Interactive Form-Finding for Biomimetic Fibre Structures

Development of a computational design tool and physical fabrication technique based on the biological structure of the lichen

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Abstract. This contribution shows a biomimetic approach to design and produce fibrous structural elements derived from the morphology of the biologic archetype ‘the lichen’. The physical form finding strategy allows for a novel self-organised reinforcement for fibrous composite systems. A computational design tool has been developed, based on the findings of various physical models. The digital device allows for shape control and therefore an interaction to and manipulation of the fabrication process. Since the form finding algorithms of the tool are based on physical experiments, every geometry is derived through the program and has its counterpart in production. For example: the fibre density in the model can be adjusted which leads to different geometries. In production the chosen denseness is utilised, thus, the production yields automatically to the desired load-optimized geometry found in the form-finding tool.

Keywords. Biomimetics; Form-finding; Self-organization; Emergence; Fibre structures.

INTRODUCTION

Based on the analysis of the morphology (structural system) of the lichen, a new form-finding method for fibre structures has been developed. The study on various physical models led to the determination of the basic variables, defining the shape of the structure. These were implemented in a computer-aided-design tool, which allows for the shaping of building structures with load-optimised geometry.

Biomimetic as means of designing in architecture

Biologic organisms acquire their functional efficiency and adaptability through the interplay of their components, as well as through time dependent optimisation. Therefore, structures in biology are extremely efficient in the use of materials having complex geometry. The biologic archetype of the lichen is defined as the symbiotic community of a mushroom, the mycobiont, and a partner, respon-
sible for the photosynthesis, the photo- or phytobi-ont. The body of the lichen is built up as a network of tube-like threads, the thallus. The configuration of the individual fibres runs continuously through the corpus of the lichen and is optimised to meet the specific functional requirements and heterogeneous environmental influences.

Nearly all load-bearing materials in nature are fibrous composites in various constellations. Threads are bound together by different substances. Their selective alignment and deposition is tailored to imposing conditions and happens as a result of “growing under stress” (Jeronimidis 2008). Nature is creating thread-like materials in a bottom-up process as an overall system; there is no distinction between structure and material. Fibre-systems are based on the distribution of the threads on geometrical and hierarchical levels (Hensel, Menges and Weinstock 2010). The material is generated in a self-accumulating manner according to physical requirements. No superfluous resources are produced in natural collectives.

**Morphology of the biological model**

The hyphal structure of the lichen can be divided into four areas, viz.: the ending area, transition, structure and load-transfer zone. These four regions were analysed individually with regards to their interconnection. The whole body of the lichen consists of masses of threadlike fibres, which are quite elaborate and durable. In the highly interwoven and organized lichens the hyphae predominate in bulk and assume a more regular arrangement. Interesting is the aspect that the fibres in the structural area are focused vertically. Close to the ending area they align themselves horizontally in a smooth transition without any discontinuities and are composed of more or less compressed, heavily gelatinized hyphae firmly cemented together (Masen & Hale 1967) (Figure 1). The threads accumulate uniquely based on internal physical constraints as structure, occurring amount of neighbours and nutrients (Ahmadjian & Hale 1973). Hyphal threads either melt together or simply entangle to form bundles and knots in order to accumulate material.

**PHYSICAL FORMING METHOD FOR FIBRE STRUCTURES**

Based on biological principles of the lichen, a self-reinforcing physical forming method for fibrous composite systems was developed. The results of the extensive material-system research and the analysis of extrinsic and intrinsic parameters allows the integration of manufacturing constraints and material characteristics in the forming process. The investigated method develops highly efficient organized fibrous structure-elements and provides the needed parameter information for the development of the computational design tool.

**State of the art**

Frei Otto (1995) from the University of Stuttgart and his design team worked on the field of “self-forming processes” of membranes, shells and various other structures. In Otto’s research the particular form of the models are obtained from a state of equilibrium depending on constrains defined by the user and ruling physics. In soap-water soaked woollen threads formed two- and three-dimensional branching networks following the line to surface technique. Due to their over length, these strings aligned themselves into a porous system with only three-armed knots. The network can shape flat or spatial configurations, at which the minimal path system (Kolodziejczyk, 1991) is nowadays well known in computer aided architectural design.

The resulting three-dimensional branching networks stay in a close relationship with the load bearing behaviour of the corresponding construction systems at the architectural scale. Nevertheless, all the models have been used as a guide- and measurement-tool to analyse building strategies to be transferred into a simplified geometry suitable for available construction methods.

Opposed to these known methods, the proposed forming method fabricates a final construction product with load-optimised geometry with a broad range of adjustable design parameters as shown below. The emerged models take time as a factor of construction into account as well as the
inhomogeneous composition of solid fibres and viscous fluids. Self-organization in physical fibrous composite systems is the process of material self-assembly to a desired state of form, according to internal behaviour, influenced by material properties and external boundary conditions.

**Experimental setup**

The materials used for the investigated forming method are glass-fibres and polyester resin. They represent the components of the biological archetype *lichen*: threads and interconnecting nutrients. The anisotropic reinforcement adjusts itself to applied forces and distributes the stabilising and protective resin over the body of the structure; this process is defined as **self-reinforcement**. Through the physical and mechanical properties of both, materials and their interaction, a symbiotic composite material is obtained with features superior to both of the single components (Knippers, Cremers and Gabler 2011). The fibres increase the material-stiffness and load bearing capacity of the composite product; the matrix component encases and supports the reinforcement through maintaining the self-accumulated shape in position.

A planar fibre tissue is attached to the bottom of the forms caffolding. In order to setup a connection between fibres and woven fabric, rovings are weaved into the planar fabric with a varied density and tied strongly. The endings of the fibres are collected to a bundle and shape a spatial figure. Thus, each start and endpoint of the reinforcement is defined and can be adjusted to the users’ necessity.

The fibres are not yet tightened and the bundle is loose (Figure 2). The polymer resin is being poured over the thread cluster, which gets well soaked and mixed with the resin. At this point it is very important that each roving gets covered over the entire
body, as dry places lead to weak structural points and are not protected. A pre-curing of +/- 26 minutes yields to suitable viscosity of the resin; the time depends on room temperature, resin type and additives. The fibres stick together pending on capillary tension at their interface and binding properties of the composite matrix.

**Self-forming and self-reinforcing**

External boundary conditions as fix-points, density, fibre overlength and 3D orientation of the fibre bundle are already defined and set up. The forming process starts with the movement of the bundle. It can be pulled in the desired direction. In the course of our research studies the bundle was moved mostly orthogonal to the bottom surface. During the iterative process of self-organisation within the spatial structure, no external control refers to the absence of direction, manipulation, interference, pressures or involvement from outside the fabric. The system’s processes acquire and maintain the structure themselves (De Wolf and Holvoet 2004).

The dead load of the composite mix acts against the applied tension due to pulling the threads. The longitudinal fibrous elements are predominantly under tension force and behave as a complex member system in which knots deflect the force direction. If the adhesion forces are smaller than the resulting tension forces, the fibres are released from each other in a parallel and simultaneous act of branching and form three-armed knots (Figure 3).

Accordingly to the adaptive growth term, cited by the biologist Claus Mattheck (1998), the structure becomes separated and is deposited in order that the deflected force flow has a greater area available, upon which it can be distributed. Material is performing a build-up at overload zones and a no build-up at under loaded zones. The matrix component forms pre-stressed sub-surfaces between the reinforcement. A porous structure that leads to a seamless and gradient transition of mass distribution emerges. At the end of the self-forming method, the matrix experiences a merging procedure in the hardening process.

**Experimental series – prototypes**

Various test were performed while altering variables, like material characteristics, fabrication processes or boundary conditions. During the self-forming process all the models showed a different behaviour, depending on the specific parameter setting and the variability in the manufacturing process. The analysis of the test results led to a design catalogue, which allows the user to influence the shape according to the users necessities. The autonomic material self-organization happens according to physical principles and the occurring shaping-phenomena evolves a load-optimised structure. Besides, the mentioned external boundary conditions the investigated structure and design variables are:

- Fibre overlength (Figure 4).
- The total length of the roving defines the de-
gree of freedom in which the fibre bundle can move and align itself. A high overlength causes more transverse joints and a random and less controllable fabric. Branching occurs not only to increase the load bearing capacity, but also according to the initial accumulation of thread clusters. The distribution of the reinforcement is influencing the stability of the structure decisively. Tide threads branch more ordinary and the overall geometry forms a shape with straight-like contours. The stitch length of the contour curvature is shorter than in models with a high overlength. In addition to structural properties, also transparency, regularity and various other design effects can be shifted and modified.

- Draw angle (Figure 5).
- Material distribution is aligned according to force progression. By pulling the threads uniformly to the base area, the bundle of rovings is not anymore arranged in the centre. Force paths in the deformed shape vary according to the distance from the fibre start position to the bundle position. Subsequently, mass ac-
cumulation happens more on shorter sides. Arches and levitating areas can be built. Pulling multiple bunches in different directions out of the surface creates a spatial structure. The interweaving of threads generates strong joints between crossing areas; the forming strategy can also be used to generate moiré patterns and not yet explored design impressions.

- Material properties of the matrix (Figure 6).
- Through admixing a thickening agent to the resin, a supporting three-dimensional network-structure is formed in the matrix and the consistency becomes thicker. A semi fluid resin sticks better to the glass fibres; this leads for more branches and therefore more matrix material is brought into the structure for a better constructional support. The overall structure will emerge in a denser concentration and this in turn also guarantees that all fibres are fully covered with the protective resin. As a positive side effect, the tested thickening agent dissolves more glass filaments from the rovings and generates stiffer and better-reinforced sub-surfaces between branches. The variation
in the amount of the sub-surfaces allows for a better design of transparency and translucency within the fibrous system.

- Time based forming (Figure 7).
- The matrix gets pre-cured for about 26 minutes to achieve a viscous consistence. The elapsed time mostly influences the porosity and branching behaviour of the fibrous system. Polymer resin hardens after a certain amount of time. By this time, the matrix becomes more viscous and sticky. Consequently adhesion forces increase and high tension forces are necessary for that the resin releases the fibresin the self-reinforcement process. Taking in advantage the factor time the initial pre-curing time and the effective time of the self-organized reinforcement can be adjusted in a certain range accordingly to structural behaviour and design matters.

- Boundary conditions of the fibre-tissue (Figure 8).
- The attachment of the planar tissue at the bottom of the structure can be varied to achieve a different formation of the woven fabric. To change the boundary conditions and fix only the edges provokes the tissue to deform in order to accomplish a cambering during fabrication. The glass-fibre-fabric is pulled by the rovings and adjusts itself together with the threads according to the force path and brings more stiffness to the overall geometry.

**Advantages of investigated morphology opposed to known form-finding methods**

The equilibrated hanging models of Gaudi were designed to develop the optimal form of structures deriving stress curves from the occurring compression forces. Still, the translation into architectural scale including the constraints scale and mass brought inaccuracy in the resulting geometry. The measuring unit varies in a range of 1:100 and therefore the material make-up differs crucial. Gaudi tried to translate his geometrical visions into physical, buildable forms under the circumstances of the time (Giralt-Miracle 2002).

The fibre structure emerged through form finding and the desired building structure is physically equal, not only affine in geometry or structural logic. Generation of form and material distribution are the same process and therefore the resulting structure is highly resource efficient. The economical material assembly process creates a strong construction system. According to the principle of the inverted catenary chain the member network becomes a finalized element in compression stress. Tension forces along the fibre axes transform into a compression member
system with force splitting and deflection at knots. The sub surfaces formed by the polymer resin are reinforced according to the force path to prevent a displacement or break of the glass strands.

Also nature shows different strategies how fibrous systems can function in compression (Jeronimidis 2008). Two of them are reflected in the opposed morphology: First, the fibres get supported in load carry by well-connected high modulus mineral phases and second, the fibres are multiple cross-linked. Due to the high porosity the construction becomes extremely light and produces a volumetric shape, which decreases the bend probability.

The possibility of interaction due to manipulating the starting parameters allows achieving various system characteristics and designing effects. A variation of the resulting system, in the manner of architectural and structural performance is possible and the technique can be seen as a new forming method for fibrous composite systems.

**COMPUTATIONAL DESIGN TOOL BASED ON INTERACTIVE MANIPULATION CRITERIA**

Variability in manufacture unfolds a variation of architectural qualities. The user designs the resulting constellation and adjusts the manipulation criteria to achieve the desired output. Unique products for context specific and location sensitive use emerge from the manufacturing machine. Possible design effects are transparency, translucency, regularity, overlapping patterns, density, branching, formation of sub-surfaces beside strands, grade of randomness, cross-linking of fibres and more (Figure 9).

**Computational design tool**

Translated into a computational model the setup is defined through iterative exchange of information depending on parameters. Digitalisation of the forming method is following the behaviour of the physical material process. The performance of the system generation in turn is nevertheless based on internal physical constraints and external circumstances. (Menges and Ahlquist 2011)
Figure 10
Variables translated into the computational design tool.

...in the computational design tool (Figure 10). For example the thickening agent synthesizes a high viscous matrix, which in turn means that the fibres stick together stronger and the overall geometry of the form will be denser. Just as the contour curve has a higher curvature and more matrix material accumulates in the structure. In the computational design tool the magnetism force is set up higher to show stickiness and the directed force is adjusted according to more weight of the resin.

The investigated parameters cannot be seen as single criteria and have smaller or bigger impact to interrelated parameters. Because each manual setting can have a drastic effect on the fitness of the emerging structure, the test trials were necessary to find the right freedom of parameter range. Each of them is in direct feedback with related parameters, affects them and the alteration bounces back and mutates the initial input. Since these dependencies are computed, taking the scale of the specimens into account, it is possible to design structures of different scale. The designer can freely define external boundary conditions (top layer, roots of columns) and adjust the described physical constraint settings as they fit the individual architectural design. For the subsequent manufacturing the boundary conditions and the chosen values of the variables can be implemented directly during production of the structure.

The details of the physical forming process are much more complex and fibrous systems in architecture are a not yet well explored branch of design research. For a complete mathematical understanding and computational simulation, a better comprehension of the fibre growth and appearance in natural systems is necessary. Nevertheless, through the design approach it is possible to predict the resulting shape of real fibrous composite structures, because the computational principles were adapted from analyses of the physical forming method.

CONCLUSION
The effective manufacturing method based on physical studies allows the user the manifold de-
sign of ultra-lightweight building structures with load-optimised geometry. The hanging models of Gaudí show interconnected force lines and an approach for the ruled surfaces, but problems arise at the envelopes and the distribution of masses along the overall structure. Therefore, the translation of the abstract chain model with point loads into volumetric geometry cannot give precise information on the optimal distribution of stress in the material of the build form (Tomlow 1989). In contradiction to historical forerunners the self-organized forming approach is capable to generate structural elements in a 1:1 scale derived from a digital design tool, which is based on physical tests. The fibrous systems involve a load-optimized geometry, generated in the self-organized forming process and are not produced according to force-paths, which are reverse engineered from test-models.

The architectural topic s computational design and form merge with the engineering fields of analysis, construction and materialisation and finally manifest a new interactive manufacturing method for fibrous systems. Through the manipulation of various variables a great range of shapes can be fabricated according to unique design results provided by the user of the digital tool. Given that the form finding method is based on physical principals the fibrous system can be adjusted to different scales. There is significant future work to be done for this method in order to become a standard approach in structural form finding.

**FURTHER RESEARCH**

The forming method can be developed into a larger construction system based on the analysis of the referred system. Thinking in a bigger scale the bottom layer could release multiple fibre bundles in order to generate spatial arrangement. Physical space evolves through a single process of structural adaptation due to pulling the ends of each bunch in the same moment. The investigated self-reinforcing forming method can be capable to erecta whole building structure, which stays in constructional equilibrium (Figure 11). Multiple performance criteria could be feed in the digital process to design unique structures of the architectural scale.

**REFERENCES**

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