# An Overview of Fabrication Techniques for Single-Assembly Folding Structures

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## Abstract

In recent years, folding techniques have been widely used by architects to make 3D forms from 2D sheets. These forms serve as inspiration for their designs, enable simpler and more intuitive solutions to design problems, and facilitate the realization of architectural intent [1]. In this research, we explore a rigid folding structure in which all deformation is concentrated in the hinges; the faces between the folds remain flat during deployment. This work provides an overview of different techniques for scaling origami folding structures for applications in architecture and develops ways of avoiding lengthy assembly times and hinge failures. To investigate these variable techniques, a wraparound hub expandable geometry is adopted, designed, and developed into a single skin assembly.

## 1. Introduction

The folding technique known as origami has been applied to many fields, such as in materials research, robotics, and architectural design [2]. However, applications of folding structures are very limited in architecture because of unresolved technical and fabrication issues. Three problems arise when applying folds to architecture. The first is scale. The joints for each fold must increase with the fold’s size. The fold also must be modified to account for the thickness of the material. The second problem is joint failure. The numerous folds inherent to origami require many hinges, and the failure of a single hinge could cause the failure of the entire structure. The third problem is the lengthy assembling process necessary for the numerous parts of an origami structure. In a case where the structure must be developed onsite, pieces can get lost, be damaged, or require special tools. These three problems comprise the main constraints to applying rigid folding structures in architecture.

In this research, we address how to provide rigidity and flexibility in specific areas of folding structures, in order to achieve a single entity and avoid the assembly of joints and rigid parts. By using Pellegrino wraparound hub geometry [3] (see Figure 1), also known as a “flasher” pattern, as a case study of rigid folding structures, we explore three fabrication techniques and test their possibilities and limitations.

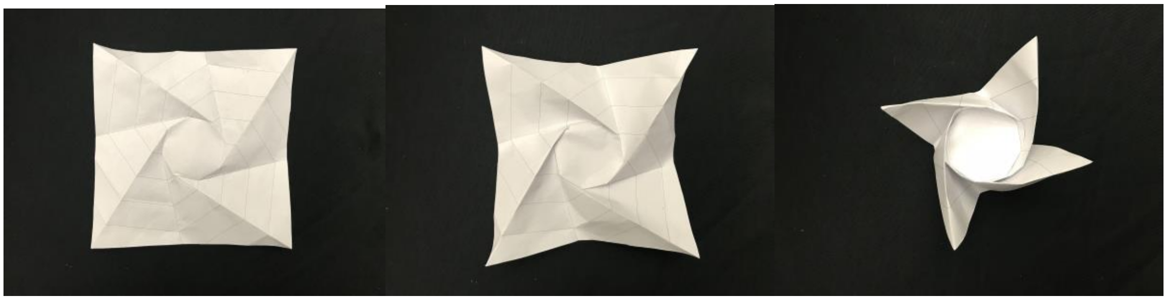
Figure 1: Paper model of the Pellegrino wraparound hub geometry.

## 2. Geometry of a Rigid Fold

In this research, we explored different rigid fold designs that could be used as cladding systems in deployable structures (see Figure 2). The deployable structure employed here had square-based openings that collapsed toward the centers of the squares. Therefore, the desired fold design needed to expand and collapse inside the square-based deployable scissor structure.


Figure 2: A square-based deployable structure with *Pellegrino wraparound hub folding geometry* (designed and fabricated by the authors).

In selecting the proper folds, we considered the following properties:
1- A square-based fold design,
2- The four corners expanding and collapsing toward the center in order to respond to the overall deployable structure design, and
3- Expansion and collapse in both the X and Y directions (and at the same speed).

The *Pellegrino wraparound hub geometry* demonstrated the potential to resolve all of the required properties; therefore, the authors modified the original octagonal design to fit into a square-based deployable structure (see Figure 3).

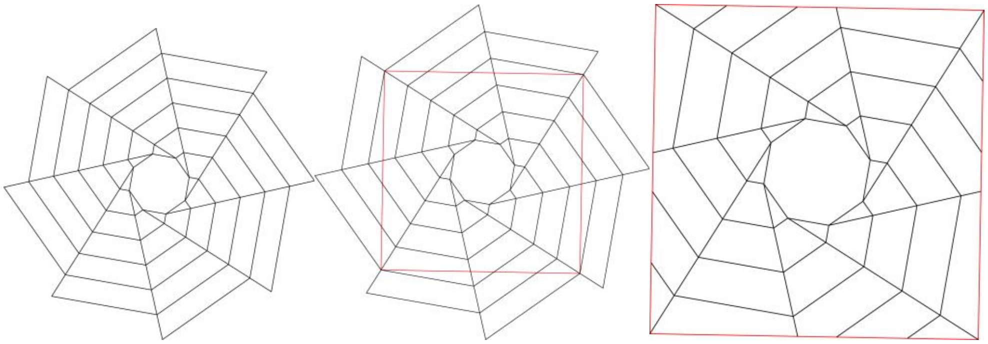

Figure 3: Modification process for the *Pellegrino wraparound hub geometry.*

## 3. Method

In this research, we explored three methods of assembly: lamination of the rigid parts with a soft and stretchy composite, 3D printing mixing soft and rigid materials on the same part, and lamination of the rigid parts with Shape Memory Polymers (SMPs). The *Pellegrino wraparound hub geometry* involved only rigid folds [12], so each method tested the deformation only of the folds.

### 3.1. Lamination of Rigid Parts with Soft and Stretchy Composite

The first method for assembly was to laminate a solid material with a soft substance, so the soft portion could bend and stretch where the solid portion was absent. As shown in Figure 1, 1/16th MDF rigid parts were laminated with a silicone rubber called EcoFlex. Eco Flex is a rubber composite material consisting of two mixed portions. As stated in Smooth-On's product sheet, Eco Flex "cures to a very soft, very strong and very 'stretchy' rubber, stretching many times its original size without tearing and will rebound to its original form without distortion."

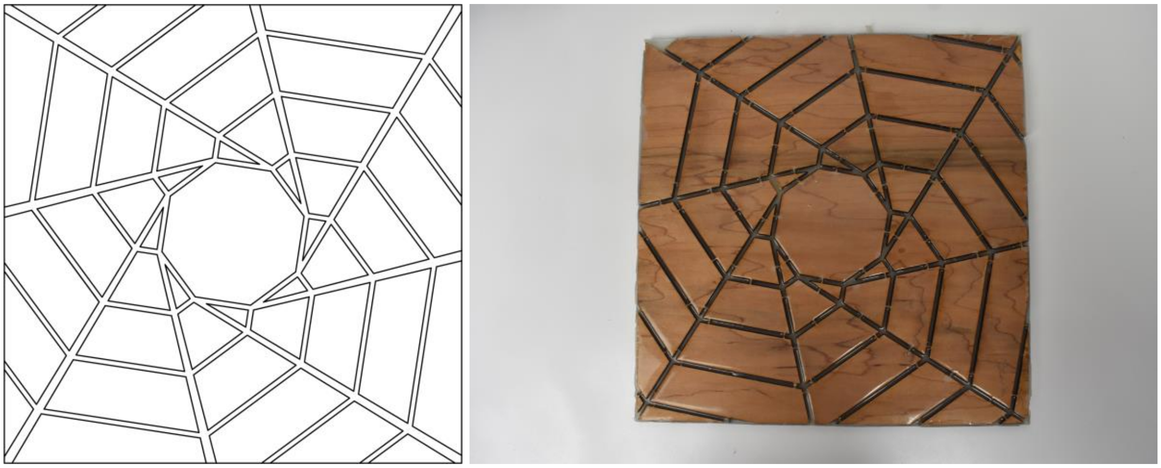

Figure 4: The gaps in the closed geometries represent soft edges (left); the rigid wooden parts are laminated with Eco Flex (right).

To accommodate the increased deformation of the folds toward the corners, the soft material between the panels gradually increased in width as it expanded from the center; this resulted in an increased range of motion and flexibility. For assembly, a thin layer of silicone was cured for twenty minutes; then, using a template, the MDF panels were placed on the silicone in a *wraparound hub* geometric pattern. Next, more silicone was cured between the gaps of the MDF board. Following, a thin layer was cured on top of the MDF board to seal the structure. The silicone encased the MDF board, creating a single structure. The flexibility of the silicone allowed for the 1/16th thick MDF panels to fold without folding into each other (see Figure 5).

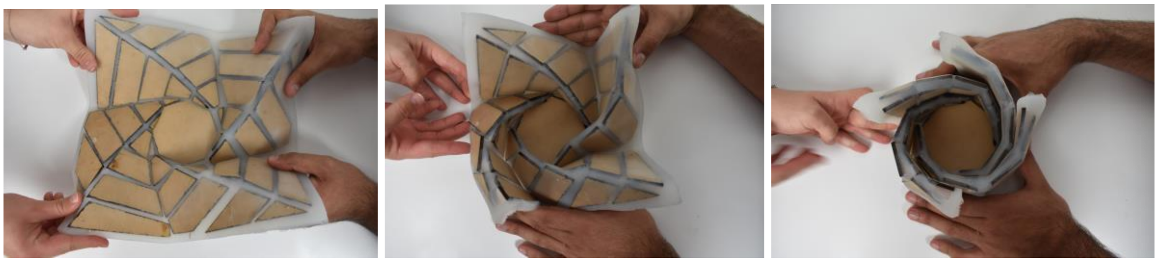
Figure 5: The silicone acting as a single joint, intermittently bending and stretching in two directions.

The major difference between the Eco Flex joints and paper model was the direction of the folds. In the paper model, after the first deployment process, all of the creases found and remembered the fold direction (up or down); however, the Eco Flex material didn’t have memory, and each time every crease had to be forced into the correct direction. The deformation of the folds led to tears in the material. The rigid panels required deformation only of the soft material, and the Eco Flex could not provide enough flexibility while maintaining a thin, 1 mm lamination.

This fabrication method resolved the issues related to scale, creation, and single-structure assembly. However, the method required two materials and time to cast and cure the soft material. The lamination also added thickness to the structure, limiting the range of each fold’s closing. For applications in architecture, the weights and thicknesses of the materials, lengthy fabrication process, and limited range of motion did not allow for the flexibility and multiple uses required for deployable structures. The next step was to fabricate with a thinner material.

### 3.2. 3D Printing a Mix of Soft and Rigid Materials on the Same Part

The second method of fabrication focused on utilizing 3D printing technology to decrease the thicknesses of the materials and fabricate a single object using two types of plastic. The rigid and soft materials were printed next to one another via two nozzles on the 3D printer. In order to accomplish this goal, we selected the Stratasys J750 printer. This printer prints flexible and rigid materials together in a single object, and builds layers down to 14 macrons (.00055 inches), allowing for thicknesses similar to sheets of paper. Decreasing thickness also decreases the required deformations in the folds; however, deformations will always be present, even in material printed to paper-like thickness [12]. The "VERO" materials had a tensile strength of D-638-03, MPa 50-65, and psi 7250-9450. They were rigid, so a softness was incorporated into the base by using a combination of "VERO" and "Tangoblack/Tangoblack+" materials. The latter had a tensile strength of D-412, MPa 1.8-2.4, psi 115-350, and tensile Tear resistance of D-624 Kg/cm 3-5 Lb/in 18-24.

Using the same modified *Pellegrino wraparound hub* geometry as the laminated MDF board, we 3D printed flexible and rigid liquid photopolymer threads next to one another. The first test print was 1 mm thick and 8.5 in x 8.5 in (see Figure 6).

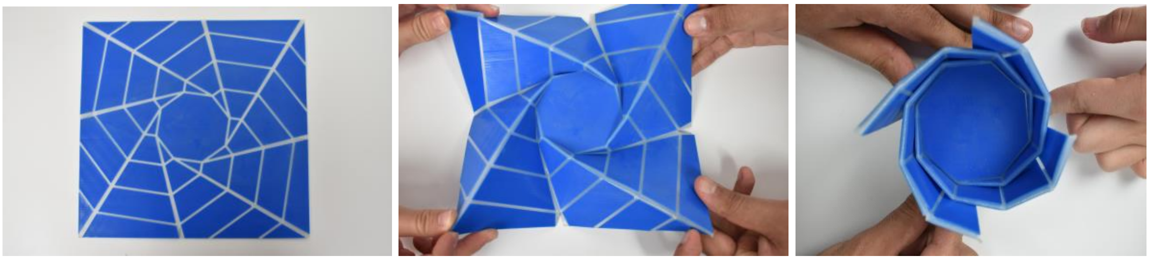

Figure 6: Prototype with 1 mm thickness.

After the test printing at 1 mm, the same geometry was printed at a .5 mm (see Figure 7). This structure folded with less resistance than did the 1 mm 3D print.

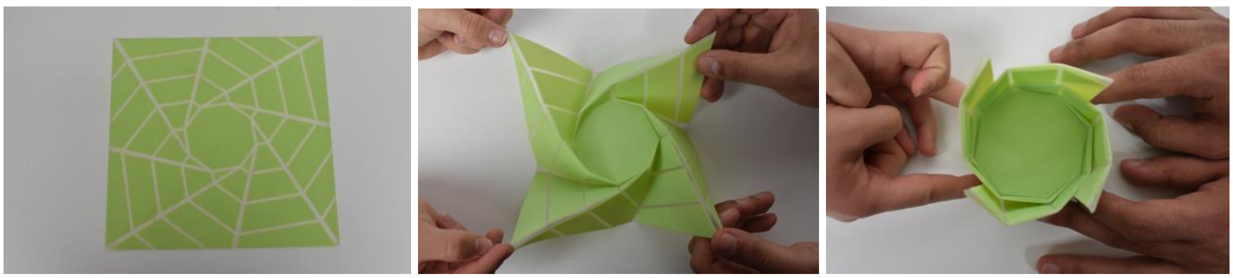

Figure 7: Prototype with .5 mm thickness.

These 3D printed prototypes required four hands to fold the diagonal joints either up or down. The resting state of the soft material was flat, allowing it to fold when a force was acted upon it. These prototypes had the same limitations as the laminated ones. The soft material didn't have the memory required to remember the directions of the folds, so each time we had to direct the creases toward the correct sides.

To overcome this limitation, instead of flat printing, we printed the structure at 15 degrees closed, with the diagonal folds rotated at 15 degrees from lying flat (see Figures 10 and 11). The joints were at a resting state when the diagonal folds were half closed, forcing the joints to fold in a particular way. The joints were printed such that they remembered the direction to fold, since in their resting state they were partially folded.

Since *Pellegrino wraparound hub* geometry is nonrigid, creating a computational model with 15 degrees-rotated rigid panels required that the soft material be drawn deformed. Using Rhinoceros 3D computer application software, the rigid panels were rotated 15 degrees and rotated around an octagon (see Figure 8). The soft material was then drawn, creating rectangular planes that connected the vertices of the rigid planes (see Figure 9). From this process, it was concluded that the folds became more deformed as the distance from the center increased.

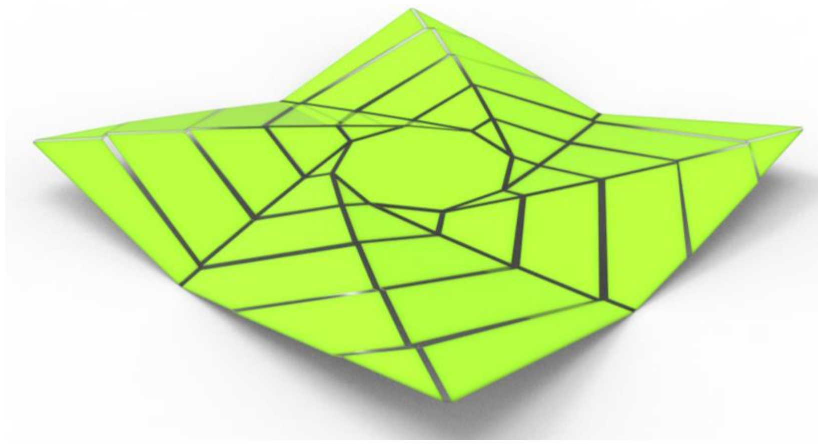

Figure 8: Prototype closed 15 degrees.

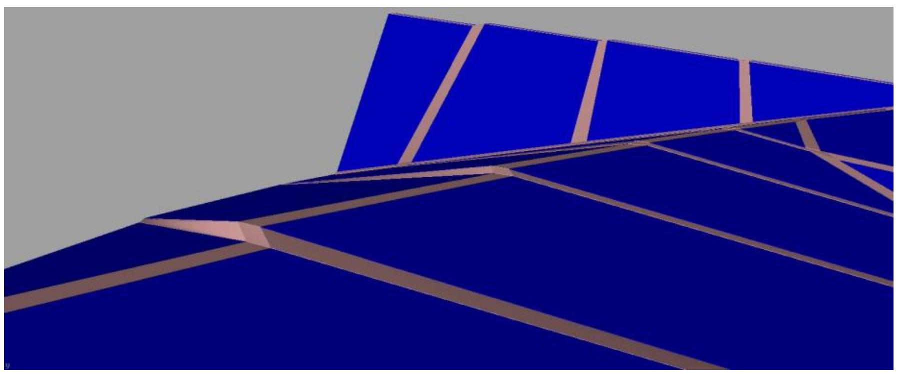

Figure 9: Soft material folds deformed via Rhinoceros 3D software.

Following the flat 3D prints, prototypes of 1 mm and .5 mm thicknesses (see Figures 10 and 11, respectively) were printed at 8.5 in x 8.5 in.

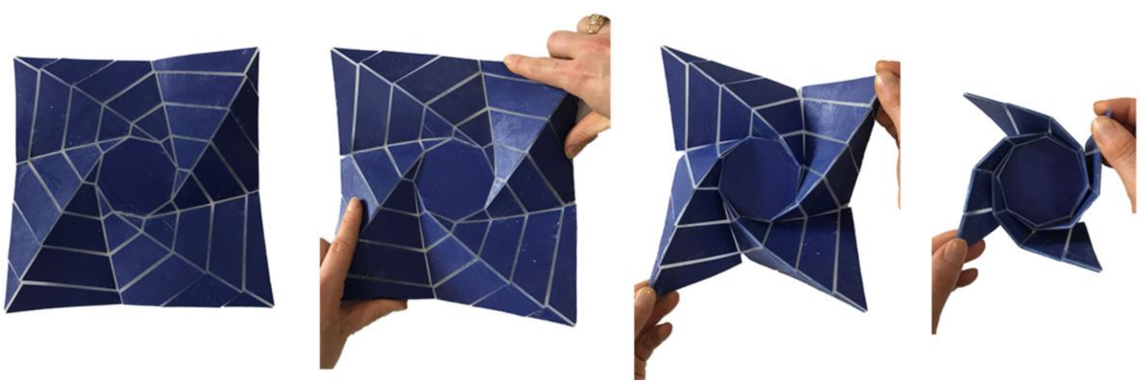

Figure 10: Prototype with 1 mm thickness.

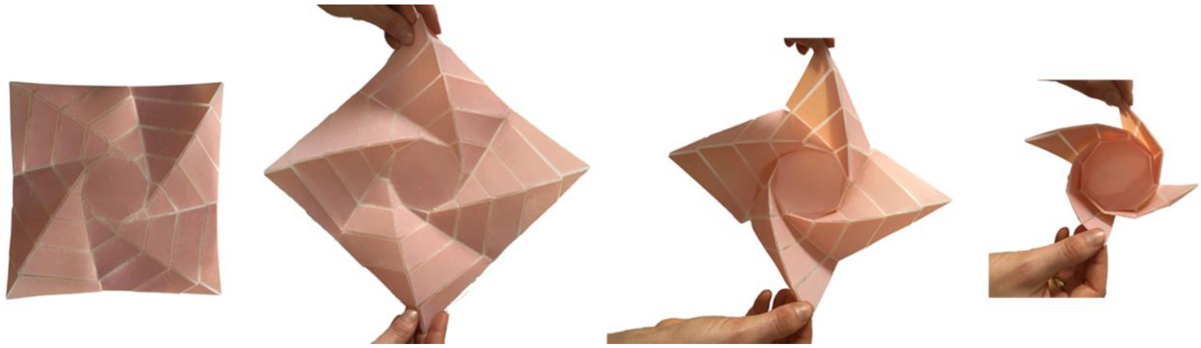

Figure 11: Prototype with .5 mm thickness.

The two prototypes (1 mm and .5 mm in thickness and each closed at 15 degrees) were folded using two hands on two opposite corners; the previous prototypes were of similar thicknesses but required four hands to force. When folded in the direction they had been printed, the 15-degree folds closed every time to the two opposite corners. The 1 mm prototype resisted more to folding that the .5 mm version. The hard material of the .5 mm prototype deformed more than the 1 mm version, due to the thinness of the material decreasing the rigidity, which in turn lessened the deformation of the soft material. This was evidenced by tears along the corners. The 1 mm prototype had more substantial tears at the ends than did the .5 mm version.

The soft material printed next to the rigid material allowed for a single flexible joint and one assembly process. The 15-degree closed fabrication allowed the joints to remember which way to fold. For architecture applications in deployable structures, however, the flexibility of the soft material prohibits the joint from locking the structure into place like a typical hinge; this is true at any deployable stage. In the next step of this research, instead of using a soft material joint, we explored the use of smart materials to provide locking mechanisms for the structure. We employed SMPs capable of changing their state from solid to soft when heat was applied.

### 3.3. Lamination of Rigid Parts with Shape Memory Polymers

SMPs are polymeric smart materials capable of embodying two solid states when change is induced by heat. Their original shape (in the present case, flat) self-recovers after heat application. The other solid state is formed when heat and applied force shape the polymer.

In this fabrication, we followed the same process as described in Section 3.1, but replaced the soft material (Eco Flex) with SMP. The SMP was fabricated by mixing Epon 826, Jeffamine D230, and neopentyl glycol diglycidyl ether (NGDE) at a ratio allowing for a transition temperature of 40 to 60 degrees and a rigid state at approximately 70 degrees [7]. The SMP was cured between a 1/16th MDF board (see Figure 12).

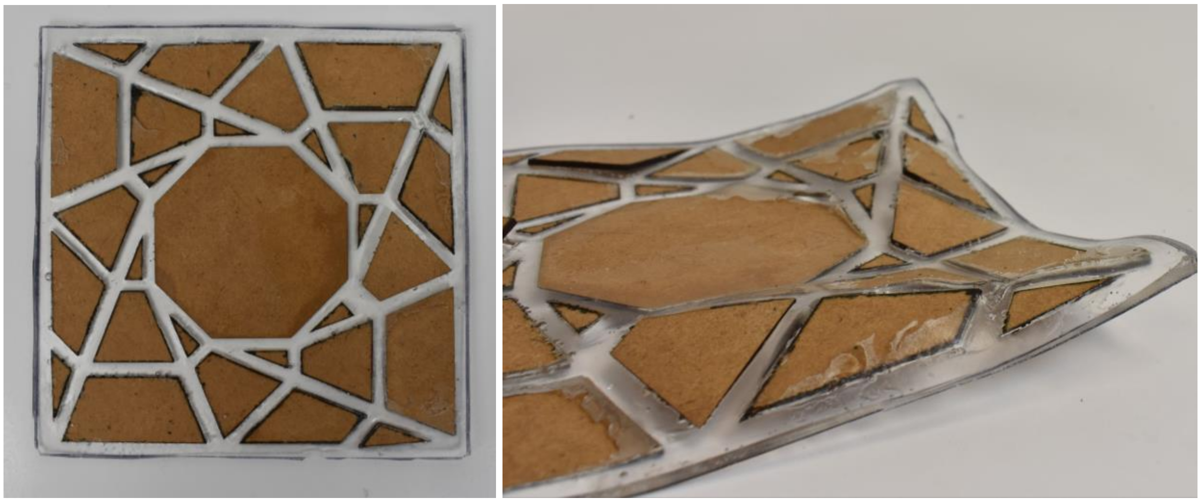

Figure 12: SMP acting as live hinges.

The SMP provided the locking mechanism for the folded structure. However, the connections between the rigid parts and SMP were very brittle and could easily detach from one another.  To avoid this problem, the 1/16th MDF board was fully laminated in SMP to hold the structure together (see Figure 13).

Figure 13: Full 1/16th MDF board laminated with SMP.

The structure could be heated and folded to any collapsed state. Once cooled, the structure held its shape until heated again. The heat then unraveled the structure back to its original shape, which was flat. These two states were capable of locking the deployable scissor structure into different positions, so it did not collapse.

However, the 1/16th MDF board with SMP was extra thick, which prohibited a full range of motion. The SMP in the folds could not stretch to allow for deformation in the nonrigid *Pellegrino wraparound hub* geometry. Due to the fabrication method of curing the liquid SMP, it could only produce small samples, also limiting the folding range. Improving this method of fabrication to allow for increasing the prototype size will be the next step taken in future research. The final step will be 3D printing SMP filaments next to PLA filaments to produce larger prototypes and single fabrications. These single assembly protypes can then be tested at actual scale for deployable structures.

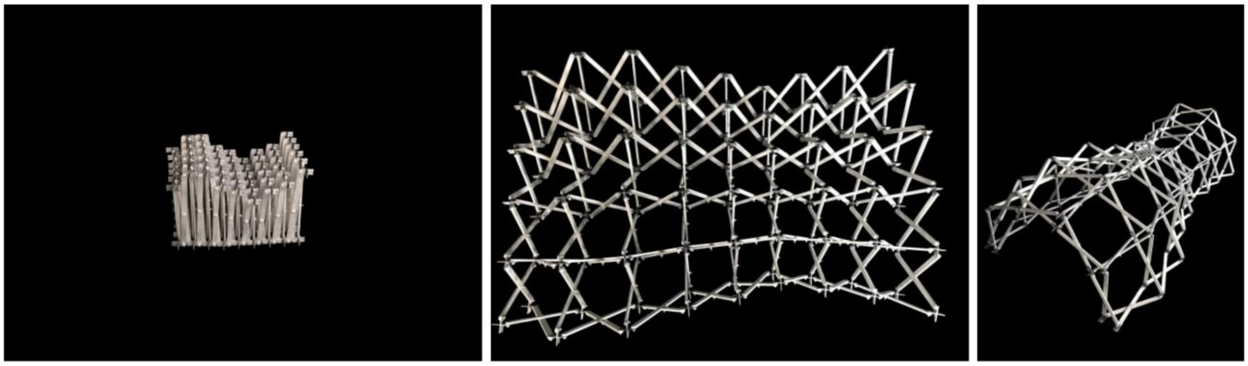

Figure 13: Prototype of the deployable scissor structure

The purpose of this research was to fabricate a single assembly cladding system for deployable structures. The prototypes were designed in an effort to fabricate a locking mechanism for deployable structures and shading devices (see Figure 13, 14). The SMP can be heated by an electrical current running through the scissor structure, allowing for the transition heat. The SMP then becomes rigid in the deployed and closed states when cooled.

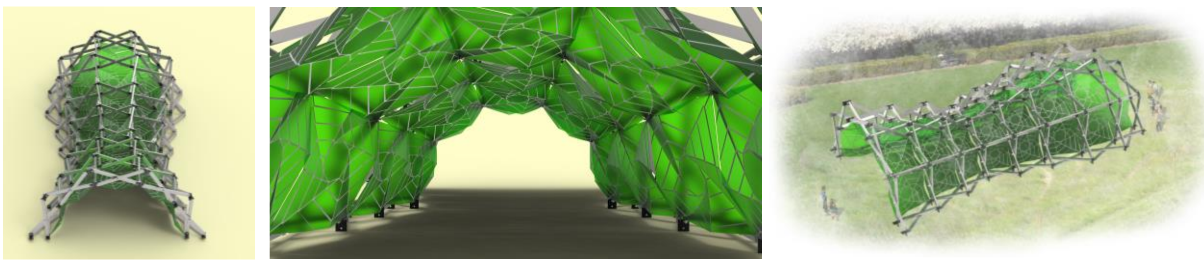

Figure 14: Final cladding system for the deployable scissor structure.

## 4. Conclusion

This paper addressed three methods for designing and fabricating rigid fold structures in which the rigid parts and hinges were fabricated in one assembly. We explained the pros and cons of the methods, and how each led us to an exploration of the subsequent iteration. Our next step will be to analyze advancements in 3D printing that might allow us to print SMPs next to rigid materials for single assembly.


## 5. Acknowledgements

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## 6. References


[1] Shen, T. and Nagai, Y. (2017) An Overview of Folding Techniques in Architecture Design. *World Journal of Engineering and Technology*, **5**, 12-19. doi: 10.4236/wjet.2017.53B002

[2] Stavric, M. and Wiltsche, A. (2014) Quadrilateral Patterns for Rigid Folding Structures. *International Journal of Architectural Computing*, **12**, 61-79. https://doi.org/10.1260/1478-0771.12.1.61

[3] Pellegrino, S. *Deployable Structures*. Springer, 2002.

[4] Beites, S. (2013) Morphological Behavior of Shape Memory Polymers toward a Deployable Adaptive Architecture in *Adaptive Architecture*. 121-127.

[5] Guest, S. D. and Pellegrino, S. (1992) Inextensional Wrapping of Flat Membranes, *First International Seminar on Structural Morphology*, Montpellier, France, Sept. 7–11, 203–215.

[6] Yang, Y. et al. (2016) *International Journal of Advanced Manufacturing Technology*, **84**, 2079. https://doi.org/10.1007/s00170-015-7843-2

[7] Mansoori, M., Kalantar, N., Creasy, T., and Rybkowski, Z. Toward Adaptive Architectural Skins: Designing Temperature-Responsive Curvilinear Surfaces.

[8] http://papers.cumincad.org/data/works/att/acadia13_121.content.pdf

[9] Wu, J. et al. (2016) Multi-shape active composites by 3D printing of digital shape memory polymers, *Scientific Reports*, **6**, 24224. doi: 10.1038/srep24224 (2016)

[10] Mather, P., Luo, X., and Rousseau, I. (2009) Shape Memory Polymer Research, **39**(1), 445-471.

[11] https://pubs.acs.org/doi/pdf/10.1021/acsami.7b07816

[12] Lang, R. J., Magleby, S., and Howell, L. (2016) Single degree-of-freedom rigidly foldable cut origami flashers. *Journal of Mechanisms and Robotics*, 8(3), 031005.