Actuated Textile Hybrids

Textile smocking for designing dynamic force equilibria in membrane structures

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This paper introduces Actuated Textile Hybrids, and describes the steps needed to steer the form finding processes necessary for their production. The method presented employs an integration of an ``activated'' instead of a pre-stressed textile membrane to design different stages of force equilibrium within the Hybrid Structure, and to investigate the potentials of ever flexible shaping of tensile elements. The set-up for the Textile Hybrid consists of three main elements which are digitally and physically analysed in their inextricable interdependence in force, form and material. Together, the bending active beam (rod), the textile membrane and an applied pattern which actively shrinks surface areas of the membrane (activation), create the base for the form finding process.With advanced Finite Element Modelling software and the architects resulting ability to engineer responsive building-systems for a dynamic environment, it is essential to rethink the construction methods and the building-material of the classic building envelope. This is to not only develop a smartly engineered sustainable skin but also a boundary object which, due to its adaptation, develops the potential to interconnect with its surrounding to re-establish the relationships between nature, home and inhabitant.

Keywords: *Textile Hybrid, Kiwi3D, Form-Finding, Material Studies, Structural System, Membrane Structure*

INTRODUCTION

The primary design factor to the form finding and aesthetic quality of the Textile Hybrid is the Textile itself. This makes it a central design concern that spans across different scales of consideration which are identified as the textile membrane and applied contraction pattern (micro scale), the resulting bending and rotation of the rod (meso scale) and the overall shape (macro scale). At the micro scale (textile membrane) the smocking pattern is the driver for the form finding behaviour since the type and array of the pattern defines the excess of material inside the membrane and as a reaction a shortage of material at the border of the patch. At the meso scale the new border condition bends the rod into its position of force equilibrium. At macro scale the tor-

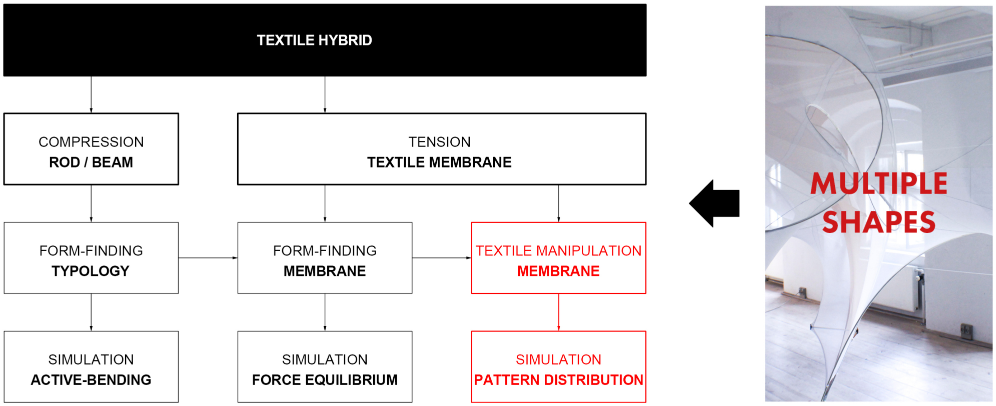


Figure 1
Actuated Textile Hybrid Methodology Diagram

sion of each frame can be used to form-find a global shape by connecting single textile-hybrid-elements to a greater system. This relation between typology, structural forces and materialization creates the complexity which is aimed to be resolved in physical and computational prototyping to prospectively form-find a globally adaptive structure (Figure 1).

TEXTILE HYBRIDS AS A STRUCTURAL SYSTEMS

Categorisation of structural systems

The categorisation of structural systems has played a significant role in developing mathematical calculation techniques that help analyse structures based on abstract static systems. Nevertheless, we no longer need to design structures to suit exclusively analytical calculation methods. The advantages of computational simulations, such as Dynamic Relaxation and Finite Element Modelling, offers new degrees of complexity and efficiency in the design of structural systems (Knippers et al. 2011).

Force Equilibrium. A structure is in equilibrium when all forces or moments acting upon it are balanced. Searching for a structural system with an internally resolved force equilibrium, I am comparing the following typologies to identify and position a suitable system for further design investigations towards responsive textile skins.

Bending-active. The term "bending-active" describes curved beam and surface structures that base their geometry on the elastic deformation of initially straight or planar elements. Bending-active structures are understood to be an approach rather than a distinct structural type.

Form-active. Form-active structures carry external loads by pure tension (cables or membranes) or pure compression (arches) without shear forces or bending moments. To achieve this, it is necessary to match the geometry of the load bearing structure to the flow of forces

Hybrid structure. Hybrid structure systems result from the linkage of two systems of dissimilar internal load transmission into a coupled system

Textile hybrid. The interdependence of form and force of mechanically pre-stressed membranes and bending active fibre-reinforced polymers is classified as a Textile Hybrid. The combination of a pre-stressed membrane and elastic bending allows the hybrid system to resolve the forces internally, thus the internalized equilibrium minimizes externalized forces at the boundary

Actuated textile hybrids. Through minimizing externally applied forces the inner force equilibrium of the structure becomes the focal point for designing the textile hybrid. Allowing the textile to tension and relax by an inner contraction pattern could expand the design possibilities towards shaping the element itself and likewise its distinct movement.

STATE OF THE ART

Textile Hybrids

The following section introduces three projects to identify the distinct qualities of textile hybrid structures. The first (Ahlquist 2015) is a prototype developed as a part of a research project which focusses on the design of tactile and responsive environments for children with ASD. SensoryPLAYSCAPE contains bending rods and a form giving bespoke knitted textile surface which showcases the touch sensitive playground for children. In order to make the structure climbable a secondary structure of rods is introduced to free the textile surface from most of the force flow, which is a conscious design decision but defers from the advantages of a classic textile hybrid in which the textile is the main active tensioned element.

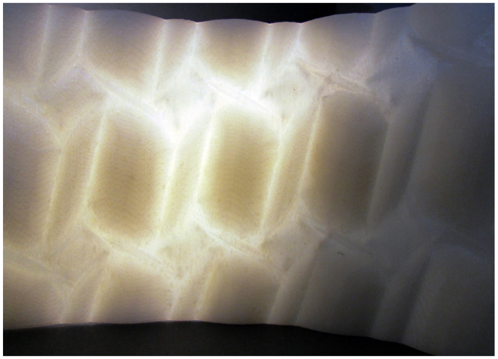
Lace Wall (Deleuran et al. 2016) showcases this force-flow as a generative cable network which explores the combination of elements in tension and compression (hybrid structure) to form a wall. Both, the fibre rod and the inner cable network are elements of low stiffness but in combination theses minimal material elements create a whole of high stiffness. Lace Wall is part of an investigation to lower material costs by keeping the structural performance intact. Each element is designed to contribute to a fixed global design - a wall.

Gossamer Timescapes (Mossé et al. 2012) on the other hand is a self-actuated ceiling based on responsive minimum energy structures. Each component of the dynamic installation is actuated by a dielectric elastomer which reacts to an impulse received from an outdoor wind-sensor. Even though this PhD-project by Aurélie Mossé is deriving from her background as a textile designer it is dealing with a highly relevant subject matter in architecture - the question of how designers and architects can use their ability to engineer the world to rethink buildings as dynamic environments which rather interconnect with their surrounding environment than obstruct it.

Figure 2
Sean Ahlquist, sensoryPLAYSCAPE Prototype (2015); CITA, Lace Wall (2016); Aurélie Mossé, Gossamer Timescapes (2012)

Dynamic Envelopes

ORAMBRA, the Office for Robotic Architectural Media and the Bureau for Responsive Architecture, developed a conceptual proposal for a single-family home with an actuated tensegrity façade system to lower the emittance of carbon to less than half in comparison to a typical household in Illinois.This change of shape is made possible by a combination of the well known structural systems like tensegrity wed with a newly developed operating devises to initiate and control the movement of the envelope. Even though this building is not realised, it impresses with the complex layering of simple state changes such as colour transitions and the exposure of coverage of different façade layers and is therefore a great example for not only an immediate environmental impact for this single household but also for a greater notion of rethinking known construction methods in combination with new technologies (Ayres 2012)To complete the circle from design-led research and prototyping to building concept and finally to full scale architectural projects, the façade of the expo pavilion by SOMA is a great example for the smart usage of a simple mechanical actuation which introduces the double-curvature buckling of the louver elements to shade or lighten the interior of the pavilion. Deriving from a research project at ITKE (University Stuttgart) the kinetic façade was finally developed together with the engineering office of Knippers Helbig. This project exemplifies the scalability of a prototype investigation and in addition to that the refined use of material properties together with efficient minimal actuation (Knippers et al. 2012)



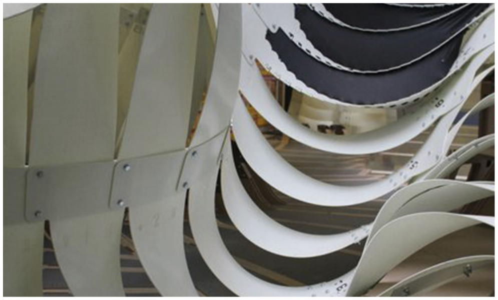


Figure 3
Tristan d'Estrée Sterk, Prairie House; SOMA and Knippers Helbig - Prototype for Expo 2012 Pavilion

While most of the realised kinetic façade systems devote themselves to one environmental impact such as sunlight, it raises the question if a dynamic envelope such as the one of the Expo Pavilion by Soma could combine the minimal initialising actuation and the consequently amplified passive actuation to form a greater dynamic system such as in the example of the Prairie House. In addition to that and as mentioned earlier, it is noticeable that most kinetic skins are designed for a simplified reaction to mostly only one environmental condition while a translation of the complexity of the outside world into a responsive envelope could not only bring an amplified and unexpected design outcome but could also blur or even dissolve the barrier between architecture and nature.

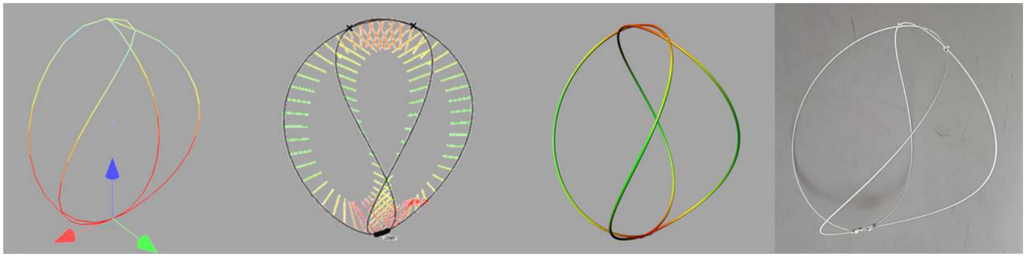


Figure 4
Pringle Simulations: From the left SOFiSTiK, K2 Pipeline, Kiwi3D

SMOCKING, AN ACTUATION MECHANISM

The techniques and methods to manipulate textiles developed in the sector of apparel are nearly endless. Most of the manipulations follow a distinct rule-set of pattern making to create a three-dimensional geometric appearance while the chosen fabric is not cut to form-fit but rather gathered in a decorative manner. While today's approach to fashion design leans towards customisation to reduce material waste, the technique of smocking was, in its own era, economically relevant, since the fabric stayed mostly untouched by being simply folded into place. Due to its mechanical flexibility and the ability to inexpensively re-use and re-shape the garment, smocked fabrics were mostly worn by farmers and craftsmen, where also its name derives from: smock, the farmers work shirt. The analysis of the folding patterns and their contraction ratio is essential for the development of the form-finding tool. Representation methods, such as Kentaro Tsubakis notation of the smocking folding behaviour, can be a valuable tool to understand the mathematics of the contraction (Ng et al. 2013).

Knowing that the fabric manipulation method of smocking is a technique to gather fabric in order to form-fit and (re-)shape textiles, I would like to investigate the relationships between the smocking pattern, the membrane it is embroidered onto, a bendable frame in which the membrane is placed in and its bending behaviour during the process of smocking to create an actuated textile hybrid. I position my method as an exploratory extension of the existing form-finding simulation methods for creating textile hybrids, which most commonly follow the strategy of shaping an elastic beam via a set of cables (Figure 2) to then form-find a minimal-surface membrane. Similar to this process I would like to investigate an extended version of those simulations by shaping the elastic beams via a smocking pattern. Aim of the exploration is to abstract each element (frame, membrane, pattern) and their behaviour to establish a simulation set-up to steer and predict the bending behaviour of the textile hybrid.

FORM-FINDING TOOLS

Sofistik

SOFiSTiK is a structural analysis software based on FEM - Finite Element Modelling. To simulate bending-active structures SOFiSTiK uses contracting cables with the same dimensions, units, material properties and cross section values as in reality. The simulation is divided into two steps: In the first step the straight rod is iteratively bent into a loop until the end points meet. For the second step a transversal contracting cable is added to bend the loop out of the plane and achieve the spatial geometry. To initiate the second step small imperfections of the geometry are used to steer the buckling of the beam into the intended direction (Bauer et al. 2018).

Kiwi3d

This plug-in for grasshopper uses Isogeometric Analysis (IGA), a subgroup of FEM, in order to directly integrate structural analysis into CAD. While most analysis tools are based on the parametrisation of geometries using meshes, Kiwi3d offers a simulation tool in which the meshing process is avoided and replaced by NURBS. Similar to SOFiSTiK, Kiwi3d uses contracting cables or membranes and the same 2-step-process in order to shape the beam. Some advanced features, such as form-finding and cutting pattern can be beneficial for designing Bending-Active-Textile-Hybrids (Bauer et al. 2018).

K2 & K2-engineering

Different from the two previous tools, Kangaroo is using Dynamic Relaxation (DR) to form-find cable and membrane-structures. In Kangaroo / K2 "Goals" are defined as functions acting on a set of points, which can describe geometric constraints, elastic material elements, applied loads and other energies. A custom computational pipeline for FAHS (Form-Active Hybrid Structures), developed by Anders Holden Deleuran, discretises the geometry, assigns topology logic, part indexing, material properties and then sends this data to Kangaroo to solve, on the fly.5 This pipeline allows the user to design more freely and modify bending-active topologies with real time feedback on structural performance (Bauer et al. 2018).

EXPERIMENTAL SET-UP

Physical model (behavioural analysis)

The base for each digital model is a physical model which provides knowledge about the important action-reaction relationships during the shape and state changing process. Three main model set-ups are chosen to provide three different types of analysis: 1. Actuation: Smocking patterns and their textile gathering behaviour, 2. Translation: Applied patterns and their resulting textile stresses, 3. Passive-Actuation: Frame rotation and bending as a design trajectory. In the following paragraphs the first two physical models are describes as they lead to main investigation of the paper - the form-finding tool for the actuated textile hybrid.

Smocking Patterns

Smocking is a type of pleating technique which gathers fabric via a geometrically defined stitch pattern. Since the behaviour of the omnidirectional folding of the fabric is very complex, especially during the process tensioning and releasing the textile, it is necessary to analyse the folding behaviour and its global impact on the shape changing process. While there is software like Marvelous Designer (Spahiu et al. 2014) which can simulate the folding accurately, it is important to mention that for the purpose of form-finding the intended textile hybrid, the impact of the textile-gathering is more important than the folding itself. Focus of the first physical tests is therefore the pattern, the resulting shape/area of the accumulation and the consequent shrinkage of the textile the pattern it is applied to. Figure 6 is showcasing that each pattern is accumulating the folds either in a proportional or non-proportional fashion in comparison to its initial unfolded state, which signifies the shrinkage of the textile is likewise proportional or non-proportional.

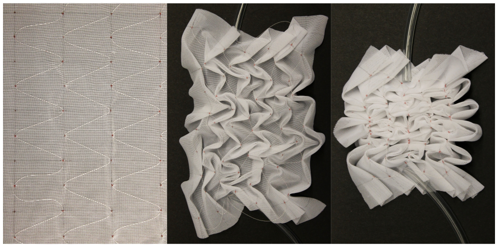


Figure 5
Smocking Test
(Shrinking
Behaviour to Scale)

Digital model

The Hyperbolic Paraboloid: As the geometric point of departure, the hyperbolic paraboloid, also known as "Pringle", is chosen to demonstrate the bending behaviour initiated by the contraction process inside the membrane. The nature of this geometrical figure is widely discussed in the world of mathematics and therefore equally observed in the world of structural engineering and architecture. The Pringle shape was well understood by the Spanish-Mexican architect Félix Candela who was able to use the strength of the hyperbolic paraboloid to build wide-spanning structures from incredibly thin concrete.

Figure 6
Contracting Behaviour of Smocking Patterns

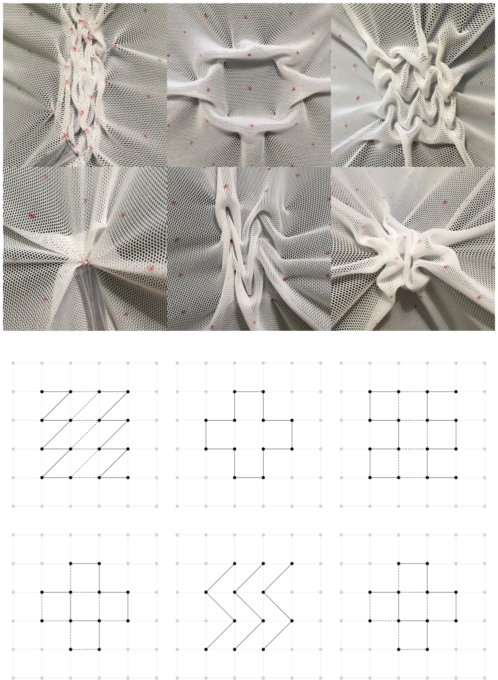
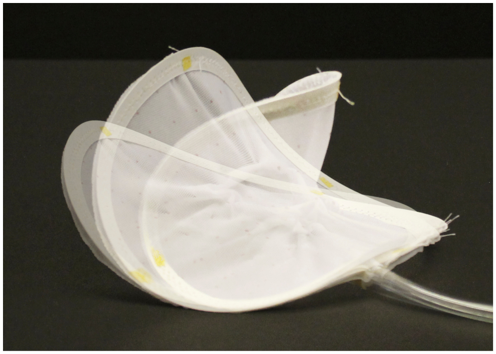


Figure 7
Smocking Test (Frame Behaviour)



The Pringle's strength is the perfect balance between tension and compression forces. Through this double curvature the shape remains thin and yet surprisingly strong and is therefore a geometry with great potential for dynamic textile hybrids and their form-finding processes.

With the aim to form a planar plastic frame with a rectangular cross-section into a regular Pringle, a smocking pattern with proportional contracting behaviour is chosen to centrally accumulate an area of the textile the frame is attached to . Figure 8 exemplifies the from the smocking resulting stress lines which become most visible by forcing the frame back into its planar position while the applied pattern is still in its smocked state. All patterns (Figure 6) reveal that the stresses occur radially around the gathered area extending eventually towards the frame. While most materials would not reveal their inner stresses until they irreversibly bend or break, textiles are able to visualise their stresses (tension and compression) within the material itself (stretch) or within deformation (folds). Based on the observations of the previously described physical models an abstracted digital model is set up to form-find the regular as well as variations of deformed Pringle shapes due to non-centrally and non-proportionally applied smocking patterns (Figure 8).

Form-finding process

Like the physical model, consisting of frame, membrane and smocking pattern, the digital model is constructed with the same three elements though abstracted to facilitate the computation-intensive form-finding process in KIWI3D. Even though Kangaroo 2 offers the same possibilities to set-up a simulation model to form-find my textile-hybrid within grasshopper, KIWI3D enables the user to easily add real material properties and cross-sections and defines the form-finding process more precisely by omitting the meshing process which is the base for most kangaroo simulations.8 Since my model is dealing with torsion the frame is set up as a shell-element for the beam-element in KIWI3D is not visualizing/enabling any doubly-curved twists which are key to the carried out investigations.

The core of actuation, the smocking pattern, is abstracted through pre-stressed cables which frame the area where the textile gathering would occur. From this area outwards radially extending cables (non-pre-stressed, based on Figure 8) connect to the frame to abstract the membrane the smocking pattern would be applied to. The frame has an initial curvature to steer the bending into the intended direction, while various support points guide the bending during the form-finding process. By simply relocating the pre-stressed cables and/or redefining the pre-stresses in each direction various "deformed" hyperbolic paraboloid shapes can be form-found and analysed. Results of these digital explorations are presented in figure 5.

DISCUSSION

While the core investigation of this paper is the systematic translation of the deformation behaviour of a by smocking actuated textile hybrid into an abstracted and easily computable simulation model, it is necessary to locate and discuss the design potentials of this made-to-measure form-finding tool. By tying the exploration back to the architectural notion it derived from, the dynamic envelope, three scales of shape and state change arise from the experiments with the actuated textile hybrid.

Micro Scale. The controlled geometric gathering of the fabric as an actuation initiating system, as well as a state changing element which densifies and accumulates the planar textile, as well as a readable ornament which could visually foretell an occurring change of shape.

Meso Scale. The through the textile shrinkage resulting deformation of the frame in both dynamic transformation from planar and non-structural to three-dimensional and structurally stable (Pringle) and the use of the occurring torsion of the bent frame as the directory element for the connection and passive actuation of a cluster of elements (Figure 6)

Macro Scale. A global shape change resulting from the dynamic behaviour of each element of the cluster.

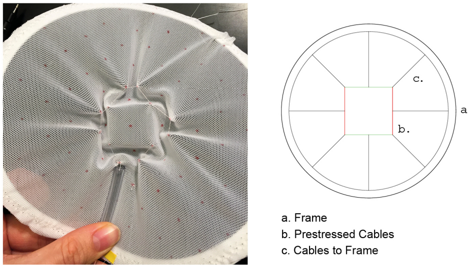
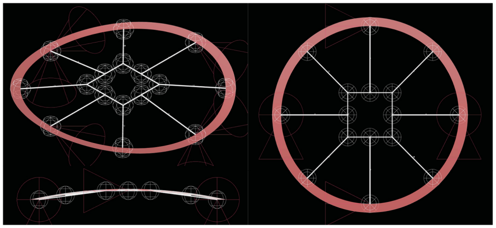


Figure 8
Simulation Base & Set-Up in KIWI3D



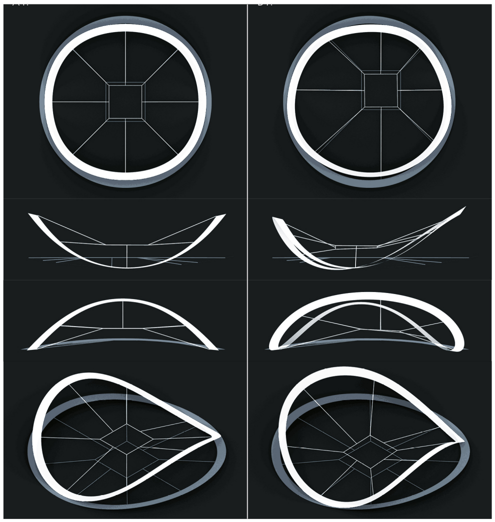
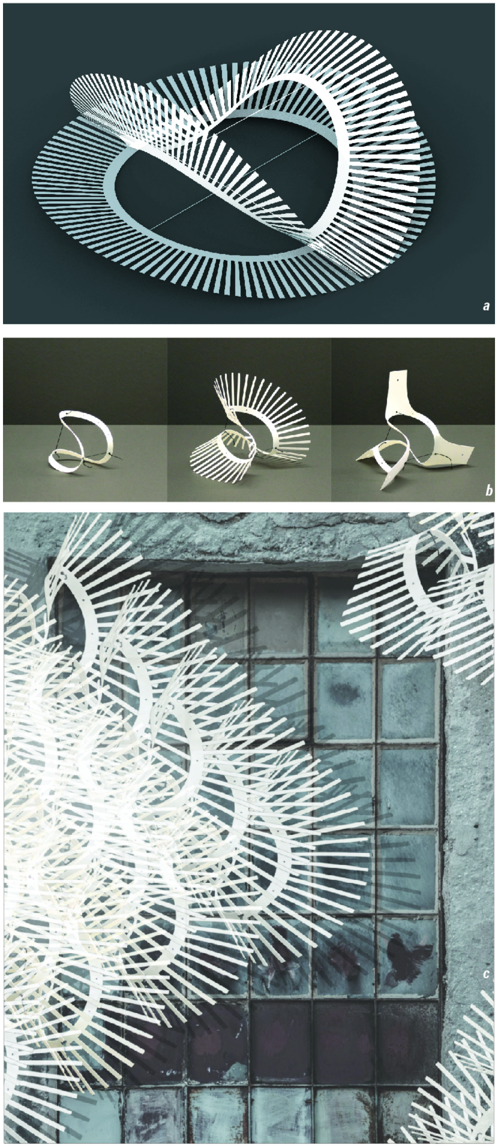


Figure 9
(a) Simulation of Pringle with Vector Extensions (b) Physical Models: A. Frame, B./C. Frame with Extensions (c) First Visualisation Potential Clustering



FUTURE INVESTIGATIONS

The dynamic design of a global shape asks for dynamic design thinking since the inextricable interdependence of each part of the textile hybrid element translates directly into the overall cluster. Further investigation would therefore not only focus on a feedback-loop in which a global shape informs the contracting mechanism for each element but also the design of the range of geometric possibilities that occur within the transition of shape and state in each mentioned scale. The Hyperbolic Paraboloid would be re-evaluated in its shape changing and structural performance during the design process for a specific site. As a work-in-progress design investigation in dynamic structures my goal is to lead those previously named potentials to form a structured skin which reacts actively and passively to multiple environmental impacts on all three scale levels. While the scalability of each element, its true materiality, the actuating system and the clustering still needs to be defined during the design process, the global notion is to create a boundary-object which reacts to the given natural impacts of a minimal site to redirect these into building typologies which lost their direct connection and relation to nature due to the present and forecasted phenomena of congestion of housing and workplaces in urban areas.

Further investigations and results were obtained during the thesis project "Over Cast - Site Specific Textile Hybrids" - currently exhibited at the KADK Royal Danish Academy of Fine Arts in Copenhagen. The project applies insights from this paper to a mega scale canopy structure which reacts to wind forces but remains structurally active using smocking as a sub-system to re-tension the membrane while being exposed to strong winds. Together with Computational Fluid Dynamics (CFD) and Isogemetric Analysis (IGA) a site specific and resonating canopy was designed and detailed. (See KADK Graduate Projects here: KADK.dk)

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