local motors

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Materials Development and Structural Evaluation for Additive Manufacturing of Vehicle Structures

Charles Hill, Greg Haye, Robert Bedsole, and Kyle Rowe
Local Motors

February 1, 2017

Institute for ADVANCED Composites Manufacturing INNOVATION

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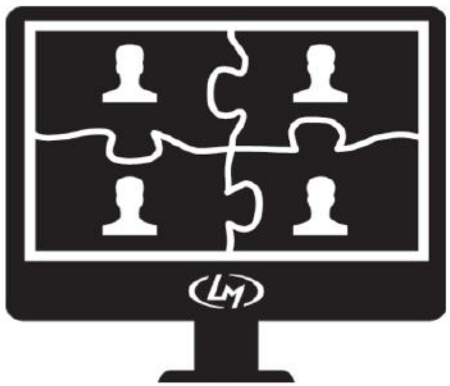
Overview

- Company Background
- Large Scale Extrusion Deposition Process (BAAM)
- IACMI Phase I Project Status
    - Materials Development Activity
    - Structural Evaluation Activity
- IACMI Phase II Project Planning
- Additional Work

Local Motors Background

Local Motors is a technology company that designs, builds, and sells vehicles.



Ideate, design and engineer products collaboratively.

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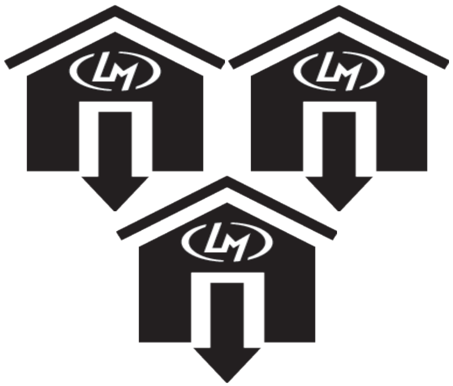

Prototype, test and make products locally.

Through Co-creation and Micro-manufacturing

Partnerships

Oak Ridge National Laboratory

CINCINNATI®
CINCINNATI INCORPORATED

STRATI

World's 1st 3D-Printed Car

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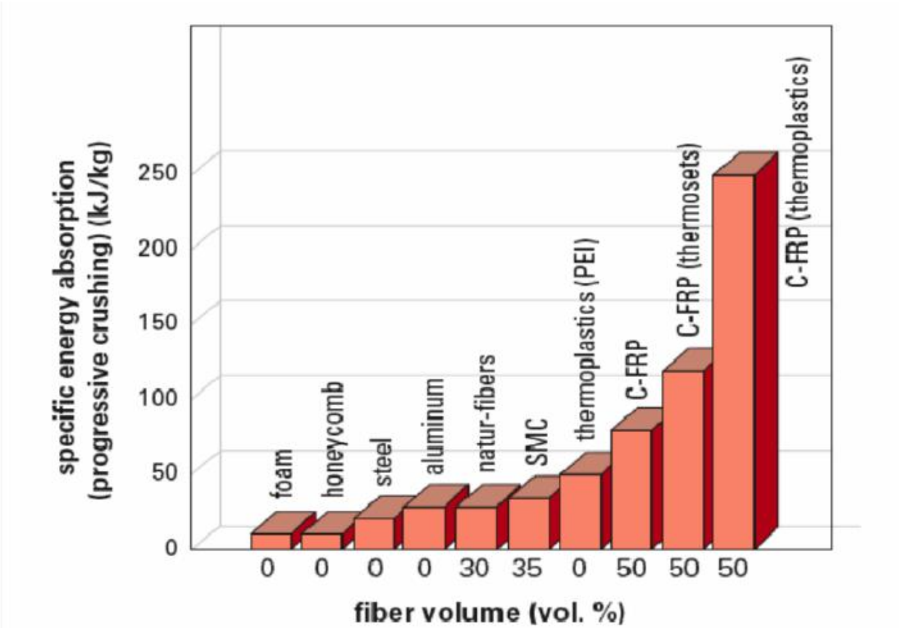
Additive Manufacturing of Vehicle Structures

- **Rapid Design and Development Cycles**
- Enables Customer Configuration and On-Demand Build Capability
- **Reduces Embodied Energy** From Vehicle Manufacturing
- Recyclability of Thermoplastic Parts: Grind, Re-pelletize, Re-print



Source: Herrman, Mohrdeck, & Bjekovic 2002, p. 17.

Concept Vehicle in Less than 2 Months

LM3D Series v1

LM3D

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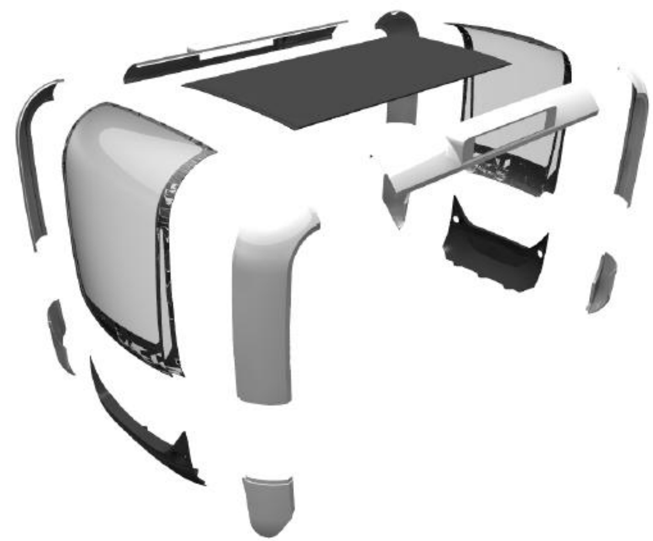
Olli Autonomous Transportation System

Olli Manufacturing Details

- 11 Parts Directly 3D Printed with CF/ABS.
- 15 Thermoforming Molds in 5 Days.
- Conventional Composite Exterior Panels.

Direct Additive Parts

Thermoformed ABS



Composite Panels

IACMI Phase I Project

BAAM Materials Development and Reinforcement with Advanced Composites

Objective 1:

- Develop a Fundamental Understanding of Printability
- Explore New Materials for Vehicle Structures
- Build Database of Printable Materials

Objective 2:

- Perform Structural Testing of Printed and Reinforced Sub-Components
- Generate Data for Verification of Structural Models (Simulation planned for Phase II)

Official Start: Oct 2016

Cincinnati BAAM Large Scale Additive

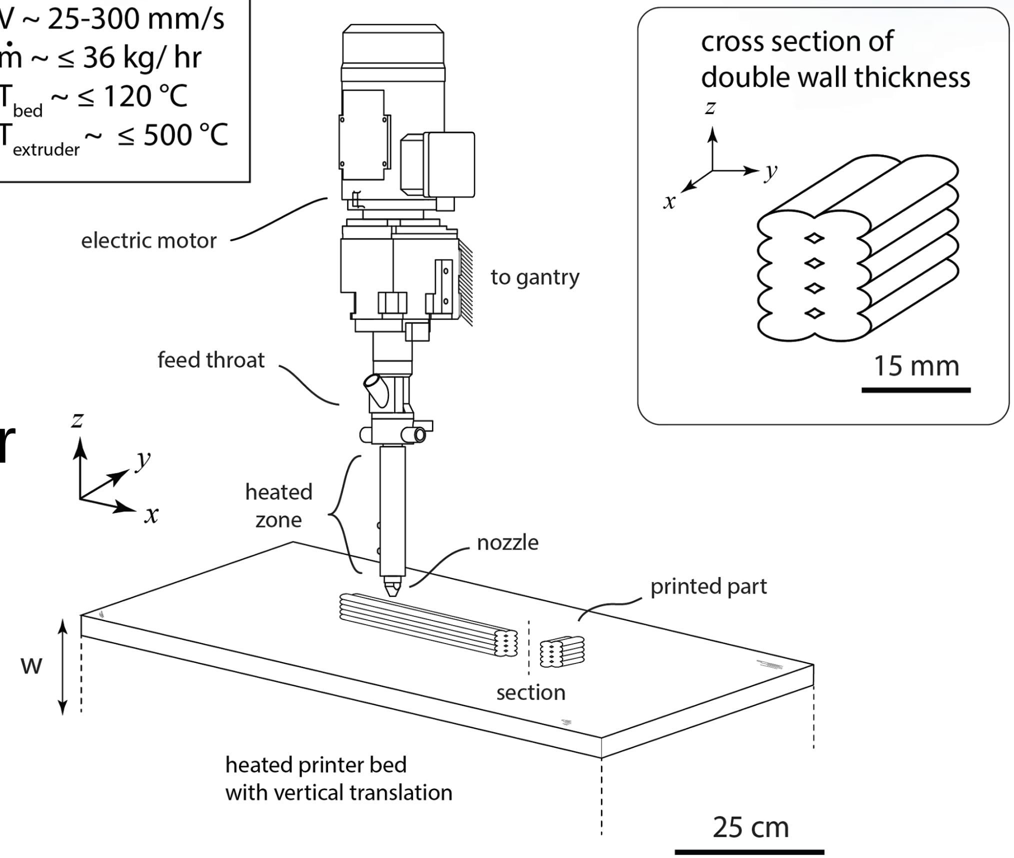
Operating Three Machines Today

Phoenix, Knoxville, National Harbor

Extrusion Deposition Process

- Pellet Feed System
- Single Screw Extruder
  - 5 Zone Temperature Control
  - 24:1 L/D
- X, Y, Z Gantry Manipulator
- Dynamic Speed Control
  - Match Pump RPM to Linear Velocity
  - Starts/Stops
  - Accelerations

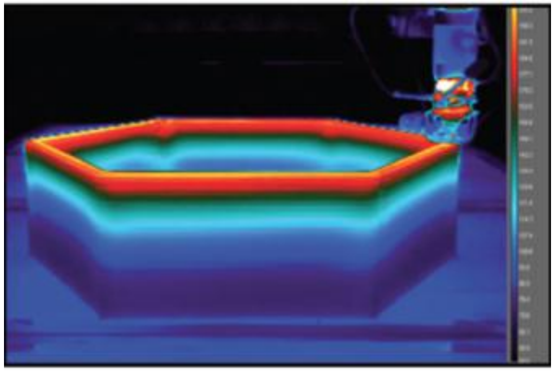
$V \sim$ 25-300 mm/s
$\dot{m} \sim \leq$ 36 kg/ hr
$T_{bed} \sim \leq$ 120 °C
$T_{extruder} \sim \leq$ 500 °C



New Materials Evaluation

Initial Evaluations Performed:

- 60+ Different Materials (6/16)
- Hexagon Print Samples
- Thermal Data on All Prints
- Notes on Printability
- 12 Selected for Rheology and TMA
- X and Z-Direction Tension Tests In-work



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New Materials Evaluation

BASF

- 18 Different Compounds
  - Polyamides
  - Carbon and Glass Fiber Reinforced
    - Ranged from 0-40% Fiber
    - Hybrids CF + GF
- Mineral Fillers

New Materials Evaluation

Sabic

- 10 Different Compounds
- Carbon and Glass Fiber Reinforced
  - ABS
  - Polyphenylene Oxide (PPO)
  - Polycarbonate (PC)
  - Polymer Blends

New Materials Evaluation

Techmer ES

- 20+ Different Compounds
- Carbon and Glass Fiber Reinforced
    - Including Recovered CF
- 20%CF/ABS (baseline, UV stable)
    - Recycled CF/ABS
        - Re-pelletized Regrind, Blended %s
- Polycarbonate (PC)
- Polyamides (PA6; PA6,12)

TECHMER ES ENGINEERED SOLUTIONS

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New Materials Evaluation

Eastman

- 8 Different Compounds
- Co-polyesters (Amphora)
    - Unfilled
    - CF Reinforced
    - Glass Fiber Reinforced
    - PPG Compounded GF Reinforced

New Materials Evaluation

Tejin
- Sereebo CF/PA6

Polyone
- 20% CF/PA6,6
- 40% CF/PA6,6

Algix
- 5 Compostable Polymers

New Materials Evaluation

Aspects of Printability:

- Dimensional Stability
  - Curl Bar Deflection
  - Hexagon Corner Lifting
- Bead Width Consistency
  - Affected by Temperature Profile
  - Affected by Back-pressure Adjustment
- Starts/Stops
  - Stringer Formation
  - Gaps

Need to Develop Standard Terminology and Quantitative Evaluation Methods

Printability Illustration

Bead Thinning, some correction possible using spindle derivative gain setting on machine.

Print Gaps, insufficient tack or delay in flow.

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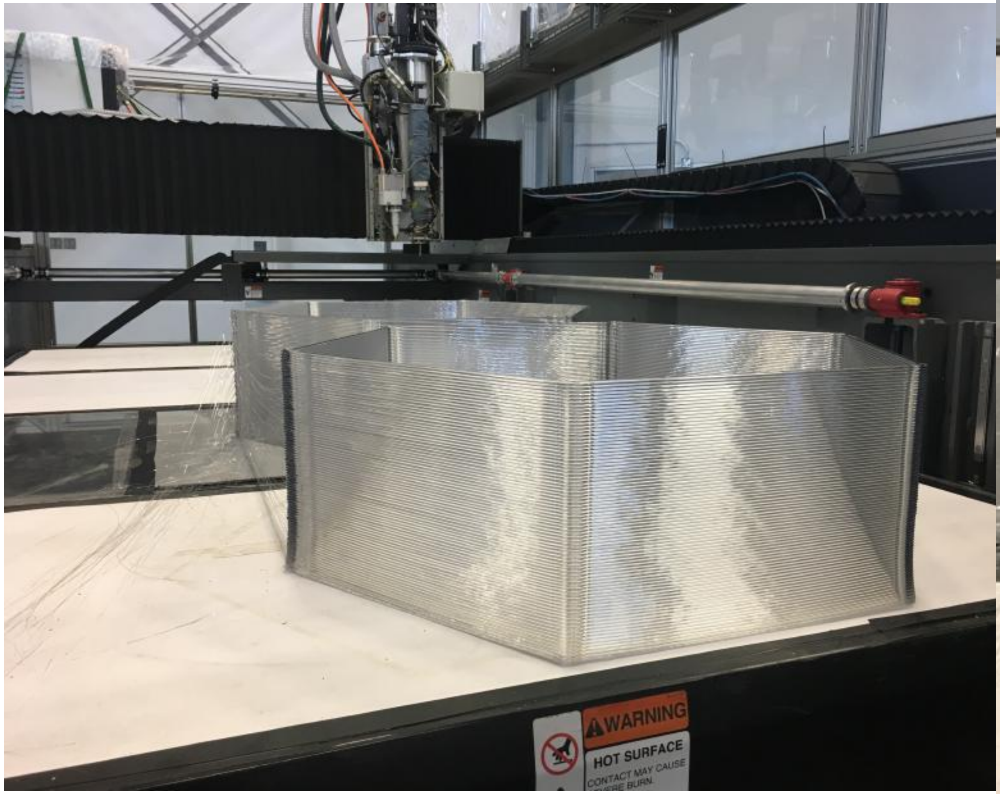
Printability Illustration

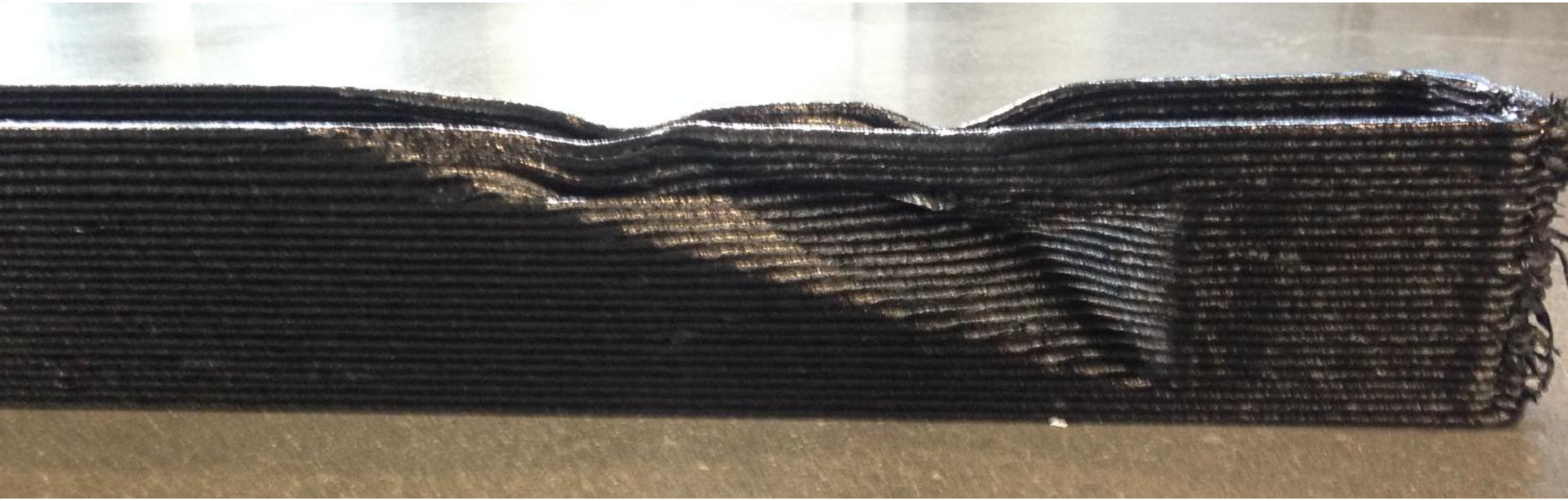
Dimensional Stability, Hexagon corner lift due to thermal effects.

Printability Illustration



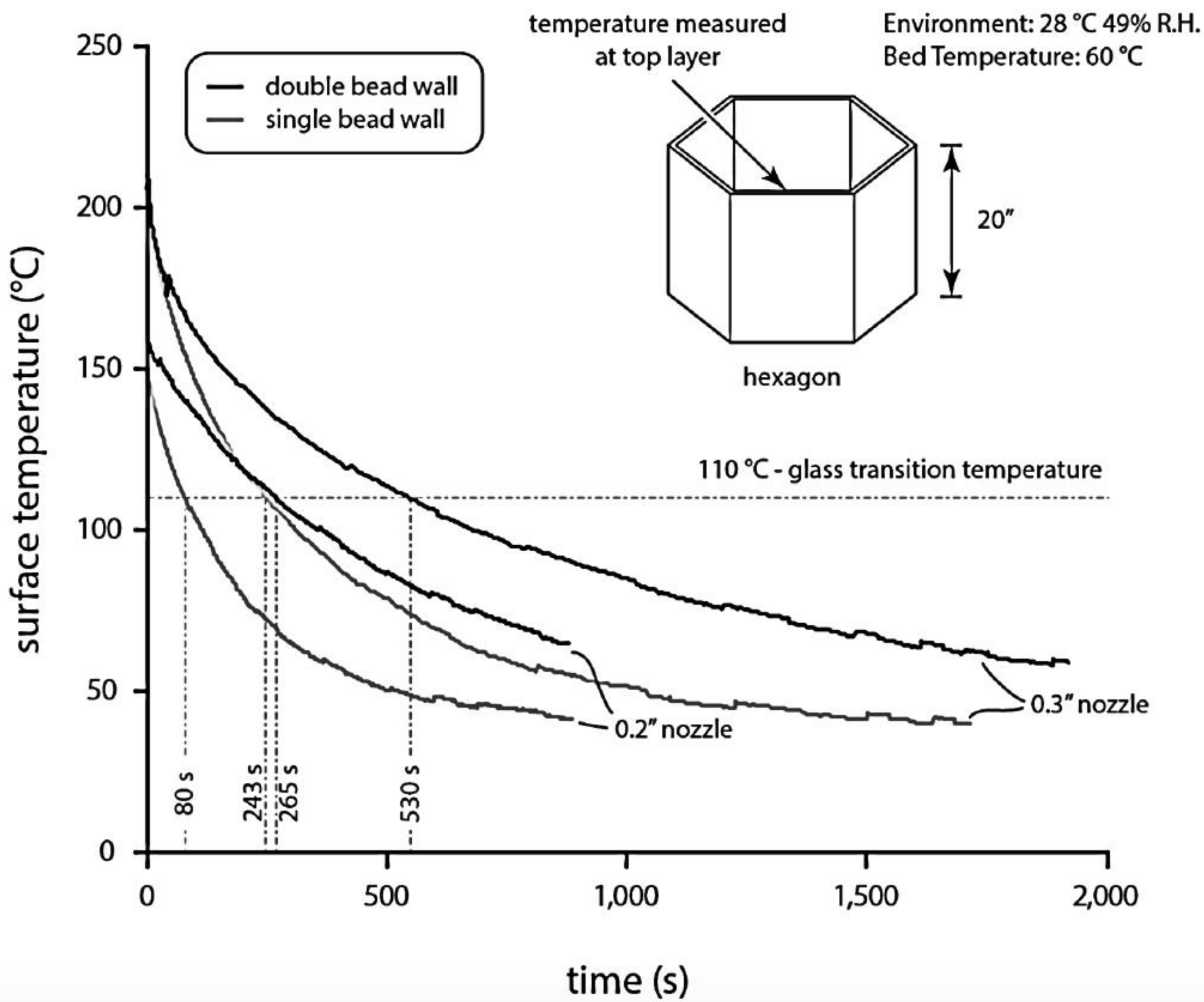
Stringers, stretching from starts/stops and pause/purge.

Printability Illustration

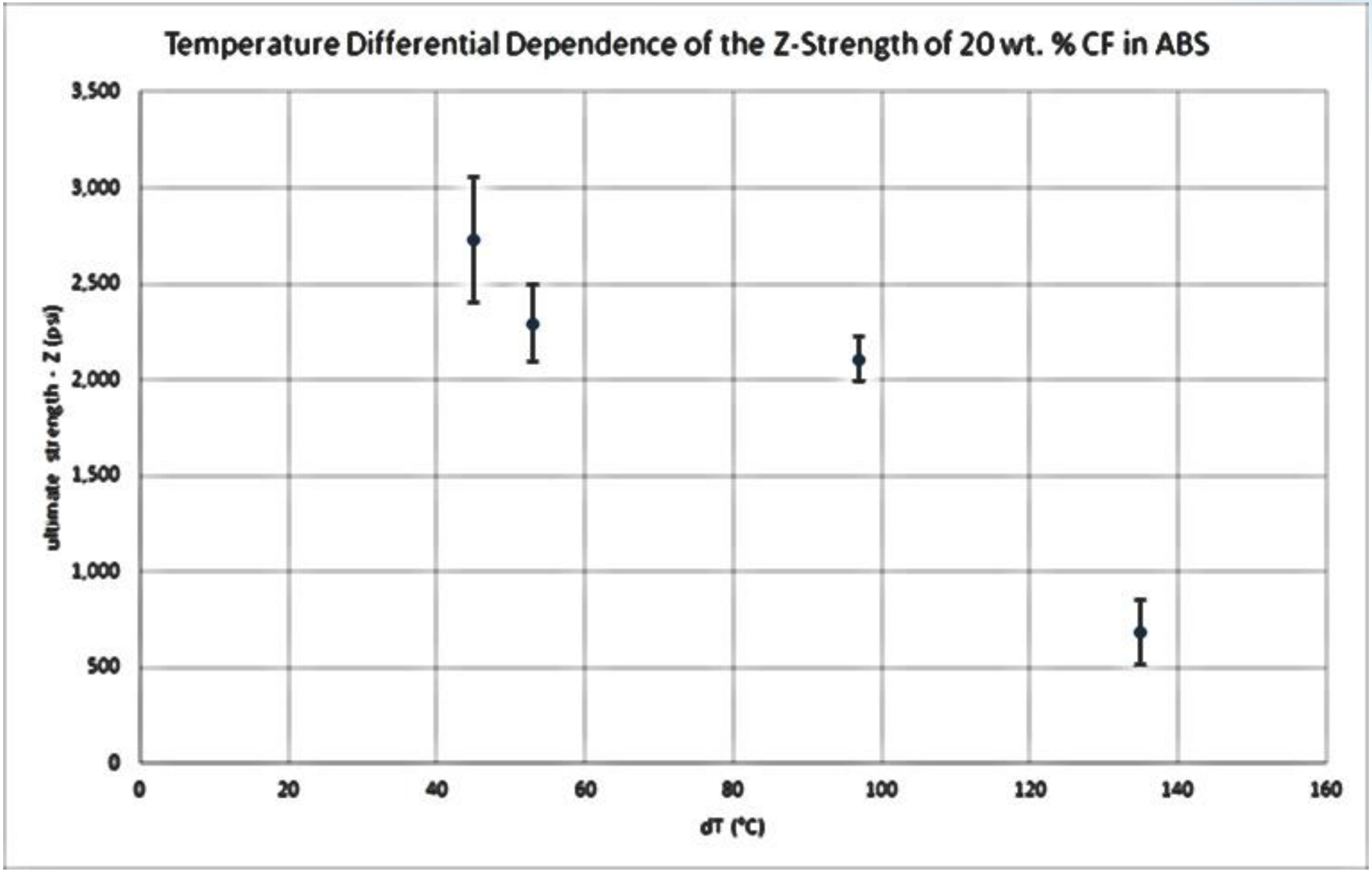


Slumping, heat retention, too low a layer time, overhang angle.

Thermal Effects



Thermal Effects

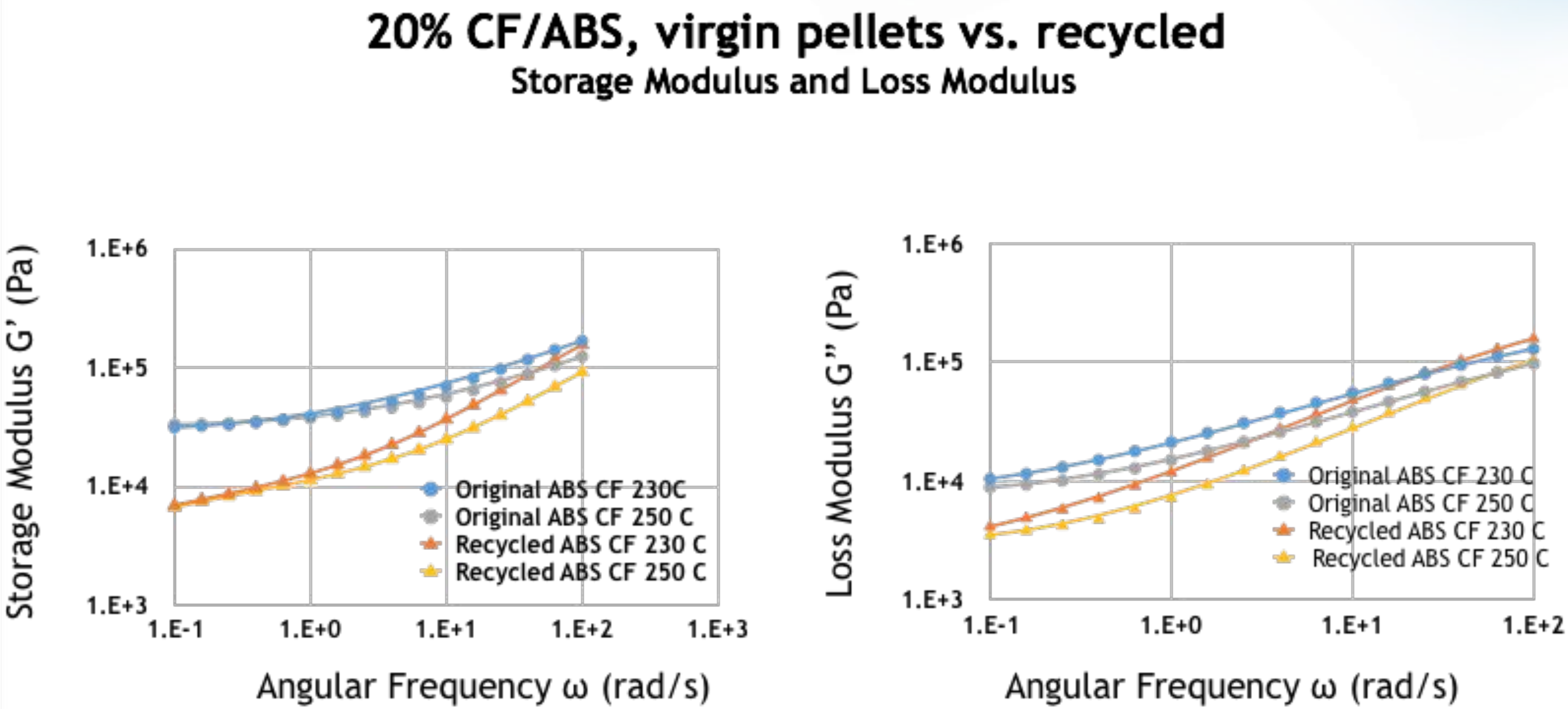


Polymer Rheology

Rheological behavior:

- Frequency sweeps were performed at the temperatures that enclose the temperature window during 3D printing process (min/max).
- 0.5 % strain amplitude was selected to ensure the material is kept within its linear viscoelastic regime.
- Time sweep test (maintain angular frequency and strain amplitude at selected isostatic temperature) is performed to monitor the material stability.
- Tests are Parallel Plate.

Polymer Rheology

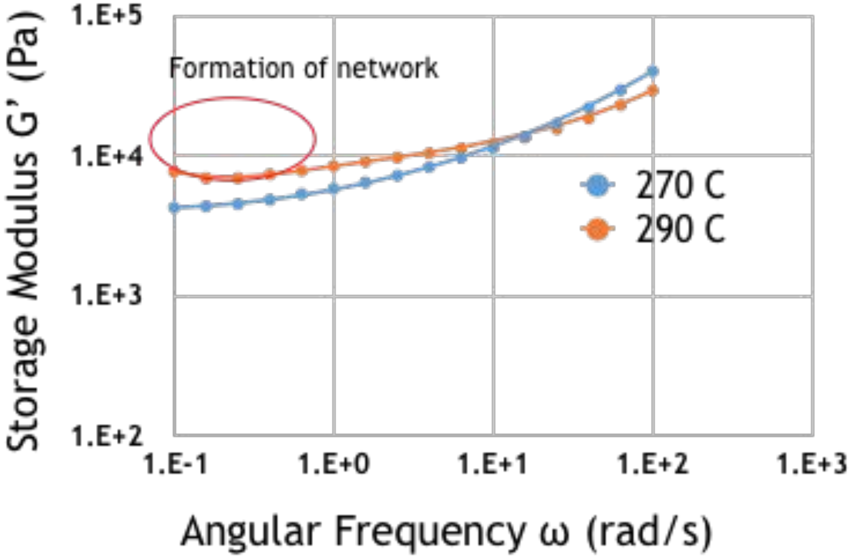


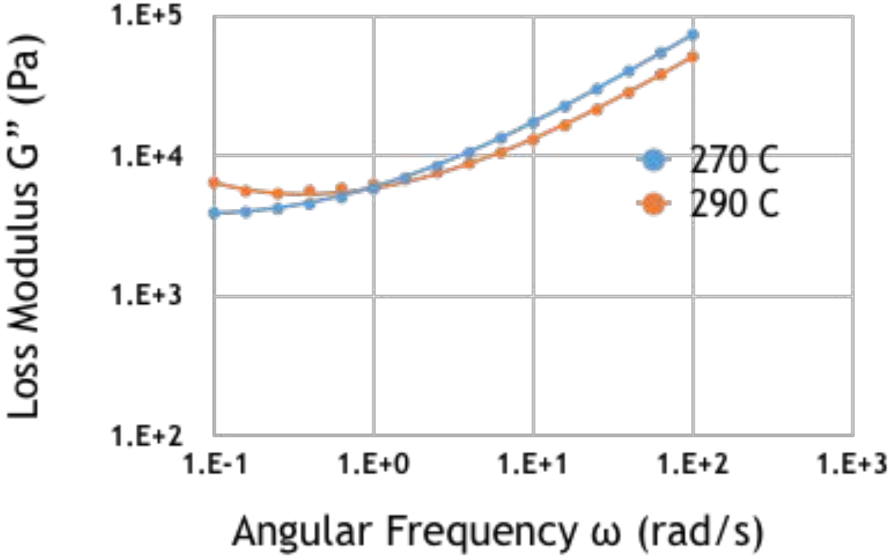
Credit: Chad Duty and Peng Liu

Polymer Rheology

CF/PA66 Storage Modulus and Loss Modulus

- Results indicate instability at 290C.

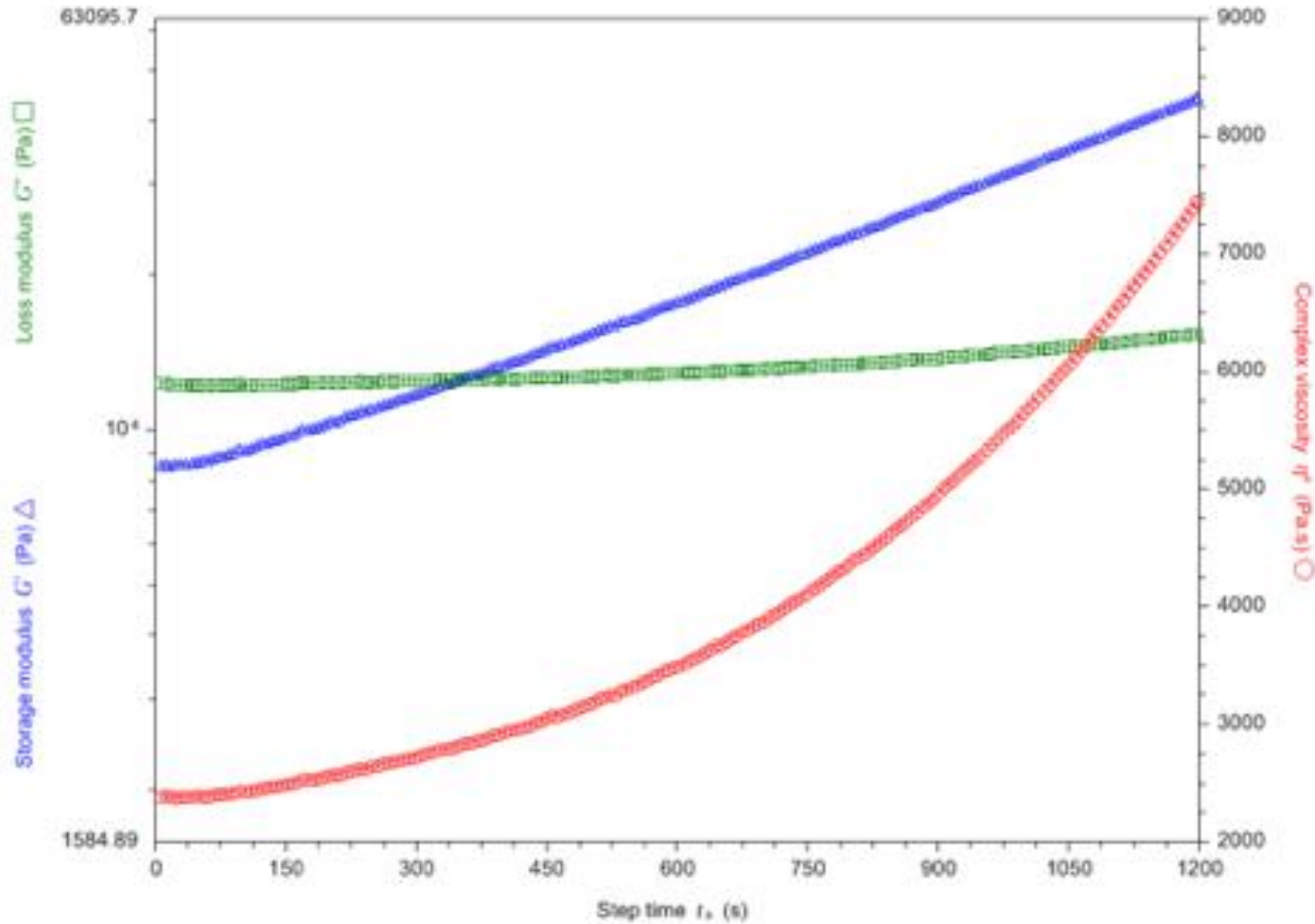




Credit: Chad Duty and Peng Liu

Polymer Rheology

Time Sweep of CF/PA66 in Air at 270



Credit: Chad Duty and Peng Liu

Mechanical Testing

- Panels from Hexagons
- Planed Surface
- Routed Dogbones
- 2X Size Type III ASTM-D-638
- Extensometer Strain

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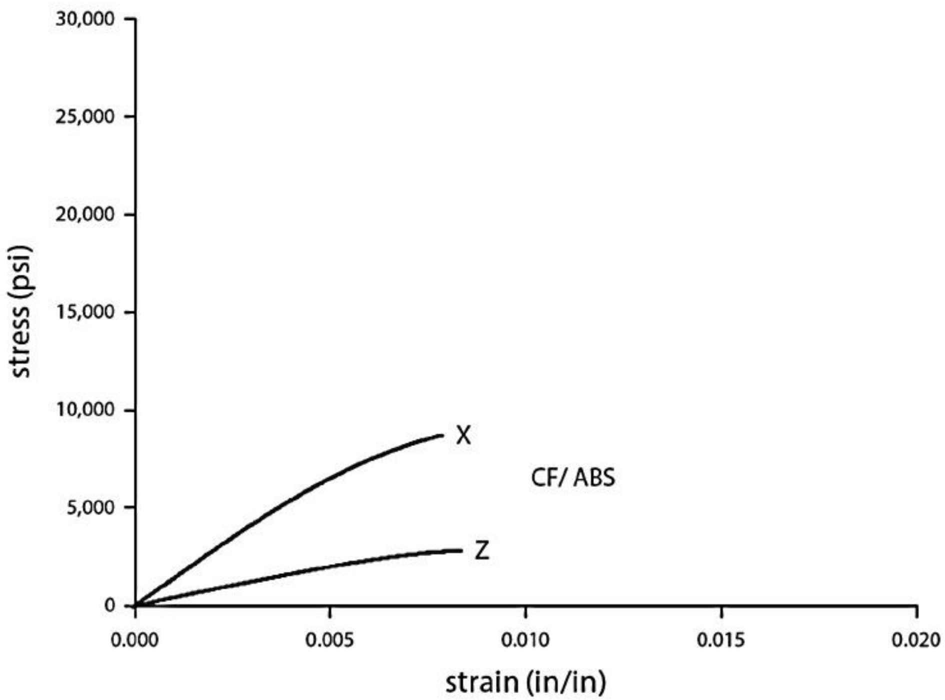
Mechanical Properties

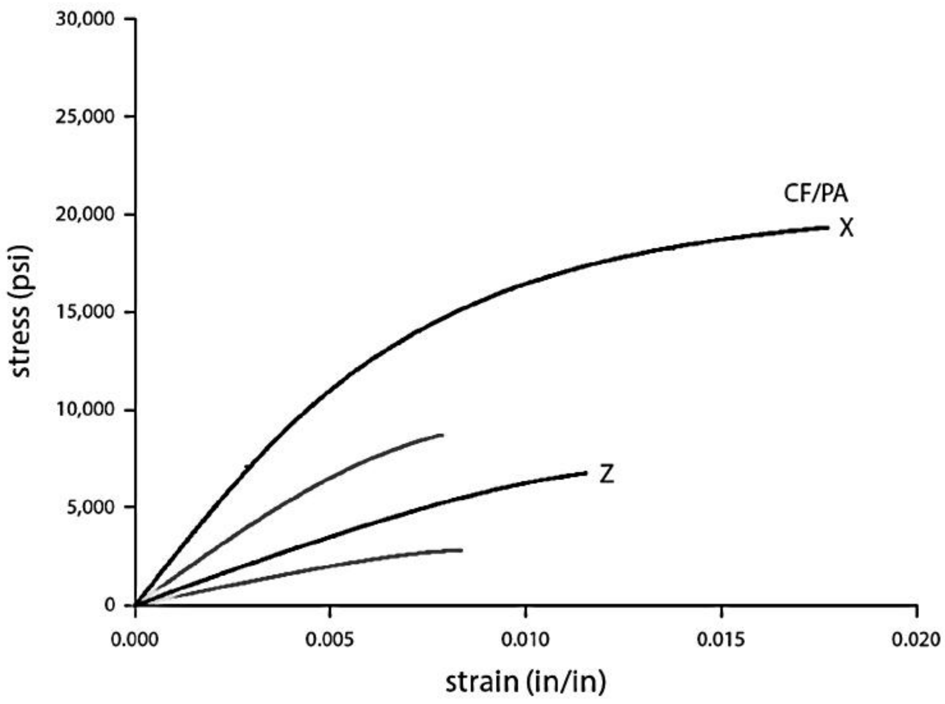
Tensile Strength and Modulus Improvements with Material



X and Z Direction Stress - Strain Curves

Mechanical Properties

Tensile Strength and Modulus Improvements with Material



X and Z Direction Stress - Strain Curves

Mechanical Properties

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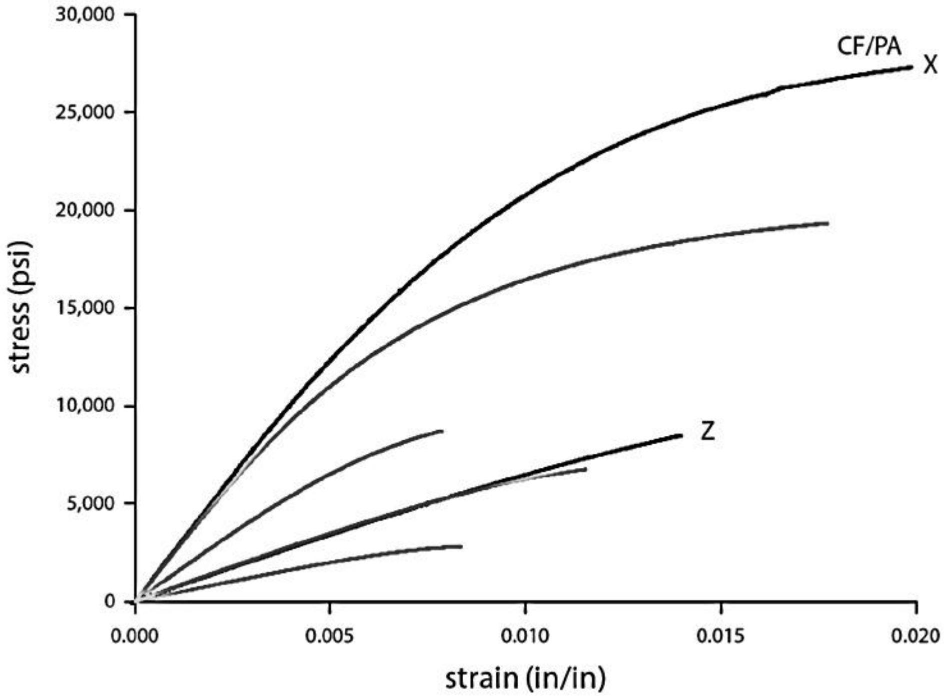
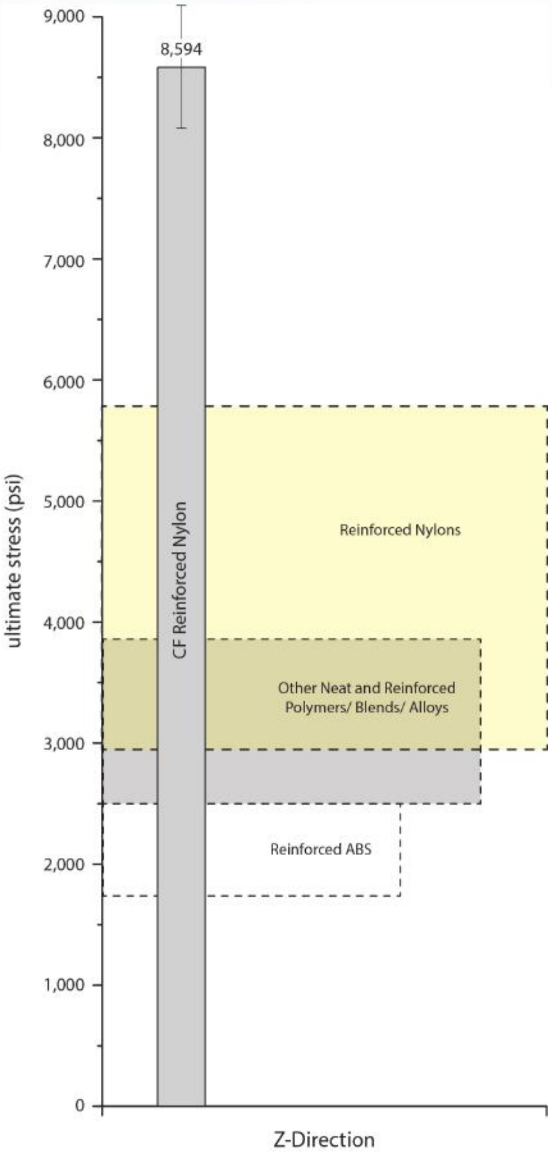


X and Z Direction Stress - Strain Curves

Mechanical Properties

Z-Direction Strengths



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Structural Sub-Component Testing

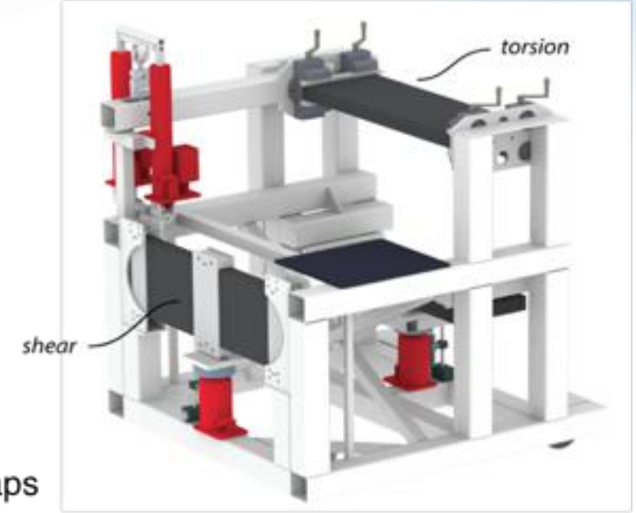
Torsion, Shear, and Bending
1’ x 3’ x 2.5” Outer Dimensions

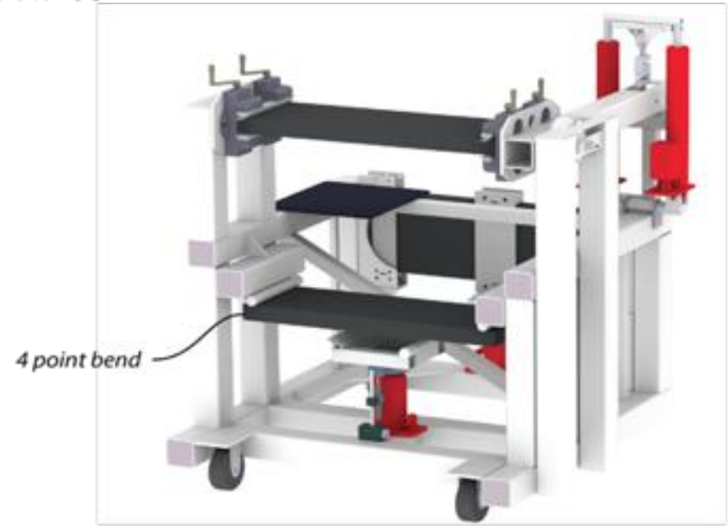
Variety of Printed Design Geometries:

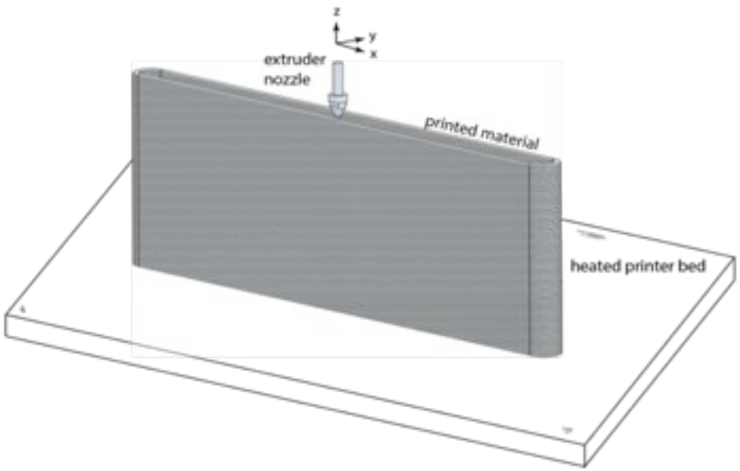
- Increasing wall thickness
- Vertical print vs flat print
- Increasing density of infill
- Manual infill patterns
- Variety of surface features

Reinforcement Methods:

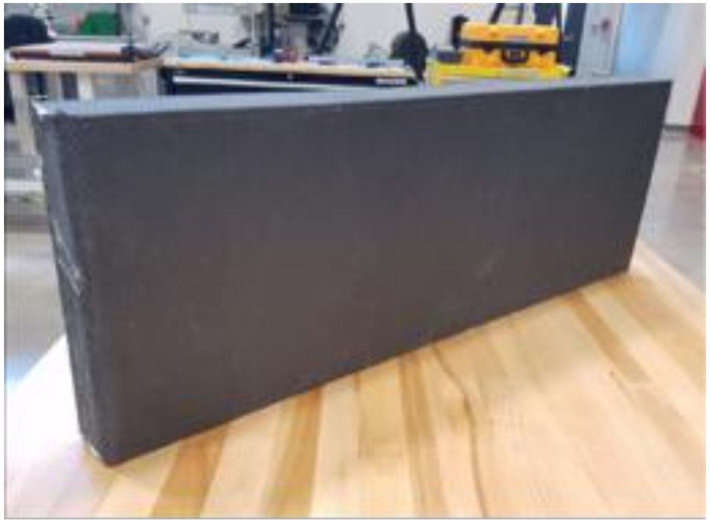
- Structural Foam Fillers
- Composite and Metallic Inserts
- Carbon Fiber Inlays and Over Wraps
- Printed Internal Support Structures

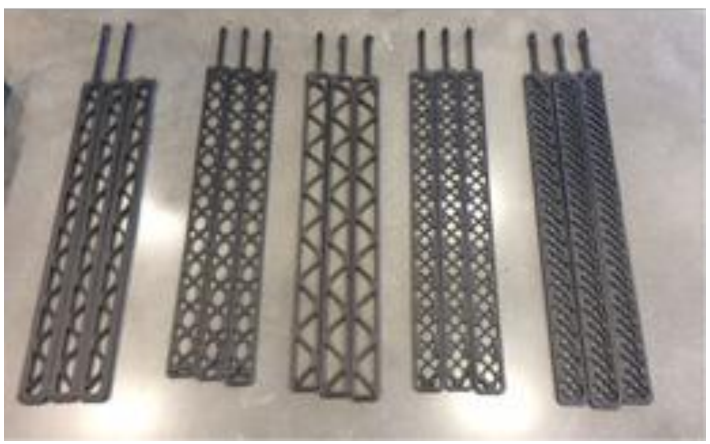






Structural Sub-Component Designs





Completed Testing 34 Different Box Designs
Total of 102 Individual Tests

Aluminum Boxes for Baseline
Hollow and Foam Filled

Results to be used to calibrate and verify FEA models in phase II

Structural Sub-Component Designs

Foam Filling

Metal Reinforcing Insert

Flat Printed Boxes

+/-45 Warped

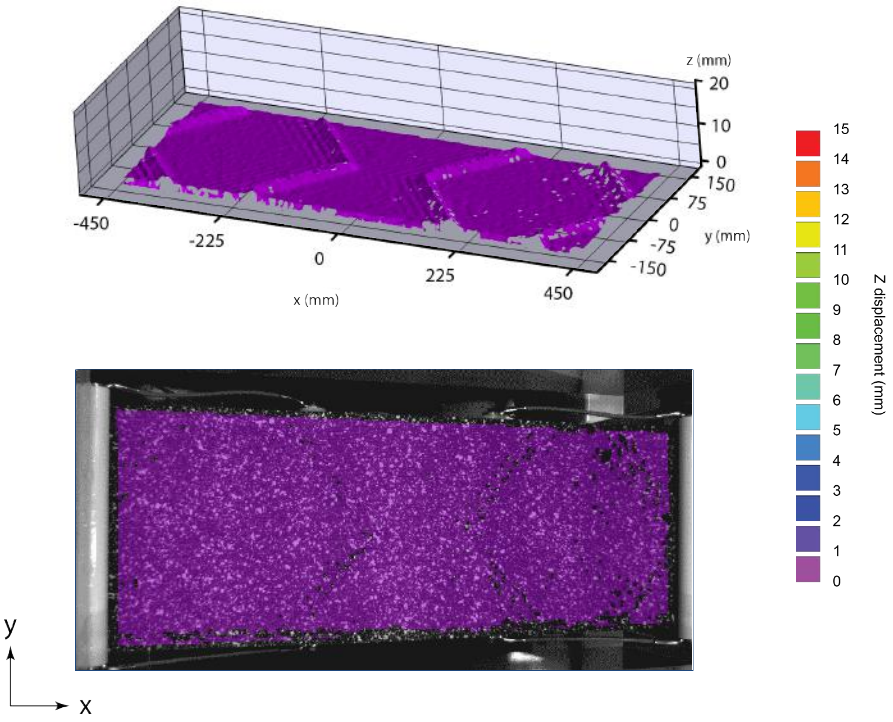
Structural Sub-Component Construction

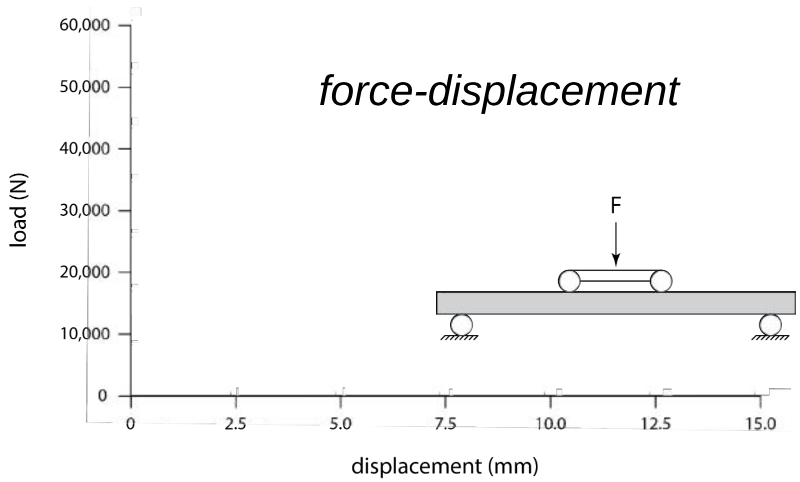
Over-Wrapped and Resin Infused

- 2-ply and 4-ply Carbon Fabric (2x2 3k Twill AS4)
- 2-ply and 4 ply 1.5 oz Fiberglass Mat
- Elium PMMA Reaction Infusion Thermoplastic

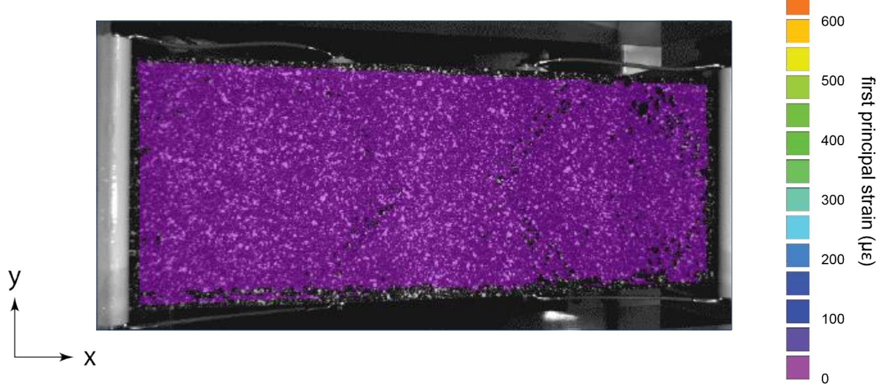
Structural Sub-Components: Bending

change in z-direction displacement, w

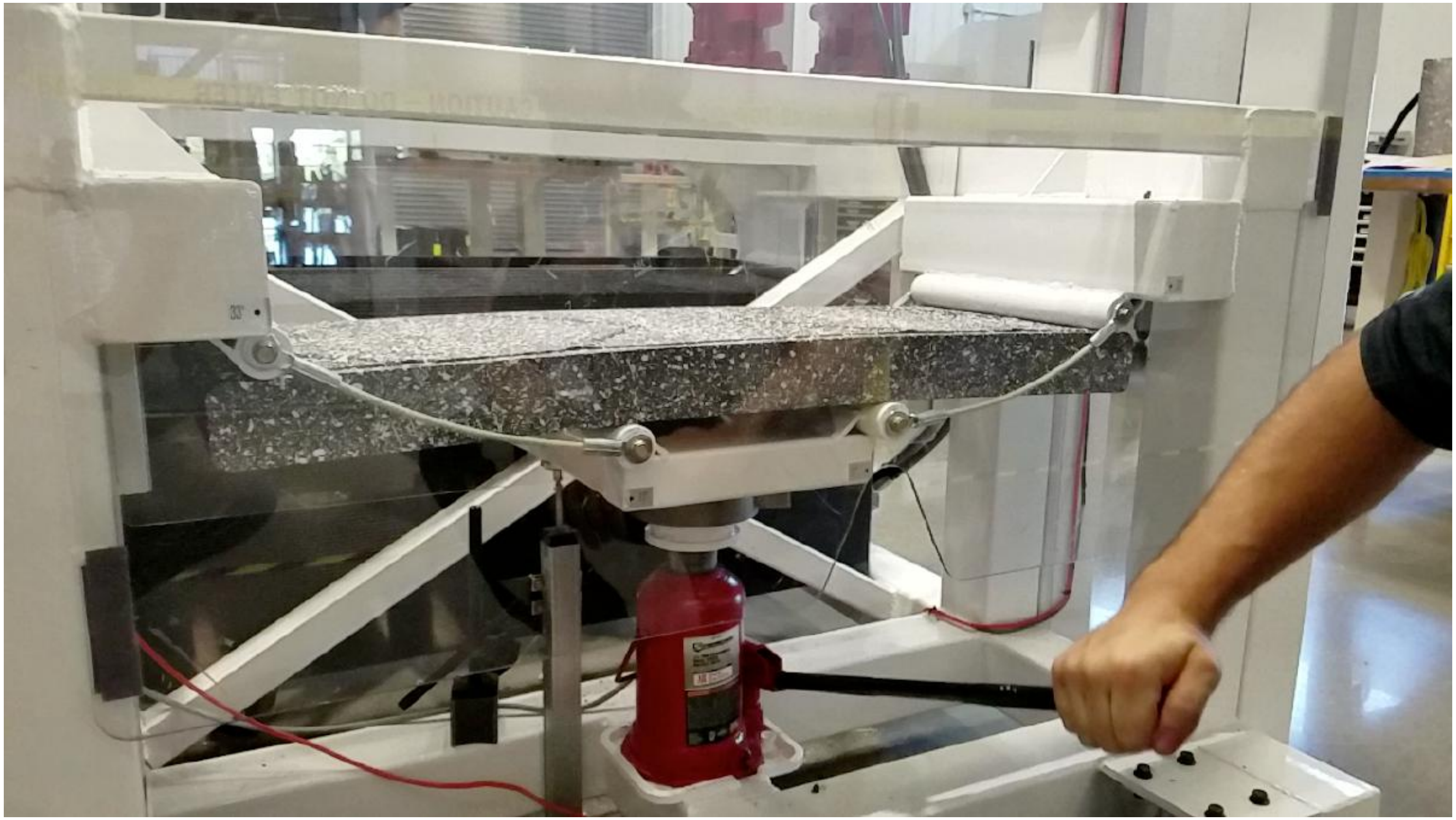




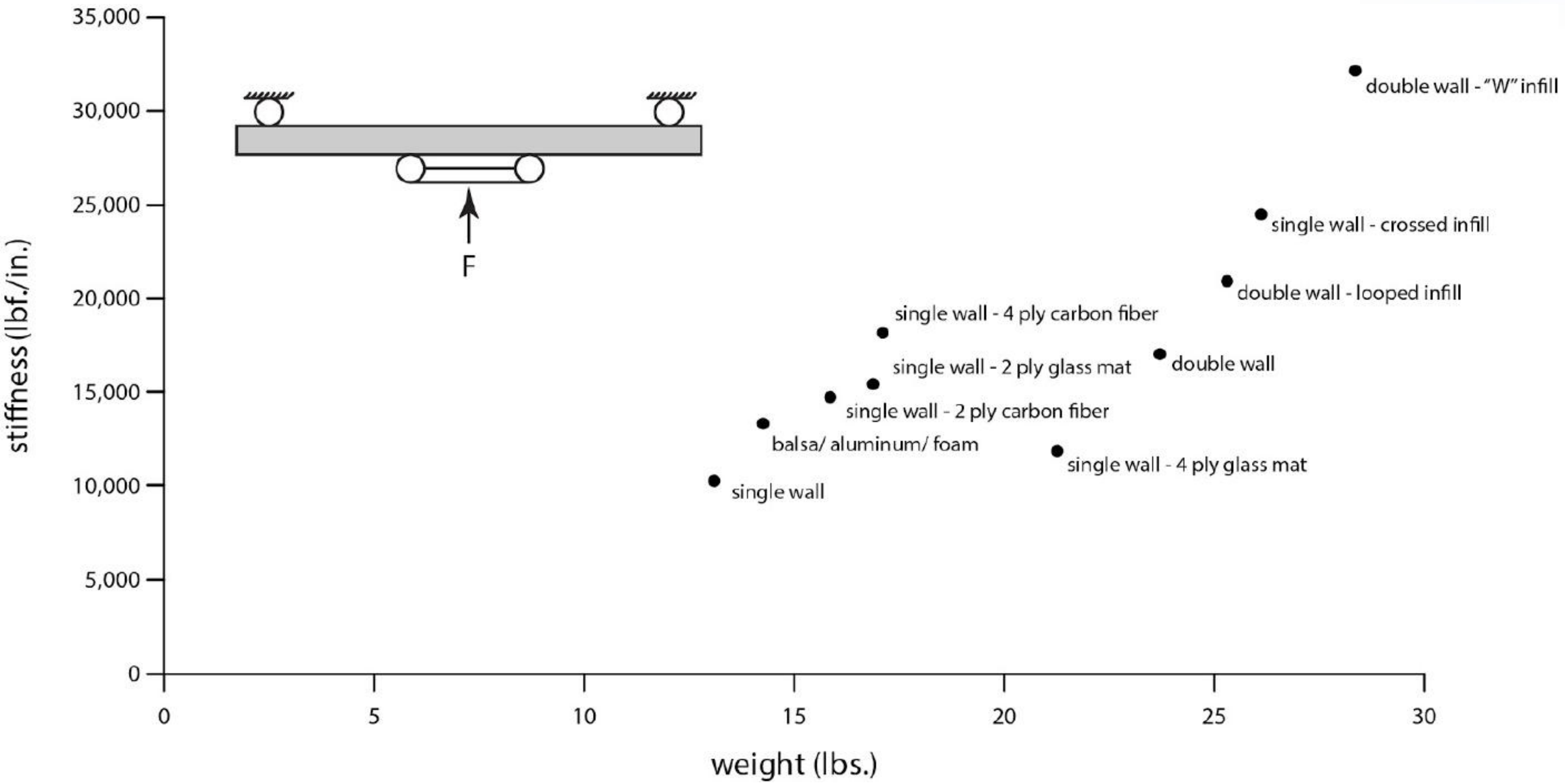
1st principal strain



Structural Sub-Components: Bending



Structural Sub-Components - Bending



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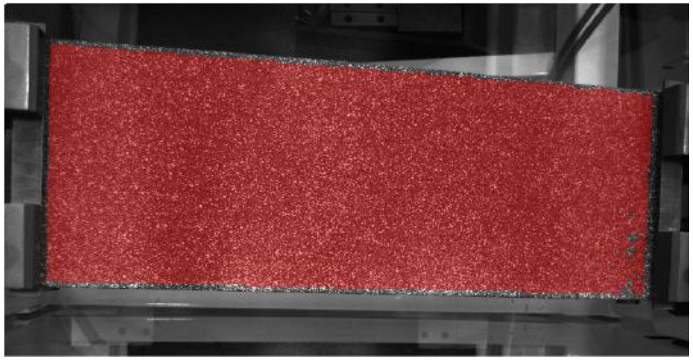
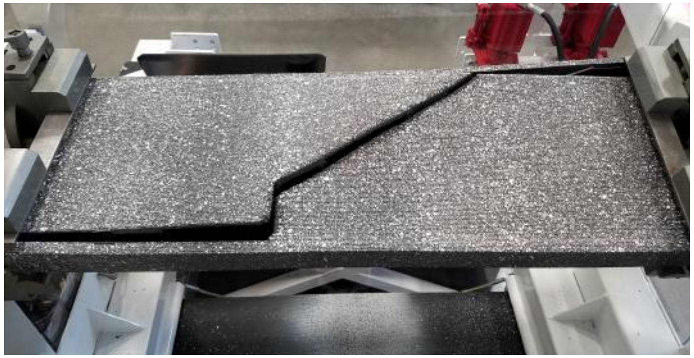
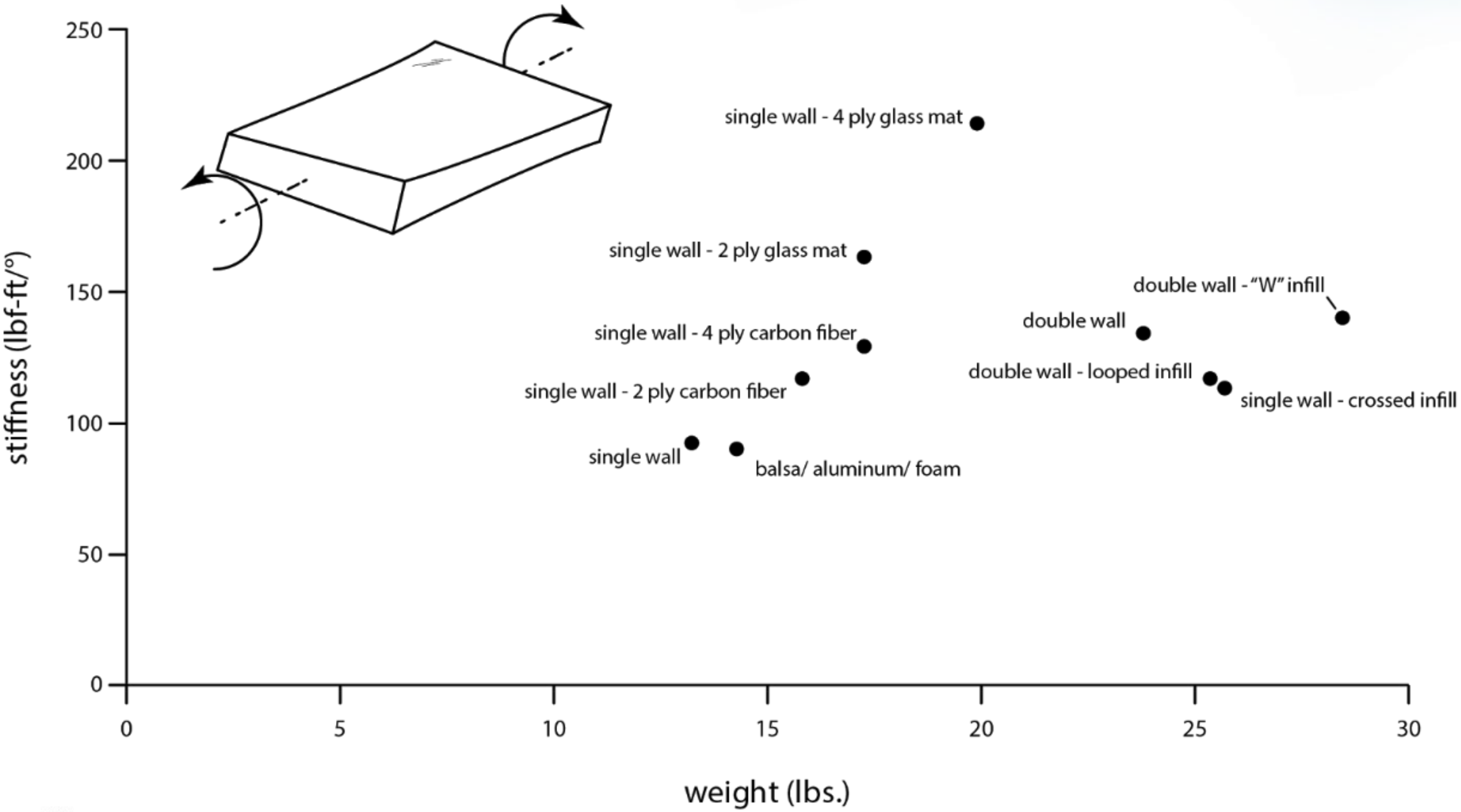
Structural Sub-Components - Torsion



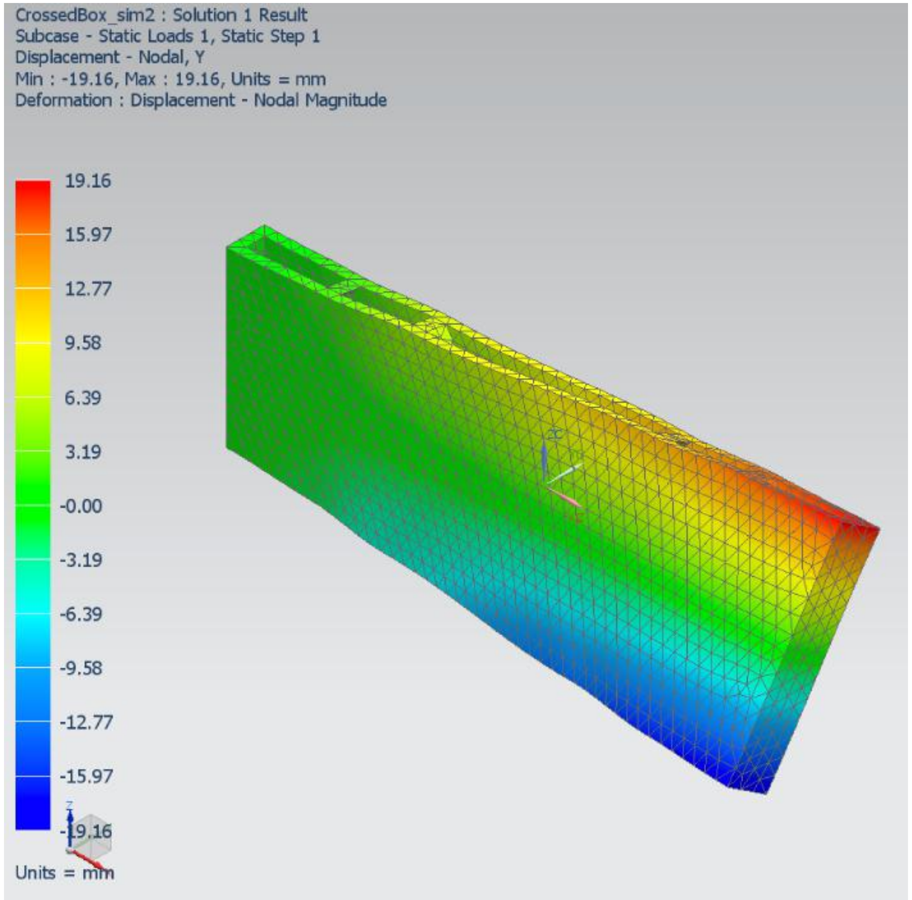
Development of shear strain during torsion.

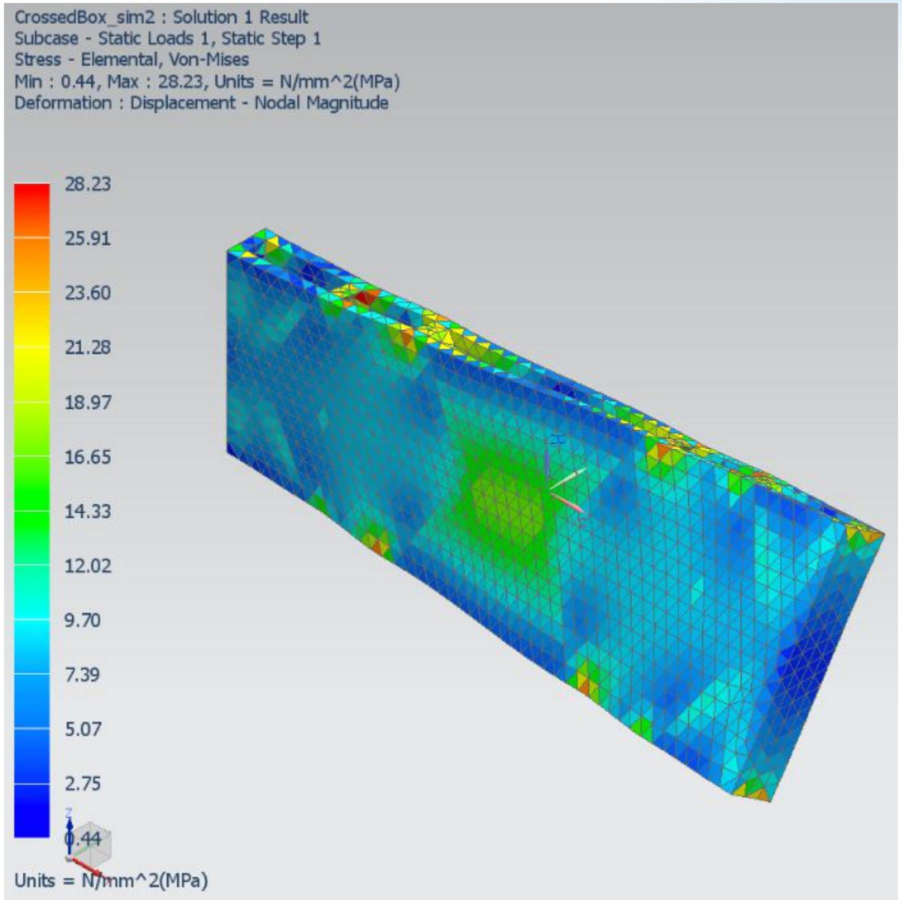


Structural Sub-Elements: Torsion Results



Structural Sub-Elements: Torsion Model





Simulated torsion test using solid elements, orthotropic properties, and global coordinate system. Working to obtain nodal orientation from G-code.

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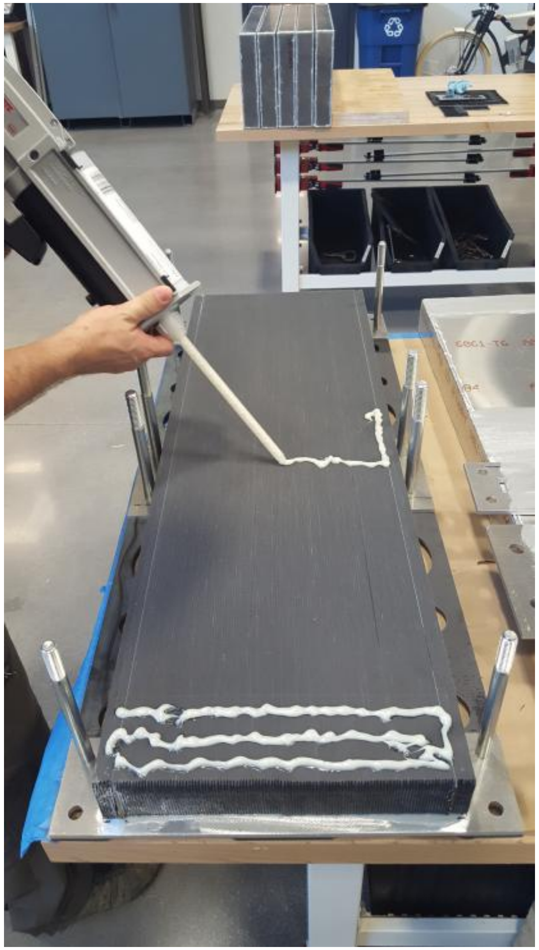
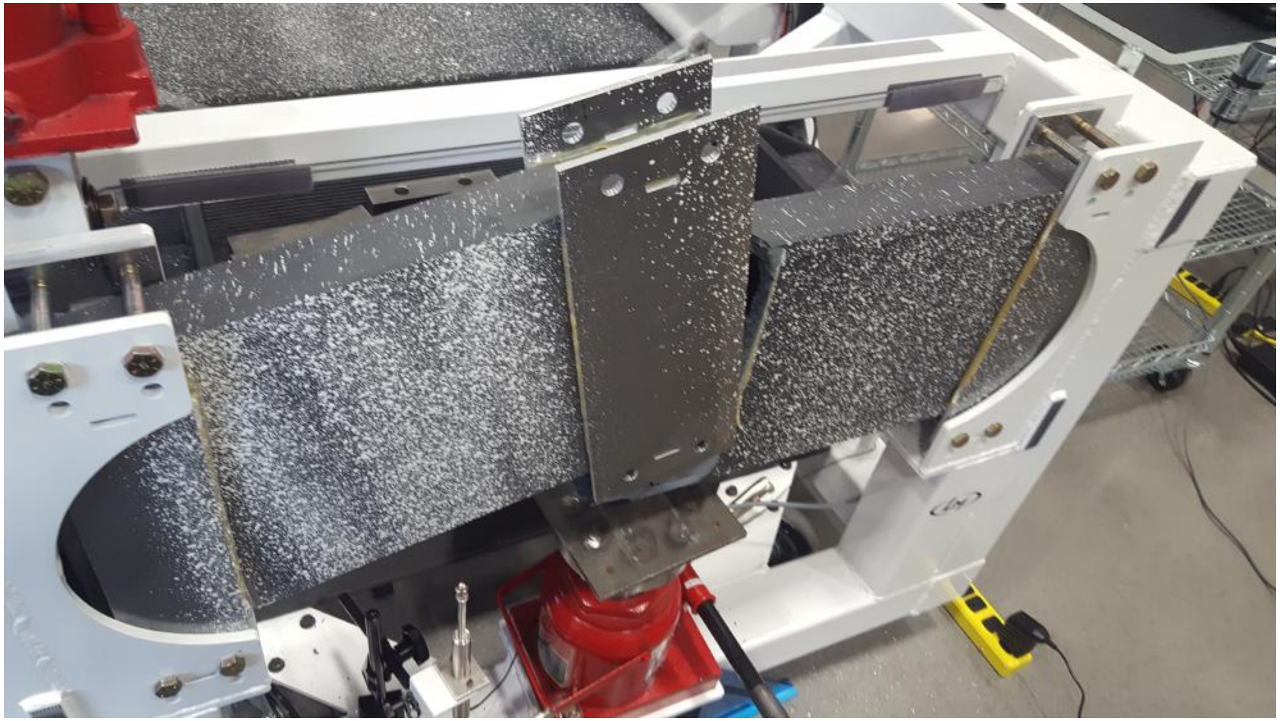
Siemens PLM Software

SIEMENS

Structural Sub-Elements: In-plane Shear



Bonding of fixture plates



Post-failure specimen shown.
Loading stopped at 25,000lbs for most specimens.
Will obtain pre-failure data.

IACMI Phase II Planning

Objective 1: Materials Development for Large Scale Extrusion Deposition Additive Manufacturing

- Continued Evaluation of New Materials Introduced after Phase I
- Further Mechanical Evaluation of Phase I Materials
- Dissimilar Material Bonding Evaluation
- Non-Destructive Evaluation and Testing
- Effects of Print Parameters on Mechanical Performance of Baseline 20% CF/ABS

Objective 2: Machine Development for Large Scale Extrusion Deposition Additive Manufacturing

- BAAM Development to Improve Inter-laminar Adhesion
- Quality Control Methods
- In-Process Monitoring

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IACMI Phase II Planning

Objective 3
Develop and Verify Simulations of BAAM Structures.

- Simulation of quasi-static testing of multi-material structural sub-components.
- Simulation of residual stress and deformations due to print process.
- Simulation of dynamic testing of multi-material structural sub-components.
- Dynamic testing of printed structures. (ORNL TMAC)
- Apply Laystitch preforming technology to the composite overwrap process.

Thank You

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