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Procedia Engineering 155 (2016) 71 – 80

Procedia Engineering

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International Symposium on "Novel Structural Skins: Improving sustainability and efficiency through new structural textile materials and designs"

Exploratory Topology Modelling of Form-Active Hybrid Structures

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Abstract

The development of novel form-active hybrid structures (FAHS) is impeded by a lack of modelling tools that allow for exploratory topology modelling of shaped assemblies. We present a flexible and real-time computational design modelling pipeline developed for the exploratory modelling of FAHS that enables designers and engineers to iteratively construct and manipulate form-active hybrid assembly topology on the fly. The pipeline implements Kangaroo2's projection-based methods for modelling hybrid structures consisting of slender beams and cable networks. A selection of design modelling sketches is presented in which the developed modelling pipeline has been integrated to explore the design space delineated by FAHS.

Peer-review under responsibility of the TensiNet Association and the Cost Action TU1303, Vrije Universiteit Brussel

Keywords: Form-Active; Hybrid Structures; Topology; Shaping; Form-Finding; Interactive Modelling; Design Space Search

1. Introduction

1.1. Form-active Hybrid Structures

Form-active hybrid structures (FAHS) are defined by the principle of connecting two or more different elements of low stiffness into one structural assembly of high stiffness [3,5,8]. That is, to construct a stiff and resilient whole using an inventory of lightweight and deforming structural elements which restrain each other in a reciprocal manner. The element inventory used for this typically comprise bending-active slender beams acting in compression, textile membranes acting in tension and cables acting in tension. These locally different material behaviours are combined to generate a global form-active hybrid behaviour. FAHS present a promising approach for

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Peer-review under responsibility of the TensiNet Association and the Cost Action TU1303, Vrije Universiteit Brussel
doi:10.1016/j.proeng.2016.08.008

designing efficient and elegant structural skins. When intelligently combined, these structures have the potential to offer high load-bearing capacity at a fraction of the weight of traditional building elements. The exploration and development of FAHS is therefore important due to their potential to improve the performance of buildings in terms of efficiency of material usage. Beyond pure structural efficiency, they provide a rich and aesthetically interesting visual language, which directly express the force flow and equilibrium state of the structure.

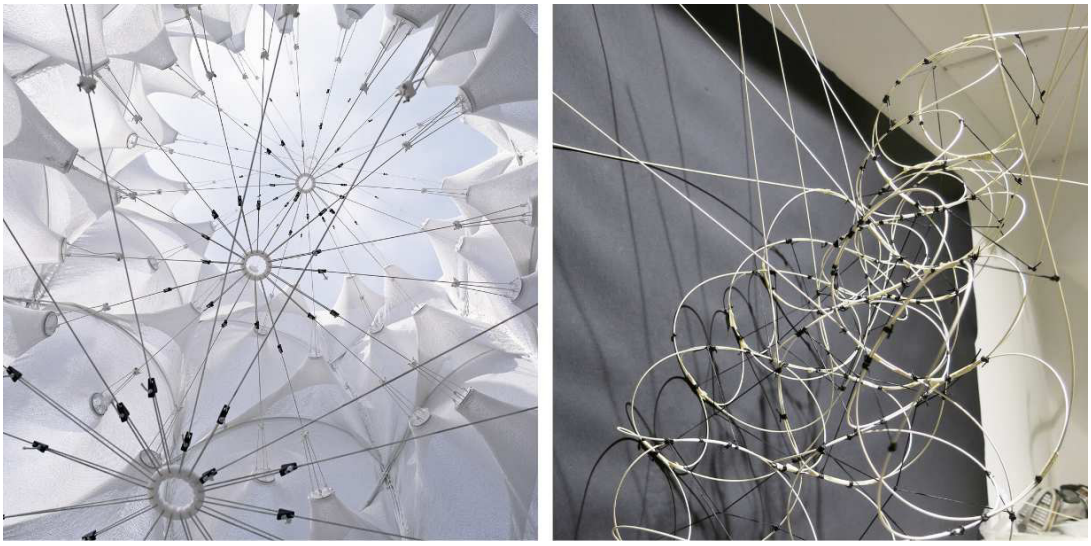

Fig 1. Examples of FAHS structures designed and constructed by CITA. Left: Inside view of "Hybrid Tower", a 10 meter tall outdoor prototype developed with UDK/KET. Right: Early small-scale prototype for the FAHS concept described in section 2.

1.2. Computational Design Modelling

FAHS are designed and constructed by transforming stress-free linear and planar elements into an assembly of curved elements through elastic bending of beams and tensioning of membranes/cables. This process is similar whether using physical or computational modelling. As a modelling problem, this is characterized by a high degree of interdependent behaviour, which adds complexity to the existing challenges of designing form-active structures, making it difficult to model using off-the-shelf modelling software. This has resulted in the development of bespoke modelling pipelines which implement various computational shaping and form-finding methods such as finite element modelling [8], spring-based modelling [2], force-density methods [9] and projection-based methods [4]. These pipelines have proven effective for modelling FAHS and have successfully automated central processes such as shaping, form-finding, analysis and patterning. They however also tend to overlook the initial process of defining assemblies of elements and supports. That is, the topological and geometrical definition of the assembly prior to the iterative shaping/form-finding processes. Where shaping implies generating a FAHS appropriate shape. When employing a fixed inventory of structural elements, the definition of how these are combined in an assembly becomes the central design and modelling task. This process is therefore a primary design driver when designing FAHS and is particularly significant in the search for novel structural systems.

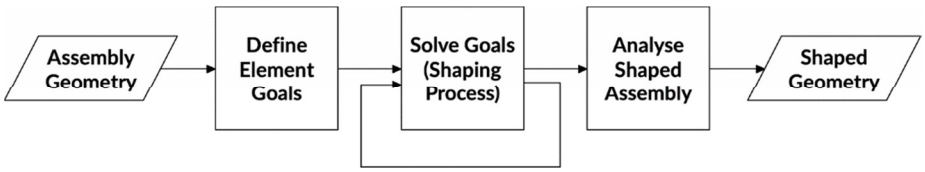

Fig 2. A design modelling pipeline for shaping FAHS using the projection-based methods of the Kangaroo2 library.

1.3. Exploratory Topology Modelling of Shaped Assemblies

Defining assembly geometry implies specifying topology and dimensions. That is, defining element types, their dimensions and how they connect in a network. This is performed by directly modelling the discrete geometries representing structural elements, or, by developing and integrating a parametric model once an assembly topology is defined and can be encoded [5]. In either case, this process is typically separate from the generative process of shaping the assembly. This has the effect that the designer (or a search algorithm) is not allowed to add, remove or edit elements during shaping. This prevents a feedback loop from occurring between assembly definition and shaping, preventing the possibility of iteratively constructing or modifying assembly topology based on its currently shaped state.

This lock-in of assembly topology, or "body plan" [4,7], during shaping impedes on both the creative and objective exploration of the shape space delineated by the inventory of the given FAHS. Exploring topological design diversity implies interactively or exhaustively exploring the connectivity of elements that define an assembly and searching for, fit candidates. When any change in topology requires downstream processes to be reset and performed again, this becomes intractable. Developing novel and unbiased FAHS therefore necessitates modelling pipelines that are more conducive to exploring topological diversity. The research presented in this paper aims to examine how to achieve this by unlocking the body plan and enabling feedback to occur between assembly definition and shaping in the FAHS modelling pipeline.

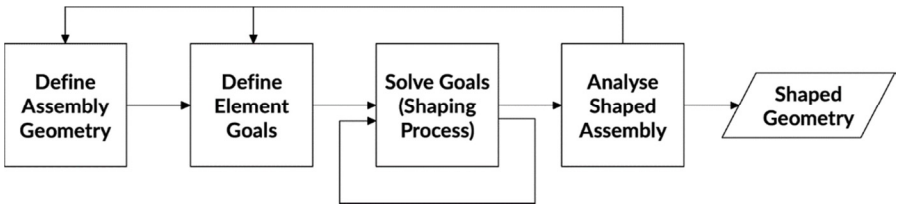

Fig 3. A modelling pipeline in which assembly definition is a process and has feedback connections from shaping/analysis.

2. Research Methodology

While the scope of challenges presented in the previous section extend to mechanically accurate modelling of FAHS, topological encoding of assemblies and automated search algorithms, the research presented here is delimited to the interactive modelling of shaped FAHS. That is, how to couple [10] a designer to a dynamic modelling pipeline and enable feedback to occur between designer, assembly definition, shaping and downstream modes of analysis. This involves identifying and developing appropriate modelling methods and integrating these in a real-time modelling pipeline, developed using IronPython as a Grasshopper definition running in the Rhino3D CAD package.

The research is situated within the CITA ground research project "Complex Modelling" which has already produced the FAHS "Hybrid Tower" [5]. The work presented here extends and builds upon an earlier design concept that lends itself well to exploring topological diversity and the use of projection-based methods for shaping. This design concept can be described as a "deep form-active hybrid skin". That is, a generic and modular space frame-like FAHS system, which can be extended in a spatial array to construct large enclosures such as walls, roofs, domes and more complex macro shapes. The design challenge is thus to develop a modular system with an increased focus on local and global topology of the structural system in comparison to Hybrid Tower. To focus the research on exploratory assembly topology modelling we adopt the strategy of minimum inventory/maximum diversity where "systems can be envisaged which consist of some minimum inventory of component types which can be alternatively combined to yield a great diversity of efficient structural forms" [11]. We therefore reduce our FAHS inventory to consist exclusively of linear elements (beams and cables) which affords a high degree of

combinatorial options using the same geometrical representation. This is explored through parallel computational and physical modelling.

3. Modelling Methods

3.1. Assembly Definition

Assembly definition is based on a set of rules, or rubrics [11], for how the designer is to construct the geometrical representation of elements, a method for discretizing this geometry and methods for dynamically coupling the Rhino document and the Grasshopper definition. Beams and cables are represented as polylines, piecewise linear curves which may approximate continuous shapes. These are drawn by the designer as coarse polylines describing assembly topology and initial dimensions. Implementing a layer naming convention, these are automatically piped to Grasshopper if anything changes on the Rhino document beam/cable layers. Here they are discretized by subdividing their edges into a user defined sub-edge length. To enable the designer snapping to the discretized geometry, all its vertices are automatically captured and sent back to the Rhino document as a locked point cloud. This modelling loop affords immediate and precise definition of assemblies.

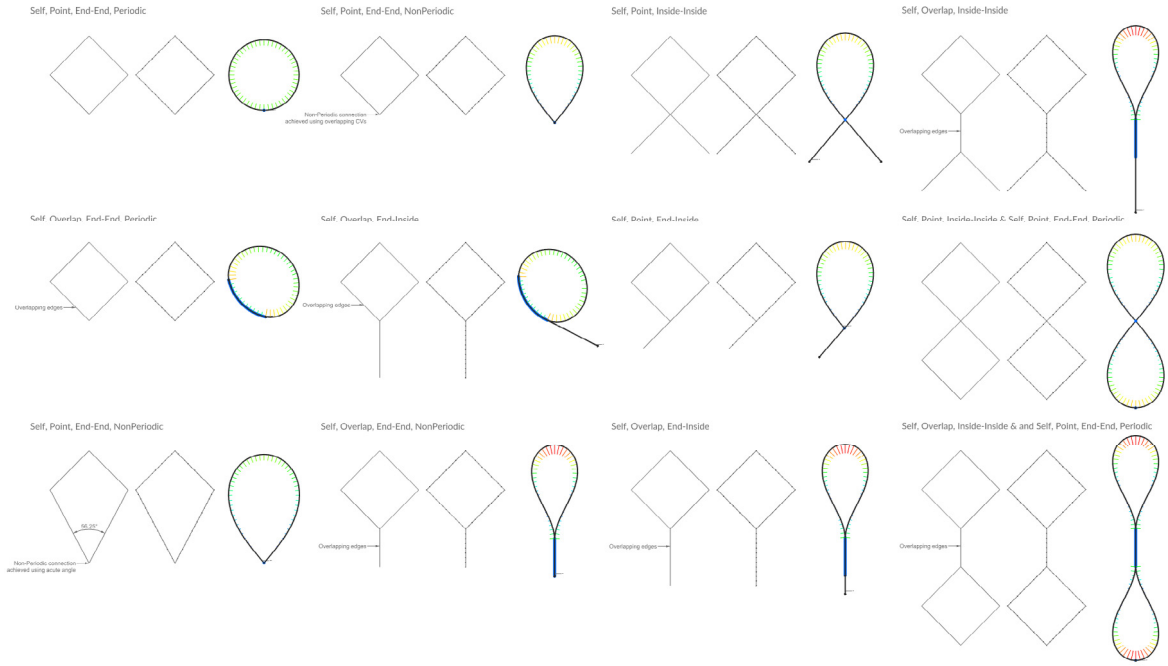

Fig 4. Definition/drawing of self-connecting beams. The rubric for a non-periodic end-end connection is to draw overlapping vertices at the connection, or, to have the incoming edges meet below a user specified angle.

3.2. Representing and Solving Shaping Behaviours

The shaping process implements the Kangaroo2 (K2) dynamic relaxation solver. K2 is based on projections [6] onto goals. A goal is a behaviour which, given the current positions of a set of points, calculates a set of vectors for how these points should be moved. This may include a weighting factor determining goal strength/stiffness. K2 has several properties which has been integral to our research: 1) The API is designed for implementation through scripting, enabling development of custom, minimal and optimised pipelines using IronPython. 2) Goal weights can be set arbitrarily high and remain stable, enabling the modelling of stiff materials with fast convergence. 3) The

bending goal implements the resolution independent Adriaenssens and Barnes model [1], enabling the shaping of non-uniformly discretized elastica beams. Shaping has three sub-processes: defining, solving and refining goals. Defining goals implies generating local K2 goals along the discretized polylines which yield overall element behaviour. A beam is represented by a goal for each edge maintaining its length and a goal for each vertex and its neighbours which attempts to keep the angle formed by the three at 180 degrees. Combining these goals enables accurate elastica behaviour. Cables are represented by edge-length goals. Minimizing these, their shaping behaviour is similar to membrane shaping. If two elements share vertices/edges they are connected at these sub-components. Goals are passed to the K2 solver which iteratively shapes the assembly until equilibrium. Any change in input (topological or numerical) will trigger this solve-equilibrium loop. This enables the designer to interactively explore shaped assembly topology, and, dimension elements by refining goals values.

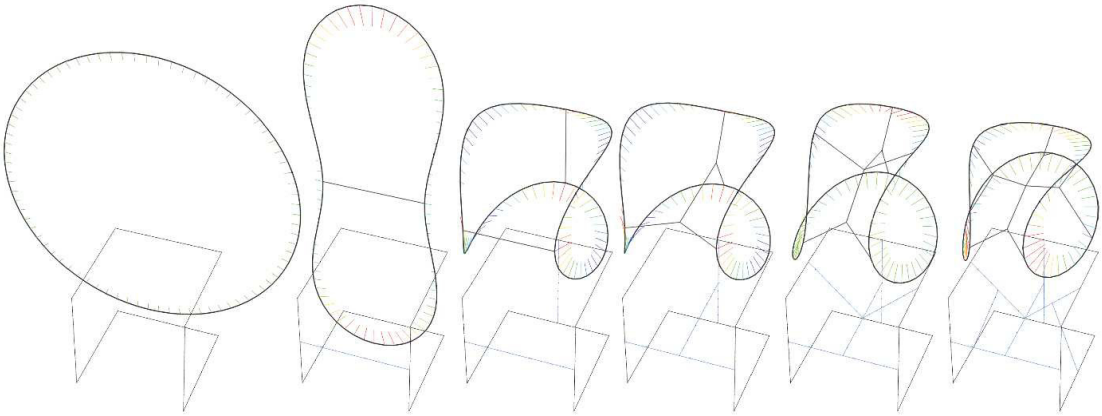

Fig 5. Interactively defining topology and shaping an FAHS assembly with real-time shaping and downstream bending analysis using our modelling pipeline

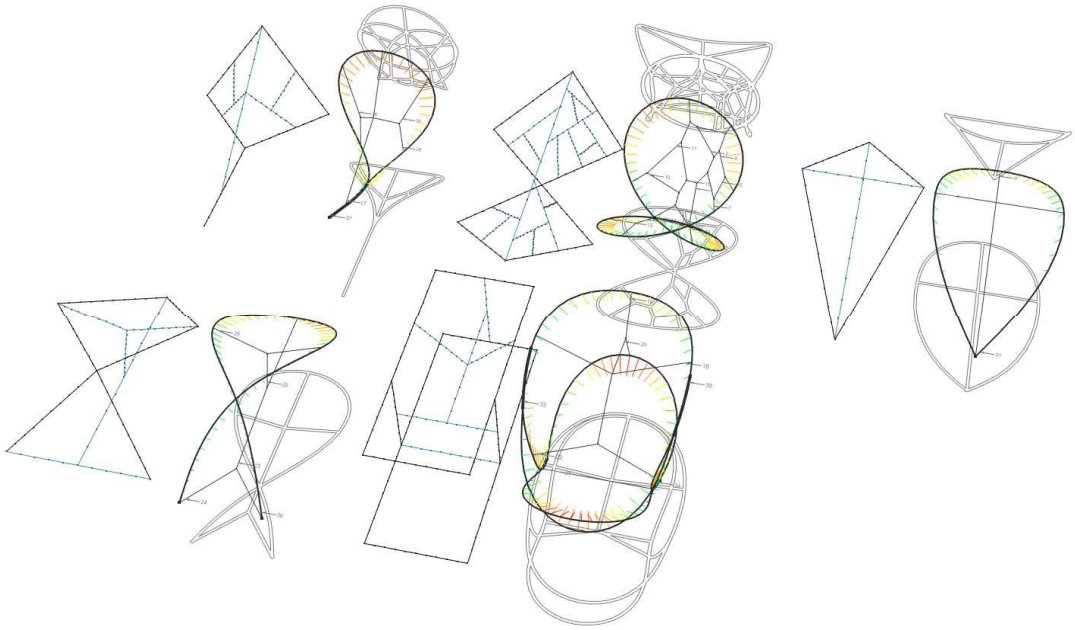

Fig 6. Example of quickly sketching topologically different FAHS assemblies. The assemblies are projected to the XY and YZ planes here to

evaluate their visual impact and shading effect.

3.3. Shaped Assembly Geometry Analysis

Analytical methods are integrated downstream from shaping which provide the designer with real-time visual and numerical feedback on the state of the shaped assembly. Cables are evaluated for whether or not their polyline vertices are on a line, signifying whether the cable is under tension. For beams a key geometric property with structural implications is the local bending radii along the polyline. This value can be mapped to the bending stress, utilisation and reserve of the beam in isolation of other load cases. The local radii is defined here as the radius of the circle constructed through a polyline vertex and its two neighbours. This property is visualised in the viewport as coloured/scaled vectors that also provide a visual representation of the bending orientation (see fig 4, 5 and 6).

3.4. Assembly Topology Analysis

Visually analysing assembly topology is difficult and provides no objective data from which to differentiate assemblies and steer design space search. Methods are therefore integrated which implement graphs as data structures for analysing and visualizing this. In discrete mathematics, a graph is an abstract construct consisting of nodes, where some pairs of these are connected by edges. Nodes describe the objects of a network and their properties, edges describe how nodes connect and the properties of these connections. In our assembly graphs, nodes represent structural elements and edges their physical connections. Nodes have two properties (element type and length) and edges have two (where along the elements the connection occurs). The directed graph class of the NetworkX Python module is implemented as the base representation. This enables us to arbitrarily add properties to nodes/edges, and to analyse assemblies for graph theoretical measures such as size, connectedness, node degree, centrality and cycles. This graph is translated to DOT graph language notation and compiled to an image using GraphViz which is rendered in the Rhino viewport. This occurs automatically and enables the designer to visualise the topology using different graph layout algorithms (hierarchical, force-directed etc.).

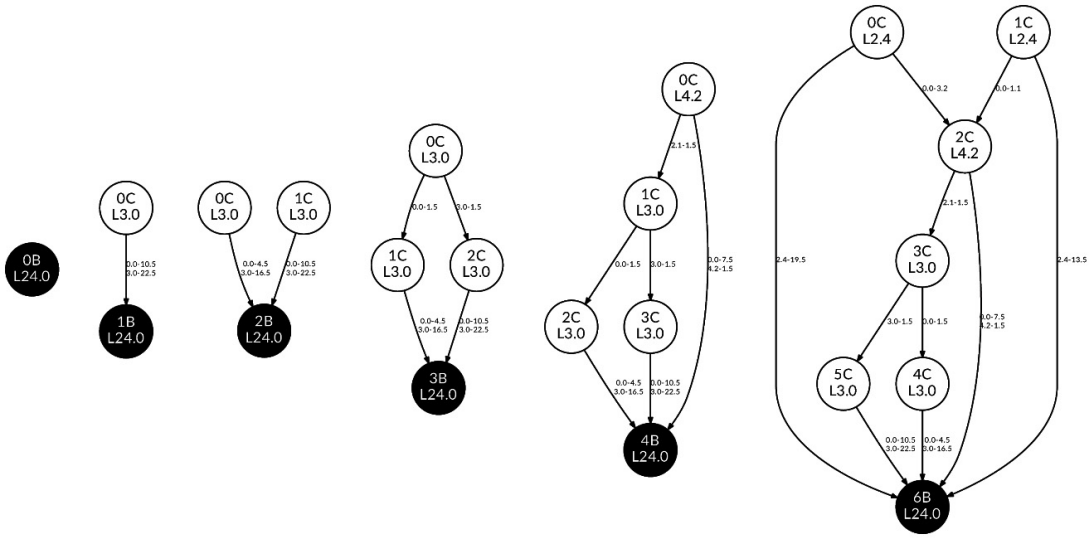

Fig 7: Hierarchical assembly graph analysis for the six construction steps presented in Fig 5. Beams are black nodes, cables are white.

4. Design Modelling Examples

4.1. Introduction

The modelling pipeline is being developed for the design of a large-scale Complex Modelling project demonstrator, similar to Hybrid Tower. Demonstrators [12] are concluding physical prototypes that demonstrate and disseminate developed research. Demonstrators are preceded by "design probes" and "material prototypes". These three modes of research and development are sequential and iteratively builds up the complexity of design objects, models and knowledge. Specific to the Complex Modelling project, this process involves operating at different design scales of engagement. From the micro scale of the beam/cable, to the meso scale of local topology, to the macro scale of the overall design object. Physical prototypes are developed using an inventory of solid circular section GFRP (glass fibre reinforced polymer) rods as beams and rope/wire and strapping as cables. The following presents a small selection of early design probes, sketches and models developed for constructing material prototypes using the presented modelling pipeline. These roughly fall into three categories and scales:

4.2. Primitives and Pairs

The smallest topological FAHS units comprise at least one beam and one cable. We refer to these basic units as primitives. When coupling multiple primitives they become a pair, slightly larger topological units which are based on how primitives may be designed to spatially aggregate. At this scale, the design development and modelling is primarily focused on generating periodic or aperiodic tileable units which have a high degree of hybrid performance.

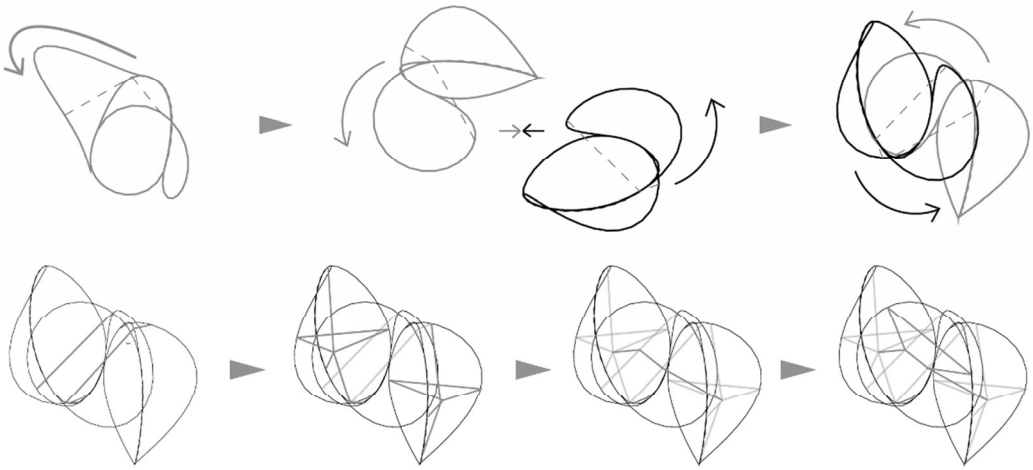

Fig 8. A shaped primitive, the process of coupling this to a pair and subsequently exploring different cable configurations.

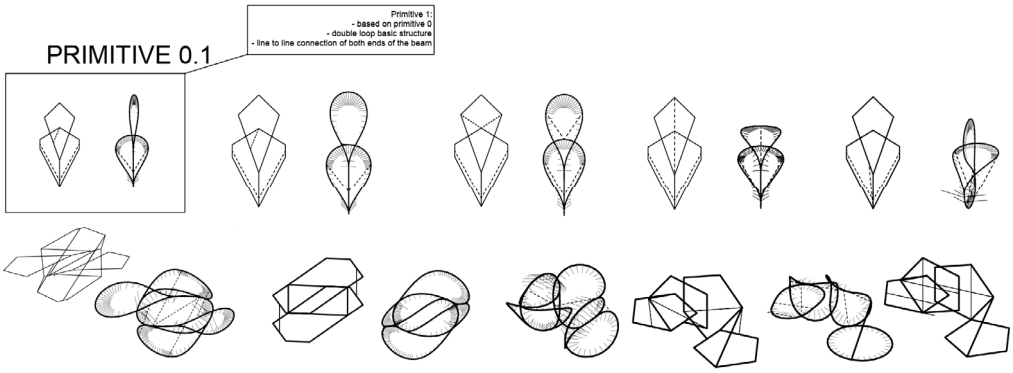

Fig 9. The same beam primitive is combined with different cable configurations and subsequently aggregated to form basic pairs.

4.3. Arrays and Fields

Aggregating primitives and pairs along an axis results in a periodic one-dimensional FAHS array. Aggregating them in two axes, a periodic two-dimensional array. Arrays may also be generated along a path, or by implementing an aperiodic tiling pattern as the base grid. All of these development strategies may be implemented to generate what we refer to as fields of FAHS units. At this scale, the design development and modelling begins to explore what a deep form-active hybrid skin might be.

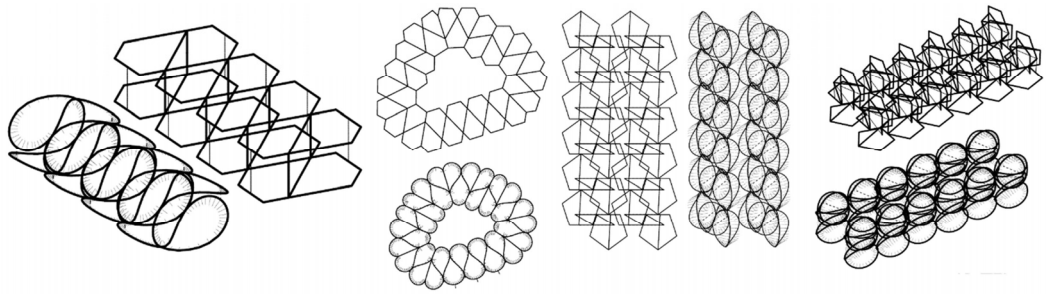

Fig 10. Primitives and pairs aggregated along a line, a curve and two different two-dimensional arrays to form deep form-active hybrid skins.

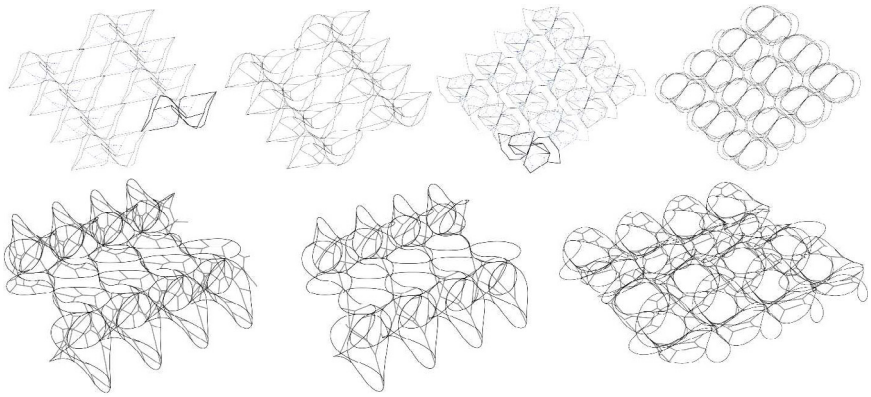

Fig 11. Three different and topologically complex primitives are aggregated to form equally complex two-dimensional FAHS fields.

4.4. Macro Shapes

Adding scale and overall macro shape to FAHS fields, they begin to suggest potential architectural directions for the full-scale Complex Modeling demonstrator. At this scale, the design development and modelling is thus focused on the exploration of which type of architectures a FAHS system might be implemented for. In the Complex Modelling project, this is currently highly unspecified and will require harder design and performance requirements to be developed, in order to meaningfully implement the developed computational design modelling pipeline.

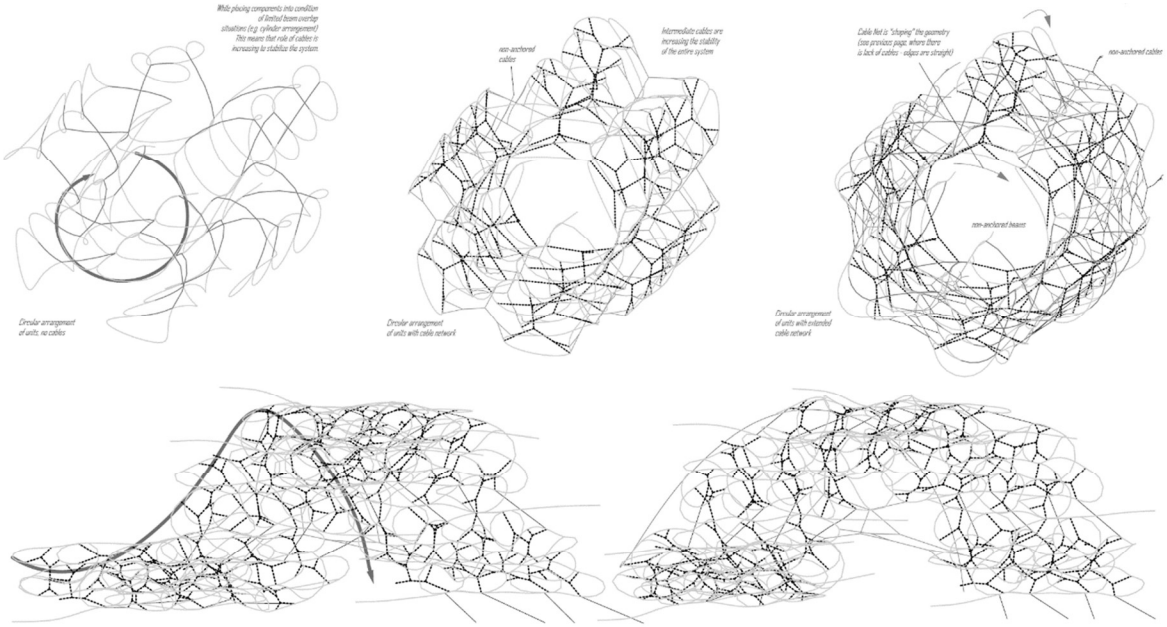

Fig 12. Top: FAHS fields connecting back onto themselves to form basic cylinder macro shapes. Bottom: Fields with additional cables that induce overall macro shaping.

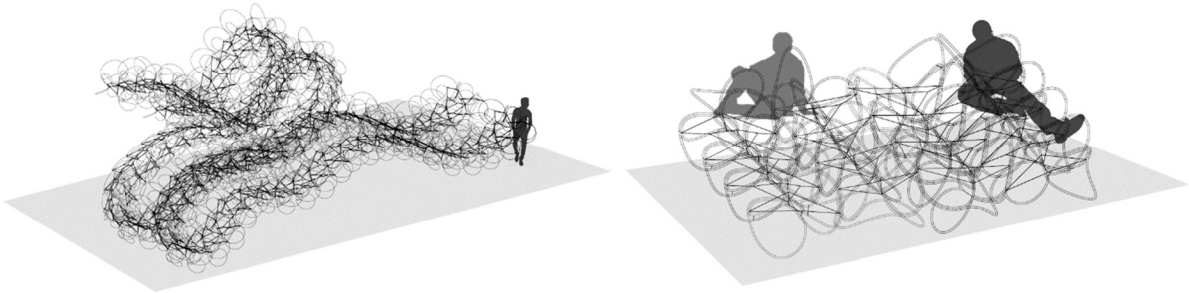

Fig 13. Macro design shapes that suggest human scale and occupancy. The relative softness of FAHS systems might serve as seating.

5. Conclusions

The primary research aim of unlocking the topological body plan and enabling feedback to occur between the assembly definition and shaping processes in the FAHS modelling pipeline has been met. The real-time coupling of designer, Rhino document and Grasshopper/K2/IronPython methods (pipelining, discretization, goals generation, goals solving, and analysis) works fast, intuitively and seamlessly. This is in large part due to a high degree of focus

on encapsulation, profiling and optimization of the pipeline and its methods, as well as the fast convergence of the Kangaroo2 solver. While K2 is both stable and fast, large and complex assemblies are still slow to converge, which impedes on the designer coupling and feedback loop. The minimum inventory/maximum diversity strategy has proven conducive for developing new FAHS assemblies and exploring topological diversity. Simply drawing, snapping and editing polylines allows for quick iteration through many options. This process however requires a high level of concentration and manual labour sustained over a long period of time to find working design solutions. This exhausts the designer and necessarily limits the range and depth of exploration - the implicit goal of the use of a computational design modelling system. Furthermore, an adequate modelling pipeline does not automatically yield good designs. This requires a deeper understanding of the structural design system, which cannot be replaced by the analytical methods of the current modelling pipeline. Leading to a noticeable lack of hybrid behaviour and under defined FAHS assemblies. This might be addressed by developing and integrating additional methods in the pipeline which emulate engineering heuristics and provide feedback to the designer. Finally, extracting fabrication data and deriving the order of events for construction is currently underdeveloped. This might be approached using the hierarchical assembly graph analysis as a base representation for developing a design and construction documentation standard for beam-cable FAHS.

6. Further Work

A significant development challenge in the Hybrid Tower project was the structural analysis downstream from shaping, which was performed using the SOFiSTiK FEA package. We plan to replace this process by extending the use of K2 to include mechanically accurate analytical modelling in the presented Rhino/Grasshopper pipeline. This includes expanding the modelling pipeline inventory to include membrane elements. This is being developed across a team of engineers and designers for SmartGeometry 2016. Finally, we are developing an encoding of FAHS assemblies based on the HyperNEAT graph representation for evolving neural network graphs. This will afford the topological generation, classification and crossover of assemblies based on a simple parametrization/genome, which may be implemented with evolutionary search algorithms and machine learning.

Acknowledgements

The project is funded by The Danish Council for Independent Research (DFF). We wish to thank Gregory Quinn for his feedback, Daniel Piker for involving us in testing Kangaroo2, and research assistants Yuliya Baranovskaya and Danica Pistekova for developing design case studies.

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