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3D Printed Origami Cellular Material Switching DOF and Poisson's Ratio

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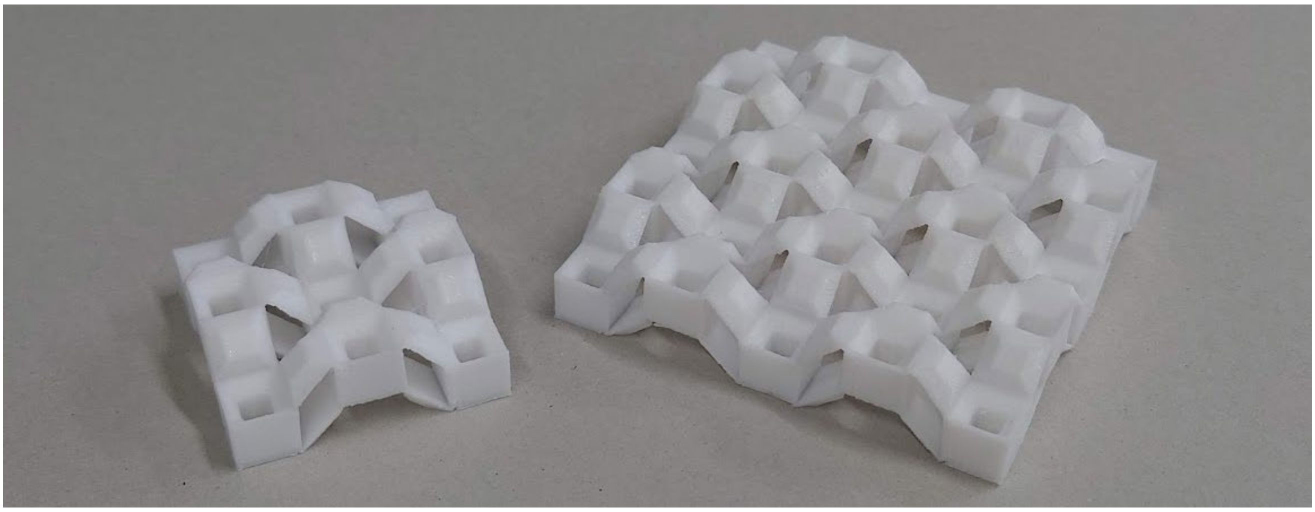

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1 Background

Cellular structures constructed by the tessellation of origami cells have been gaining attention for their special mechanical properties such as flexibility and anisotropic stiffness. This type of structure was explored by artists: 'Snapology' by Strobl [1] and 'BuildVoid' by Tokolo (fifth author).

Our previous study [2] proposed an origami cellular structure inspired by BuildVoid. Figure 1 shows the composition of the structure. A *module* is constructed by connecting four cubic *solids* with four pairs of square *arms*. The module can be folded into two modes: parallel mode and skew mode, distinguished by the directions of opposite edges of the quadrangular hole. In parallel mode, the module has 2 DOFs: folding in x and y directions are independent. In skew mode, the module has 1 DOF: folding in x and y directions are synchronized. By arraying the modules in x and y directions, we can construct a *tessellation* of the structure. The choice of assignment of parallel/skew to each module can switch DOF and Poisson's ratio of the tessellation (Detailed kinematics is described in [2]).

2 Concept

In this work, we 3D-print the structure with a single material (TPU) as a compliant mechanism. This allows for easier fabrication. Moreover, the structure gets multi-stable, switching DOF and Poisson's ratio. This model can be an educational toy for learning mechanical principles through squeezing it.

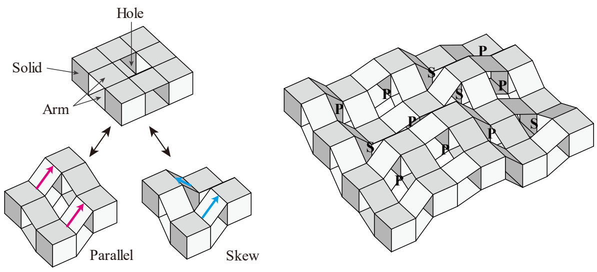

Figure 1: Composition of the mechanism proposed by [2]. Module (Left) and 4×3 tessellation (Right).

3 Modeling

Figure 2 shows a detailed view of a part of the 3D-printed model. The structure is printed so that all the modules are in skew mode folded by $\pi/4$. To utilize bending deformation of the material as hinges, the thickness of the hinge regions t must be sufficiently smaller than that of the other regions, making the ratio of bending stiffness $\propto t^3$ sufficiently large. We used $t = 0.75$mm. We added a thickness to the solids and the arms with a taper of $45°$. This taper is for overhanging, reducing material (also printing time and weight of the structure), and avoiding collision while folding (Figure 3). The support material required at isolated boundary edges can be easily removed (Figure 4). We can construct tessellation by repetition.

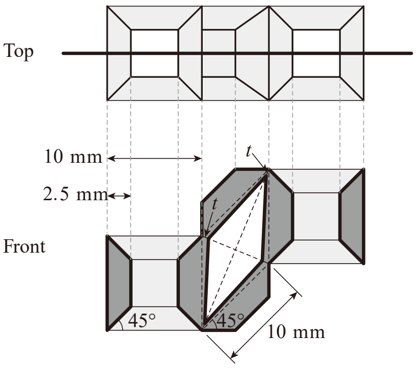

Figure 2: Top and front (section) views of a part of the model.

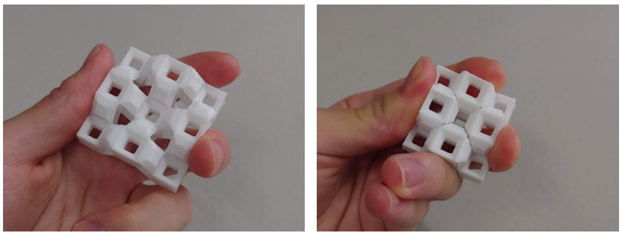
Figure 3: Tapered faces contact together when fully folded.

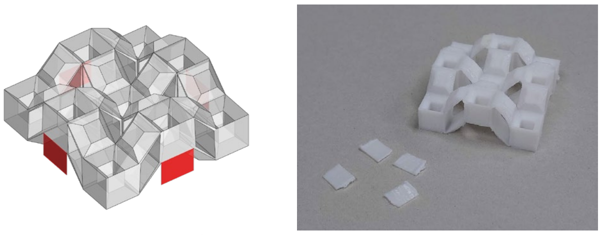
Figure 4: Locations where support material is required (Left).
Removal of support material (Right).

4 Multi-Stability

Due to the elasticity of the material and the half-folded printed state, the model gains multi-stability; inner arms can be flipped up and down (Figure 5). To analyze this behavior, we consider a simplified model where rigid solids and arms are connected by rotational springs that produce a moment proportional to the rotation angle: $M = k/4 \times \Delta\theta$, where $k/4$ is the spring constant (Figure 6 Left). Strain energy $U = k\,\Delta\theta^2/2$ is stored in four springs in the pair of arms. In the flipped state, flipped arms rotate more than the other arms. Due to the kinematic condition, the absolute angle θ between the arm and the horizontal plane must be equal in all the arms. By using $\Delta\theta = \theta - \pi/4$ and $\Delta\theta_f = \theta + \pi/4$, we find $\Delta\theta_f = \pi/2 + \Delta\theta$. In the case of 2×2 tessellation, there are 12 pairs of arms, and 4 of those can be flipped. Therefore, the potential energy of the two modes are

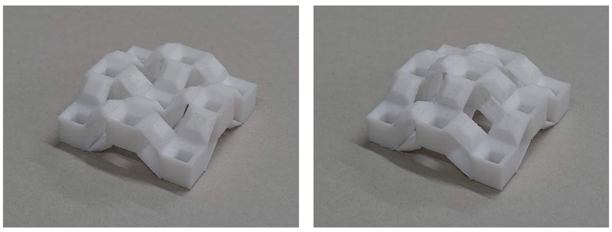
Figure 5: Two stable states of the 3D printed model.
Left: printed state, right: flipped state.

$$U_1 = 12 \times \frac{k\Delta\theta^2}{2} = 6k\left(\theta - \frac{\pi}{4}\right)^2,$$

$$U_2 = 8 \times \frac{k\Delta\theta^2}{2} + 4 \times \frac{k\Delta{\theta_f}^2}{2} = \frac{k(\pi - 12\theta)^2}{24} + \frac{\pi^2 k}{3}.$$

Figure 6 Right shows plots of these functions. U_1 takes the minimum of 0 when $\theta = \pi/4$, which corresponds to the printed state. U_2 takes the minimum of $\pi^2 k/3$ when $\theta = \pi/12$, which corresponds to the flipped state. The two plots intersect with $U = 3\pi^2 k/8$ when $\theta = 0$. Because this is larger than the minimum of U_2, the flipped state can be stable.

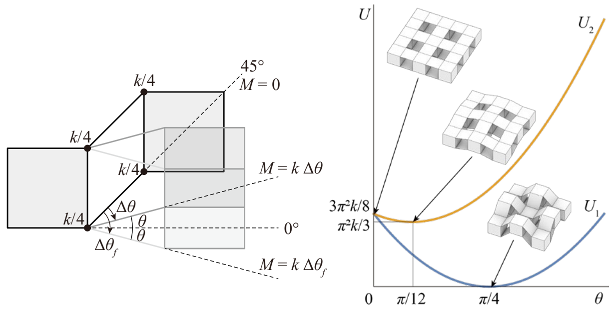

Figure 6: Rigid body and rotational spring model (Left).
Plots of potential energy (Right).

5 DOF and Poisson's Ratio

The two stable states of 2×2 tessellation have different DOFs and Poisson's ratios as follows:

(1) Printed state: All the modules are in skew mode, so all the rows and columns of the arms are synchronized. This results in 1 DOF and Poisson's ratio $\nu = -1$ (auxetic).

(2) Flipped state: All the modules are in parallel mode, so two rows and two columns of the arms are independent. This results in 4 DOFs and $\nu = 0$.

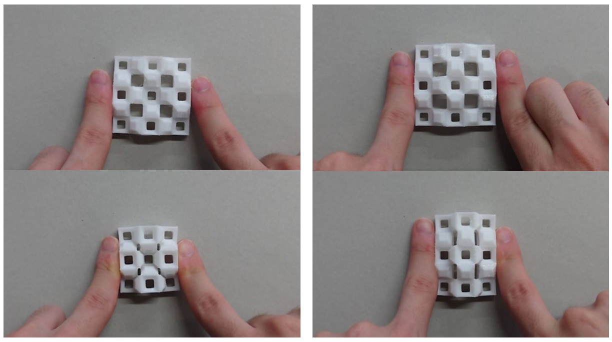
Figure 7: Model compressed in one direction.
Left: printed state ($\nu = -1$), right: flipped state ($\nu = 0$).

6 Software & System

Modeling software: Rhinoceros/Grasshopper
Printer: Qidi X-Pro
Filament: PolyFlex TPU95-HF

References

[1] Strobl, H.: Snapology, https://www.snapology.eu/, last accessed 2024/05/27.

[2] Adachi, A., Nishimoto, S., Totsuka, H., Warisaya, K., Tokolo, A., Tachi, T. (in press): Origami Cellular Material Switching Between Single and Multiple DOF Modes. 8OSME (2024).