INTEGRATIVE COMPUTATIONAL DESIGN METHODOLOGIES FOR MODULAR ARCHITECTURAL FIBER COMPOSITE MORPHOLOGIES

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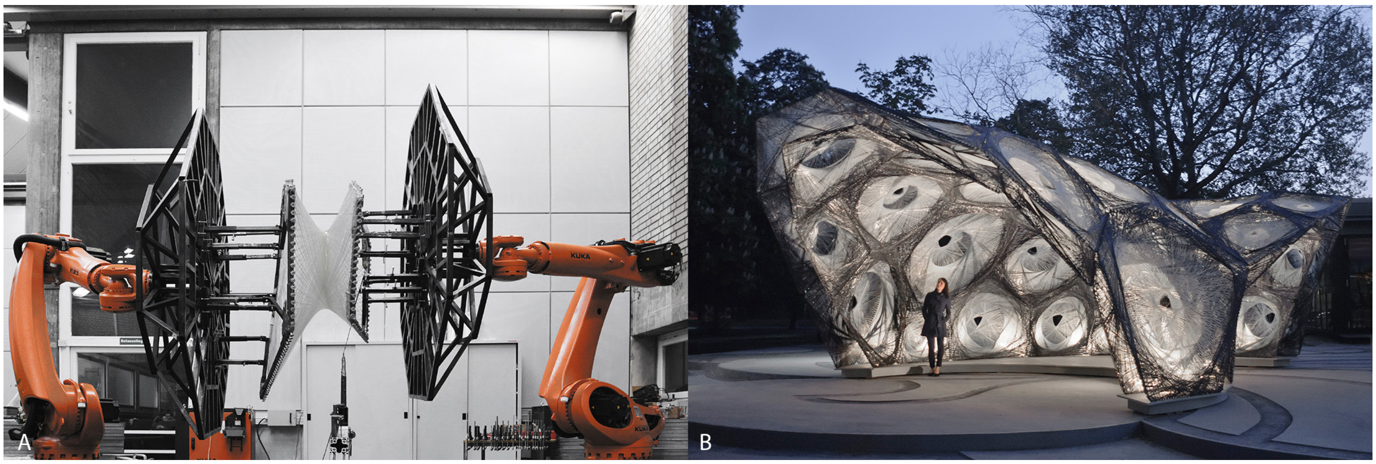


1 A. Custom developed fabrication setup for coreless filament winding with collaborating robots; B. Resulting demonstrator structure: ICD/ITKE Research Pavilion 2013-14

ABSTRACT

How can design computation work as an interface between the virtual design space and the physical realization space, while forming a point of confluence within a multidisciplinary design and construction methodology? In an integrated design process for fiber composite structures in architecture (one based on morphogenesis of fibrous structures in nature), form generation and materialization are highly interrelated thereby leading to a synergy of form and materiality. This paper examines the framework of integrative computational design methodologies incorporating material, structure, fabrication and morphogenetic principles for the design development and digital fabrication of lightweight fiber-reinforced composite components. This process is discussed through the case study, ICD/ITKE Research Pavilion 2013-14, including project-specific applications and the implementation of computational tools.

INTRODUCTION

Natural morphogenesis is characterized by the capacity of an organism to develop a form in response to multiple, often contradictory intrinsic and extrinsic stimuli. The resultant form synthesizes these conditions into one of many possible robust, adaptive outcomes rather than a unique optimization solution (Webster 1996). Classical architectural planning processes work entirely different, as they are often performed as a linear sequence of architectural design, engineering and implementation. This can either lead to discrepancies between initial design intentions and build results or requires multiple iterations of the linear process. Integrative design methodologies seek to establish processes in architecture which bear resemblance to natural morphogenesis, where intrinsic material and fabrication logics are generative design drivers rather than inert receptors of form. This creates a bottom-up morphogenetic design approach, synthesizing material and fabrication constraints through the development of integrative computational design tools.

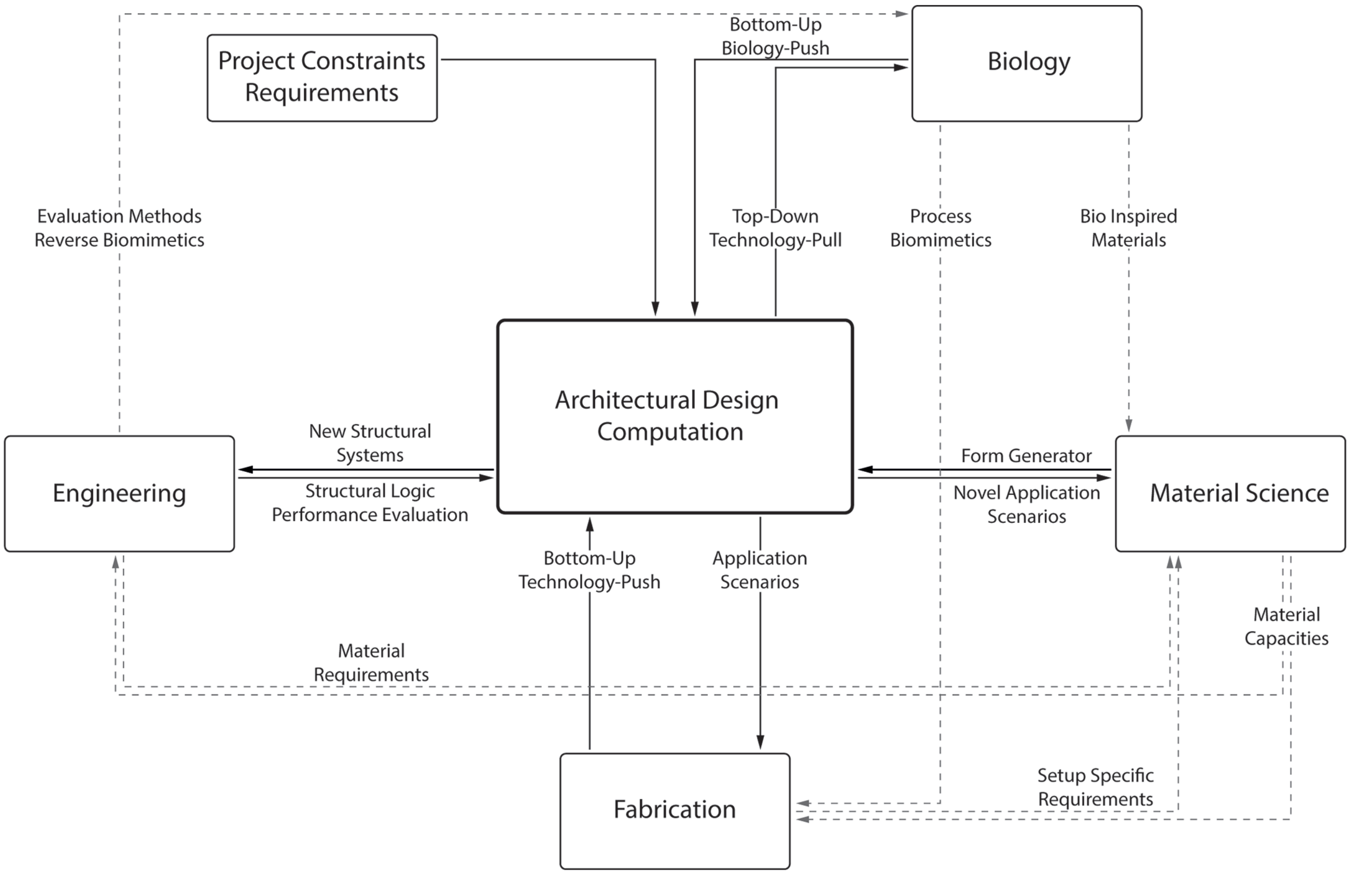
In recent years several developments in material, fabrication and computation have made this methodology possible. Composite materials, such as fiber-reinforced polymers (FRP), have been used in performance based, engineering application since they were developed in the 1930s. These performative materials have found their way into architectural applications due to a high strength to weight ratio (Voigt 2007). The formability of FRP provides a wider spectrum of geometric freedom than that of standard construction materials (such as plywood sheets or timber framing), allowing the system to adapt more effortlessly to various design criteria. This is especially important in an integrative design process, where form is not predefined as in traditional top-down design methodologies. Instead, highly differentiated global and local morphologies are generated as a result of multiple design criteria. Fiber-reinforced composites provide the opportunity to determine material behavior through the controlled fabrication of heterogeneous, anisotropic fiber arrangements. This allows design processes to expand beyond the traditional scope of architectural design incorporating the scale of material organization.

Fabrication processes for geometrically complex and performative composite structures have evolved beyond labor intensive hand-laying methods to the use of numerically controlled winding tools. This allows seamless flow of information from complex computationally generated fiber layouts into precisely fabricated fiber composite parts. Industrial robotic arms, with their multiple degrees of freedom and controlled precision, are well-suited for the task of winding complex geometries. These "generic machines" are adaptable to a wide range of potential operations which become specialized through various tools, effectors or tasks (Menges 2012). The versatility of these machines makes fabrication techniques possible that were previously prohibitive due to costs or complexity.

The intricacy of natural morphogenesis, which inherently deals with complex interrelated systems, can now be explored architecturally through developing computational design techniques. This equips architects and designers with the tools to negotiate large data sets of information, propelling digital explorations into previously unknown territory (Terzidis 2003). Data-embodied architecture is, however, not a new concept in design. The notion of building information modeling (BIM) has existed for several decades and is a popular methodology in the architecture industry. A BIM model serves as a virtual database tool for storing and accessing of building information. BIM is a streamlined building delivery system capable of coordinating large building data sets. Yet it remains based on a traditional top-down approach to design, demanding the supply of information (such as building form) during the design process. In digital morphogenesis, this initial information is unknown, thus a bottom-up computational design process is required.

Research at the ICD/ITKE has explored several integrated design methodologies through the design and fabrication of full scale architectural demonstrators. In the ICD/ITKE Research Pavilion 2012, a single monocoque shell was developed, that integrated the structural capacity of FRP with the fabrication constraints of a 7-axis robotic setup including a rotational positioner. The formwork was minimized to allow the wrapped fibers to interact in a core-less winding process (Reichert et al. 2014). The wrapped geometry was therefore a direct result of the relationship between the material behavior and the machinic morphospace (Menges 2012).

The ICD/ITKE Research Pavilion 2013-14 continues this research on integrated design and fabrication processes while focusing on the development of a modular FRP structural system for a prototypical pavilion (Figure 1B). This requires the synthesis of a new set of design constraints and the deployment of novel design strategies. This paper focuses on the integrated design methodology that was developed for the ICD/ITKE Research Pavilion 2013-14, including the integration of the morphological rules derived from biomimetic principles, material characteristics for the core-less winding of FRP building components, robotic fabrication limitations, structural performance, architectural framework and organizational constraints into a single generative process, creating a continuous and reciprocal exchange of information.



2 Generic integrative design process diagram

INTEGRATIVE DESIGN COMPUTATION WITHIN A MULTIDISCIPLINARY DESIGN PROCESS

In order to orchestrate the complex network of interrelations within a multidisciplinary design and construction process, design computation is used to translate various process inputs into tool parameters and encoding the interrelations into an algorithmic framework (Figure 2). Setting up a robust tool is not merely to digitize or automate the design process (Bechthold 2010), but allows for the production and evaluation of multiple design iterations which can be used to navigate the design space in an explorative way. This is an excellent usage of digital design processes, where the computational capacity to negotiate complex interrelationships works as a tool for the interface and expansion of design thinking. By serving as a point of confluence computational design methodologies allow an interdisciplinary information exchange which drastically changes the way each field operates.

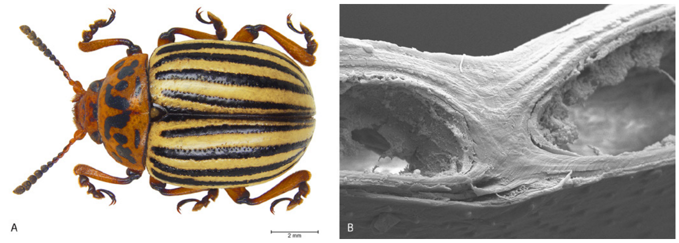
Traditionally, structural engineers have been trained to identify and think in typologies of structures. This was necessary to identify the right set of formulas for calculation or to provide guidance in the conceptualization of a structural system. The integration of structural design into a multidisciplinary design process through novel simulation tools permits engineers and architects to explore structural systems beyond predetermined typologies, as well as enabling them to include precise and meaningful structural analysis into the formally decoupled design process (Knippers 2013).

Recent developments of computational and fabrication processes allow for the generation and materialization of complex information driven geometries. This opens up greater potentials for the transfer of functional principles from biology to novel material and structural systems within a multidisciplinary process, while generating potential biological insight through the use of cross-disciplinary methodologies within a reverse biomimetic process. The convergence of material and materialization allows fabrication technology and material behavior to push new architectural possibilities as creative inputs.

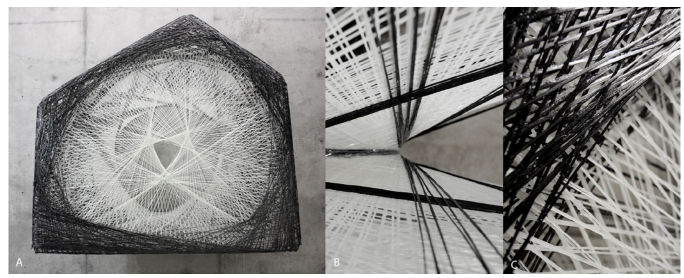
BIOMIMETICS

Functional morphologies and material organization processes in biology are highly relevant within an architectural context. They achieve fundamental architectural tasks like materialization of form and functional integration in a materially efficient manner.

As part of the ICD/ITKE Research Pavilion 2013-14, various natural fiber composite structures were investigated. The structural morphology of beetle elytra, particularly those in flying beetles, served as a versatile role model for the abstraction of light weight construction principles, since it is both the rigid protection for the beetle and has a minimized weight for flight (Figure 3A). The structural capacity of the elytra is based on the complex geometry and anisotropic organization of the natural chitin fiber composite material. From this biological role model the double layered shell with internal hyperbolically shaped interconnections (Trabeculae, Figure 3B), was abstracted into a modular arrangement of components. Both the structural morphology of the elytra and the distribution of trabeculae provided guiding principles for efficient material usage and geometric differentiation of FRP building components.



3 Leptinotarsa decemlineata: A. Top view, light microscopy by Dr. Thomas van de Kamp; B. Section view into elytron's internal trabecel bracing structure, SEM by Prof. Oliver Betz



4 Carbon and glass fiber building component: A. Front view; B. Differentiated carbon fiber reinforcement; C. Omni-directional carbon fiber reinforcement

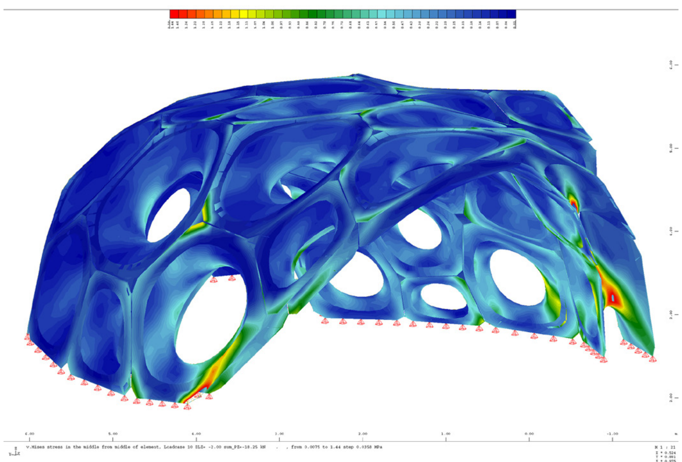
MATERIAL AND STRUCTURE

In an integrated design methodology materiality is regarded as an intrinsic part of the design process, rather than playing a subordinated role to a predetermined geometric form. Subsequently, the relationship between material behavior and the form generation process results in a design outcome which is strongly informed by material potentials and constraints.

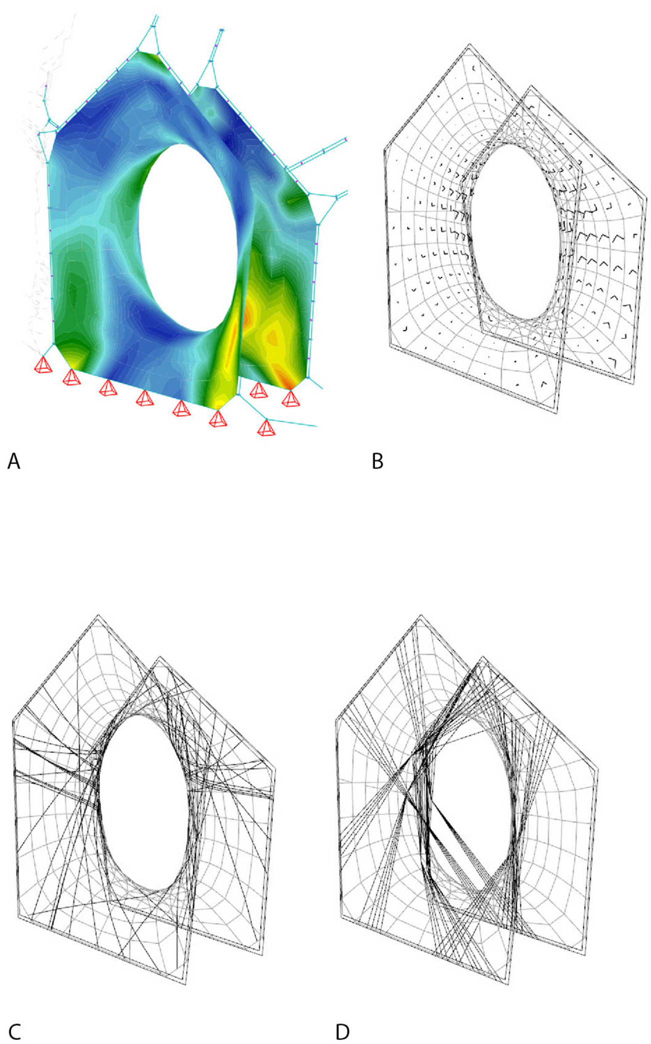
While topologically and conceptually informed by the biomimetic investigation, the specific materialized geometries of the components are defined by the core-less filament winding process, a fabrication system that requires no positive mold for the generation of double-curved geometries (Waimer 2013) and the winding syntax, the systematic sequence of fiber placement. The structurally and materially informed winding syntax is intended to create adequate fiber-fiber interaction in order to achieve a structurally active composite surface.

Several winding syntax codes were developed in order to cover the various material functions of the fiber-based system. The winding syntax of the initial glass fiber layer describes helicoidal fiber arrangements which ensure forming of anticlastic geometry. This is the result of the system deforming under the tension applied by the subsequent layers of fibers. There is an interdependency between the geometric variation of each component and the winding syntax, which must be resolved to translate the differentiated geometry into the hyperbolic column-like structures. The glass fiber layer acts as scaffolding for the carbon fiber layers, which structurally reinforces each component and the global geometry. For this purpose, two winding syntaxes were developed. The first is a layer of carbon fiber that transfers generic, omni-directional structural forces in each component; the second reinforces the components in regard to predominant global structural force flows.

Structural input occurs through all hierarchical levels, influencing material placement and properties, components local geometries and the global design system. The process is accompanied by structural FE simulations (Figure 5), which lead to results that were then interpreted into parameters for the design process. The differentiated carbon fiber layer integrates both geometric requirements and variable boundary conditions such as possible component to component connection points and structural analysis information. This enables the position and direction of the carbon fiber to be differentiated according to the load distribution along the global structure, and allows for the effective transfer of loads through adjoining components. Through simulating the global structure, high forces occurring in the system are identified and translated into fiber directions. This results in carbon fibers which are specifically placed according to the force vector orientations and fiber density that is defined by the amplitude of the vector



5 Finite element analysis of the global structural system



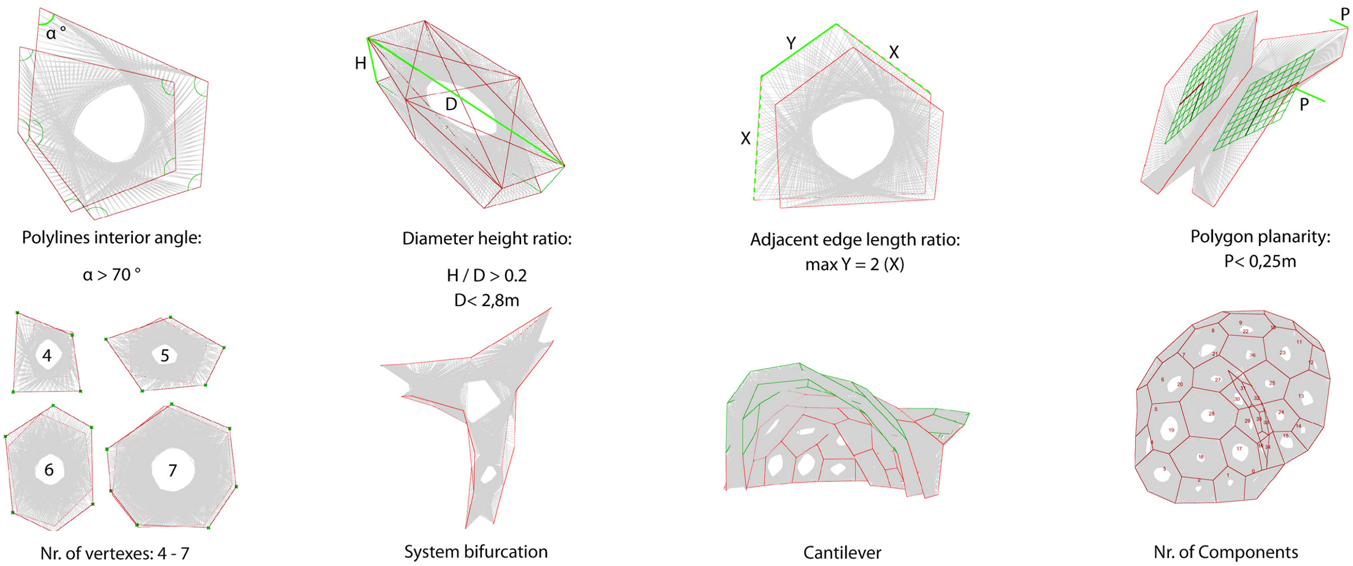
6 Structurally differentiated winding syntax development diagram: A. Finite Element simulation; B. Force vectors; C. Traced force directions; D. Differentiated Fiber reinforcements

(Figure 6). Both carbon fiber layers are strongly informed by the geometric constraints of the glass fibers, since they must negotiate the double curved surface geometry and ensure a proper fiber-to-fiber bond on each component. The algorithm used to create the adaptive winding syntaxes bridges the gap between the structural simulation and the geometric environment, while being informed by the other conditioning factors (the global constraints and fabrication requirements).

MATERIALIZATION

Bottom-up design strategies often result in complex geometries which explore the potentials of an open-ended system. This poses a difficult challenge for implementation as standard methods of fabrication are not always suitable. In an integrated design process, in which fabrication is intrinsically linked, materialization is inseparable from material and form. This requires the development of novel fabrication strategies in parallel to computational techniques in order to negotiate the expression of form and materialization. The geometric outcome is then charged with fabrication constraints, and therefore limiting what is buildable to the machinic morphospace (Menges 2012). In the ICD/ITKE Research Pavilion 2013-14, the fabrication strategy is closely tied to the component and system geometry as well as the fiber syntax. The general size and complexity of the components determine the approximate fabrication setup needed, for example, two robots, their distance from each other and the size of their effectors (Prado 2014) (Figure1A). This setup, in turn, plays a crucial role in determining the limitations of the components geometry such as the degree of non-planarity, maximum component size and angle between components, thus defining the design domain of the overall project (Figure7). The fiber syntax, which was hand-modeled with a scaled version of the fabrication process, was incrementally optimized to streamline winding. The fiber syntax also formed the basis for the robotic winding code which was generated from the integrated data using custom scripted computational processes.

Computation played a vital role in integrating fabrication into the design process. Not only does it create opportunities to mitigate design and fabrication challenges, but also allows for the coordination of the digital model and fabrication setup. Custom scripts were developed to translate component geometry from the digital information model to the robotic assembly code for each effector frame. The robot assisted assembly of the effectors was not only intended to automate the process, but to compensate for manual inaccuracies through robotic precision. Digitally fabricated guides are used to secure the effector frame geometry, which has a high degree of geometric freedom, to the correct orientation for fabrication. Defining the geometry of these guides



7 Component morphologic parameters and Global system variations

required the integration of multiple, potentially conflicting, fabrication criteria (attachment points, angles of rotation, support planarity and fiber interference). This digital design tool allowed for the control of multiple parameters and the visual feedback of underperforming criteria for quick evaluation and iteration.

Since the interrelationship between the robotics setup, winding syntax and component geometry all jointly contributed to the fabrication limitations, it becomes increasingly important to optimize the fabrication process and simulate potential problems virtually in order to utilize the extents of the fabrication setups geometric possibilities. Genetic algorithms are used to determine the tool planes for each effector and base rotation for winding. These cannot be determined geometrically from the component center point or column axis, but rather require cross-referencing all the robot orientation planes with the robotic limitations of the twelve axis setup in order to determine if any orientations are out of reach. A robotic simulation and adaptive base plane are used to avoid collisions. These computational processes demonstrate the dependency between form generation and fabrication as well as the need for integrative tools for the design of both.

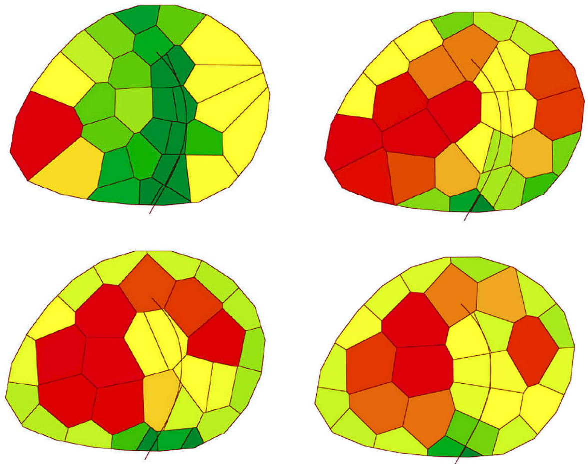
SOLUTION SPACE

The design space encompasses the domain of all possible outcomes which can be generated by computational design tools. To achieve meaningful results within a certain target zone, a well-defined design domain is required.

Within an integrated computational design process, the design space is an outcome of the reciprocal constraints between the various integrated process parameters. It serves as a purposeful truncation of the design outcomes. Over- or under-constraining of the solution space can either lead to predefined results or unfeasible outcomes.

To maintain the explorative character of the computational design process and diversity of results while still generating feasible designs, the design space needs to serve as a boundary within which manifold solutions can emerge through the interplay of the various integrated process parameters.

In the ICD/ITKE Research Pavilion 2013-14, a project-specific solution space is defined in order to maintain a feasible scope of the project for full scale implementation. Therefore basic boundary conditions regarding size and covered area, as well as the overall spatial layout, are defined to serve as the architectural domain for the bottom up computational design process. Based on these boundary conditions, an initial network of component arrangements is determined by principles regarding the distribution of trabeculae which is found in various beetle elytra. This initial component layout served as a starting point for the more complex negotiation of other process parameters. The integration of fabrication constraints, such as the general range in size of producible components and geometric rules for component distribution based on biomimetic principles, led to meaningful constraints of the solution space for the computational design process.



8 Behavior based cell arrangements

The computational strategy defining the initial component layout is based on interaction between the boundary conditions utilized in the architectural framework and a bottom-up behavioral integration method. The component layout emerges through an iterative process of cellular arrangement, which is based on simple rules for neighboring cell interactions (Figure 8). Biomimetic design principles and fabrication processes are integrated into the computational design process from the beginning, thereby informing the initial cellular layout and contributing to the definition of the design space.

NEGOTIATING INTERRELATIONS

Within the design space defined by this initial component topology, a morphogenetic design process unfolds which instrumentalizes process constraints as active drivers for variation and adaptation of structural morphologies on a global and component level. The integrative design methodology does not rely on linear optimization strategies, but utilizes a flexible design exploration tool that navigates through the solution space by negotiating potentially antagonistic constraints. The system resolves itself through a non-linear open-ended process into one of many states of equilibrium (Attar 2010).

In order to establish the interrelationships between different fields, the influences of each must be represented systematically. A physics simulation forms the framework for the synthesis of both physical forces (such as gravity) and non-physical "forces" (fabrication constraints) (Piker 2013). The components morphology is represented by particles connected with springs. Forces are employed as abstract representations of extrinsic and intrinsic process requirements. This allows the components morphology to adjust within a cyclical interaction of a particles spring system ensuring the emergence of a global morphology through local interactions.

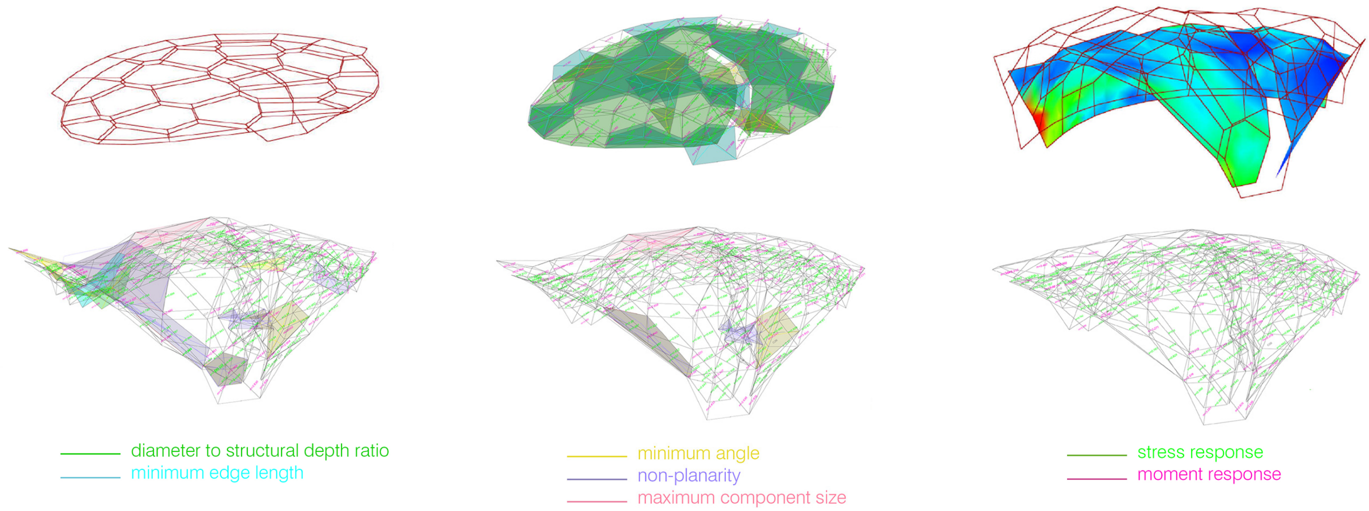
Information gathered during hand and robotic test winding was formulated as geometric rules to ensure proper fiber-fiber interaction, and encoded into forces or constraints acting onto the spring system. This includes component polygon angles, edge length relations or the overall components diameter to height ratio (Figure 7). Other forces are informed by constraints derived from the specific robotic setup and certain effector characteristics in order to avoid out of reach errors or collisions within the winding process. This applies for example to the allowable range of non-planarity for each component polygon and the overall component diameter. The structural principles which were abstracted by biomimetic investigation of the beetle elytra structural morphology were transferred into the design process through the definition of forces, affecting the components global distribution as well as their local morphologic differentiation.

Various methods of evaluating criteria are applied to the system within the process. Geometric relationships are verified, for each iteration of the computational solver, and are used to activate or deactivate adaptive parameters. Some forces are controlled by gradual falloffs or soft transitions, while other evaluation criteria rely on rigid constraints to override other forces. The differentiated effects of the design drivers allow for the hierarchical control and evaluation of each process parameters impact. A finite element solver calculated information from the structural performance of each iteration, creating a morphologic response to specific loading scenarios in order to implement the biological lightweight construction principles (Figure 9). Evaluation processes are integrated into the system which allow for the monitoring and adjustment of critical design or fabrication criteria (component sizes, overall enclosed volume and area) which lead to an online estimation of required resources (winding time and material requirements).

CONCLUSION

The design methodology discussed here, through the case study of the ICD/ITKE Research Pavilion 2013-14, highlights the potential for design computation to serve as a common language within a multidisciplinary process (Figure 10). The non-linear design process allows for parallel bottom up developments and exploration of solutions which emerge through the instrumentalization of process constraints as design drivers. Ultimately, this leads to novel possibilities in design exploration and materialization of architectural structures.

The project-specific development of a computational design framework within the ICD/ITKE Research Pavilion 2013-14 led to the implementation of structural principles derived from biological role models, and to a parallel bottom up exploration of

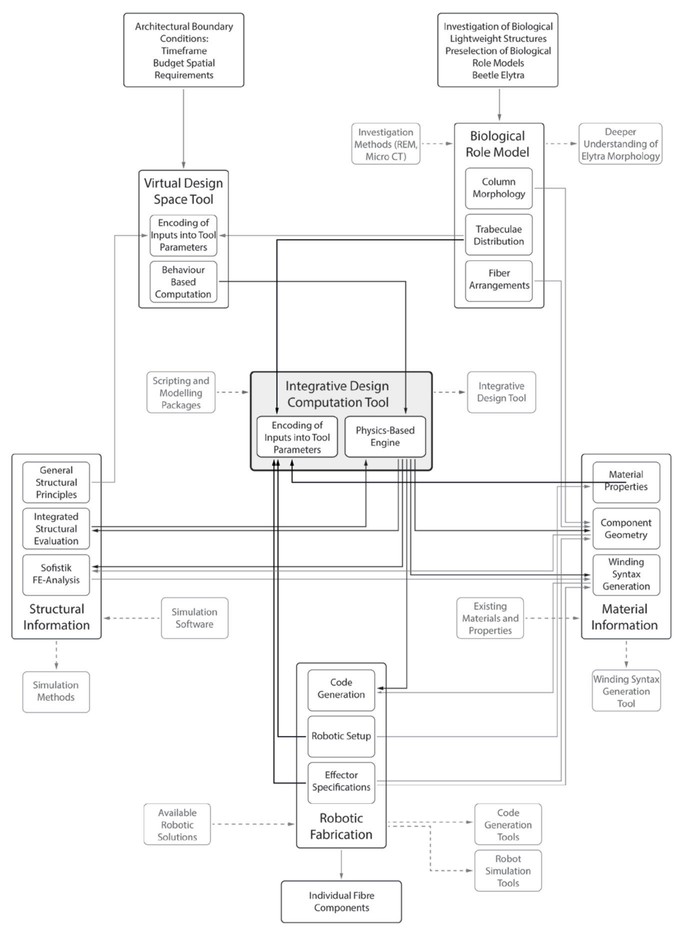


9 Iterative physics based simulation with integrated FE feedback

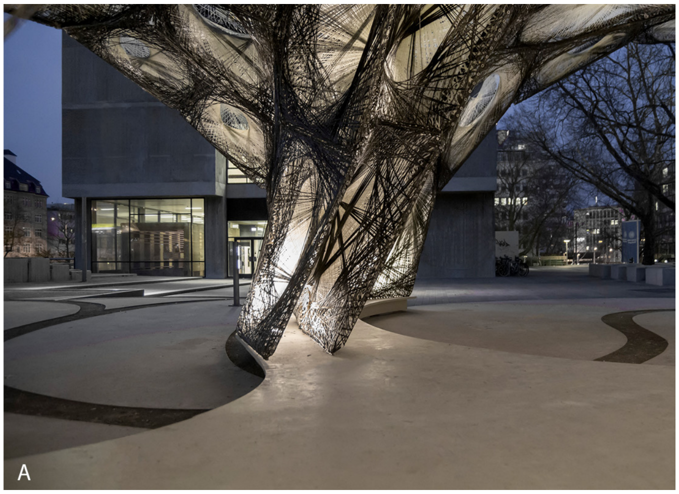
material capacities and fabrication strategies. This enabled the materialization of an architectural prototype that is built from 36 fiber composite components with individually differentiated fiber layouts, and adapted morphologies resulting in a double layered, highly efficient lightweight structure (Figure 11, 12). The complexity in the components geometric articulation and the high level of detail in its material arrangement showcase how novel experiential qualities arise through the application of novel design and fabrication processes in architecture. The research pavilion covers an area of 50.3 m^2 and encloses a volume of 122 m^3 with an overall weight of 594 kg.

Future challenges include expanding integrative design methodologies to include the use of sensor data and real time robotic control, allowing for design adaptability during the materialization process. Such an approach would require a shift from instruction based fabrication, in which robots follow preprogrammed movements, towards flexible fabrication strategies, where movements can respond to changing fabrication conditions.

The main outcome of the presented research is the development of the integrated design methodology, whose full potential is yet to be explored. The inherent capacity of this design methodology is to generate form as the direct outcome of the underlying processes of material organization and functional integration. While the case study achieved morphological variation of a modular lightweight construction based on material capacity and fabrication processes, functional integration should be further explored. In architectural terms that may include climate adaptation (weather proofing, insulation and thermal regulation); thus, a fully developed building construction system could be developed through the integration of further architectural aspects.



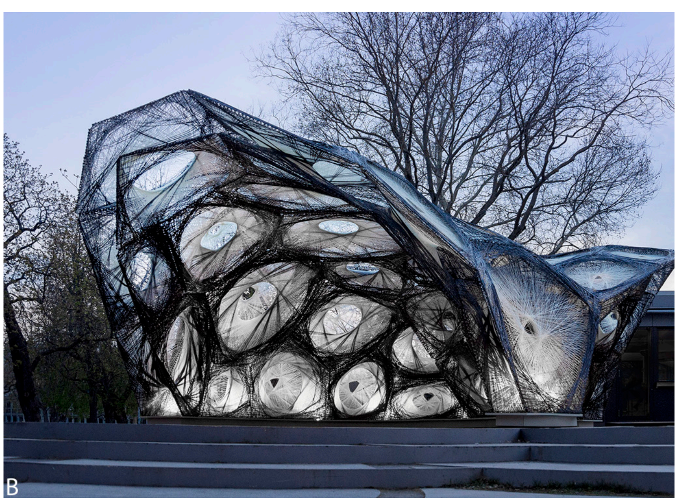
10 Project specific integrative design process diagram



11a Pavilion: Interior image

11b Pavilion: Overhang image

12a Pavilion: Component system



12b Pavilion: Exterior image

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IMAGE CREDITS

Figure 1A, 1B, 2. ICD/ITKE University of Stuttgart (2014)

Figure 3A. Dr.Thomas van de Kamp (2013)

Figure 3B. Prof. Oliver Betz, Anne Buhl, University of Tübingen (2013)

Figure 4A, 4B, 4C. ICD/ITKE University of Stuttgart (2014)

Figure 5. ICD/ITKE University of Stuttgart (2014)

Figure 6A–6D. ICD/ITKE University of Stuttgart (2014)

Figure 7–10. ICD/ITKE University of Stuttgart (2014)

Figure 11A and 11B. ICD/ITKE University of Stuttgart (2014)

Figure 12A and 12B. ICD/ITKE University of Stuttgart (2014)

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