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Fibrous structures: An integrative approach to design computation, simulation and fabrication for lightweight, glass and carbon fibre composite structures in architecture based on biomimetic design principles[☆]

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HIGHLIGHTS

- We designed and fabricated a full-scale architectural pavilion as a fibre-reinforced polymer monocoque.
- We developed three digital models to design, simulate, analyse and optimize geometric solutions.
- We transferred biomimetic principles into the fibre-reinforced polymer laminate design.

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ABSTRACT

In this paper the authors present research into an integrative computational design methodology for the design and robotic implementation of fibre-composite systems. The proposed approach is based on the concurrent and reciprocal integration of biological analysis, material design, structural analysis, and the constraints of robotic filament winding within a coherent computational design process. A particular focus is set on the development of specific tools and solvers for the generation, simulation and optimization of the fibre layout and their feedback into the global morphology of the system. The methodology demonstrates how fibre reinforced composites can be arranged and processed in order to meet the specific requirements of architectural design and building construction. This was further tested through the design and fabrication of a full-scale architectural prototype.

1. Introduction

Since the 1950s, the introduction of synthetic composite materials has had a profound impact on a wide range of industries including automotive, aeronautics, sailing and sports. However, despite an initial phase of experimentation in the 1960s, [1] composite materials still have not found wide applications in the architectural environment. In the contemporary context of computational design and digital fabrication, composites have again been recognized as offering unique architectural possibilities [2], but most projects still remain on a speculative level [3].

In this paper the authors present a novel approach which integrates robotic filament winding, material-oriented computational design, and digital simulation resulting in an ultra-lightweight, self-supporting pavilion fabricated as a seamless, monocoque construction using fibre-reinforced polymers (FRP) (Fig. 1). This interdisciplinary project was conducted by architectural and engineering researchers of the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) together with students of the faculty and in collaboration with biologists of the University of Tübingen. It investigates the possible interrelation between biomimetic design strategies and novel processes of robotic production for composite structures.

In architectural history, pavilions have served as vehicles for developing future concepts of architecture through the employment of new materials, fabrication techniques and design strategies.

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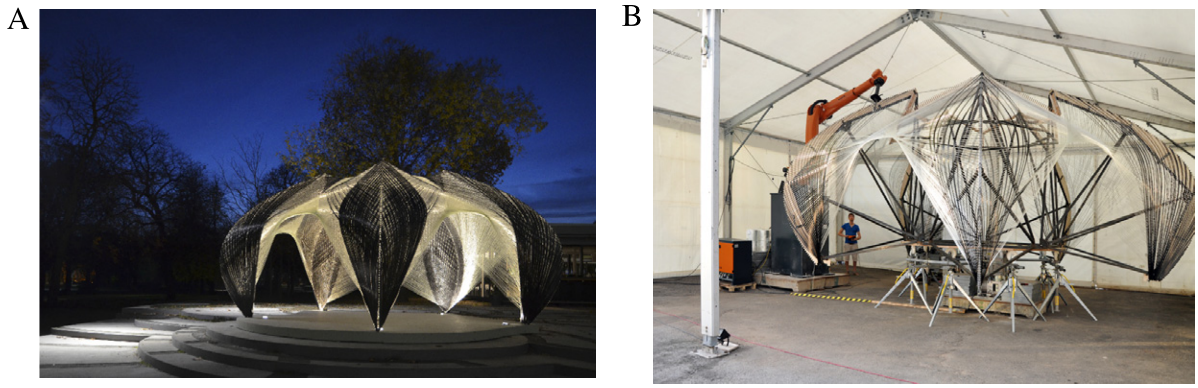

Fig. 1. Full-scale prototype. (A) View of finished pavilion. (B) View of robotic winding process.

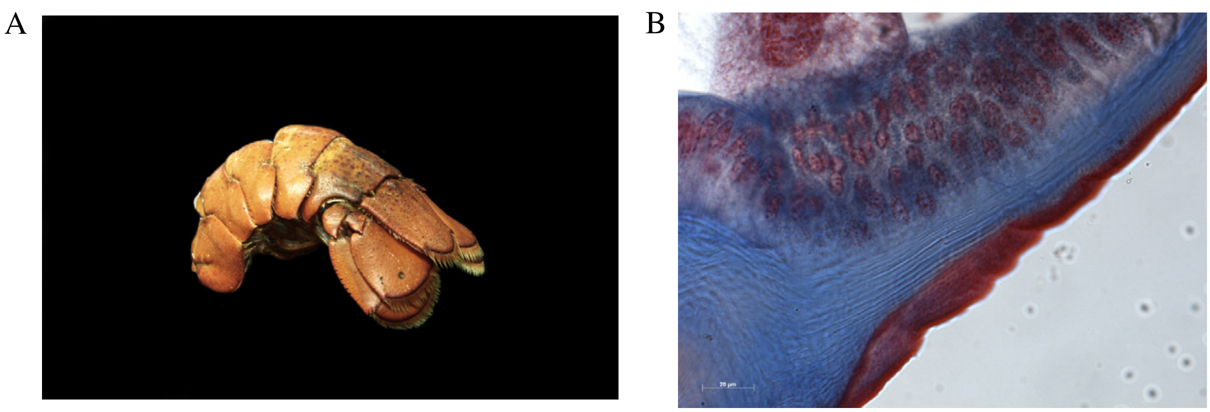

Fig. 2. Biological role model. (A) Shell of the American lobster (*Homarus americanus*). (B) Microscopic view of the cuticle and its fibre layout.

The architectural pavilion, with its reduced demands in regard to program and permanence, provides a suitable context for exploring construction-oriented innovation. The research project presented here is based on the consideration of the following 5 points:

(1) *Biomimetic principles*: Natural systems produce highly complex structures that integrate different functional properties on a global geometric and a local material level.
(2) *Fibrous composite materials*: In nature, most load-bearing structures are constructed from fibrous materials. The directionality of such anisotropic materials allows to specifically strengthen defined directions of stress while reducing the overall weight of the structure.
(3) *Robotic fabrication*: Numerical controlled fabrication processes enable the possibility to produce differentiated parts of constant quality. The additional freedom of multi-axis fabrication processes like robotic fabrication widens up the overall machinic morphospace [4].
(4) *Computational design*: Integrating algorithmic logic into the design process to design architectural structures with a complex set of constraints.
(5) *Time*: The overall project development time including completion of the research pavilion was limited to one year.

1.1. Biomimetics

In the first part of the paper, the authors present the relevant aspects of the biological analysis, along with the structural and morphological principles of the chosen biological role model (*Homarus americanus*) that were later transferred into a high-performing material system. The geometric layout, chemical composition of fibre and matrix, mechanical anisotropy and material behaviour of the biological model's exoskeleton (Fig. 2(a)) – a high-performing natural fibre composite structure – form the basis for the development of a novel structural and tectonic system in architecture.

1.1.1. Biomimetic design approach

The promise of a biomimetic design approach [2] is that through the in-depth analysis of biological role models, some of the ingenuity, resilience, efficiency, and perceived gracefulness of natural structures can be transferred into a technological application. To the extent that not only the results of the natural evolutionary process offer a source of inspiration for applications in technology, but also the process itself has become a model for computational problem solving, optimization, and design exploration in the form of evolutionary algorithms [5]. However, the abundance of morphological differentiation in nature (form, colour, materiality) can be seen as being in sharp contrast with the hitherto application of technology in the man-made environment. This contrast is summed-up in the following quote by biomimeticist J. Vincent [6]: "in biology material is expensive, but shape is cheap (the opposite is true in the case of technology)".

The objectives of the investigation of morphology are to (1) identify biological principles that enable lightweight, materially efficient load-bearing structures; (2) the development and integration of these principles into a computational design process in combination with aspects of constructability and fabrication to enable a performative material system [7]; and (3) the implementation and evaluation of the developed material system in a prototypical full-scale structure.

1.1.2. Arthropods and 'deep principles'

The focus of the biomimetic aspects of the research presented in this paper is on the analysis of the exoskeletons of arthropods with respect to their properties as natural lightweight fibre composites and their potential to inform applications of FRP in architecture and design. The exoskeleton (*cuticle*) serves multiple functions to its organism, ranging from protection against predators, to gripping and grinding food, up to optical lenses in their eyes