

3D-Printed Multi-Material Deployable Structures: Programmable Shape Transformation through Additive Manufacturing

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Abstract

Curved funicular structures can reduce bending-dominated material demand by aligning geometry with force flow, but their construction often relies on molds, formwork, segmented assembly, or temporary support. This paper investigates whether flat robotic multi-material printing can embed the shaping process within the fabricated component and produce self-morphing funicular canopy modules at pavilion scale. The central problem is the scale translation from controllable bilayer bending samples to architectural lattice modules, where hinge rotation, passive-scaffold stiffness, drying shrinkage, gravity, and module registration become coupled. Small active/passive hinges can bend reliably, but meter-scale lattices can tear, delaminate, or lose geometric control when water-rich active deposits soften the passive scaffold before shape locking occurs. To address this problem, the study combines 3D graphic statics, fold-based module rationalization, active/passive hinge calibration, robotic flat printing, passive-first drying, localized agarose hinge deposition, suspended forming, and temporary-frame assembly. The system uses a cellulose–chitosan–fibroin passive lattice to provide geometric constraint and dry-state handling stiffness, while agarose hinges generate drying-driven shrinkage for programmed fold rotation. Results show that flat-bed actuation concentrates stress at softened hinge lines, while suspended forming uses gravity as a controlled boundary condition to support meter-scale curvature during drying. The assembled pavilion demonstrates a mold-free workflow for translating force-informed canopy geometry into flat-printed, self-morphed, and connected modules.

Keywords: self-morphing structures, shellular structures, funicular geometry, multi-material additive manufacturing, robotic fabrication, hygromorphic bilayers, graphic statics, deployable structures

1. Introduction

This paper studies how flat, robotically printed material systems can self-morph into curved funicular canopy modules. Funicular shells and spatial structures reduce bending-dominated material demand by aligning geometry with force flow, and graphic-statics methods make this relation explicit through reciprocal force and form diagrams [1–4]. Yet the construction of curved force-informed geometries often depends on molds, stay-in-place formwork, segmented assembly, or temporary support, which can move material and labor demand from structural design into fabrication [5, 6]. Flat-to-curved self-morphing offers a different fabrication route: the component is printed as a planar element, and the shaping operation is embedded in the material organization of the module.

Hygromorphic bilayers provide a material mechanism for this flat-to-curved transformation. When bonded layers develop different moisture-driven swelling or shrinkage strains, the mismatch generates an internal bending moment across the thickness [7, 8]. In an active/passive hinge, the active layer supplies

drying-driven contraction, while the passive layer constrains that contraction and converts it into rotation. Multi-material robotic extrusion extends this mechanism beyond isolated bending strips because active material can be placed only at selected hinge regions while passive material forms the larger printable lattice field. This placement control links material actuation, fold geometry, and structural layout within one fabrication process.

The research problem is the scale translation from a controllable bilayer hinge to an architectural canopy module. A small bending sample can rotate because the bonded layers remain compatible, the hinge length is short, and the self-weight is low. A pavilion-scale lattice introduces coupled constraints: the hinge must rotate a wider passive network, the active material must shrink without tearing or delaminating from the scaffold, and the morphed module must preserve curvature long enough to register with adjacent units. The same water content that enables agarose deposition and shrinkage can also soften the passive scaffold before shape locking occurs. Gravity then becomes part of the morphing process, because self-weight can either help establish curvature or concentrate stress at wet hinge lines.

This study therefore asks how a planar multi-material printing workflow can produce self-morphing funicular canopy modules that remain geometrically controllable at pavilion scale. The work focuses on three linked difficulties: translating force-informed funicular geometry into flat module patterns, calibrating active/passive hinges so that local shrinkage produces usable fold rotation, and controlling the fabrication sequence so that drying, gravity, and assembly support the target curvature. The objective is not only to demonstrate a bending material pair, but to test whether self-morphing can become a construction strategy for mold-free curved canopy fabrication.

The method combines computational form finding, fold-based module rationalization, bilayer hinge calibration, and robotic multi-material fabrication. A 3D graphic-statics model defines the global funicular canopy geometry. The canopy is then divided into module families that can be encoded through developable curved folding and tuck folding [9, 10]. Material tests connect passive-layer thickness, active-layer thickness, and hinge length to the rotation required by these module geometries. The fabrication sequence uses a cellulose–chitosan–fibroin passive lattice and localized agarose active hinges, with passive-first drying used to stabilize the scaffold before active shrinkage drives morphing.

The paper first introduces the force-informed canopy geometry and explains how the global form is translated into printable module patterns. It then describes the active/passive material system and the hinge calibration used to connect bilayer curvature with fold rotation. The following section presents the robotic fabrication workflow, including passive lattice printing, localized active hinge deposition, and suspended forming. The final section evaluates the assembled canopy modules by examining geometric transformation, hinge performance, module registration, and curvature retention under the four-column support condition.

2. Related work

Graphic statics provides a design framework for funicular structures by linking reciprocal force diagrams with compression-oriented form geometry [1–4]. Printed and knitted stay-in-place formwork systems show how digital fabrication can support curved concrete construction, but their target geometry still depends on an external shaping medium during material placement [5, 6]. Self-morphing modules shift this shaping task into the fabricated element by using programmed deformation to produce curvature after flat printing.

Hygromorphic bilayers generate curvature through incompatible moisture-driven strains across bonded layers, a mechanism described by bimetallic curvature theory and biomimetic hygromorph models [7, 8]. Wood-based architectural systems have scaled this mechanism into self-forming timber surfaces, weather-responsive elements, curved mass-timber components, and self-shaped tower construction [11–14]. Multi-material 4D printing extends this approach by distributing active and passive materials within

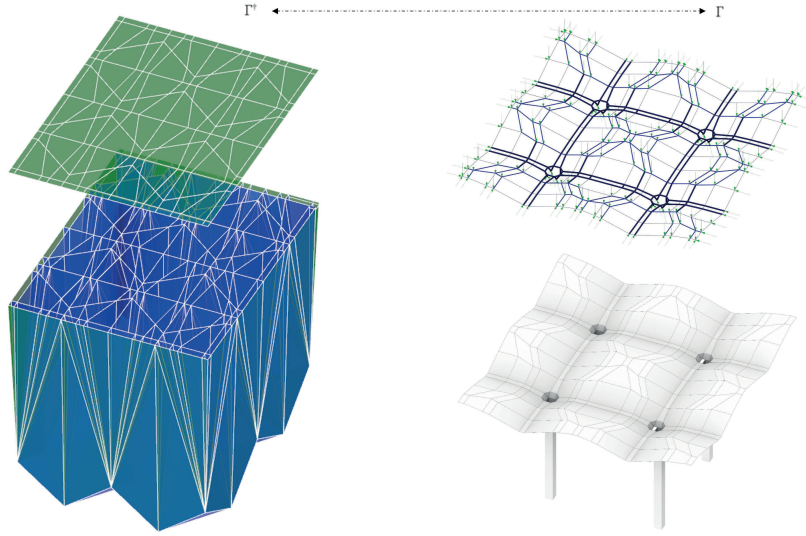


Figure 1: Graphic-statics setup for the pavilion canopy. The reciprocal force diagram $\Gamma^\dagger$ encodes boundary and support constraints, and the dual form diagram Γ resolves the funicular spatial network used for fabrication planning.

one printed body, enabling programmed hygroscopic transformations, shape-shifting lattices, and self-actuated shells [15–17].

Curved-folding research connects planar fabrication with three-dimensional module geometry through fold lines, tuck molecules, and programmed crease rotations [9, 10]. Bio-based extrusion constrains this geometric programming because printability, gelation, shape fidelity, and post-deposition stability govern whether active and passive regions remain connected during morphing [18, 19]. Multi-material additive manufacturing adds process-level constraints because material switching, mixing, and interface quality determine whether local functional regions can be fabricated at architectural scale [20, 21]. The present workflow targets the gap between these domains by coordinating funicular form finding, module rationalization, active/passive hinge calibration, robotic flat printing, suspended forming, and pavilion assembly.

3. Methods

3.1. Force-informed pavilion geometry

The pavilion geometry was generated through 3D graphic statics, where reciprocal force and form diagrams define a compression-oriented spatial configuration. Plan boundary and support locations set the external constraints for the force diagram $\Gamma^\dagger$. The dual form diagram Γ translated the prescribed force state into the spatial canopy network, as shown in Figure 1. Force-diagram subdivision introduced internal members under the same support conditions and produced a canopy geometry suitable for module discretization.

3.2. Module rationalization and flat patterns

The resolved canopy was divided into three module families to convert the global curved geometry into printable components, as shown in Figure 2. Modules A and B were assigned developable curved-folding geometries because their target surfaces could be produced from planar patterns through prescribed fold rotations. Module C was assigned an anticlastic tuck-folding geometry because its saddle curvature required local material insertion and fold-line activation [9, 10]. The flat pattern in Figure 3 inserts tuck regions into connected planar facets to encode the fold rotations required for anticlastic curvature. Each

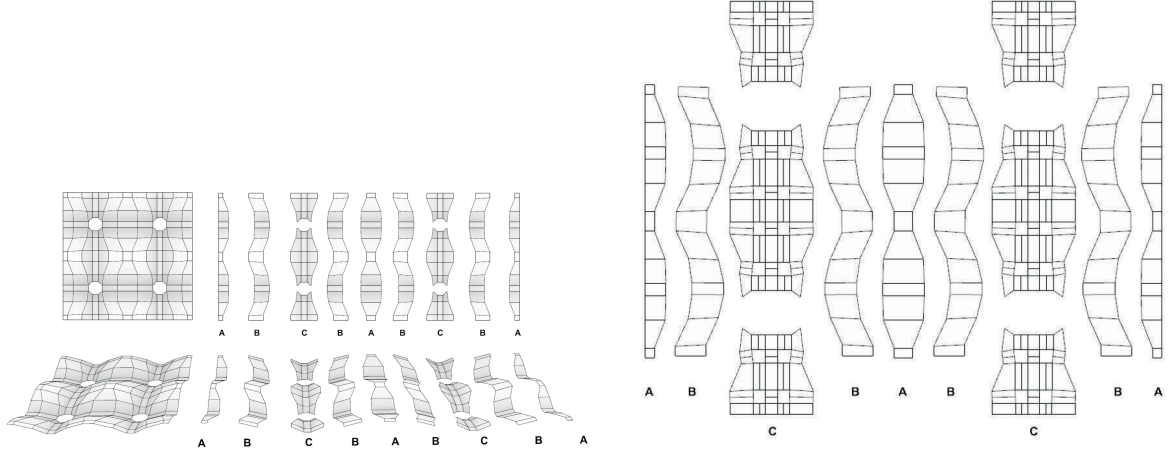


Figure 2: Module rationalization for flat fabrication. The global canopy is divided into Modules A, B, and C, and each module family is translated into a planar printing pattern with preserved boundary edges.

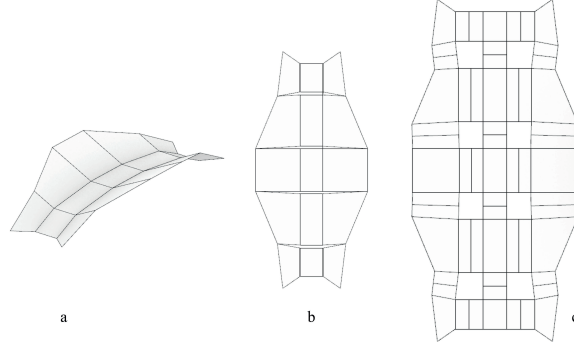


Figure 3: Flat-pattern generation for the anticlastic Module C. The target saddle geometry is unrolled into connected planar facets, and tuck regions are inserted to encode local fold rotations.

module pattern preserved boundary edges for registration, connection, and canopy continuity during assembly.

3.3. Active/passive hinge design

The self-morphing hinge used a dried cellulose–chitosan–fibroin lattice as the passive constraint and agarose as the drying-responsive active layer. The passive lattice provided in-plane restraint and dry-state handling stiffness. The agarose layer supplied shrinkage during drying and converted the free-strain mismatch into local bending. The passive-first deposition sequence in Figure 4 made the active hinge contract against a stabilized passive substrate. The design-level hinge rotation was estimated from the measured curvature radius R and hinge length L_h using

$$\theta = \frac{L_h}{R}, \quad \theta_{\text{deg}} = \frac{180}{\pi} \frac{L_h}{R}. \quad (1)$$

A matched bilayer thickness of 2 mm passive material and 2 mm agarose was used to balance active shrinkage and passive restraint [7, 8]. A 50 mm hinge length was selected for the pavilion modules because it converted local bilayer curvature into the fold rotation required by the tuck-folding pattern.

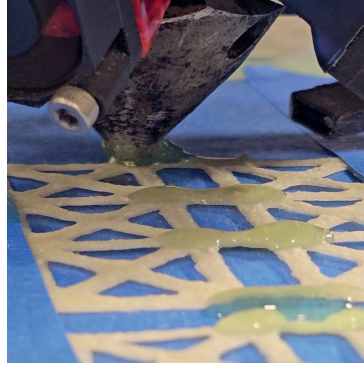


Figure 4: Passive-first active-hinge sequence. The passive lattice is printed and dried before agarose deposition, so drying shrinkage develops against a stabilized geometric constraint.

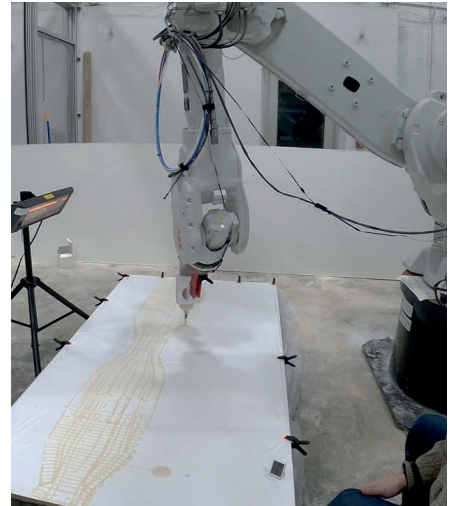
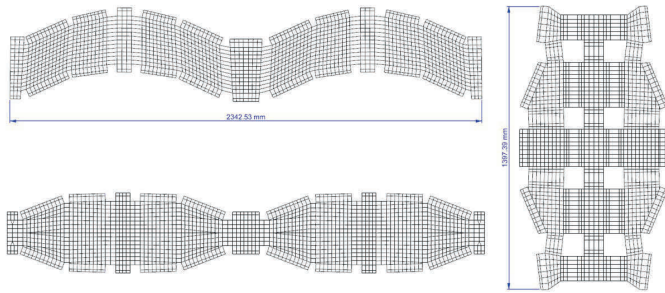


Figure 5: Robotic flat-printing setup for passive modules. Continuous lattice toolpaths are generated from flat module patterns and printed with an ABB IRB 6640 using the cellulose–chitosan–fibroin passive composite.

3.4. Robotic flat printing and active-hinge deposition

Flattened module patterns were converted into lattice toolpaths for robotic extrusion. The segment network was processed as an as-continuous-as-possible polyline to reduce start–stop defects during long-path deposition. The toolpath and robotic setup in Figure 5 show the flat-printing process used to fabricate the passive lattice modules. An ABB IRB 6640 printed the passive cellulose–chitosan–fibroin lattice on a flat heated printbed with approximately 25 mm cell size, 6 mm bead width, 2 mm passive thickness, and 120 mm/s TCP speed. The robotic workspace allowed a single module to reach approximately 2.3 m in plan span. Each passive lattice remained on the heated bed until dry-state stiffness and dimensional stability were reached.

Agarose was deposited after the passive lattice had dried. Hinge maps defined the active regions on the front and back faces of each module, as shown in Figure 6. The module was printed on one face, manually flipped, and printed on the opposite face where the fold direction required two-sided activation. Large A and B modules were subdivided during agarose deposition to keep each two-sided hinge-printing operation within the workable gelation and drying window. Module C was printed as one compact two-sided hinge layout because its active regions fit within the available processing time.

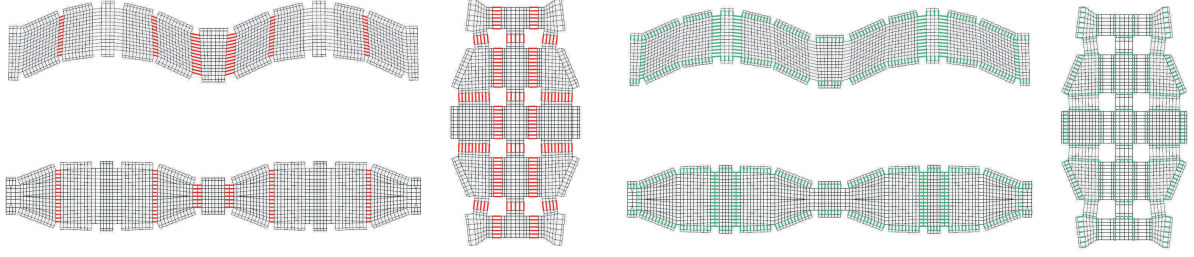


Figure 6: Two-sided agarose hinge maps. Front and back hinge layouts localize active material along fold regions that drive the required module rotations.

3.5. Suspended forming

The forming procedure treated gravity as a controllable boundary condition during drying. Wet agarose increased module mass and locally rehydrated the dried passive scaffold at hinge regions, which made flat-bed actuation vulnerable during the lowest-stiffness stage. Suspended forming moved the fully printed module from the printbed to prescribed rope supports before drying was complete. Rope locations and rope lengths established a catenary-like intermediate geometry, and agarose shrinkage refined the target curvature under that boundary condition. The suspension reduced early tensile demand at hinge lines while the active material transitioned from gelled deposit to dried actuator.

3.6. Pavilion assembly

Morphed modules were transferred to a pre-built temporary support frame for canopy assembly. The frame fixed elevation, edge position, and local curvature while neighboring modules were connected. Zip ties were threaded through boundary lattice openings and tightened progressively along shared edges to close seams without forcing abrupt curvature changes. The assembly sequence connected all modules over approximately 13 hours. The temporary frame was removed after the module network was closed, leaving the canopy supported by the four-column system defined in the original funicular geometry.

4. Results

The 3D graphic-statics workflow produced the four-support funicular canopy defined by Figure 1. The reciprocal force diagram fixed the load-path organization, and the form diagram converted that organization into the target pavilion geometry. The resolved canopy provided three fabrication targets: global curvature, module boundary position, and support-to-canopy force continuity.

The rationalization workflow in Figure 2 converted the continuous canopy into three printable module families without removing the global curvature. Modules A and B resolved the developable regions of the canopy through curved-folding patterns. Module C resolved the anticlastic region through the tuck-folding pattern shown in Figure 3. The rationalized module set preserved shared boundaries for assembly registration and canopy continuity.

The hinge-length study in Figure 7 showed that longer active regions converted the available bilayer curvature into larger fold rotation. Hinges with $L_h \approx 18$ mm and $L_h \approx 32$ mm initiated folding but reached partial closure. The 50 mm hinge produced the deepest and most stable rotation under the same 2 mm/2 mm active/passive thickness and 6 mm bead width. This result set the pavilion hinge rule as $L_h = 50$ mm with matched active/passive thickness.

The ABB IRB 6640 produced meter-scale passive lattice modules from continuous flat toolpaths, as shown in Figure 8. The lattice toolpath maintained approximately 25 mm cell size, 6 mm bead width, 2 mm passive thickness, and 120 mm/s TCP speed across long uninterrupted paths. The largest module-scale passive prints reached approximately 2.3 m in plan span, which reduced segmentation

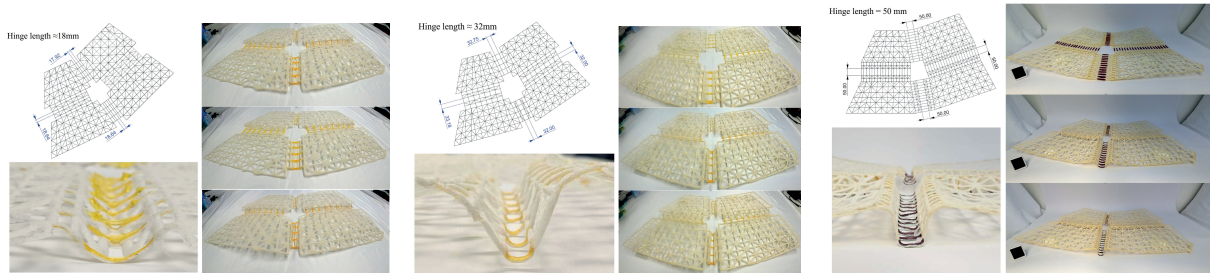


Figure 7: Hinge-length comparison under fixed cross-section parameters. The 18 mm and 32 mm hinges produce partial rotation, while the 50 mm hinge provides the fold depth required for pavilion-scale tuck activation.

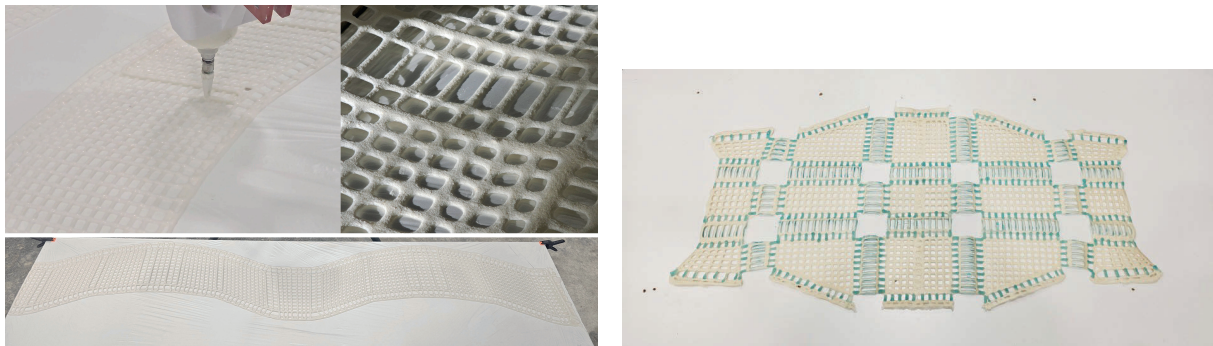


Figure 8: Robotic fabrication outputs for passive and active stages. The dried passive lattice provides the meter-scale geometric substrate, and the deposited agarose remains localized along mapped hinge regions for subsequent self-morphing.

before morphing and assembly. The dried passive lattices retained enough handling stiffness to receive mapped agarose hinges on one or both faces. Figure 7 shows that active material remained localized along fold lines after hinge deposition.

Flat-bed actuation exposed the scale-dependent failure mode shown in Figure 9. Water-rich agarose increased module mass and rehydrated the dried cellulose–chitosan–fibroin scaffold at hinge regions. Modules A and B amplified this condition through high hinge counts, with approximately 460 hinges in Module A and 380 hinges in Module B. Early bending concentrated stress along softened hinge lines, causing tearing before the target curvature could lock.

Suspended forming changed the actuation outcome by redistributing self-weight through rope supports during drying. The suspended boundary condition produced a catenary-like intermediate shape, and agarose shrinkage refined the module curvature during water loss. Module B retained a stable developable curvature after drying, as shown in Figure 9. Module C moved from a flat two-sided hinge layout to a locked anticlastic shape through tuck activation, as shown in Figure 10.

The self-morphed modules were assembled on a temporary support frame and connected through zip ties along lattice boundaries, as shown in Figure 11. The frame held elevation, edge alignment, and local curvature while seams were tightened progressively. The full canopy required approximately 13 hours of module placement and connection. After joint closure, the temporary frame was removed and the canopy transferred to the four-column support condition defined by the graphic-statics geometry. The completed pavilion retained curved surface continuity across module seams and connected the self-morphed lattice canopy to the branching support node.

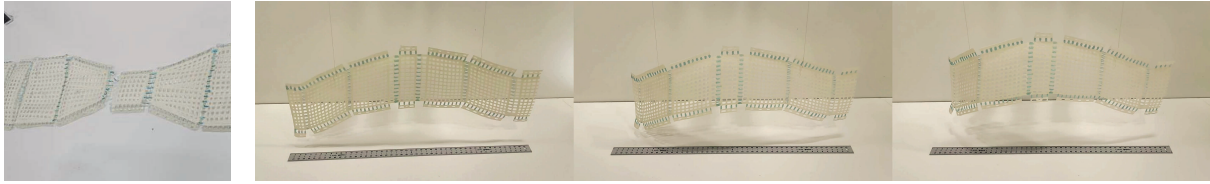


Figure 9: Scale-dependent actuation outcome. Flat-bed drying concentrates tearing at softened hinge lines, while suspended forming enables Module B to reach and retain meter-scale curvature during drying.

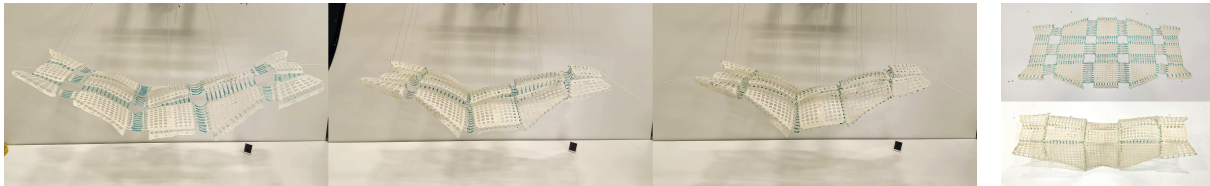


Figure 10: Suspended self-morphing of Module C. Rope-supported drying establishes the gravity-assisted base geometry, and agarose hinge shrinkage activates the tuck pattern into an anticlastic module.

5. Discussion

The prototype identifies scale transfer as the central problem in self-morphing canopy fabrication. The graphic-statics model in Figure 1 defined a four-support funicular canopy, the rationalization workflow in Figures 2 and 3 converted the curved geometry into three printable module families, and the hinge tests in Figure 7 selected a 50 mm active/passive hinge for pavilion-scale rotation. Robotic flat printing produced meter-scale passive lattices, localized agarose deposition supplied fold activation, suspended forming stabilized the drying stage, and zip-tied assembly transferred the morphed modules to the four-column support condition shown in Figure 11.

The results show that self-morphing at canopy scale depends on the coordination of geometry, material placement, and boundary condition. small-scale bilayer bending explains local hinge rotation [7, 8], but the module results in Figures 9 and 10 show that gravity and drying support control whether that rotation survives at meter scale. Flat-bed actuation concentrated water, self-weight, and early bending at softened hinge lines; suspended forming redistributed self-weight through rope supports and gave the agarose hinges time to refine curvature during drying. Module B reached stable developable curvature through this boundary-condition change, and Module C reached anticlastic curvature through tuck activation.

The workflow reframes self-morphing as a construction sequence rather than a material effect. Compared with formwork-based curved fabrication [5, 6], the proposed sequence moves initial shaping into flat-printed modules while still using temporary supports for drying and assembly control. Compared with hygromorphic architectural precedents based on continuous timber behavior [11–14], the pavilion uses discrete active hinges to localize rotation within a passive lattice. Compared with multi-material shape-changing prints [15–17], the work tests how hinge actuation interacts with module size, self-weight, seam registration, and support transfer.

The prototype also defines the current limits of the system. The 50 mm hinge rule gives a design-level rotation target, not a predictive model for drying time, modulus evolution, or interfacial fracture. Wet agarose deposition can temporarily reduce passive-scaffold stiffness at hinge regions, so modules with high hinge counts remain vulnerable before drying restores handling strength. Zip-tie seams enabled rapid assembly and curvature registration, but they did not quantify joint stiffness, long-term creep, or structural capacity under environmental loading. The completed pavilion demonstrates geometric feasibility and assembly continuity, not a certified load-bearing building system.

Future implementations should reduce early-stage hinge vulnerability by lowering water transfer,

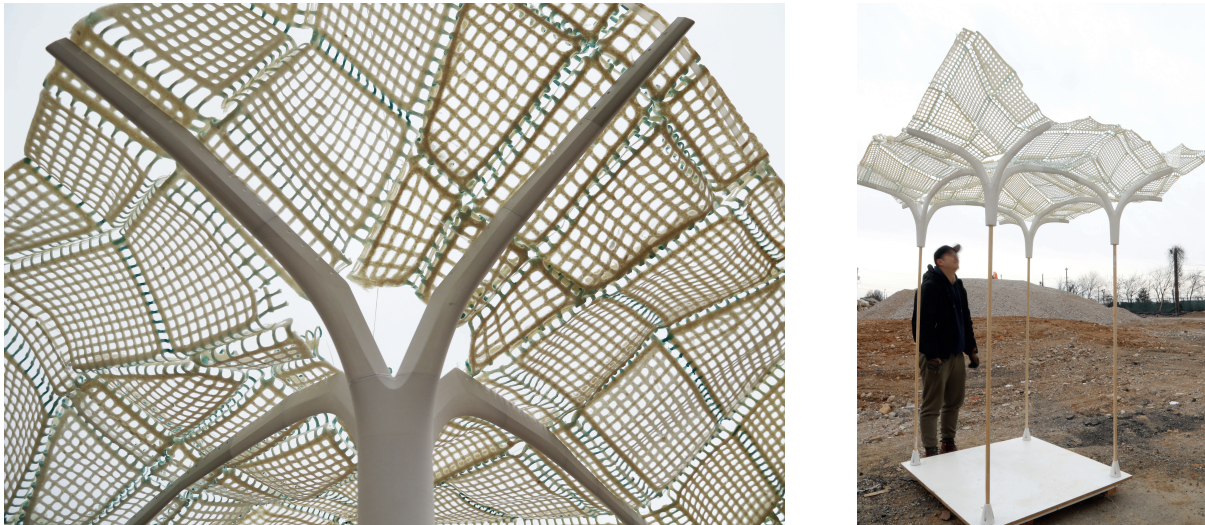


Figure 11: Final pavilion assembly. Zip-tied self-morphed modules form a continuous canopy surface, and the completed structure transfers from temporary assembly support to the four-column funicular support system.

staging active deposition, or tuning hinge density against module span. Suspended forming should be parameterized through rope position, rope length, module mass, and drying time so the catenary-like intermediate shape becomes a controlled fabrication input. Module boundaries should integrate designed connection features that preserve curvature while providing measurable joint stiffness. Structural validation should test assembled canopy behavior under self-weight, lateral disturbance, humidity cycling, and support settlement so flat-to-curved self-morphing can move from pavilion demonstration to repeatable funicular construction.

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References

- [1] Mohammad Bolhassani, Ali Tabatabaie Ghomi, Andrei Nejur, Mustafa Omer Furkan, Ivan Bartoli, and Masoud Akbarzadeh. Structural behavior of a cast-in-place funicular polyhedral concrete: Applied 3d graphic statics. In *Proceedings of IASS Annual Symposia*, volume 2018, page 1–8. International Association for Shell and Spatial Structures (IASS), 2018.
- [2] Hao Zheng, Xinyu Wang, Zehua Qi, Shixuan Sun, and Masoud Akbarzadeh. Generating and optimizing a funicular arch floor structure. In *Proceedings of the 40th Annual Conference of the Association for Computer-Aided Design in Architecture (ACADIA)*, 2020.
- [3] **Teng Teng**, Yefan Zhi, Yiliang Shao, and Maximilian E. Ororbia. Funicular systems with combined force. In Masoud Akbarzadeh, editor, *Architected Structures*, DETAIL Special. DETAIL, Munich, 2025. Planned publication date: March 12, 2025.
- [4] M. Akbari, Y. Lu, and M. Akbarzadeh. From design to the fabrication of shellular funicular structures. In *Proceedings of the Association for Computer-Aided Design in Architecture (ACADIA)*, 2021.
- [5] A. Jipa, M. Bernhard, M. Meibodi, and B. Dillenburger. 3d-printed stay-in-place formwork for topologically optimized concrete slabs. In *TxE Emerging Design + Technology Conference 2016*,

2016.

- [6] Mariana Popescu, Lex Reiter, Andrew Liew, Tom Van Mele, Robert J Flatt, and Philippe Block. Building in concrete with an ultra-lightweight knitted stay-in-place formwork: prototype of a concrete shell bridge. In *Structures*, volume 14, pages 322–332. Elsevier, 2018.
- [7] Stephen Timoshenko. Analysis of bi-metal thermostats. *Journal of the Optical Society of America*, 11(3):233–255, 1925.
- [8] Etienne Reyssat and Lakshminarayanan Mahadevan. Hygromorphs: from pine cones to biomimetic bilayers. *Journal of the Royal Society Interface*, 6(39):951–957, 2009.
- [9] Tomohiro Tachi. 3d origami design based on tucking molecule. *Origami*, 4:259–272, 2009.
- [10] Yasaman Tahouni and Achim Menges. Self-shaping curved folding: A 4d-printing method for fabrication of self-folding curved crease structures. *Materials & Design*, 183:108131, 2019.
- [11] Dylan Marx Wood, David Correa, Oliver David Krieg, and Achim Menges. Material computation—4d timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces. *International Journal of Architectural Computing*, 14(1):49–62, 2016.
- [12] David Wood, Céline Vailati, Achim Menges, and Markus Rüggeberg. Hygroscopically actuated wood elements for weather responsive and self-forming building parts—facilitating upscaling and complex shape changes. *Materials & Design*, 142:145–154, 2018.
- [13] Philippe Grönquist, Dylan Wood, Mohammad M Hassani, Falk K Wittel, Achim Menges, and Markus Rüggeberg. Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures. *Science Advances*, 5(11):eaay5344, 2019.
- [14] Simon Bechert, Lotte Aldinger, Dylan Wood, Jan Knippers, and Achim Menges. Urbach tower: Integrative structural design of a lightweight structure made of self-shaped curved cross-laminated timber. *Automation in Construction*, 89:304–314, 2018.
- [15] David Correa, Athina Papadopoulou, Christophe Guberan, Nynika Jhaveri, Steffen Reichert, Achim Menges, and Skylar Tibbits. 3d-printed wood: programming hygroscopic material transformations. *3D Printing and Additive Manufacturing*, 2(3):106–116, 2015.
- [16] J William Boley, Wim M Van Rees, Charles Lissandrello, Mark N Horenstein, Ryan L Truby, Arda Kotikian, Jennifer A Lewis, and L Mahadevan. Shape-shifting structured lattices via multimaterial 4d printing. *Proceedings of the National Academy of Sciences*, 116(42):20856–20862, 2019.
- [17] Ruslan Guseinov, Connor McMahan, Jesús Pérez, Chiara Daraio, and Bernd Bickel. Programming temporal morphing of self-actuated shells. *Nature Materials*, 20(3):336–342, 2021.
- [18] Saman Naghieh and Xiongbiao Chen. Printability—a key issue in extrusion-based bioprinting. *Journal of pharmaceutical analysis*, 11(5):564–579, 2021.
- [19] Andrea Schwab, Riccardo Levato, Matteo D’este, Susanna Piluso, David Eglin, and Jos Malda. Printability and shape fidelity of bioinks in 3d bioprinting. *Chemical reviews*, 120(19):11028–11055, 2020.
- [20] Adam Pajonk, Alejandro Prieto, Ulrich Blum, and Ulrich Knaack. Multi-material additive manufacturing in architecture and construction: A review. *Journal of Building Engineering*, 45:103603, 2022.
- [21] Teng Teng, Yefan Zhi, and Masoud Akbarzadeh. Prototyping high-fidelity multifunctional objects using single-nozzle multi-filament additive manufacturing system with active mixing. *Materials Design*, 249, 1 2025.