Self-shaping Curved Folding:

A 4D-printing method for fabrication of self-folding curved crease structures

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Figure 1: Self-shaping curved folding prototypes and their transformation from flat (left) to folded (right) state.

ABSTRACT

Curved folding, a method to create curved 3D structures from a flat sheet, can be used to produce material and manufacturing efficient, static or dynamic structures. However, the complex assembly and folding sequence of curved crease patterns is the bottleneck in their fabrication process. This paper presents Self-shaping Curved Folding: a material programming approach to create curved crease origami structures that self-assemble from flat into 3D folded state

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SCF '20, November 05, 06, 2020, Virtual Event, USA

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ACM ISBN 978-1-4503-8170-3/20/11...\$15.00

<https://doi.org/10.1145/3424630.3425416>

upon exposure to external stimuli. We propose a digital fabrication process via the 3D-printing of shape-changing materials, accompanied by a computational design workflow in which the geometry of a crease pattern is correlated with the printing toolpaths and the layout of stimuli-responsive and passive materials to achieve a target shape-change. We demonstrate our method by producing multiple prototypes and documenting their shape-change upon actuation. Lastly, we explore the functional and performance benefits of self-shaping curved folding under three application scenarios relevant to the field of industrial design and architecture.

CCS CONCEPTS

• **Applied computing** → Computer-aided manufacturing.

KEYWORDS

Self-folding origami, Shape-changing, Smart materials, Material programming, 3D-printing

ACM Reference Format:

YASAMAN TAHOUNI, TIFFANY CHENG, DYLAN WOOD, RENATE SACHSE, REBECCA THIERER, MANFRED BISCHOFF, and ACHIM MENGES. 2020. Self-shaping Curved Folding: A 4D-printing method for fabrication of self-folding curved crease structures. In *Symposium on Computational Fabrication (SCF '20)*, November 05, 06, 2020, Virtual Event, USA. ACM, New York, NY, USA, 11 pages. <https://doi.org/10.1145/3424630.3425416>

1 INTRODUCTION

Folding a sheet material along a curved crease forms a three-dimensional geometry that integrates synchronized bending and folding on developable surfaces. The ability to form elegant 3D shapes and efficient structures with a simple geometric concept presents many opportunities ranging from industrial design to aeronautical engineering and architecture [Epps and Verma 2013; Miyashita et al. 2015]. From a structural mechanics' perspective, such 2D-folded 3D geometries are valuable across scales for creating materially efficient, lightweight and deployable structures. [Seffen 2012; Robeller et al. 2014]. As kinetic mechanisms, curved folding geometries have been explored for their application in kinetic architectural façade systems [Korner et al. 2016; Vergauwen et al. 2017].

While computational design methods for modeling curved origami have steadily advanced [Bhooshan 2016; Tang et al. 2016; Koschitz 2014; Kilian et al. 2008], methods for their fabrication and folding actions still need to be further developed. As opposed to straight-crease origami, where the motion mechanism is concentrated on the hinges, the geometry of curved folding requires the origami faces (surfaces) to transform and bend in varying curvature as the creases fold. Moreover, the folding sequence of curved crease patterns usually requires multiple creases to be folded simultaneously. Failing to perform such synchronized action may cause the structure to lock and end the folding sequence before it is completed. These characteristics make the folding of the curved crease patterns a complex task that requires extreme dexterity and coordination – a task that is difficult for both humans and machines.

In this paper, we introduce self-shaping curved folding, an approach that combines material and geometric programming to create curved-folded structures that can transform from flat to 3D folded states autonomously upon exposure to external stimuli (Figure 1). The self-shaping process is enabled by using stimuli-responsive shape-changing materials, and a computational fabrication method that allows for predicting and physically programming the transformations within the structure. Taking advantage of inherent material properties, by distributing the actuation throughout the bending surfaces, the self-shaping process eliminates the need for external force, actuators, or intervention during the folding process.

To achieve this, we first outline the relationship between the design parameters for programming both the geometry and the material. Using these principles, a design is translated to an associated mesostructural layout and material assignment that can be tuned and additively manufactured in 2.5D using a standard Fused Deposition Modeling (FDM) 3D printer and commercially available hygroscopic filaments. After a design is printed, it is actuated by placing it in an alternative Relative Humidity (RH) level to that of its production. A computational design workflow has been developed

to assist the generation and fabrication of self-shaping curved folding designs by determining mesostructure layouts, predicting and visualizing the shape-change upon actuation, and automatically generating machine instructions, specifically 3D-printing toolpaths and GCODE, for direct fabrication.

To show the versatility and potentials of the methods, we fabricate a series of prototypes with different folding mechanisms, including free-form curved folding designs, curved pleated structures, curved folding tessellations, and kinetic curved folding modules. The main contributions of this research include:

- **The Self-shaping curved folding method:** A method for fabrication of self-folding and self-assembling curved crease structures.
- **Definition of the design space:** Demonstrating the programmability of fold angle via mesostructure and/or geometry (crease curvature)
- **The computational fabrication workflow:** A computational workflow and a digital design tool that allows for tailoring the mesostructural properties, visualizing the transformation, and automatically generating the 3D-printing toolpaths and GCODE.
- **Novel applications for the technology:** Showcasing multiple applications for self-shaping curved folding structures relevant to the field of architecture and product design

2 RELATED WORK

Physical and automated production of curved folding has been shown through the use of sheet materials with pre-engineered creases combined with string actuators [Kilian et al. 2017], the coordination of industrial robots [Verma and Epps 2013], and simply through the reliance on gravity [Maleczek et al. 2019]. While successful in increasing the scale from tabletop origami, these automated folding methods severely limit the design space – reducing the amount, continuity, and complexity of the folded structures.

Self-shaping mechanisms, due to their ability to transform into a complex shape from an initial flat state, offer a range of benefits, including simplifying the complex assembly processes, flat-packaging, and dynamic shape adaptation [Callens and Zadpoor 2018; Raviv et al. 2014; Wood et al. 2016]. Self-folding origami structures have been explored for their capability to create 3D folded structures from flat sheets of material. Previous work is primarily based on straight folding methods in which the actuating material is integrated as a hinge along the fold lines. [Tolley et al. 2014; Mao et al. 2015; Janbaz et al. 2016; Miyashita et al. 2015]. Surface actuation to produce self-shaping has been shown in basic configurations that utilize curved folding at large scale. [Correa et al. 2020; Wood et al. 2016].

4D-printing combines the stimuli-responsive property of materials with a precise and digitally controllable manufacturing process, to create self-shaping structures with complex and highly controllable transformations [Tibbitts 2014]. Previous work have explored bending mechanisms in single curved and double curved surfaces with different configurations [Gladman et al. 2016; Correa Zuluaga and Menges 2015; Wang et al. 2018; Yao et al. 2015; Gu et al. 2019]. Previous explorations of 4D-printed self-folding structures, although sophisticated in sequencing and production [Ge et al. 2014;

Figure 2: Geometric components of self-shaping curved folding: Definition of the crease, bending direction, bending orientation, and resulting fold angle.

Mao et al. 2015], are limited to straight-line folding where bending mechanisms are placed on the fold lines [van Manen et al. 2017; An et al. 2018], requiring large volumetric changes in order to achieve relevant fold angles.

3 SELF-SHAPING CURVED FOLDING METHOD

Curved folding is a hybrid of *folding* on the creases and *bending* on the origami faces (surfaces). Our self-shaping method for folding the curved crease structures is based on inducing targeted bending on the surfaces via material-based stimuli-responsive shape-change. The surfaces are connected through a layer of flexible material, which defines the hinge zones on the curved creases. Upon exposure to stimuli, the surfaces bend in pre-defined convex or concave geometries, which results in buckling and folding the structure on its creases (Figure 2).

As opposed to the previous work on self-folding origami which places the active material on the fold lines, we chose such indirect method for folding for two reasons: First, the curved crease geometry requires the hinge zones to stretch and form into high-curvature non-developable surfaces, a transformation that is impossible to reach with the known 4D-printing processes. Second, by placing the actuating material on the faces, we distribute the shape-changing material mechanism throughout large surface areas, which generates higher self-shaping forces and creates sharp fold angle on the creases.

3.1 Folding: Geometry meets material programming

To successfully achieve a fold on a crease line, the bending direction and the bending orientation in origami faces need to be choreographed. Following the geometric principle of curved folding, the target bending in the surfaces is defined according to the mountain and valley assignment of the folds in the crease pattern. In terms of bending direction, the two adjacent faces should bend in the opposite convex or concave directions to facilitate folding on

their mutual edge (crease line). Whether the crease folds as *mountain* or *valley* depends on the placement of the convex and concave bending surfaces in relation to the crease. A curved crease folds as a *mountain* if the surface on the convex side of the crease bend upwards, and the surface on the concave side bend downwards [Demaine et al. 2015]. With the reverse assignment bending direction, the crease will fold as a *valley* [Demaine et al. 2015]. In terms of the in-plane bending orientation, the bending of the surfaces should be aligned with the surface rule lines, which are oriented perpendicularly to the tangent of the curved creases. These principles construct the geometric programming rules for designing self-shaping curved folding structures.

3.2 Bending: Mesostructured material mechanism

In the bending surfaces, a bilayer mechanism is used to transfer volumetric shrinking and swelling of a material to surface bending. Bilayer surfaces are created by combining a layer of shape-changing stimulus-responsive "active" material that shrinks and swells with a corresponding layer of "restrictive" material. The structuring within each layer can be variably adapted in orientation and spacing within the x-y plane to create an anisotropic build up to reach a target bending. The bending direction in the bilayer surfaces is determined by the placement of the active and restrictive layers. The out-of-plane bending orientation corresponds to the anisotropic mesostructure of the surfaces, which is constructed by the 3D-printing paths. With the active material used in this study, the main direction of material expansion/shrinkage, and the resulting bending orientation, is perpendicular to the active layer's printing paths.

The bending radius is directly related to the actuation stimulus, but the maximum bending curvature can be specifically tuned by adjusting the mesostructure parameters. In this work, we control the bending curvature by adjusting the density of the active layer's printing paths, and more specifically, by controlling the spacing between two adjacent paths. We performed a series of experiments on the 3D-printed test samples (dimensions: 75mm x 15mm x 1mm) with varying toolpath spacing. Figure 3 shows the relationship between the toolpath spacing parameter, ranging from 0.4mm to 0.6mm, and the maximum bending curvature. We use this data both as a design reference and as a guide for the development of our computational workflow.

4 FABRICATION METHODS AND MATERIALS

4.1 Multi-layered, multi-material 3D-printing

The FDM 3D-printing technique is used to additively manufacture the flat structures with high resolution and precision. This can be understood as a 2.5D fabrication process in which multiple thin layers are produced to create flat structures with dimensions of approx. 150mm x 150mm x 2mm. A standard commercially available dual nozzle 3D-printer (Felix Tec 4) was used for the multi-material printing conducted in this research. As the active material, we chose a wood-filled filament (Laywood Meta5, Lay Filaments) that undergoes a large volumetric change during a change in its moisture content. In contrast, a moisture stable generic ABS filament is used for the restrictive layer. The flexible connection in the hinge

Figure 3: The relationship between bending curvature radius and the active layer's toolpath spacing

layers is constructed using the Thermoplastic polyurethane (TPU) filaments (NinjaFlex, NinjaTek) (Figure 4). The TPU material is chosen because of its low stiffness and high elasticity, which ensures the compliance in the hinge zones and facilitates folding. To print the three materials using a dual-nozzle 3D-printer, the filaments are manually changed. To facilitate this change, the 3D-printing GCODE is generated in two separate files. The first GCODE is printed with the Laywood and the TPU filaments loaded in the 3d-printer, followed by the second GCODE which is printed using the Laywood and the ABS filaments.

Within the prints, the width of the mesostructure lines directly correlates with the width of the 3D-printer nozzle (0.4mm) with a specific flow rate and printing temperature per material (0.033-0.044mm/min flow rate, 200-210 °C). The number of printed layers which determines the height varies within the functional layers. However, as a general rule, the active layer is printed in the proportions of 3:1 to the passive layer to maximize bending curvature in the bilayer structures. To enhance the bonding between multi-material layers and prevent delamination, two additional *bonding layers* are printed on the top and the bottom of the structure. These layers, which are printed with the wood-filled filament, link the outermost layers to the inner active layers with the same material composition.

4.2 Shape-change triggering

After removing the prototypes from the print bed, they keep their flat shape until going through the first shape triggering cycle. With the specific type of filament used in this research, the shape change is triggered by submerging the prototype in the water at room temperature for minimum 30 minutes. Upon drying, the prototypes undergo significant shape change from flat to bent/folded state. The folded state can be maintained by keeping the prototype in a space with relatively low humidity (below 50% RH). The drying time varies between 2 to 12 hours based on the environment's

Figure 4: Fabrication methods and materials: Multi-layered, multi-material structure and the 3D-printing sequence of a sample prototype

temperature and RH level and the thickness and porosity of the prototype. Alternatively, the prototypes can retrieve their flat state by water submersion or placement in high RH (above 90% RH). A secondary effect of a high moisture content is a reduction in the material stiffness, which is regained when the prototype is dried. For testing the cyclic shape-change of the prototypes, a climate system (MiniOne, Preservatech) is used for generating consecutive high RH and low RH cycles.

5 DESIGN SPACE COMPONENTS

5.1 Controlling the fold angle via crease curvature and bending radius

Through digital and physical experiments, we investigated the relationship between the crease curvature and fold angle in the 3D-printed prototypes in relation to the amount of surface actuation. To simplify the designs, the creases are a part of a circle, and the faces are in the form of cylindrical developable surfaces. Four geometric cases with a crease curve radius of 40mm, 50mm, 75mm, and 100mm, and the overall dimensions of 70mm x 100mm x 1mm were designed. For each case, three test samples were 3D-printed. After actuation, we measured the fold angle of each sample at the mid-point of its crease line. The averaged measurement of the samples for each case is shown in Figure 5. In parallel, we used FEM simulations to simulate the shape-change for each of the geometric designs. (For the details of the FEM simulation implementation, refer to the Appendix A.1). The results of the physical and digital experiments show a direct correlation between the fold angle and the crease curvature (Figure 5). Within the four cases, the samples with the largest crease curvature radius (100mm) showed the smallest fold angle (41.5 degrees). As the crease curvature radius decreases, the fold angle increases. Thus, the curvature of the creases can be

	Crease Curvature R = 100mm	Crease Curvature R = 75mm	Crease Curvature R = 50mm	Crease Curvature R = 40mm
Actuation 0.9% ~ S 0.60mm	73.0°	91.2°	120.1°	138.3°
Actuation 1.75% ~ S 0.55mm	48.7°	64.3°	94.5°	117.7°
Toolpath Spacing 0.50mm	41.5°	53°	82.5°	102.5°
Actuation 2.25% ~ S 0.50mm	41.2°	55.4°	84.7°	108.9°
Actuation 2.50% ~ S 0.45mm	38.7°	52.4°	81.3°	105.5°

Figure 5: Geometric and material programming design space for a single fold self-shaping component, created through digital and physical modeling.

reliably used to adjust the maximum fold angle in self-shaping curved folded structures.

Moreover, we explored the relationship between surface curvature and the fold angle. We used the FEM simulation to simulate the structural behavior and the resulting fold angle for each geometric design under different surface actuation values. In parallel, we correlated the surface actuation value to the mesostructural toolpath spacing parameter. This was done by simulating bilayer specimen shown in Figure 3, and correlating their curvature to the curvature of the 3D-printed samples via polynomial function (R value = 0.9725). This experiment shows that, within a constrained geometric design, the fold angle can be controlled by adjusting the mesostructure layout. The results of the two studies indicate the design space for a single-fold component, where a target fold angle can be achieved through both geometric and material programming processes.

5.2 Geometric Variations: initial design, prototyping, and testing

We explored the geometric variations in the design space by prototyping different aggregations of curved creases and bent surfaces. In the simplest form, Figure 6a showcases the layer arrangement and printing toolpaths for a single mountain fold.

Figure 6b shows a curved fold with an inflection point on its midpoint, where the bending direction of the two faces change sign.

Figure 6: Basic components of self-shaping curved folding, showcasing the rules for assigning layer placements according to the mountain and valley folds in the crease pattern.

A pleated curved folding geometry is constructed by aggregating alternating convex and concave surfaces. When the creases are aligned in the XY-plane with the same curvature direction, alternating mountain and valley folds are attained (Figure 6c). When the creases are aligned in the opposite curvature directions, a pleated structure with repeating mountain or valley folds is created (Figure 6d). Figure 6e showcase the geometric variations in the bent surfaces, realized by aligning the printing toolpaths on surface rulings of a conic developable surface.

6 COMPUTATIONAL WORKFLOW

We've developed a computational workflow and a forward-design tool to assist the design to fabrication process of self-shaping curved folding prototypes. The tool is built in Rhinoceros 6 as the design environment and Grasshopper plugin both as a computational tool and as the user interface. In general, the tool consists of four main modules: Meso-structure setup, mesh generation, geometric shape-prediction, and 3D-printing toolpath and GCODE generation (Figure 7).

Figure 7: Flowchart of the computational workflow

6.1 Walkthrough

Mesostructure setup: The workflow starts by referencing the flat surfaces of origami faces and hinge zones in the grasshopper environment. In the next step, the mesostructural properties, including the bending direction, bending orientation, and surface actuation percentage are individually assigned to the input surfaces (Figure 8a). Slider components are used for adjusting the parameters, which are automatically populated based on the number of input surfaces.

Geometric shape-prediction and motion simulation: The geometric shape-prediction module simulates the shape-change in bending surfaces, which results in the folding of the creases in a structure (Figure 8b). Using this module, a designer can get feedback on the shape-change and the final folded shape while they iterate on the mesostructure setup. They can also input an overall “actuation percentage” to qualitatively simulate a median RH stimuli response [Wood et al. 2018].

3D-printing toolpath and GCODE generation: After a design is finalized, the assigned mesostructural properties are automatically translated into the toolpaths design and layer assignment of the active, restrictive, and flexible materials (Figure 8c). The toolpaths are then converted into GCODE, which is used for the 3D-printing.

6.2 Implementation

The mesostructural properties are collected in data lists, which are used throughout the pipeline for mesh preparation, geometric shape-prediction, and toolpath generation. To prepare the model for shape-prediction, a directional mesh is constructed from the input surfaces. To construct the mesh, the bending orientation paths are extracted and spaced according to the desired mesh resolution. The mesh triangulation is created between the oriented lines using the Meshmachine component (D. Piker, Grasshopper, Rhinoceros 3D Rhino, Robert McNeel & Associates). To model the bilayer bending, a volumetric bilayer structure is built from the mesh, and a scaling constraint is applied to the mesh edges aligned with the bending orientation. The shaping process is modeled using a constraints based solver implemented with a custom script and the grasshopper plugin Kangaroo2 (D. Piker, Grasshopper, Rhinoceros 3D Rhino, Robert McNeel & Associates) [Bouaziz et al. 2012].

The 3D-printing toolpaths are generated based on the mesostructure setup data. The layer arrangement of the active and passive materials is determined based on the assignment of the bending direction for each surface. The toolpaths of the active and the passive

Figure 8: Computational workflow: A) Input design and mesostructure setup, B) Geometric shape-prediction, C) Toolpath and GCODE generation for the 3D-printing, D) Self-shaping upon drying after 30 min. water submersion.

layers are generated as one-directional hatches, aligned according to the bending orientation. The spacing of the active layer is mapped from surface actuation percentage input value, using data shown in Figure 3. The toolpath of the hinge layer is designed as linear paths perpendicular to curved creases, and their spacing can be adjusted for tuning the stiffness. After the toolpaths are generated, the Voxel2GCode (by N. Alonso, Autodesk) component is used to generate the GCODE.

7 APPLICATIONS

Three application scenarios were chosen to showcase the functions and performance benefits of self-shaping curved folding. For each application, we focus on one of the temporal forms of the self-shaping curved folding: 1) before transformation, 2) after transformation, 3) cyclic shape-change. These temporal forms are achievable immediately after printing (1), after one-time water submersion and drying (2), or through cyclic positioning in high and low RH within the intervals of 8 to 12 hours (3). For the first category, we explore the advantage of curved folding geometries in designing novel flat-packable objects and products. In the second application, we explore the structural and mechanical properties of the curved folded

Figure 9: A prototype of a self-shaping curved folding PPE face shield in flat (after printing) and 3D folded states.

structures after self-shaping. Here, we focus our study on curved folding tessellations, which are beneficial in terms of their structural performance but are highly challenging in terms of their folding actions. Lastly, we explore the kinetic performance of self-shaping curved folding. Taking advantage of cyclic actuation of hygroscopic materials, we explore how curved folding geometry can be used as a motion amplification mechanism in environmentally-responsive architectural elements.

7.1 Curved folding for flat-packed product design

4D-printing is advantageous in terms of flat production and flat packaging, saving material and fabrication time, and self-assembly. Specifically, curved crease geometries open up new design possibilities for flat-packed product design and manufacturing. On one hand, the geometry of curved folding allows creating complex 3D-forms from a limited number of creases. On the other hand, our self-shaping method allows creating sharp folds with programmable fold angles, which are reached autonomously by the material mechanism. These features can lead to new types of design and manufacturing processes for consumer products.

To demonstrate this application, we designed a self-shaping curved folding PPE face-shield (Figure 9). The face shield can be packaged and shipped flat, which helps to save space for large quantity shipments during high-demand, such as during a pandemic. After arrival, the face-shields will be ready to use after one-time water submersion and drying, without requiring any assembly effort. In designing the face shield, we adjusted the geometry of the creases to reach a fold angle that fits the human forehead, and also holds the transparent protective sheet perpendicularly to the face. The overall curvature is tailored to fit the average human's head. To customize the face shield for specific users, the curvatures can be adjusted by tailoring the mesostructure, following the method described in section 3.2.

Figure 10: Self-shaping curved pleated corrugated surface. A) Toolpath design and layering, B) folded structure under 500g load, C) the structure in flat (Dim. 16cm x 14cm x 1mm) and folded (Dim. 14cm x 9cm x 2.5cm) states, D) a curved pleated prototype with a dense crease pattern.

7.2 Self-shaping tessellations for structural depth and stiffness

Curved folded geometries have proven to be useful in designing corrugated structures with engineered mechanical properties [Sef-fen 2012; Dias and Santangelo 2012]. We have explored self-shaping curved folding tessellations with a focus on their ability to create structural depth and stiffness. There are two major advantage of the self-shaping process in these structures. First, it automates their complex assembly process by autonomously folding numerous creases at the same time. Second, it stabilizes and stiffens the folded shape through inducing and preserving bending on the faces. To demonstrate this function, we have fabricated multiple curved pleated and tessellating prototypes and documented their shape-change upon actuation. We also performed mechanical tests to experimentally study the self-stiffening performance of these structures.

The first prototype is based on a curved pleated crease pattern with parallel sinusoidal mountain and valley creases, which folds into a corrugated surface structure (Figure 10). We studied the self-stiffening performance of the structure by measuring the maximum load it can bear while maintaining its folded shape. For this experiment, the structure was placed on a flat surfaces and it was loaded from the top with calibration weights until it collapsed / unfolded. The structure, with the self-weight of 8 grams, resisted unfolding under maximum of 1990g load. Next, we compared the load-bearing capability of the structure in flat and 3D folded state as it spanned between two supports. In the flat state, the prototype

Figure 11: Self-shaping lens tessellation design. A) Toolpath design and layering B) folded structure under 200g load, C) Folding sequences from flat (Dim. 23cm x 16cm x 1mm) to folded (Dim. 19.5cm x 5cm x 4cm) state upon drying in 30% RH

could hold 90g load before it collapsed, while in the 3D folded state, this threshold raised to 620g.

The second prototype is based on the lens tessellation crease pattern by David Huffman [Demaine et al. 2015], which is an example of a modular curved tessellation (Figure 11). The lens tessellation geometry is especially attractive because it creates large volumetric transformations, which can be controlled and programmed through adjusting the fold angles. The target fold angle of 90 degrees is particularly useful because the surface is stiffened in both the X and Y directions at the same time. The lens tessellation prototype was tested similarly to the first prototype. The structure, with the self-weight of 12 grams, resisted unfolding under max. 590g load. Spanning between two supports, the flat structure collapsed under 70g load, while the self-folded structure held up to 300g before collapsing.

7.3 Motion amplification mechanism in responsive architecture

The third application focuses on simple curved folding modules and their application as motion mechanisms in responsive architectural components. These mechanisms change their shape in response to the changes in the environment's RH level, without requiring external actuators or consuming any energy. Since the environment's RH level is a function of both temperature and humidity, the self-shaping prototypes can be tuned to perform a wide range of environmentally-responsive functions. Curved folding geometry is specifically advantageous because it offers motion amplification that converts small changes in form of bending to large angular transformations in the overall structure. We've produced prototypes of self-shaping curved folding modules, and documented

Figure 12: Transformation of a curved folding module A) Time-lapse imaging upon drying in 25% RH in the duration of 8 hours, B) Changes in the surface coverage area (%) in relationship to the fold angle

their cyclic transformations by placing them in consecutive high (90-100% RH) and low (30%) RH levels (Figure 12a).

As architectural façade components, curved folding modules exhibit a wide range of surface coverage area between their open and closed states (Figure 12b). Figure 13 shows a comparison of the surface coverage area between two prototypes, one incorporating curved folding geometry and one using a pure bending mechanism. Both prototypes have the same mesostructural setup and were tested in the same environments. In high RH, they both attain a flat state, and thus, provide a 100% surface coverage. However, upon drying, the curved-folded prototype shrinks its coverage area to 30%, leaving 70% surface area open. The bending prototype, on the other hand, can only provide 27% opening in its open state. This striking difference demonstrates the advantage of self-shaping curved folding geometry as a motion amplification mechanism for this architectural application.

Lastly, we designed and fabricated a prototype that consists of 16 modules with different geometries. In order to cluster the modules into a façade system demonstrator, we designed a base structure in which the modules were tilted in different directions. The unique geometry of each module required custom tailoring of the structure to ensure the same fold angle is achieved in the various modules (Figure 14).

8 DISCUSSION

In this paper, we demonstrated that self-shaping curved folding is achievable through a combination of materially programmed bending surfaces and flexible hinges. These structures, regardless of their geometric or manufacturing complexities, do not require manual or machine assembly and rather autonomously transform from flat to a 3D folded state. Our method induces bending distributed through the origami faces rather than the fold lines. This is especially useful for smart materials that have limited range and force of shape-change: by distributing the shrinking and swelling to a greater area on the surfaces, sharp folds and larger movement can be created

Figure 13: Demonstration of the motion amplification effect: Comparing the ratio of open/closed surface area in two façade components with A) Simple bending mechanism, B) curved folding mechanism, supported from their midpoint

Figure 14: Prototype of a multi-module weather responsive façade system in high, low, and median RH levels.

with less actuation force. The geometry itself also provides motion amplification, again remedying the main shortcomings of some shape-changing materials. The hygroscopic shaping process can work as a reversible or irreversible movement mechanism, allowing us to create a wide range of shape-changing mechanisms and explore their potential applications.

We presented a computational fabrication workflow in which the 3D-printing toolpaths and the material deposition layout is correlated with the material properties and the geometry of a crease pattern to achieve a target shape-change. Through digital and physical experiments, we showed how a crease can be physically programmed to reach a target fold angle via adjusting the geometric and/or mesostructure design parameters. Using the computational

workflow, we produced multiple prototypes, showcasing the capabilities of our method, which can be adapted for a wide range of geometries.

Finally, we presented three application scenarios for self-shaping curved folding. On a small scale, our method broadens the design space of the 4D-printed flat-packable objects and products by enabling a new type of performative geometry. In an architectural scale, we explored the application of self-shaping curved folding tessellations in structural systems, which are both stiff and lightweight. Their self-stiffening capability allows them to resist unfolding under load, which differentiates them from typical hinged-based origami structures. The self-shaping process is especially beneficial because it automates the folding of numerous creases, which is inherent to the tessellating crease patterns. Finally, we explored the applications of self-shaping curved folding modules as a motion amplification mechanism, offering a promising approach for creating weather-responsive architectural elements with a wide range of motion.

8.1 Limitations and future work

We used desktop FDM 3D-printers and commercially available filaments to produce a series of lab-scale prototypes. In order to create architectural-scale self-shaping structures, the fabrication method needs to be scaled up from desktop 3D-printers. This can be potentially achieved by using robotic arms and large-scale thermo-plastic extruders.

In terms of the material system, we chose hygroscopic materials that undergo a cyclic transformation in response to the changes in their moisture content. With the specific material used in this study, the shape is maintained unless the prototypes are submerged in the water or are placed in high humidity (Above 80% RH). This is favorable for irreversible self-shaping mechanisms that should maintain their folded shape in the ambient humidity. To block the motion in high RH environments, the prototypes can be covered with off-the-shelf wood coating to prevent moisture absorption. Another possible strategy to stabilize the shape is through devising a final locking step that blocks the movement after one-time self-shaping. Such locking mechanism can be integrated in the 3D-printed structure itself. To enhance the performance of the cyclic environmentally-responsive mechanisms, the future work can explore alternative materials with a wider range of environmental RH responsiveness. Moreover, the future work can explore the use of other stimuli-responsive materials, such as Shape-Memory Polymers, to allow for fast actuation or diverse stimuli response. Lastly, While the cyclic shape-changing systems showed to be stable and performative in short term (within 10 cycles of shape-change), long-term experiments need to follow up this study to assess the lifetime of these systems.

In our computational workflow, we implemented a forward design tool that visualizes the transformations of a flat crease pattern upon actuation. However, we plan to expand the design tool by implementing an inverse design process. This can potentially include interfacing with existing computational origami design tools. Moreover, the future work can explore an integrated pipeline between

the FEM simulation and the design tool, which would facilitate precise modeling and optimization of the self-shaping curved folding structures.

9 CONCLUSION

We introduced self-shaping curved folding: a 4D-printing method to create curved folded structures that transform from flat to 3D folded state upon changes in the environment's RH level. This was achieved through design and fabrication at the mesoscale level, enabled by a computational workflow that integrates design, simulation, and digital fabrication. We created self-shaping curved folding structures that have a wide range of motion and can resist unfolding under load. These prototypes emphasize the versatility of our computational fabrication method, the advantage of self-shaping mechanisms in automating their complex folding sequences, and the performance benefits of self-shaping curved folding. Our presented methods enable new and more complex patterns and functions for both 4D-printing and curved folding, which are applicable to the fields of industrial design, architecture, and building systems.

ACKNOWLEDGMENTS

The authors thank the Ministry of Science, Research and Arts of the State of Baden Württemberg for funding this research. They also acknowledge the support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618. The authors thank Philipp Koeser for his insightful feedback and discussion, and Hooman Salyani for his assistance with the graphic design production.

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A APPENDICES

A.1 FEA Simulation Method

We used FEM simulation to precisely explore the design space of a fold angle, as described in Section 5.1. The motion mechanism is simulated using a geometrically nonlinear analysis in ANSYS (Release 18.0, ANSYS Inc., Canonsburg, USA) and assuming quasi-static behavior. A linear elastic material model with a bending modulus directly related to the Young's modulus of $E=100$ MPa and a Poisson's ratio of $\nu=0.3$ is applied for the active as well as for the passive material. Furthermore, the material is assumed to be isotropic due to the various layer setup with varying printing

angles. As only a qualitative analysis of the deformation behavior is envisaged without evaluating stress values, only the stiffness ratio between the different regions is crucial, and, therefore, not the exact value of the Young's modulus is required. The geometry is discretized by four-node quadrilateral elements using a shear deformable Reissner-Mindlin shell model (SHELL181). In order to map the bilayer structure, a multi-layered shell is defined and the cross-section of the functional bilayer is split into the active layer (0.6 mm) and the passive layer (0.2 mm). For the actuation, a temperature load case is applied that simulates the swelling of the active layer by a volumetric expansion due to a temperature increase. This expansion is defined to be orthotropic in the printing direction of the active layer. In addition, nodal supports are positioned in such a way that no rigid body motion is possible, but the targeted deformation is still enabled.