction generates double curved surfaces from initially straight deposited fiber connections. The order in which the resin impregnated fiber bundles (rovings) are wound onto the effectors is decisive for this process and is described through the winding syntax. The specific sequence of fiber winding allows controlling the layout of every individual fiber leading to a material driven design process. These reciprocities between material, form, structure and fabrication are defined through the winding syntax which therefore becomes an integral part of the computational design tool.

The effectors are adjustable to various component geometries, leading to only one reconfigurable tool setup for all 36 elements. Coreless filament winding does not only save substantial resources through the needlessness of individual molds, but in itself is a very material efficient fabrication process since there is no waste or cut-off pieces.

The specific robotic fabrication process includes the winding of six individual layers of glass and carbon fibers. A first glass fiber layer defines the elements geometry and serves as formwork for the subsequent carbon fiber layers. These carbon fiber layers act as structural reinforcement and are individually varied through the fibers anisotropic arrangement. The individual layout of the carbon fibers is defined by the forces acting on each component which are derived from FE Analysis of the global structure. The generated winding syntax is transferred to the robots and allows the automatic winding of the six fiber layers.

In total 36 individual elements were fabricated, whose geometries are abstracted from the beetle elytra. Each of them has an individual fiber layout which results in a material efficient load-bearing system. The biggest element has a 2.6 m diameter with a weight of only 24.1 kg.

3. The biomimetic prototype

The research pavilion covers a total area of 50 m² and a volume of 122 m³ with a weight of 593 kg. The overall geometry of the pavilion reacts to site-specific conditions at the University of Stuttgart. By generating more complex spatial arrangements than a simple shell construction, it demonstrates the morphologic adaptability of the system. The research pavilion shows how the computational synthesis of biological structural principles and the complex reciprocities between material, form and robotic fabrication can lead to the generation of innovative fiber composite construction methods. Beetle elytra proved to be suitable role models for lightweight constructions in architecture. The multidisciplinary research approach does not only lead to performative and material efficient lightweight constructions, it also explores novel spatial qualities and expands the tectonic possibilities of architecture.

Project team

ICD Institute for Computational Design – Prof. ACHIM MENGES
ITKE Institute of Building Structures and Structural Design – Prof. Dr.-Ing. JAN KNIPPERS
Scientific Development
MORITZ DÖRSTELMANN, VASSILIOS KIRTZAKIS, STEFANA PARASCHO, MARSHALL PRADO and TOBIAS SCHWINN
Concept Development
LEYLA YUNIS, ONDREJ KYJÁNEK
System Development, Fabrication & Construction
HASSAN ABBASI, YASSMIN AL-KHASAWNEH, DESISLAVA ANGELOVA, HANS-CHRISTIAN BÄCKER, YULIYA BARANOVSKAYA, MARTA BESALU, GIULIO BRUGNARO, ELENA CHIRIDNIK, EVA ESPUNY, MAXIMILIAN FICHTER, EUGEN GRASS, MATTHIAS HELMREICH, MICHAEL HERRICK, NAM HOANG, JULIAN HÖLL, ALEJANDRO JARAMILLO, NORBERT JUNDT, SHIM KARMIN, GEORGI

Kazlachev, Sebastian Kröner, Vangel Kukov, Taichi Kuma, Ondrej Kyjánek, Sophia Leistner, David Leon, Luca Menghini, Claire Milnes, Amanda Moore, Martin Nautrup, Paul Poinet, Gergana Rusenova, Emily Scoones, Djordje Stanojevic, Andrei Stoiculescu, Kenryo Takahashi, Petar Trassiev, Sascha Vallon, Shiyu Wie, Maria Yablonina and Leyla Yunis, supported by Michael Preisack and Michael Tondera

Collaboration partners

Institute of Evolution and Ecology, Evolutionary Biology of Invertebrates, University of Tübingen – Prof. Dr. Oliver Betz;
Department of Geosciences, Palaeontology of Invertebrates, University of Tübingen – Prof. Dr. James Nebelsick;
Module Bionics of Animal Constructions, University of Tübingen – Gerald Buck, Michael Münster, Valentin Grau, Anne Buhl, Markus Maisch, Matthias Loose, Irene Viola Baumann and Carina Meiser;
ANKA/Institute for Photon Science and Synchrotron Radiation, Karlsruhe Institute of Technology (KIT) – Dr. Thomas van de Kamp, Tomy dos Santos Rolo and Prof. Dr. Tilo Baumbach;
Institute for Machine Tools, University of Stuttgart – Dr.-Ing. Thomas Stehle, Rolf Bauer and Michael Reichersdörfer;
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Dr. Thomas van de Kamp
Dipl.-Ing. (FH) Tomy dos Santos Rolo
Prof. Dr. Tilo Baumbach
Karlsruhe Institute of Technology (KIT)
ANKA / Institute for Photon Science and Synchrotron Radiation (IPS)
& Laboratory for Applications of Synchrotron Radiation (LAS)
Hermann-von-Helmholtz-Platz 1
D-76344 Eggenstein-Leopoldshafen
E-Mail: thomas.vandekamp@kit.edu

Mag. Arch. Moritz Dörstelmann
Prof. Achim Menges
University of Stuttgart
Institute for Computational Design (ICD)
Keplerstr. 11
D-70174 Stuttgart
E-Mail: moritz.doerstelmann@icd.uni-stuttgart.de

Prof. Dr.-Ing. Jan Knippers
University of Stuttgart
Institute of Building Structures and Structural Design (ITKE)
Keplerstr. 11
D-70174 Stuttgart
E-Mail: info@itke.uni-stuttgart.de