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Hybrid Bending Active Systems: A Novel Application of Carbon Fiber in Lightweight Structures

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Abstract

The recent development of bending-active structures has broadened the opportunity for extensive exploration into the design of efficient, lightweight, bending-active structural systems. Moreover, the design and use of carbon fiber-reinforced polymer (CFRP) have expanded significantly in recent years and transformed industrial applications, including aerospace, automotive, and marine engineering. CFRP is a lightweight material with exceptionally high strength to stiffness ratios rendering it ideal for bending-active applications. A distinctive approach in this research is the novel application of CFRP in a bending-active hybrid lightweight roof system.

This research expands the current potential to which computational form-finding and finite element analysis can be used for bending-active structures design optimization. The main objective of this research is to examine the construction of a hybrid CFRP plate, cables, and tensile membrane lightweight roof structure for an amphitheater design. The bending-active plates composed entirely of layers of CFRP, which are bent and stabilized by cables in tension-dominating configuration supports the tensile membrane. As bending-active structures increase in scale, CFRP cable-stabilized aches are simpler to fabricate than a CFRP grid shell of comparable strength and can be individually assembled on-site by tensioning into position from a flat plate. The funicular form of the arches, developed using computational form findings and structural optimization algorithms, result in a high-performance structure while reducing material usage, making it structurally efficient while reinforcing the overall architectural expression.

This research examines the fabrication methods of a physical structural scale model for the study of a hybrid CFRP bending-active structure and analyzes the forces and internal stresses throughout each component. The procedure includes computational form-finding simulation, finite element analysis, and fabrication techniques. The work presented in this paper investigates the overall research methodology with an emphasis on design, assembly, analysis, and preliminary assessment of hybrid bending-active structure system.

Keywords: bending-active hybrid structures, bending-active plates, carbon fiber reinforced polymers, computational form-finding, finite element analysis, structural optimization.

1. Introduction

Bending-active construction-techniques have the potential to introduce a wide range of provocative, lightweight, and materially efficient designs to architectural and engineering lexicon. Vernacular precedents have for centuries demonstrated the ease with which bending-active techniques make use of simple, easily transported materials to generate diverse curved forms. The limited flexural stability and predictability of bending elements have limited their use in large-scale, modern construction (Schleicher *et al.,* [1]). Modern advancements in computational modeling and composite materials have unlocked a new potential for bending-active systems. Despite these advancements, acceptance and full-scale adoption of such technology is undermined by continued issues of lateral and flexural stability, and cultural distrust of pre-bent elements. By using a modified version of a cable-actuated plate system and a hybrid CFRP/tensile-design, the research in this paper seeks to demonstrate the feasibility and advantages of a novel design for bending-active hybrid systems (Takahashi *et al*, [2]). Using computational form-finding and structural optimization, a simulated bent-arch topology was modeled, subject to various load scenarios, and translated into a scale model using actual CFRP plates.

1.1 Background

Bending active structures are defined as a class of lightweight structural elements that utilize the elastic deformation of naturally straight or flat elements, usually sheets or rods, to achieve curved geometries (Leinhard and Knippers, [*3*]). The relative ease with which these elements achieve curved geometries - and the historical availability of materials like reeds and bamboo in certain areas - have produced a variety of vernacular precedents. The Ṭāleš tents of Iran (Fig. 1a) and Mudhif reed houses of southern Iraq (Fig. 1b) all utilize the active bending of strong, flexible materials (Leinhard *et al*, [4]). These materials have limited flexural strength and stability, making them inappropriate for large, modern structures.

Figure 1: Vernacular precedents of bending-active construction (Andrews, A. 2009) : a) Ṭāleš Tent of the western Alborz Range, Iran, b) Mudhif reed house of Southern Iraq (Pierre, F., 2010), c) Buckminster Fuller's Self-Strutted Geodesic Plydome. (Fuller, B. 1959)

Buckminster Fuller revisited the potential of bending-active structures in the 1950s during his search for an optimal balance between stability, weight, and cost. His geodesic plydomes (Fig. 1c) introduced the use of deformed plywood sheeting to create a doubly-curved global structure. The difficulty in calculating the amount of overlap and connection between sheets limited the implications of this design (La Magna *et al.* [5]). Other material fabrication process and manufacturing techniques for curved components have long been cost-prohibitive and require extensive investments in both time and resources toward form-finding, engineering, and planning. As such, traditional engineering has sought to limit the amount of bend in structural elements, limiting the scope of modern efforts largely to exhibitions and temporary installations.

Recent developments in computational analysis have reinvigorated the exploration of bending-active structures. Computational physics engines and Finite Element Simulation (FEM) tools enable accurate evaluation of mechanical behavior and structural capacity of bending-active (Schleicher *et al.,* [6]). The ICD/ITKE Research Pavilion 2010 introduced an advanced integrated approach, utilizing an advanced Finite-Element-Analysis (FEA) process to accurately model the deformation and structural performance of their birch-plate pavilion under different bending processes and load scenarios. The Umbrella Marrakesh and Textile Hybrid-M1 utilized FEM and spring-based computational modeling to demonstrate the potential of bending-/form-active hybrids to expand the formal and functional vocabulary of tensile membrane structures, also showing that hybrid systems achieved much more structural stiffness that the individual bent members, stabilizing the individual beams against buckling and deformation. Helbig's work on the Thematic Pavilion for Expo 16 introduced the first kinetic façade that operated solely on the basis of elastic bending (Leinhard and Gegnagel, [7]).

2. Novel Methodologies for Bending-Active Plate Structures

The improved fabrication and expanded use of CFRP in recent years has already transformed the fields of aerospace, automotive, and marine engineering (Knippers *et al.*, [8]). The low weight, and high strength-to-stiffness ratio of CFRP make them an ideal candidate for the large elastic deformations and flexural stresses required of bending-active elements. However, high fabrication costs and accessibility issues have precluded widespread application of CFRPs in architecture. Utilizing advanced spring-based computational modeling and FEM analytical techniques, this research seeks to contribute to the current methods of generating predictable and stable bending-active structures. What's more, this work aims to improve the stabilization of the bending-active plates through the addition of integrated weaving cables.

Preliminary tests showed that the addition of cables achieves stable deformation and increases span range of bending active members under loads. The proposed design features a continuous-cable system, wherein a single tension cable is threaded through the plate and back on itself. Ideally this produces an even more stable bending actuation and reduces the number of individual members and connections needed for construction. For this research the addition of a tensile membrane stretched between members was tested not as a deforming membrane but to create a hybrid system that can increase lateral stiffness and improves the stability of the structure. Using all these techniques in combination can make bending-active systems not only feasible, but also materially more efficient, and potentially much easier to transport and assemble on-site than existing systems for lightweight roof structures (Liuti *et al.,* [9]).

2.1. Preliminary Design Workflow

The design of this structure utilized both physical and digital form finding approaches (Fig. 2), beginning with the design of a static model based on the bending behavior of 1.59 mm thick, 25.4 mm wide strips of poplar, then strips of laminated carbon fiber pultrusion. The target model consisted of eight, arched plates making up three distinct formal groups, improving the elevation profile of the design and establishing multi-tiered vertical hierarchy (Fig. 3). Computational form finding simulations were used to generate the final model. The benefit of this approach is a completely predicable final geometry, allowing both more flexibility in designing the analysis model and verification of its accuracy.

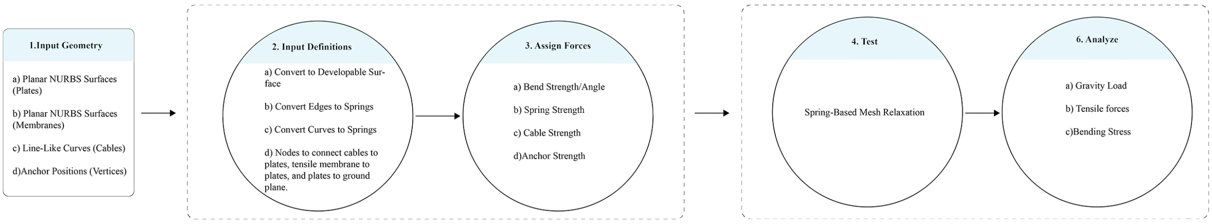

Figure 2: Design workflow diagram: form finding simulation utilizing a static initial model as a target and FE analysis

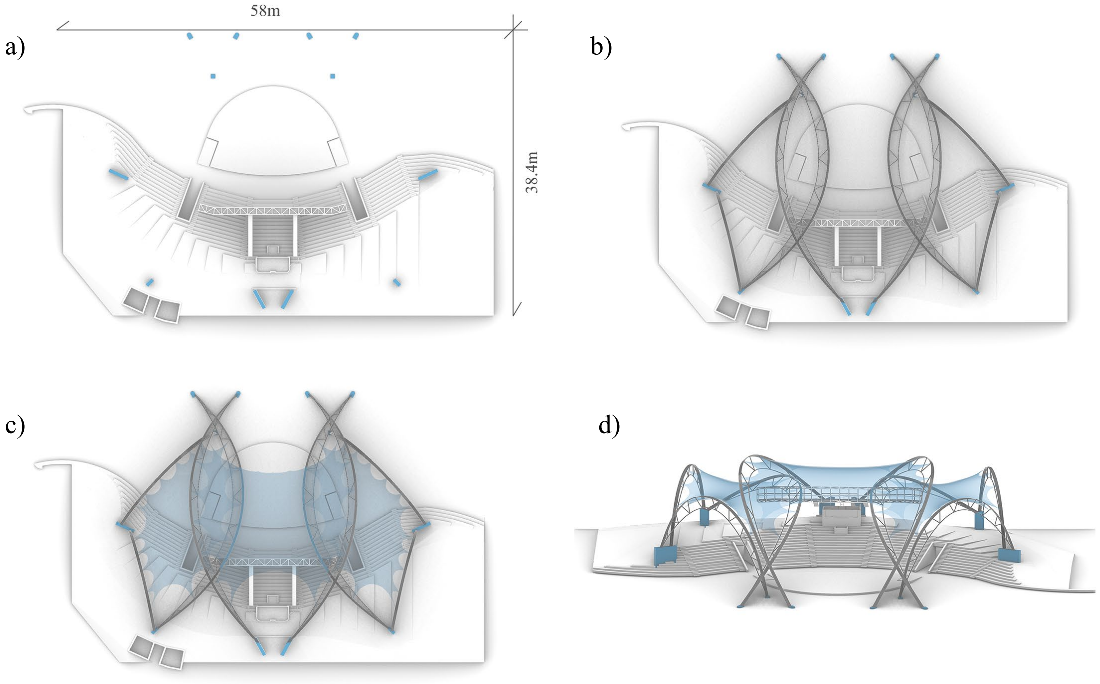

Figure 3: Preliminary design model: a) existing concrete support piers and site dimensions, b) bending-active arches, c) tensile membranes, d) Elevation view of spring-based analytical model.

2.2. Computational Form Findings of Bending Active Plates

The computational form-finding began with the generation of planar, rectangular non-uniform rational basis spline (NURBS) surfaces in Rhinoceros® by Robert McNeel & Associates, using Kangaroo physics engine plugin for Grasshopper® (GH), to convert them into developable surfaces (Piker, D. [10]). This required division of the surfaces into quadrangular mesh units. Though quadrangular meshes don't produce as smooth or high-resolution mesh surface as triangular meshes, the quad mesh has two benefits: (1) adds additional axial stiffness that prevents uncharacteristic deformation during bending, and (2) creates a much lighter analysis model that allows for rapid iterations. Since the proposed geometry relies only on singly-curved elements, the resolution provided by triangular meshes was unnecessary and significantly slowed down the analysis model. The script was designed to extract the long surface edges and middle axis, essentially converting them to flexible rods. An adjustable bending resistance as applied uniformly to each rod, creating a flexible surface that can be tailored to match singly-curved geometries.

2.3. Parametric Bending of Developable Plates

Contracting cables were then created for each plate to initiate elastic deformation, with connection points exactly in the middle of opposing short edges. Spring-based computational modeling with Kangaroo effectively allowed for the shortening and lengthening of these cables, imitating the actuating forces that would tighten the tension cables. This method enables significant parametric customization and control of elastic deformation with an allowance for rapid iterations. While cable length could be adjusted to achieve a wide range of one-dimensional bending behaviors, in this case the cable lengths were set so that the resulting plate geometry matched that of its static twin (Fig. 4).

2.4. Tensile Membrane Simulation

The design also features tensile membranes connecting the plates of each structural unit, designed to provide not only cover for the stage and seating, but also the lateral stiffness inherent in bending-active hybrid structures. Adding additional cables keeps the plates from being pulled inward and to anchor the entire system to the ground, the tensile membranes serve as stiffening agents, potentially allowing the structure to achieve the same rigidity with a reduced plate thickness, reducing material use. These support cables are modeled much in the same way as the tension cables, instead anchored 1/3 and 2/3 of the way along the plate length, then to the appropriate corner of the site surface.

Before applying bending forces to the developable plates, planar surfaces were modeled between and anchored to the plates to represent a tensile membrane. Spring-based computational analysis facilitated the conversion of the surface to high resolution mesh with the UV grid converted to springs. Once the activation forces are applied to cables, the entire assembly begins to deform, including the dynamic relaxation of the membrane mesh that responds to changes in plate topography. As a result, the behavior of the entire assembly – tension cables, plates, support cables, and tensile membrane – can be modeled simultaneously as cohesive system, providing insights into behavior that treatment of each members as a discrete system wouldn't capture (Fig. 4).

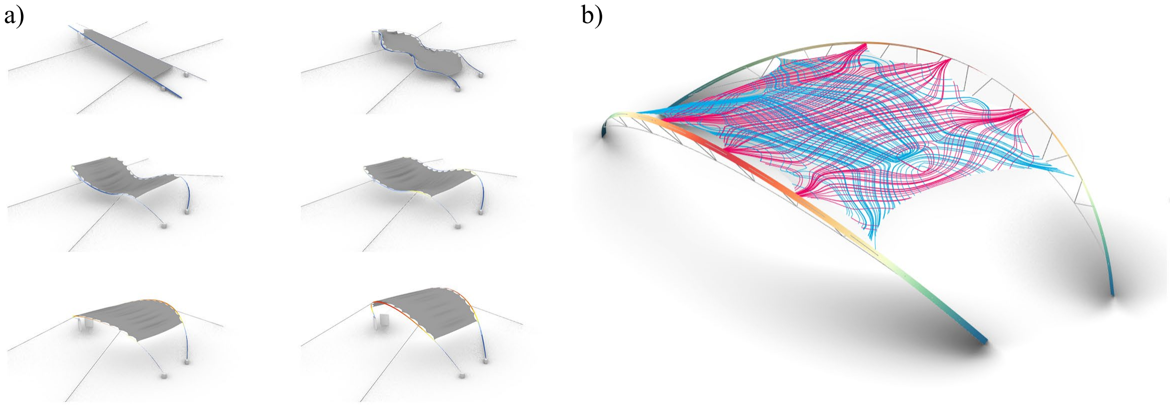

Figure 4: Computational Form-Finding: a) spring-based mesh relaxation simulation of the bending-active plates and tensile membrane, b) principle stress lines and FEA

3. Materials and Methods

In considering an outdoor amphitheater, the most material-efficient method for covering a large area is a tensile membrane. As an open-air venue, the thin covering will provide occupants with the necessary shading and moderate protection against rain. The weight of the membrane material and supporting cables is low compared to other roof options, and additional structural loads can be minimized by suspending lighting and other equipment from independent scaffolding. Under proper tension, the membrane can withstand wind, rain, snow and ice loads with minimal structural mass.

Unlike the common high point surface design, with one or more internal masts to elevate the membrane and develop the form, this design incorporates bending active elements forming a perimeter around the membrane sections, developing an arch surface. With the bending active arches on hinged supports, both membrane and arch stabilize one another. As needed, additional cable stays around this perimeter maintain the proper final tension on the membrane. The proposed hybrid construction more closely resembles a modern camping tent, with long and slender bending active elements supporting, giving form to and tensioning the membrane in concert with the anchors.

3.1. Materials for Bending Active

3.1.1. The Role of the Second Moment of Area

The relationship between the actualization forces needed for elastic deformation of a plate and the ability of the deformed element to withstand dead loads has significant implications for material and formal decision-making. While appropriate materials are crucial for success, the geometry of the bending-active element is also key. This geometric effect is encapsulated by the *second moment of area*, which for a rectangular cross section about the x-axis follows the equation:

$$I_x = \frac{bh^3}{12}$$

Where b is the length of the base and h is the height or thickness of the cross section. Maximum flexural stress in the beam (σ_{fmax})is estimated using normal stress for a rectangular beam in bending,

$$\sigma_{fmax} = \frac{3Pl}{2bh^2}$$

where *P* is the point load and *l* is beam length.

As plate thickness increases, the deflection in the structure reduces at a quadratic rate for a given load, with the peak flexural stress following a similar trend. Figure 5 shows the effect of increased thickness for a CFRP plate with a 150 GPa elastic modulus, 12 mm wide and 1 m long, under a constant 1 N flexural point load in a simply supported beam configuration. At 1 mm thickness, even a small out-of-plane load produces a 125 mm deflection, but when the plate thickness increases to 5 mm, deflection drops to 1 mm.

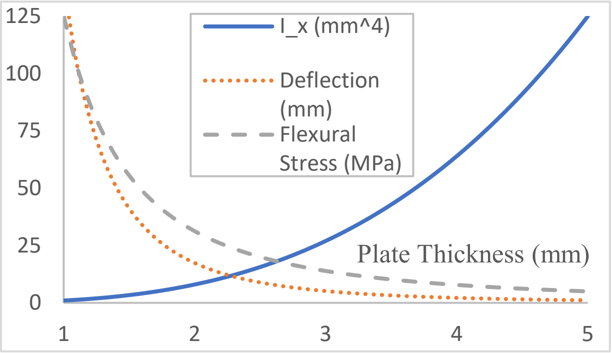

Figure 5: Effect of plate thickness on area moment of inertia, deflection and flexural stress under a constant load

For structures under significant dead loads, the beneficial effect of cross-sectional thickness is critical, and I-beams and other structural beams are often designed to maximize the second moment of area for a given amount of material. For a bending active structure, the force required to bend a plate into a given curvature increases cubically with cross-sectional thickness, which is why bending active structures are often made from long, slender beams or thin plates. The designer strikes a balance, selecting a beam profile width and depth that facilitate bending while maintaining acceptable deflection under expected dead loads.

The most suitable materials for bending-active structures are those with a flexural strength (in MPa) to elastic modulus (in GPa) ratio greater than 2.5 [Leinhard 11]. Under this guideline some metals, many species of wood and most fiber-reinforced polymers (FRP) can qualify. Though prevalent in many bending-active structures, wood has disadvantages such as natural defects and creep deformation. Defects could lead to stress cracking in a large strain, long span structure such as the bending active elements in the amphitheater design under consideration, and creep deformation could lead to a loss of pre-stress and potential elevation drop of the amphitheater's arches under the membrane load over time. Metals such as spring steels may merit further investigation, but for this application the ideal material option for the bending active elements is FRP.

3.1.2. Fiber Reinforced Polymers

As their name suggests, the fibers in an FRP are added to enhance polymer properties in some way. Typically, fibers can impart higher stiffness and strength, but they may also be selected to improve projectile resistance, thermal stability, conductivity, etc. For example, adding certain carbon fibers to epoxy can result in a composite and improve stiffness by a factor of 60. While most FRPs achieve less dramatic mechanical properties than this example, many can match or exceed metals, and their lower density makes them an attractive option for building lightweight structures. Many FRPs can withstand harsh environments without corroding or rotting and require little maintenance over time.

FRPs are inherently anisotropic, behaving more like wood than a metal or plastic. As with wood, the strength and stiffness of a composite are higher along the fiber direction. The highest performance is achieved with continuous fibers, all perfectly aligned along a single axis. Nevertheless, such unidirectional composites are weak and prone to failure if off-axis loads are present. This anisotropy can be a disadvantage in applications where a designer desires more uniform material behavior, and various fiber forms exist where continuous or chopped fibers are arranged as randomly as possible to mitigate anisotropy (Fig. 6).

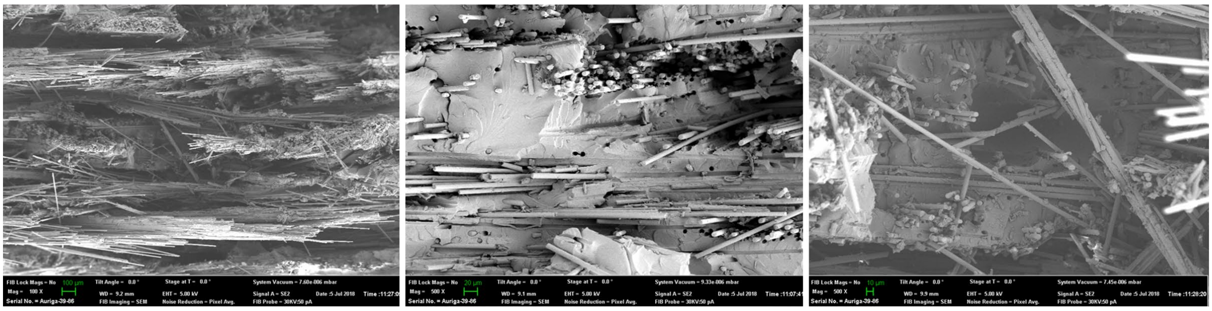

Figure 6: Scanning Electron Microscope (SEM) images showing random fiber orientation in a nonwoven carbon fiber reinforced epoxy material [Photo courtesy Ghossein et al., [12]]

In high-performance applications, engineers often utilize the anisotropic behavior of FRP to maximize material efficiency by arranging fibers in a specific stack of layers or plies called a laminate, controlling the orientation of each ply to best resist the loads present in a structure. Such highly efficient structures require specialized engineering knowledge and manufacturing capabilities not widely available outside of the aerospace industry, which is why many FRP applications utilize either "quasi-isotropic" fiber arrangements or pre-fabricated FRP elements such as pultruded beams and tubes with known properties and pre-determined fiber architecture.

3.1.3. FRP for Bending Active Structures

For the amphitheater prototype model, carbon fiber and epoxy were selected as the highest performance and therefore most material efficient fiber and polymer system. There is a wide range in mechanical properties within carbon fiber when comparing fiber architectures (chopped, fabric, unidirectional) and grades (standard modulus, intermediate modulus, high modulus). Pultruded standard modulus carbon fiber has the best combination of mechanical performance and economical cost and is well suited for bending active applications.

3.2. Membrane Materials

Tensile membrane structures are well established, with standardized materials that have undergone extensive testing to validate their suitability. The most common membrane materials are fluoropolymer foils, polyester/ Polyvinyl Chloride (PVC) fabric and Polytetrafluoroethylene (PTFE) /fiberglass fabric. For large span structures, coated fabrics are the preferred option. PTFE/fiberglass is both durable and has the highest strength to weight ratio, making it the most efficient material option and the ideal selection for the amphitheater roof design. However, special care must be taken with PTFE/fiberglass during installation to avoid kinking and minimize creep (Seidel, [13])

5. Fabrication

5.1 Novel Cable Integrated Plate Design

In designing the amphitheater, there were several options to consider for actuating the eight bending active plate elements supporting the tensile membrane roof. By transferring dead load from the tensile membrane onto just eight plate elements, the structural requirements for each plate are much higher and the plates must be thick enough to counteract the higher loads, further limiting bending due to self-weight alone.

The same cable used to resist lateral loads can also be used to actuate bending in the structure. In the simplest form, the cable is fixed to one end of the plate and routed through a point on the other end of the plate. Traction on cable pulls the two ends of the plate closer together, similar to a bow. While this simplest cable-actuated system is functional, in an architectural application such as a roof there may be practical drawbacks to a permanent cable that spans the chord of an arc along its lowest point.

One solution that doesn't obstruct the open space of a bending active roof routes the cable through a series of points close to the plate, elevating the path of the cable above the bottom plane of the plate's curvature. The cable-integrated elastic kinetic plate design, with the cable routed through a series of struts attached to the plate at longitudinal intervals.

For the hybrid structure considered in this research, the eight plate elements adopted a cable-integrated approach with a novel variation that enabled more rapid fabrication. Since the struts in a cable-integrated plate will, if properly designed, experience pure tension loads when traction forces are applied to the cable, these struts could simply be replaced with tension cables. Further, instead of placing struts perpendicular to the longitudinal axis of the plate, potential stress concentrations on the plate may be more evenly distributed by replacing the struts with pairs of tension cables in plane with the longitudinal axis of the plate. When a traction force is applied to the cable, the tension cables become taut and restrict the cable path into an arc following the curvature of the plate.

5.2 Plate Prototypes

For CFRP fabrication trials, arches were first constructed using 1 mm thick sheets of twill weave carbon fiber fabric with epoxy matrix. Flat strips 25 mm wide were cut out on a CNC router, with holes placed at even spacing for routing the cable in truss arrangement. Instead of using rigid truss frames to support the tension cable, the trusses geometries are formed as load is applied to the tension cable, and the resulting cables will be under pure tension loading, planar with the tension cable. The cable configuration in the trial CFRP beams featured one continuous length of cable forming both truss and tension cable.

Figure 7 illustrates the method of cable routing for these bending active trusses. The cable is first loosely guided through the machined hole pattern in an alternating "stitch" pattern (Fig. 7a), after which the free end of the cable is routed through each of the previous stitch loops on one side of the plate (Fig. 7b). When this free end is actuated (Fig. 7c), the loose stitch pattern pulls taut to form a truss pattern.

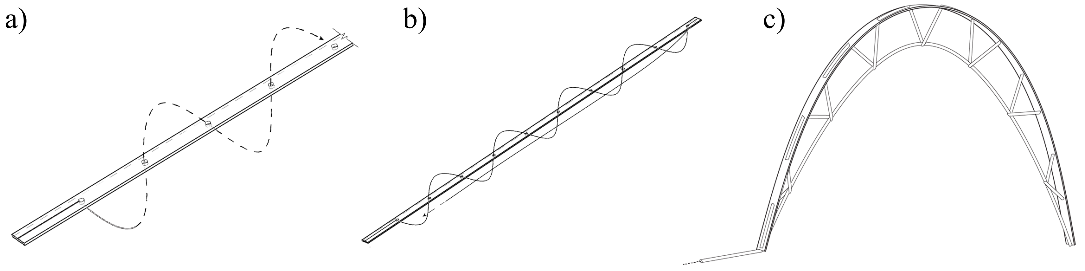

Figure 7: Method of routing one or two lengths of rope to form novel cable-actuated plate

5.3 Scale Model Prototype Fabrication and Assembly

5.3.1. Curved Plate Fabrication

In fabricating the curved plates for the final scale model prototype, several changes were implemented. First, the material switched from twill weave CFRP panels to unidirectional pultruded CFRP flat bar stock. With this change, the material most closely resembles what would be readily available for use in a large scale bending active structure, making it a more accurate material behavior. Second, the single cable method was altered to use two cables, one to form the trusses and another to form the tension cable. This made it easier to adjust the height of the truss and was particularly useful when different gauges of wire were needed to handle the higher stresses in the tension cable.

The CFRP arches were prepared by first splitting the bar stock to the proper width for the model. The bar stock began at a profile of 62.5 mm x 1.3 mm, but the design required 12 mm width. Fortunately, because unidirectional CFRP has fibers aligned along its length, it can be split by scoring then cutting along a line parallel to its length. It was imperative to then thoroughly wet sand the split surface to avoid splinters during construction.

Once the bar stock profile was at the proper dimensions, the stock was then cut to length for the various arches. The lengths were determined using the arc length dimension on the Rhino model (Table 1), then the stock was precisely cut using a wet saw with a diamond cutting blade. Each piece was then marked with the proper hole spacing (100 mm for long arches and 50 mm for short arches) and drilled along the beam centerline using a jig on a drill press. After wet sanding and cleaning with acetone to remove carbon fiber dust, the pieces were ready for cable routing.

	Span Length (mm)	**Arc Length (mm)**
Short Span	460	725
	850	925
Long Span	1050	1400
	1110	1500

Table 1: Span and Arc Lengths for Trimming CFRP bar stock

5.3.2. Cables Routing

Cable routing began with the truss pattern section, lacing 0.61 mm stranded steel wire rope loosely through the holes to create an alternating stitch pattern, starting at the second hole on the palate and terminating at the second to last hole. This wire was permanently secured on one end and temporarily secured on the opposite end to allow for later adjustment to achieve proper height and arch span. Next, the tension cable was secured to the first hole at the end of the beam, then laced through each loop along one face of the beam before terminating at the last hole at the opposite end of the plate. Once thus routed, a traction force could be applied to the free end of the tension cable, causing the trusses pattern to form and bending the plate into an arch. Once the proper arch length and truss pattern was achieved by adjusting the length of the two wires, both wires were secured, and the arch shape became fixed in a stable pre-stressed state (Fig. 8)

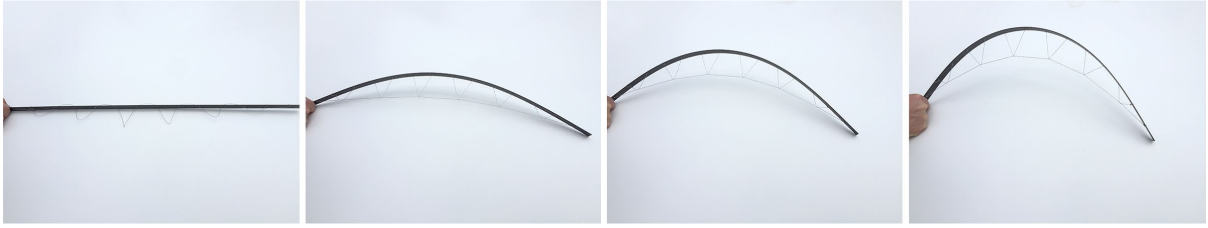

Figure 8: CFRP plate actuation of the scale model prototype

5.3.3. Stability under loading for long span arches

In constructing the arches, adjustments to the fabrication process were required for the long span (1050 mm to 1110 mm) variety. With short span (460 mm to 850 mm) arches, a single layer thickness of CFRP and tension with the 0.61 mm wire sufficed to fabricate a pre-stressed structure that could remain stable under its own weight and the dead load of the tensile roof membrane.

At longer spans, the pre-stress on a single layer of CFRP bar stock was insufficient, and a larger area moment of inertia was needed to create a beam rigid enough for subsequent roof membrane loads. With larger area moment of inertia, the traction force also increased and larger diameter, 1.59 mm stranded steel wire was used as the traction cable to withstand the higher loads. Increasing the plate thickness solved the instability issue and was achieved by bonding together 2-3 layers of pultruded bar stock for the large span plates (Fig. 9).

Figure 9: Instability under loading for long span arches

5.3.4. Site Model Assembly

Apart from the self-stable bending active plates, the remainder of the prototype was constructed on a scale site model. Each pre-fabricated bending active element was adhesively bonded into 3D printed anchors, with the anchor holding the arcs at the proper angle for the design. The self-stability of each cable-actuated arc removed what would otherwise be significant thrust loading from the anchors, allowing relatively small anchor structures to carry the remaining dead load.

Once the arches were in place, the tensile membrane was cut to size and hand sewn in place. Instead of PTFE coated fiberglass, the site model used a lightweight fabric with high stretch to simulate the behavior of a full-scale membrane. Corners of the membrane were attached the existing hole pattern on each arch, with the arches providing most of the membrane tension. For additional tension and to prevent inward rotation of the arches, several rope stays were added to the outermost arches and anchored to the ground (Fig. 10).

Figure 10: Scale model with CRFP bending active plates and tensile membrane anchored on site the model

6. Conclusion

The authors consider this research as a first step toward a novel, fully integrated approach of a hybrid bending-active high-performance structure system and enabling that will yield fresh insights into the possibilities of bending-active application for the future of lightweight structure.

The work presented in this paper demonstrates a new potential for carbon-fiber-reinforced-polymers in realizing formally engaging, curved structural elements through active bending. The high flexibility to strength ratio of such plates paired with the current customization potential of fiber topology provides an ideal material for elastic deformation. CFRP can also achieve smaller member thickness and lighter weight while increasing potential span lengths compared to wood plates or glass-fiber-reinforced-polymers. What's more, such structural elements can be transported as planar sheets and assembled on site, reducing costly transportation.

The use of spring-based computational design and FEM of the elastic deformation process, addition of a stiffening tensile membrane, and overall performance of the structure opens new pathways for the design of bending-/form-active hybrid structures. This process overcomes the historic unpredictability of bending behavior and structural performance of pre-bent elements, enabling designers to accurately use computational form-finding and analysis to generate models that go beyond modeling bending behavior alone. The parametric iterative nature of such computational analysis also allows for the design and testing of myriad arch, cable, and membrane topologies with zero material waste.

The construction of a scaled physical model further serves as proof of concept, joining CFRP plates, a self-equalizing modification of a cable actuation system, and tensile membranes to construct a lightweight, materially and high-performance roof system. The modified cable system provides additional support along the long axis of the plates, resulting in more consistent flexural stresses along the length of the CFRP plates and reducing unanticipated deformation under dead loads.

Scaling Considerations: While this research demonstrates the conceptual viability of bending-active hybrid high performance lightweight structures, it also opens the door to future investigations regarding full scale application. While the tensile membranes certainly demonstrate a lateral effect on the arches, the nature of the materials used for model support piers (rigid foam insulation and PLA prints) necessitated the addition of wire cables to counteract the pull of the membrane. This points to the need for future investigation into support anchors and attachment points for the tensile membranes to achieve maximum stiffness.

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