FORM-FINDING OF AN ECOLOGICAL "GREEN" WALL USING BENDING-ACTIVE BIOTENSEGRITY STRUCTURE

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ABSTRACT: Interaction between form and force defines the inseparable relationship between architecture and structural design. Many new architectural forms with complex curved geometries can be generated by active elastic bending and pre-stresses introduced by materials with large elasticity and inner stress state. In addition, these structural systems with reversible elastic deformations are shape adaptable. Three case studies were completed in this study, which include a static bending-active Textile Hybrid M1 at La Tour de 1'Architecte designed by ICD/ITKE, a bending-activated tensegrity structure designed by Technische Universität München, and a bending active tensile membrane hybrid tower designed by CITA and KET. Based on the findings, principles for a new type of bending-active structure with biotensegrity logics are formulated through systems thinking to address its function, architectural form-finding, and structural stability. A pre-stressed and self-stabilized ecological "green" wall prototype was designed and built using elastically bent glass fiber reinforced plastic (GFRP) rods in combination with flexible and expandable connections. The new adaptive and dynamic structural form, coupling bending-active systems with biotensegrity logics, explores the opportunities of elasticity, resiliency, and strength within a self-supporting structure. This study presents the design, material selection and iterative form-finding of the wall prototype. The GFRP bending rods play an important role in the structural system, and need to be carefully arranged and connected to carry the loads transferred from the plants, and to enhance the rigidity and stability of the structure.

KEYWORDS: Form-finding; bending active; biotensegrity

INTRODUCTION

The inseparable relationship between architecture and structure is defined by the interaction between form and force. "Force follows form" is an essential precept for an efficient and sustainable structural design. Advanced technologies have enabled new types of structural thinking and making that support the testing of more complex and dynamic structural topologies including: shells/gridshells, lightweight membranes, tensegrity systems, and newly emerged bending-active assemblies,

The structural principles of 'tensegrity' have continued to advance research in disciplines from architecture to human anatomy. Since its formulation by Fuller, Snelson and Emmerich (Gómez-Jáuregui, 2010), and subsequent adoption into the fields of biology and cellular mechanics by Steven Levin's and Donald Ingber's, '*tensegrity*' logics have launched new paradigms of understanding in biomechanical movement and natural kinematic systems (Scarr, 2014). Arguably 'biotensegrity' has emerged as "one of the most significant developments in human anatomy" (Sharkey, 2015). More broadly, its principles introduce a relevant model for adaptive, 'living' structures characterized by networks of interconnected components and tendons with the capacity for "non-linear fluid movement" (Scarr, 2014). Lienhard et al (2013) first proposed the concept of "bending active". Rather than a type of structural system, they contend bending-active structure is an approach to actively curve beams and surfaces based on the elastic deformation of their initial straight or flat geometries to form force equilibria (Lienhard and Knipers, 2015). Many new architectural forms e.g. bending-active textile hybrids, bending-active tensegrity, with complex curved geometries can be generated by active elastic bending and pre-stresses introduced by materials with large elasticity and inner stress state. In addition, these structural systems with reversible elastic deformations are shape adaptable.

Principles for a new type of bending-active structure with biotensegrity logics are formulated in this study through case studies on three bending-active architectural forms, and through systems thinking to address its function, architectural form-finding, and structural stability. The three innovative architectural forms studied include: (1) a static bending-active Textile Hybrid M1 at La Tour de 1'Architecte designed by architects and engineers from the Institute for Computational Design (ICD), and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart; (2) a bending-activated tensegrity structure designed and built by designers from the Technische Universität München (TUM); and (3) a bending active tensile membrane hybrid tower designed by researchers from Centre for Information Technology and Architecture (CITA) at Royal Danish Academy of Fine Arts, and Department for Structural Design and Technology (KET) at University of Arts Berlin. This paper analyzes these case studies and discusses the design for a pre-stressed and self-stabilized ecological "green" wall developed and prototyped using elastically bent glass fiber reinforced plastic (GFRP) rods in combination with flexible and expandable connections.

1.0 BENDING ACTIVE STRUCTURES

1.1. ICD/ITKE Textile Hybrid M1

Defined by Lienhard and Knipers (2015), Textile Hybrid integrates bending-active rods with form-active membranes, taking advantages of their flexibility, lightness, and adaptability to applied loads. The forms of Textile Hybrid structures depend on the mechanical behaviors of materials and pre-stresses applied to the structures. The Textile Hybrid M1 (Figure 1) was built to exhibit a historical and structurally sensitive tower originally designed by Leonardo Da Vinci from the 16th century in Monthoiron, France, which required minimum loading and least intrusion to the tower. 110 meters (361 feet) of glass fiber reinforced polymer (GFRP) rods and 45 m2 (484 ft2) membrane created an overlapping grid-shell, arching with 6 to 8 meters (20 to 26 feet) span, covering an approximately 20 m2 (215 ft2) area with doubly-curved tensile surfaces. The structure was anchored to existing masonry structure neighboring the tower with three supports, weighing only approximate 60 kilograms (132 pounds) (Lienhard et al, 2013; Ahlquist and Menges, 2013; Lienhard, 2014; Lienhard and Kniper, 2015).

Physical, computational, and finite element modelling (FEM) were employed to find the form of Textile Hybrid M1 (Figure 2). Exhaustive physical form-finding experiments were carried out at various scales informed by intuitions to initially define configurations of bending-active rods and geometries for the interaction of pre-stressed membranes. "*The complexity of the form-active textile hybrid belies intuition, iterative feedback through the computational environment elicits knowledge in particular topological and behavioral manipulations*" (Ahlquist and Menges, 2013). The complex topologies of the Textile Hybrid were then explored using spring based computational modelling with established numerical methods including cross-over, vertex position and vertex normal (Volino and Magnenat-thalmann, 2006). The computational modelling allowed quick feedback from the prototypical physical modelling, and explored relationships between complex topologies of the structure and physical behaviors of the materials. The overall geometry of the structure and configurations of the rods, which were defined in physical and computational modelling, informed the finite element analysis using Sofistik® to evaluate its structural stability and specify materials for construction. Elastic cable approach was adopted in the Sofistik® to pull an initial planar system of the rods into a bending-active configuration. Then the membrane was attached to the beams and applied with pre-stress. The pre-stress in the membrane was iterated and the structure was reshaped until the permissible stresses occurred in the bending-active rods. The finite element modelling verified the geometrical shape of the structure, evaluated its residual stresses in the rods, and analyzed the deformations as well as stress levels under external loads.

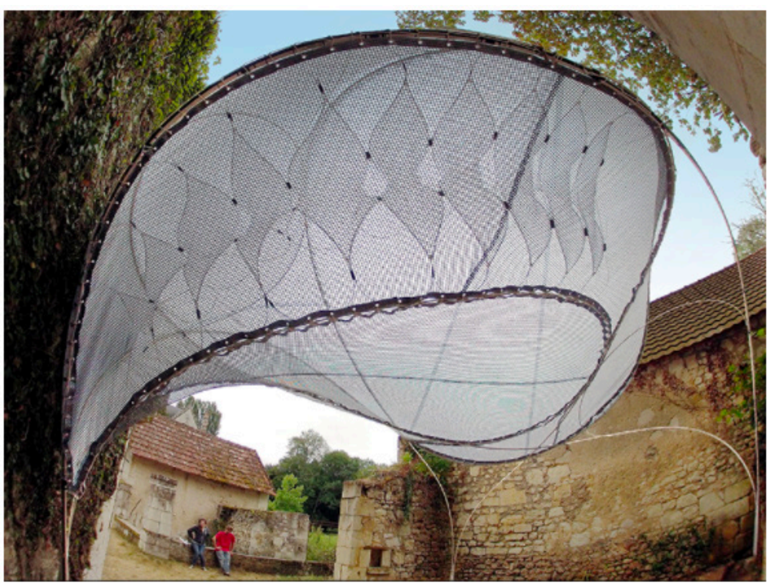


Figure 1: Textile Hybrid M1, (Lienhard and Knipers, 2015; reprint with permission)

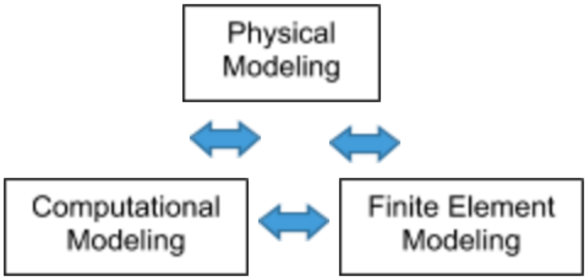


Figure 2: Form-finding techniques for Textile Hybrid M1

1.2. Bending-activated tensegrity structure designed by TUM
Schling et al (2015) presented a full scale bending-activated tensegrity structure in the symposium of the International Association for Shell and Spatial Structures (Figure 3), which integrates "*principles of active bending, tensegrity, and structural membrane*". The 6m X 6m (19.7 ft X 19.7 ft) structure was constructed using four 10m (32.8 ft) long elastic GFRP bundles each consisting of three GFRP rods, four polyvinyl chloride membranes and eighteen polyester belts. The minimum radius of curvature designed for the GFRP bundles was 1400 mm (55 in.), which is larger than the theoretical minimum radius of curvature of 1,250 mm (49 in.).

Figure 3: Bending-activated tensegrity structure (Schling et al 2015, reprint with permission)

The structural prototype was originally proposed in a design studio at TUM. The prototype was scaled up approximately tenfold, which required studying the impact of self-weight and physical properties of materials. Bending tests were performed to verify the flexural strength and modulus of elasticity of the GFPR rods. A FEM software Strand7® was used by the researchers to simulate the form-finding and perform the structural analysis. In the simulation, the GFRP bundles were bent by induced displacement of supports. Tension elements e.g. cable nets and membranes were incorporated into the model to define the configuration of the structure by adjusting pretensions in these elements. Modal analysis was completed to detect the most flexible locations in the structure. Additional tension elements were used to connect the bundles at the middle points to increase its stiffness.

1.3. CITA/KET tower
A bending-active tensile membrane hybrid tower was designed and constructed using GFRP rods and membranes, by researchers from CITA and KET (Holden Deleuran et al, 2015). The tower was exhibited in the Courtyard of the Danish Design Museum (Figure 4). Computational modelling was employed to find its form and FEM was used to evaluate its structural performance. A newer version of the tower was built by the research team in 2016 with "*convergence of the simulated and real behaviour of the structure*" (Tamke et al, 2016).

Figure 4: CITA/KET Tower (Deleuran et al, 2015, reprint with permission)

Due to its complex bending-active system, the elastic cable approach proposed by Lienhard (2014) using FEM hit its limits and did not work for this project. The researchers proposed a two-stage strategy to find the form of the tower using Kangaroo 2, a plug-in in Grasshopper/Rhino environment first, and then to evaluate its structural performances using Sofistik®, a FEM software. The form-finding process is illustrated in Figure 5.

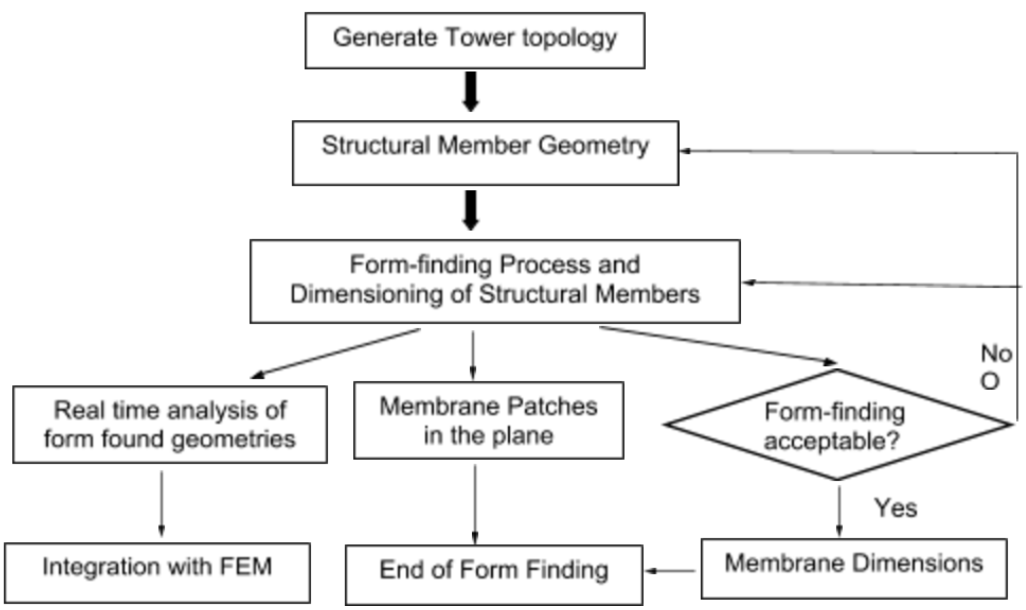


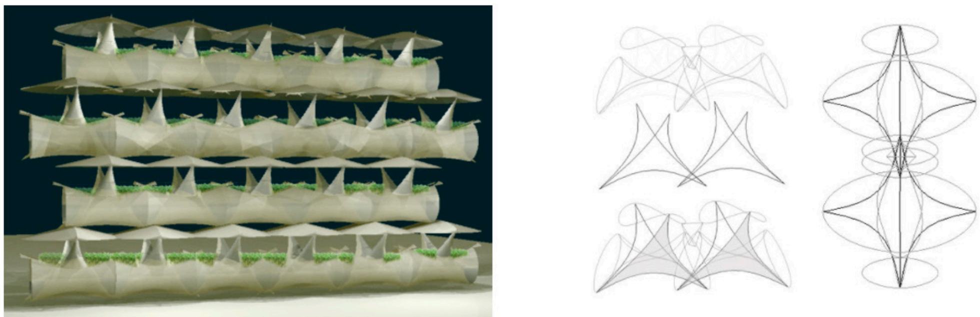
Figure 5: Form-finding process (adapted from Holden Deleuran et al, 2015)

Equilateral polylines input in the computational model were further processed to generate the tower typology with "*overlapping bending members around a central vertical axis*". A mass spring system in the Kangaroo 2 was used to perform the form-finding and dimension the structural members with three stages, e.g. "generating, exercising, and refining constraints". Real-time feedback was provided to evaluate if the form-finding was acceptable. The residual stresses in the bending active GFRP rods can be determined theoretically according to the form found geometry. However, axial and bending stiffness of structural members in Kangaroo are based on mathematical approximations. Its precision needs to be validated by the FEM. After the form-finding, the geometry of the tower was baked and exported to Sofistik® to evaluate its structural integrity and stability under the dead load and external wind forces by superimposing residual stresses generated from the form-finding.

2.0 ECOLOGICAL "GREEN" WALL USING BENDING ACTIVE BIOTENSEGRITY STRUCTURE

2.1. Design steps and processes

Biotensegity precepts were instrumental in developing new concepts for an adaptive, structural indoor farming system. The proposed ecological "green" wall (Figure 6) incorporates aeroponic (soilless) gardening system within a modular bending active structure. The *biotensegrity* typology was selected for its ability to test techniques of structural efficiency in combination with flexural dynamics of wall geometries. Inspired by the biomechanical organizational principles of the spinal column (Figure 7), the project builds from a single regular tetrahedron module approximately 91cm X 91cm X 30cm (3ft X 3ft X 1ft) in dimension. The tetrahedron was selected for its structural, geometric efficiency and aggregation patterning.



(a) Conceptual Rendering (b) Diagram (Exploded and Top View)

Figure 6: Bending-active biotensegrity "green" wall

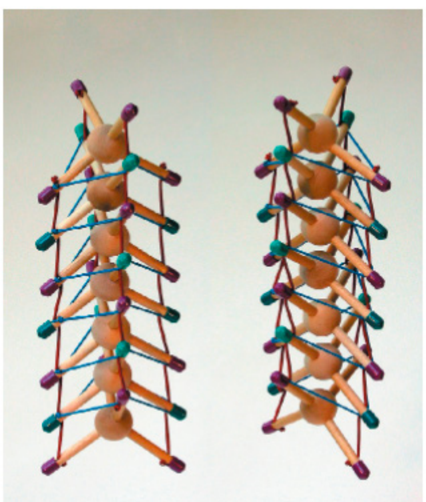


Figure 7: Tetrahedral vertebral masts model (@copyright Flemons 2006, reprint with permission)

Individual tetrahedral modules were constructed of 3.175 mm (1/8 in.) solid GFRP rods that were tensioned with a layered waterproof, knit membrane enclosure that retains internal moisture for plant germination and growth. Each tetrahedron shell houses one custom-growing tray within its cavity. Trays are composed of a waffle weave set with integration irrigation channels that supports plant growth. Researchers at the Kent State University tested two custom woven growing tray patterns for crop development. Each test found germination of culinary vegetation from seed through agricultural harvest. The crafting of textile trays included the development of a three-dimensional weaving pattern with integrated irrigation channels to support a low-pressure aeroponic system. Two fiber combinations were also tested including: 1) all monofilament, and 2) monofilament and nylon thread. Curly Cress and Alfalfa microgreen crops were tested on each tray; both with and without growing media. A total of four experiments were completed, and analyzed against a commercial aeroponic system that served as a control.

Outcomes for plant development and growth were promising within our sample set, particularly within the two main performance categories analyzed (germination rate and root length) (Figure 8). Germination for all experiments ranged between 50% and 84%, a statistic competitive with, if not well above, the rates for the aeroponic control. Equally encouraging were the sampling of root lengths for the Alfalfa, which grew longer than the control among all trays tested. Root lengths for the Curly Cress were generally near or matching the lengths of those in the control. Stem length data was also competitive with the overall growth of the control for each sample set tested. Fresh weight, stem, and root length data collected from these studies drove the size and scaling of tetrahedral geometries, edge lengths and aggregation patterns. A maximum 22 cm (8.66 in.) root length identified in initial growing tray tests served as the minimum benchmark for the lowest tetrahedron cavity interior depth. The growing wall benefits include: 1) materially efficient construction, 2) low-consumption irrigation, 3) a year-round, pesticide free, growing environment, and 4) locally sourced access to sustainable fresh produce.

*Trays *Roots (c) Measurement (d) Germination Rate*

Note: * 1 Control; 2 Nylon+ Monofilament with Media; 3 Nylon + Monofilament without Media; 4 Monofilament with Media; 5 Monofilament without Media

Figure 8: Plants harvest and data collection

The growing wall is composed of a linear array of self-stabilized, regular tetrahedron modules, individually balanced on two vertices. Each tetrahedral structure is pre-stressed with a network of 1.588 mm (1/16 in.) GFRP rods. These rods provide additional structural support though elastic bending, as well as outline the geometry of each tetrahedron's fabric enclosure. Top and bottom vertices of each tetrahedron module are networked within this 'tendon' system. Final textile design will be outfitted with a flexible, sewn in LED grow lighting systems within each tetrahedral canopy surface.

2.2. Form-finding method

Based on the three case studies, physical modeling, computational modeling, and FEM inform each other to address the function, architectural form-finding, and structural stability of the design. Extensive physical modeling was adopted in this project to define the form of individual tetrahedral module. Testing indicates these models are self-supported and stable. Pre-stress applied by the knit membrane could further increase the global structural stability of the bending-active biotensegrity structure. A full-scale physical bending-active tetrahedral module was designed and built. The final typology was then modeled in the computer to confirm the selection of construction material, and determine its ultimate loading capacity by employing FEM.

The design process was initiated with a set of full-scale physical experiments that tested material elasticity associated with a variety of GFRP rod cross-sections. Preliminary studies included tetrahedron and closed ring geometry investigations (Figure 9). Computational simulations in Kangaroo 2 (plug-in for Rhinoceros® and Grasshopper®) were used in tandem with full-scale prototyping, to compare active bending behaviors with physical models. Formal qualities of bending experiments and tessellation patterns were also explored during this phase. Similar to the form-finding process of CITA/KET Tower, polylines were input in Kangaroo 2 using mass spring system, combining dynamic mesh relaxation and active bending protocols.

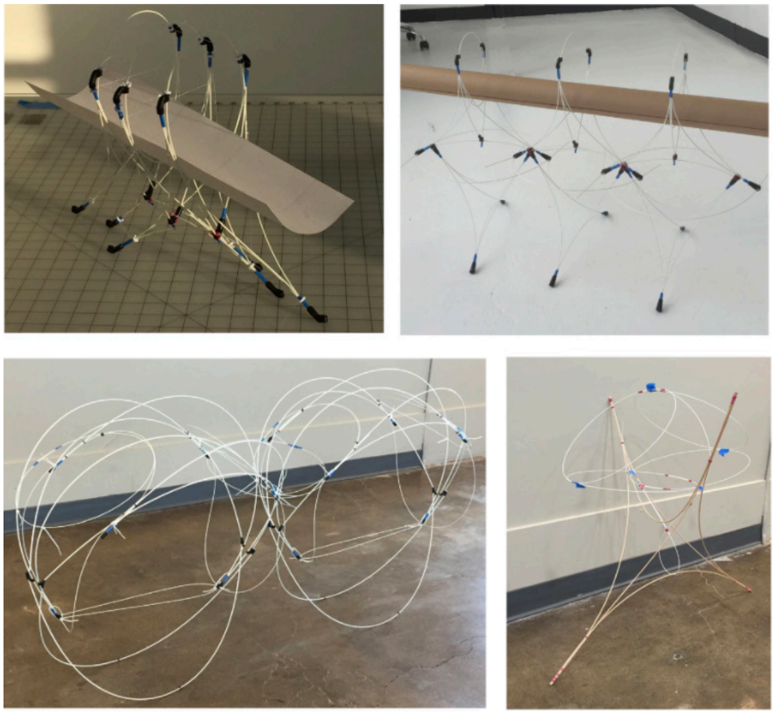


Figure 9: Physical modelling

2.3. Materialization and structural performances

Physical modeling used solid fiberglass rods with plastic connectors. The engineering properties for the fiberglass rods are listed in Table 1.

Table 1: Engineering Properties of Fiberglass Rods

Flexural Strength		Flexural Modulus		Compressive Strength		Density		Coefficient of Thermal Expanshion
MPa	ksi	Mpa	ksi	Mpa	ksi	kg/m3	lb/in3	in./in./°C X10-6
827	120	41,368	6,000	483	70	2,021	0.073	5.3

The relationship between the flexural strength and minimum radius of curvature of the GFPR rod characterizes the bending active nature of various rod types, which can be derived from classical mechanics of materials for beams (Eq. 1-2).

$\sigma = \frac{Mt}{I}$ Eq. (1)

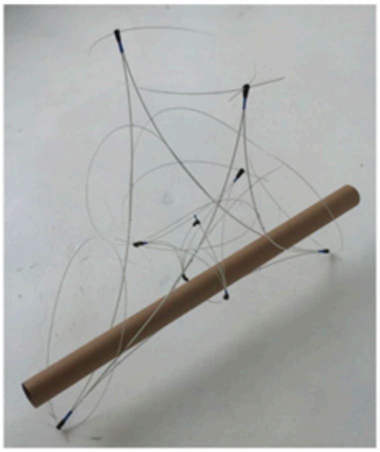
$\frac{1}{r} = \frac{M}{EI}$ Eq. (2)

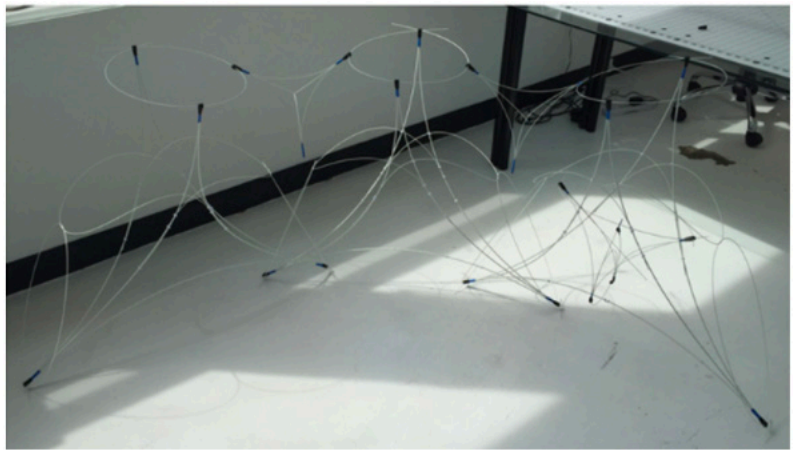
Where σ = flexural strength
M = bending moment applied to the rod
t = radius of the rod
I = moment of inertia of the rod
r = radius of curvature due to the applied bending moment

Solving for M/I from Eq. (1) and substituting derived M/I into Eq. (2),

$r = \frac{Et}{\sigma}$ Eq. (3)

Based on the Eq. (3), the minimum radii of curvature are determined to be 7.9cm (3.125 in) for rods with a diameter of 3.175mm (1/8 in.) and 3.9cm (1.55 in.) for rods with a diameter of 1.588mm (1/16 in) respectively. The minimum radius of curvature of the bent rod in the physical prototype is 19.41 cm (7.64 in.), which is 2.45 times larger than the minimum value determined by its flexural strength. The early prototype of the bending active, tetrahedral growing wall module is shown in Figure 10 (a) .





(a) Early prototype

(b) Final prototype

Figure 10: Prototype of the bending active biotensegrity module and structure.

Regions between modules are designed as flexible, form active connections that offer restricted yet effectual patterns of expansion, contraction and omni-directional movement. The prototyping and testing of the networked tetrahedron modules confirmed high degrees of spatial adaptability and flexure with sustained structural integrity. Studies revealed continued loading–bearing capacities and limited geometric deformation to be well within the system's elastic range. Final prototypes employed a hybridized biotensegrity and bending active system in which legs of one tetrahedron module are interwoven with the adjacent leg of the neighboring tetrahedron module (Figure 10b). Preliminary prototyping and testing of this technique has revealed a more robust structural assembly system based upon preferred module size and levels of flexural control needed for the growing wall system. The authors will "bake" and export the computational model from Rhino to ANSYS, a finite element analysis software, to determine the ultimate loading capacity of the designed prototype by including the residual stress in the bending-active rods.

2.4. Context of Application

The proposed growing wall system is designed as an urban repurposing strategy that transforms vacant, large-volume structures into indoor farming environments. It asks if it is possible to rebuild social capital at the community and neighborhood level through temporary agricultural programming. Urban vacancy has for decades challenged the economic development of post-industrial cities. Strategic demolition has successfully reduced foreclosures in targeted legacy cities; though recent discussions question if demolition alone can resolve a building surplus rooted in low demand (Warminski, 2014). This project therefore proposes an interim solution for these large properties that supports healthier urban living that is local, deployable, and community-based.

CONCLUSION

FEM and physical and computational modeling, are important techniques for architects and structural engineers to explore the interaction between stress and form in the design of innovative structural systems. Iterative design processes have been adopted by the three bending active hybrids studied in this paper. A pre-stressed and self-stabilized ecological "green" wall was designed and prototyped using elastically bent GFRP rods in combination with flexible and expandable connections, which were then wrapped by the knit membrane to generate the form. The GFRP bending rods play an important role in the structural system. They are strategically arranged and connected, to carry the loads transferred from the plants and to enhance the rigidity and stability of the structure. The new adaptive and dynamic structural assembly couples bending-active systems with biotensegrity logics. It explores the opportunities of elasticity, resiliency, and strength within a self-supporting structure. The project also presents an opportunity to address the challenge of food equity and social resilience in legacy urban communities.

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