Ultra-Lightweight, Ductile Carbon-Fiber Reinforced Composites

Vlastimil Kunc

Oak Ridge National Lab

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Project ID#: mat146

Overview

Timeline

- Project start date: Oct 2018
- Project end date: Dec 2023
- Percent complete: 50%

Budget

- DOE project funding: $500K
  - DOE: 50%
  - Contractor: 50%
- Funding for FY21: $500K

Barriers and Targets

- **Barrier**: Use of lower-density materials with suitable mechanical properties, i.e., materials with higher strength-to-weight and/or higher stiffness-to-weight ratios.[1)]
- **Target:** Hybrid hierarchical CF reinforced materials that are ultralight, strong and tough for 3D printing.

Partners

- Oak Ridge National Laboratory (ORNL)
  Prime contract
  ORNL project lead: Vlastimil Kunc
- University of California, Los Angeles (UCLA)
  Subcontract
  UCLA project lead: Xiaoyu (Rayne) Zheng

[1)] source: 1. U.S. DRIVE MTT Roadmap Report, section 4

Relevance

Overall Objectives

Create hybrid hierarchical materials that are **ultralight**, **strong** and **tough** for 3D printing.

VTO's Mission

Reduce the transportation energy cost while meeting or exceeding vehicle performance expectations.

Current Limitations

- Lightweight materials: Unsatisfactory strength, toughness and weight density
- Direct deposition: Uncontrollable voids and micro-porosity → Reduced strength and toughness.
- Mutually exclusive properties:
  strength ⟷ toughness

  stiffness ⟷ damping

Our Strategies

- Material Combinations
  - Brittle carbon fiber and multi-material polymers
- Smart Structure
  - Optimal structure **for high stiffness and high damping**

Milestones

Milestone	Due Date	Type	Milestone	Status
M1.0	12/30/2020	Regular	Demonstrate Parallel Optics System for large area UV curing.	Completed
M2.0	3/30/2021	Regular	3D printing of high strength CFRP close cell foams and mechanical property measurement.	Completed
M3.0	6/30/2021	Regular	Integrate multi-extrusion nozzles for multi-material extrusion and switching.	On Track
M4.0	9/30/2021	Regular	Demonstrate high resolution CFRP lattice materials with size spans from 10 cm - 25 cm	
Go/No-go	9/30/2021	Go/No-go	Properties of a microlattice should be: density of <500kg/m3, High specific strength of > 1kPa/(kg/m3) with the size of > 10 cm span	

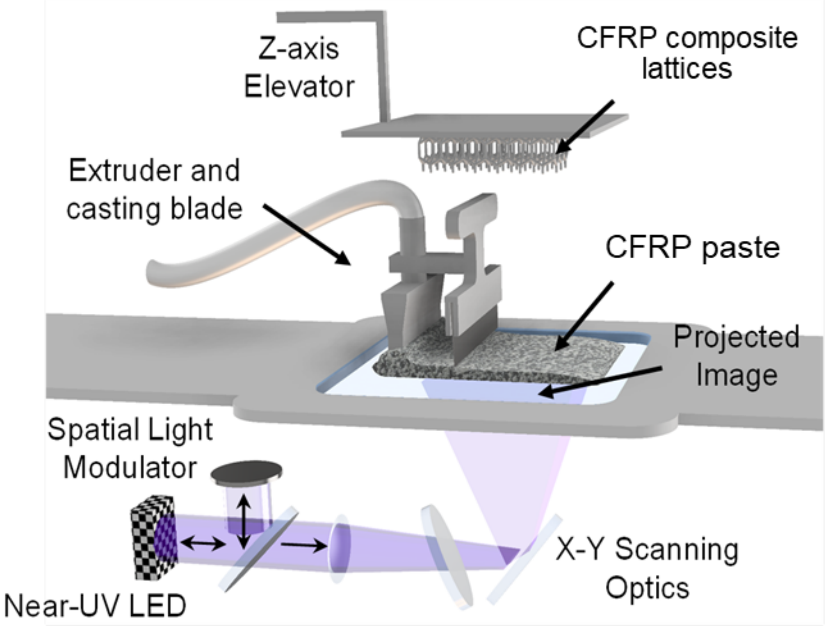
Technical Accomplishments

Part 1 – Large-area projection stereolithography system setup and demonstration of large-area printing

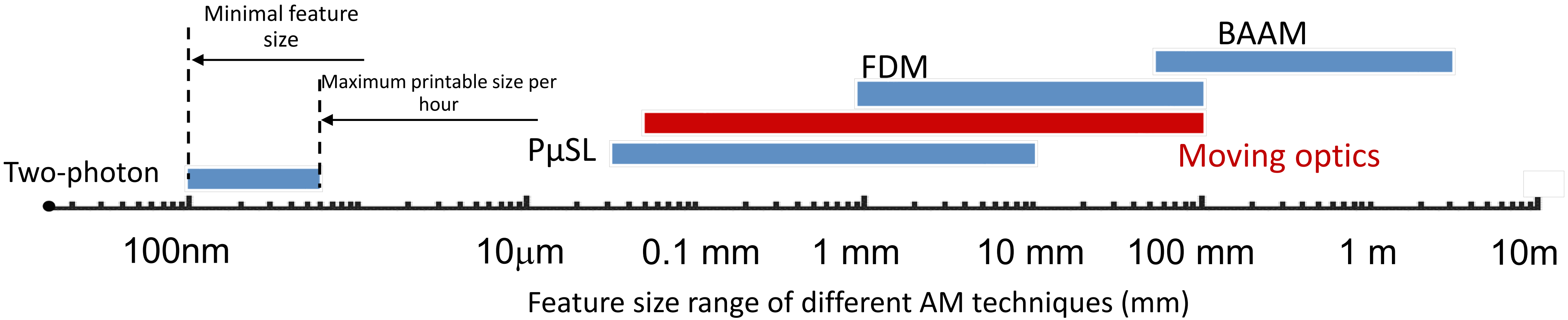
Projection Stereolithography

- Most high-resolution 3D printing systems for carbon fiber composites are limited in the achievable feature size spans, with overall size span to feature resolution typically < 1000.

Ref: Kunc, et. al., ORNL-BAAM, 2017
Ge, et. al., International Journal of Extreme manufacturing, 2020



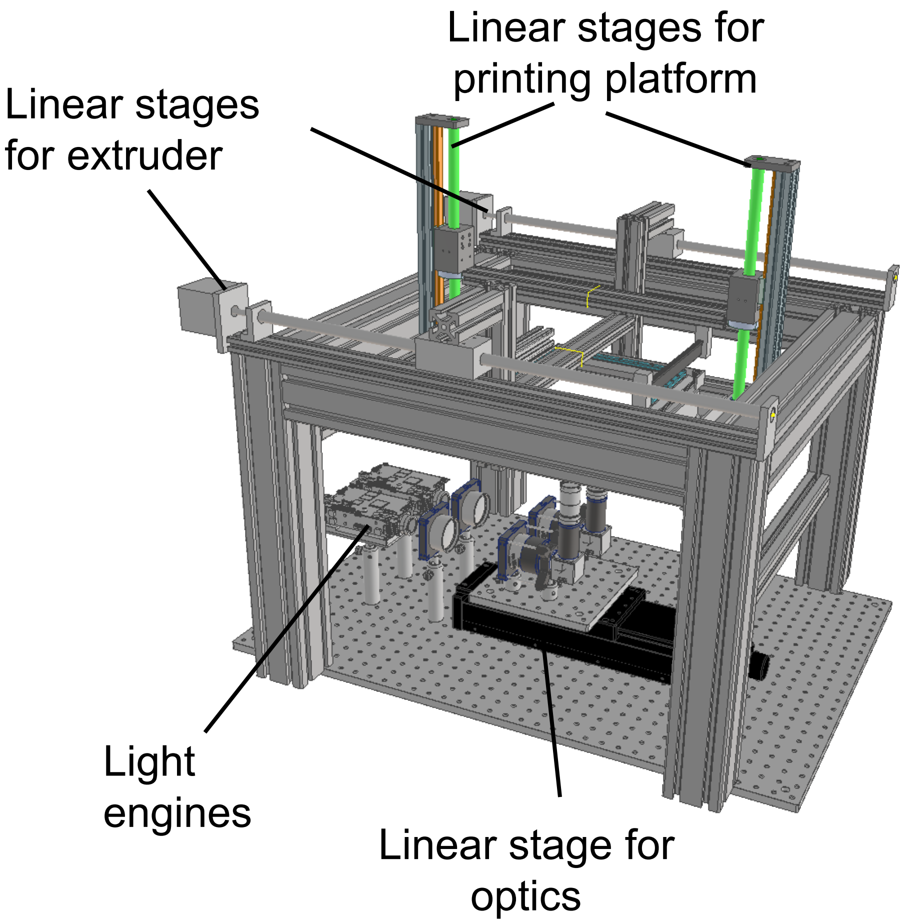
Our work has high resolution comparable to PμSL (Projection micro-stereolithography), and large throughput



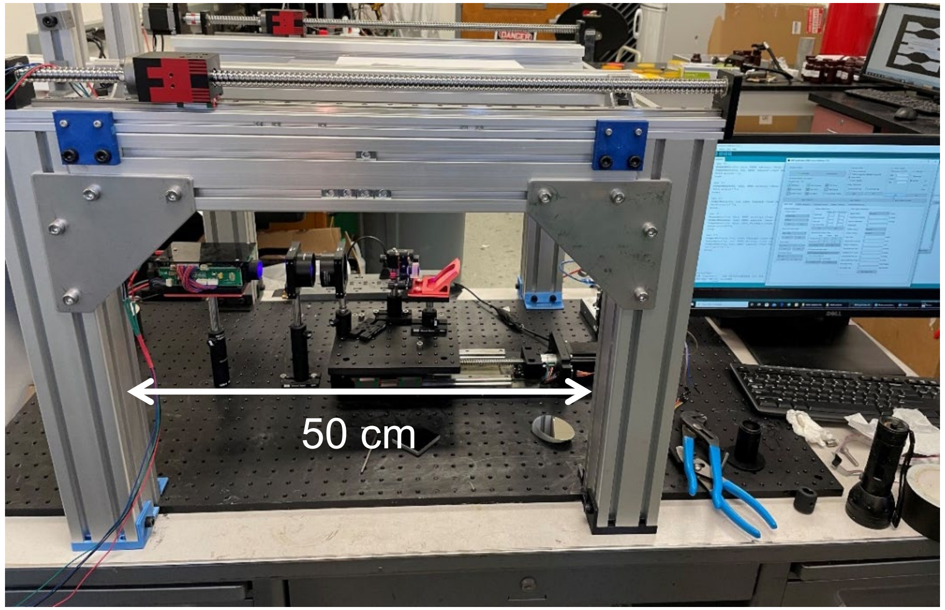
The objective of this work is to enable high-speed, large-area and high-resolution printing of carbon fiber reinforced composites.

Large-Area Projection Stereolithography System

Schematic of the overall setup



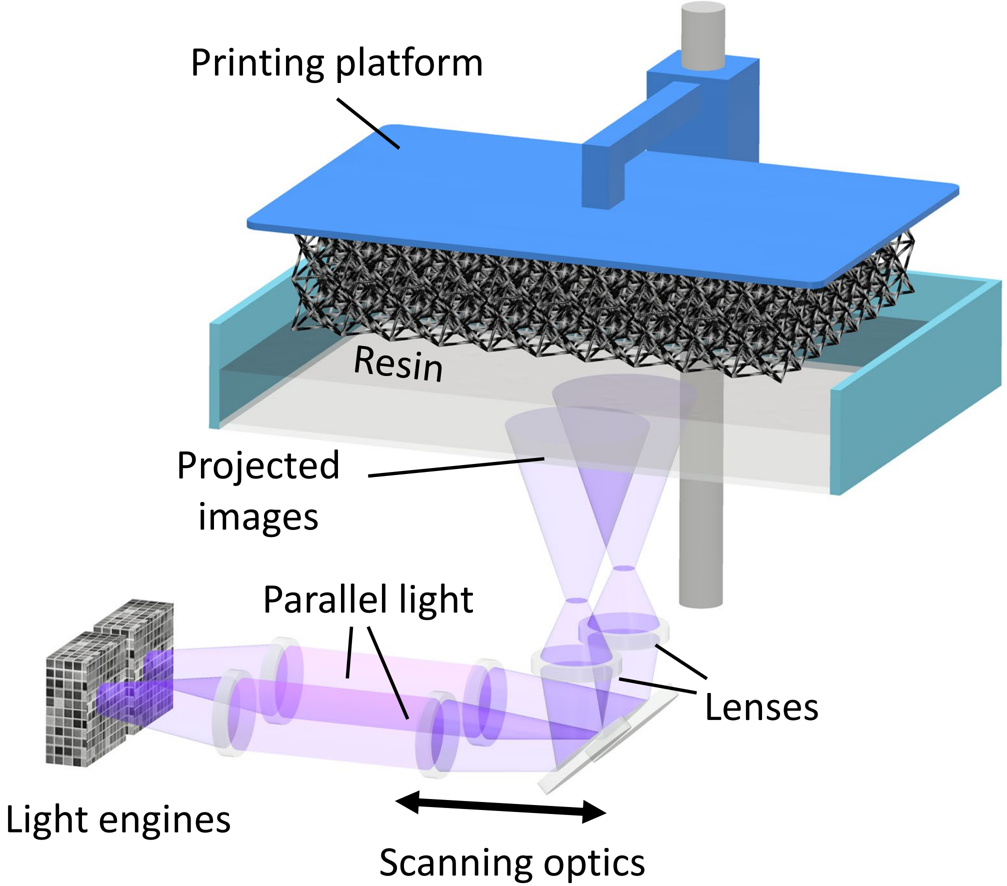
- Travel range: 20-500 mm
- Minimal printable feature size: 50-100µm (adjustable)
- Adjustable print size/resolution
- Extrusion system is under development

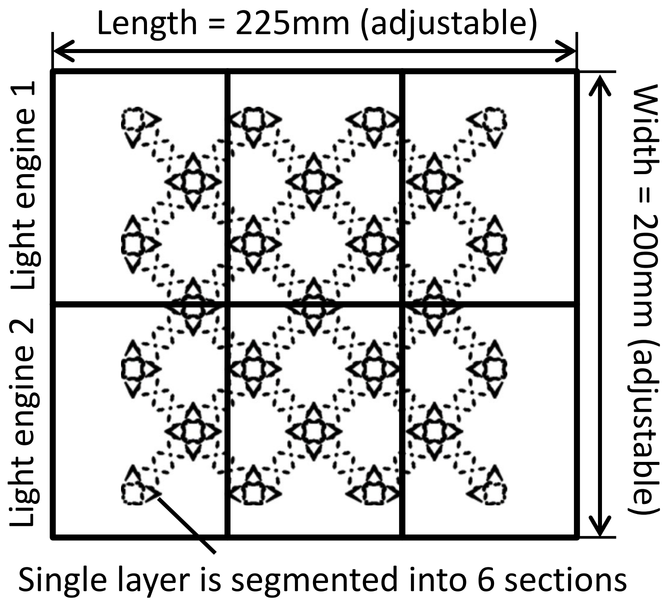


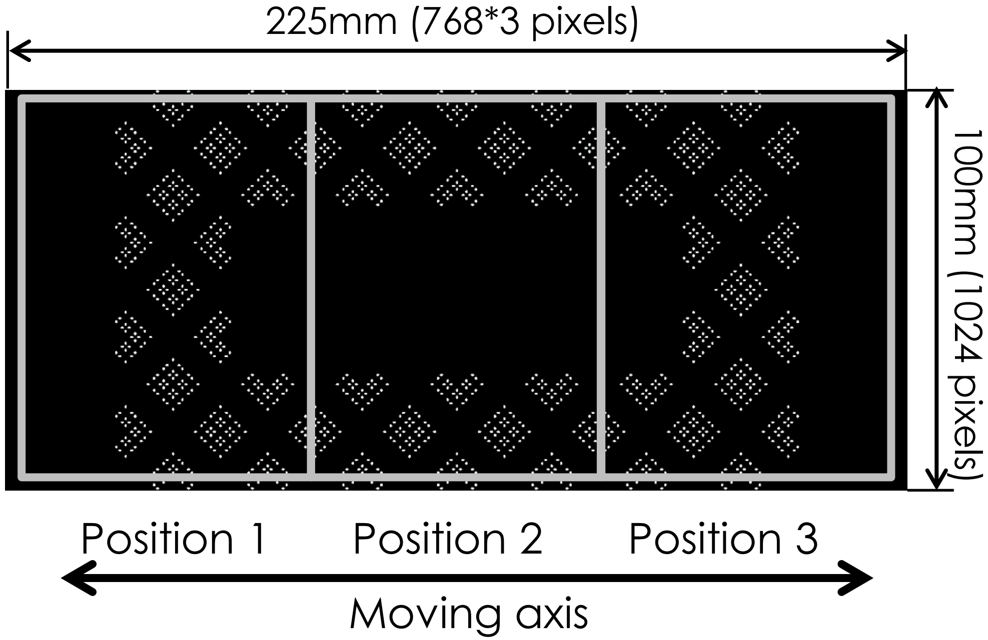
The large-area projection stereolithography system is comprised of a multi-material extrusion system and a moving projection system, which could extend the printing area over a wide range.

Large-Area High-Resolution Projection System

Schematic of the large-area high-resolution projection system







Large Area Hybrid Optical Printing System

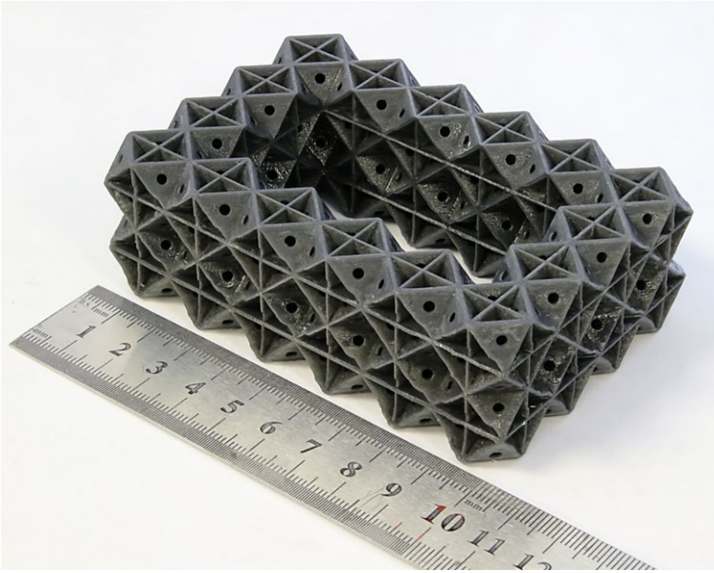
Infinity-corrected projection design

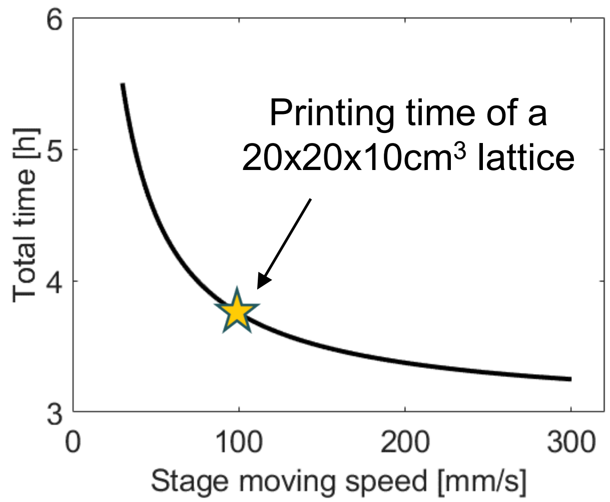
This

$$T_{layer} = T_{coat} + n \times T_{exposure} + (n-1) \times T_{move}$$

Resin recoating — UV exposure — Stage moving

- High light power density ($2mw/cm^2$) over a large working distances (2cm~40cm), therefore lower UV exposure time (~5s for 1vol% CFRP).
- Lightweight optics, enabling a larger moving speed (>100mm/s), therefore lower stage moving time.



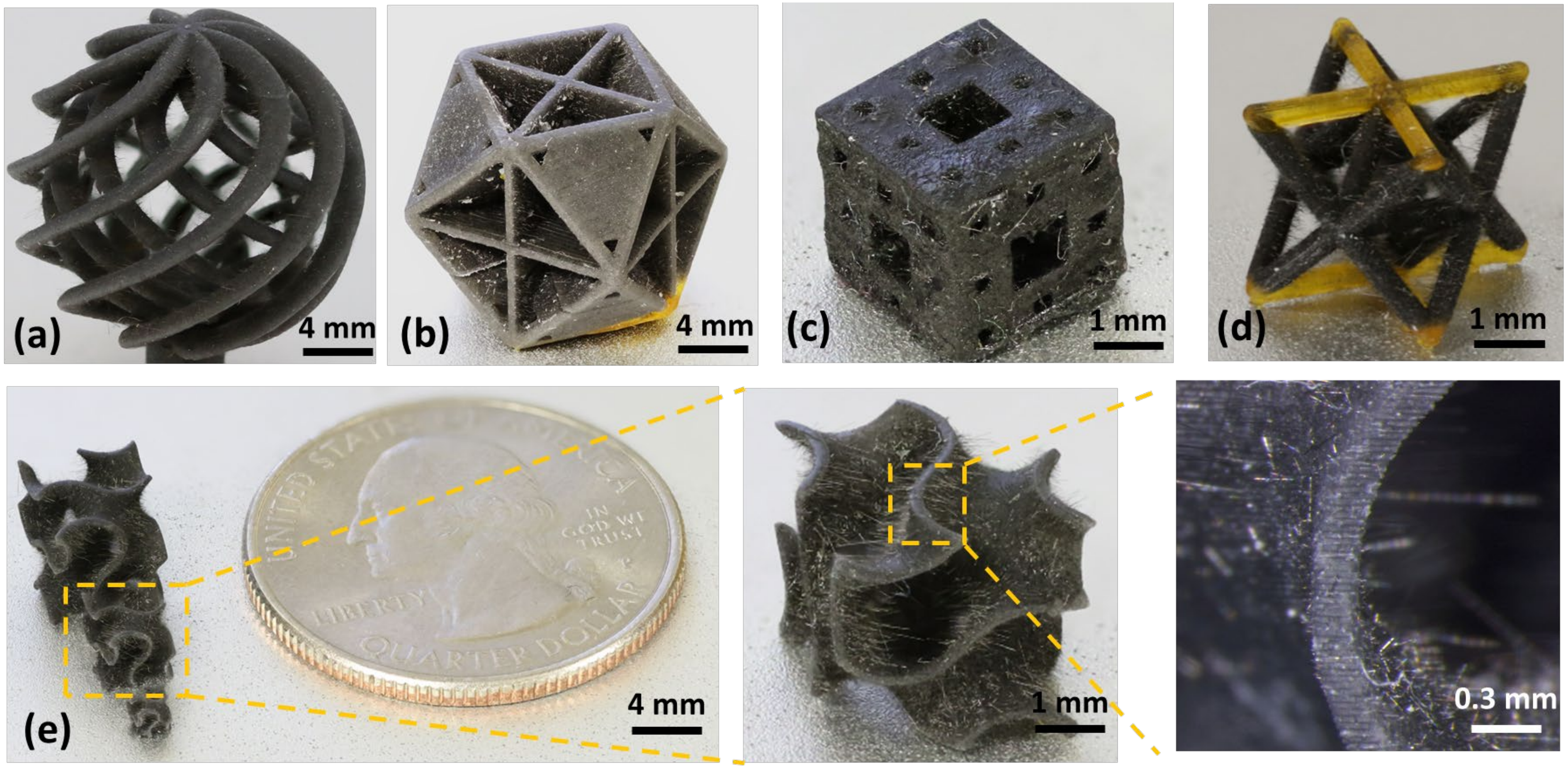


The infinity-corrected projection design has higher photon coupling efficiency at large distance, making the UV exposure process faster, and the scanning stage can move faster with lighter optics.

Part 2 – Lightweight CFRP composites with simultaneously high strength and high stiffness

CFRP Composites with Complex Micro-Architectures

Previous year's work

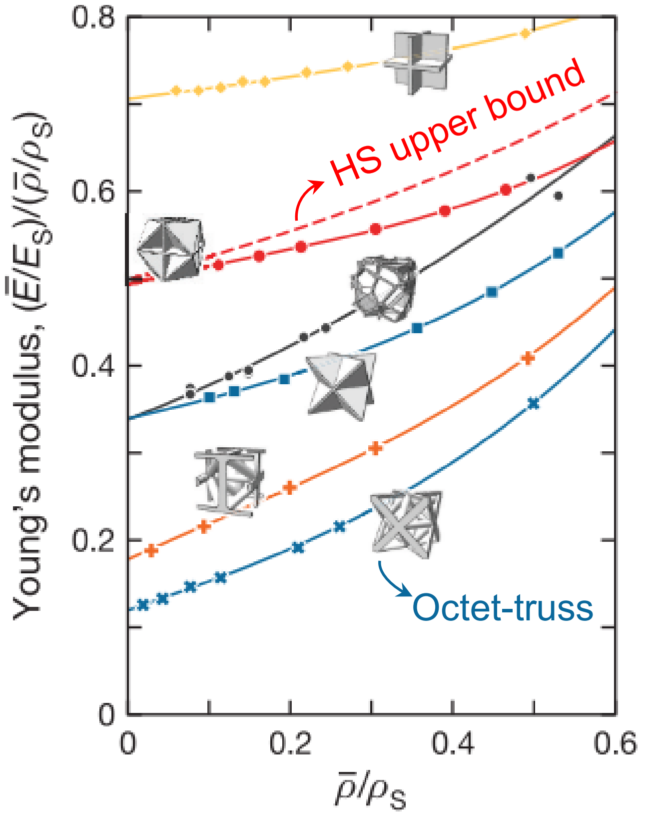


CFRP lattice materials. (a) Spiral ball. (b) Plate-lattice. (c) Menger sponge. (d) Multi-material microlattice with stiff (CFRP) and soft phase (PEGDA). (e) CFRP gyroid lattice.

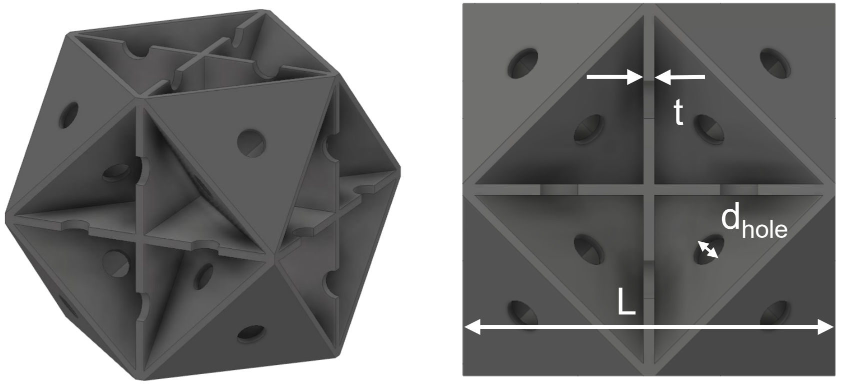
Ref: Xu, Kim, Kunc, Zheng et al., Additive Manufacturing, 2020

Past year's accomplishment: Achieved CFRP composites with complex 3D micro-architectures.

Closed-Cell Plate Lattice Achieving Theoretical Stiffness Bound



The Young's modulus of six representative cellular structures



cubic+octet plate-lattice unit-cell design

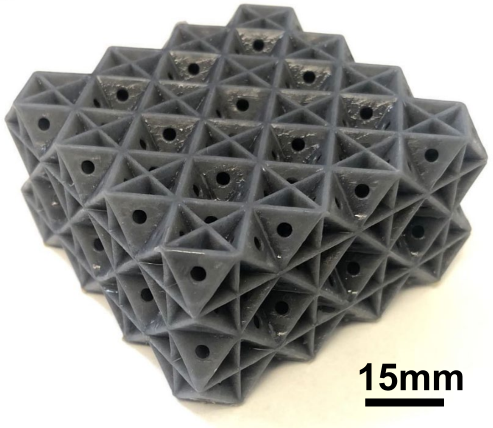
Advantages of cubic+octet plate-lattice

- Lightweight
- Theoretical $E - \overline{\rho}$ relationship bound
- Greater stiffness per unit weight than truss-based lattices

Ref: Berger, et al., Nature, 2017
Zheng, et al., Science, 2014

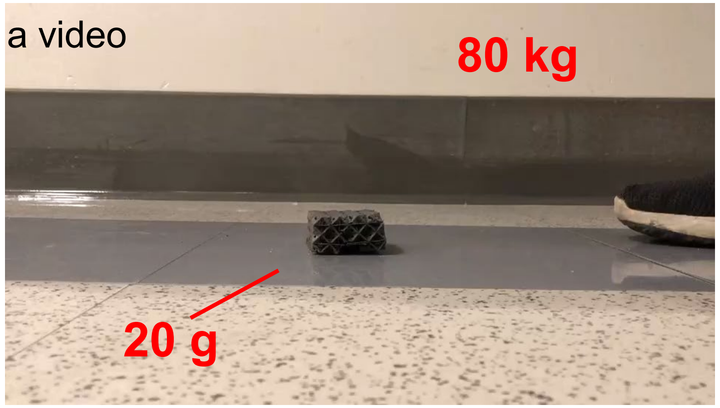
Cubic+octet plate lattice is selected as a base architecture because of its lightweight and greater stiffness per weight than truss-based lattices.

Cubic+Octet Plate-Lattice with High Strength and Stiffness

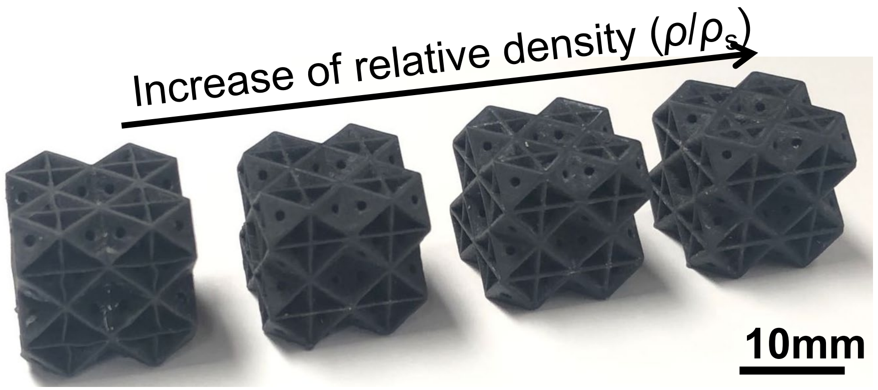


cubic+octet plate-lattice made by CFRP
(4-4-2, relative density =25.4%)

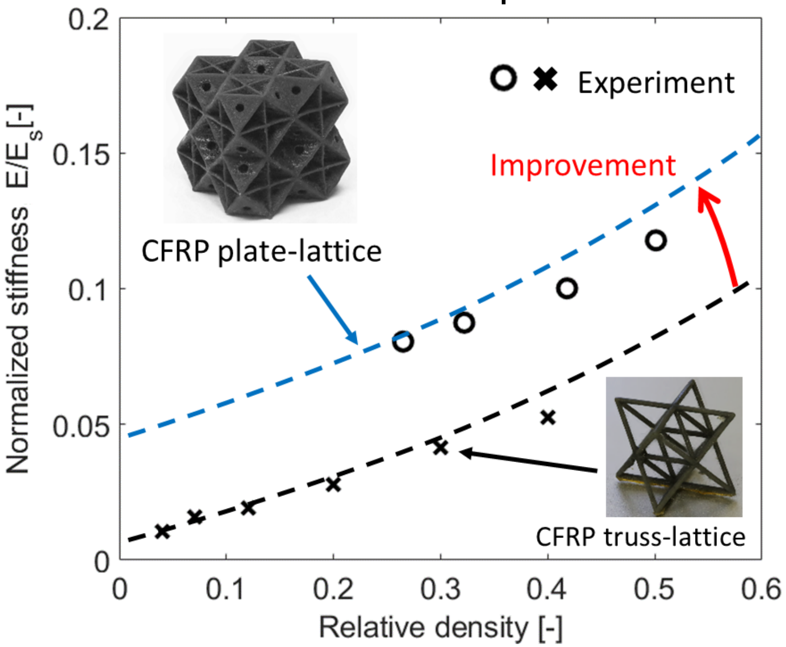
This is a video



Video: Demonstration of the high strength of the cubic+octet plate-lattice



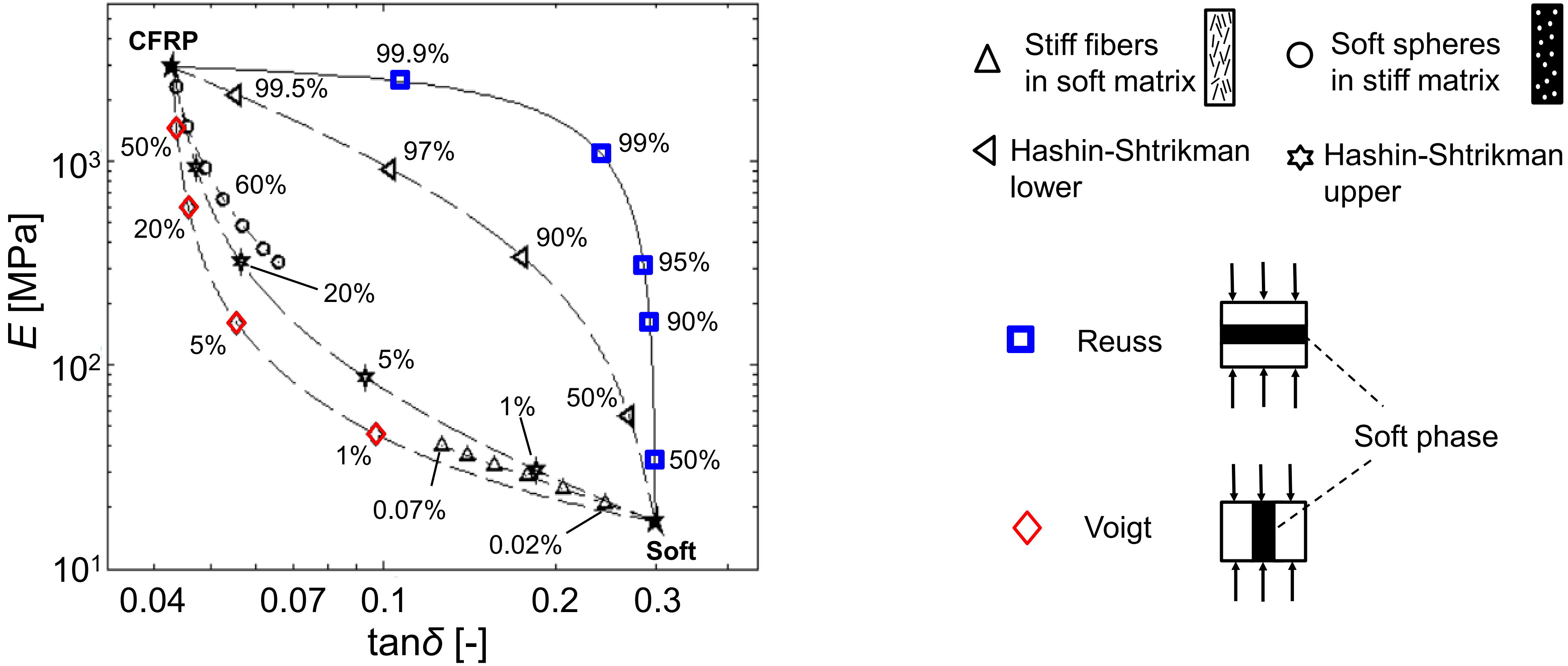
Cubic+octet plate-lattices with different relative densities made by CFRP composite



Cubic+octet plate-lattices were designed and additively manufactured. The lattices can withstand a high load and shows high stiffness.

Part 3 – Design, 3D printing, and evaluation of stiff, strong and lightweight bi-material sandwich plate-lattices with enhanced energy absorption

CFRP Composites with High Damping and Stiffness



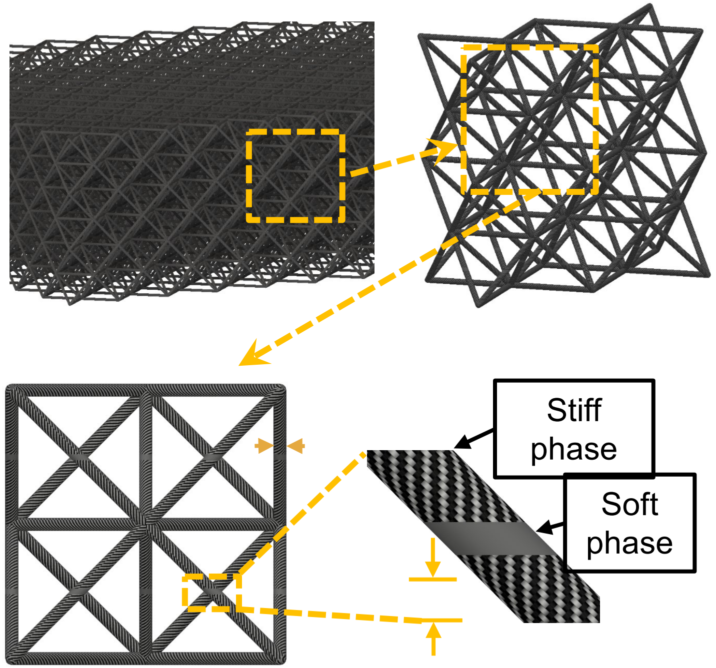
Low fraction of soft phase inclusion enables dramatic increase of damping coefficient

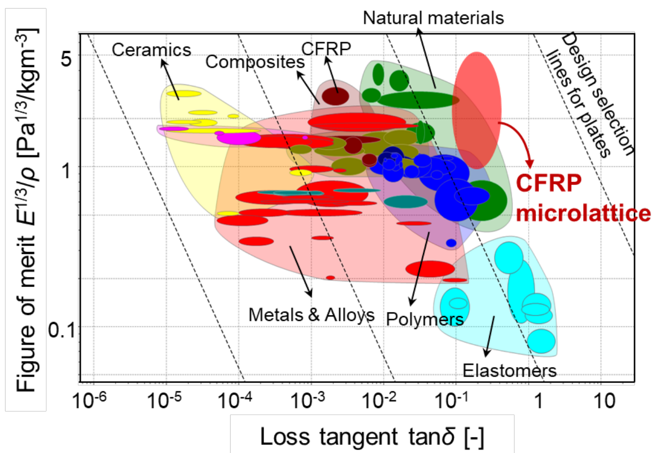
Ref: Xu, Kim, Kunc, Zheng et al., Additive Manufacturing, 2020

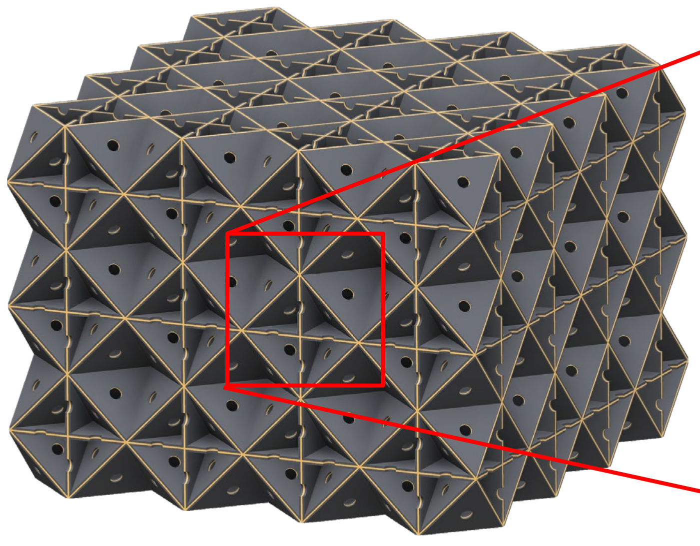
A two-phase composite configuration incorporating the CFRP composites with a soft phase can lead to high stiffness-loss efficiency and energy absorption.

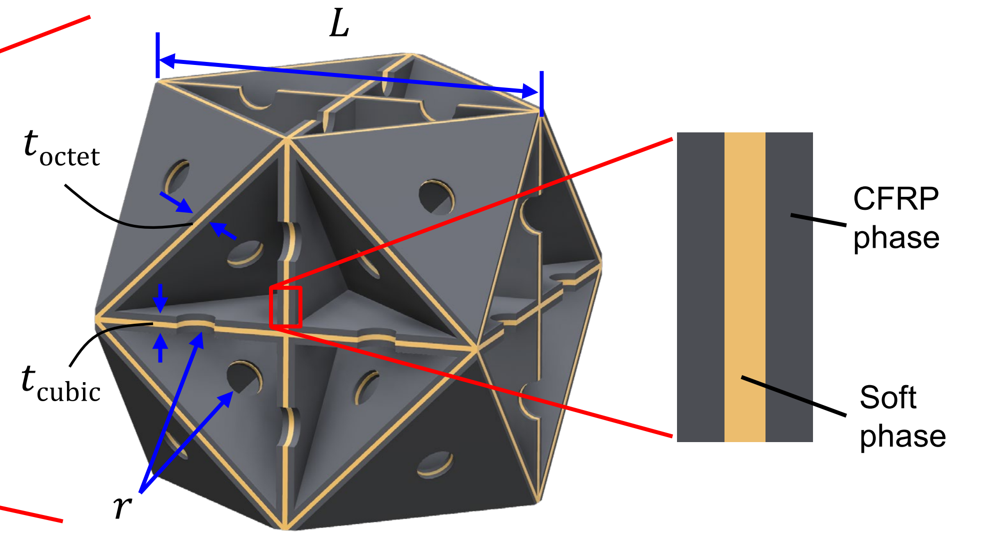
Bi-Material Cubic+Octet Plate-Lattice

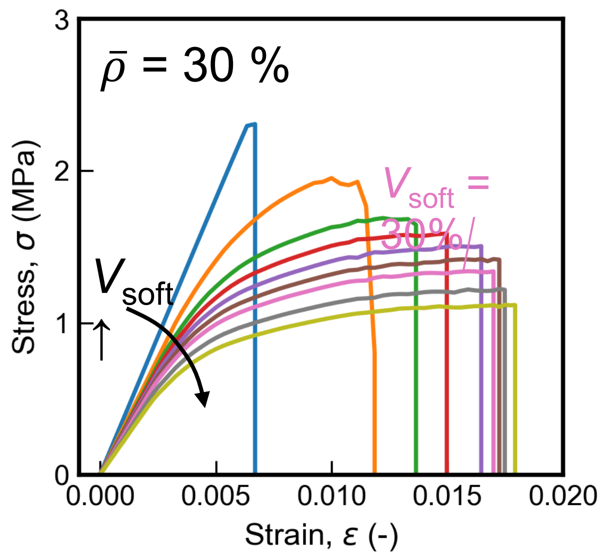
Previous year's work

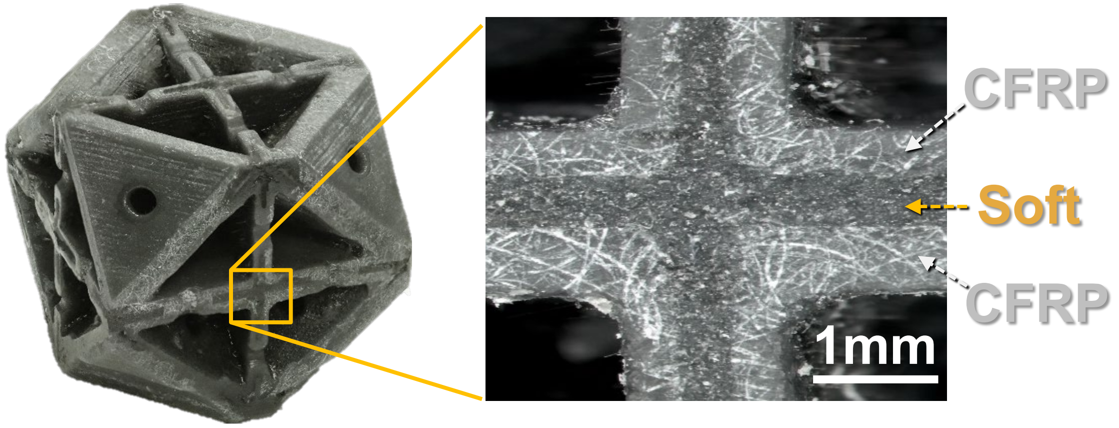






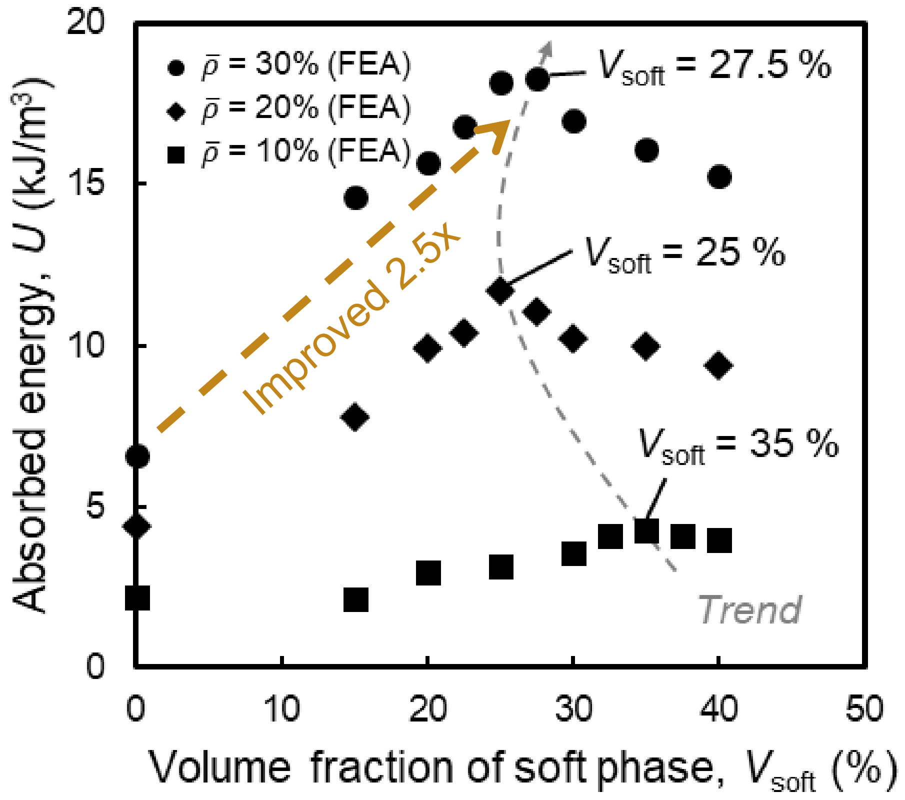




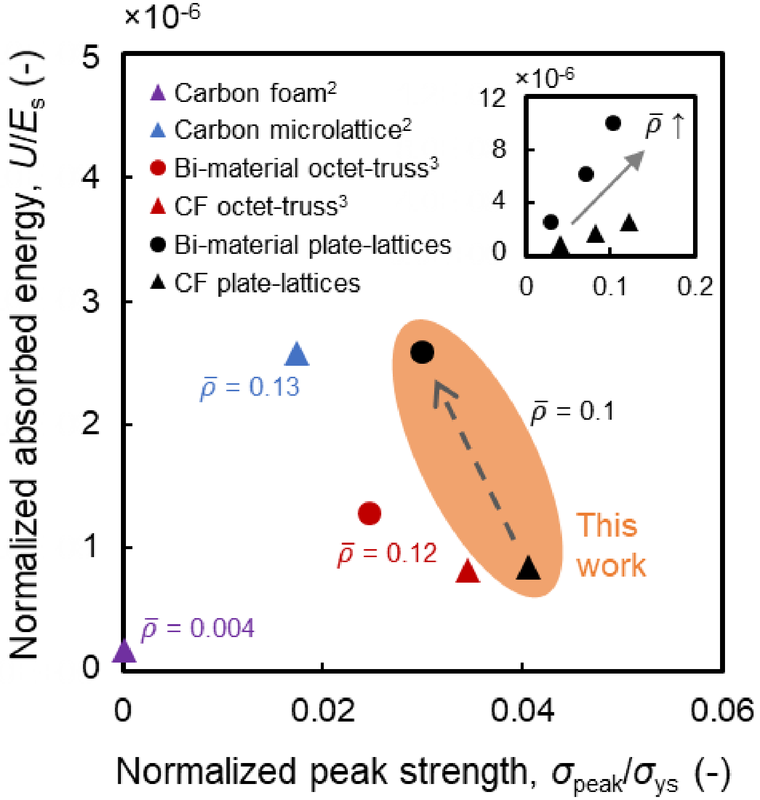


Inspired by the idea of the two-phase composite in the previous year, a bi-material isotropic cubic+octet plate-lattice was designed comprising the sandwich plate (CFRP-soft-CFRP) that can achieve high energy absorption.

High Energy Absorption Capability of the Bi-Material Plate-Lattice



Energy absorption capability of the bi-material plate lattice is improved by introducing soft phase



Our lattice outperforms the other reported carbon-based energy-absorbing materials in terms of the strength-energy absorption pair

Ref: [1] Jacobsen et al., Carbon, 2011
[2] Chen et al., Energy Environ. Sci., 2013
[3] Xu et al., Additive manufacturing, 2020

According to the simulated stress-strain curves, the absorbed energy was calculated, and the performance was compared with previously reported carbon-based energy absorption materials

Future work

- Hybrid CFRP extrusion and alignment
  - Achieve fiber alignment via extruder nozzle shear alignment of CFRP loaded resin
  - Optimize shear rate and fiber orientations based on different aspect ratios
- Expand to 500mm edge size with micro-architectures
  - Study moving optics and motion control schemes for high-speed exposure and printing of large-area samples
- Integrate multi-material exchange for soft inclusions within CFRP
  - Develop large-scale CFRP lattice material with high damping and stiffness

Publication

[1] Xu, Z., Ha, C. S., Kadam, R., Lindahl, J., Kim, S., Wu, H. F., Kunc, V., & Zheng, X. (2020). Additive manufacturing of two-phase lightweight, stiff and high damping carbon fiber reinforced polymer microlattices. Additive Manufacturing, 32.

[2] Hsieh, M. et. al., (2021). Stiff and strong, lightweight bi-material sandwich plate-lattices with enhanced energy absorption. *Under review*

[3] Xu, Z., et. al., (2021) Multi-material Stereolithography of Metamaterials with Dissolvable Support. *In progress*

[4] Gerard, N., Xu, Z., Zheng, X., et. al., (2021) Ultra-light metamaterial for wide-band low frequency vibration attenuation. *Under review*

[5] Cui, H., et. al., (2021) Fracture toughness of architected metamaterials. *Under review*