MEASURING THERMAL-INDUCED DISTORTION OF LARGE-FORMAT COMPOSITE PRINTED STRUCTURES USING DIGITAL IMAGE CORRELATION

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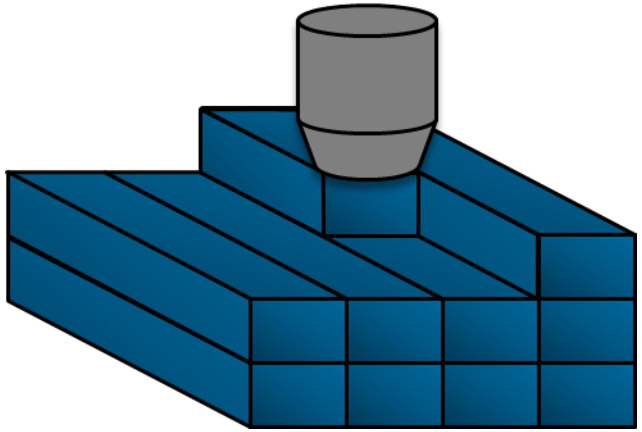
Welcome!

- Tyler Corum
- University of Tennessee, Knoxville
- Master's Student
- Graduate Research Assistant
- Mechanical Engineering background
- Research focus in fiber alignment and thermal deformation of composite polymers created using Large-Format Additive Manufacturing (LFAM)

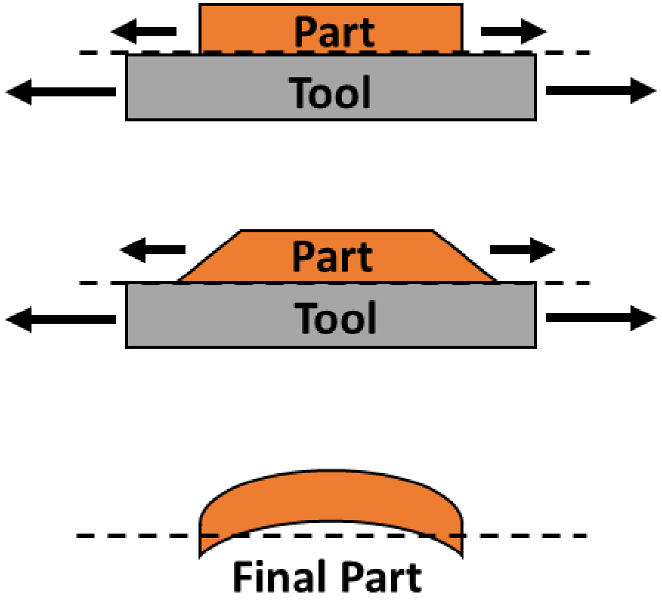
First, a couple questions…

- Why measure thermal-induced distortion of Large-Format Composite Printed Structures?
- Why use Digital Image Correlation?



The BIG Picture of Large-Format AM

- Large-Format AM (LFAM) is advantageous for tooling applications
- Big Area Additive Manufacturing (BAAM) type system can create large and complex parts[1]
- Fiber Reinforced Polymers (FRP) feedstock increases part stiffness and lowers CTE[2]
- AM tools may still experience warpage at autoclave conditions



Tool warping due to poor tool-part interaction

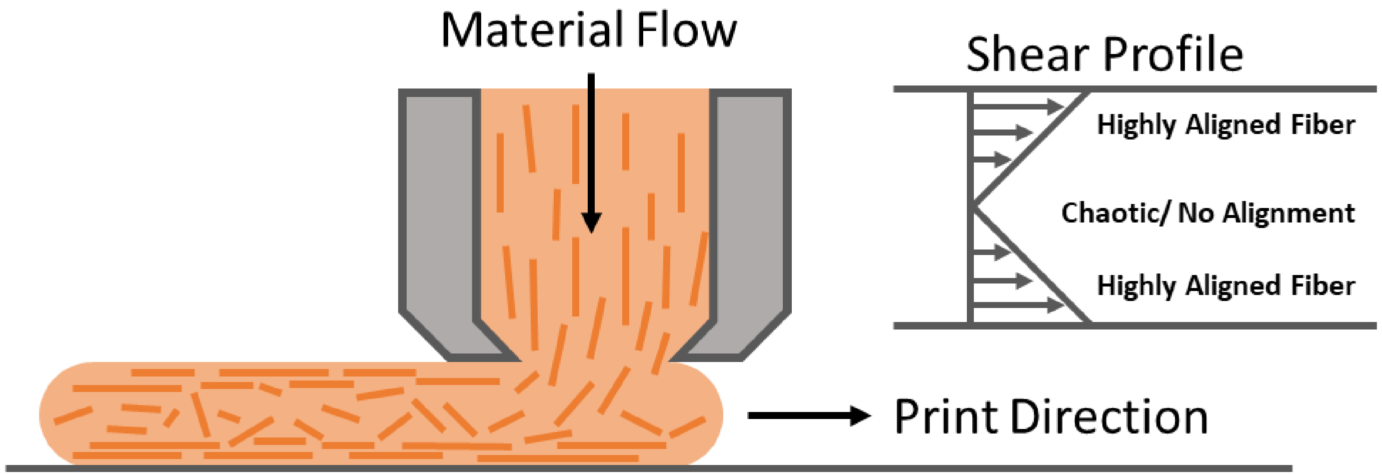
What leads to this part warpage?

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

Fiber Alignment

Fiber Reinforced Polymer Composites = MATRIX + FIBER

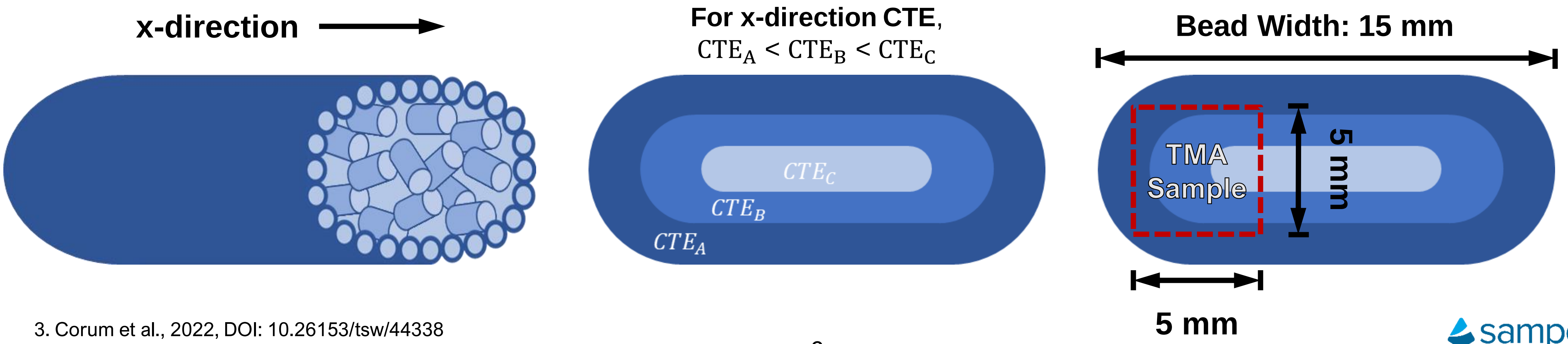
- During extrusion, fibers are aligned by nozzle shear in the print direction[3,4]
- This results in a bead with highly aligned edges and randomly aligned center
- After extrusion, the printed fiber aligned bead has an anisotropic cross section
- Anisotropic beads lead to a highly anisotropic structure



3. Corum et al., 2022, DOI: 10.26153/tsw/44338
4. Hassen et al., 2022, DOI: 10.1002/pc.26645

Thermomechanical Anisotropy

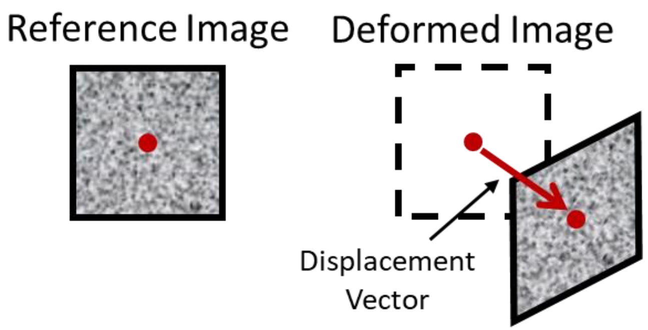
- Different thermal properties in the x, y, and z-direction
- Fibers resist expansion much more in the x-direction than in the y-direction
- Alignment causes different tiers of CTE in based on amount of alignment
  - Ex: less fiber alignment at center, lower x-dir CTE than at highly aligned edge
- Thermomechanical Analysis (TMA) does not accurately capture tiered CTE due to sample size limitations as shown by previous work[3,5]



3. Corum et al., 2022, DOI: 10.26153/tsw/44338
5. Hoskins et al., 2019, DOI: 10.33599/nasampe/s.19.1598

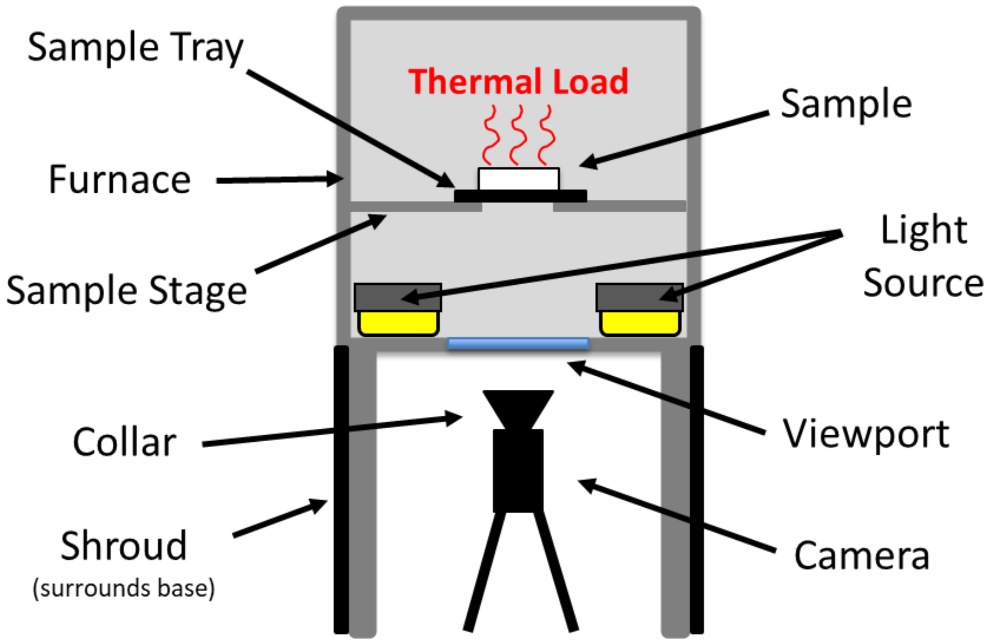
DIC Oven

2D Digital Image Correlation

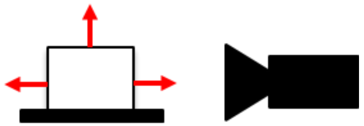


Digital Image Correlation (DIC) tracks location of speckles from reference to deformed state to create displacement vectors

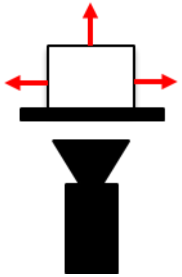
Major Components of the DIC Oven



Camera Placement



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

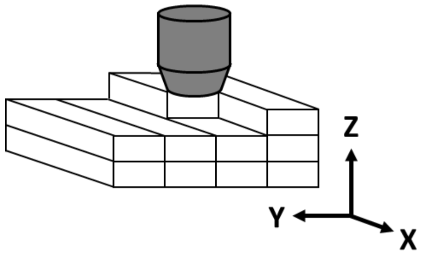


DIC Oven camera placement greatly reduces chances of capturing false strain

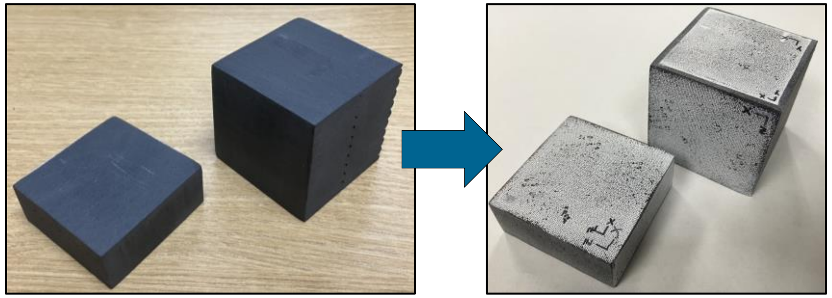
Research Objectives

- Measure the CTE of FRP made LFAM prints
  - Various sample geometry, effects on system measurement
  - Various material, effects on CTE
- Perform thermocouple study to confirm when a sample has reached steady state
- SolidWorks Thermal Simulation to model thermocouple study conditions for future samples
  - Custom geometry and material properties

Materials

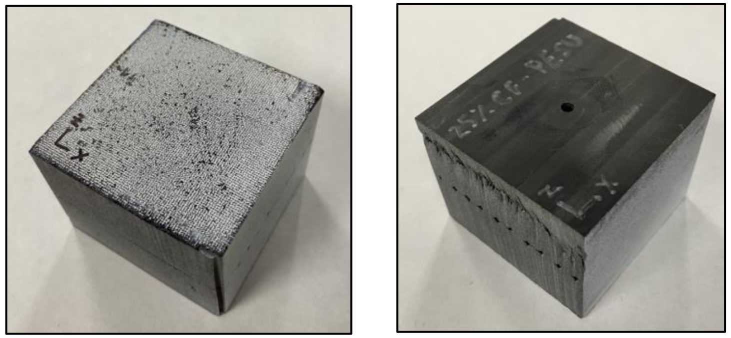


- BAAM printed samples by Oak Ridge National Labs (ORNL) and Additive Engineering Solutions (AES)
- Plate (50x50x20 mm) & cube (50x50x50 mm) geometries printed
- Faces of interested speckled
- For thermocouple study testing, hole drilled in CF-PESU cube for thermocouple placement (diameter = 2.5 mm, depth = 25 mm)



Before (left) and after (right) speckling

Material Details				
Matrix Material	***% Fiber Material by weight***	***Acronym***	***Printed Geometry***	***Images Face(s)***
acrylonitrile butadiene styrene	20% Glass Fiber	GF-ABS	plate, cube	XY, XZ
acrylonitrile butadiene styrene	20% Carbon Fiber	CF-ABS	plate, cube	XY, XZ
polyether sulfone	25% Carbon Fiber	CF-PESU	cube	XZ



Speckled face (left) and channel for thermocouple insert (right)

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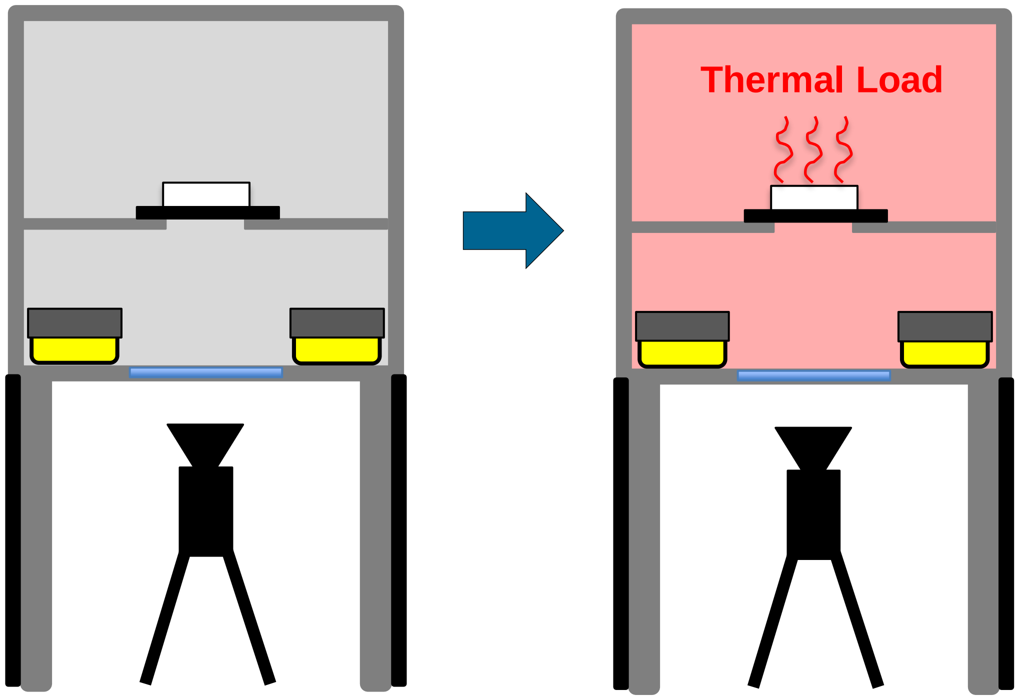
DIC Oven Testing



Room Temperature ***Steady State Temperature***

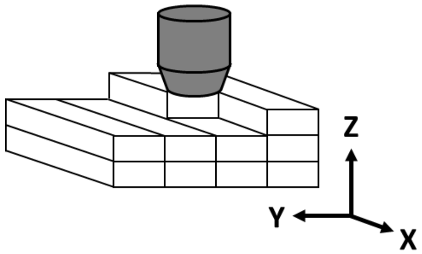
Procedure Overview

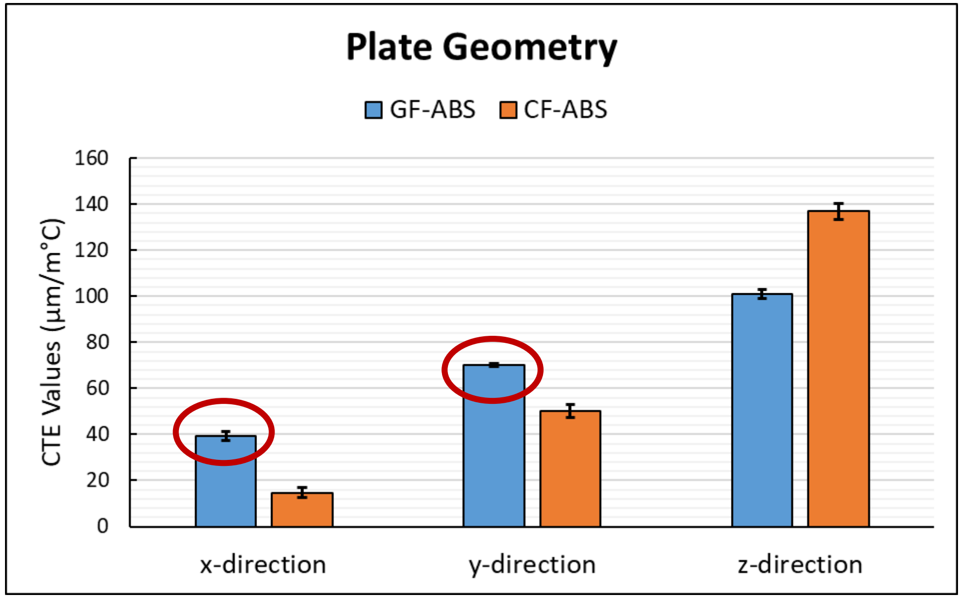
- Set sample (position, brightness)
- Room temperature image capture
- Allow sample to reach steady state temperature
  - 4 hours for plate
  - 6 hours for cube
- Steady state image capture
- Upload images to Vic-2D software
- Enter data in equation below to find CTE

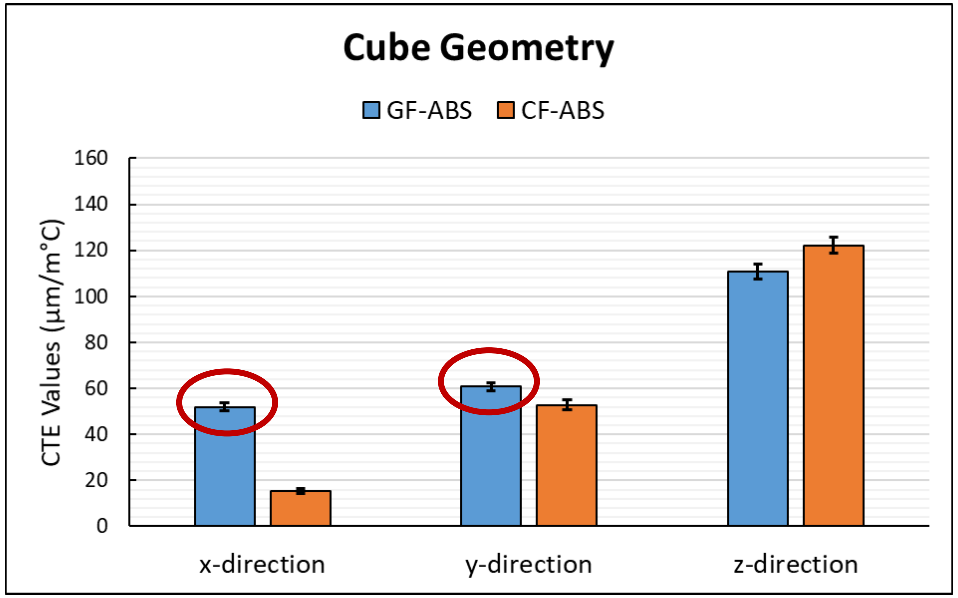
$$CTE = \frac{\varepsilon_{SS} - \varepsilon_{RT}}{T_{SS} - T_{RT}}$$

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

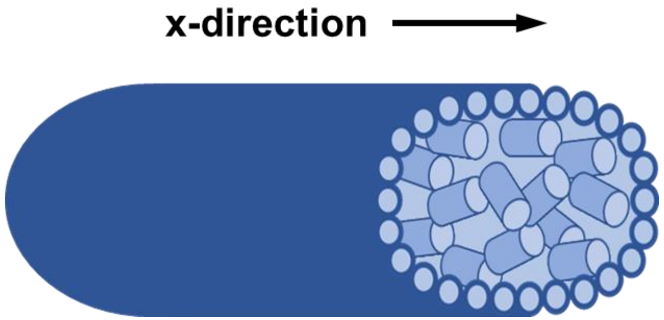
DIC Oven CTE Values



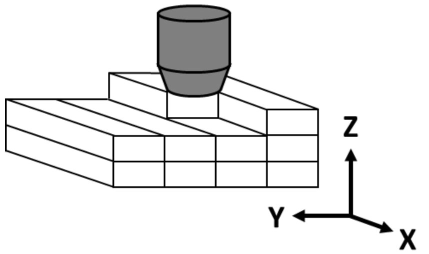




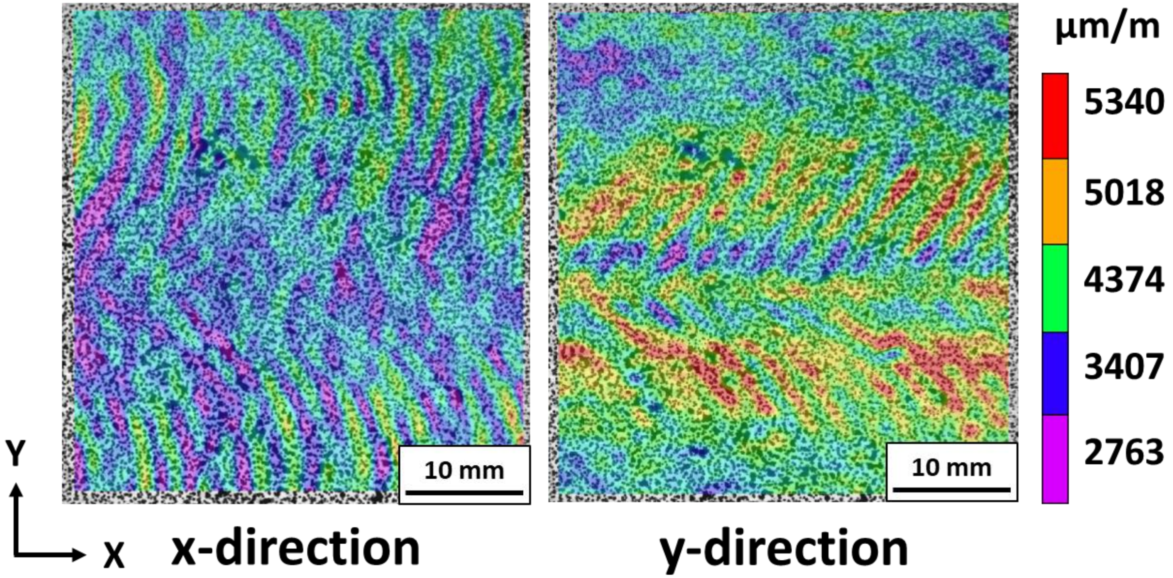
- Overall trend of CTE: x-dir < y-dir < z-dir
- CF-ABS showed higher z-dir CTE with the cube geometry
  - Δx = 4%, Δy = 5%, and Δz = **12%**
- GF-ABS x and y-dir CTE affected by geometry
  - Δx = **24%**, Δy = 16%, and Δz = 9%



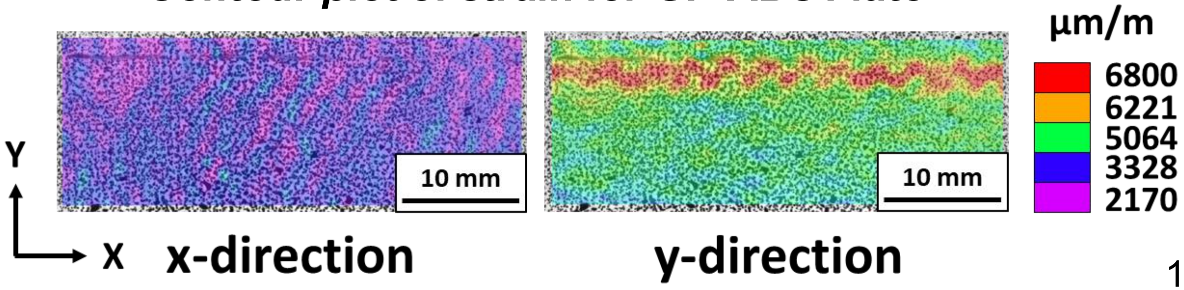
DIC Oven Strain Plots, XY



Contour plot of strain for GF-ABS Cube

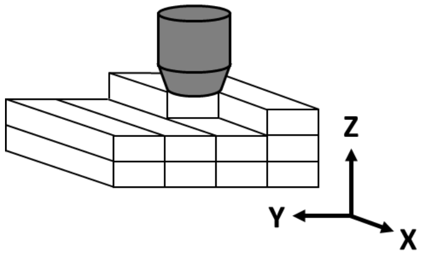


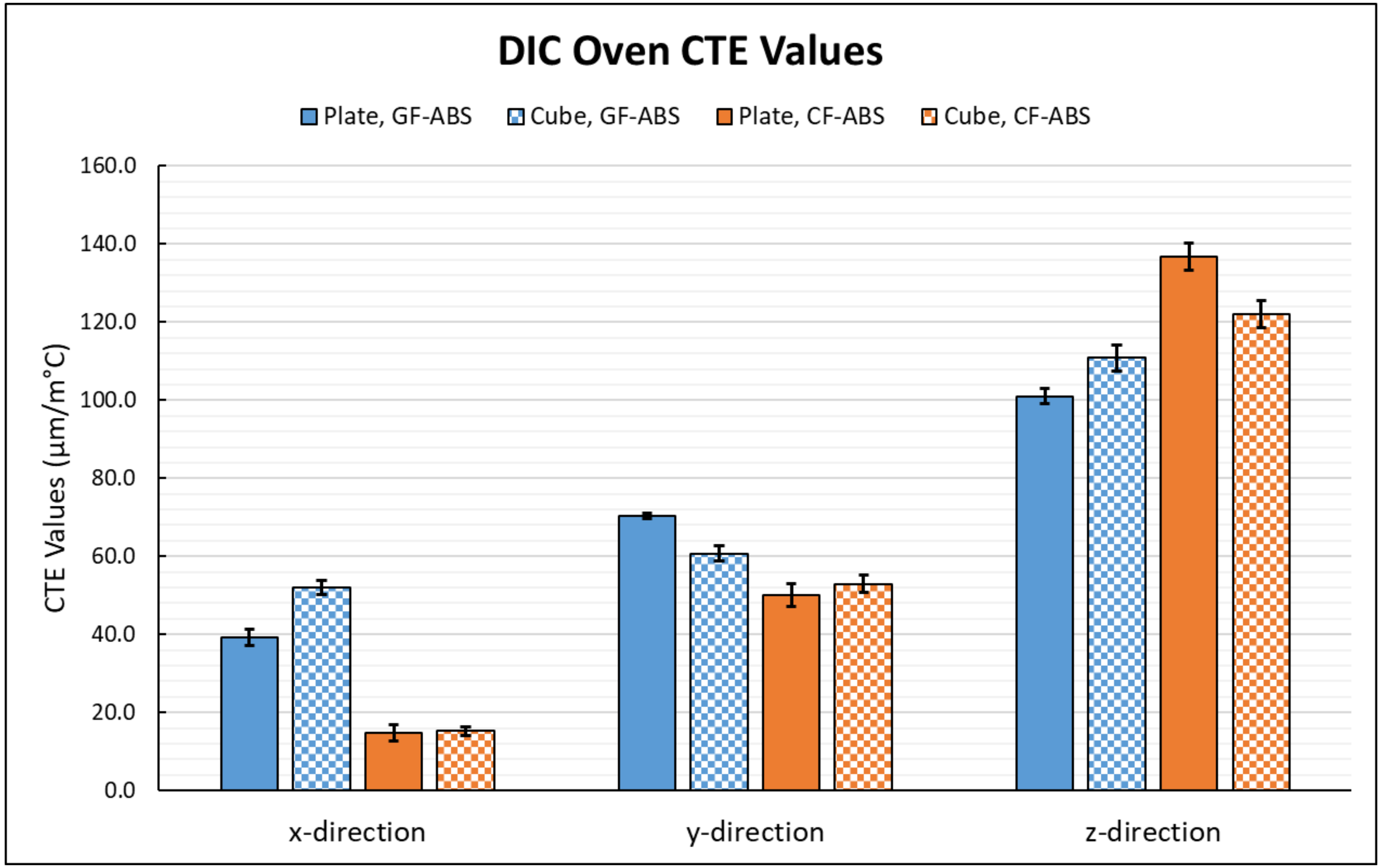
Contour plot of strain for GF-ABS Plate



- Cube geometry provided much more surface area to examine than the plate
- DIC camera captured more unique areas for cube geometry
- More bead interaction captured lead to better understanding of CTE from aligned fibers
- X-direction for each showed homogenous spread of relatively low strain from FRP
- Y-direction captured high areas of strain from aligned fibers

DIC Oven CTE Values

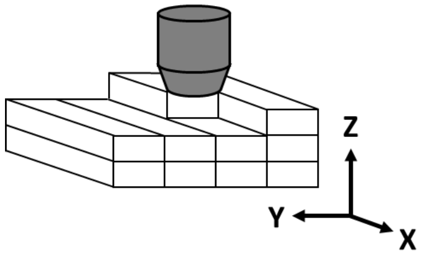




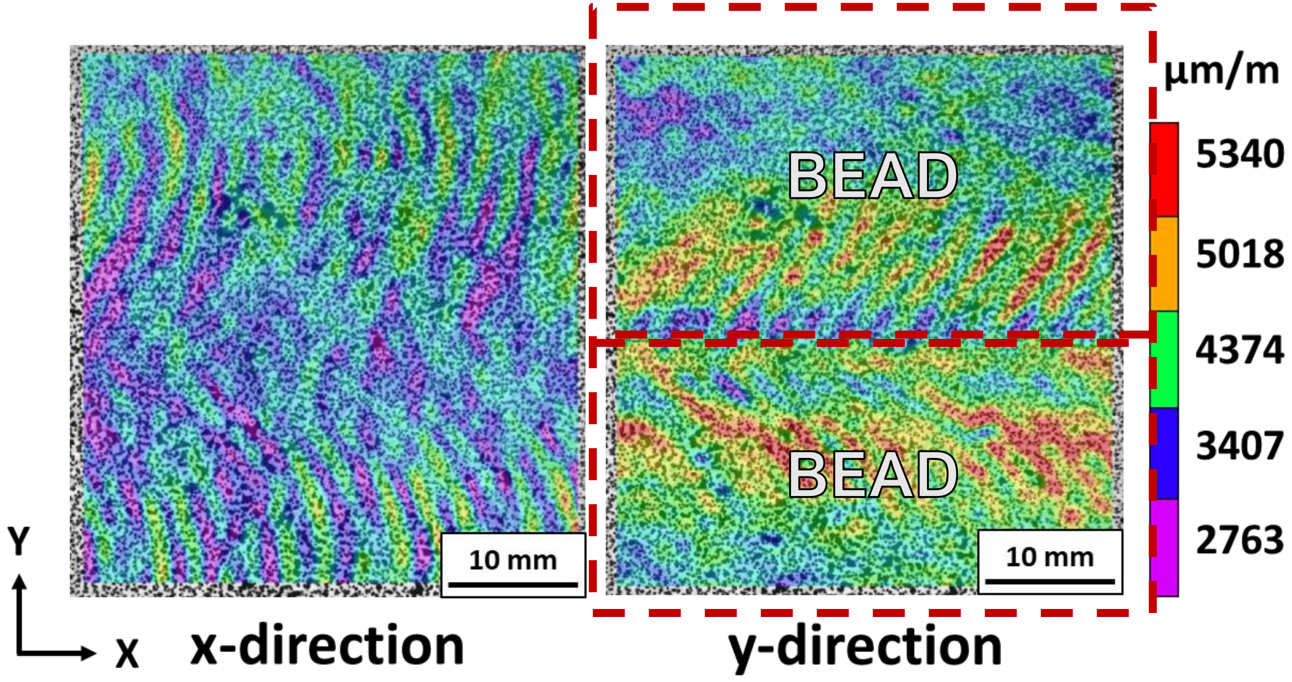
- Overall trend of CTE:
  x-dir < y-dir < z-dir
- CTE values similar to those found by Billah and Colón Quintana using TMA[6,7]
- GF-ABS CTE appeared to be more homogenous based on CTE
- Bead width skewed comparison
  - GF-ABS = 27 mm, CF-ABS = 15 mm

6. Billah et al., 2020, DOI: 10.1016/j.addma.2020.101299
7. Colón Quintana et al., 2022, DOI: 10.3390/ma15082764

DIC Oven Strain Plots, XY



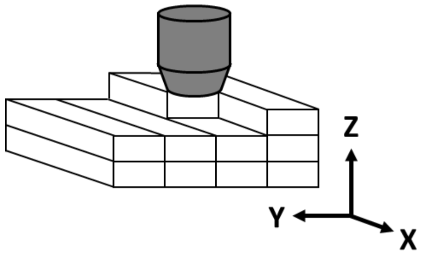
Contour plot of strain for GF-ABS



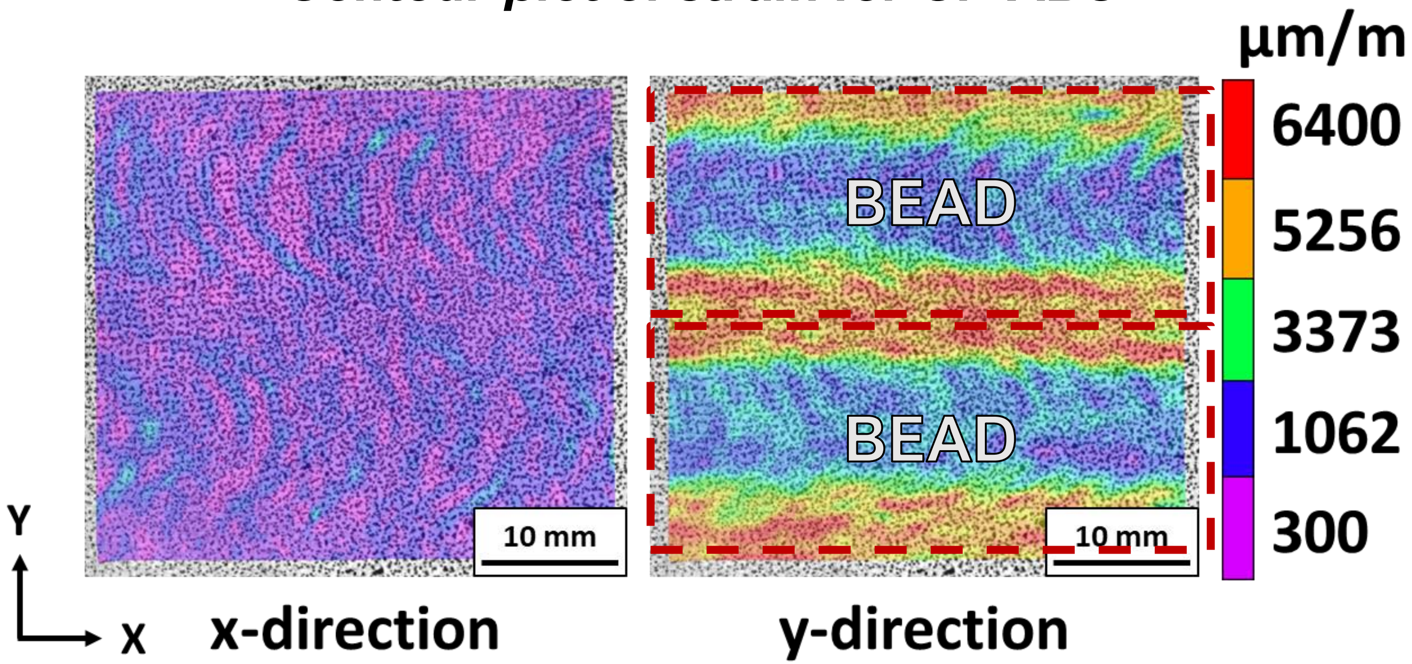
The y-direction image captured more homogenous than aligned fiber (wide bead)

- Strain contour plots were created using Vic-2D
- The x-direction showed spread of relatively low expansion
- The y-direction showed areas of high strain
- The high strain areas corresponded to the highly aligned edges of the bead
- GF-ABS saw only one bead interaction due to the larger bead width (27 mm)

DIC Oven Strain Plots, XY



Contour plot of strain for CF-ABS



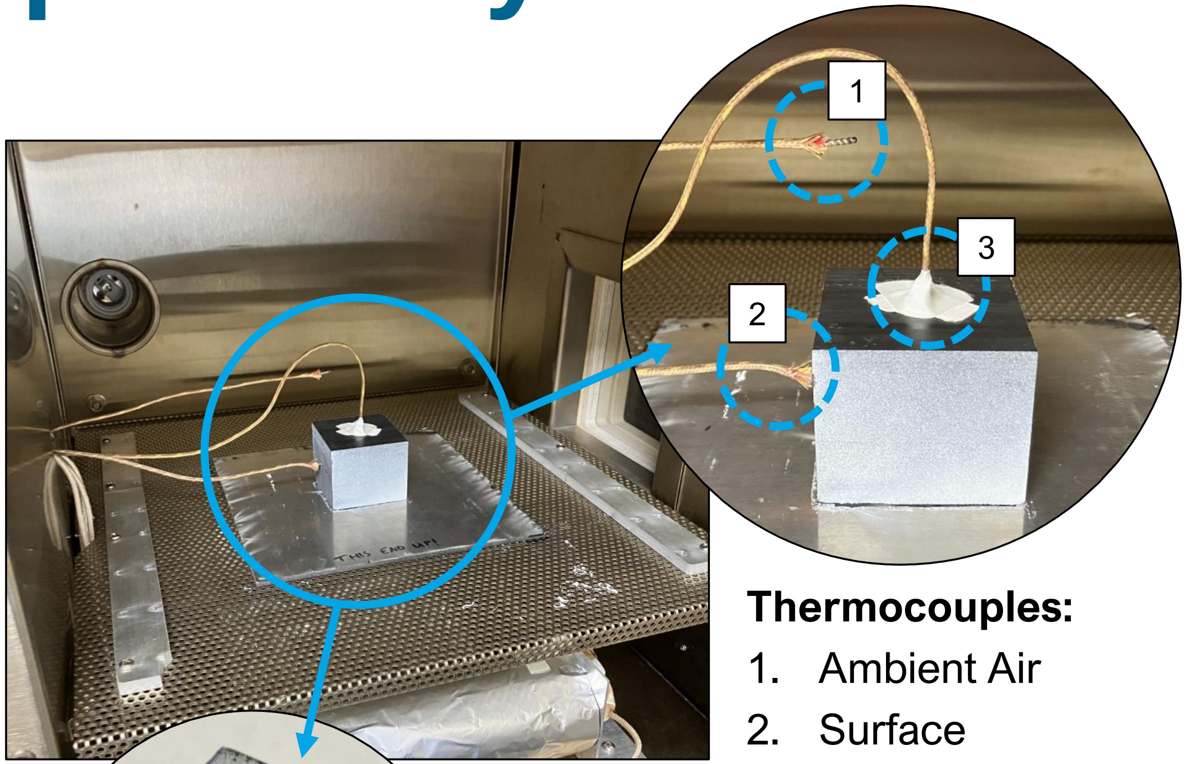
The y-direction image shows fiber alignment across multiple beads!

- Strain contour plots were created using Vic-2D
- The x-direction showed spread of relatively low expansion
- The y-direction showed bands of low (blue) and high (red) strain
- Low strain occurred at the more homogenous bead center
- High strain occurred at bead edges
- The CF-ABS was able to capture more bead interactions from smaller bead width (15 mm)

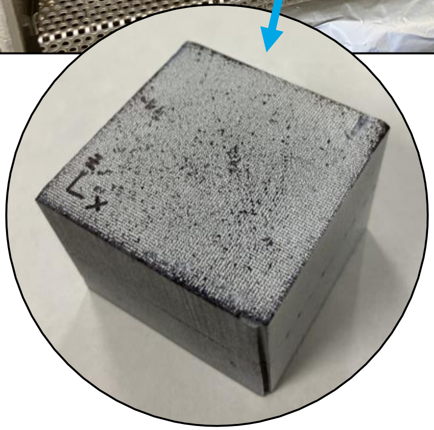
Thermocouple Study

- Imaged XZ face in time intervals below
- Type-K thermocouples placed
- Data recorded using DAQ
- Furnace temperature set to 90°C

DIC Oven Imaging Time Intervals		
Frequency	***Duration***	
5 minutes	30 minutes	*Room Temperature*
2 minutes	30 minutes	*Thermal Load Applied*
5 minutes	30 minutes	
10 minutes	30 minutes	
30 minutes	120 minutes	
60 minutes	Remainder of test	

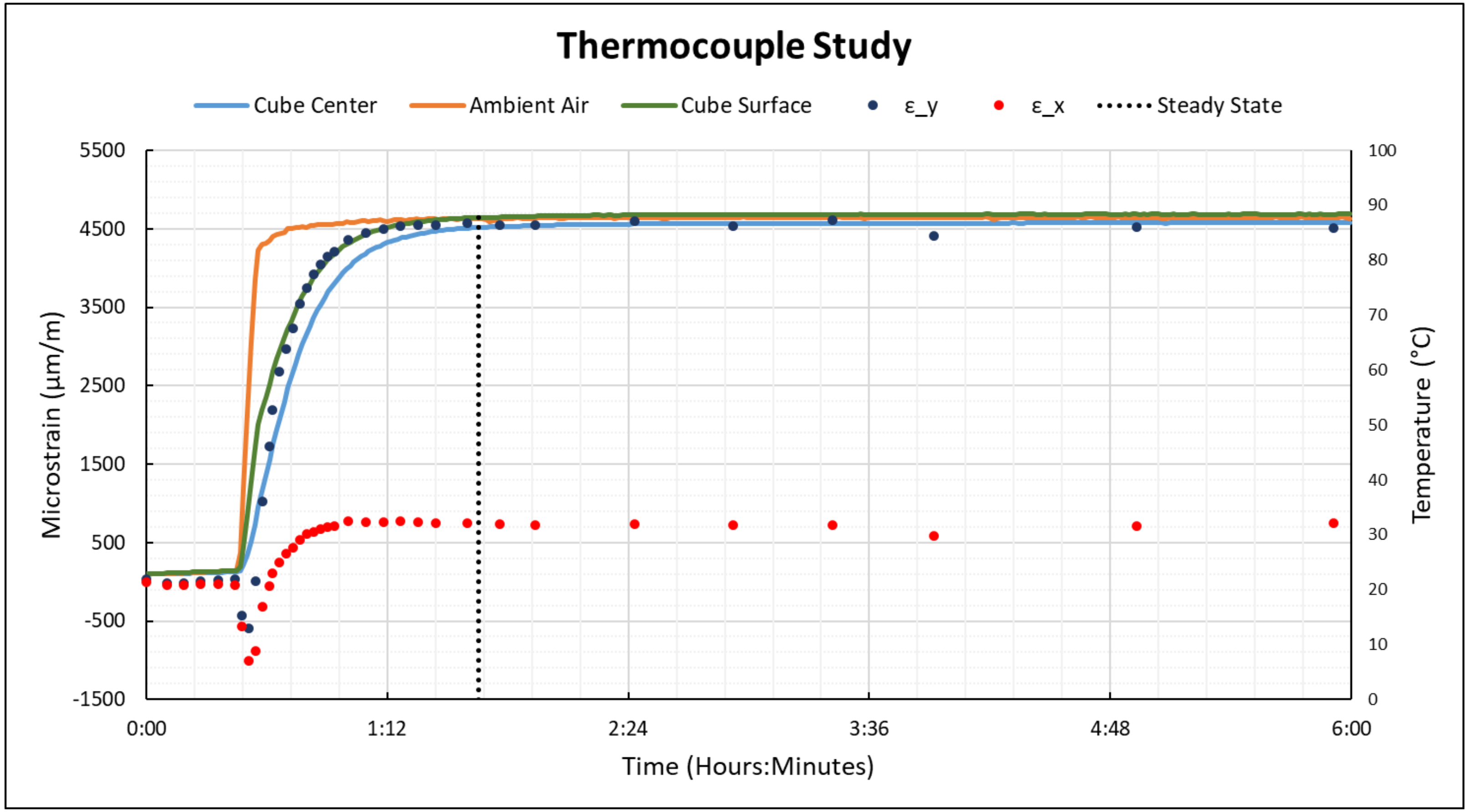


Thermocouples:
1. Ambient Air
2. Surface
3. Center (25mm depth)



2D-DIC:
XZ face imaged using intervals to the left

Thermocouple Study



Steady State = ± 1% of average value from final hour

- Thermocouple Study (90°C) was ran using CF-PESU
- Strain and temperature shown over time
- Baseline values show near zero strain at room temperature
- Thermocouples met steady state as expected
- Cube center reached steady state 61 minutes after loading
- DIC testing well at steady state (4 hr plate, 6 hr cube)

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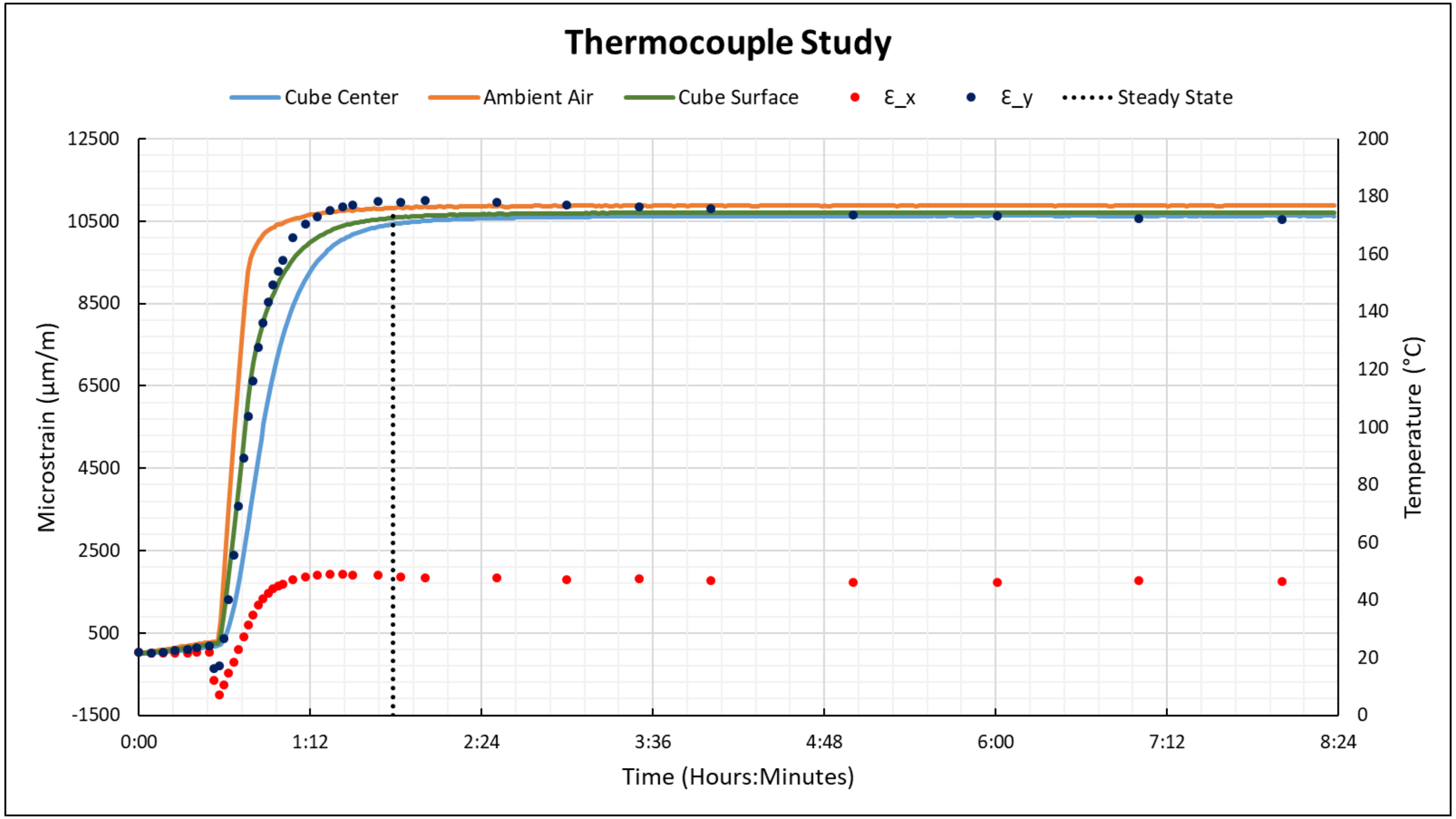
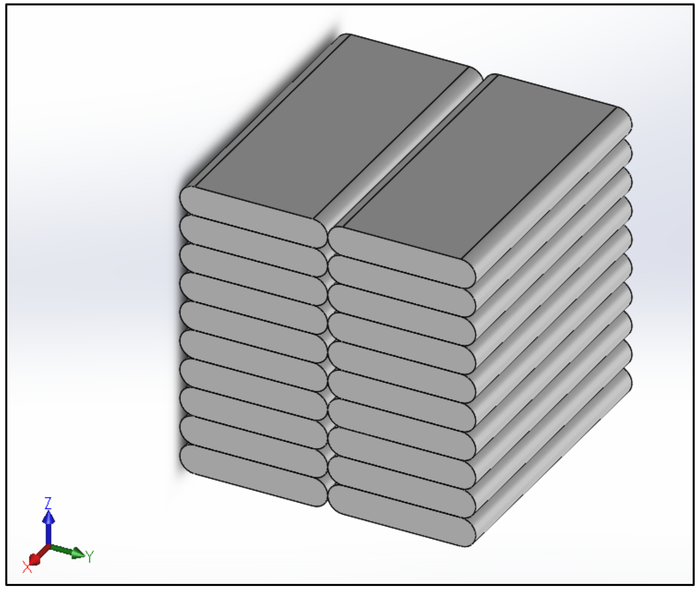
Thermocouple Study

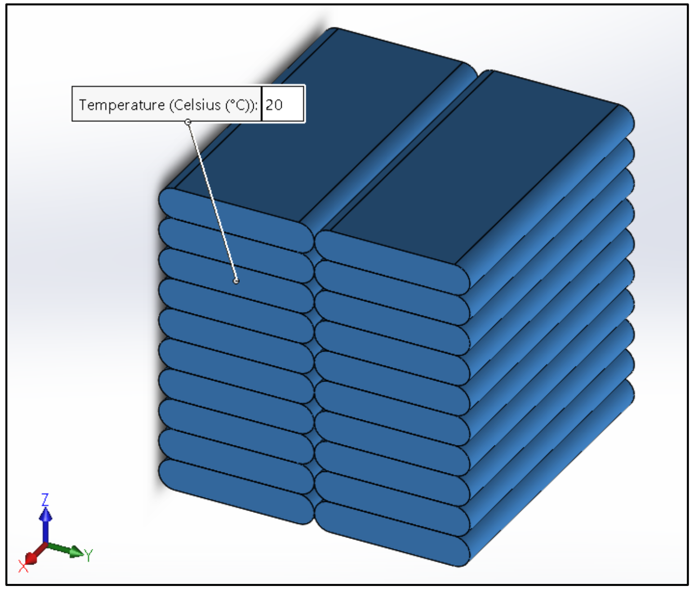


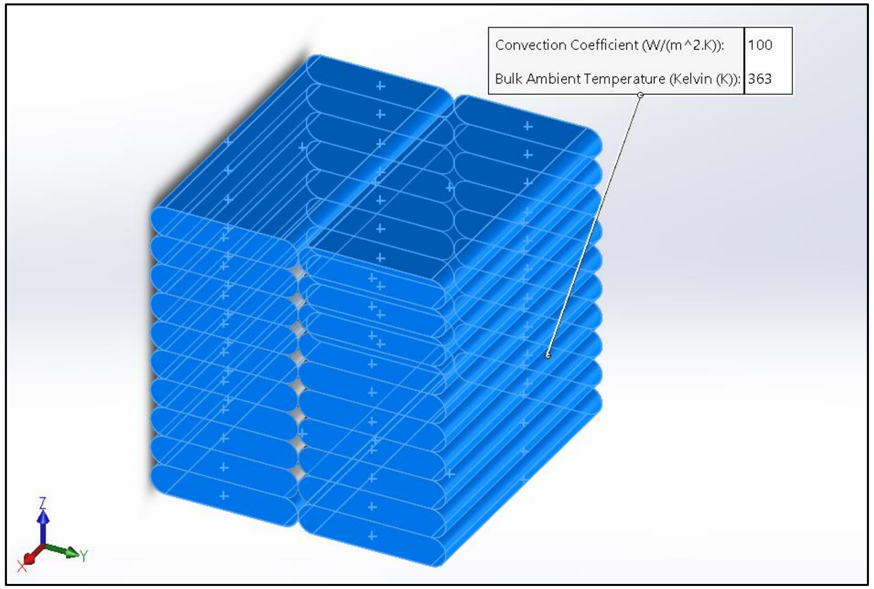
Steady State = ± 1% of average value from final hour

- Thermocouple Study (180°C) was ran using CF-PESU
- Baseline correct, thermocouple reach steady state correct
- Cube center reached steady state 65 minutes after loading

SolidWorks Thermal Simulation





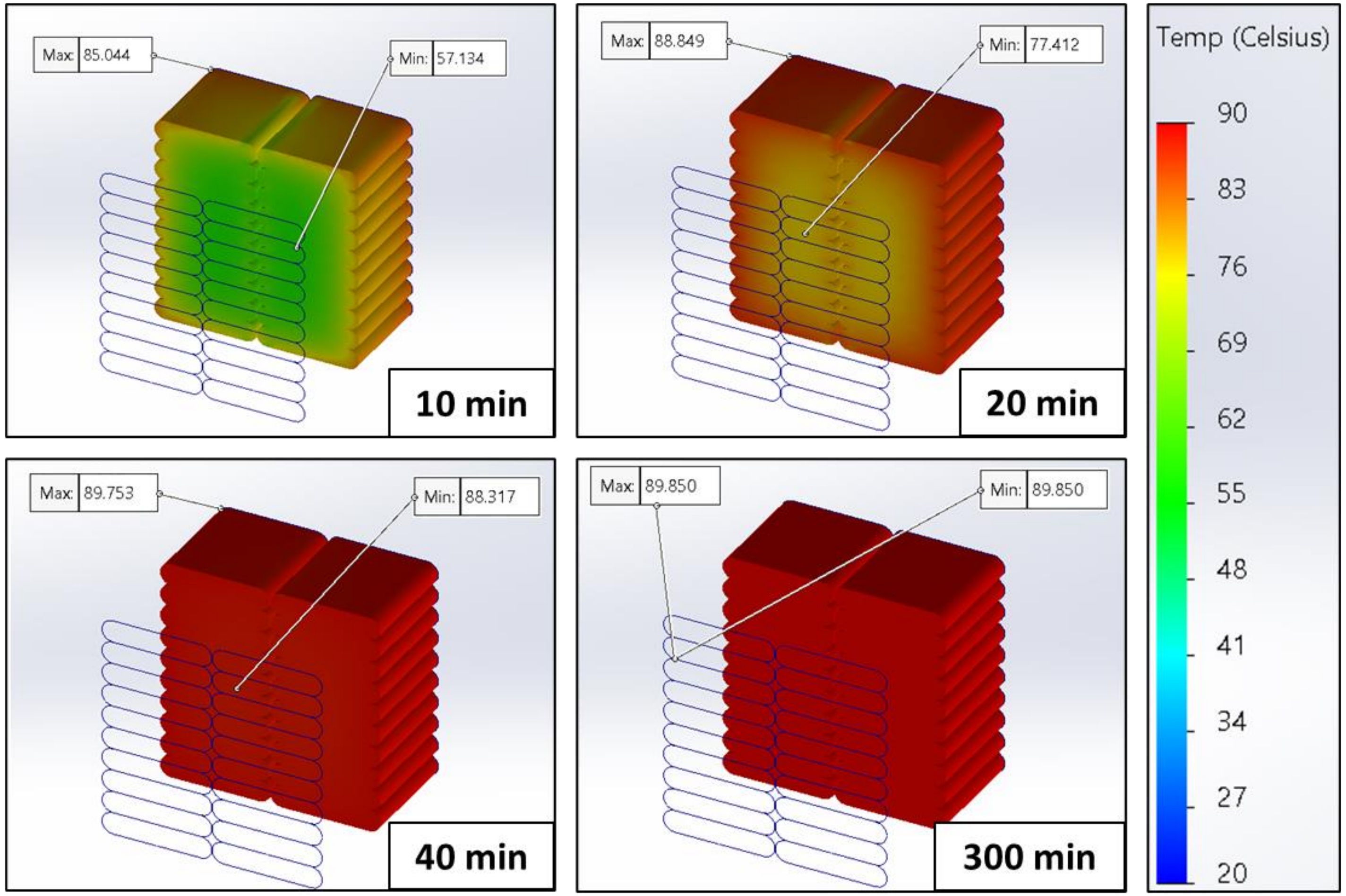


- Customizable based on sample dimensions and directional material properties

- Initial conditions of entire cube at 20°C
- Simulate room temperature conditions

- Thermal load input of convection heating
- Convection Coeff = 100 W/m^2K
- Bulk ambient temp of 90°C

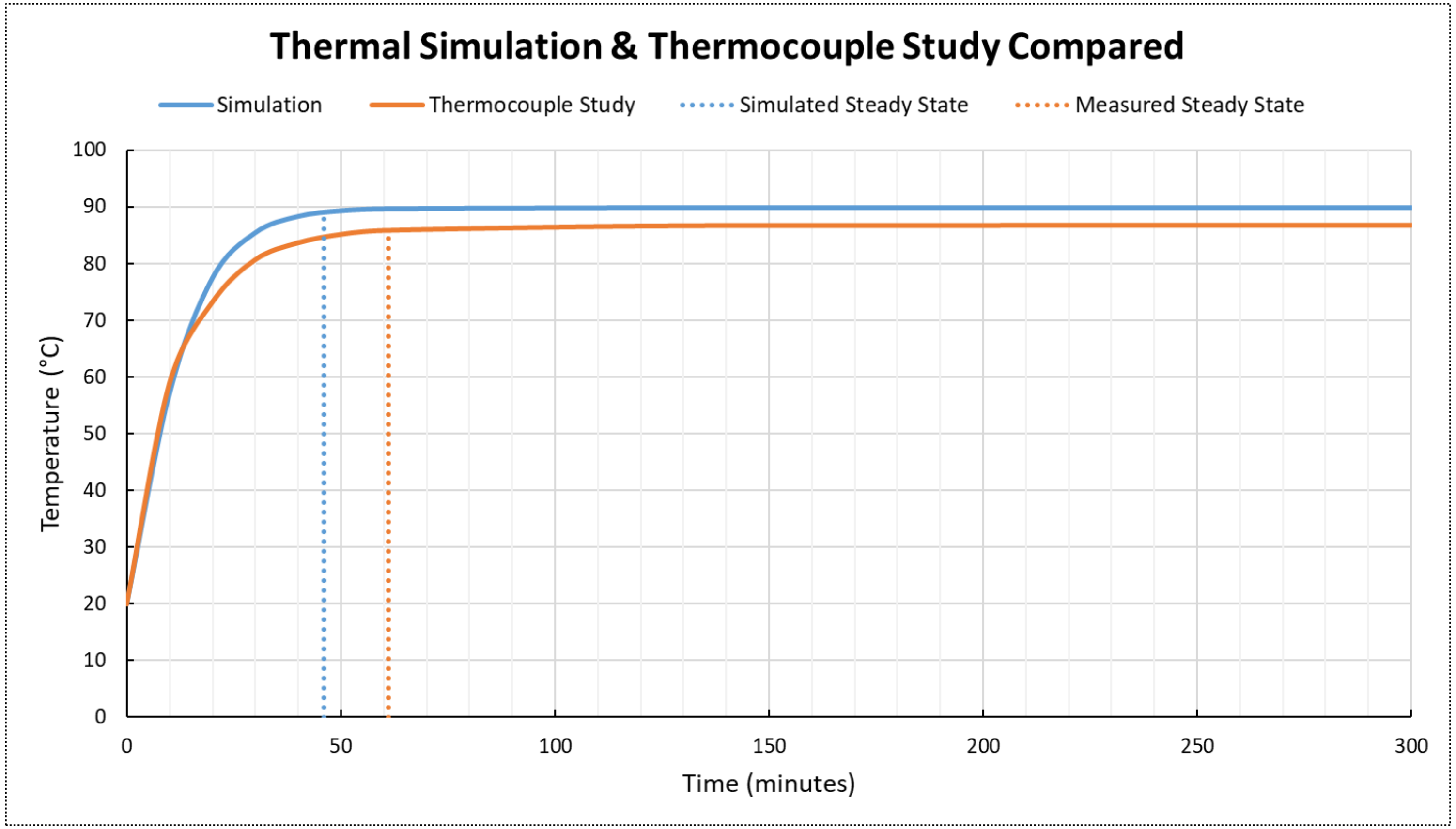
SolidWorks Simulation



Steady State = ± 1% of average value from final hour

- Cut section of thermal gradient from simulation
- Even heating across center
- Surface reached steady state before center as expected
- Simulation tested values for 300 minutes (5 hours)
- Let's compare to the thermocouple study…

SolidWorks Simulation



Steady State = ± 1% of average value from final hour

- Values compared from thermocouple study and thermal simulation
- Very similar trend through first 30 minutes
- Simulation reached steady state 46 min after loading (15 min faster than measured)
- Will better meet oven conditions with ramp heating from thermocouple study

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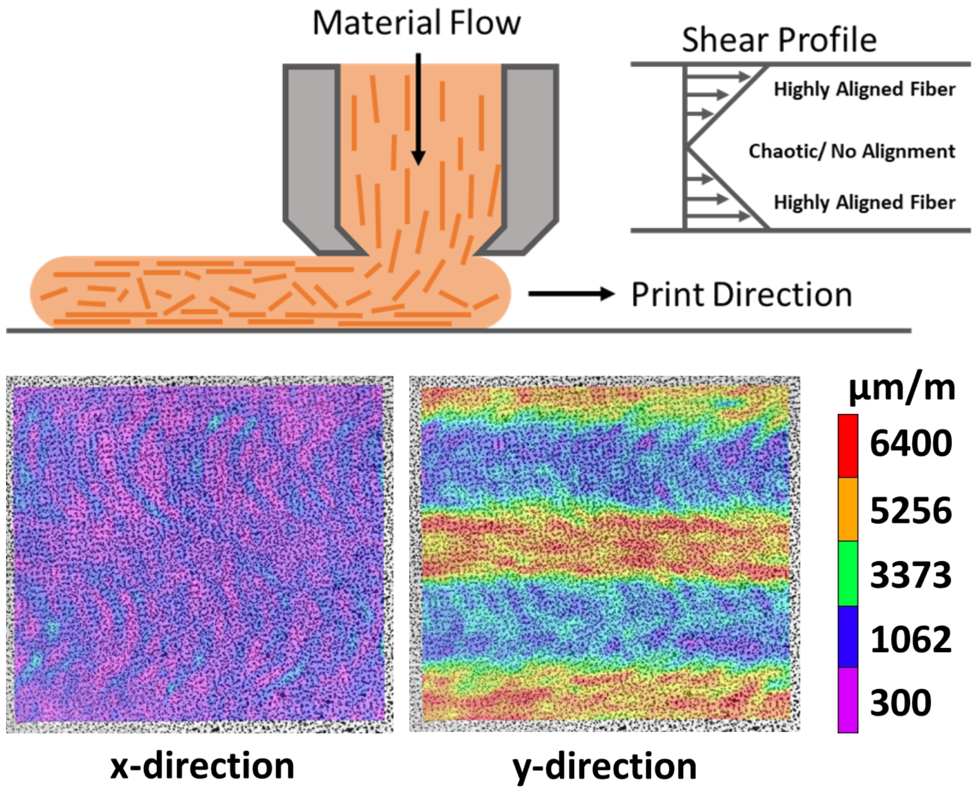
Conclusions

- Successfully measured and compared CTE from fiber reinforced LFAM structures
- GF-ABS & CF-ABS, plate & cube samples
- Identified effects of fiber alignment
- Thermocouple study performed confirmed DIC Oven testing occurred at steady state
- Thermal simulation created as tool for DIC testing to avoid a thermocouple study for every geometry and material



Fiber alignment (top) and effects on thermomechanical properties (bottom)

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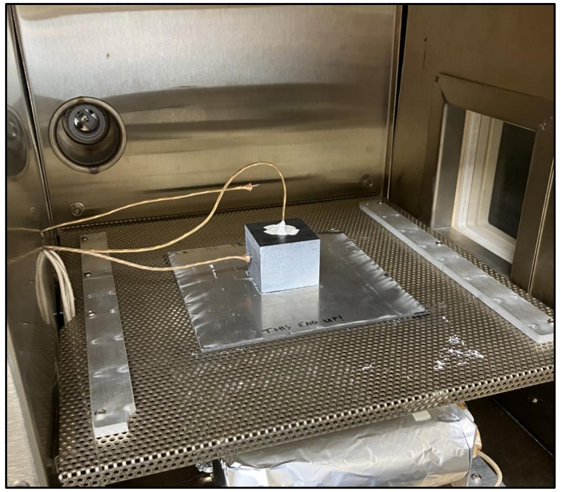
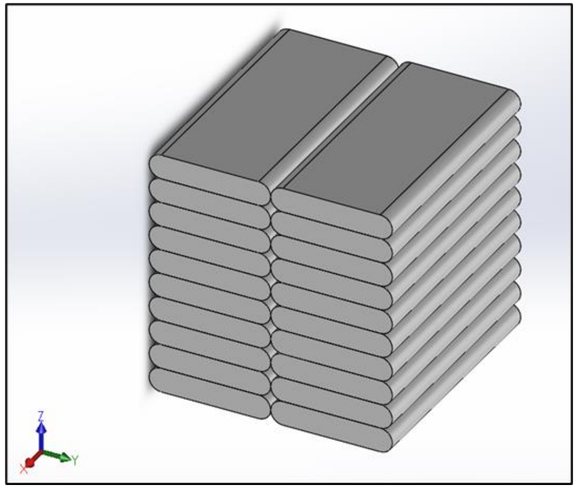
Future Work

- Further compare samples of different print dimensions
- Explore other ways to make CTE more homogenous (e.g. control fiber alignment)
- Improve thermal simulation by adding ramp heating from thermocouple study

Thermocouple validation ran during to ensure steady state conditions





Modeled CF-PESU cube for thermal simulation in SolidWorks

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SEAMTN Southeastern Advanced Machine Tools Network

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