Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Pop-up Asymptotic Structure with Woven GFRP Rods Fabricated in Mixed Reality

Nicholas BRUSCIA*, Emily VOLLO[a], Yau Wai LAM, Huiying TAN[a]

*Department of Architecture, University at Buffalo, State University of New York
Buffalo, New York, USA
nbruscia@buffalo.edu

[a] Department of Architecture, University at Buffalo, State University of New York

Abstract

The research outlined in this paper has a dual focus: first, to investigate asymptotic structures made from GFRP rods and tensioned membranes, and second, to develop a mixed reality workflow to assist in the design and assembly of the structure. Drawing inspiration from the elegance of Frei Otto's music pavilion at the 1955 Bundesgartenschau, we reimagined the tensioned membrane to rely on a stable bending-active asymptotic frame. Instead of cables and masts, the hyperbolic surface is autonomously formed as the frame reacts to its internal bending forces. The placement of nodes along curved cylindrical beams, calibrating bending behavior to a predictive simulation, and the shaping of a custom textile are discussed as a useful case study for mixed reality fabrication.

Keywords: Pop-up Structures, Asymptotic Grids, Lightweight Structures, Mixed Reality

1. Introduction

The work outlined in this paper demonstrates the use of mixed reality (MR) toward the form finding and assembly of a lightweight bending-active frame with a tensile fabric covering. MR workflows can help facilitate real-time visual information exchange between the designer and fabricator, allowing for accurate assembly without the need for CNC or robotic fabrication equipment. An important consideration in the successful deployment of MR fabrication is the fidelity of calibration. Dynamic structures, for example form-active (Engel, [1]) and bending-active systems (Lienhard et al., [2]) remain a challenge for MR calibration. While the simulation of their physical behavior has become far more accessible with the sharing of user-friendly computational form-finding tools, often arbitrary numerical inputs stand in for actual physical attributes. MR presents an interesting opportunity to pair those attributes with the on-screen simulation by comparing it visually at 1:1 scale to its physical (and fraternal) twin. Since each are dynamically adjustable to an extent, the MR user can attempt to adjust the simulation to match the prototype in real time, vise-versa, or both. Within the context of an educational setting, we aimed to investigate a MR workflow that would guide the fabrication and assembly of a small hybrid structure consisting of bending active elements and a tensile membrane by first studying each independently. We adopted the definition of hybrid structures as the combination of two or more structural concepts and materials to create a stronger whole (Holden Deleuran et al., [3]) and for the purposes of this investigation, blended elements of preceding research on bending active and asymptotic structures. Asymptotic grids materialized by cylindrical bending-active rods is presented here alongside the MR workflow as both a work in progress and as a contribution to the ongoing and preceding research.

A series of methodological experiments were conducted to gain an understanding of material behavior, sewing requirements, and joint connections. Holographic guides of 25 individual templates developed from the simulation guided the manual tracing and cutting in a mixed reality process akin to tailoring. The same simulation was used to fabricate a full-scale jig that allowed for the precise placement and bending of GFRP rods and their connections along the flattened asymptotic grid. The center lines and node locations were then holographically calibrated to the jig to guide the assembly of the frame. Upon releasing the assembled frame from its constrained position, an anticlastic surface pops up as the bending stresses find equilibrium. MR mapping was also used to adjust and confirm the structure's likeness to a desired target form.

Figure 1: Lightweight GFRP asymptotic grid.

2. Model-Material Coordination

Direct connections between digital models and physical environments have long been studied and applied to the AEC industry. Precisely locating 2D drawings within corresponding physical spaces and part placement in a larger assembly through marker-based systems has been an area of investigation for several years (Jahn et al. [4]). Much more recently, advancements to the accuracy of marker detection and improved accessibility to cutting-edge hardware and software have given rise to an increasingly growing community of interdisciplinary researchers contributing a wide variety of uses for MR in design and construction. Coordinating digital models to physical objects is a critical step in MR fabrication. While one can decide on the amount of visual discrepancy is allowable within the specific task at hand and the materials used, it is of course advantageous to achieve low tolerance calibration in the holographic reproduction of the model. However, if MR is to guide manual fabrication and assembly sequences to create non-standard results outside the range of experience, it is useful to consider what the MR experience offers that low tolerance machine fabrication processes do not. The design space of allowable tolerance to measured precision is a topic worthy of further discussion.

2.1. Calibrated and Interactive Modeling

Coordination between digital models and material systems with variable stiffness and inherent flexibility has precedent prior to the release of AR technology into the public sphere. For example, the computational modeling pipeline developed by Deleuran, Quinn et.al combined the geometry definition, form finding, and structural analysis into a single, flexible 3D modeling environment (Quinn et al., [5]). The pipeline allows for intuitive but materially informed proof-of-concept models to be quickly analyzed for structural performance by applying real-world material characteristics and mechanical properties to the various elements. To calibrate the digital elements to represent actual material behavior, the authors devised a "validation rig" to map the computational simulation to a material test using a 2D projector [5]. The user specifies the material properties, the specific locations of anchor points, and the exact load applied to a physical component that is affixed to the same surface used for the projection. By visually aligning the bending simulation of the component to its actual bending geometry, the numerical inputs that are typically arbitrary are given specificity and the simulation of larger structural systems are thus calibrated to the specific material, resulting in accurate and predictive models.

Inspired by this work, previous attempts by the first author at precisely calibrating material behavior to simulations were done using a Vicon Vantage V8 and Vero v2.2 optical motion capture system. Infrared reflective markers were placed along the length of a timber laths that were bent upward using a rig that applied consistent force at a measurable distance. The motion capture system recorded the movement of the markers and published the coordinates into a spreadsheet that was fed into a parametric model. Cycling through the data animates the motion of the lath. A bending simulation using Kangaroo2 [Piker, [6]) was performed simultaneously using the same two end points extracted from the dataset, and the simulated polyline was adjusted using numerical inputs to match the form of the motion capture data. A structural analysis using K2Engineering followed, adding further accuracy to the comparison. Motion capture is useful for calibrating materials to models but requires highly specialized equipment. MR is less limited by cost and space requirements, but calibration tolerances must be considered.

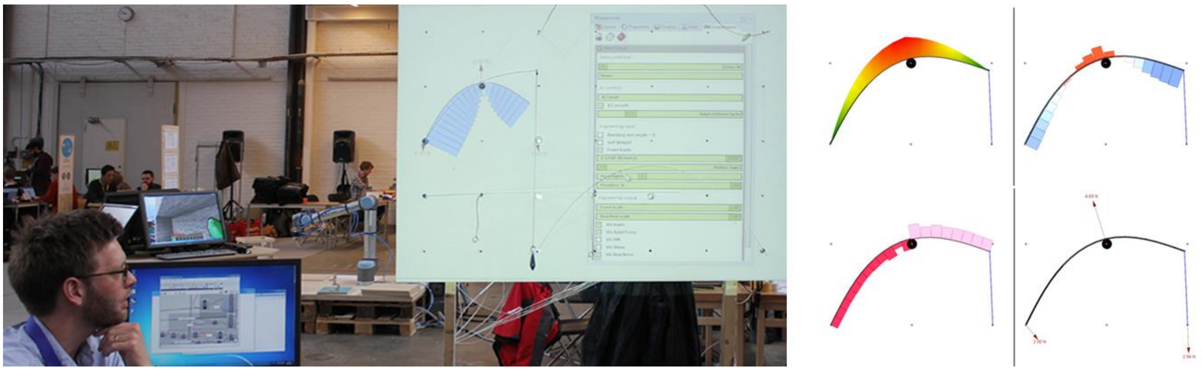


Figure 2: Quinn et.al [5]: AR projection board for calibrated bending simulation, SmartGeometry 2016. Photo: Cecilie Brandt-Olsen. Custom GUI visualizing internal and external forces.

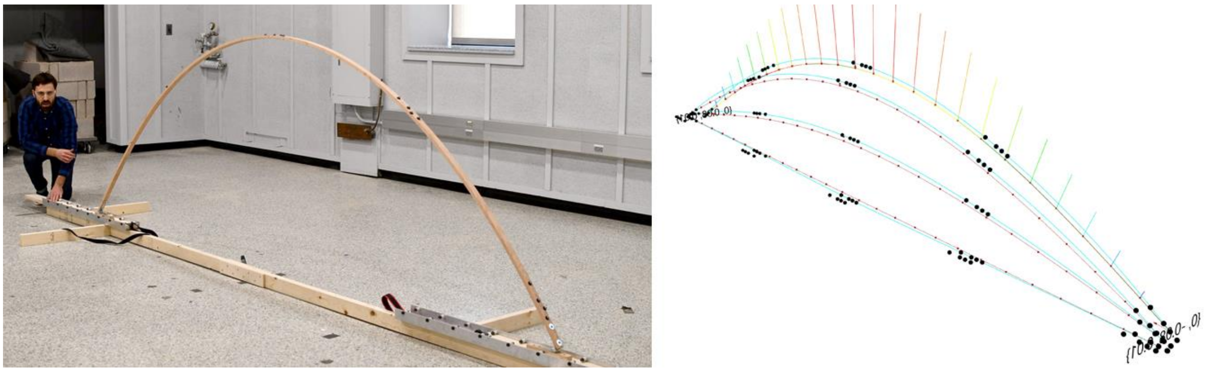


Figure 3: Motion capture and simulation of timber lath bending at the SMART Motion Capture Lab, University at Buffalo, SUNY, 2018.

2.2. Mixed Reality Guides

More recently, a wide range of projects have successfully implemented a MR fabrication workflow and have shared their findings through numerous publications. Perhaps the most aligned with the MR portion of this work is the physics-based MR fabrication of bamboo structures by Kyaw, Otto, and Lok [7]. A MR user interface provides direct access to numeric parameters that adjust characteristics unique to bamboo while on site, allowing for real-time adjustments that improve accuracy and influence in-situ design decisions. By comparison, physics-based simulation is used in this research as an interactive assessment of physical models, and as a design model used to determine the correct length and geometry of bending active composite rods when laid flat on the 2D plane, and to precisely locate the positions of node connections that maintain a specific angle between the rods.

The calibrated MR model of the flattened grid geometry acts as the visual component to the hybrid digital/physical jig used for assembly and guides the manual bending of each member in the system. The simulation of the 3D model in MR space is used as a benchmark to compare the resulting structure to the predicted target form but is not required for assembly. Since the rods are guided into a flat configuration of asymptotic curves that are derived from the simulation, the structure self-forms when released from the physical components in the jig. The internal bending forces inherent to the asymptotic grid find equilibrium by forcing the structure to twist into an anticlastic surface.

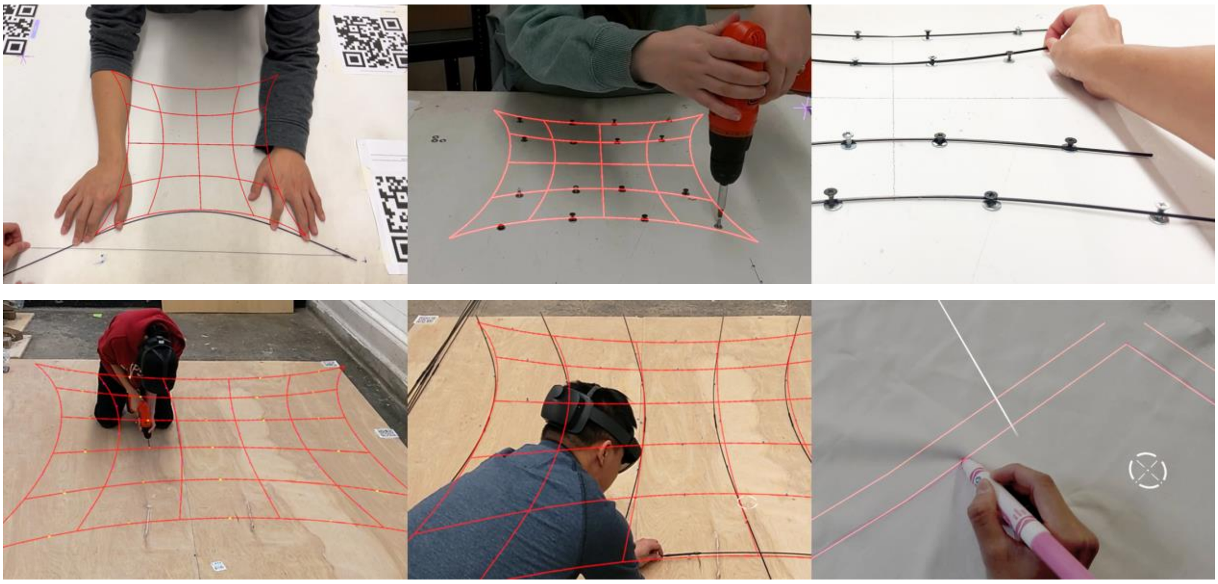


Figure 4: Mixed reality guides the fabrication and assembly of the asymptotic frame and tailored fabric patterns.

3. Rod and Tube Asymptotic Lattices

To further investigate an MR workflow that pairs bending simulation with physical action, we looked to preceding research on asymptotic structures and were primarily inspired by the work of Eike Schling et.al. [8] and Emil Adiels et al. [9]. Asymptotic grids provide a pathway to efficient fabrication and material usage because when drawn from a surface with complex curvature, their extrusions along the normal direction can be unrolled into straight and planar lamellas without distortion. They are particularly interesting due to their inclination to reshape from a flat configuration into a 3D form due to the internal energy that builds within the material as the individual elements are bent into position. Although we recognize the structural advantages of utilizing flat lamellas to resist normal loads (Schling et al. [10]) we sought to maintain our interest in lightweight composite rods within the asymptotic framework and evaluate the scalability of their behavior as a compliant mechanism (Howell, [11]).

Material continuity is advantageous to bending active structures, and in addition to the connections between crossing elements, are key details that must be considered prior to assembly. Flat lamellas when used in a single layer can be notched at the crossing to form a simple connection between the two thereby easing assembly, but the notch weakens the material and reduces its bending resistance at the joint. This limitation can be overcome, and successful implementations of this type have been documented in the above examples. To avoid notching, lamellas can be configured in two non-intersecting levels and each lamella can be built with two parallel slats creating a square node between the crossing set of four planks. Recent prototyping has shown that inserting studs or capping and post-tensioning the node both increases the lateral stiffness of the structure while maintaining material continuity [10].

Pultruded and filament wound composite rods in asymptotic configurations also require attention to the connection detail. To increase length (and by extension, scale) planks can be lapped and extended and rods can be coupled either internally (in the case of tubes with inserted ferrules) or externally as seen in common tent poles. Rods can be connected at their crossings with swivel clamps (see scaffolding clamps for a common application at a larger diameter), tied lashings (common in bamboo construction), or with custom details that maintain specific angles while the structure transitions between its flat and formed states.

4. Discussion

4.1. Initial Investigations in Mixed Reality Modeling

We started the investigation by creating a series of four maquettes based on Frei Otto's music pavilion built in 1953. For each study, the team used K2 to simulate the pavilion's structural form at a small scale. Four textiles with varying degrees of elasticity and stretch bias were cut into 6" x 6" squares (~150mm). With the pavilion's physical characteristics established, we employed a Microsoft HoloLens2 headset to overlay our digital simulation onto the physical model. Fologram [4], a third-party plug-in for developing mixed-reality models in Grasshopper and Rhino3D, was used to calibrate the K2 simulation. In MR we were able to pinpoint the locations of anchors, and with the fabric secured in these two opposing corners, two team members could pull the adjacent upper corner in equal opposite directions introducing equilibrium amongst all four force origins.

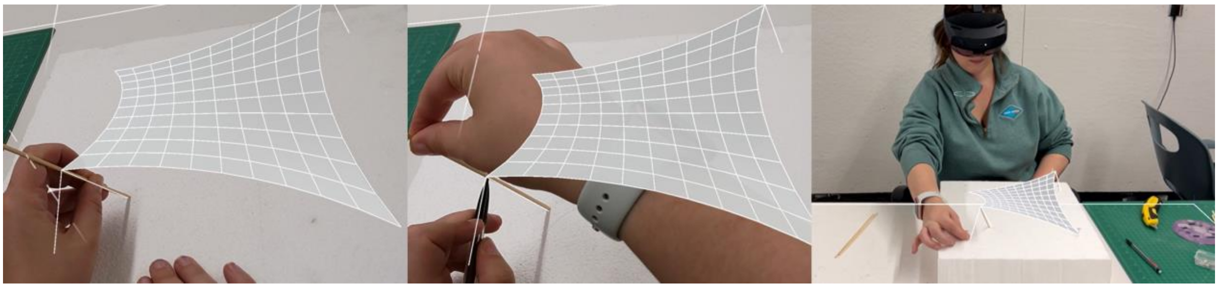


Figure 5: Mixed reality modeling of angles, lengths, and form of a simple cable-stayed tensioned membrane.

These two upper anchor points belay onto a 1/8" diameter bamboo rod which receives the thread through a tiny notch cut perpendicular to the cylindrical form's top face. The bamboo supports are 2" in length and penetrate the earth at an acute angle. The angle and length of these members were quickly measured by aligning the physical material to the holographic projection. With the notch threaded, there is enough friction to stabilize the structure temporarily. The end of the thread is then tied back to the ground plane to their exact coordinates located using HoloLens.

Further investigations reconsidered the tensioned membrane from a variable to a control component. We used the same 24" x 24" textile cuts in each iteration to focus our testing efforts on variable form connection locations. Three variants maintained four edges while adjusting the quantity and location of connection points. One variant assessed a connection point along the textile surface. In the final three variants we increased the polygon edges from five to six and finally eight edges while confining the edge points to the polygon corners only. For this next iteration, the K2 script required a set of arbitrary numerical inputs assigned to the spring force to start the simulation and adjusted the parameters to find the closest numeric value that best described the elastic properties of the control textile. We calibrated the model's parameters to the physical model using HoloLens, working backward to find a representative value for the textile. Once we achieved a suitable alignment, we were able to use the established values for the remainder of the form-finding investigations.

Figure 6: Form finding tensioned membranes (black textile) guided by mixed reality overlay (white and green).

Understanding how to establish goals and adjust variables quickly provided a foundation for rapid exploration and iterative AR-guided form finding. MR calibration requires precise coordination between the digital coordinate system and the physical environment. Although absolute precision was a lower priority at this stage due to the maquette's scale, it was beneficial to walk the designated workspace exploring all spatial conditions in-situ. This dramatically improves the level of precision due to the increased amount of environmental data collected by the headset.

4.2. Asymptotic Grid Development

Transitioning in scale, our design objective was to reimagine Frei Otto's classic structure as a rapidly deployable, self-supporting structure that relinquished earth's counterforces while still embracing the elegance of the original. Asymptotic grids built from GFRP elastic rods became the technique in focus. The flat asymptotic grid is modeled first in 3D along the targeted hyperbolic surface, followed by a bending simulation that flattens the grid onto the XY plane. A hyperbolic surface is modeled within a bounding cube, with the two high points lifted to a height that matches the width in both directions.

Using the Bowerbird plug-in for Grasshopper, asymptotic curves were drawn along the surface from a series of equidistant points along two adjacent edges. Given the target geometry, these lines match the generating lines of the ruled surface in 3D but translate to curves when flattened. The intersecting lines are subdivided into polylines. K2 performs the bending simulation on the polylines by enforcing a 0-degree angle between each pair of polyline segments. The vertices of the polyline grid are forced onto the XY plane, while the bending forces applied to the polylines maintain their overall lengths and node locations. The resulting curves represent the asymptotic grid in its most active and unstable state. The structure is assembled flat using this model as a guide, and when lifted away from the work plane the internal forces cause the structure to automatically twist into a stable approximation of the target surface. This behavior was observed in each of the trials described in the following sections.

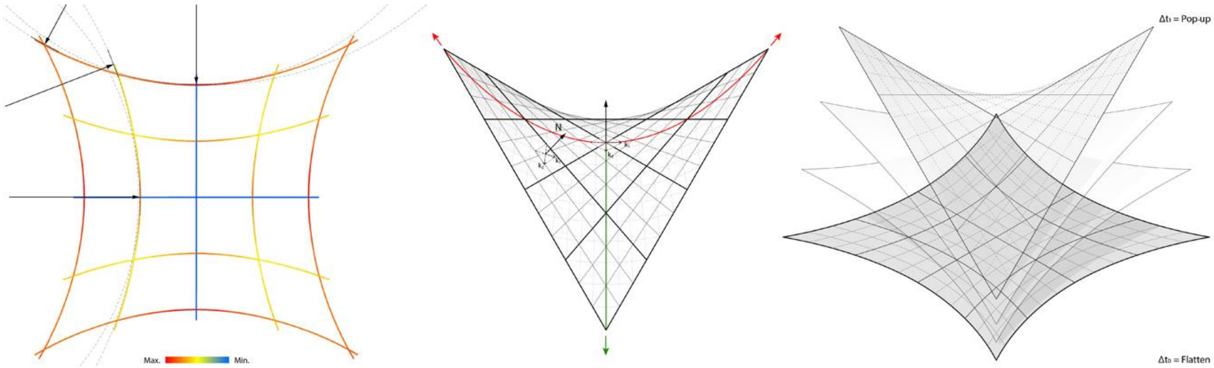


Figure 7: Physics-based simulation to find the flat asymptotic grid and visualize compliant behavior.

4.3. Small Woven Study

With the HoloLens visualizing the flattened asymptotic grid, we drilled pilot holes at each of the 25 nodes due to receive both a small screw and washers. A washer provided leverage tolerance, which was handy when it came time to assemble the framework. With the screws in place, 1/8" (~3mm) solid carbon fiber rods were woven latitudinally first, going under the outer two nodes and over the inner two nodes. With the five horizontal rods in place, we continued with the vertical rods, starting in the bottom left-hand corner below the horizontal rod and alternating over and then under each of the horizontal members, and alternating the vertical member's starting point above and below the horizontal member as we moved from the center outward. This created a bilaterally symmetric weaving pattern. A diagonal lashing knot technique hardened with a dab of epoxy adhesive secures each intersection. The same textile used in previous trials accompanies the framework with grommeted attachment points at the ends of the rod members. With all the materials in place, the model is released from the jig constraints, immediately popping up into its stable, anticlastic state. The internal forces are high at this scale. The model springs up and off the table if not released gradually. We observed that the weaving increased the internal forces and overall stability.

Figure 8: Natural elastic transformation from flat to form. The model rises from the table automatically.

4.4. Woven Prototype 1

An emergent goal of the research was aimed at scaling up the observed pop-up behavior of rod-based asymptotic grids. We decided to enlarge the form's overall dimension to six feet by six feet in the next iteration. At this scale, the support of HoloLens was instrumental in streamlining the MR workflow. To start, the digital model is calibrated to accommodate the new dimensions, an additional curve in both the x and y direction is added, increasing the number of nodes tangent to each curve from five to six resulting in a central square cell.

A physical work plane was constructed from two sheets of 4'x8' plywood to which we fastened a screw and washer at each node location as indicated by the holographic overlay, as shown in figure 3. The twelve asymptotic curves, woven into a similar warp and weft pattern as described above, were materialized with 48" solid GFRP rods at 5/32" dia. (~4mm). Each curve was made of 2 rod lengths which were spliced together with an external ferrule at their midpoint. We again employed the HoloLens to view the form's flat state overlayed on the plywood work plane to determine each curve's length and midpoint locations. Once all 24 rods were properly spliced, cropped, and capped and the jig was assembled, the group was ready to weave the GFRP framework. Once assembled, each intersection was lashed with braided fishing line and hardened with a coating of two-part epoxy.

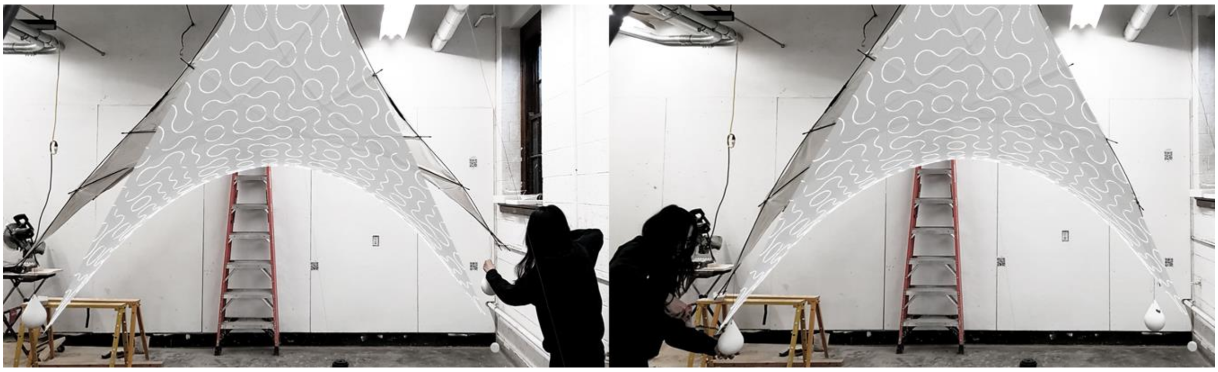


Figure 9: Adding weight to the corners of a suspended elastic frame to match target form in mixed reality. The holographic pattern aids in the visual calibration.

The MR workflow was again integral to the fabrication and assembly of the covering membrane. Each of the 25 individual patches were isolated in the parametric model and visualized in MR. With a simple UI, the user toggled through the list of parts and manually traced the selected profile onto the fabric following the MR template. With the ability to draw geometries freehand we eliminated a significant amount of fabric waste. The MR workflow sped up the workflow process eliminating the need to cut a physical template for each geometry. With the sewn textile overlaying the woven GFRP framework, the fully assembled structure was released from the jig, failing to pop-up automatically. We attribute this to two variables. First the GFRP diameter to length ratio did not provide the necessary stiffness, and secondly, the textile was too heavy for the frame to exhibit what minimal pop-up behavior of which it was capable. When the textile was removed, the frame did exhibit subtle snap-through compliancy.

4.5. Woven Prototype 2

Taking inventory of the previous iteration's learning outcomes, we adjusted the rod network, materials, and connection details. Waterjet cut ⅛" (~3mm) aluminum plate was fitted between the larger 0.370" (~9.5mm) OD filament wound GFRP hollow rods with an ID of 0.290" (~7.5 mm), spliced together at two joints each using internal ferrule with an OD of 0.290 (~7.35 mm). A series of aluminum threaded spacers fastened to the plate with #4-40 (~M3) socket head cap screws constrain the rods to the angles at which they cross, reinforcing the desired bend in each. Standard plastic cable ties secure the rods to the plate in two places, providing enough friction in the joint to prevent sliding.

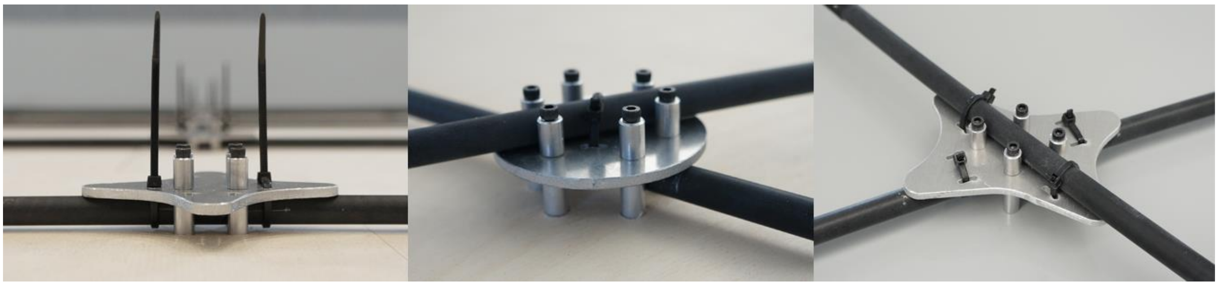
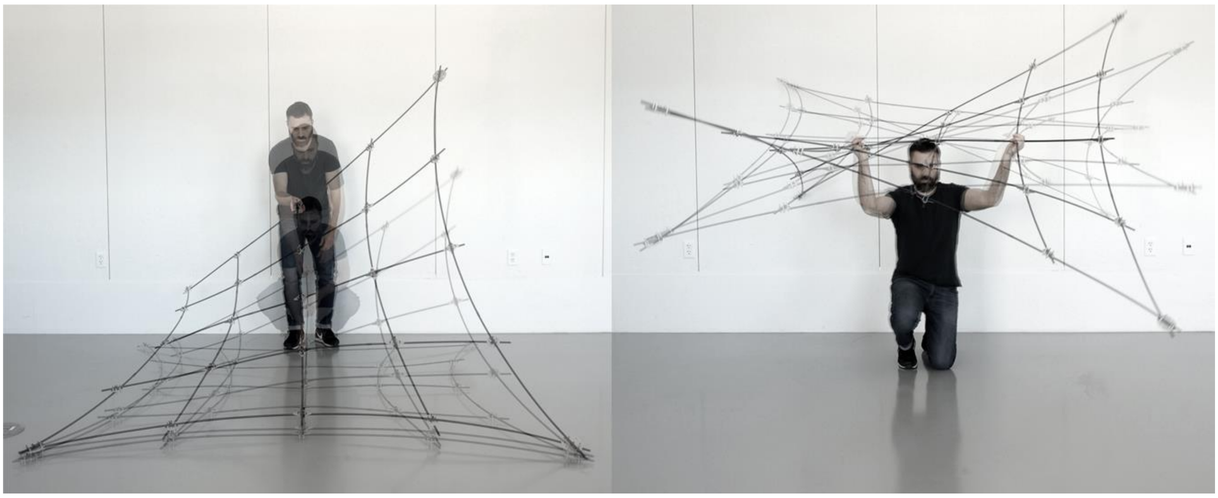


Figure 10: Plate-and-tie connections enforce intersection angle between woven rods. The longer threaded spacers attached to the bottom of the plate are set into holes in the jig, maintaining plate position during assembly.

The plate-and-tie connection is versatile and may be deployed for other cylindrical extrusions as a supplement to traditional lashings. A combination of both fixed angle plates and connections that allow rotation at the crossing may also be an option for kinetic rod-based asymptotic grids (Schling and Schikore, [12]). A variety of other node types are being considered for future experimentation, such as fixed nodes that allow stacked crossings of continuous rods and in-plane rod segments that start and end at each joint to form a single layer grid. In this current iteration, CNC drilled holes fix the position of the threaded spacers extended in length at the bottom of the plate connection. In earlier iterations, nodes were located using MR, a process that remains a case study for future investigations at a larger scale where the use of a constructed jig is cost prohibitive and unnecessary. MR is seen here as particularly useful in the assembly of rod and tube lattices when member lengths exceed a dimension that can be reasonably accommodated, and because cylindrical materials are difficult to process with digital fabrication equipment. This prototype with its increased bending stiffness due to improved node connections, larger diameter rods, and woven topology exhibits noticeable improvement in the expected behavior.



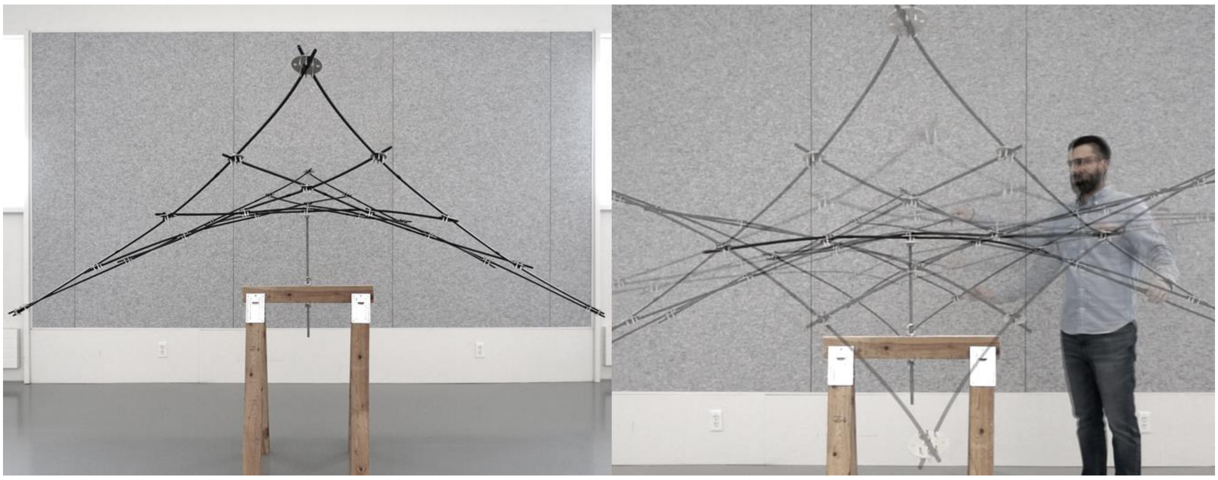


Figure 11: Woven GFRP asymptotic frame snapping between stable positions.

5. Conclusions and Outlook

As noted by Schling et.al., a structure utilizing a material's elastic deformation will face challenges in supporting its own self-weight and external loading and increasing the bending stiffness contradicts the intention to productively incorporate bending forces into the structure's stability [8]. Our small-scale model demonstrates great stability, easily supports its own self-weight and resists loading, but this is difficult to repeat at a larger scale.

The most recent prototype was first assembled in two layers, with parallel rods residing in-plane. The structure was also unable to resist its own self-weight while laying against the ground but did exhibit self-forming when manually suspended such that the rods were able to bend and re-adjust freely. The structure's form that arises is far from the target geometry modeled digitally. While some discrepancy is to be expected due to friction, torsion resistance and other physical conditions, we assumed that by increasing the bending forces in the rods, a closer approximation may be possible. In the described prototyping we recognized that a unique characteristic of elastic rod elements is that they can be woven, thereby increasing overall bending resistance. Plank lamellas provide stiffness in the normal direction, but they must be assembled with notches in a single layer or stacked into two uninterrupted layers. Alternatively, FRP rods can be woven between the nodes, can be fabricated into short lengths with couplings for easy transport, and are extremely lightweight. The second woven prototype demonstrates a noticeable increase in overall stiffness, a closer approximation to the target form, and increased resistance to snap-through buckling (revealing that the flat state is under more stress). These results have encouraged future investigations into woven asymptotic grids and their potentially unique characteristics.

Acknowledgements

The work presented in this paper was produced with grant funding awarded to co-author Bruscia by the University at Buffalo School of Architecture and Planning, the Buffalo Renaissance Foundation, and the Nohmura Foundation for Membrane Structure's Technology. Co-authors Vollo, Tan, and Lam developed an initial version of the project in the 'Fidelity and Tolerance: Phantom Fabrication' graduate research studio taught by Bruscia. Woven Prototype 2 was developed and completed by the authors in collaboration.

References

[1] H. Engel, *Structure Systems*. New York: Praeger Publishers, 1968.

[2] J. Lienhard, "Bending-active structures: Form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein," Ph.D. dissertation, Institute of Building Structures and Structural Design (ITKE), University of Stuttgart, Stuttgart, DE, 2014.

[3] A. Holden Deleuran, M. Schmeck, G. Quinn, C. Gengnagel, M. Tamke, M. Ramsgaard Thomsen, "The Tower: Modelling, Analysis and Construction of Bending Active Tensile Membrane Hybrid Structures," In *Proceedings of the IASS Annual Symposium 2015 – Future Visions*, Amsterdam. 17-20 August 2015.

[4] G. Jahn, C. Newnham, N. van den Berg, "Making in Mixed Reality – Holographic design, fabrication, assembly, and analysis of woven steel structures," In *Recalibration: On imprecision and infidelity – Proceedings of the 38th Annual ACADIA Conference*, Mexico City. 18-20 October, P. Anzalone, M. Del Signore, A.J. Wit, Eds. 2018. pp. 88-97.

[5] G. Quinn, A. Holden Deleuran, D. Piker, C. Brandt-Olsen, M. Tamke, M. Ramsgaard Thomsen, C. Gengnagel, "Calibrated and Interactive Modeling of Form-Active Hybrid Structures," In *Proceedings of the IASS Annual Symposium 2016 – Spatial Structures in the 21st Century*, Tokyo. 26-30 September, K. Kawaguchi, M. Ohsaki, T. Takeuchi, Eds., 2016.

[6] D. Piker, "Kangaroo - Form Finding with Computational Physics." *Architectural Design* 83 (2): 136-137.

[7] A.H. Kyaw, J.M. Otto, L. Lok, "Active Bending in Physics-Based Mixed Reality: The design and fabrication of a reconfigurable modular bamboo system," In *Digital Design Reconsidered - Proceedings of the 41st eCAADe Conference, Volume 1*, Graz. 20-22 September, W. Dokonal, U. Hirschberg, G. Wurzer, Eds. 2023. pp. 169-178.

[8] E. Schling, M. Kilian, H. Wang, J. Schikore, H. Pottmann, "Design and Construction of Curved Support Structures with Repetitive Parameters," In *Advances in Architectural Geometry 2018*, Gothenburg. 22-25 September, L. Hesselgren, A. Kilian, O.S. Hornung, S. Malek, K-G Olsson, C. Williams, Eds. 2018.

[9] E. Adiels, C. Brandt-Olsen, J. Isaksson, I. Naslund, K-G Olsson, E. Poulsen, C. Williams, "The design, fabrication and assembly of an asymptotic timber gridshell," In *Proceedings of the IASS Annual Symposium 2019 – Form and Force*, Barcelona. 7-10 October, C. Lazaro, K.-U. Bletzinger, E. Onate, Eds. 2019.

[10] E. Schling, H. Wang, S. Hoyer, H. Pottmann, "Designing Asymptotic Geodesic Hybrid Gridshells," *Computer-Aided Design*, vol. 152, 2022.

[11] L. Howell, *Compliant Mechanisms*. New York: Wiley & Sons, 2002.

[12] E. Schling and J. Schikore, "Morphology of Kinetic Asymptotic Grids," In *Towards Radical Regeneration – Design Modelling Symposium Berlin 2022*, Berlin. 26-28 September, C. Gengnagel, O. Bavarel, G. Betti, M. Popescu, M. Ramsgaard Thomsen, J. Wurm, Eds. 2022. pp. 374-393.