Design and analysis of origami-based mechanical metamaterials via three-dimensional Ashby chart

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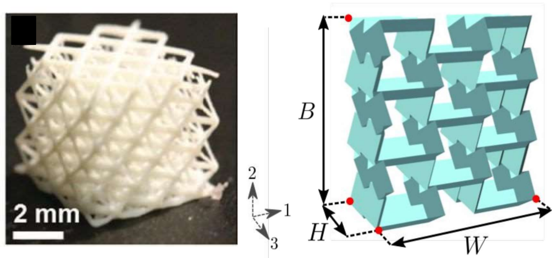
Introduction

Mechanical metamaterials offers unprecedented mechanical properties and rich functionalities due to the plentiful design freedom available within their architecture. Among a variety of approaches to construct metamaterials with such unique properties, lattice-based mechanical metamaterials are the emerging concepts. Their voluminous nature has the possibility to work as constructional elements of the mechanical system while achieving the superior performance compared to the conventional materials.

Here, to offer tunable nature to three dimensional voluminous mechanical metamaterials, we adopt techniques of origami to build a space-filling tessellation. To this end, Tachi-Miura Polyhedron (TMP) can perform as an ideal platform as the mechanical metamaterials with the reconfigurability and tunability. While conventional materials can represent only one specific point on the Ashby chart., **origami-based mechanical metamaterial can achieve multiple properties with one fabricated metamaterial**



Left, Zheng, et. al "Ultralight, Ultrastiff Mechanical Metamaterials", **Right**, manufactured prototype with the process inspired by honeycomb structures

Research objective

In this work we aim at:

(i) proposing a TMP tessellation as a mechanical platform that has a in-situ tunability of mechanical properties within the elastic deformation regime;

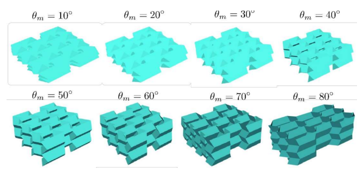
(ii) reporting a unique behavior where the stiffness decreases as the density increases;

(iii) presenting anisotropic positive/negative Poisson's ratios visualized with the density and stiffness
in three-dimensional extended Ashby chart;

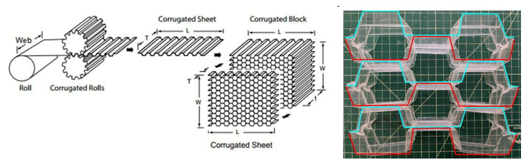
(iv) validating the analysis and visualization of the design space via experiments on the prototypes manufactures with the efficient method inspired by honeycomb structures.

Design and Prototype Manufacturing

- TMP tessellations can transform its shape in a large margin through a folding process
- **Inspired by honeycomb structures,** we introduce a new manufacturing method for tessellation of TMPs
- By combining corrugated long origami sheets, we can construct a tessellation of TMPs with preserving the geometries and properties of unit cells.
- This manufacturing method is **highly efficient** compared to the method



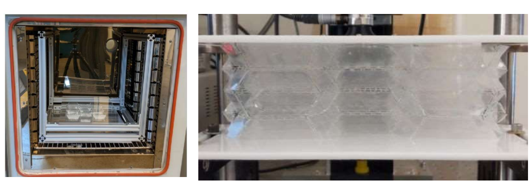
Folding process of TMP tessellation



Left, G. Clarke, "Characterization of Low Velocity Impact Damage in Metallic Honeycomb Sandwich Aircraft Panels using Finite Element Analysis", **Right**, manufactured prototype with the process inspired by honeycomb structures

Analysis and Experiments

- Theoretical analysis of the geometries and mechanical properties are done with the rigid origami model where we assume facets are rigid panels and crease lines are nonlinear springs.
- To control the natural posture of a tessellation, we develop a heat process in a convectional oven
- We conduct compression tests on a manufactured prototype to obtain mechanical properties

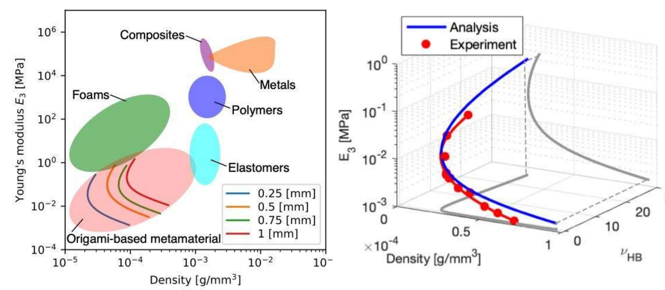


Left, setup of the heat processing in a convectional oven, **Right**, experimental setup for compression tests on a manufactured TMP tessellation prototype

Conclusions

By combining origami-based tessellation design, analytical method with rigid-origami modeling, efficient manufacturing of a prototype, and experimental verification, we show the effectiveness of the origami-mechanical metamaterials as a tunable mechanical platform that has a wide range of the stiffness, density, and Poisson's ratio. Specifically, **we find a change in stiffness by a factor of 60, density by a factor of 10, and specific stiffness by a factor of 700, approximately**.

Given the simplicity of the analysis and manufacturing, this metamaterial can be further leveraged through the active actuation methods such as pneumatic actuation. In this report, we have controlled the initial posture of the tessellation via heat processing with fixing the height to the desired value. This method satisfies the goal to obtain the desired posture. However, this is rather a passive method and takes a long to obtain the goal. Therefore, active active methods can offer a great enhancement to the ability of this metamaterial so that it can transform and adapt its mechanical properties to the quickly-changing outer environment.



Left Plot of the mechanical properties of TMP tessellations made of PET in Ashby chart, **Right**, Comparison of experimental and theoretical result of the mechanical properties in three-dimensional Ashby chart

References

1. K. Yamaguchi, J. Yang, "Design and analysis of origami-based mechanical metamaterials via three-dimensional Ashby chart", To be submitted
2. K. Yamaguchi, H. Yasuda, K. Tsujikawa, T. Kunimine, J. Yang, "Graph-theoretic estimation of reconfigurability in origami-based metamaterials," *Materials & Design* 213, 110343, 2022
3. H. Yasuda, B. Gopalarethinam, T. Kunimine, T. Tachi, J. Yang, Origami-Based Cellular Structures with In Situ Transition between Collapsible and Load-Bearing Configurations, *Advanced Engineering Materials* 21 (12) (2019) 1900562
4. H. Yasuda, J. Yang, Reentrant Origami-Based Metamaterials with Negative Poisson's Ratio and Bistability, *Physical Review Letters* 114 (18) (2015) 185502

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