MEASURING THERMOMECHANICAL RESPONSE OF LARGE-FORMAT PRINTED POLYMER COMPOSITE STRUCTURES VIA DIGITAL IMAGE CORRELATION

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PCAM Polymer Composite Additive Manufacturing

OAK RIDGE National Laboratory

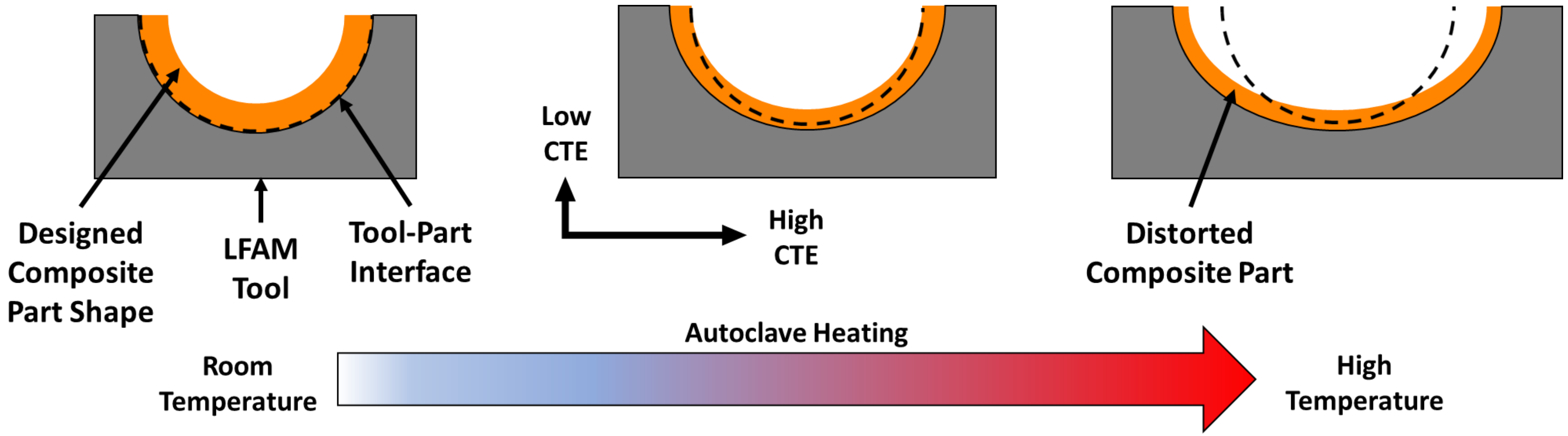
Overview Moving Forward

- Background
- Materials for Study
- TMA Testing
- DIC Oven Testing
- Predictive Modeling
- Conclusions

DIC Oven at the University of Tennessee

Large-Format Additive Manufacturing

- Large-Format AM (LFAM) is advantageous for tooling applications[1]
- Big Area Additive Manufacturing (BAAM) and other LFAM type systems can create large complex parts using Fiber Reinforced Polymer (FRP) feedstock
- The use of FRP feedstock lowers material costs, increases part stiffness, & lowers coefficient of thermal expansion (CTE)[2]
- LFAM tools may still experience warpage at autoclave conditions



1. Duty et al., 2015, DOI: 10.2172/1209207
2. Love et al., 2014, DOI:10.1557/jmr.2014.212

What leads to this warpage?

Structural Hierarchy of LFAM

Macrostructure

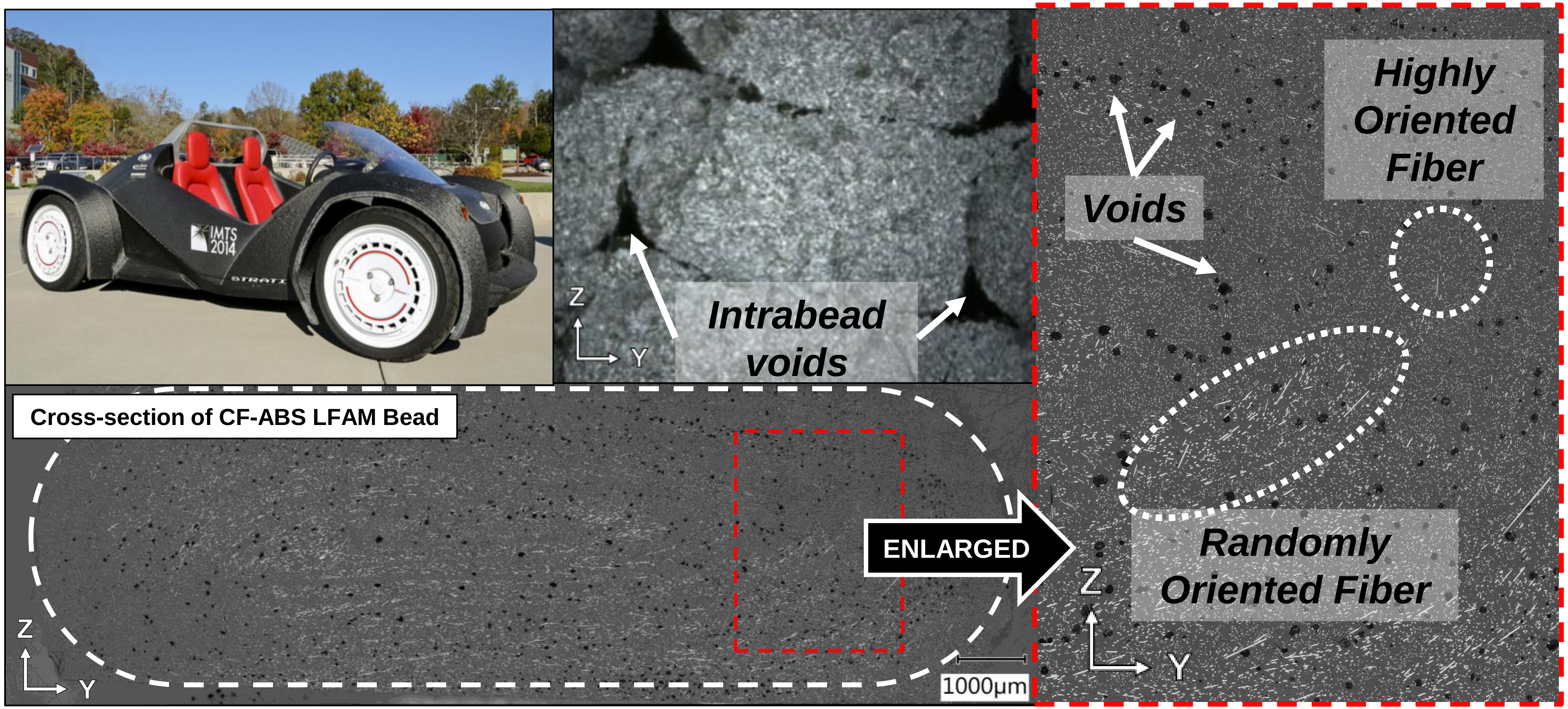
Behavior of structure as a whole

Mesostructure

Interaction of layers/beads

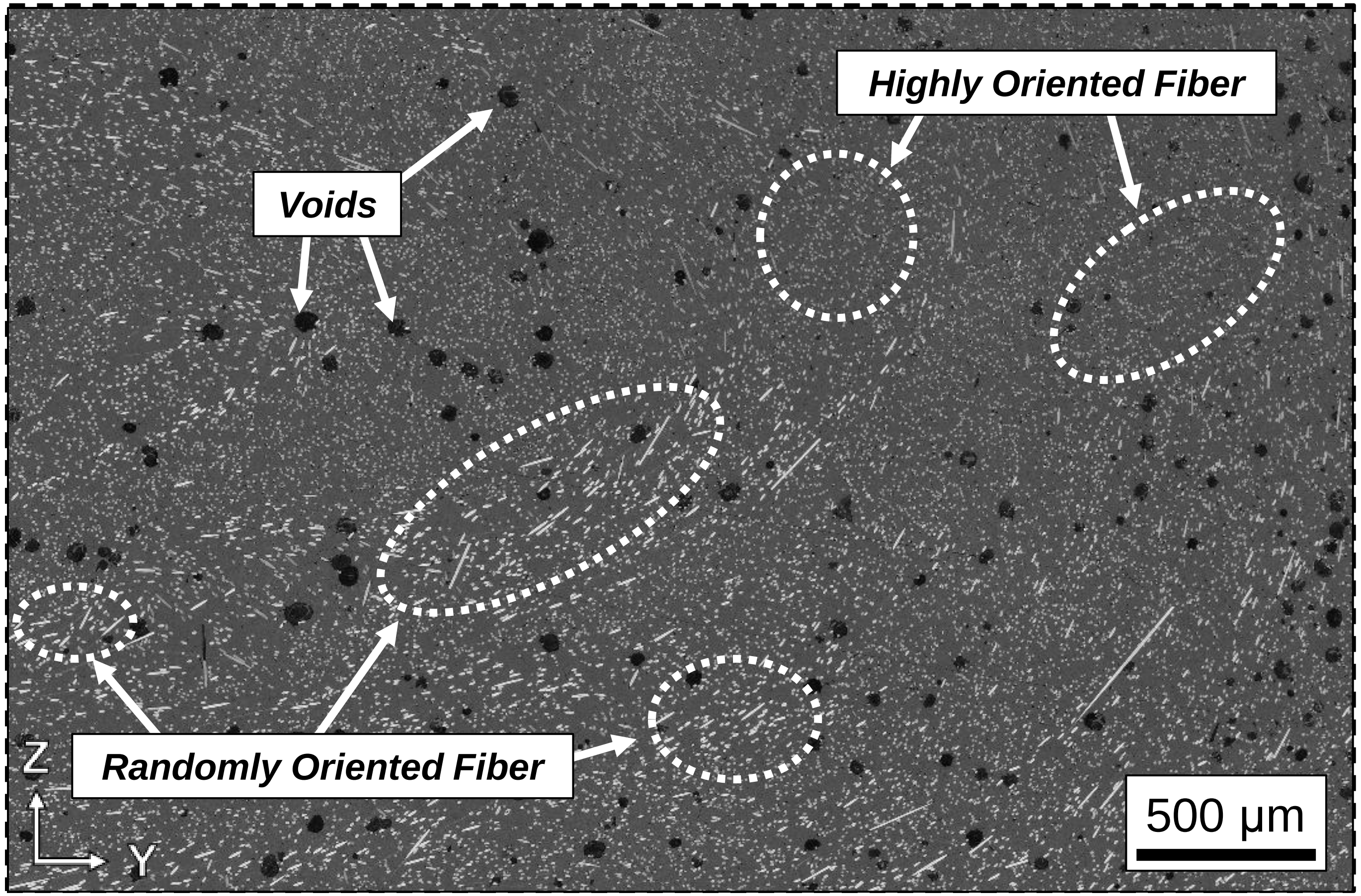
Microstructure

Arrangement of fiber & porosity within bead



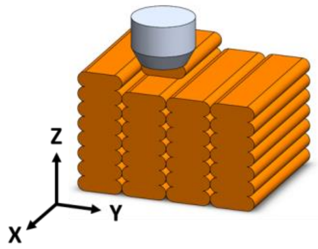
Non-homogeneous Microstructure

- Varying fiber orientation results in a nonhomogeneous microstructure
- Fiber orientation & void distribution varies across bead
- Properties are **dependent on location** within the bead



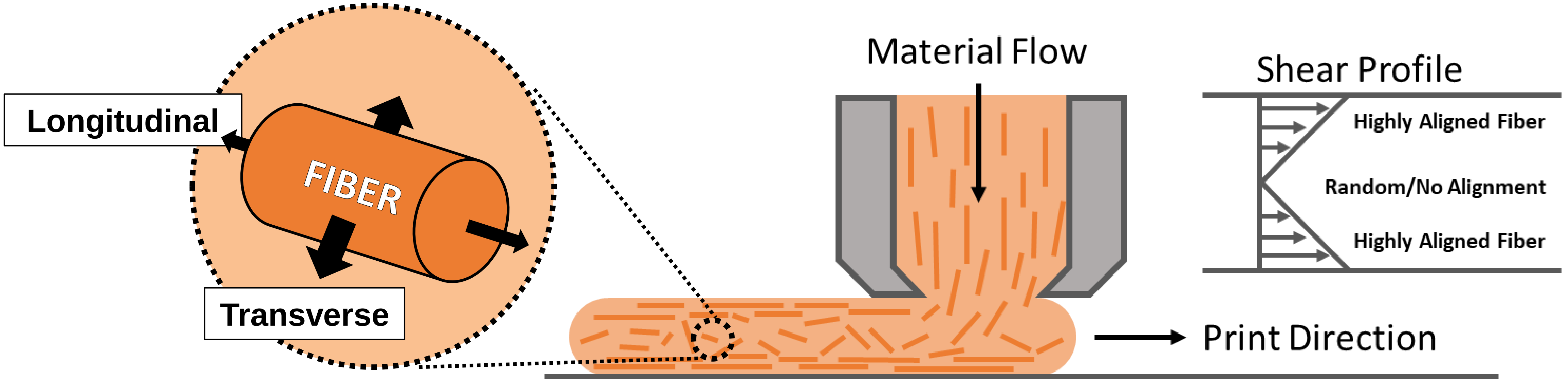
CF-ABS bead printed via LFAM

Fiber Orientation



Fiber Reinforced Polymer Composites = MATRIX + FIBER

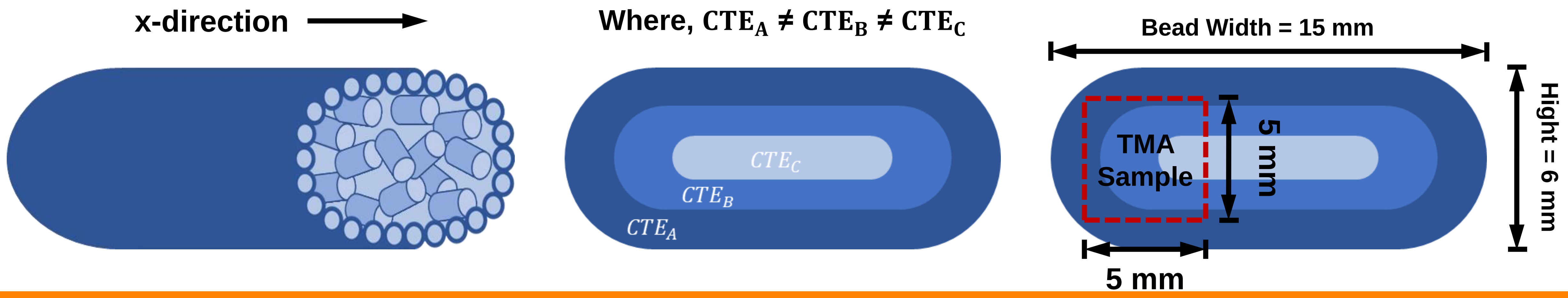
- During the extrusion, fibers are aligned by nozzle shear in the print direction[1]
- This results in highly aligned bead edge with a randomly oriented center by comparison[2]
- Anisotropic fibers resist expansion more (over 10x) in the longitudinal than transverse direction
- Properties are **dependent on fiber orientation**



1. Hassen et al., 2022, DOI: 10.1002/pc.26645
2. Colón Quintana et al., 2022, DOI: 10.3390/ma15082764

Traditional CTE Measurement

- Thermomechanical Analysis (TMA) traditionally used for CTE measurements
- Highly accurate test
- TMA measures a small specimen (max 10 mm x 10 mm x 10 mm)[1]
- Assumes isotropy, homogeneity
- Struggles to accurately measure LFAM printed FRP



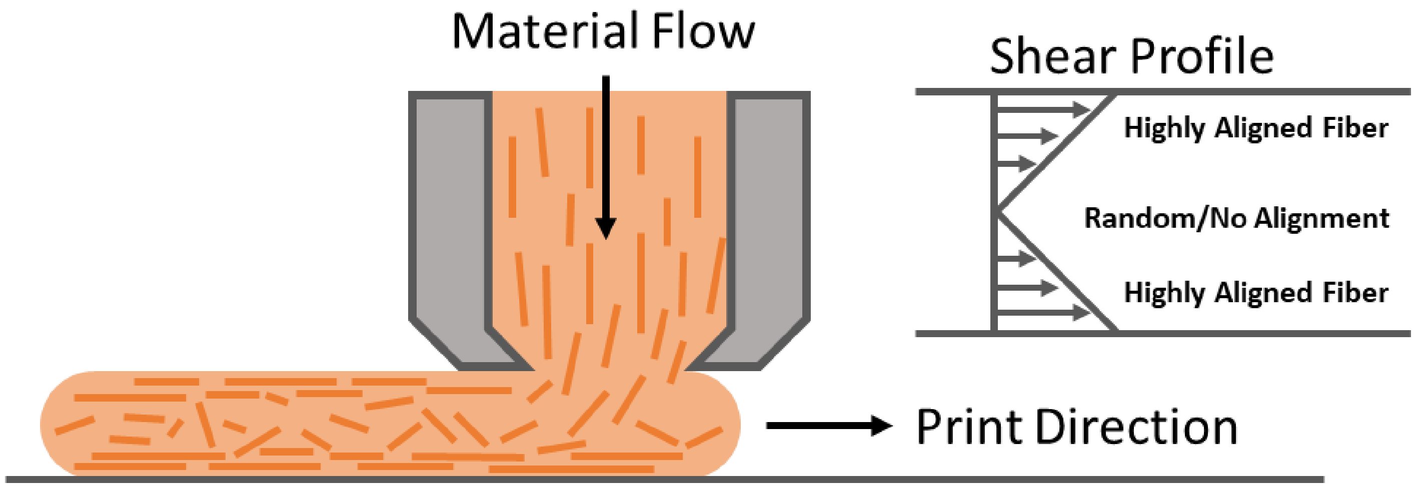
1. ASTM E831, DOI: 10.1520/E0831-19

Due to complex microstructure of LFAM, we need a better way to measure these parts…

Digital Image Correlation

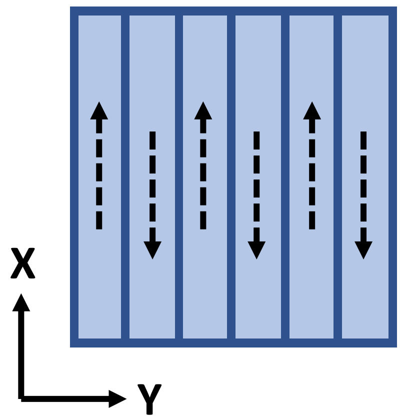
Objectives

- Observe dependence of CTE on direction & location using TMA
- Measure global response using DIC & compare results to (local) TMA values
- Develop predictive model that incorporates degree of fiber orientation & validate using the DIC Oven

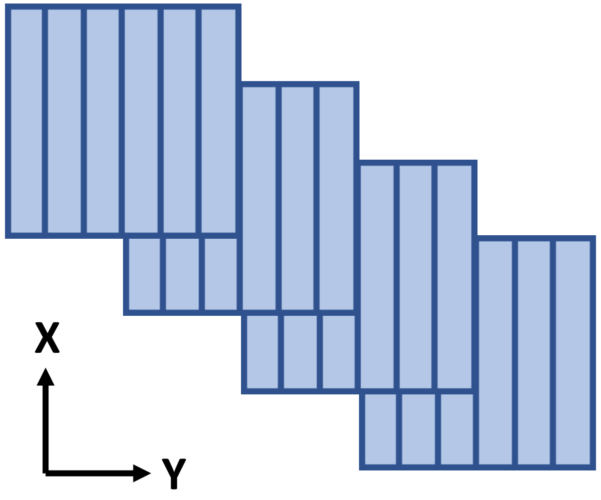


Materials for Study

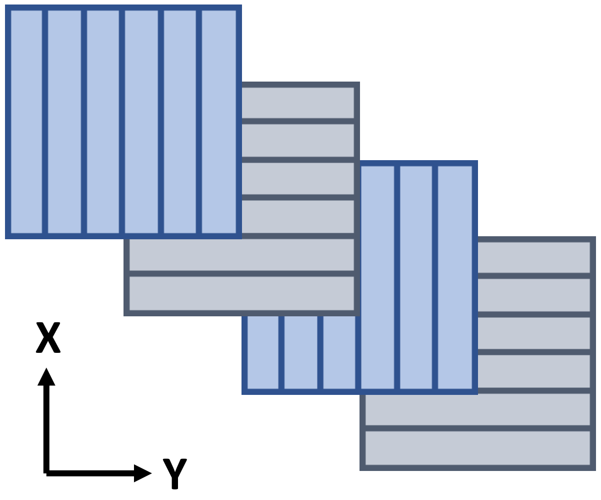
- 20% wt. carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS) feedstock
- Printed using Big Area Additive Manufacturing[1] (BAAM)
- Bead geometry: 15 mm x 6 mm
- Printed 0-0 and 0-90 layer orientation



"Serpentine" Toolpath taken by the printer



0-0 Layer Orientation

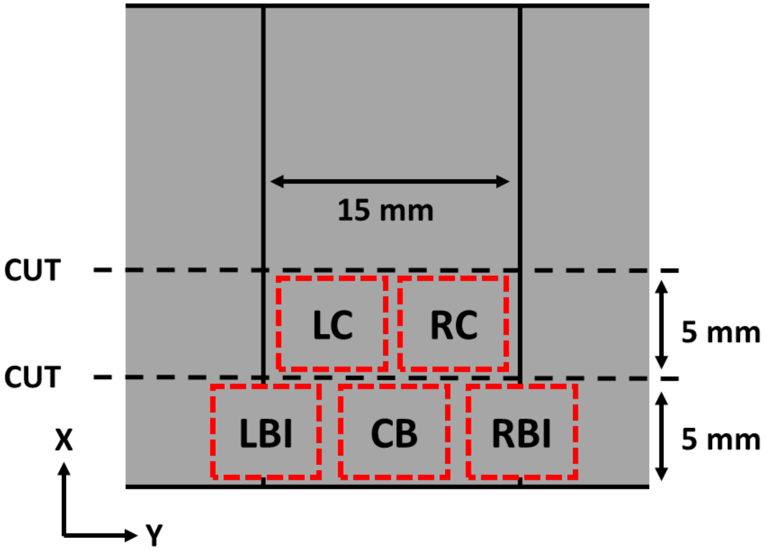


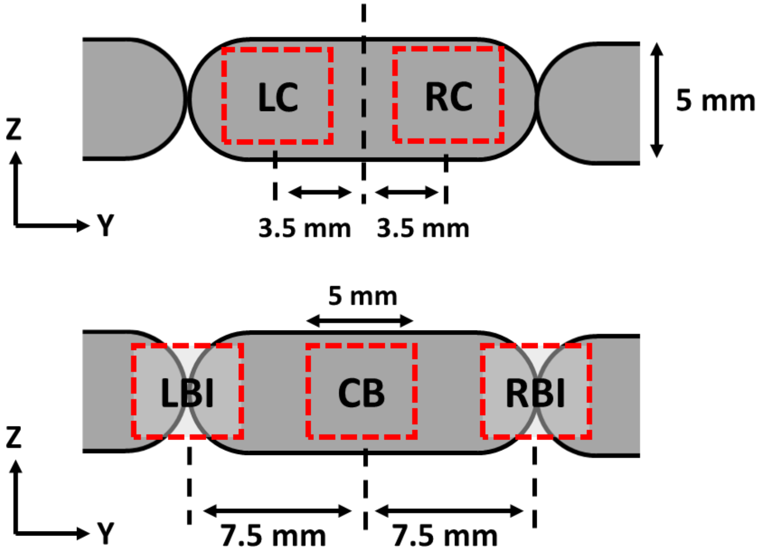
0-90 Layer Orientation

1. Duty 2017, DOI: 10.1108/RPJ-12-2015-0183

TMA Approach

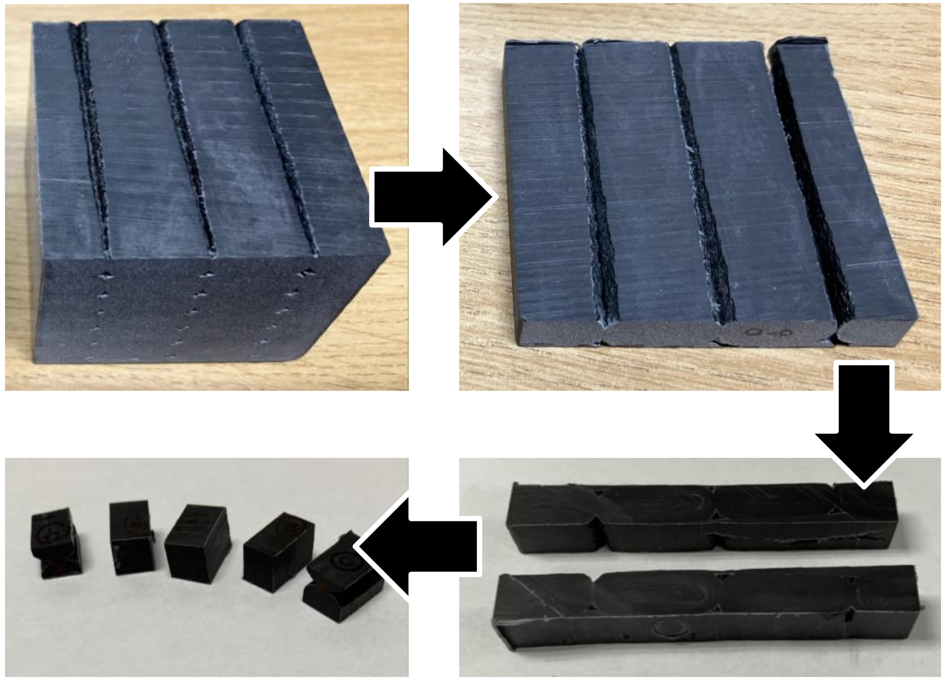
- Multiple samples across single LFAM bead (rather than single test)
- Cut locations chosen to capture different degrees of fiber orientation
- Left bead interface (LBI), left center (LC), center (CB), right center (RC), and right bead interface (RBI)





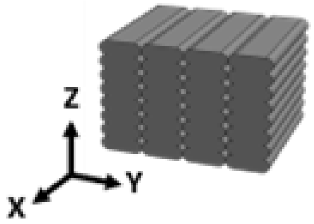
TMA Approach

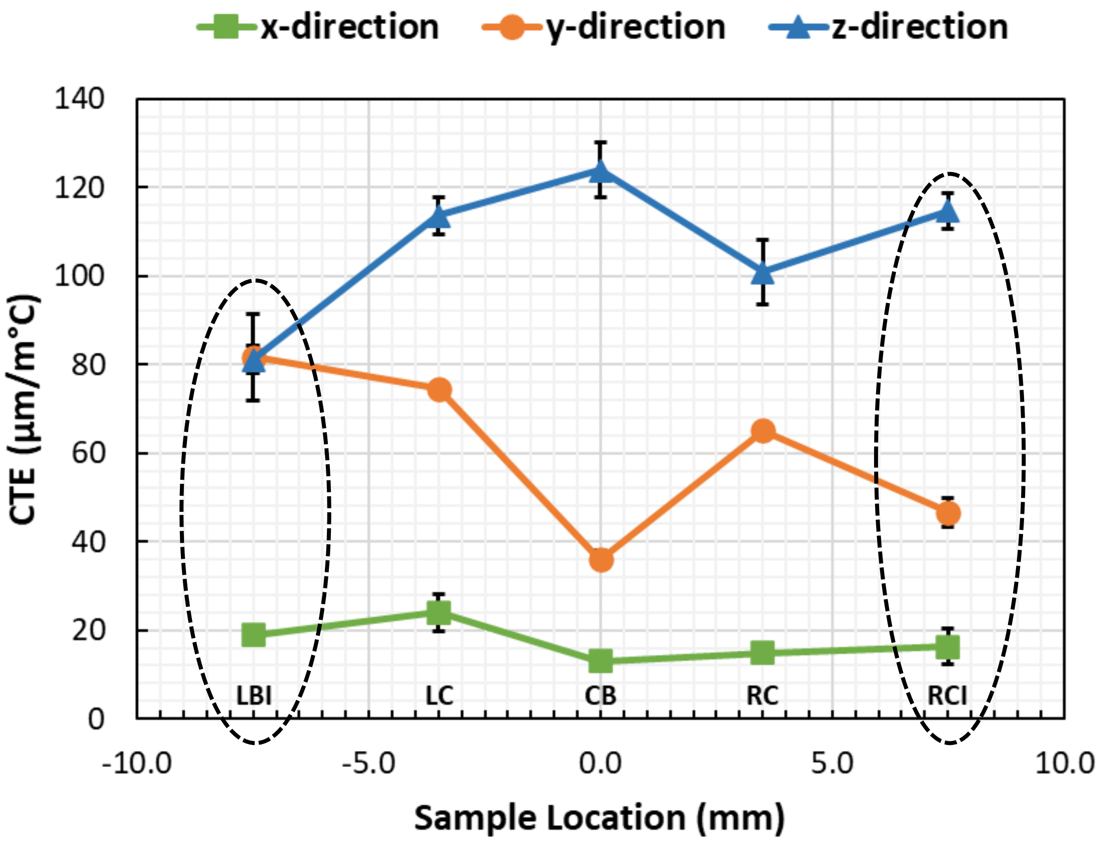
- Cuts made using a Buehler IsoMet diamond saw
- Individual layer cut from cube
- TMA samples cut from layer slice
- Final dimensions: 5 mm x 5 mm x 5 mm
- Dried in furnace overnight at 80 °C before testing
- Samples heated to 90 °C at 5 °C/min



Sampling process from BAAM Cube

TMA Results



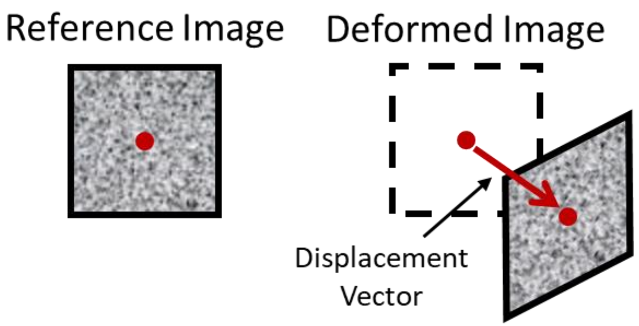


- Similar TMA results to other CF-ABS studies[1,2]
- Overall trend, $CTE_x < CTE_y < CTE_z$
- Non-symmetric about bead center → serpentine toolpath
- Relatively consistent CTE_x across bead
- Inverse response for CTE_y & CTE_z values across bead
    - *Rotating fiber orientation tensor*

1. Colón Quintana 2022, DOI: 10.3390/ma15082764
2. Billah 2020, DOI: 10.1016/j.addma.2020.101299

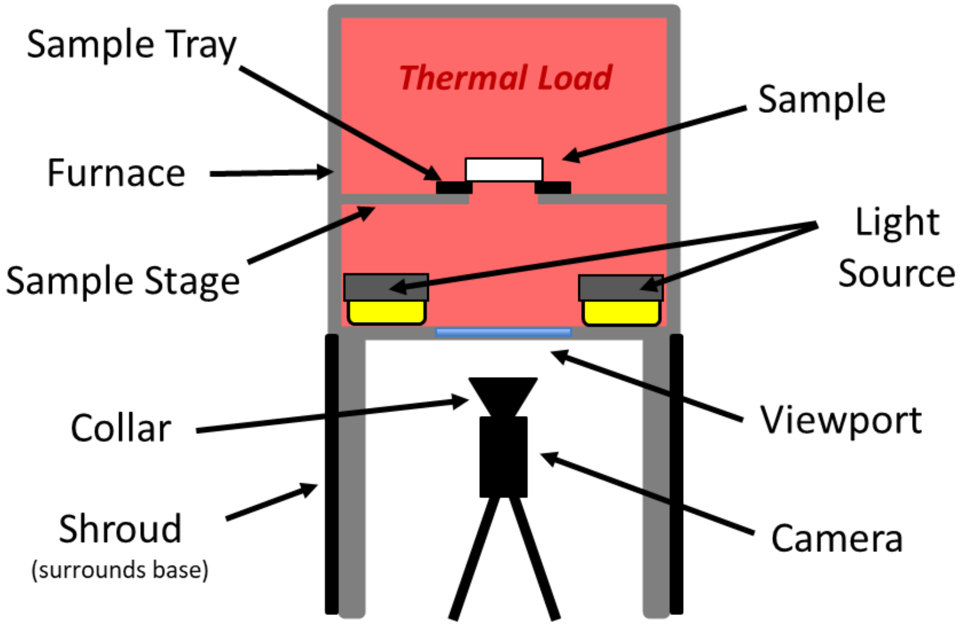
DIC Oven

2D Digital Image Correlation

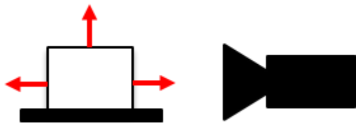


Digital Image Correlation (DIC) tracks the location of speckles from a reference to deformed state to create displacement vectors

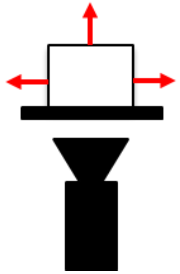
Major Components of the DIC Oven



Camera Placement



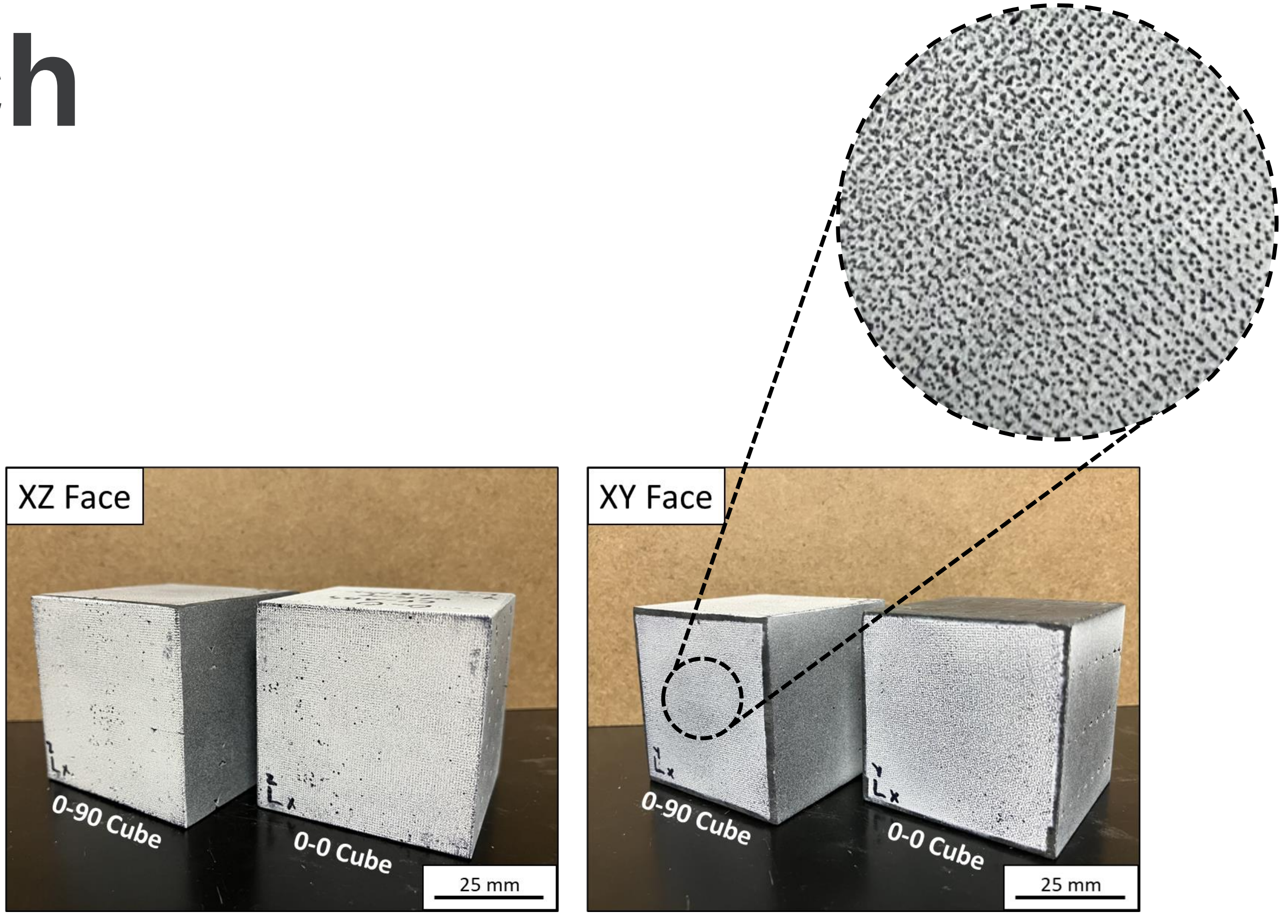
Typical 2D DIC camera placement can record expansion towards camera as false strain



DIC Oven camera placement greatly reduces chances of capturing false strain

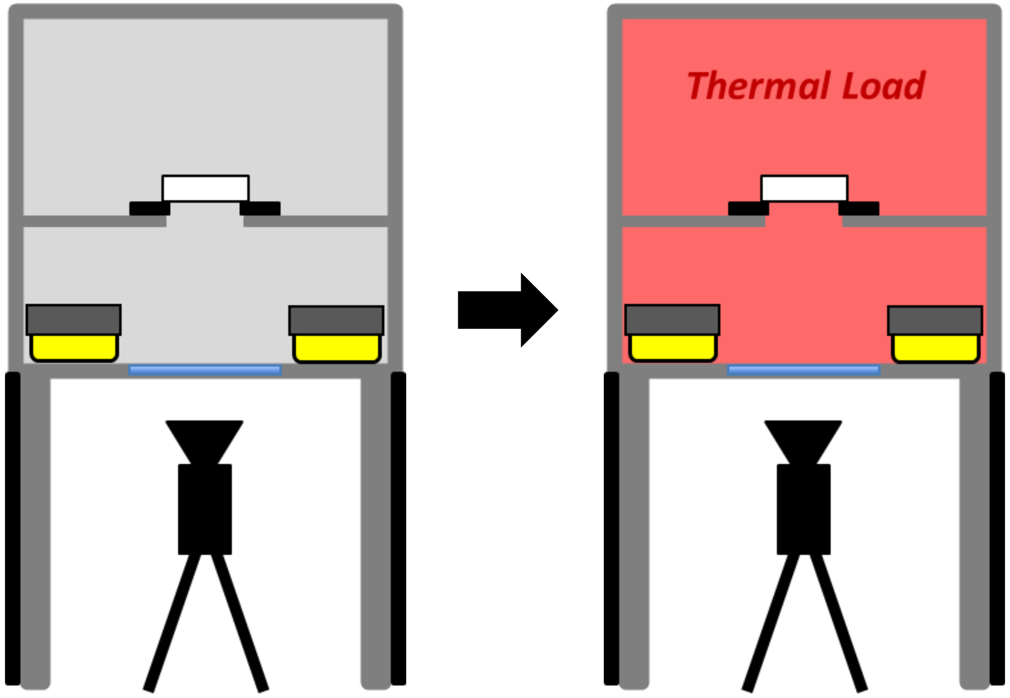
DIC Oven Approach

- Machined to flat, parallel faces
- Dried in furnace overnight at 80 °C before testing
- Lightly sprayed with high temperature white spray paint
- Speckled using Correlated Solutions speckle kit (0.007” stamp) with black ink



Speckled DIC samples

DIC Oven Approach

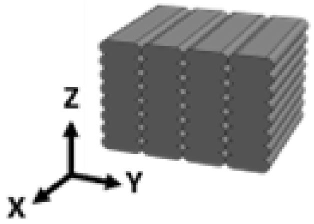


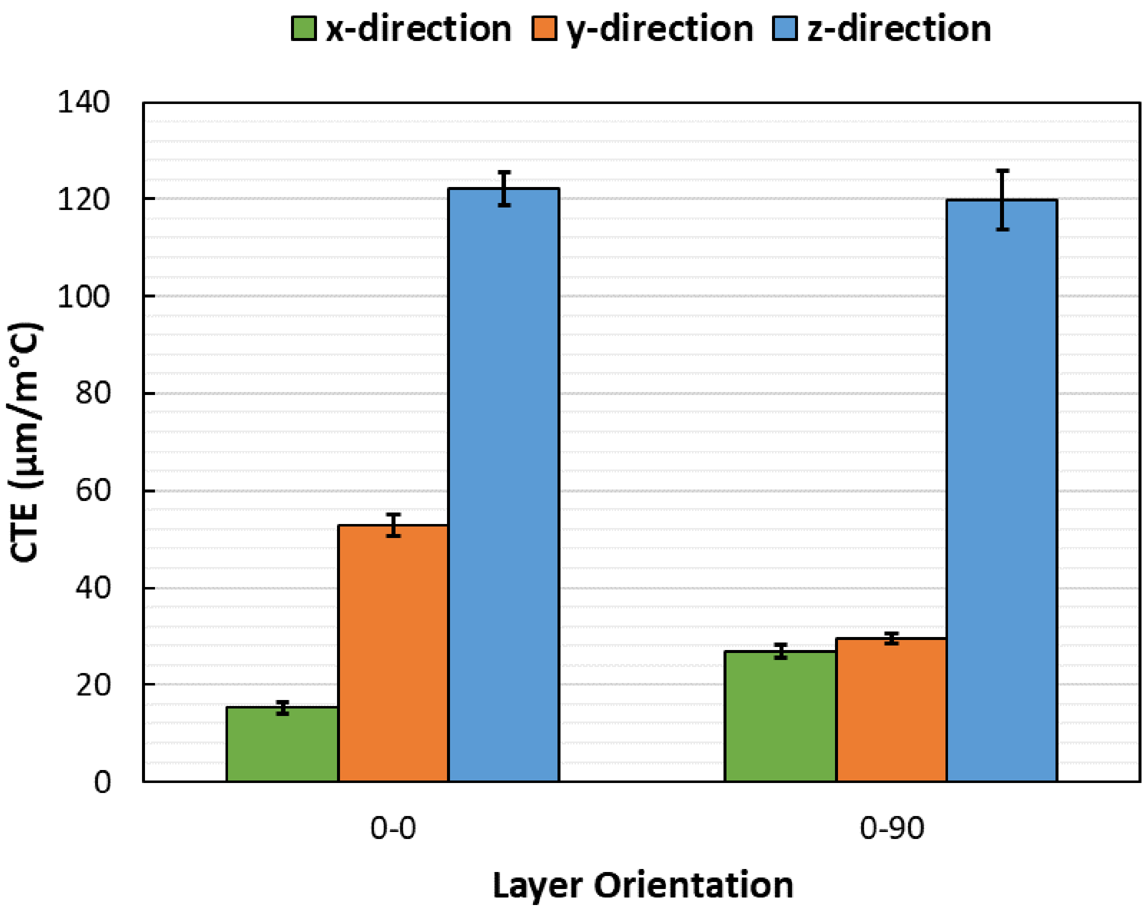
- Set sample position, brightness
- Room temperature imaging
- Allow the sample to reach steady state temperature of 90 °C
- Steady state imaging
- Upload images to Vic-2D for stain values
- Enter data in equation below to find CTE

$$CTE = \frac{\varepsilon_{SS} - \varepsilon_{RT}}{T_{SS} - TRT}$$

ε = strain
T = temperature
SS = steady state temperature
RT = room temperature

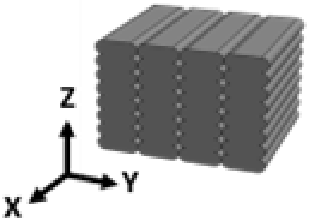
DIC Oven Results

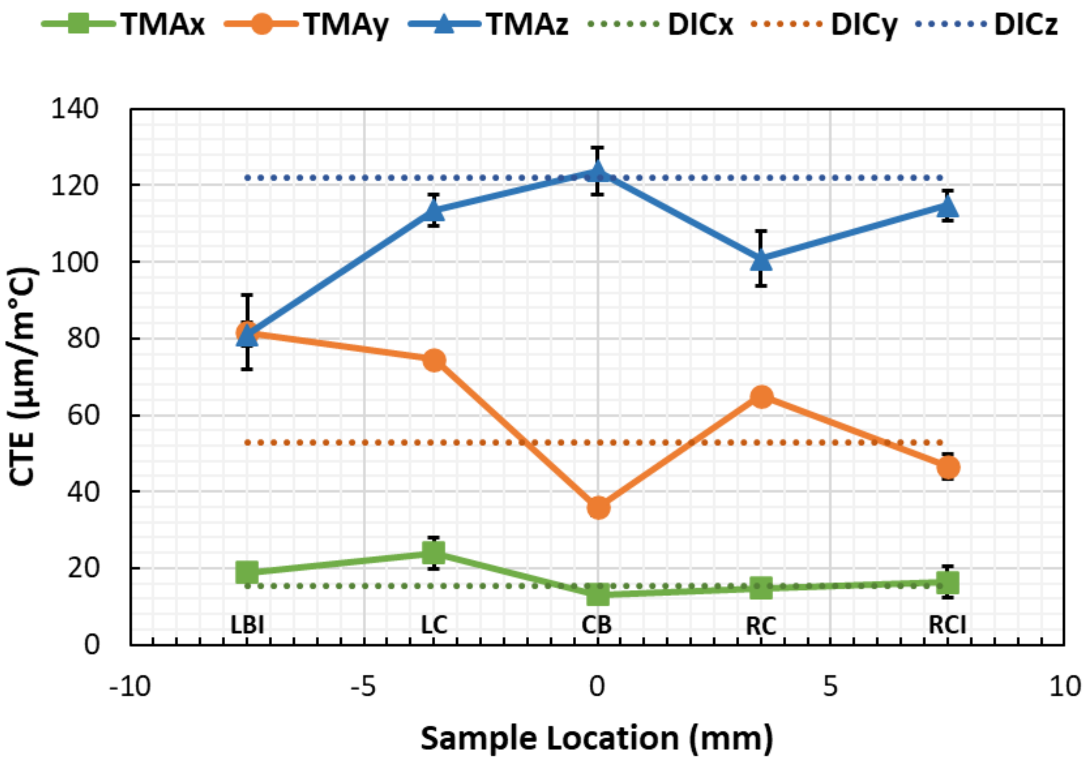




- Overall trend, $CTE_x < CTE_y < CTE_z$
- Clear influence of layer orientation on CTE values
  - *Difference in CTE_x and CTE_y from 246% (0-0) → 10% (0-90)*
- DIC Oven able to capture **mesostructural** properties

TMA vs. DIC Oven Results





- Plot of 0-0 cube with TMA & DIC Oven data
- Similar CTE_x values
- Mesostructure effects influenced CTE_y values
    - *The DIC Oven captured effects of surrounding beads*
- TMA CTE_z values were lower than the DIC Oven
    - *The DIC Oven captured expansion of multiple layers*
- The DIC Oven captured **mesostructural** properties as **influenced** by **microstructure**

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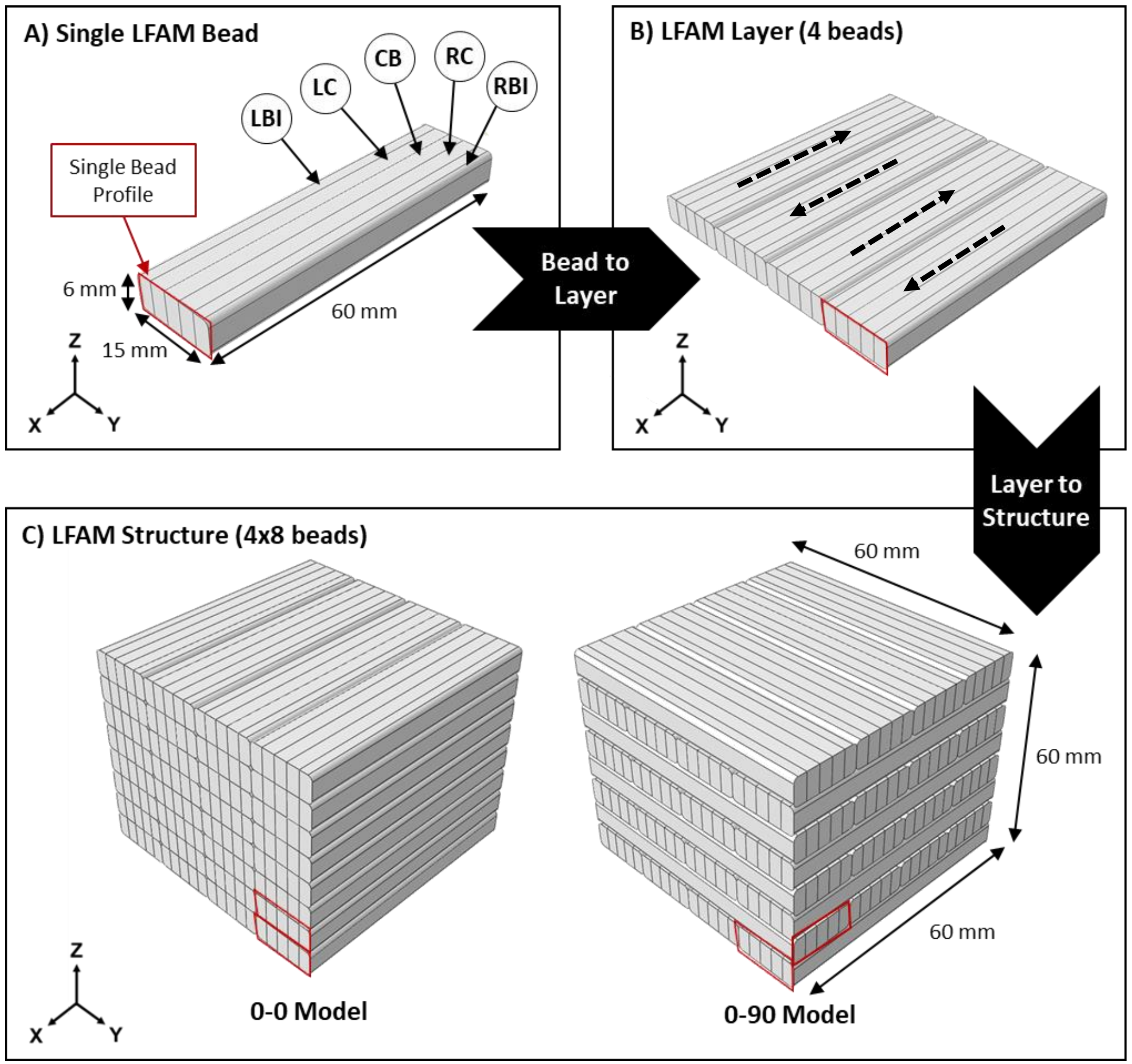
Modeling Approach

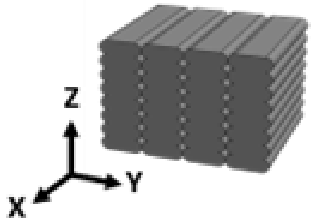
- Finite Element Analysis (FEA) model developed using Abaqus
- Single bead created
  - *Regions correspond to TMA*
  - *CTE inputs from TMA*
  - *Remaining inputs from other LFAM studies w/ CF-ABS*[1,2]
- Single bead used to create layers
- Layers used to create structure
- Both 0-0 & 0-90 models developed

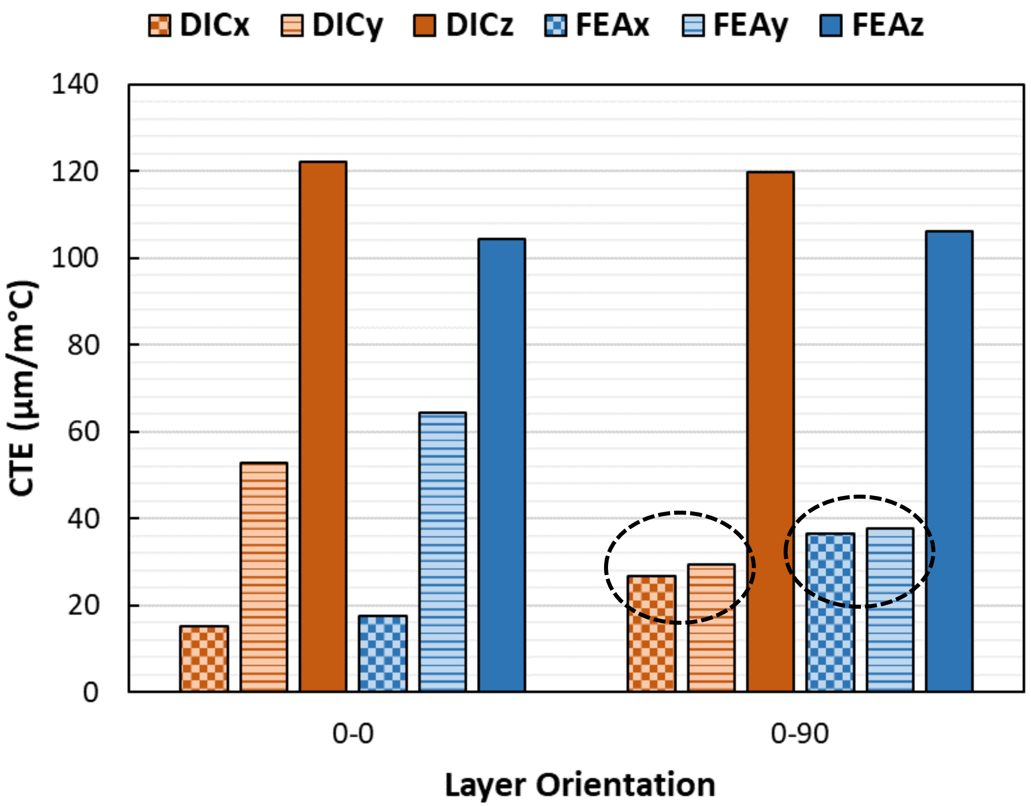


Development of Abaqus Model

1. Hassen 2022, DOI: 10.1002/pc.26645
2. Kim 2019, DOI: 10.33599/nasampe/c.19.0694

Predicted CTE vs. DIC Oven





- Trend of $CTE_x < CTE_y < CTE_z$ for 0-0 & 0-90
- The 0-0 model predicted values 13-15% higher than DIC Oven
  - *Site-specific sampling is a viable input*
- FEA showed similar change in CTE_x & CTE_y values for the 0-90 model as the DIC Oven
- Predictions showed sampling & model technique as valid method for LFAM

Conclusions

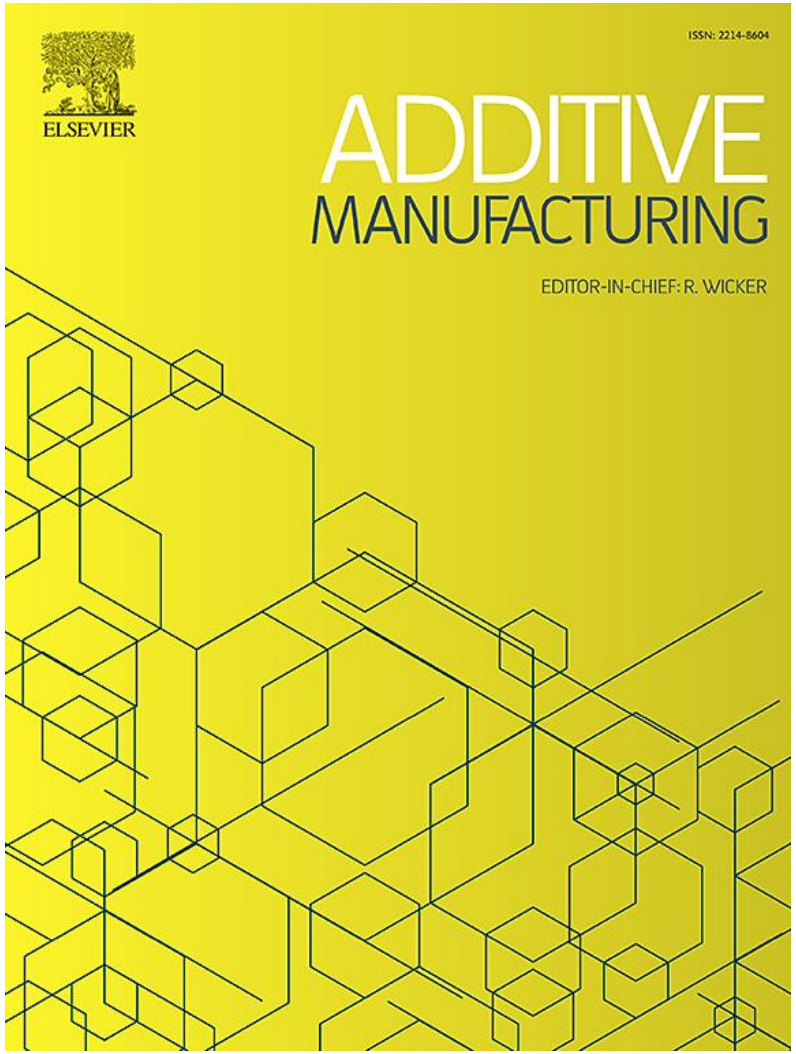
- Difficult to accurately measure thermomechanical response of LFAM structures
- Printed FRP = Nonhomogeneous structure
- TMA testing showed variation of CTE across bead
- Data from the DIC Oven compared well to TMA
- The DIC Oven demonstrated ability to capture mesostrucural properties of LFAM material
- FEA showed site-specific sampling & localized inputs can accurately predict CTE values

DIC Oven at the University of Tennessee

Submitted to Journal

"*Measuring Thermomechanical Response of Large-format Printed Polymer Composite Structures Via Digital Image Correlation*"

- Submitted July 2024 to **Additive Manufacturing**
- Anticipated release in Fall 2024
- Co-Authors:
  - Tyler Corum (*first author*)
  - Johnna O'Connell
  - James Bracket
  - Ahmed Arabi Hassen
  - Chad Duty



Acknowledgements

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SEAMTN Southeastern Advanced Machine Tools Network

NSF

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Thank you for your time

Any Questions?

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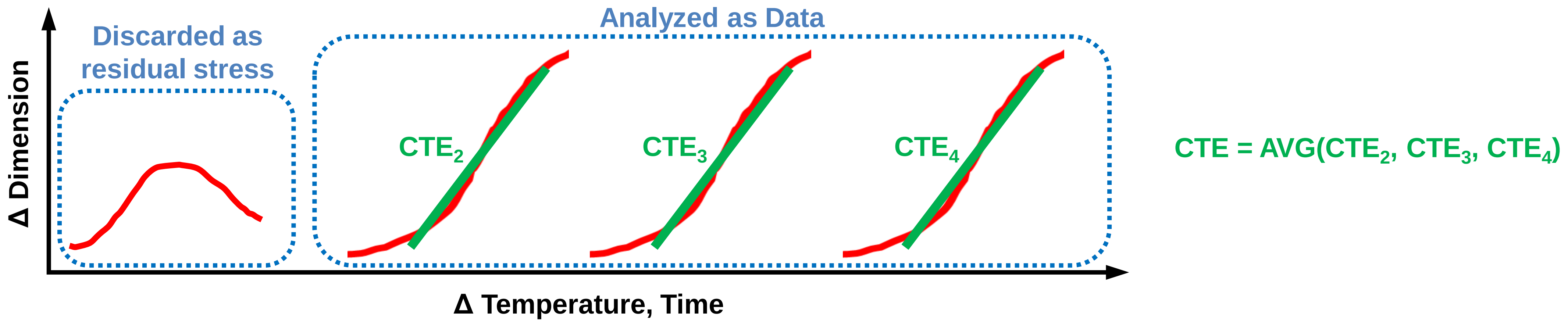
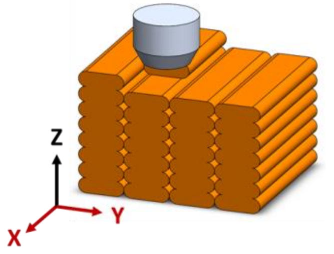
REFERENCE SLIDES

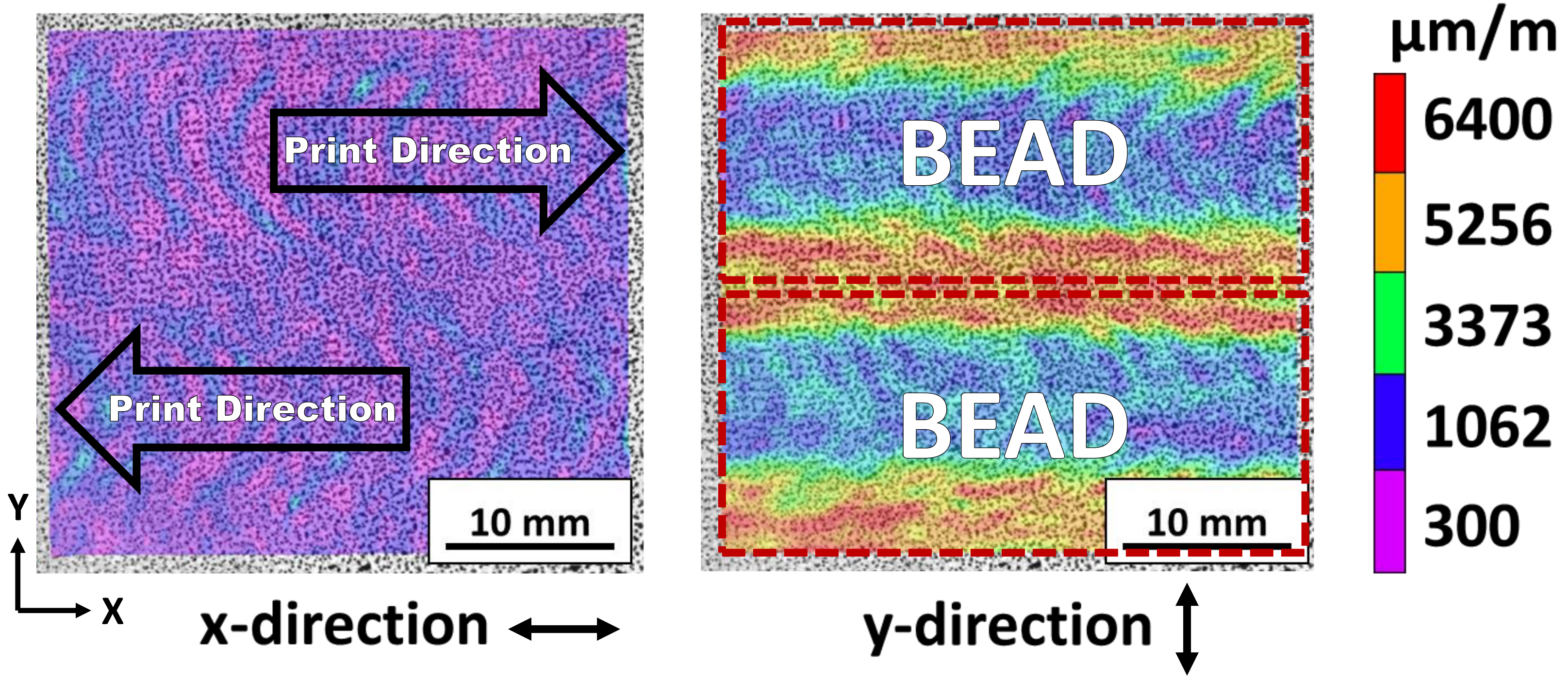
TMA Approach

- Measured using a TA Instruments Q400 TMA
- Sample was heated from room temperature to 90 °C at 5 °C/min
- Four temperature cycles with natural cooling between for each test
- Linear region of curve measured to determine CTE
- Data from curves 2-4 averaged to represent average CTE for each region
- Two tests per sample to ensure consistency



Strain Map, XY Plane



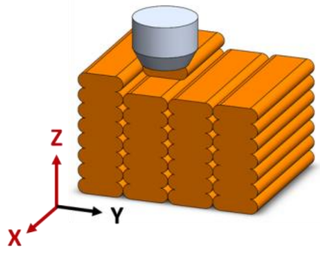


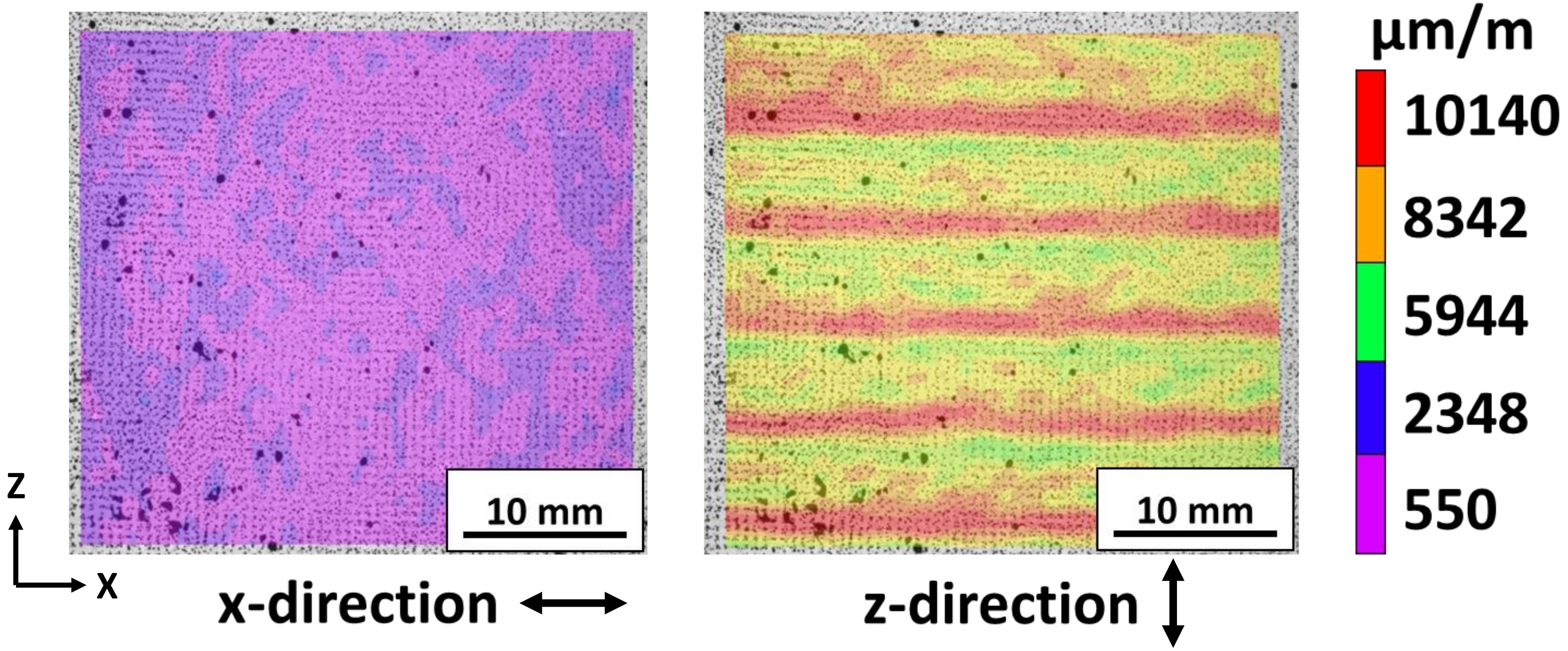
Scallops from print direction

Effects of fiber alignment influencing strain

- Created using Vic-2D
- Homogenous spread of relatively low strain in the x-dir
- Notice red & blue bands of strain in the y-dir
  - Red is high strain at bead edges
  - Blue is lower strain at the more randomly oriented bead center

Strain Map, XZ Plane

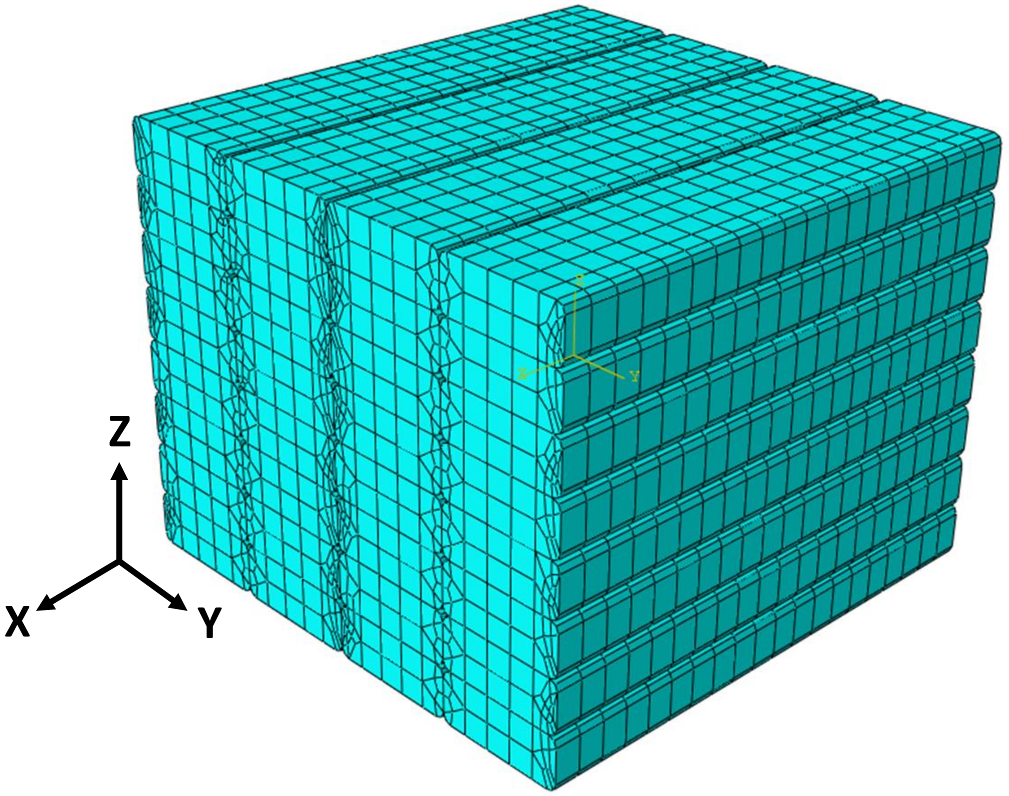




- Created using Vic-2D
- Homogenous spread of low strain in x-dir
- Bands again in the y-dir
  - High strain from aligned fibers at layer interfaces (red)
  - Fibers provide **much less resistance** in transverse direction
  - Lower strain from random orientation (orange-yellow)

Modeling Approach

- Thermally loaded by a temperature change of 70 °C (20 °C → 90 °C)
- 15900 total 3D stress elements
- Linear, hexahedral elements
- Thermally-coupled trilinear displacement 8-node element (C3D8T element type)



Mesh Applied to model