BENDING-ACTIVE BUNDLED STRUCTURES:
PRELIMINARY RESEARCH AND TAXONOMY TOWARDS AN ULTRA-LIGHT WEIGHT ARCHITECTURE OF DIFFERENTIATED COMPONENTS

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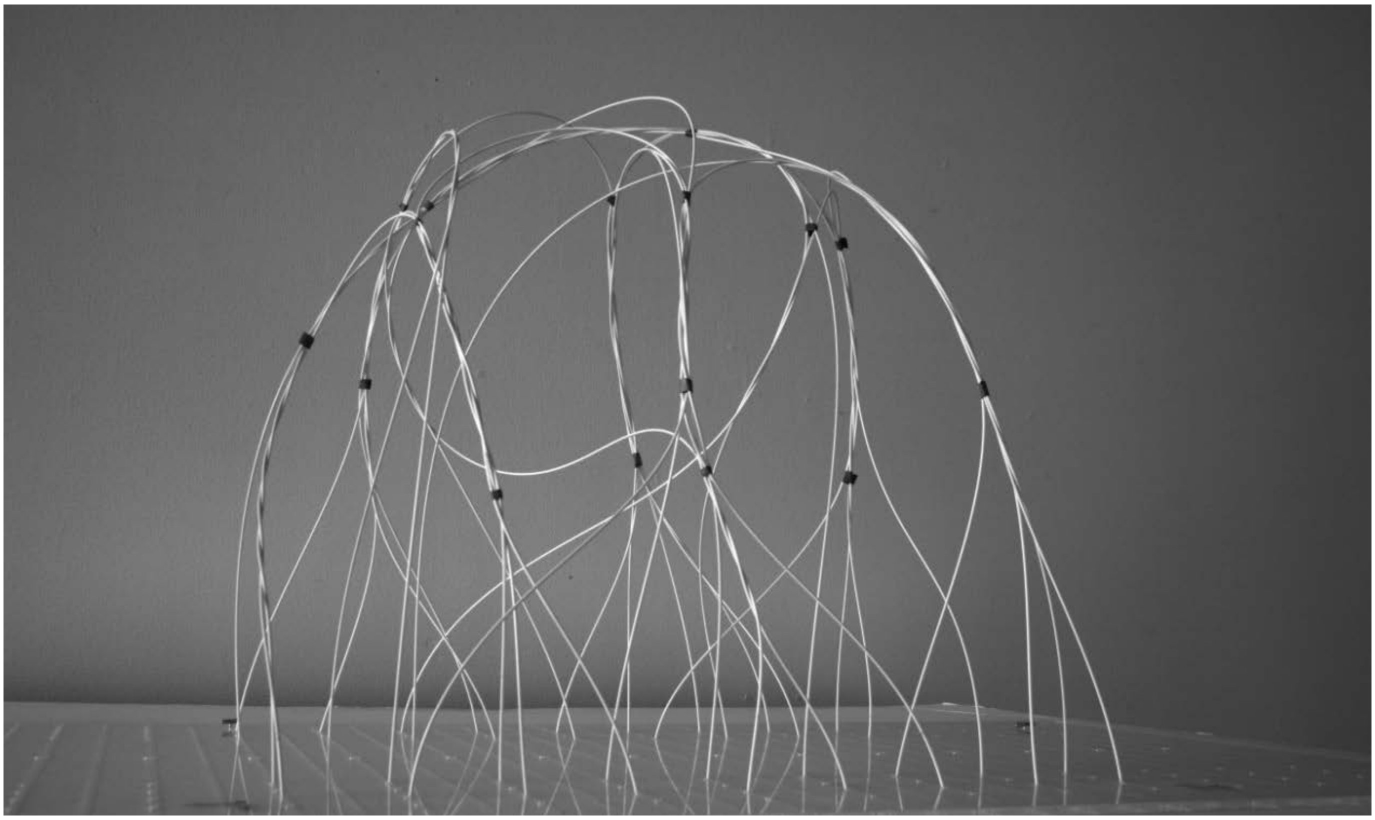


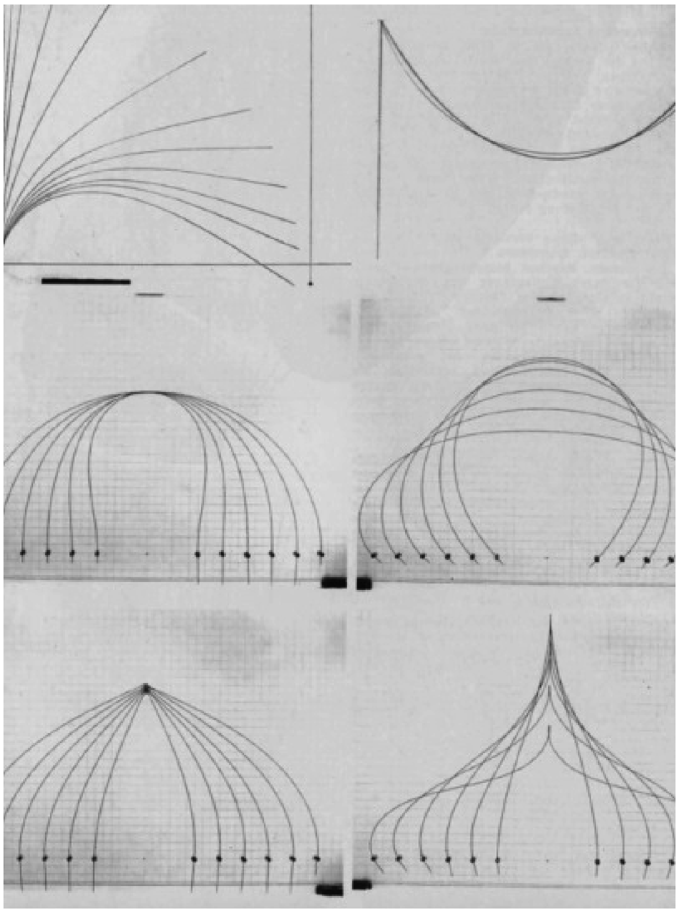
9 "Mangrove" Model

ABSTRACT

This paper documents preliminary research into a bending-active architecture that leverages the "bundling" of linear force-active elements in order to create spatial diversity and differentiation. The primary design components of the system are light-weight GFRP rods and tubes that perform well in elastic bending. Material testing and iterative physical model studies are documented, and provide a framework to guide the further development of emerging spring-based computation methods. Challenges to the system include the analysis and resolution of rod-to-rod bundled connections, as well as the development of predictable bifurcation and crossing unions. The paper identifies key precedents to the work followed by a brief summary of the material selection and testing framework. A speculative taxonomy of bundled bending-active "types" is proposed and supported by examples and prototypes.

INTRODUCTION

This paper documents preliminary research into a bending-active architecture that leverages the "bundling" of structural elements in order to create spatial diversity and differentiation. This architecture is characterized by ultra-light structural components resolved in a stable equilibrium state (Lienhard et al. 2012, 650-657). The primary design components of the system are the "bending-rods", light-weight structural members that perform well in elastic bending. Tensile forces in the system are supported by cables; precedent projects propose system elements including tensioned fabric and cable-net structures to resolve these forces. Iterative physical testing and form-finding is integral to the design/discovery process in this work, as are computational simulation and analysis. Bending-active architecture can be studied through three separate variables: topology, structural forces, and material description (Ahlquist and Menges 2011, 82-89). "Bundling" of the force-active elements constitute multiple rod configurations that allow for localized variation in stiffness and deflection, and open up exciting possibilities for design and spatial complexity. Challenges include the analysis and resolution of rod-to-rod bundled connections, as well as the development of predictable bifurcation and crossing unions in the system. In this paper, precedents are identified followed by a brief summary of the material selection and rod testing framework. A speculative taxonomy of bundled bending-active "types" is proposed and supported by selected examples and prototypes.



1 Diagrams - Linear Elements

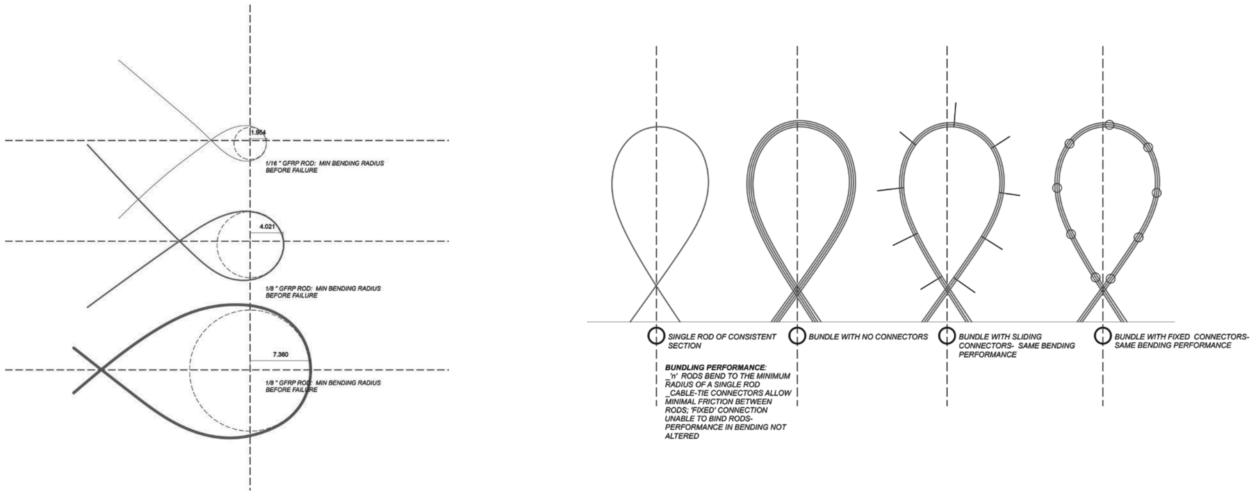
FORM-FINDING FRAMEWORK

The broad context of this research is rooted in the empirical material studies and procedures undertaken by Frei Otto and others at the Institute for Lightweight Structures from the mid 1960s to the mid 1970s at the Stuttgart University in collaboration with various academic institutes. In the foreword to IL08, *Nets in Nature and Technics*, Otto writes, "[The IL provided] a unique opportunity to cooperate interdepartmentally with engineers, architects, mathematicians, geodesists and psychologists on an overall investigation of this subject"(Otto 1974: 3).

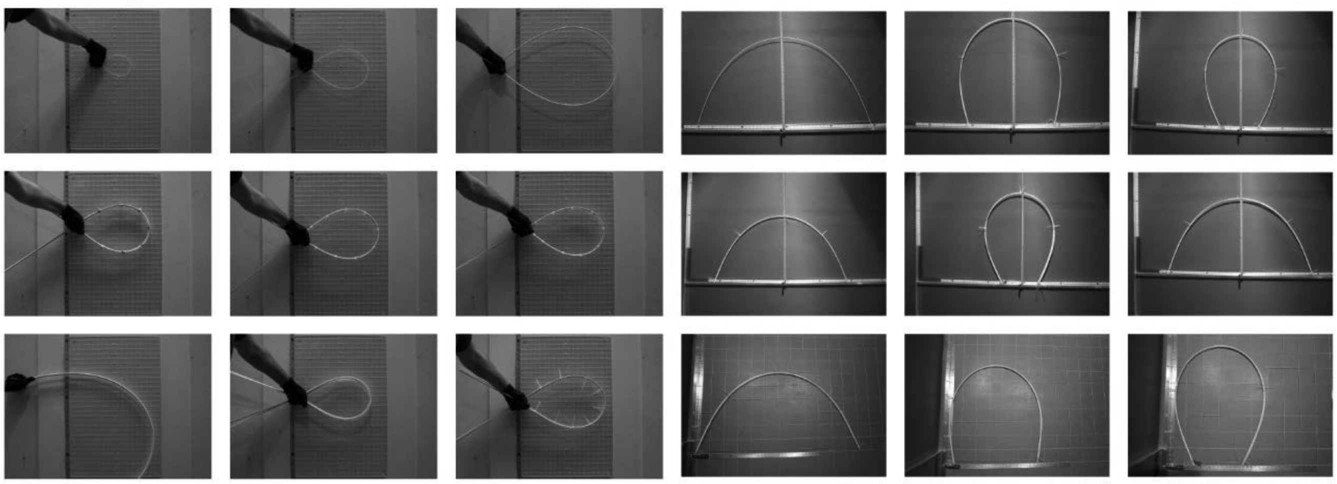
Over many years, Frei Otto coordinated an exhaustive range of material testing, form-finding and other explorations into natural and artificial systems and assemblies. His scientific methods and testing strategies resulted in a broad and detailed taxonomy of material behaviors and characteristics. These materials and methods have been very influential upon a current generation of architects and academics interested in developing material systems and computation models that attend to original analog studies and procedures (Figure 1).

In his research at the Institute for Computational Design, Achim Menges makes the case for form finding through computation methods:

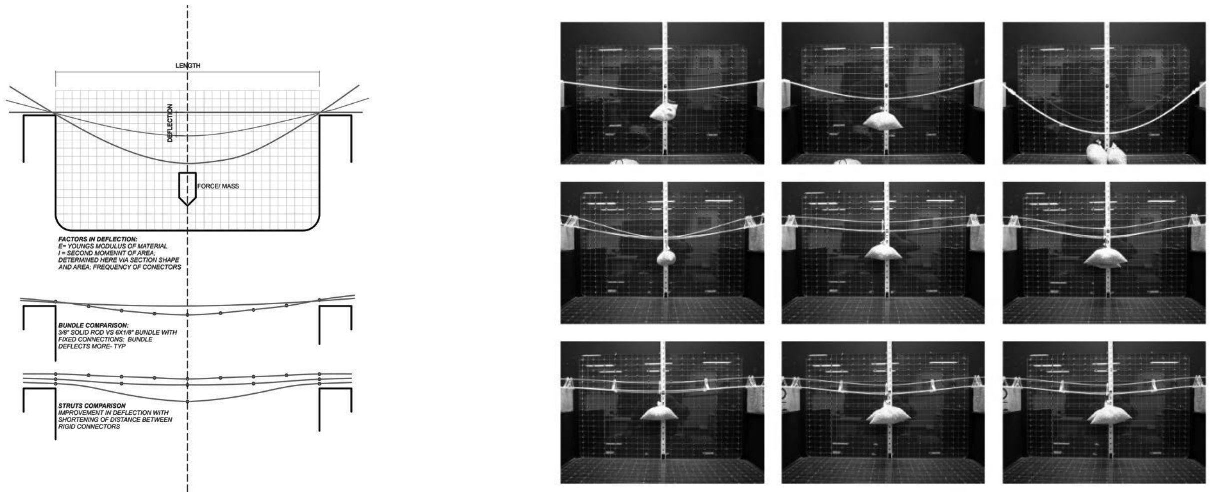
2 Material Equilibria Installation



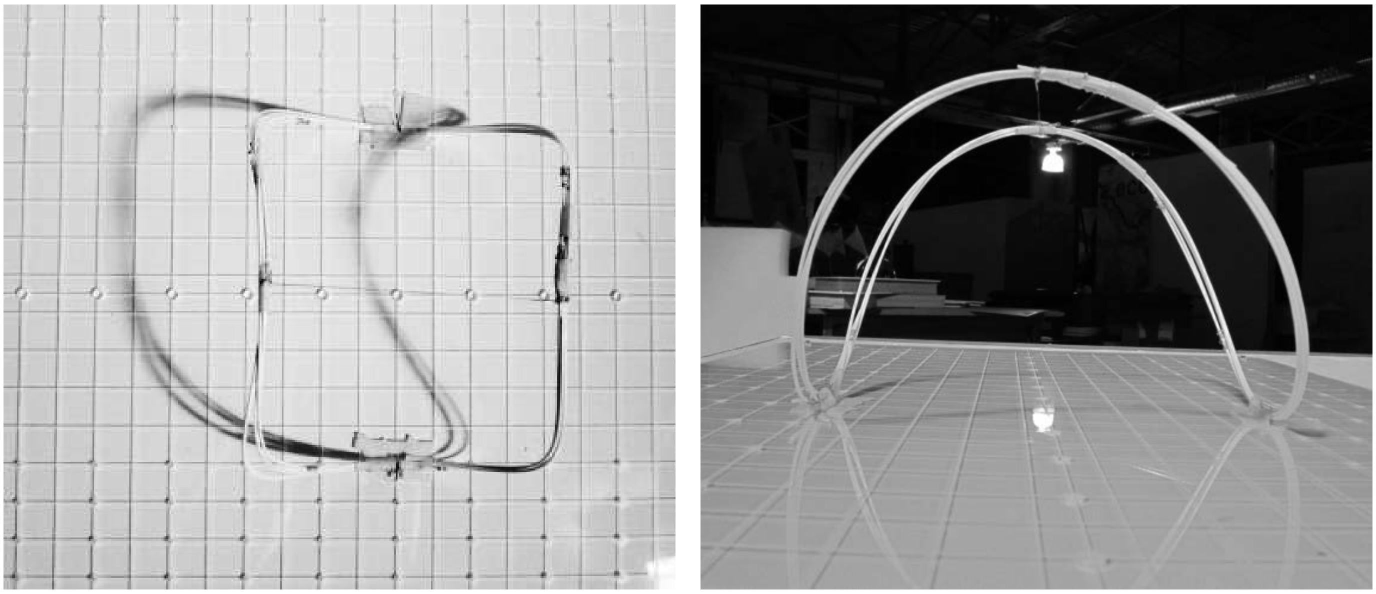
3 Diagrams - Bending Test, Bundling Test



4 Bending and Bundling Tests - Process Photos



5 Deflection Test Set-up Diagrams and Photographic Index



6 Closed Loop Study Model with Evenly Distributed Bundling

> The larger research project aims for developing a computational design approach that synthesizes performance-oriented form generation and physical processes of materialization. Here, the design space is defined and constrained by material behavior, fabrication and production. This understanding of design computation as a calibration between the virtual processes of generating form and the physical becoming of material systems, should not be conceived as limiting the designer, but rather as enabling the exploration of unknown points in the search space defined by the material itself (Menges 2011: 73)

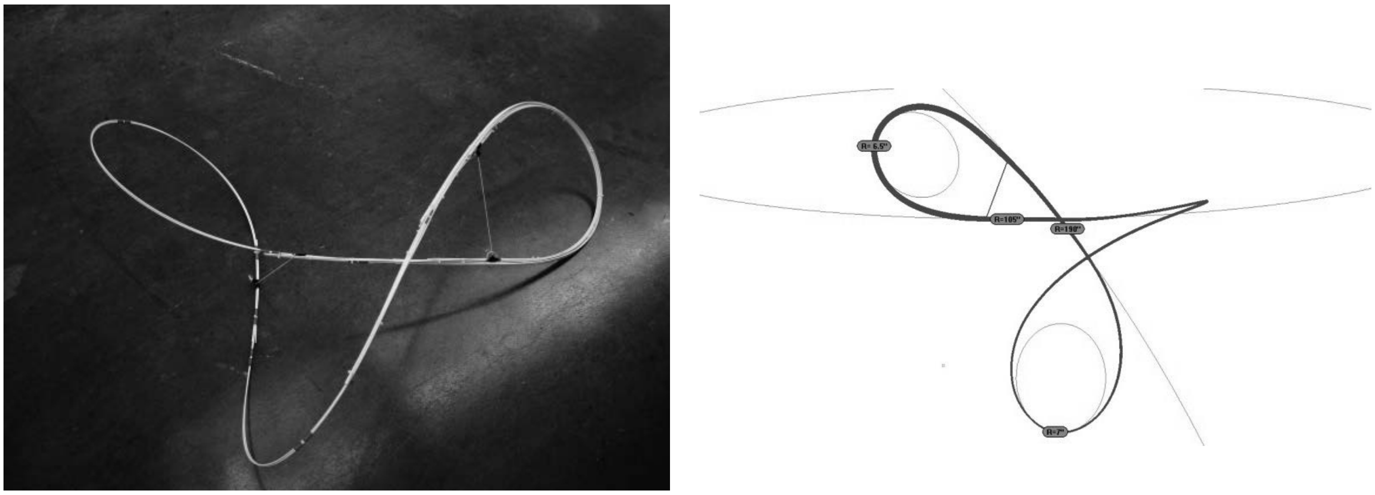
In the essay, Menges cites several examples of bending-active structures, making particular reference to the 2010 ICD Research Pavilion, a structure made entirely of light-weight plywood strips. A computation model built upon parametric principles derived from the material properties of the birch plywood was integral to the design, prototyping and fabrication of the pavilion. In the ongoing design and research work of Sean Ahlquist and Julian Lienhard, light-weight bending-active equilibrium structures are constructed from a minimal palette of pultruded fiberglass rods, flexible textiles and meshes. Material testing and digital simulation are integral to form-finding and to the design process.

> Physical form-finding offers the most direct feedback of behavior through modeling with GFRP rods and textiles. In design scenarios where the rod cross-sections and textile make-up are homogenous, the geometry produced by the behavior of the physical model is generally scalable. As with any physical modeling effort, the pursuit of variation from a fundamental strategy is exhaustive. A springs-based modeling environment serves to bridge this moment from the single design instance to an examination of a field of possibilities. (Ahlquist and Lienhard 2013: 187-209) (Figure 2)

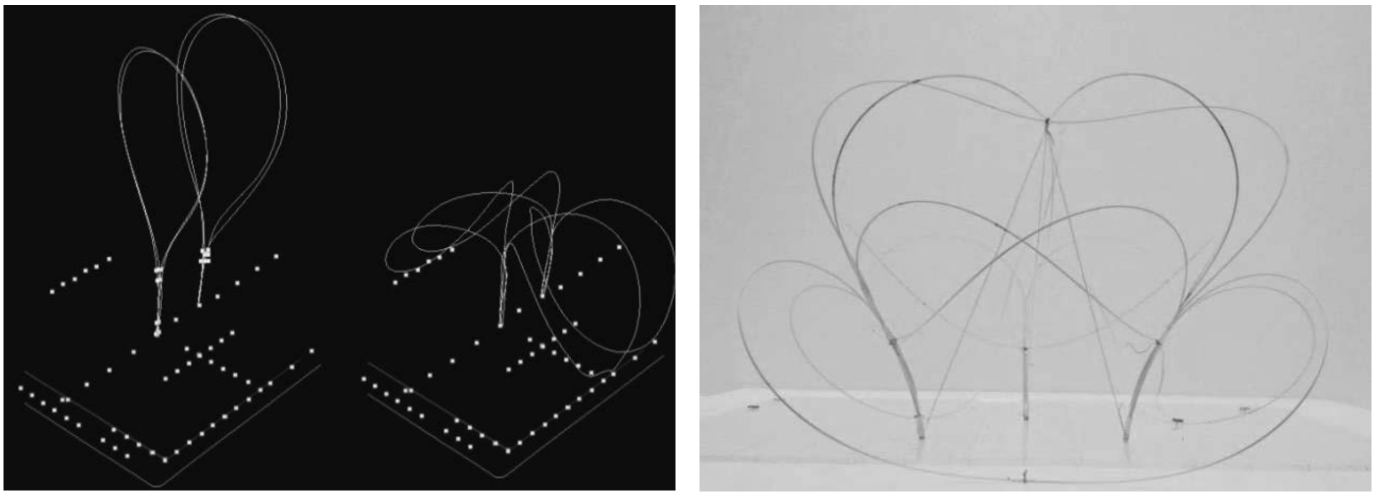
In order to achieve predictive design capability for force-active systems in real world situations, complementary physical and computation models are necessary. Due to the complexity of the material behavior of bundled bending-active elements, the early focus of this research project has been on physical form-finding and material testing. The digital simulation framework for predictive design of bundled systems will follow as the research evolves and as available software evolves.

Bending-Active Materials, Selection and Testing

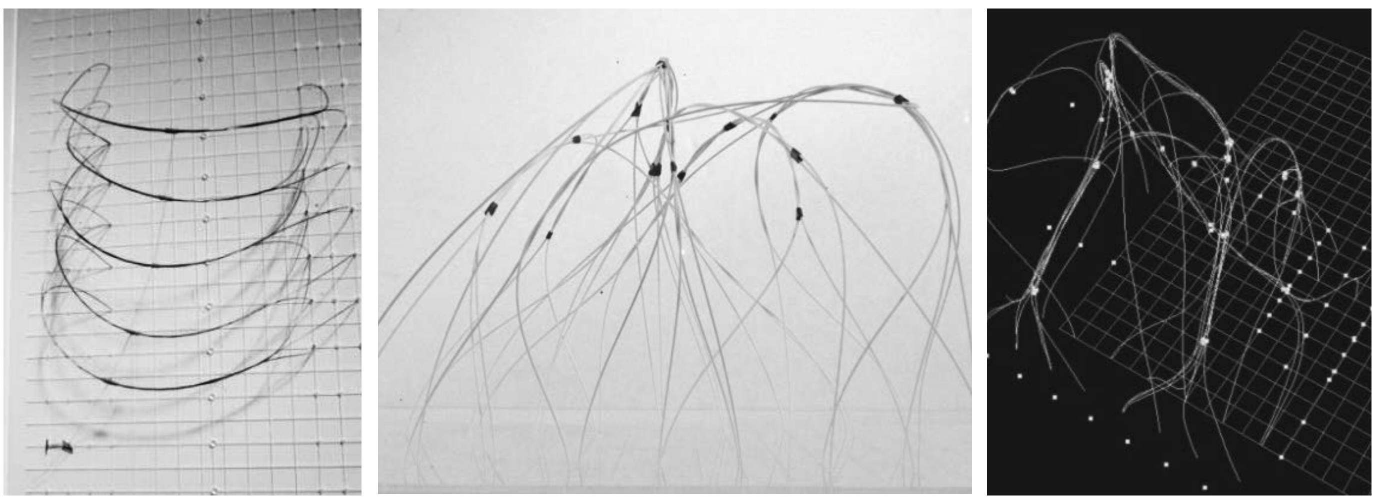
GFRP rods and tubes were selected and tested at specific diameters and lengths for deployment in scale models and larger prototypes. The material is characterized by a median Young's modulus with high yield strength. This combination of properties delivers significant elastic bending with



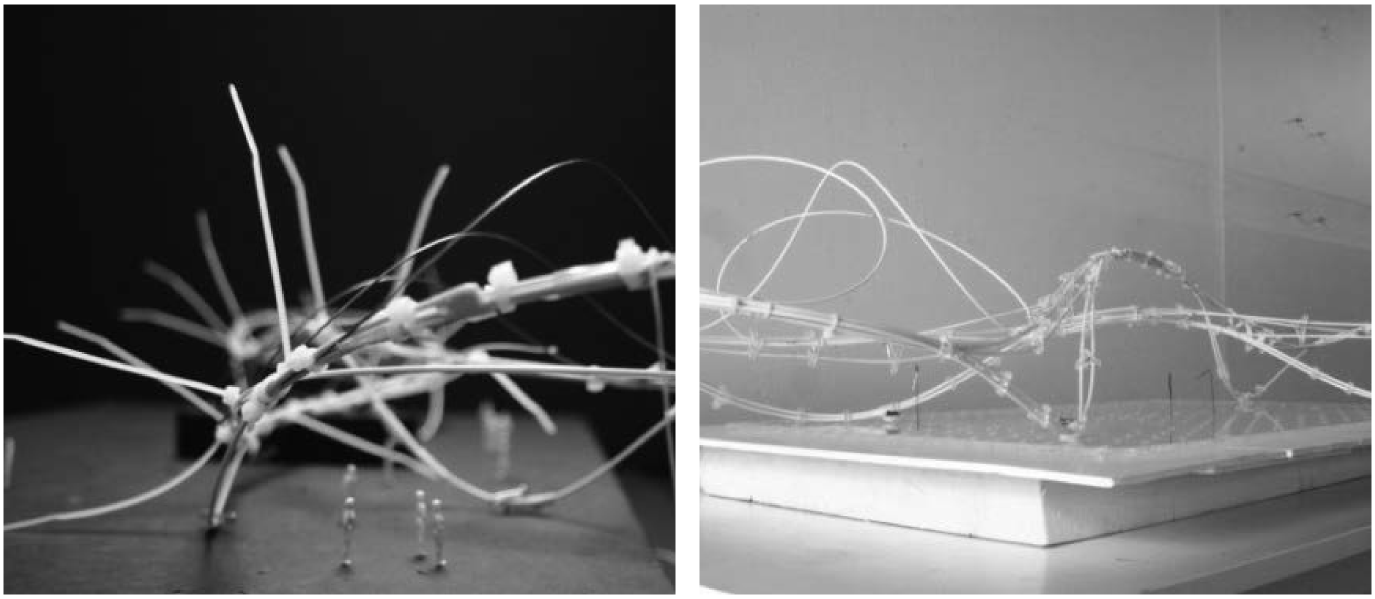
7 Physical and Digital Model - Closed Loop with Differential Bundled Condition



8 Digital and Physical Models, Type 2 Studies



9 Left, Arcade Model on Measuring Grid with Regular Column Placements; Bundled Spanning Elements; Middle and Right, “Mangrove” Model Studies



10 Bending-active Bundled Pavilion Study Models

high loading capacity. GFRP is low in cost and suitable for customized fiber lay-up. Other candidate materials that perform well in bending are carbon fiber, natural wood profiles oriented in the direction of the grain, and aluminum extrusions. Three key material tests were conducted on the chosen profiles to develop metrics for bending, bundling and deflection. The bending test renders the minimum bending radius for the given profile before fracture. Comprehensive studies of performance in bundling have not been previously conducted. Preliminary bundling tests suggest that minimum radius in bending for *n* rods is equal to a single rod when there is minimal friction between bundled elements (Figure 3 and 4).

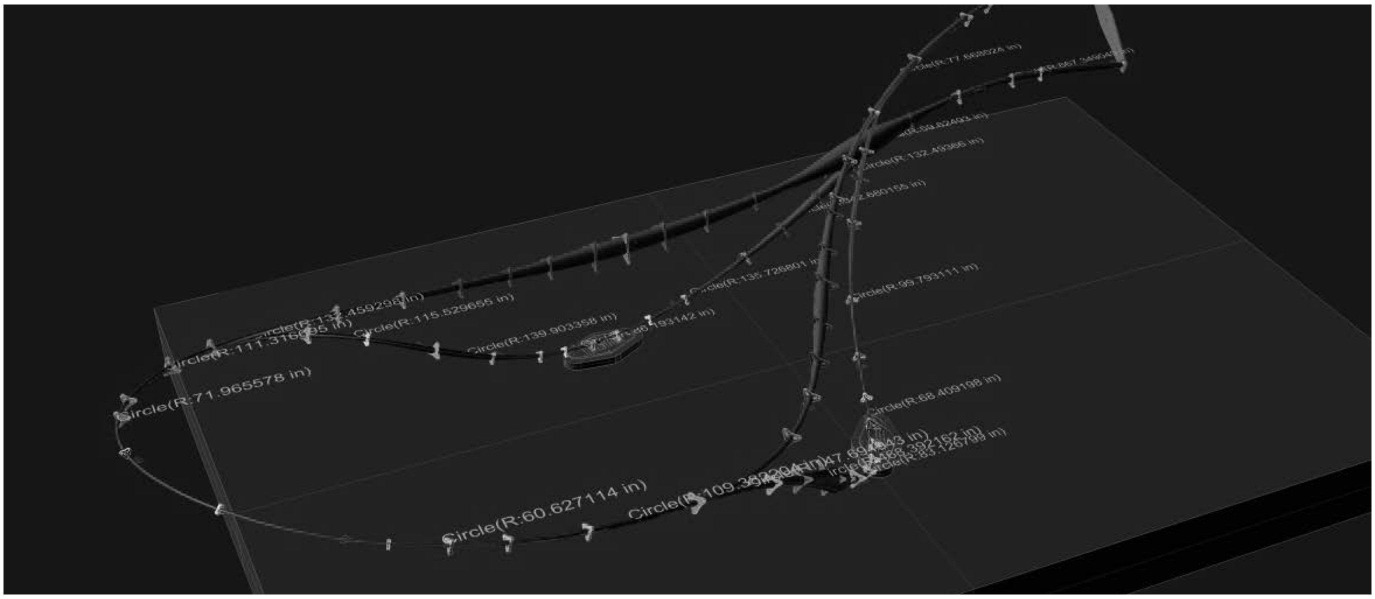
Standard testing for deflection ratio was used to measure beam displacement under load as governed by the equation *Deflection = FL3/ 48EI*, where *F*= force, *L*=length of span, 48 indicates the constant for a simply supported beam, *E*=Young's modulus and *I*=Second Moment of Area, varying with sectional geometry and area. Where standard structural beams under self-weight and live load require deflection ratios between 1/250 and 1/600 in North American construction standards, no set standards for acceptable deflection of bending-active spanning structures has been determined. A minimum ratio of 1/80 was set as a preliminary standard for model and prototype performance. More comprehensive deflection metrics for materials in a bending-active state will be explored in future tests (Figure 5).

TAXONOMY OF BUNDLED BENDING-ACTIVE TYPES

TYPE 1: CLOSED LOOPING BUNDLES

Topologically, these studies each form a closed loop with no fixed endpoints. Tensile forces maintain the model in an equilibrium position with no crossing joints. In the preliminary studies, no external forces are exerted on the closed loop. Bundling is evenly distributed throughout the figure, achieving minimum bending radius in combination with minimal deflection. (Figure 6)

In the second example, a closed figure with two cables and two symmetrical loops is bundled in one area only, reducing deflection, increasing stiffness, and changing the balance and geometry of the figure without altering the topology. Closer study and development of this closed two-loop figure commenced after the initial types were determined (Figure 7).



12a Closed Loop Pavilion GH Definition-Components Based Upon Minimum Bending Radius

TYPE 2: TRUNK AND BRANCH LOOPS

These models are characterized by fixed endpoints. Intermediary rods are continuous and either bundled or follow individual paths. Both tensioned and crossing forces were explored. In the studies with bundled end-points, strength and stiffness are concentrated at the fixed bundled trunks. Individual rods at the furthest distance from the endpoints are capable of the greatest deflection, but cannot achieve large spans (Figure 8).

A series of models with regular individual endpoints produces the inverse balance of forces. The individual endpoints tend to evenly dissipate the system's forces at the edge condition producing a very light footprint. Bundled concentrations are capable of long spans that can be regulated or harnessed with tensile member (Figure 9). A more willful distribution of arching rods creates compelling formal possibilities akin to a mangrove tree in organization and hierarchy of elements. This formation presents challenges to the computation and engineering framework described above, but sets itself as a goal for future research (Figure 9 and 10).

Future Exploration, Prototype

This research begins to establish terms of reference for the design of an ultra-light weight bending-active architecture that is characterized by the delicate balance of structural forces into stable equilibria through bundled configurations. Material testing and classification of early physical model studies provide a framework to guide the further development of already established spring-based computation methods, and guide future design directions and tolerances.

Finally, a series of experimental prototypes that expand the syntax and detailing of the closed two-loop bundled configuration of the Type 1 studies has been created to explore detailing and architectural performance at the scale of a small pavilion. While speculative in terms of the evolving performance of bundled systems in their structural robustness and spatial differentiation, the prototype explores the rapid deployment of such systems at a larger scale, driving detailing and material choices forward and dealing directly with curvature related to increasing spans. Valuable feedback on the tolerances of components and systems was derived from these large scale studies that will be directed towards the more comprehensive computation modeling and simulation of the evolving material system (Figure 11, 12 and 13).

12b Left: Large Scale Closed Loop Pavilion Prototype - Components Based Upon Minimum Bending Radius

13 Right: Polycarbonate Bundling Component Detail

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WORKS CITED

Lienhard, J., Alpermann, H., Gengnagel, C. and Knippers, J. 2012. "Active Bending, a Review on Structures where Bending is used as a Self-Formation Process". In: Proceedings of the International IASS Symposium, 650-657. Seoul.

Ahlquist, S. and Menges, A. 2011. "Behavior-based Computational Design Methodologies – Integrative Processes for Force Defined Material Structures, Integration through Computation". In: Proceedings of the 31th Conference of the Association For Computer Aided Design In Architecture (ACADIA), edited by Branko Kolarevic, 82-89. Calgary.

Otto, Frei. 1974. Nets in Nature and Technics. Stuttgart: Kramer

Menges, Achim. 2011. "Integrative Design Computation". In: Proceedings of the 31th Conference of the Association For Computer Aided Design In Architecture (ACADIA), edited by Branko Kolarevic, 72-81, Calgary.

Ahlquist, S. and Lienhard, J. 2013. "Exploring Materials Reciprocities for Textile-Hybrid Systems as Spatial Structures". In: Prototyping Architecture, The Conference Papers, edited by Michael Stacey, 187-209. London: Building Centre Trust.

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