# Ultra-Lightweight, Ductile Carbon Fiber Reinforced Composites


**Vlastimil Kunc**

**Oak Ridge National Lab**


**6/11/2019**


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Project ID#: mat146



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# Overview

## Timeline

- Project start date: Oct 2019
- Project end date: Sept 2021
- Percent complete: 40%

## Budget

- DOE project funding: $500K
  - DOE: 50%
  - Contractor: 50%
- Funding for FY19: $460K

## 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
- Virginia Polytechnic and State University (VT)
  Subcontract
  VT 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

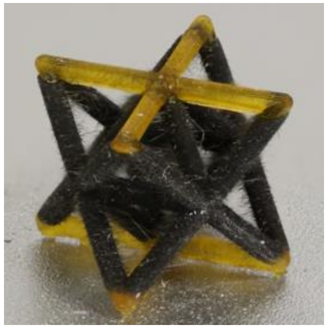
Reduce the transportation energy cost while meeting or exceeding vehicle performance expectations.

## 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**



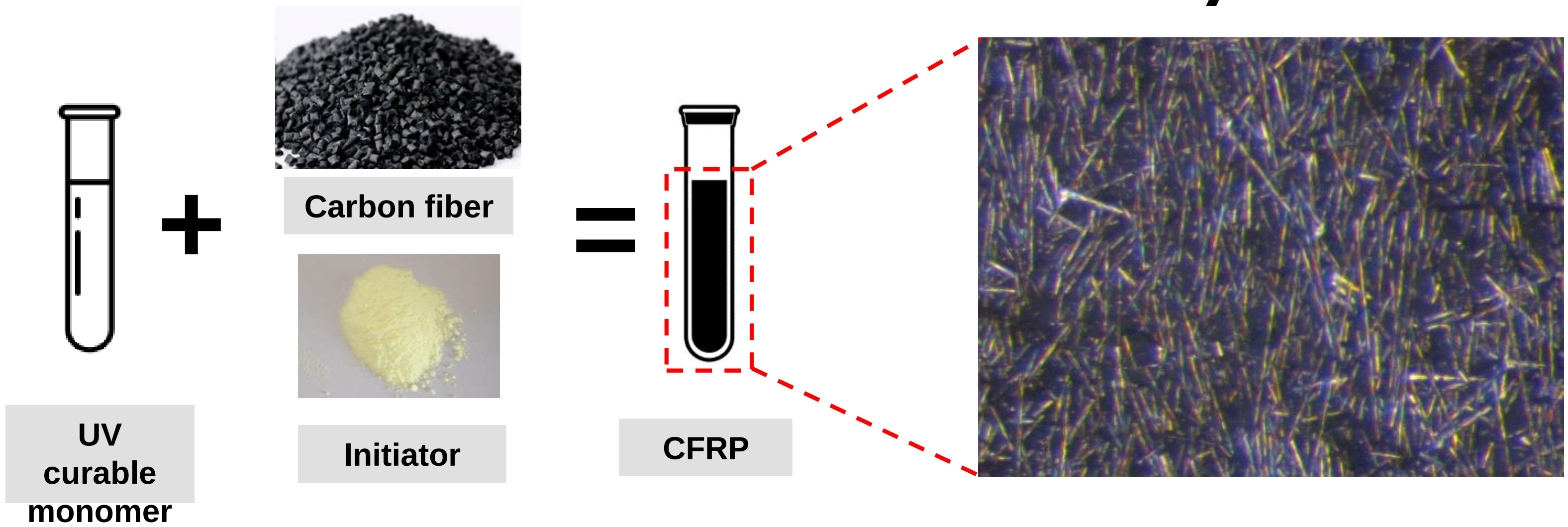
# Milestones

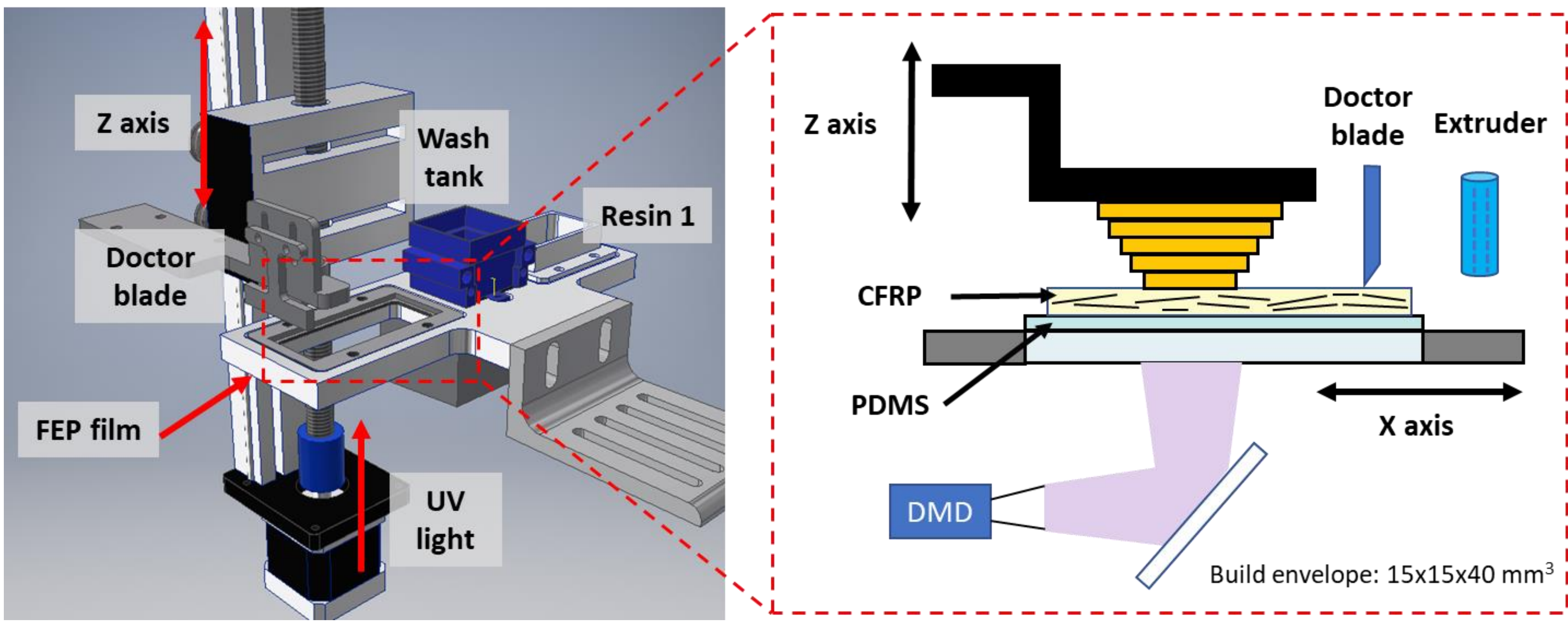
| Milestone / End Dated | Description | Status |
|---|---|---|
| Milestone 1 12/30/2018 | Mechanical properties (compression, shear, tensile) verified through theoretical and numerical calculations and experimental testing of microlattice materials | Completed |
| Milestone 2 9/30/2019 | Printing hierarchical two-phase carbon fiber reinforced mesoscale lattice materials, comprised of microscale carbon fiber fillers and large scale structural components. | On track |
| Milestone 3 12/30/2019 | Size effects of carbon fiber composited printed with varying lengthscales from micrometers to centimeters | On track |
| Milestone 4 07/30/2020 | Demonstrated ultralight (<200 kg/ $m^3$) hierarchical carbon fiber composites with tailored energy absorption and high strain recovery (>10%) | On track |
| Stretch Milestone 12/30/2020 | Printing hierarchical carbon fiber lattice materials (<500 $kg/m^3$) with tunable directional or isotropic functionally graded designed stiffness and  energy absorbing capabilities | On track |
| Stretch Milestone 9/30/2021 | Additive manufacturing of lightweight carbon fiber composite microlattice materials (<100 $kg/m^3$, with <100 micron feature size cotrol) with superior recoverability ( >20% strain as compared to 0.5% strain) | On track |

# Technical Accomplishments

I. **Part 1 – Additive Manufacturing of light, high stiffness carbon fiber (CF) composite**

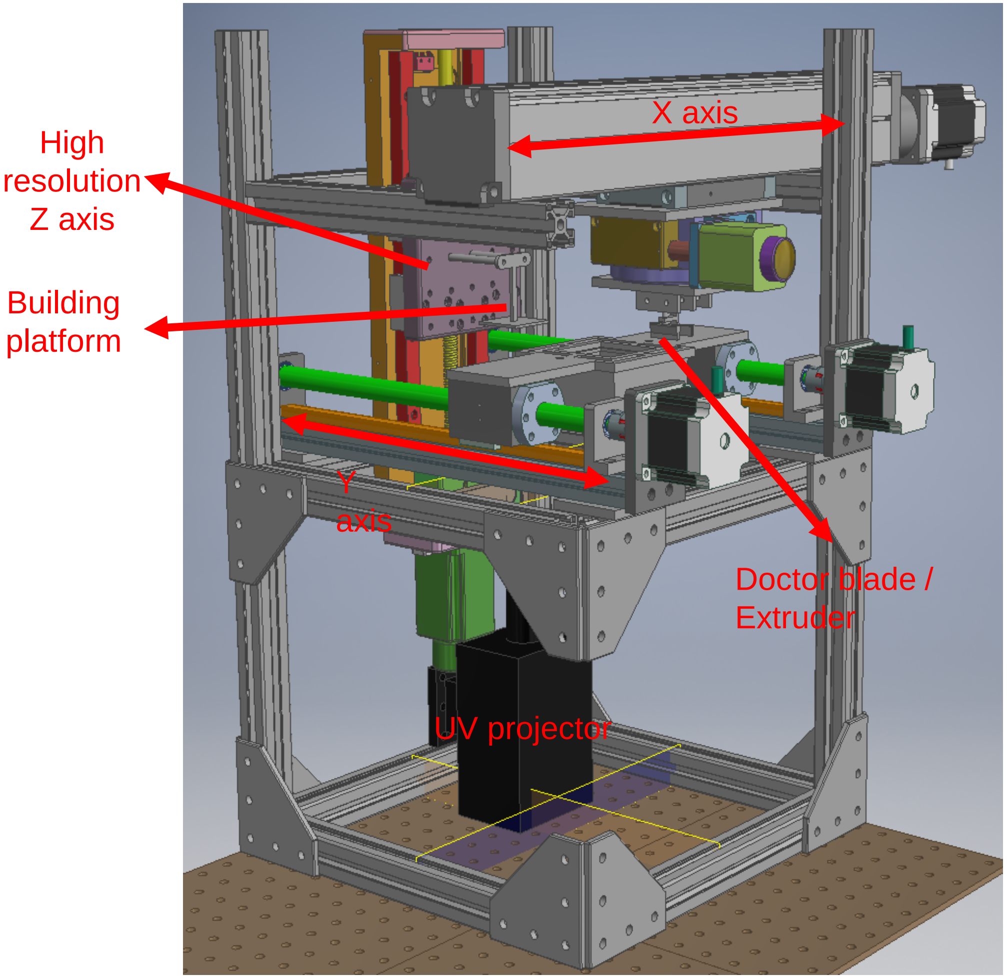
# Carbon Fiber Reinforced Polymer



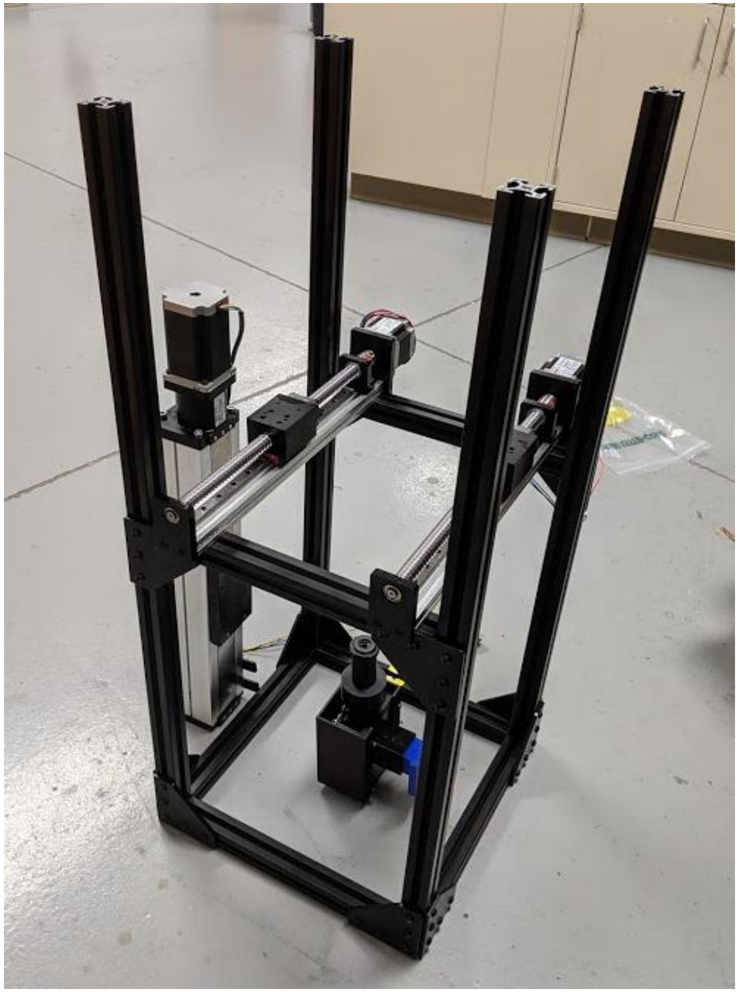




Our PµSL 3D printing system can fabricate samples with carbon fiber reinforced polymer (CFRP) with the resolution of 200 microns.

# New CF Printing System

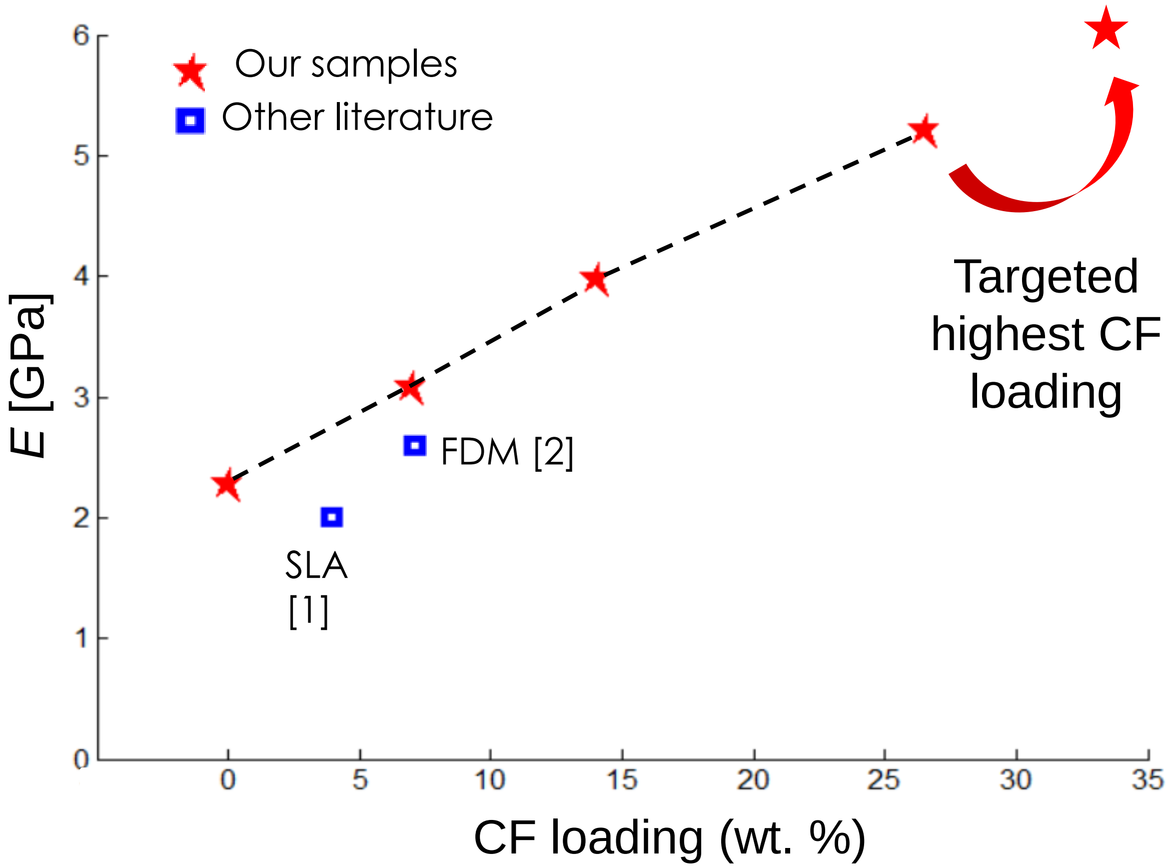



*System design*

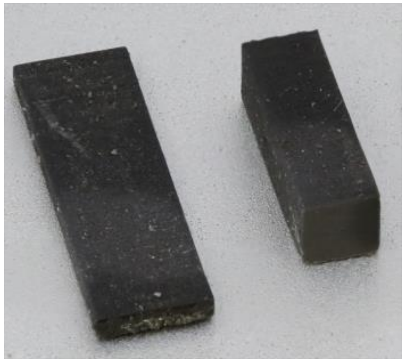


We are working on the building of the new CF printing system which has a larger printing area (adjustable).

# Carbon Fiber Reinforced Polymer




Comparison of elastic modulus of CFRP



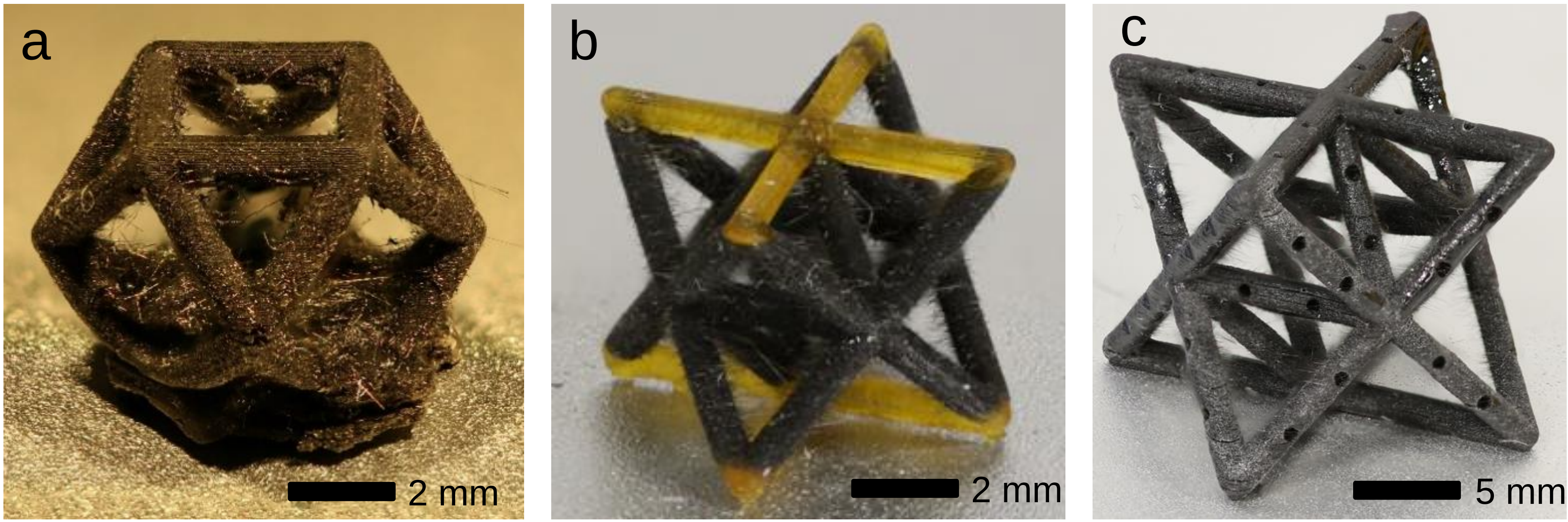
7.5wt% Bulk samples

27wt% CF loading dog bone

Our CFRP samples are stiffer than other similar CFRP samples reported in literature.

# Lattice Structure

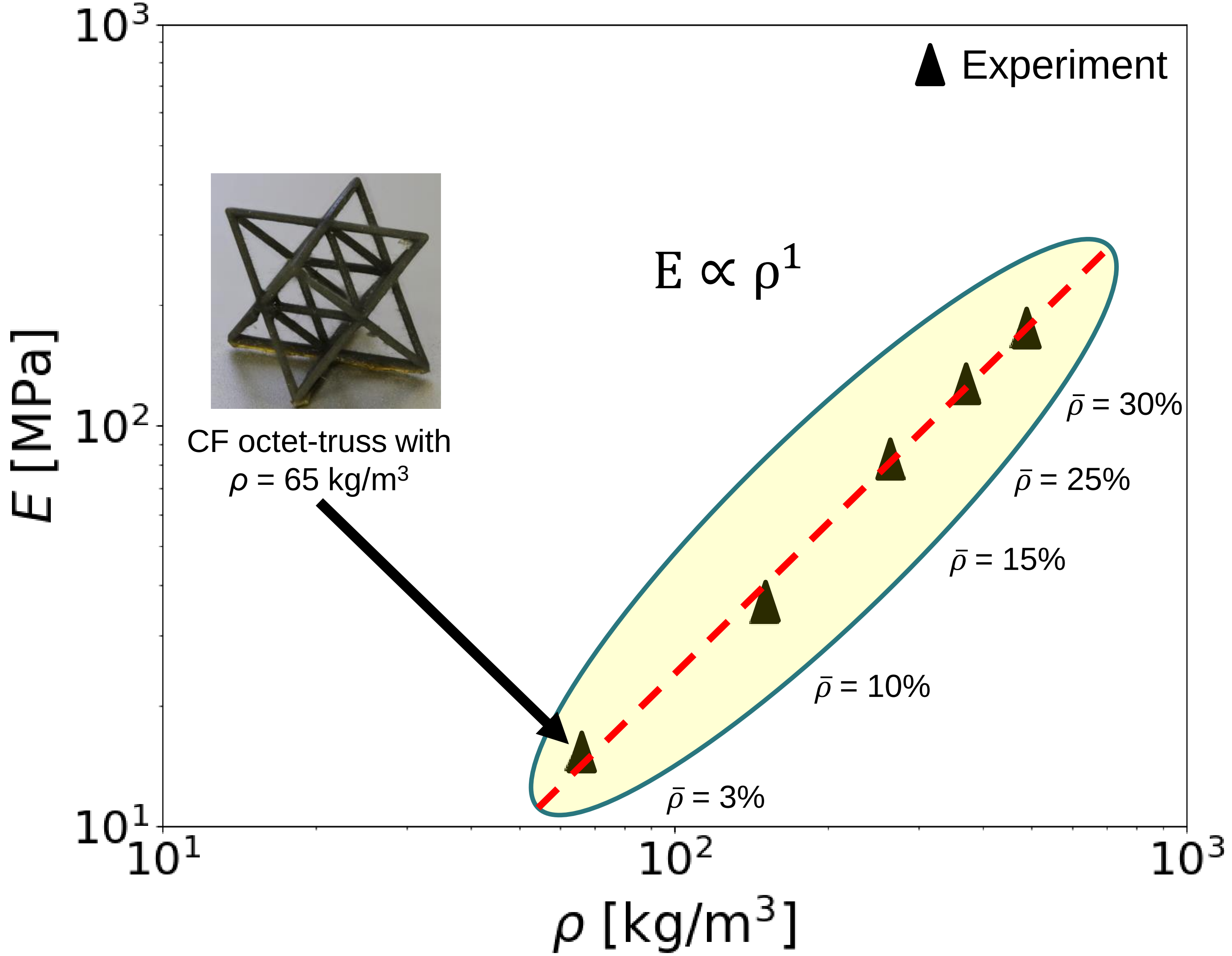
CF kelvin | CF octet-truss with PEGDA | CF octet-truss with holes




Complex 3D structures printed by our multi-material 3D printer

Achieved CF composites with complex 3D micro-architectures with multi-materials.

# Lightweight, High-Stiffness CF Microlattice



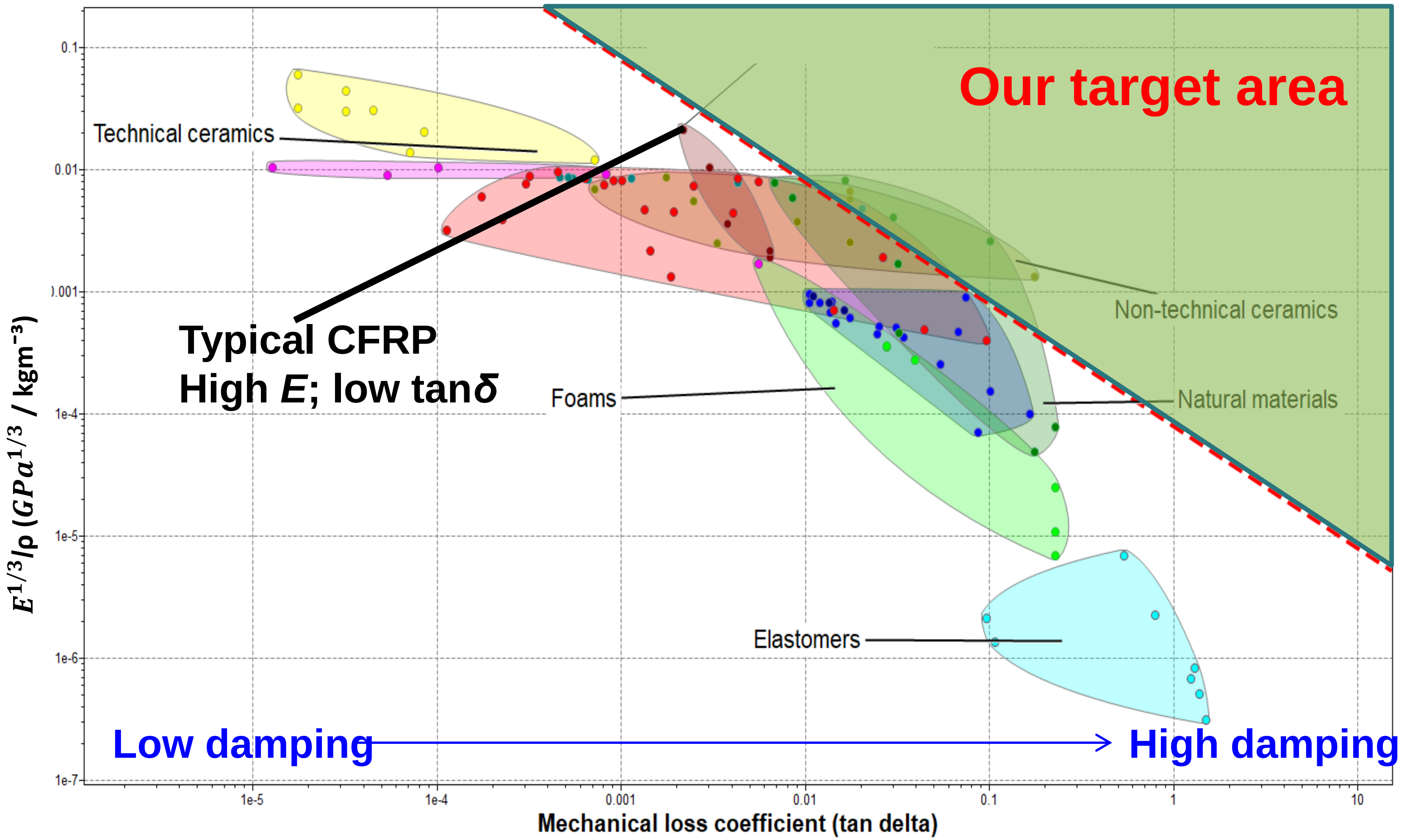

Achieved CF lattice with density as low as ~60 kg/m$^3$, and with near constant specific stiffness at ultralow density.

# Technical Accomplishments

## II. Part 2 – Multi-phase of light, high stiffness and high damping carbon fiber (CF) composite structures

# Design Goal

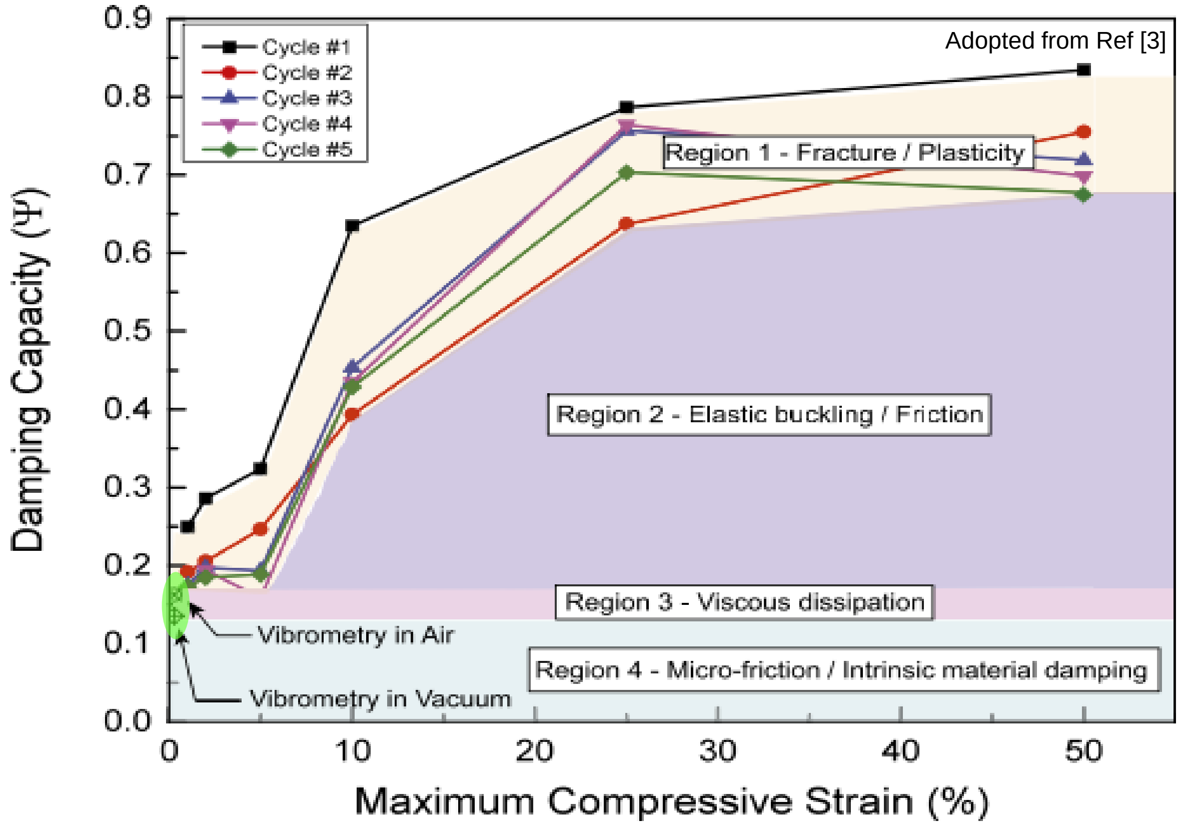
- Maximize the figure of merit $\frac{E^{1/3}tan\delta}{\rho}$




$E^{1/3}/\rho$ vs. $\tan\delta$ chart for CFRP and other family of materials

With the use of our multi-material fabrication method, we aim to design a CF architecture with high stiffness and high damping simultaneously.

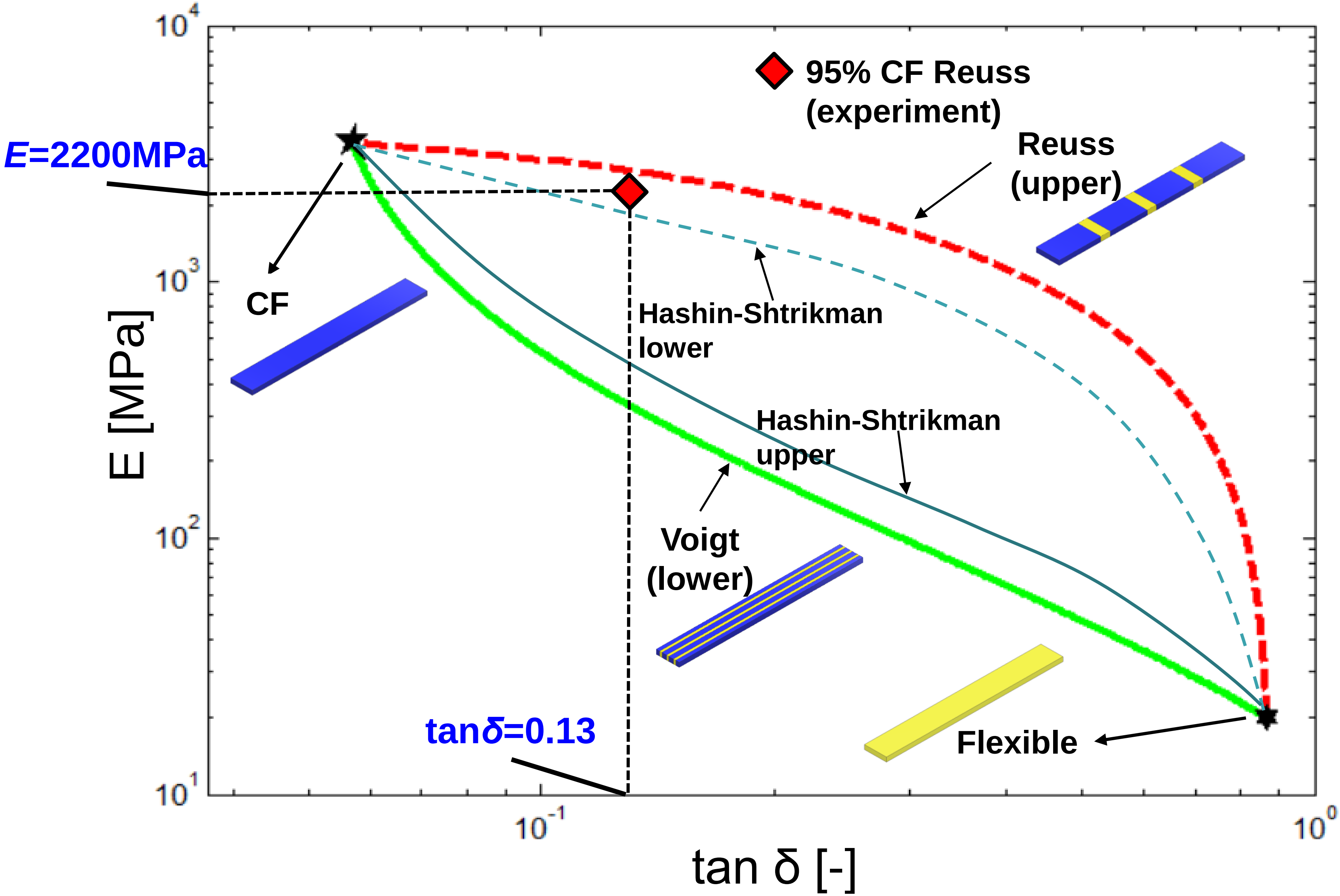
# Intrinsic and Structural Damping




| Damping type | Cause | Dominant at |
|---|---|---|
| Intrinsic | Viscoelastic property of constituents | Small strains |
| Structural | Deformation mechanism | Large strains |

Mechanism of intrinsic (small strain) and structural (large strain) damping are incorporated to achieve high damping capacity of CF composite microlattice.

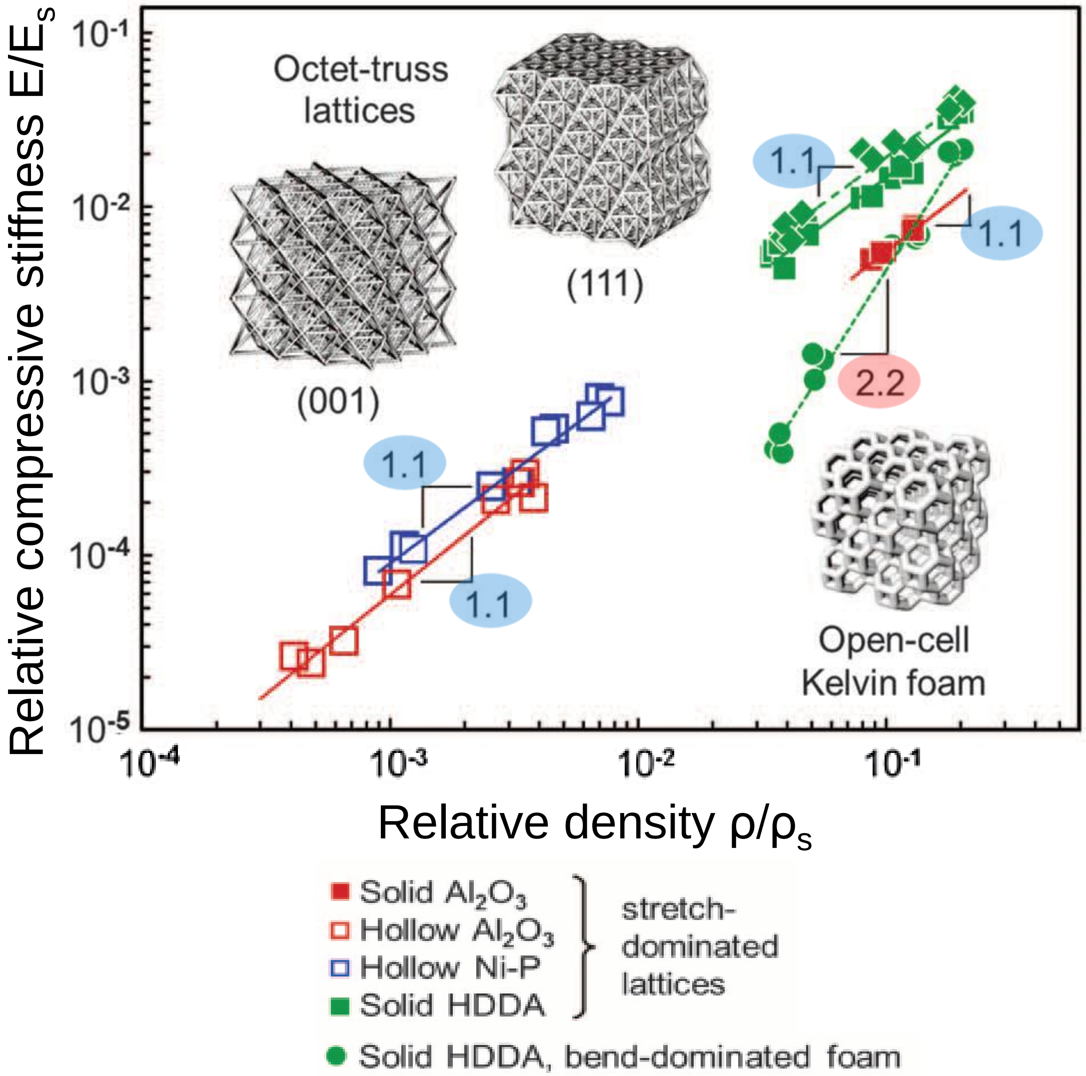
# Intrinsic Damping of CF Composite




We have achieved a solid CF reinforced composite (having 5% soft phase) having both high stiffness and high damping, which reaches the upper bound of stiffness-damping pair.

# Lightweight, High-Stiffness CF Microlattice

Adopted from Ref [4]




**Octet-truss geometry**

- Lightweight
- Favorable $E$-$\rho$ relationship
- Stretch-dominated ($E \sim \rho^1$)
- Greater stiffness per unit weight than bending-dominated

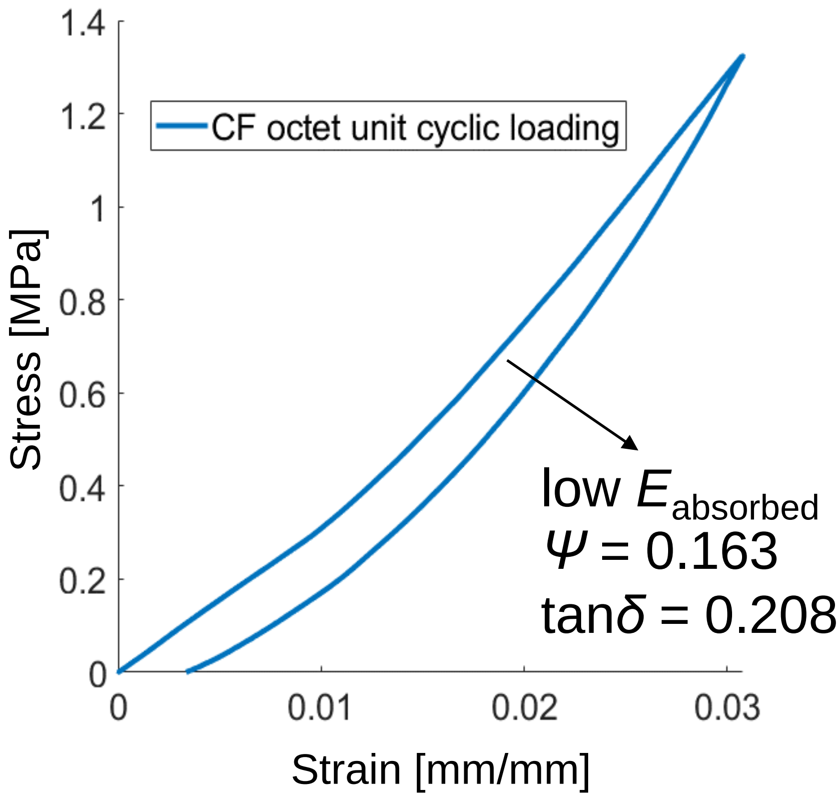
We selected octet-truss unit cell as a base architecture since it is lightweight and can provide a greater stiffness per unit weight than bending-dominated cells.

# Intrinsic Material Damping for Lattice Structure

**Intrinsic damping**

tan$\delta$ (at 10 Hz at rt) = 0.038 via DMA test

**Structural damping**



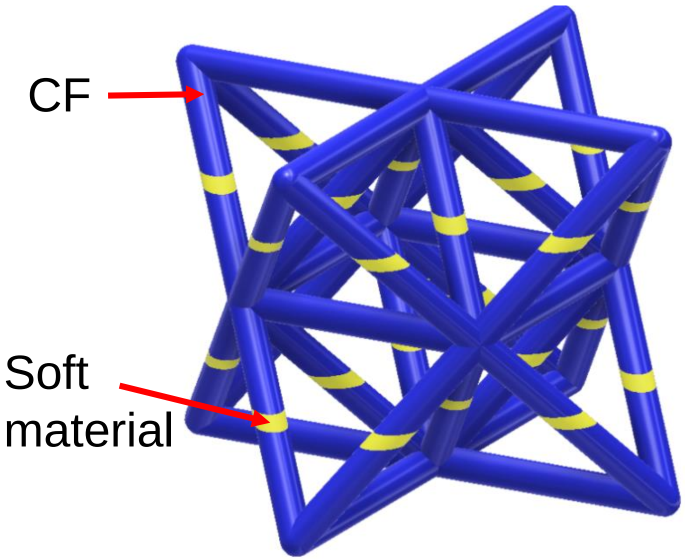


CF octet-truss with $\bar{\rho}$ = 20%

$\psi = \frac{\Delta U}{U} = \frac{\pi}{4} tan\delta$ from theory

At much lower density, a stiff CF reinforced lattice may display high stiffness but with damping coefficient comparable to bulk material.

# Microlattice Design with High Stiffness-Damping Pair




**Theoretical model**

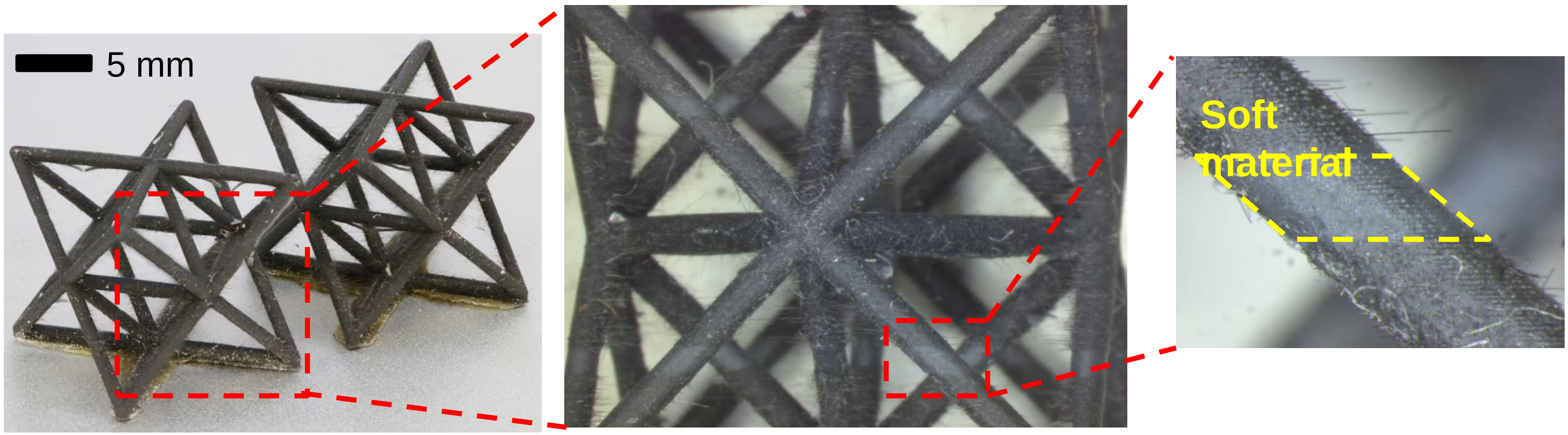
- Intrinsic damping: $\tan\delta \sim f(\bar{\rho}, E_{strut})$

$$E^*_{octet} = \left[\frac{2\sqrt{2}}{3}\pi\left(\frac{r}{l}\right)^2 + 4\sqrt{2}\pi\left(\frac{r}{l}\right)^4\right]E^*_{comp}$$

$$E^*_{comp} = \left[\frac{V_1}{E^*_1} + \frac{V_2}{E^*_2}\right]^{-1}$$

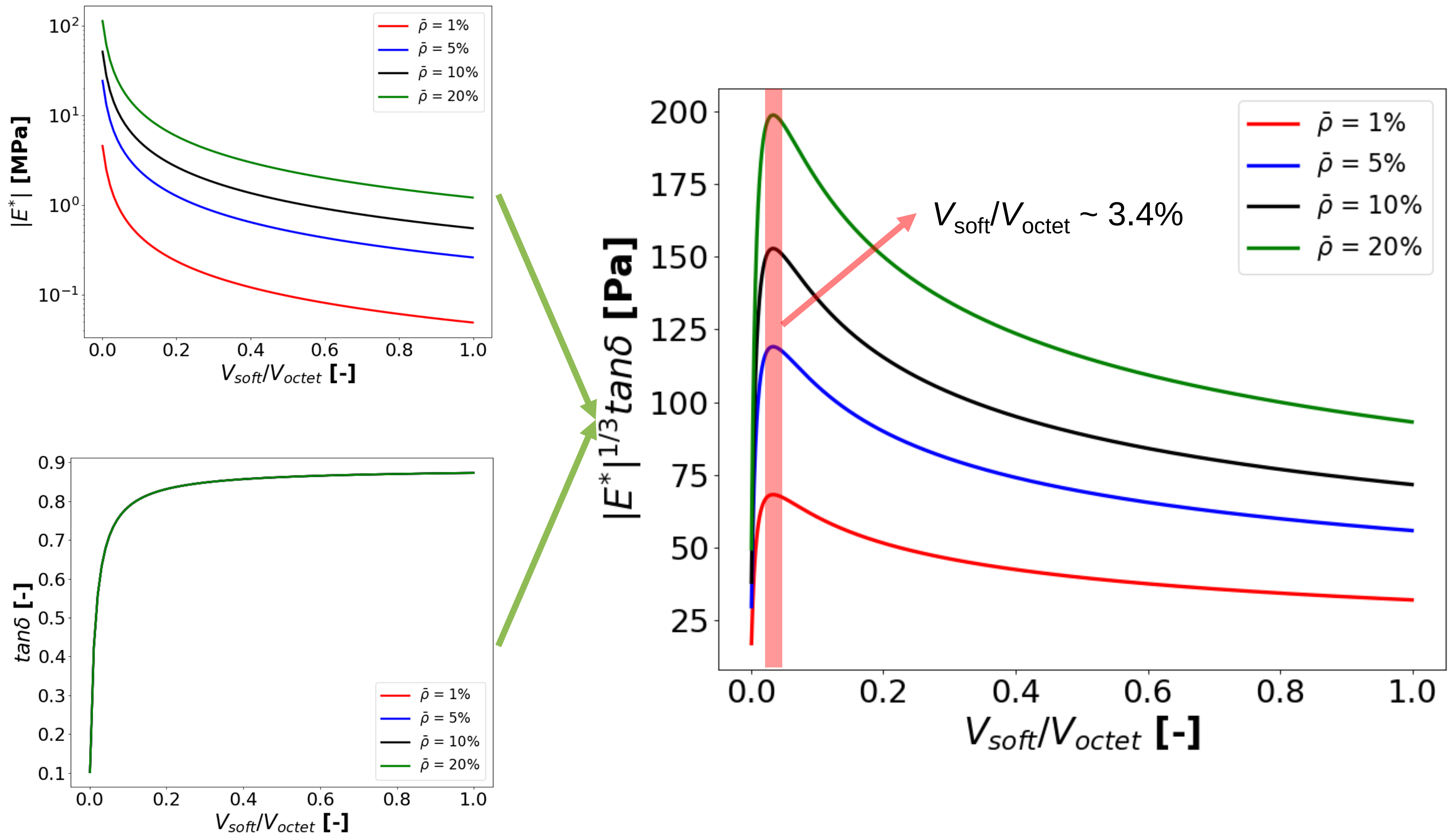
$$tan\delta = \frac{E''_{octet}}{E'_{octet}}$$

- Structural damping (in progress)



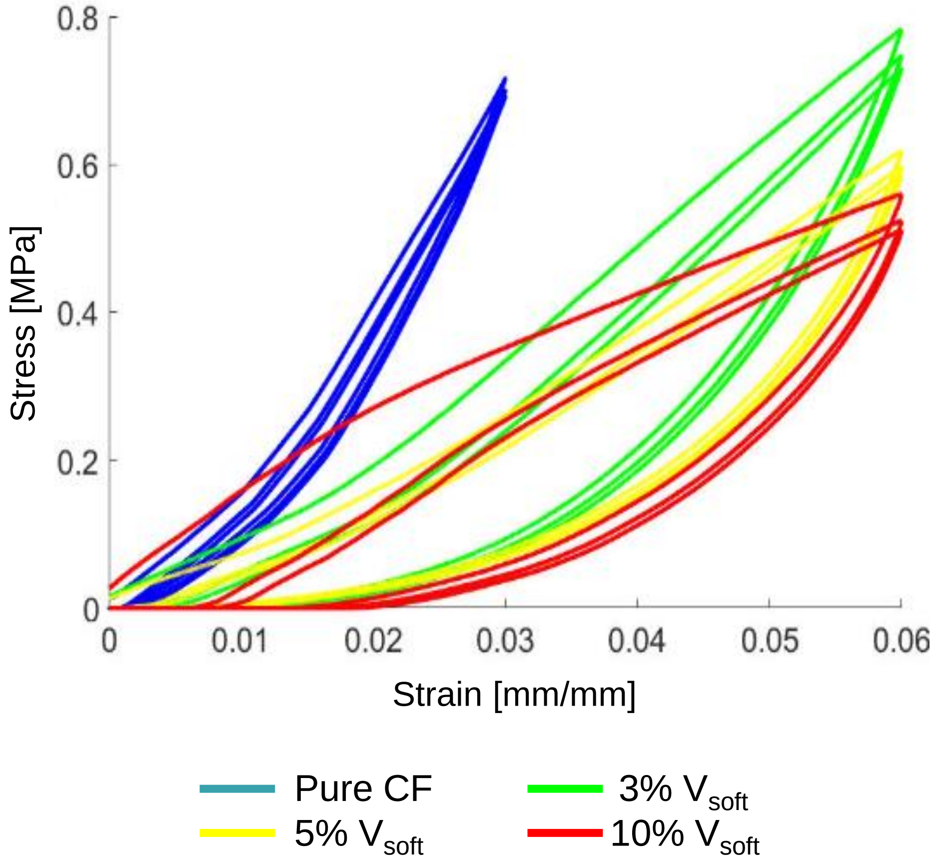

We designed CF octet-truss unit cell with soft material to achieve high stiffness-damping pair.
CF octet-truss unit cells having 3% and 5% flexiable volume fraction have been fabricated.

# Intrinsic Damping (Theory)

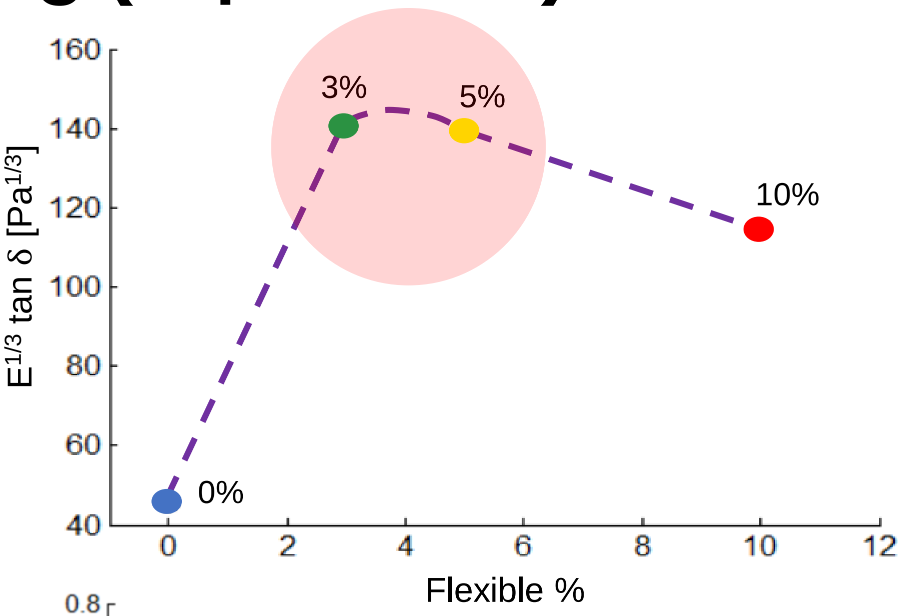


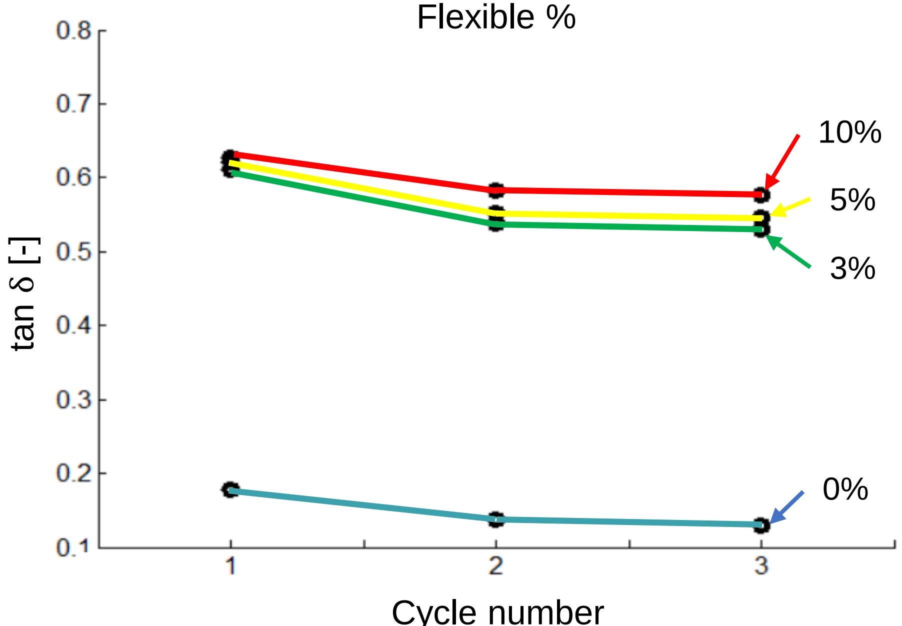

Our theoretical derivation for intrinsic damping predicts that an optimized architecture for high $E\tan\delta$ requires a specific volume ratio of soft material.

# Structural Damping (Experiment)



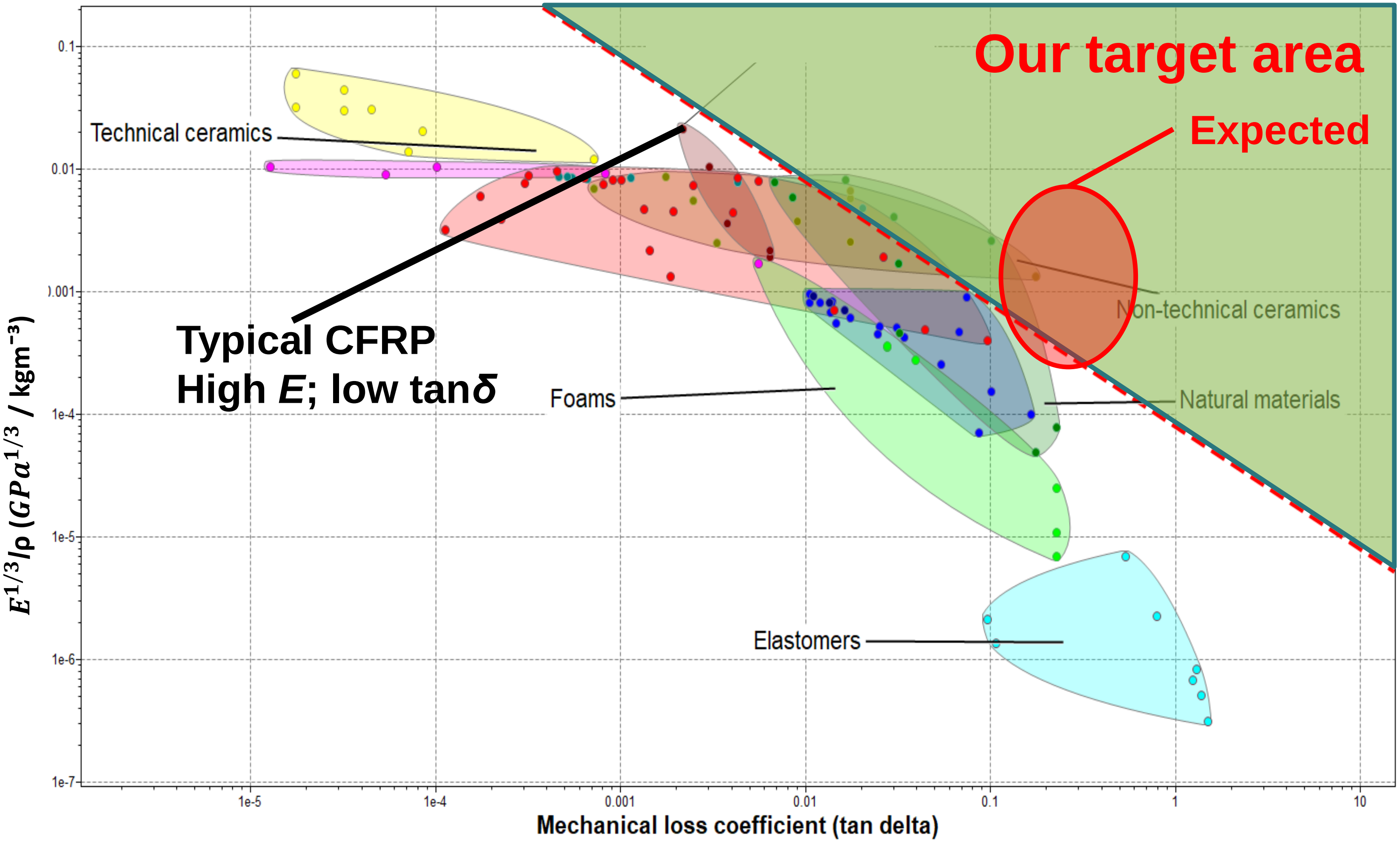

CF octet-truss with $\bar{\rho}$ = 5%




From our preliminary experiments for structural damping, it seems that there is the maximum $E^{1/3}tan\delta$ for a specific volume fraction of soft material.

# Evaluation of Our Design




$E^{1/3}/\rho$ vs tan$\delta$ chart for CFRP and other family of materials

Again, with the use of our multi-material fabrication method, we believe that our design can achieve high stiffness-damping pair and outperform existing designs.

# Response to Previous Reviewer's Comments

**This project was not previously reviewed.**

# Collaboration

- Subcontractor: Virginia Tech
  - Xiaoyu Rayne Zheng,  Zhenpeng Xu,  Chan Soo Ha, Ruthvik Kadam,

# Remaining Challenges

- Fabrication of high loading carbon fiber composites
  - Increase UV light penetration depth and prevention of interlayer delamination.
  - Managing viscosity and processability: viscosity of the resin increases as carbon fiber loading increases.
- Tradeoff between resolution and building area.
  - Scaling up printing method in progress
- Theoretical model for structural damping optimization.
- Scale up of technology for vehicle demonstration

# Proposed Future Research

Ongoing:

- Theory of structural damping.
- Conduct cyclic testing to obtain stiffness-damping map.
- Manuscript in preparation.
- Enlargement of the printing area to tens of centimeters.

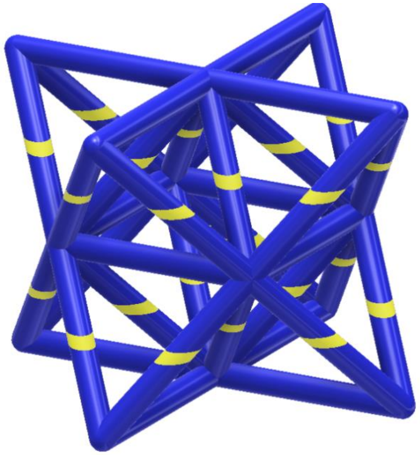
Planned:

- Demonstrate ultralight hierarchical carbon fiber composites with tailored energy absorption and high strain recovery (> 10%).
- Fabricate hierarchical carbon fiber lattice materials (< 500kg/m3) with tunable directional or isotropic functionally graded designed stiffness and energy absorbing capabilities.

Any proposed future work is subject to change based on funding levels.

# Summary

- Target: Hybrid hierarchical CF reinforced materials that are ultralight, strong and tough for 3D printing.
- Developed: Multi-material lattice structures with high stiffness and high damping / energy absorption.
- Future: Fabricate hierarchical carbon fiber lattice materials (<500kg/m3) with tunable directional or isotropic functionally graded designed stiffness and energy absorbing capabilities



# Reference

[1] G. D. Goh et al., Recent Progress in Additive manufacturing of polymer reinforced composites, Advanced materials, 4 (1), 1800271 (2019).

[2] F. Ning et al., Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling, Composite part B: engineering, 80, 369-378 (2015).

[3] L. Salari-Sharif et al. Energy dissipation mechanisms in hollow metallic microlattices, J. of Materials Research, 29 (16), 1755-1770 (2014).

[4] X. Zheng et al., Ultralight, Ultrastiff Mechanical Metamaterials, Science, 344 (6190), 1373-1377 (2014).