Additive Manufacturing for Property Optimization for Automotive Applications

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June 23rd, 2021

Project ID#: mat200

ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

Overview

Timeline

- Project start date: Oct 2020
- Project end date: Sept 2023
- Percent complete: 15%

Budget

- DOE project funding: $500K/yr
  - DOE: 100%
- Funding for FY21: $500K

Partners

- Ford Motor Company - Industry partner
  Ford project lead: Ellen Lee
- UCLA - Subcontract
  UCLA project lead: Xiaoyu (Rayne) Zheng

Barriers and Targets

- **Barrier**: (1) Lack of understanding of properties with respect to fracture and energy absorption*, (2) Lack of predictive engineering and modeling tools*, (3) Cost/availability of most lightweight materials and current manufacturing processes are not competitive*

(* Ref.: Light-Duty Workshop Final Report (DOE-VTO))

- **Target:** (1) Design, optimization, and performance simulation of tailored 2.5D cellular structures for extrusion-based AM incorporating ML, and (2) Fabrication and performance evaluation of parts printed using the multi-material BAAM system and OPP technology.

Relevance

Overall Objectives

- Combine multiple technologies associated with AM to increase the performance and reduce the manufacturing cost and the weight of components using composites.

Current Limitations

- Design constraints with conventional manufacturing methods → AM
- Design requires a series of stress simulation - design modification cycles → ML
- AM provides design flexibilities in 2D but still has constraints in 3D
→ Out-of-plane printing
- AM for large scale utilizes single material deposition for large scale printing
→ multi material printing

VTO's Mission

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

Our Strategies

- Large-scale structure optimized for structural design and multi-material placement printed in BAAM.
- Control technique of an out-of-plane printing will be developed, and the sub-component of a vehicle will be fabricated.
- ML algorithm development for a sub-component structure with tailored energy absorption characteristics

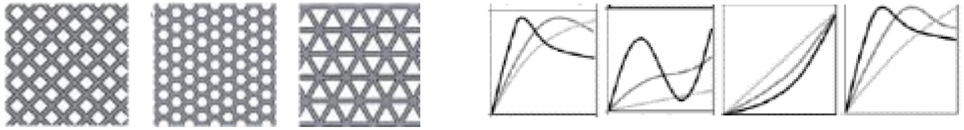
Milestones

			Y1				Y2				Y3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	T1.M1	**Part design** selection based on discussions with the industry partner (e.g., frontal bumper)												
	T1.M2	**Load cases and criteria** for mechanical responses (e.g., deflection and energy obsorption)												
	T1.M3	**Mechanical property evaluation** for BAAM materials.												
	T1.M4	**Material composition optimization** for BAAM printed structures.												
	T1.M5	**Scalability test** of the of the structure from small-scale prints to BAAM												
	T1.M6	**Toolpath optimization** for the latticed structures for BAAM with multi-material												
	T1.M7	Demonstrate **printing** of performance optimized multi-material structures on the BAAM system												
	T1.M8	Mechanical **testing and evaluation** of a BAAM printed structure												
Task 2	T2.M1	**Part design** selection for out-of-plane printing with the industry partner (e.g., door arm rest)												
	T2.M2	Define **load cases and criteria** for mechanical responses (e.g., deflection and energy obsorption)												
	T2.M3	**Performance simulation** for the out-of-plane structure												
	T2.M4	Material **property evaluation** for a multi-axis extrusion system												
	T2.M5	**Slicing technology** development for the multi-axis extrusion system												
	T2.M6	**Toolpath planning** for the out-of-plane structure												
	T2.M7	**Robot arm control & extrusion control** optimization for the multi-axis system												
	T2.M8	Demonstrate **printing** of an out-of-plane property optimized structure												
Task 3	T3.M1	Development of a **simulation technique** for 3D-printed lattice structures												
	T3.M2	**Calibration** of the simulation **parameters** (small-scale)												
	T3.M3	**Perform simulations** for multiple lattice structuers and material combinations (small-scale)												
	T3.M4	**Mechanical tests** for multiple lattice structures and material combinations (small-scale)												
	T3.M5	Development of an **ML Approach** & **Training Data Acquisition** for lattice structures												
	T3.M6	Generation of **Tailored Lattice Structures** and Evaluation (small-scale)												
	T3.M7	Lattice structure combined with **self-sensing material** (small-scale)												
	T3.M1-6	Regular milestones for BAAM and stretched milestones for out-of-plane printing structure												

Approach

MATERIAL & DESIGN OPTIMIZATION

Tailored Lattices & Multi-Materials

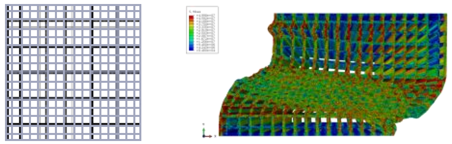


Lattice Structures with Tailored Stress-Strain Response

+

Fiber-Reinforced Thermoplastics, Elastomers, Thermoplastic Foams, Polymer Blends

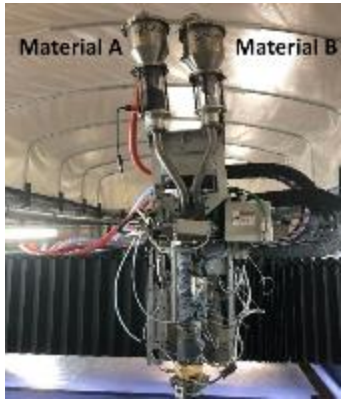
SIMULATION



Deformation Prediction
Strength/Stiffness Prediction

ARTIFICIAL INTELLIGENCE

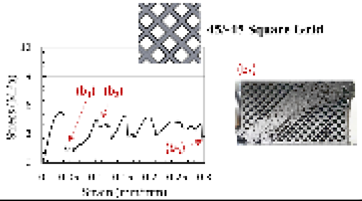
FABRICATION (Extrusion AM)



Out-of- Plane AM
Single Material (Mid-Scale)

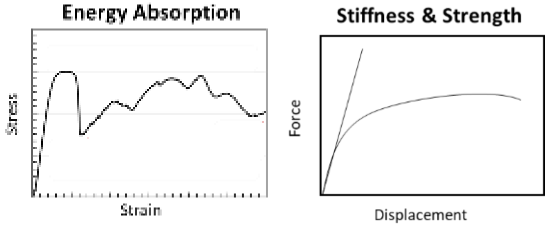
TESTING

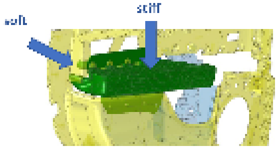
Mechanical Properties such as Energy Absorption, Stiffness, Strength



PERFORMANCE

Multi-Property Optimized Structures





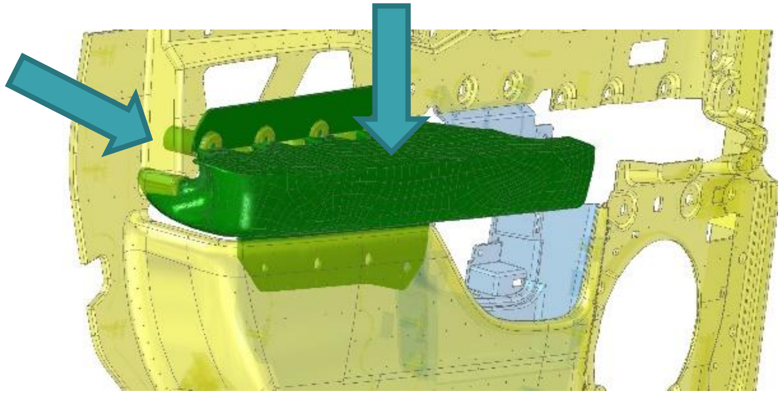
Technologies

- Multi-material extrusion BAAM system
- Lattice optimization algorithm
- Simulation technique for lattice deformation
- Out-of-plane printing with a robot arm (5 axis)
- Design selection algorithm via machine learning (UCLA)

Target Applications

- Front bumper and door panel arm rest

Frontal bumper design from FORD (blurred)

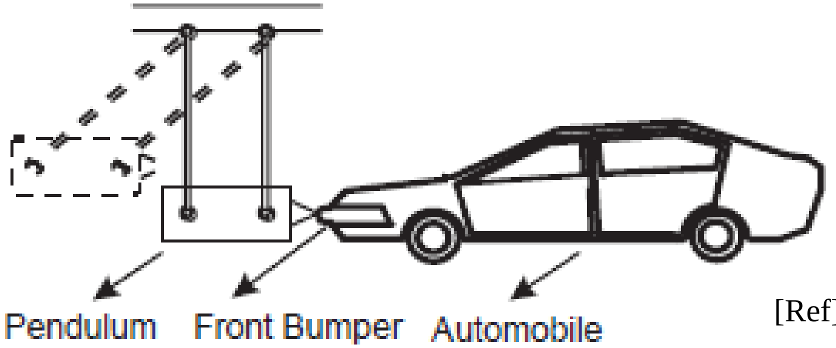


Task 1: Design Requirements for a Bumper

Frontal Bumper (Energy Absorber Portion) of Passenger Vehicle

Conflicting design/performance requirements:

- Pendulum intrusion testing:
  - Large footprint impactor at low speed (2.3 mph) with relatively large deformation (< 85 mm)
- Leg flexion testing:
  - Small footprint impactor at high speed (24.6 mph) with relatively small deformation (< 13 - 22 mm) replicating the scenario of impact with a pedestrian's leg



[Ref]

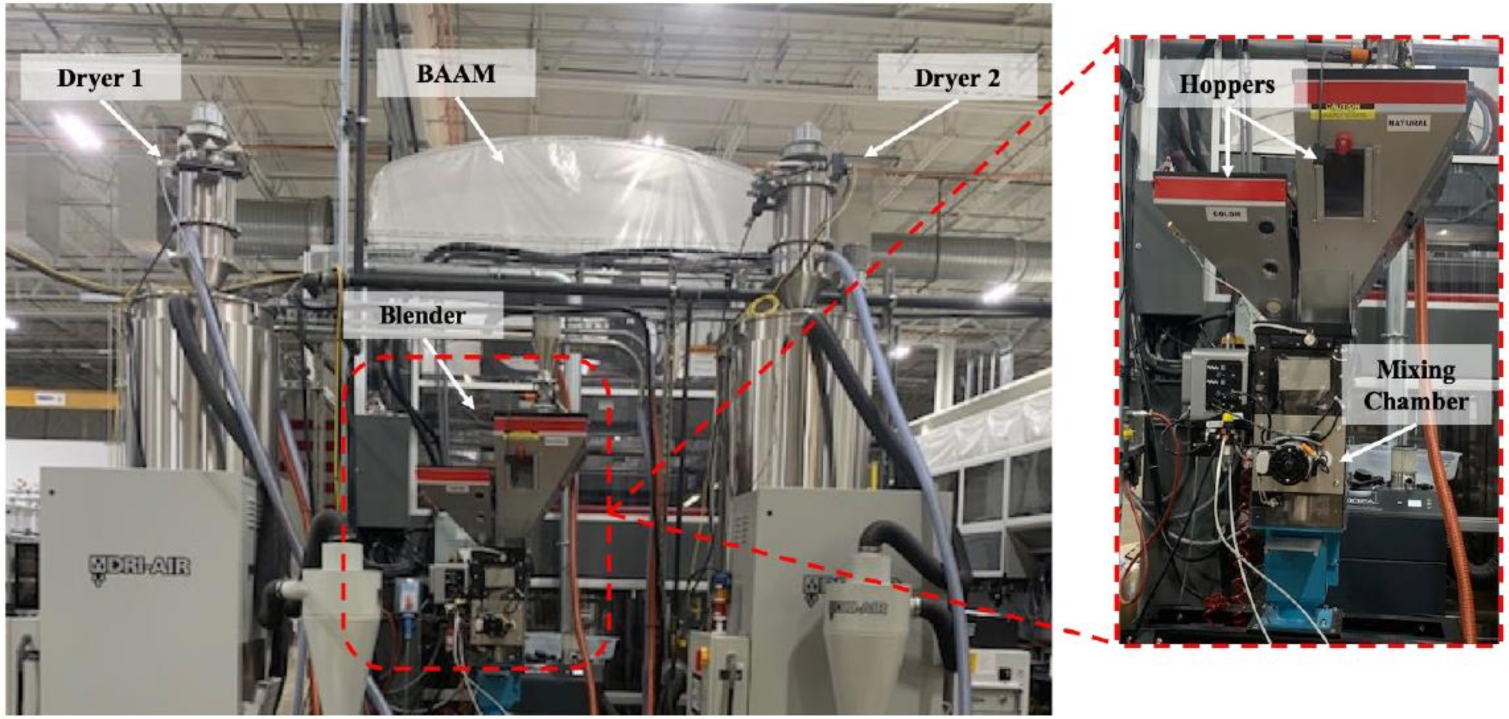
Pendulum test

Leg test

[Ref] Katkar, A.D. and Bagi, J.S., Bumper Design Enhancement through Crash Analysis. Int. J. Eng., Tech., Mgmt. & Appl. Sci. 2015.

Multi-Material Large-Scale Printing of Optimized Structures

Multi-Material Printing on the Big Area Additive Manufacturing System



Complex structures

Alternating materials between layers

Local reinforcement

- Enables printing of with multiple materials in a single build for site specific properties or functionally graded material (FGM) structures.
- Blending system enables mixing feed pellets with foaming agents for extruding thermoplastic foams (density $\geq$ 0.2 g/cc) for lightweight

* Printed in previous years

Materials Selection

BAAM-Printable Materials

- Low Temperature Thermoplastics & Composites
- High Performance Thermoplastics & Composites
- Bio-Derived Materials
- Magnetic Materials
- Elastomers
- Foams
- Dissolvable Polymers
- Recycled Materials

For multi-materials printing

- Similar processing temperature range.
- Chemical and rheological compatibility for good interlayer bonding, and continuous printing for graded properties.

For thermoplastic foam printing

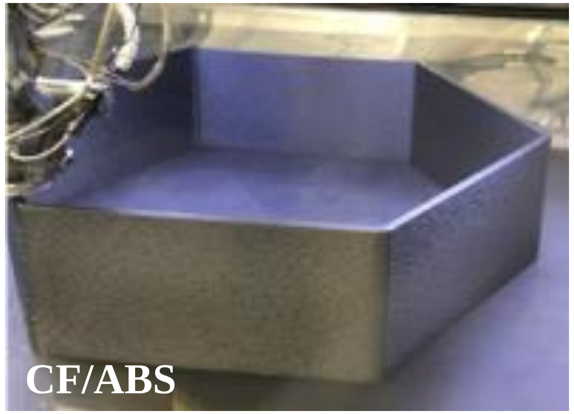
- Feed material processable below the degradation temperature of foaming agents.
- Layer time to be optimized to prevent warping/cracking.

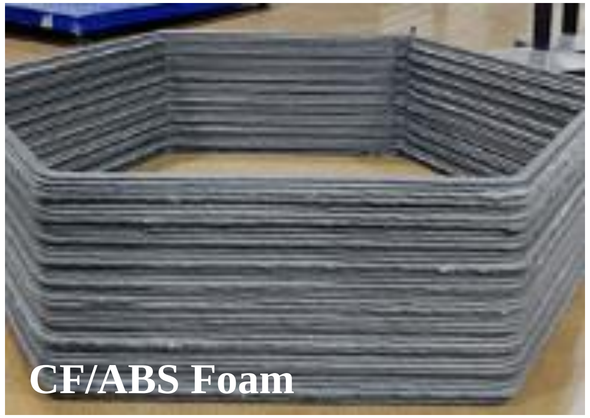
Materials selection criteria for preliminary screening

- Low temperature thermoplastics/composites compatible with expandable microspheres (foaming agents).
- Elastomeric matrices with good energy absorption properties.
- Materials processable as blends (stiff and elastomeric material blends) to tailor mechanical properties.

Material Properties Characterization for Optimization

Gravimetric blender for mixing feed pellets and foaming agents.





Examples of test parts printed on the BAAM for individual material properties characterization.

Feed Pellets (Ex: 20 CF/ABS)

Expandable Microspheres (Foaming Agent)

Materials chosen for preliminary screening: CF/ABS Foam, TPU (Elastomer), TPU Foam, ABS, ABS Foam, CF/ABS & TPU blend, CF/ABS & TPU blend foam, Xenoy® 1102.

Properties of interest for optimization: Dynamic mechanical properties (torsion, flexure), tensile properties, flexural properties.

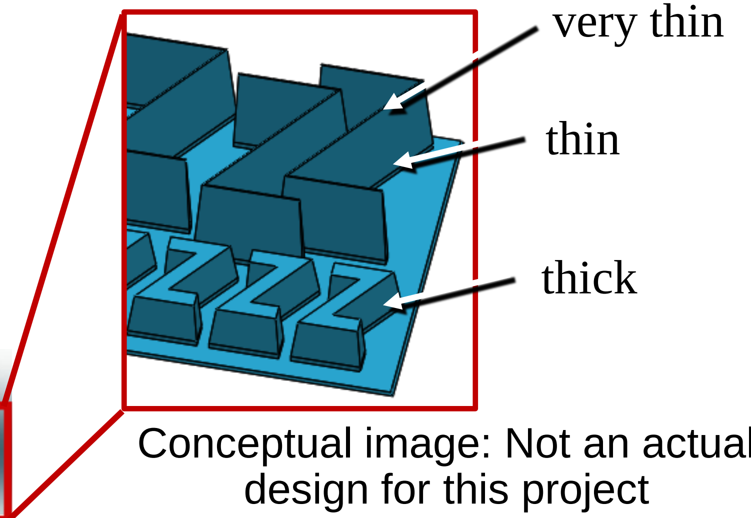
Other properties of interest for application: Impact, density

Reference Design

(Bumper with supporting inner curved structure)

- 3 parts: Base, long & thin inner structure, short & thick inner structure
- Challenges
  - Base has a curvature. → Out-of-plane printing in BAAM
    - Technology to be developed (slicing and control).
  - Small features
    - Not feasible in BAAM → Thicker design with a softer material (TPU foam)
  - Continuously varying thickness
    - Extrusion flow rate control
  - Switching materials (short structure vs. long structure)
    - Layer time calibration based on the heat capacity

Bumper design from FORD (blurred)

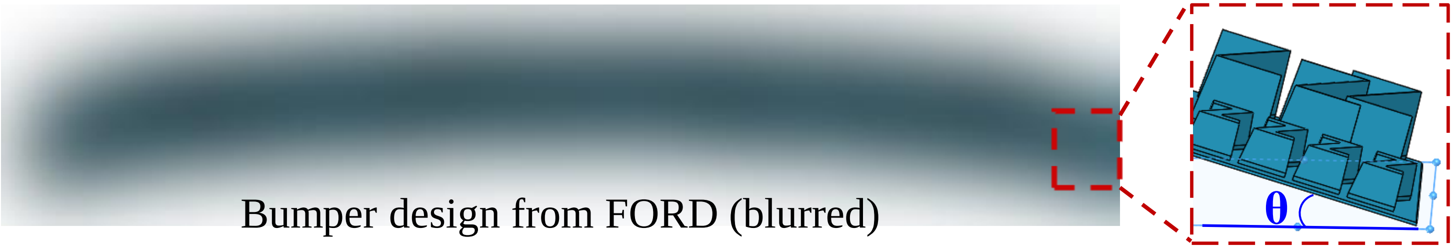


Conceptual image: Not an actual design for this project

Slicer Modifications

- Slicer 2.0 under development will incorporate the capabilities for slicing curved parts
- Currently the bumper toolpath was created using the slicer of Mazak hybrid manufacturing system*

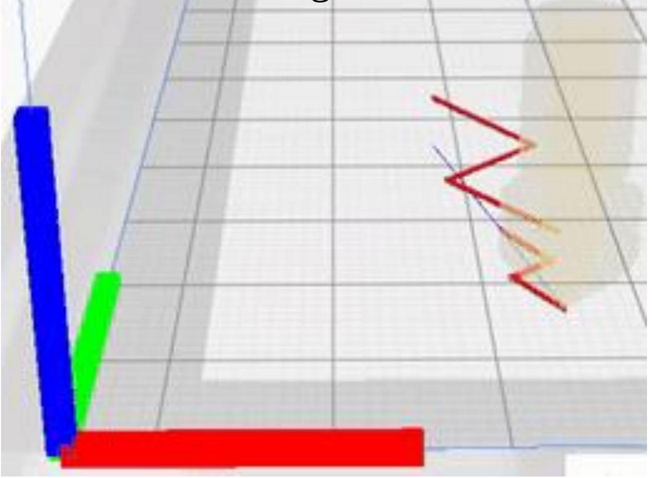
* Slicing performed by Tom Feldhausen and Rebecca Kurfess, ORNL

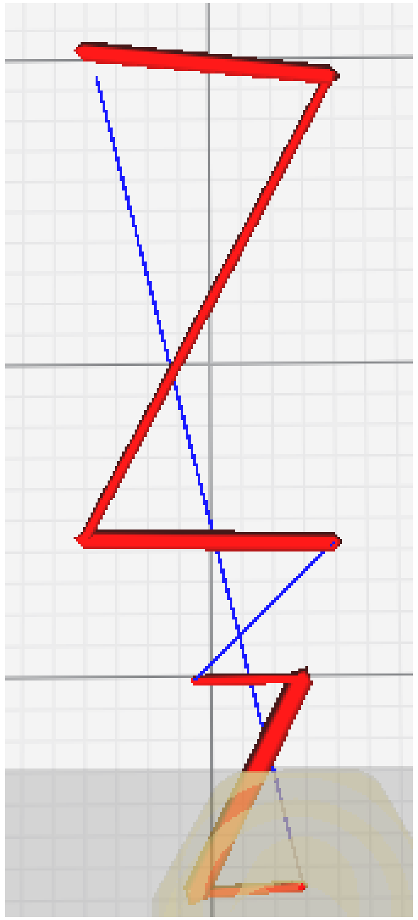


Bumper design from FORD (blurred)

Top view

Angled view





Conceptual animation: Not an actual design for this project

Subtasks in Progress in This FY

- Printing test samples with the selected materials for mechanical properties characterization.
- Machining printed parts for harvesting test samples.
- Testing of mechanical properties.

Material Characterization

- Print trials with the reference design for printability test with CF/ABS and TPU to identify potential design related challenges that may arise for large-scale printing moving forward.

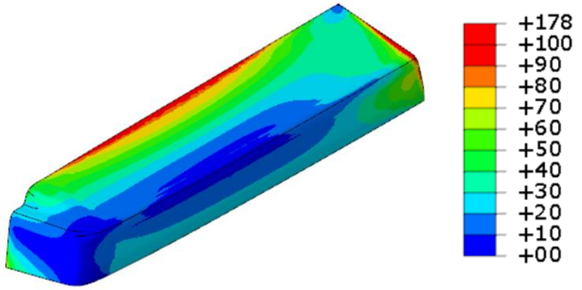
Any proposed future work is subject to change based on funding levels.

Task 2: Arm Rest

Load case and design criteria

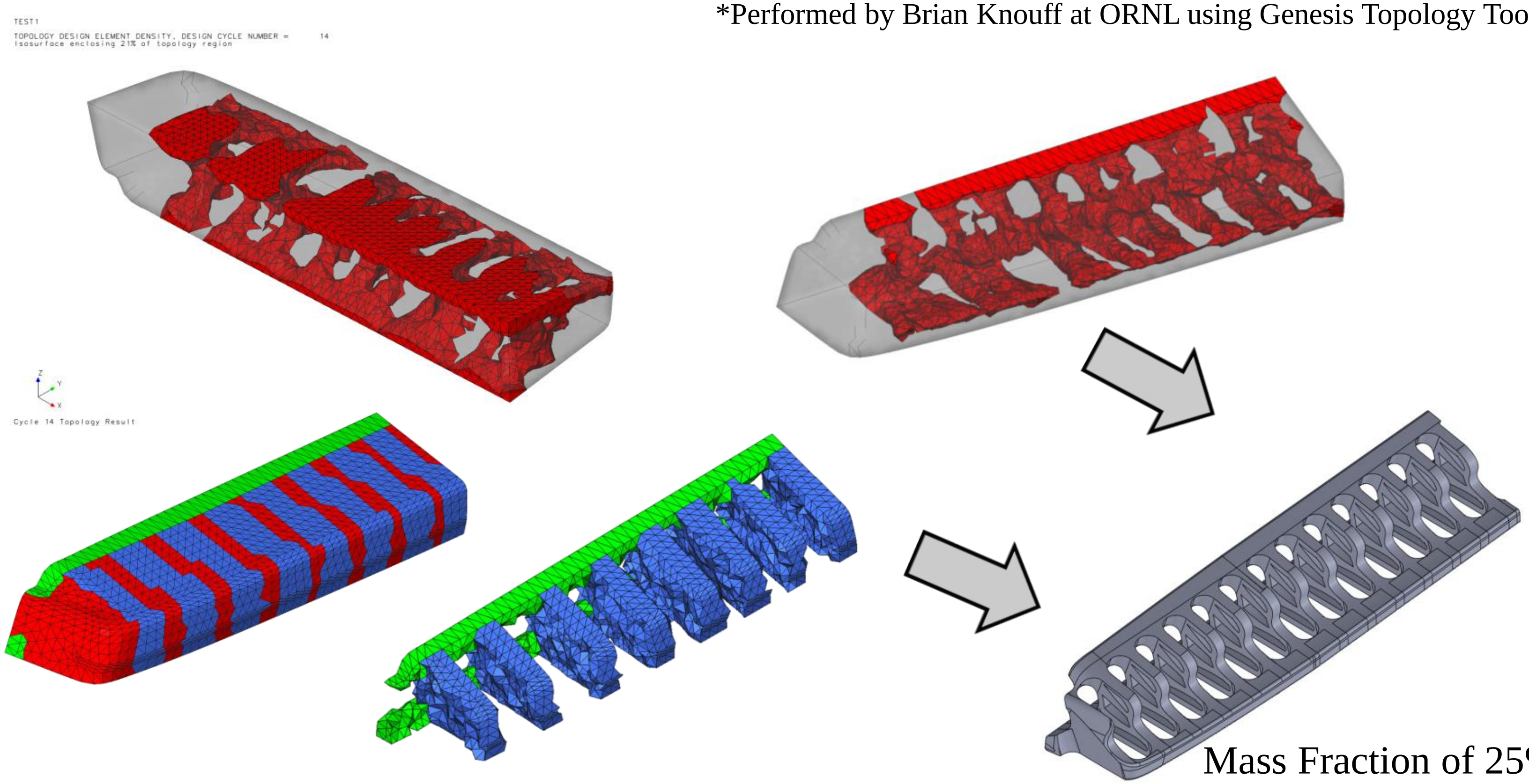
Requirement: < 15mm deflection

FEM Simulation



Topology Objective* = Minimize Strain Energy, Constrain Mass Fraction to 25%

*Performed by Brian Knouff at ORNL using Genesis Topology Tool



Mass Fraction of 25%

*Designed by Amiee Jackson at ORNL

Subtasks in Progress in This FY

- Further optimization of design of armrest.
- Print trials in an out-of-plane printer with 5-axis robot arm.
  - It is a new system, and the control framework should be further calibrated.
- Printing test samples for mechanical properties characterization.
- Testing of mechanical properties.

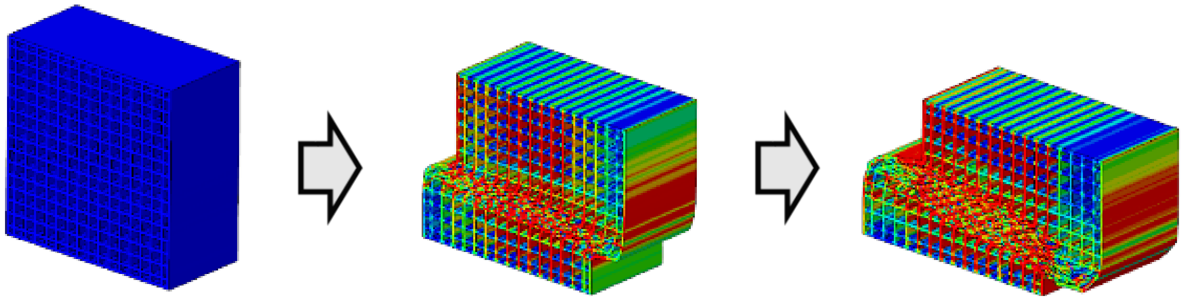
Material Characterization

- Deformation prediction of the optimized design via FEM simulation

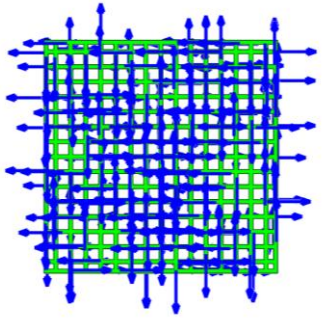
Any proposed future work is subject to change based on funding levels.

Task 3: Simulation Technique Developed

- **Simulation via Finite Element Method (FEM)**
- **Constitutive Relations Used:**
  - Elasticity
  - Plasticity
  - Damage/Element removal
  - Contact detection/repulsion

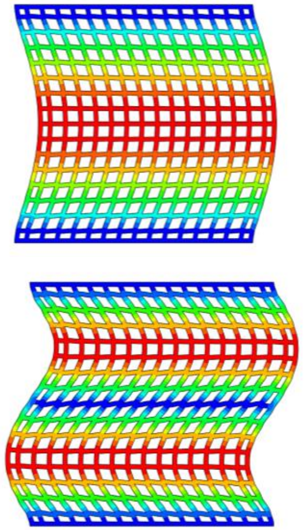


Crush simulation



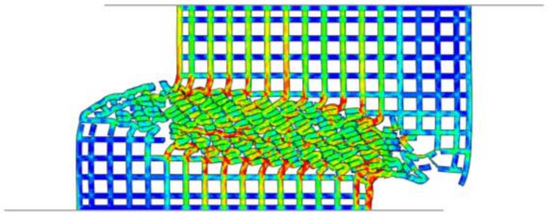
Property direction assignment

Import Material Orientations



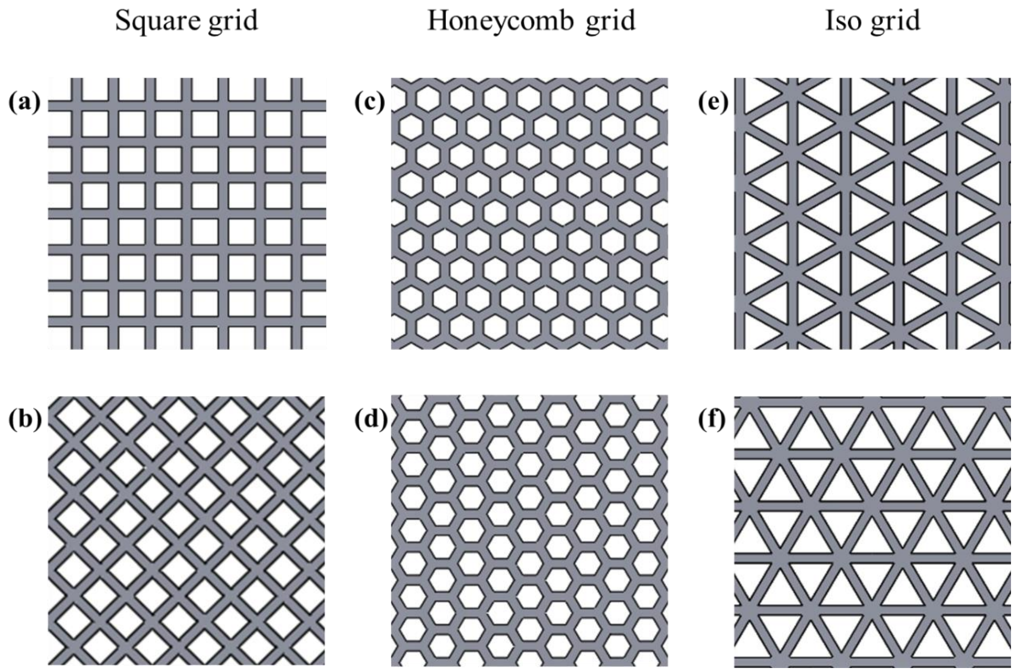
Frequency Analysis

Import Initial Imperfections

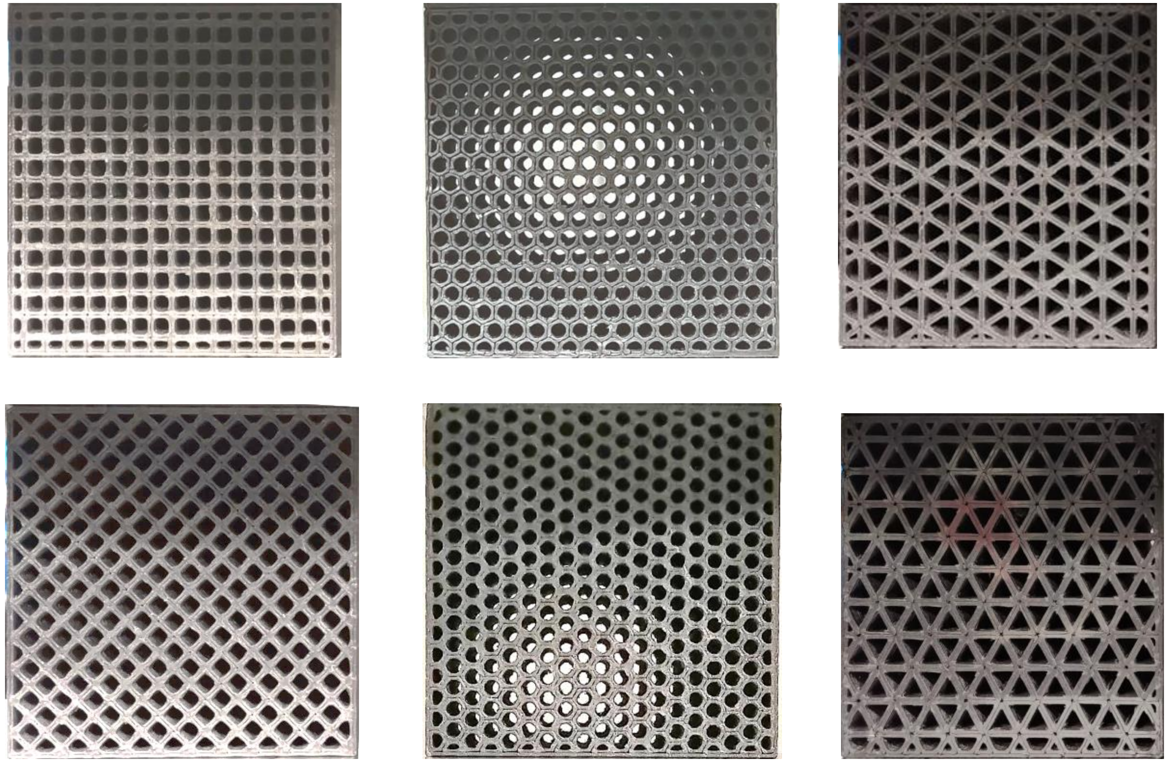


Crush simulation

Lattice Structure Designs

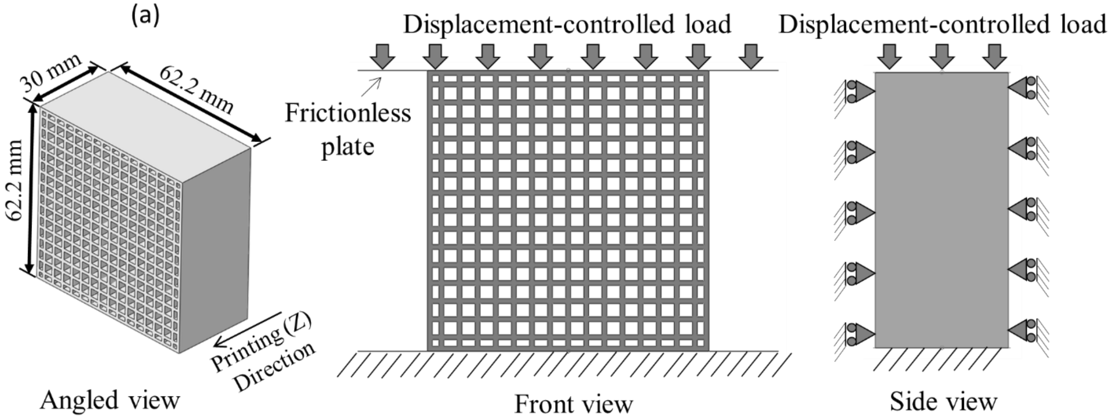


Lattice structure designs



Experimental samples

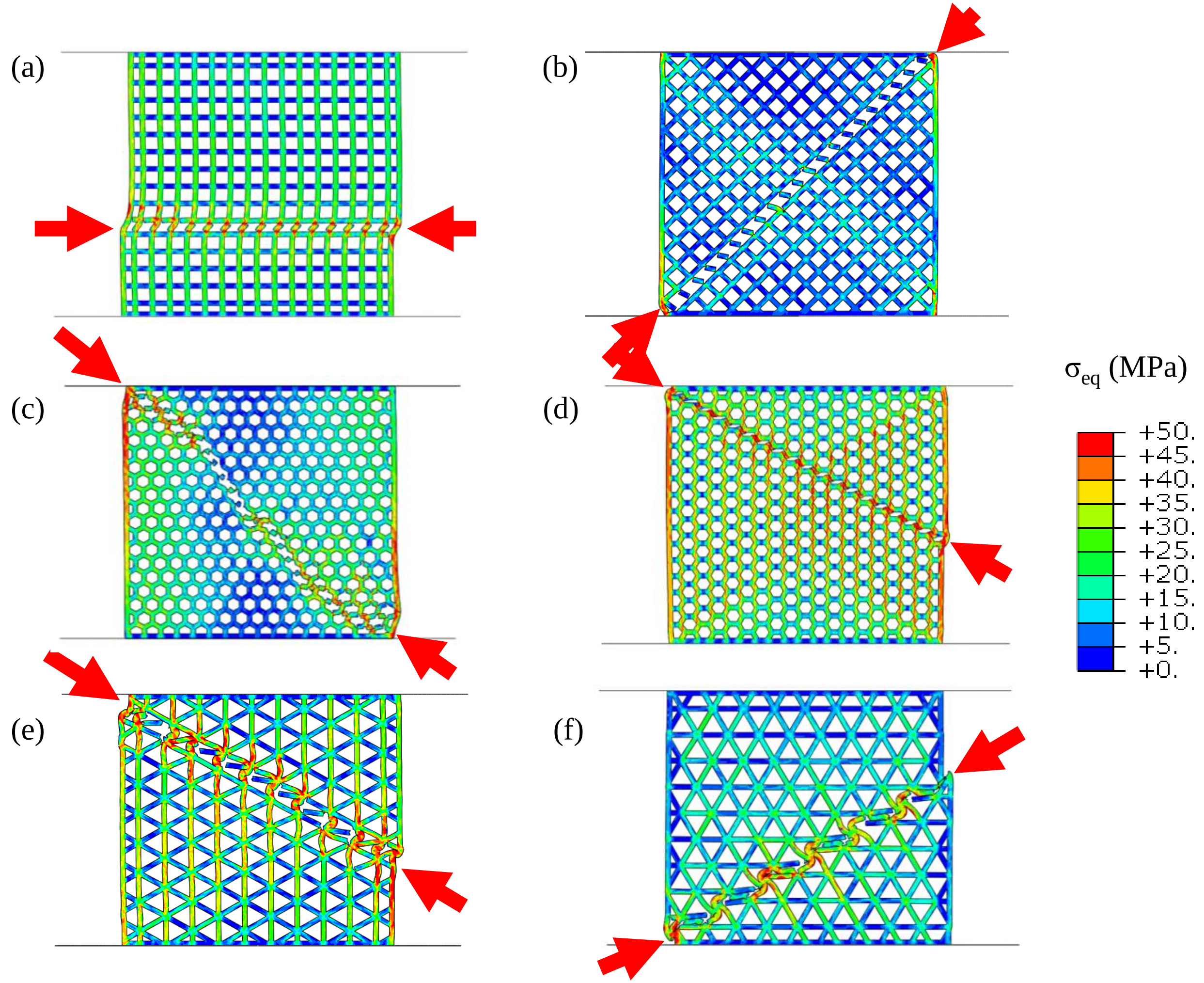
(experiments performed in FY2018)

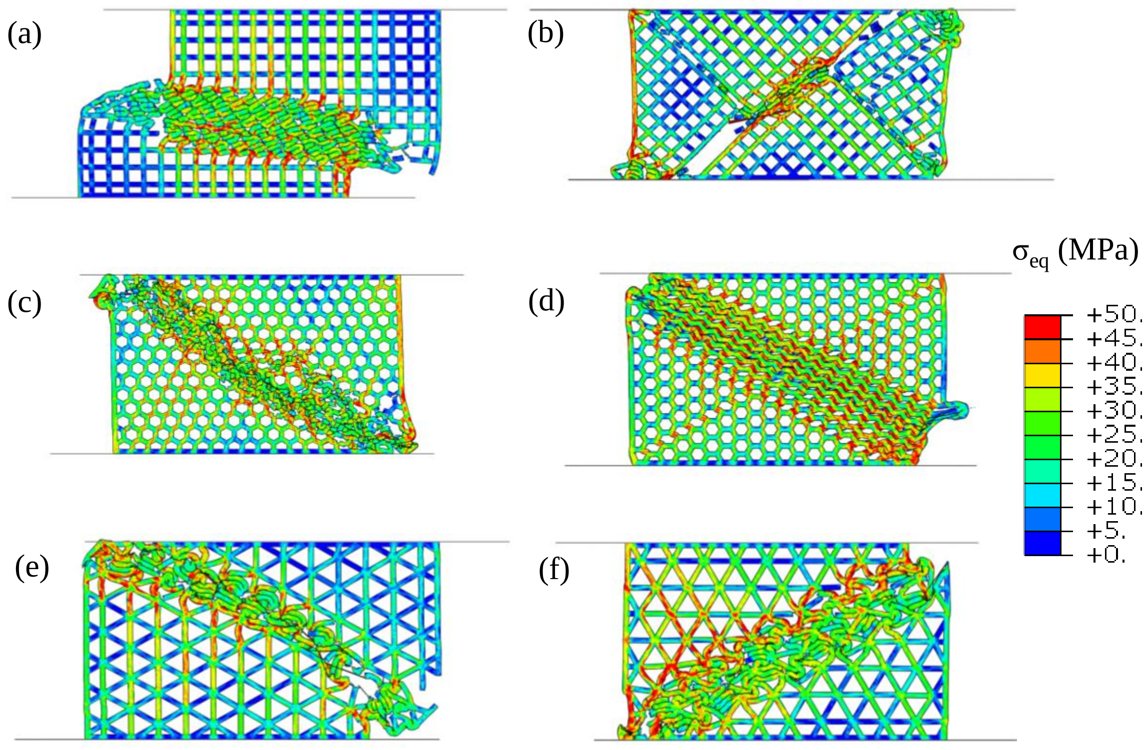


Boundary/load conditions

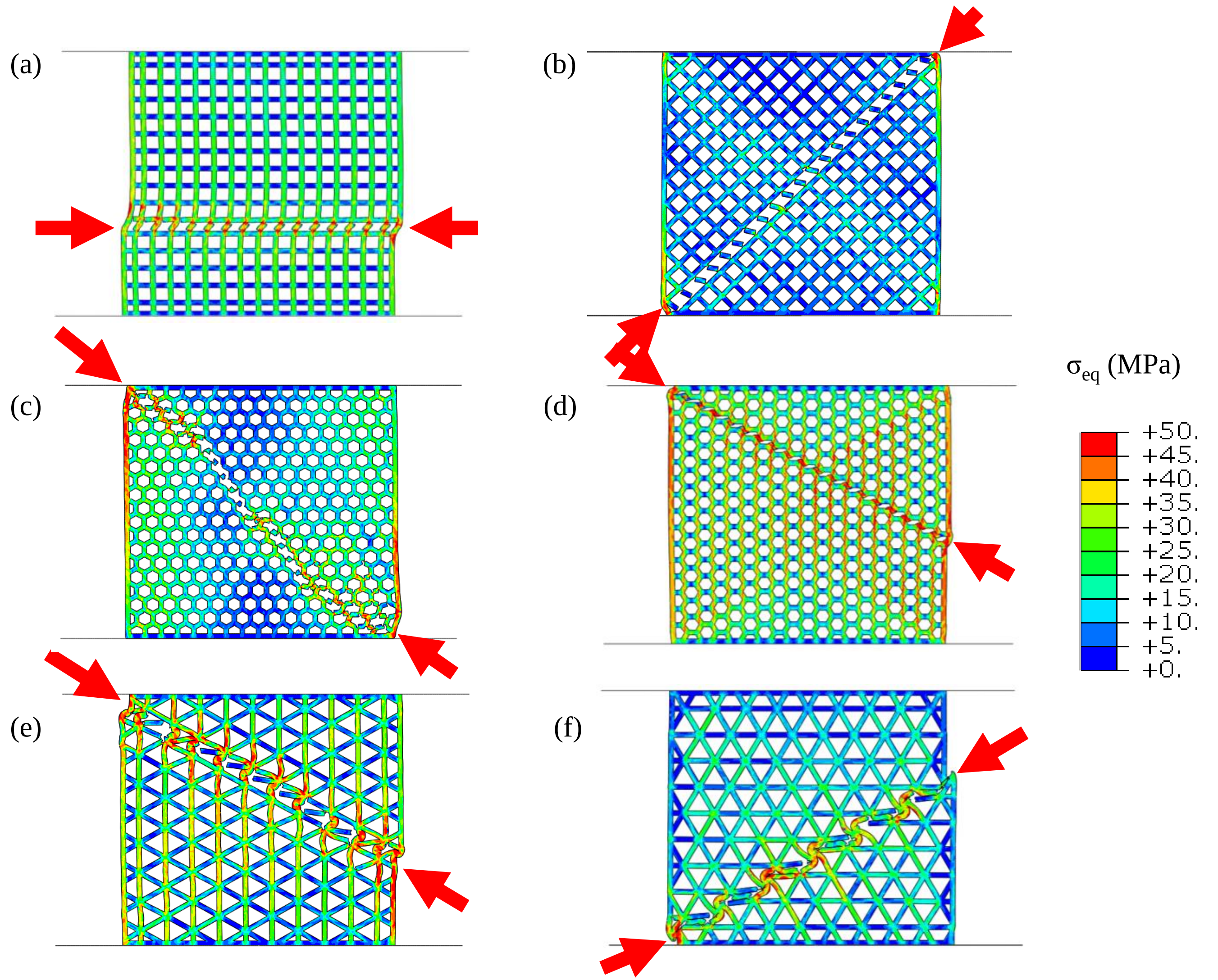
Task 3

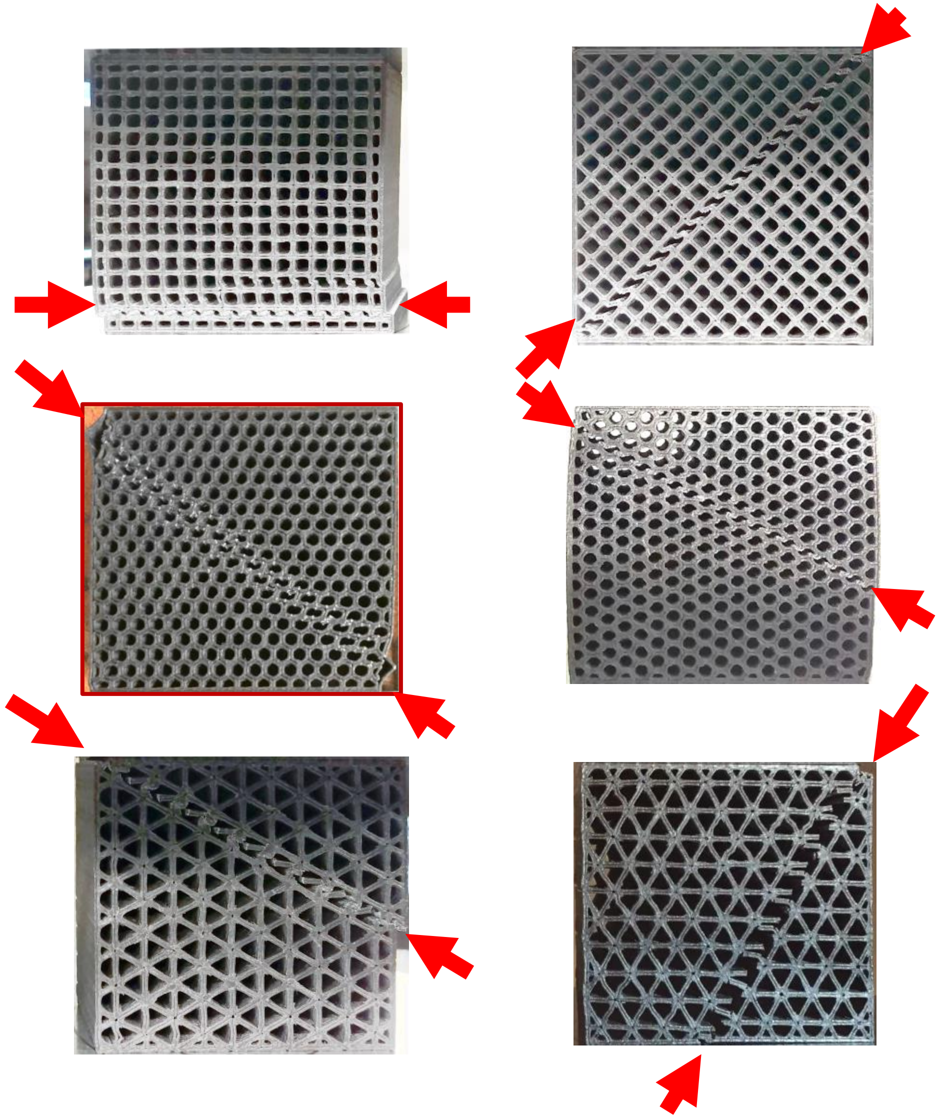
Fracture/Crush Pattern from Simulation





Comparison: Simulation vs. Experiment

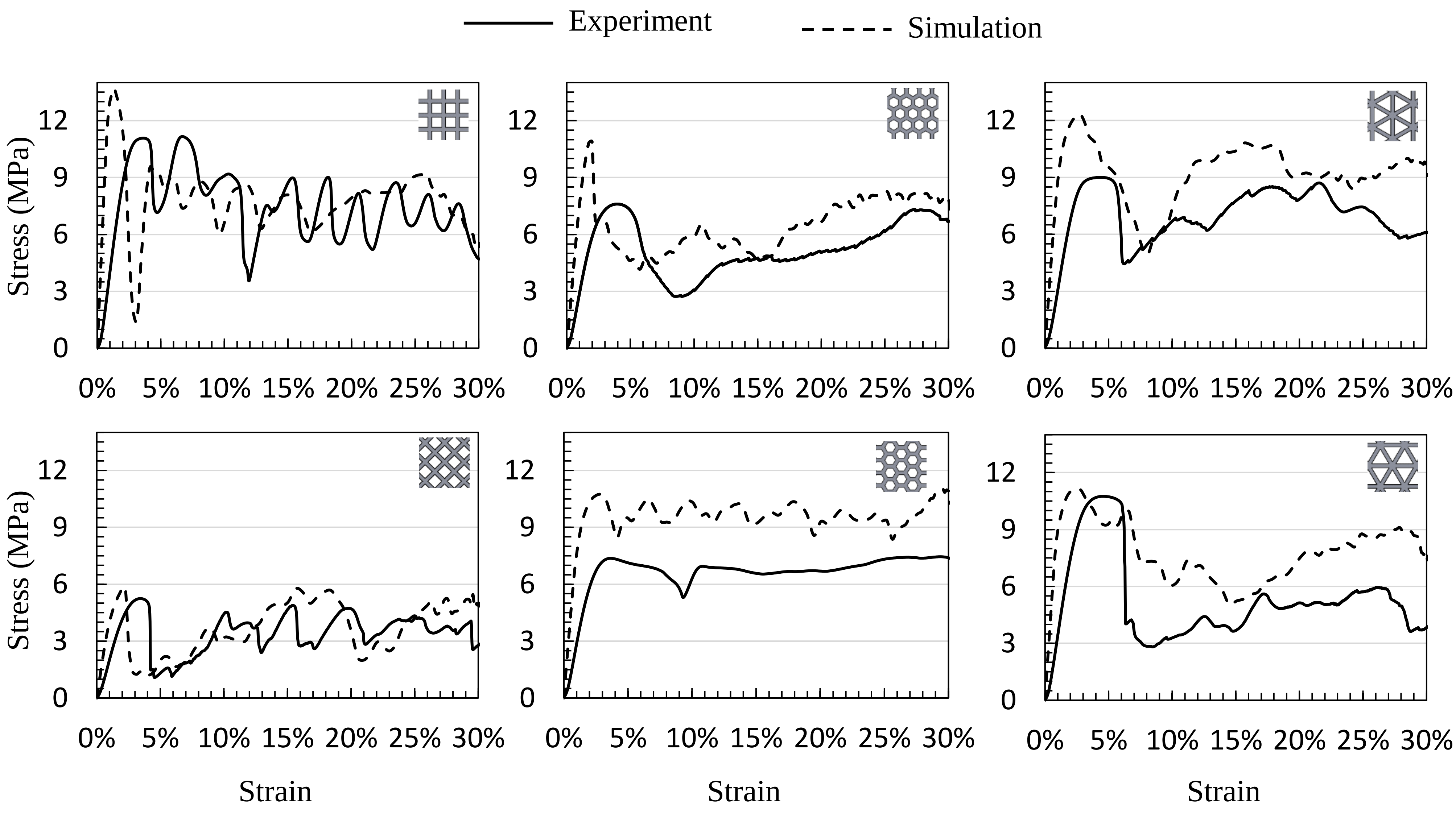




Experiment performed in Yr 2018

Task 3

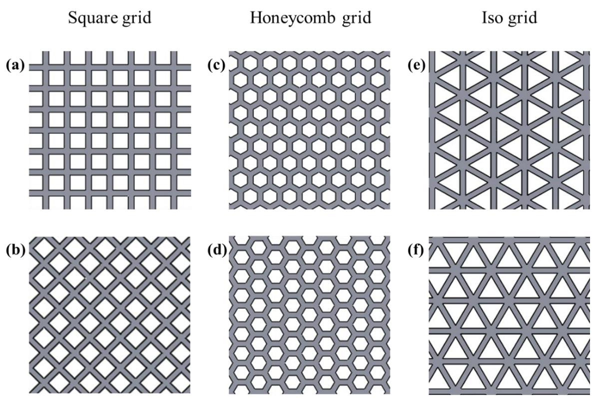
Comparison: Simulation vs. Experiment (Stress-Strain)



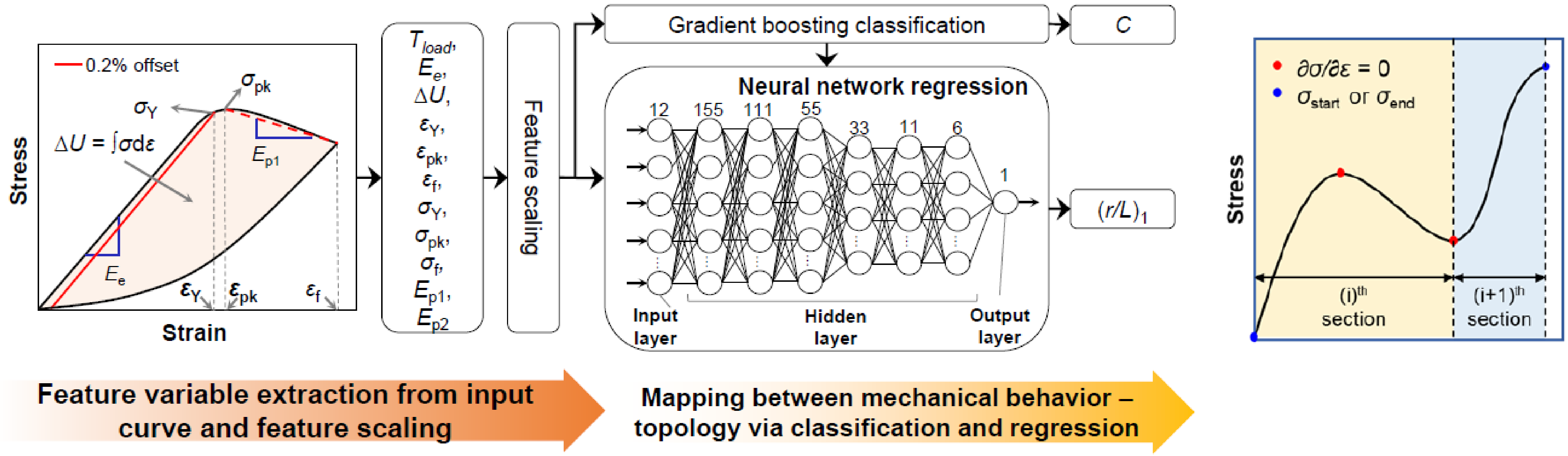
* Manuscript submitted to Materials & Design Journal, currently under review.

Plans for Task 3

- Further <u>crush simulations</u> on various lattice designs
  - Training data for ML
- <u>Material property library</u> for simulation
- Development of <u>machine learning framework</u> for lattice structure design optimization



Various lattice designs



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

Collaborations

- Industry Partner: Ford Motor Company
  - Ellen Lee, Iskander Farooq, Zach Pecchia, Sushmit Chowdhury, Matthew Rebandt
- Subcontractor: University of California, Los Angeles (UCLA)
  - Prof. Xiaoyu Rayne Zheng,

Remaining Challenges

- Task 1
  - Slicing and creating a toolpath of a single bead structure on a curved surface for the entire part printing.
  - Printing calibration for a small feature with a small nozzle.
- Task 2
  - Robot arm control
  - Toolpath generation without collision on a curved structure for out-of-plane printing
- Task 3
  - Machine learning algorithm development for a bumper design

Proposed Future Research

- Task 1
  - Printing test samples with the selected materials for mechanical properties characterization.
  - Machining printed parts for harvesting test samples.
  - Testing of mechanical properties.
  - Print trials with the reference design for printability test with CF/ABS and TPU to identify potential design related challenges that may arise for large-scale printing moving forward.
- Task 2
  - Further optimization of design of armrest.
  - Print trials in an out-of-plane printer with 5-axis robot arm.
  - Printing test samples for mechanical properties characterization.
  - Testing of mechanical properties.
  - Deformation prediction of the optimized design via FEM simulation
- Task 3
  - Further crush simulations on various lattice designs: Training data for ML
  - Material property library for simulation
  - Development of machine learning framework for lattice structure design optimization

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

Summary

- Target:

  (1) Design, optimization, and performance simulation of tailored 2.5D cellular structures for extrusion-based AM incorporating ML, and

  (2) Fabrication and performance evaluation of parts printed using the multi-material BAAM system and OPP technology.

- Progress:

  (1) BAAM materials have been prescreened.

  (2) Single bead features have been sliced using a metal welding-based AM hybrid system.

  (3) Armrest has been designed based on topology optimization.

  (4) Simulation framework developed for a lattice crush response with various lattice types.

  (5) Simulations have been verified by experimental results.