Tow-steered Composite Panels with Defects and an Initial Analysis Framework

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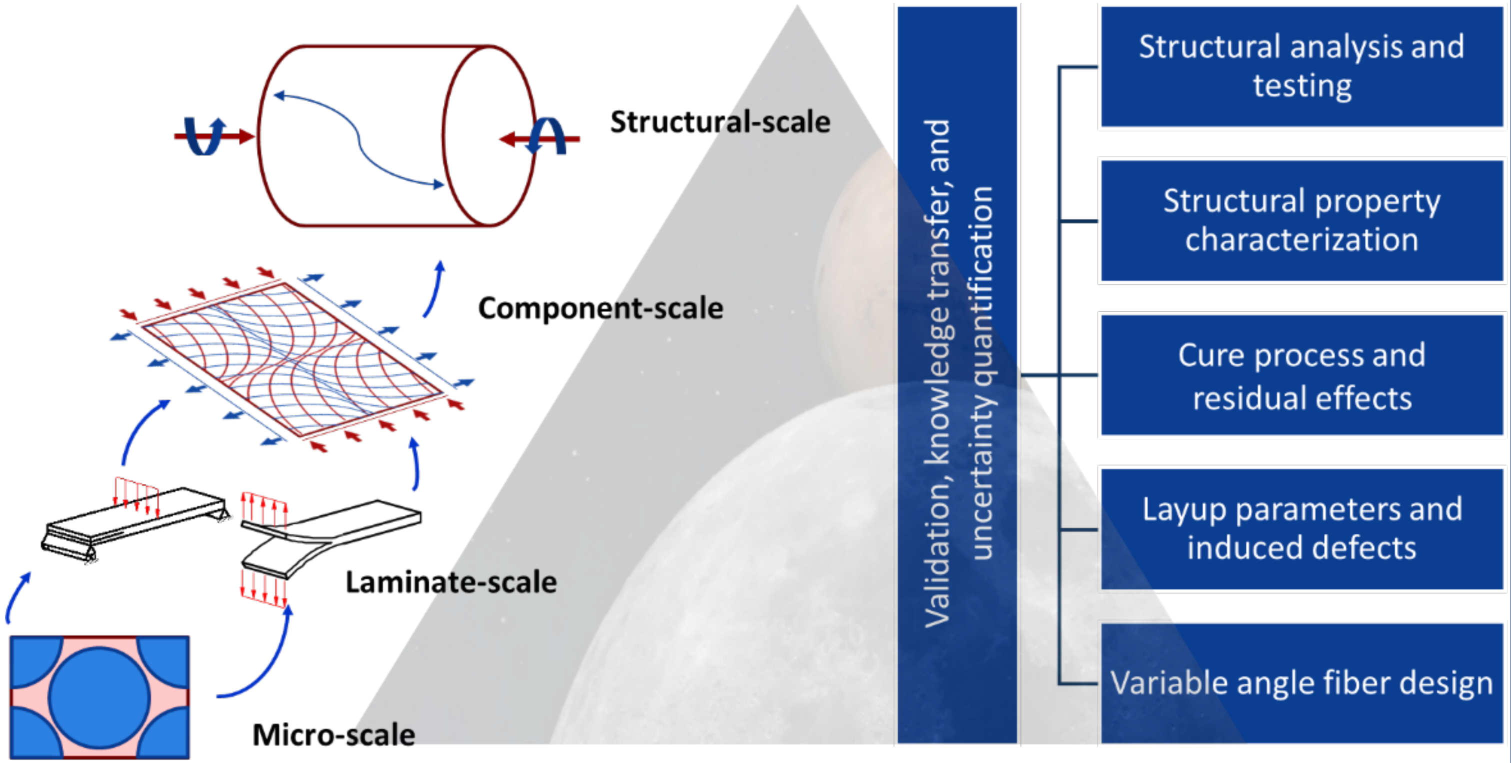
Outline

- Background
- Motivation for the current work
- Tow-steering and a recent panel design
- Intentional defect design
- Panel fabrication
- Inspection techniques
  - Thermography
  - In-situ cure ultrasonic transmission (UT)
  - Post-cure UT
  - Structured light scanning
- Initial framework development
- Concluding remarks

Background

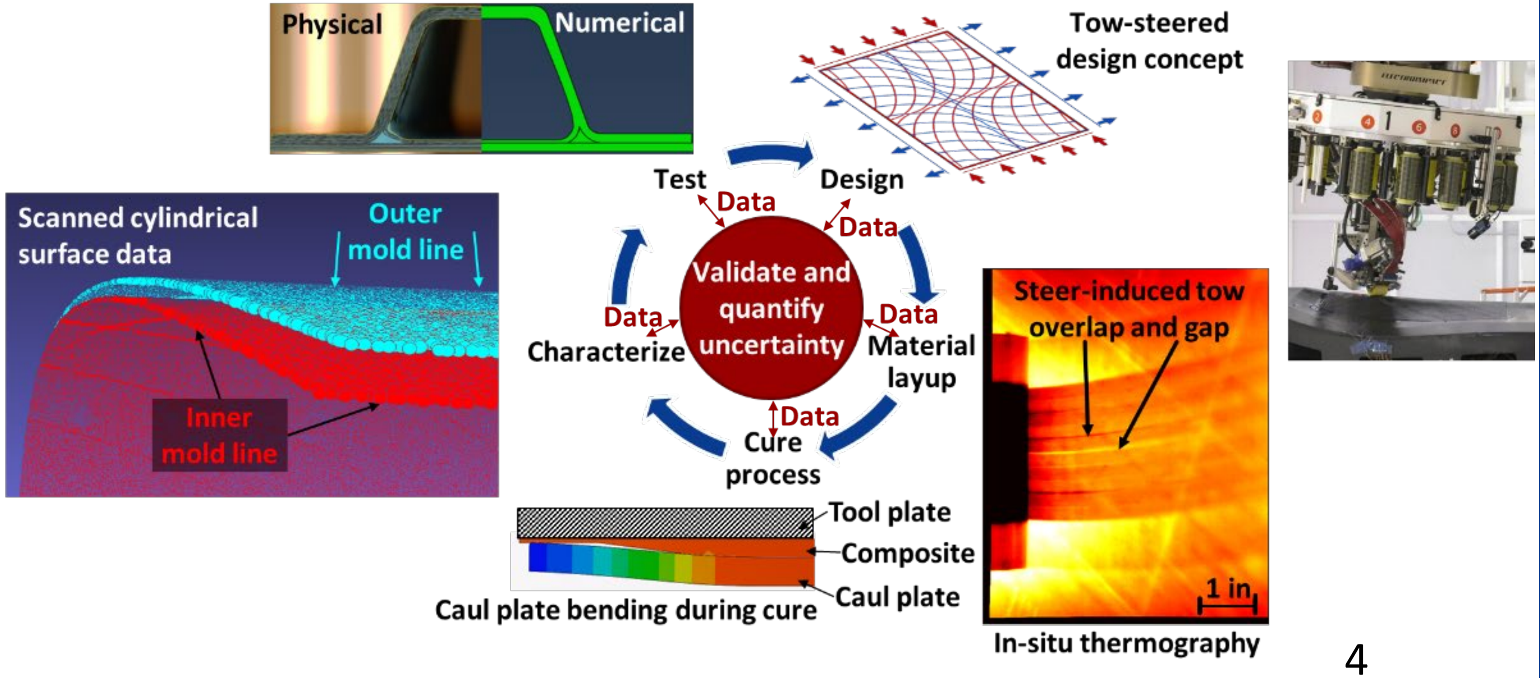
- Unidirectional carbon fiber reinforced polymer (CFRP) composites offer designers many ways to tailor specific structural properties and performance
- When combined with automated fiber placement (AFP) techniques, variable fiber angles within a ply are often called **tow-steered composites**
- Building block approaches have been successfully applied for material and structural characterization of composites
- Tow-steered CFRP structures are currently difficult to design, manufacture, analyze, and characterize



Motivation

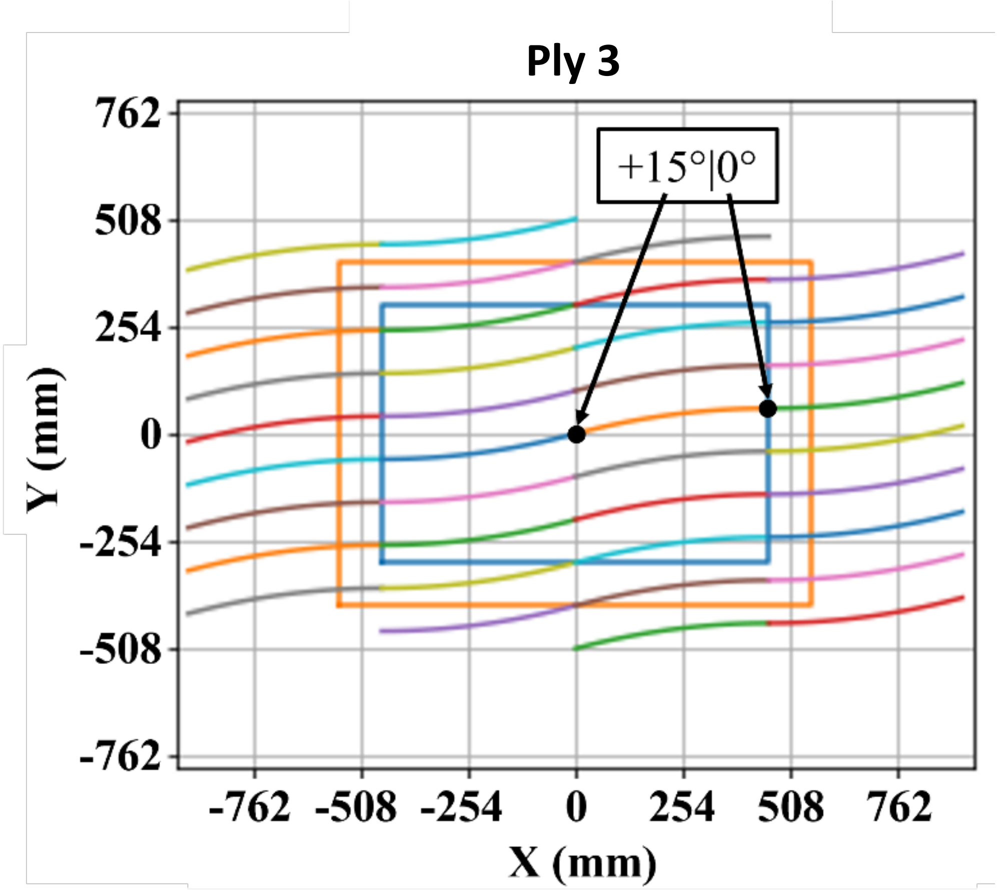
- Complex thermo-chemo-mechanical interaction during cure often results in tow-steered structures with detrimental residual stresses and deformation
- Advanced workflows such as Industry 4.0, digital engineering, and digital twins focus on integrating data and processes into numerical analyses to increase confidence that a virtual process will resemble a physical structure
- Understanding nontraditional data collection methods can be informative to an iterative process, particularly while defects are known to occur

Advance Air Transport Technology (AATT)
Transonic Truss-braced Wing (TTBW)



Panel Design

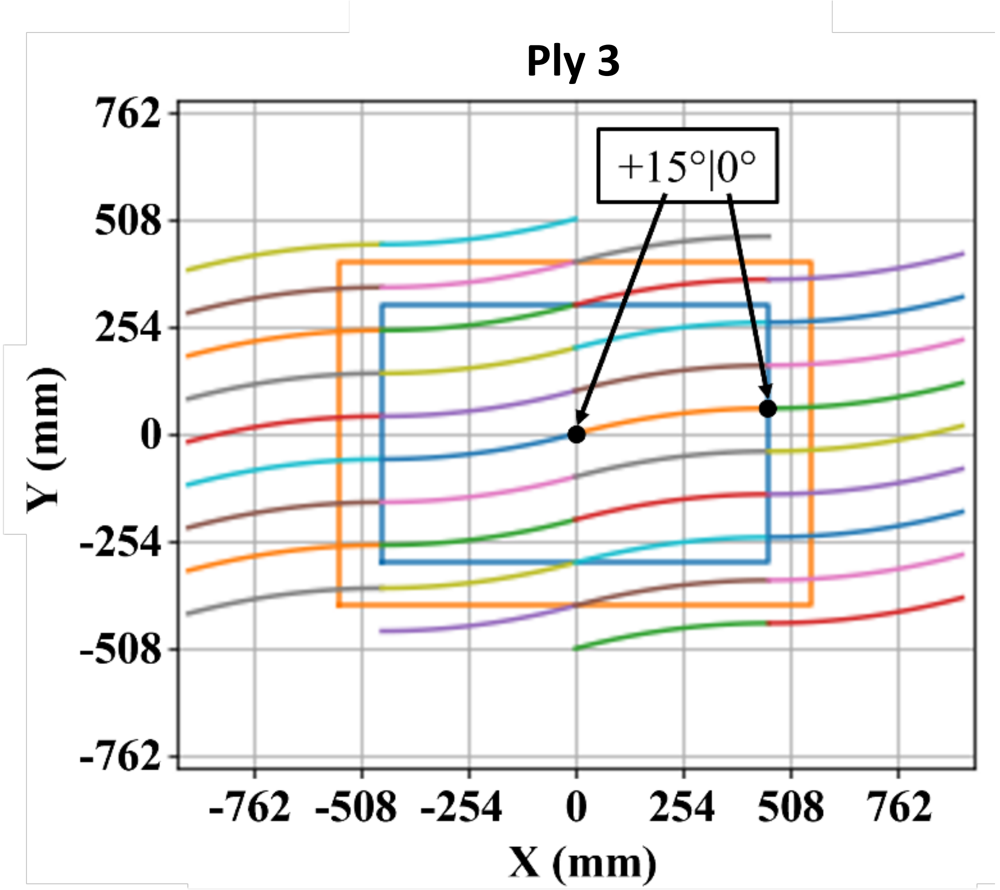
- Panels were a hybrid of straight and tow-steered plies
  - Panel-1 was fabricated with all observed defects corrected
  - Panel-2 was fabricated with intentionally placed defects
- In-house developed tow-steering design tool
  - Automated Tool for Steered Composite Optimizable Laminates (ATSCOOL)*
  - Uses constant circular arcs to define curvilinear fiber paths
  - Applicable to flat laminates
  - Simple input (four variables) to define a complete tow-steered ply



*Mason, et al., "A Tool for Defining Tow-Steered Laminates for Finite Element Grids," NASA/TM-2023-0015301

Panel Design

- Nominally flat panel
  - Thickness variation due to tow gaps and overlaps resulting from tow-steered design
- Hexcel®* IM7/8552-1 unidirectional carbon fiber prepreg tows
  - 6.35 mm wide
  - 160 gsm
  - 16 tows per course
  - No tow-width offsets
- Panels dimensions of 914 mm by 609 mm
- Constant 1,767 mm radius-of-curvature for all tow-steered plies



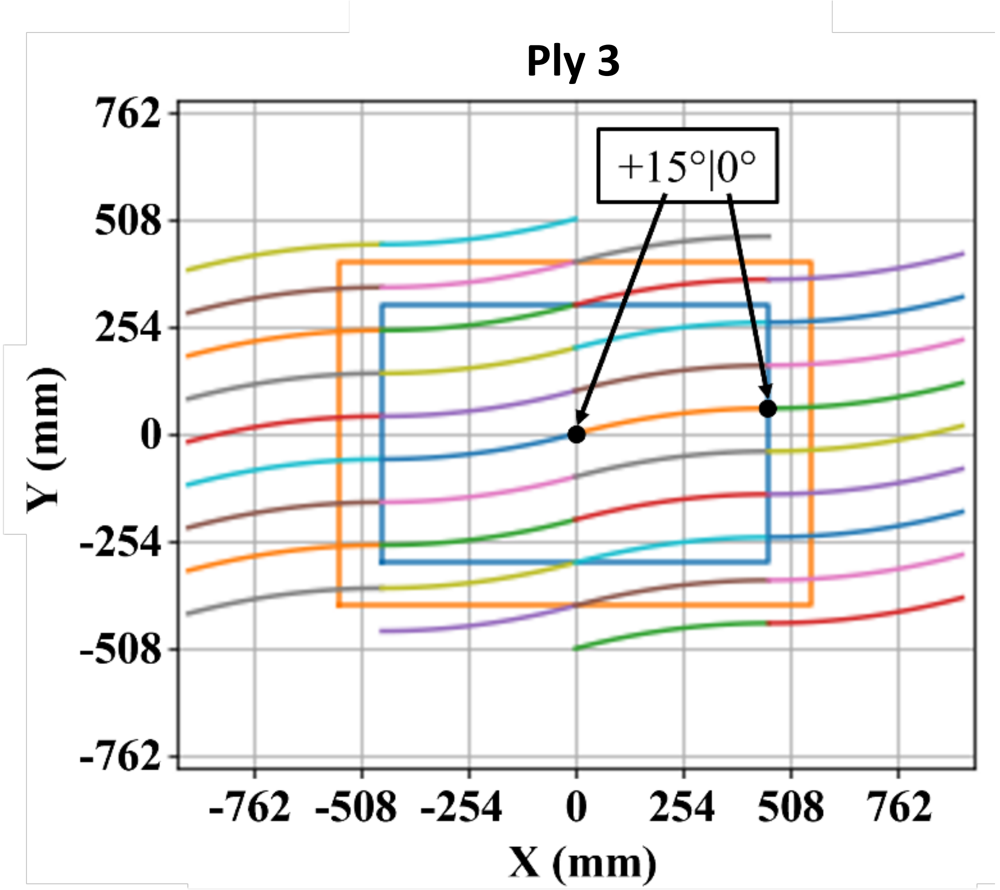
*The use of trademarks or names of manufacturers in this presentation is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration

Panel Design

Ply	Orientation
1	+45°
2	-45°
3	+15°|0°
4	-15°|0°
5	+75°|+90°
6	-75°|-90°

Ply	Orientation
7	0°|+15°
8	0°|-15°
9	+75°
10	-75°
11	0°
12 (symmetric)	90°

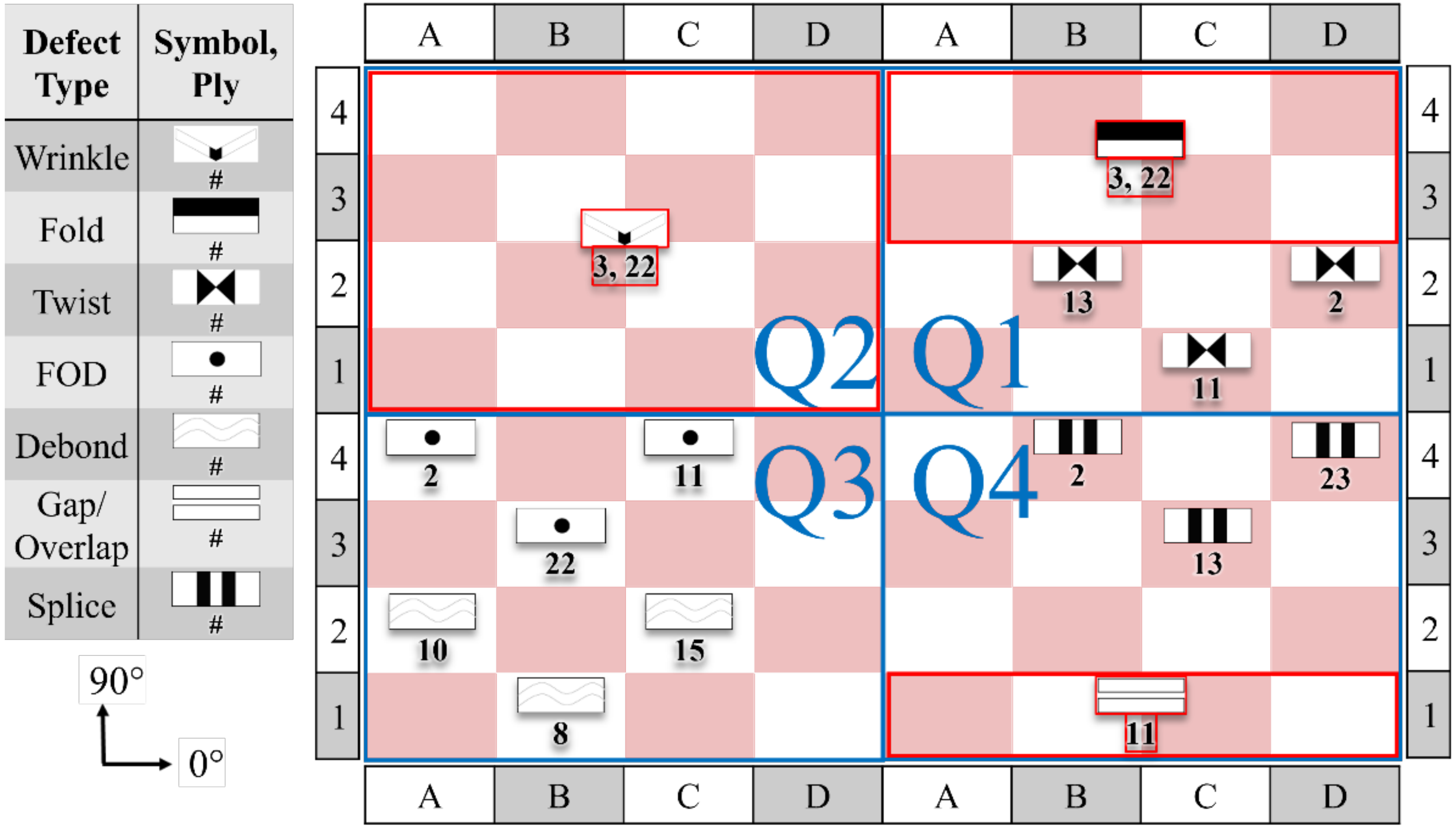
Shaded ply orientation denotes a tow-steered ply



Panel design was from previous work by Kosztowny and Simmons, "The Effect of Fiber-angle Fidelity on the Linear Response of Tow-steered Composite Plates," *American Society for Composites 38th Technical Conference*, Woburn, MA, September, 2023.

Intentional Defect Design

- Panel-2 was fabricated with 17 intentionally placed defects
  - All unintentional defects that were observed were corrected
  - Defect symbols adapted from Harik, et al.*
- Panel-2 segmented into
  - Four quadrants
  - 16 cells within each quadrant
  - Only one defect type was placed in a cell

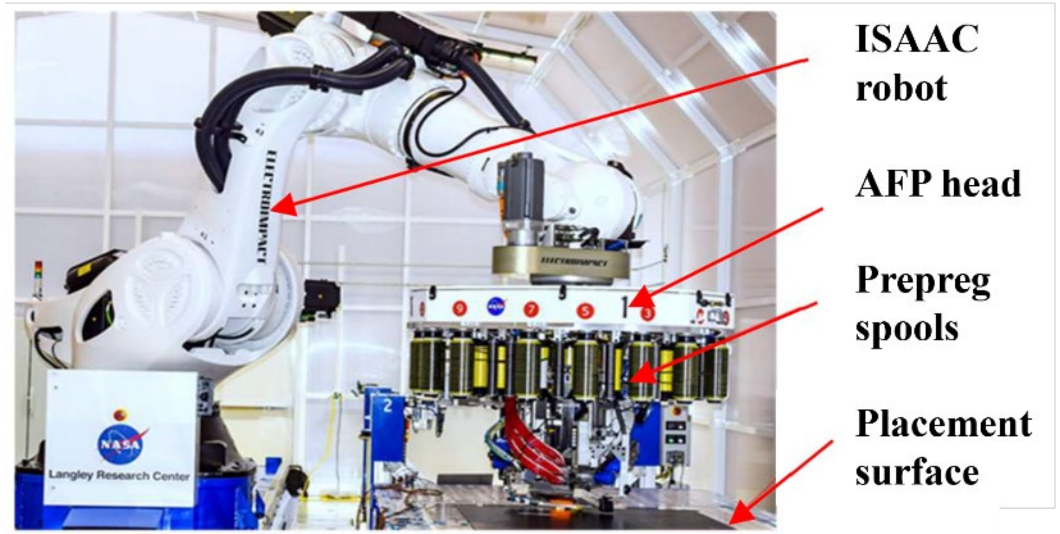


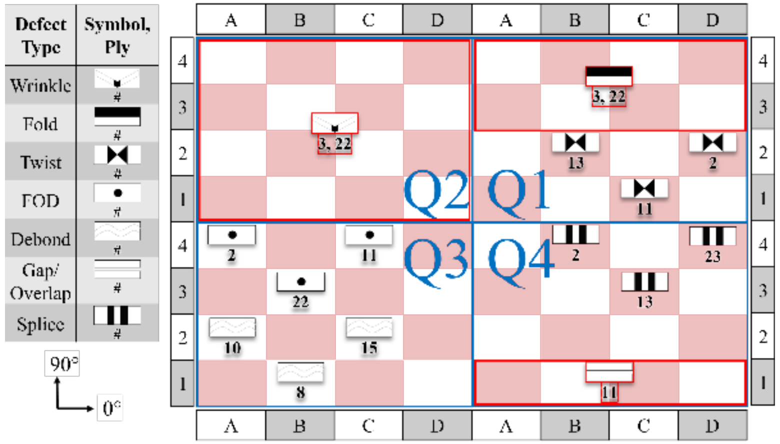
FOD = Foreign object debris

*Harik, et al., "Automated Fiber Placement Defect Identity Cards: Cause, Anticipation, Existence, Significance, and Progression," SAMPE Technical Conference, Long Beach, CA, May, 2018

Panel Fabrication

- Integrated Structural Assembly of Advanced Composites (ISAAC)
  - Electroimpact® robotic arm
  - 16-spool AFP head
  - Used to place straight and tow-steered plies
- Manual correction of unintentional defects in Panel-1 and Panel-2
- Manual implementation of intentional defects in Panel-2
- A 30-minute debulk was performed after the 12th and 24th ply placement

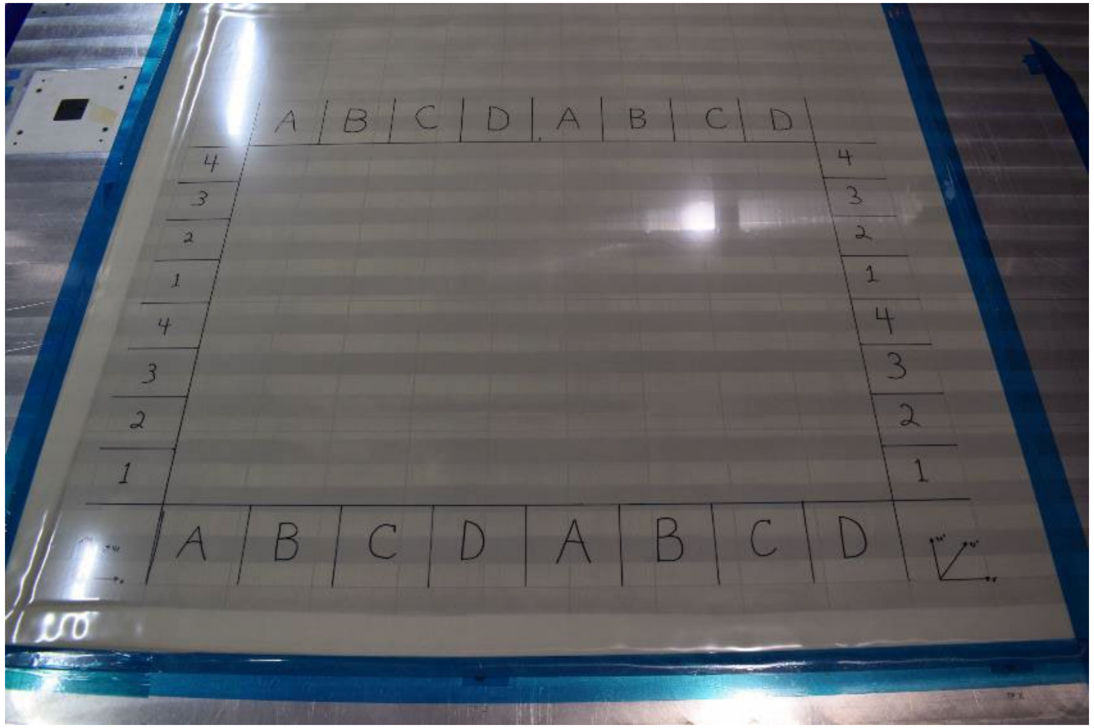




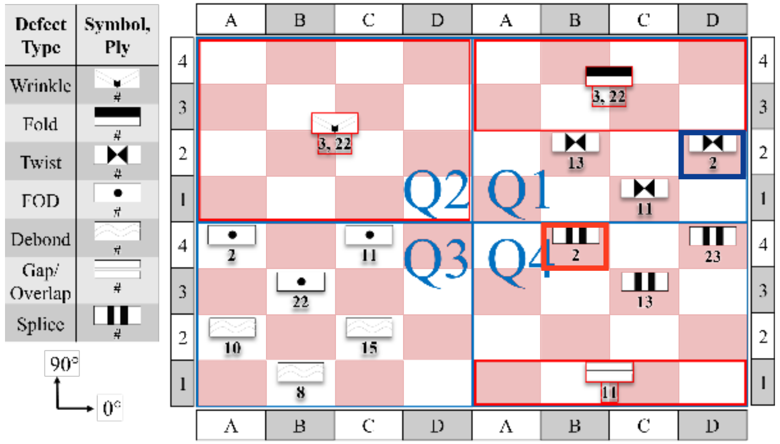
Panel Fabrication

Initial build template for Panel-2

Ply 1 (+45°) of Panel-2

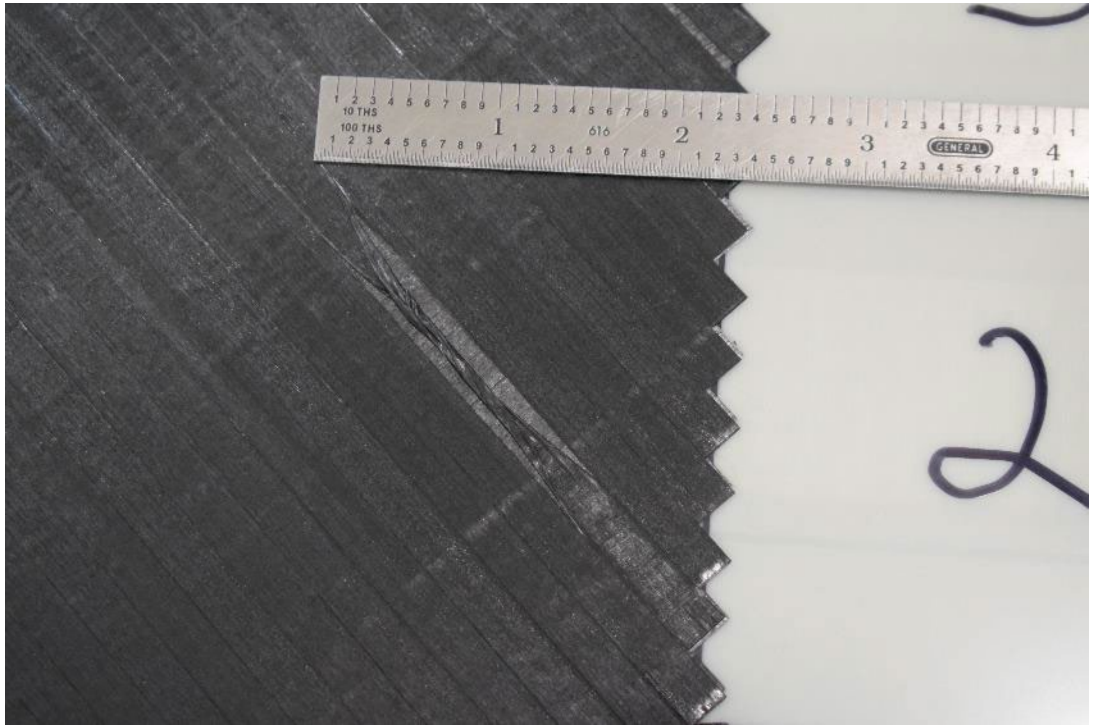


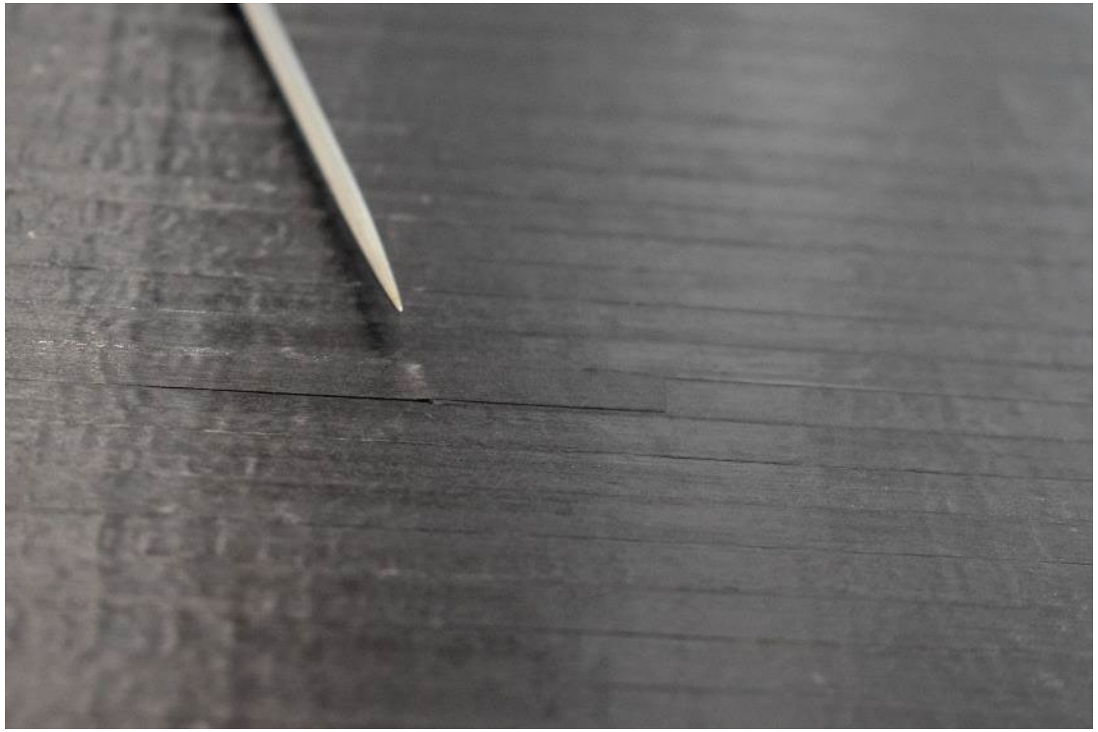
Panel Fabrication



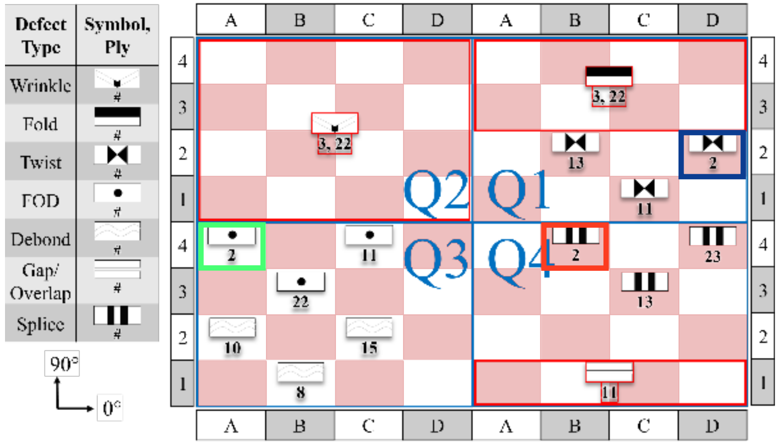
Q1D2 twist in ply 2

Q4B4 splice in ply 2



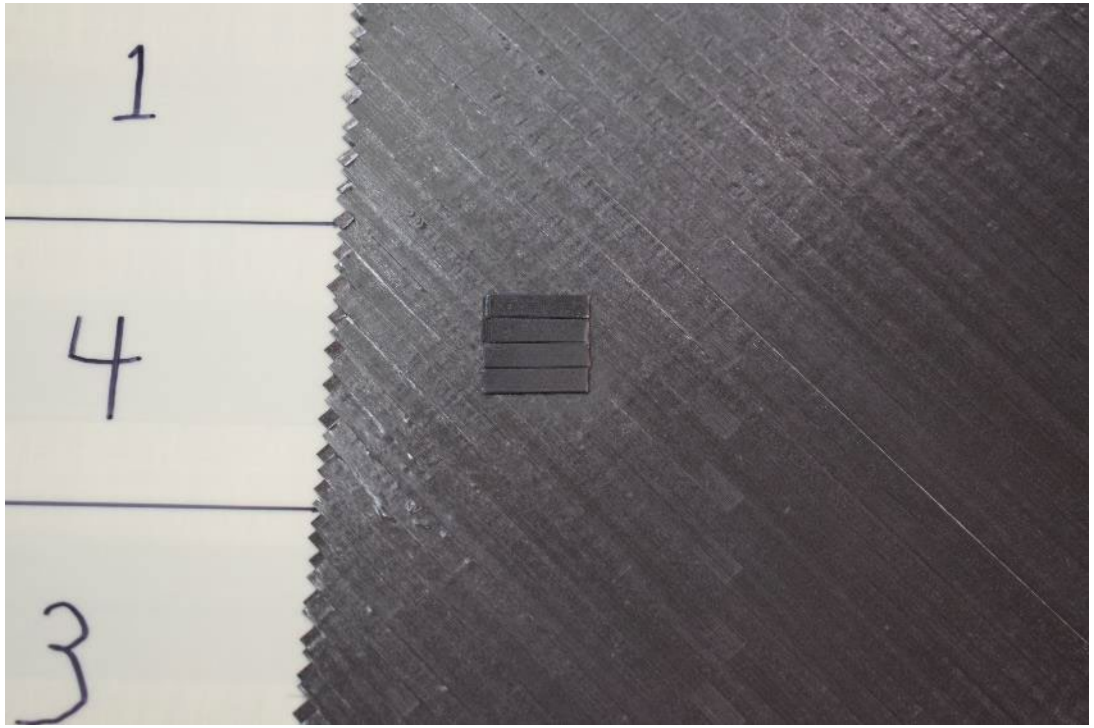


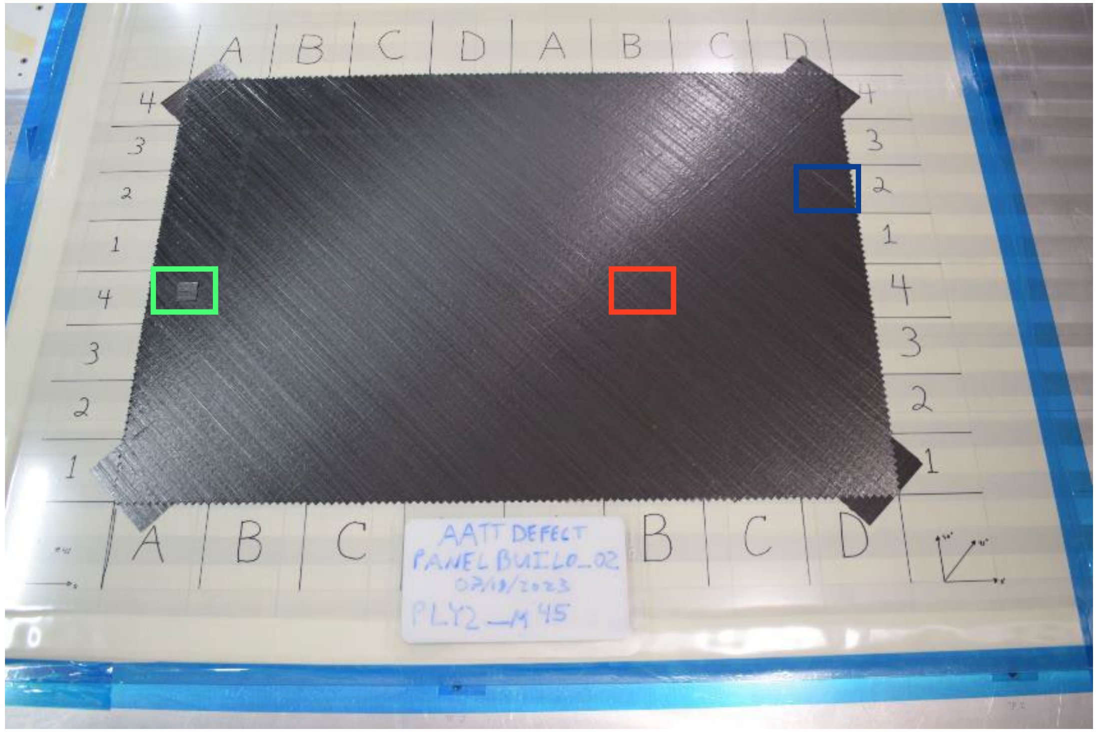
Panel Fabrication



Q3A4 FOD in ply 2

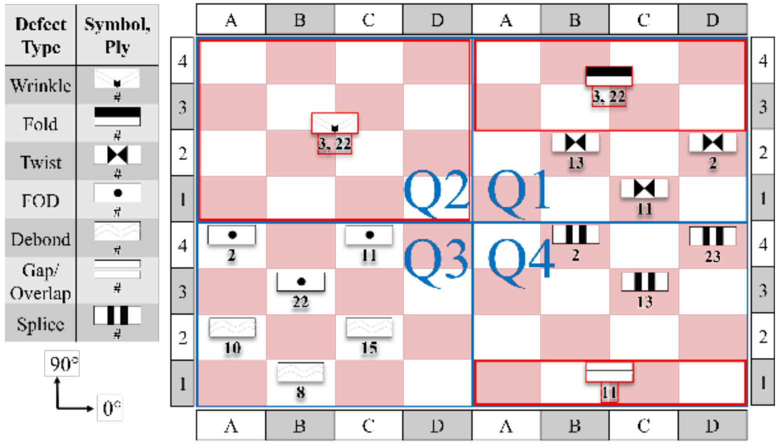
Overview of ply 2 defect locations





Ply 2 Defects after Ply 3 Placement

Panel Fabrication



Panel-1 (no intentional defects)

Panel-2 (with intentional defects)

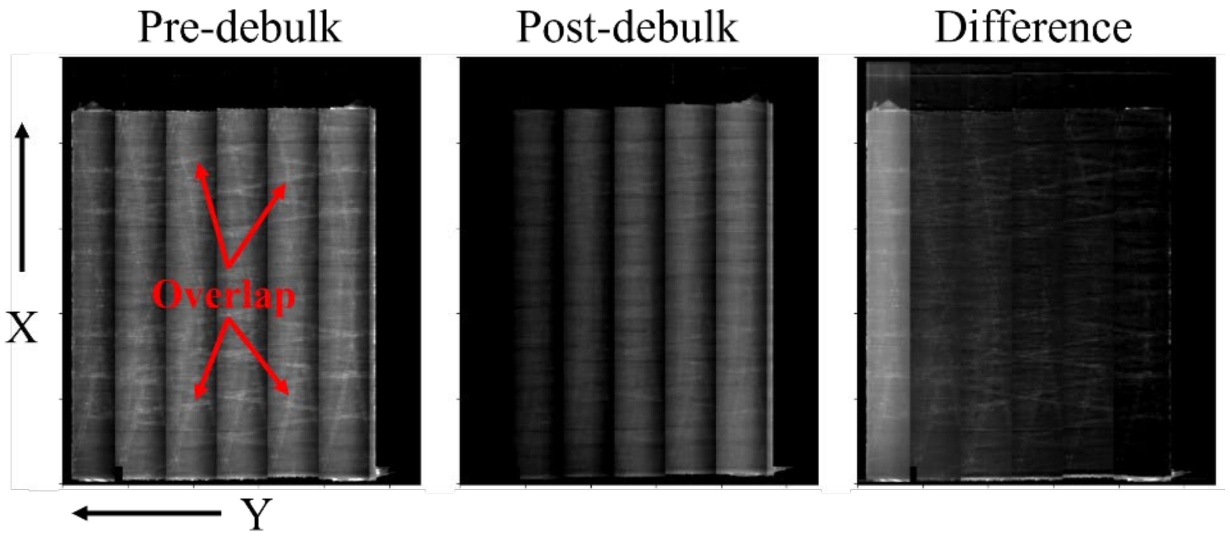
- The manufacturer's recommended cure cycle in an autoclave was followed for both panels
- Vacuum was maintained (instead of released) to ensure panel was secured against tool

Inspection Using Four Techniques

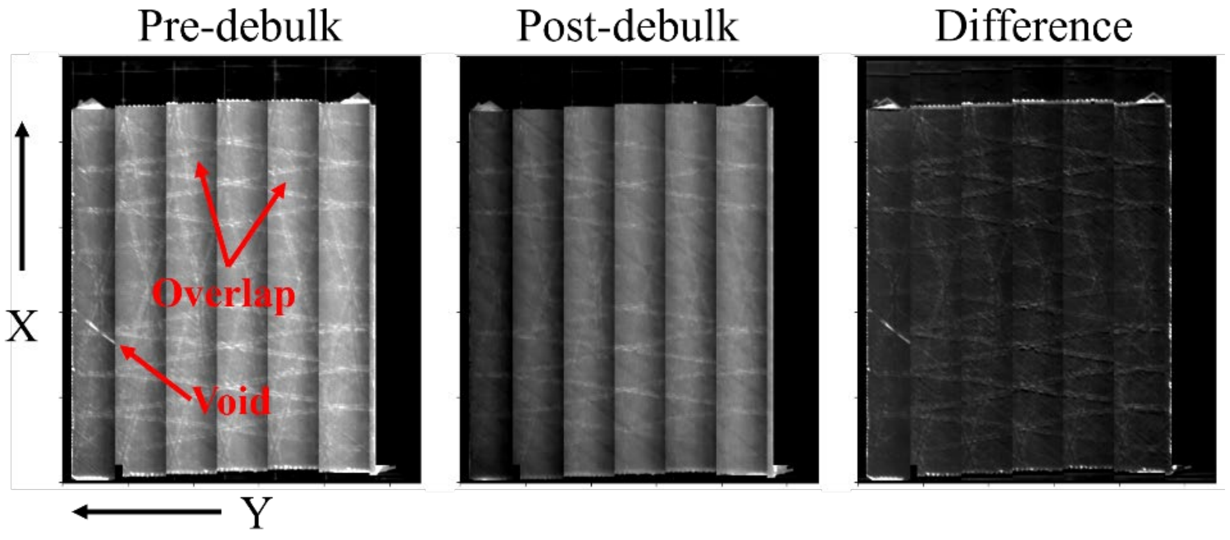
- Thermography
  - FLIR A65 thermal camera mounted to ISAAC AFP head
  - Collected pre- and post-debulk full-panel scans
- In-situ cure UT
  - High-temperature, in-house developed system to monitor cure process
  - Inspection region with 2.25 MHz transducer around tow folds and twist
- Post-cure UT
  - Water-immersion, in-house developed system to detect porosity and delamination
  - Full-panel inspection with a 2.25 MHz and 10 MHz transducer
- Structured light scanning
  - MetraSCAN 750 Elite photogrammetrically located 3D handheld system
  - Scans of bag- and tool-sides were post-processed into thickness and 3D surface data

Inspection: Thermography

Panel-1, after 12th ply placement



Panel-1, after 24th ply placement

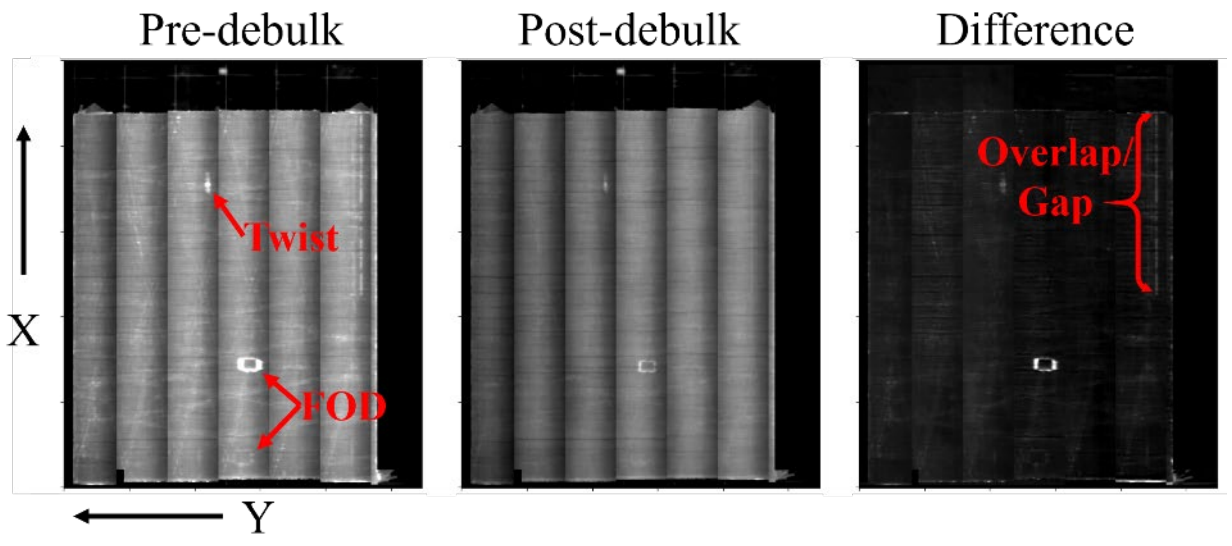


- Changes in brightness or intensity indicate how much heat flow occurred in the material
- Air gaps, thickness changes, or other interfaces may alter heat flow

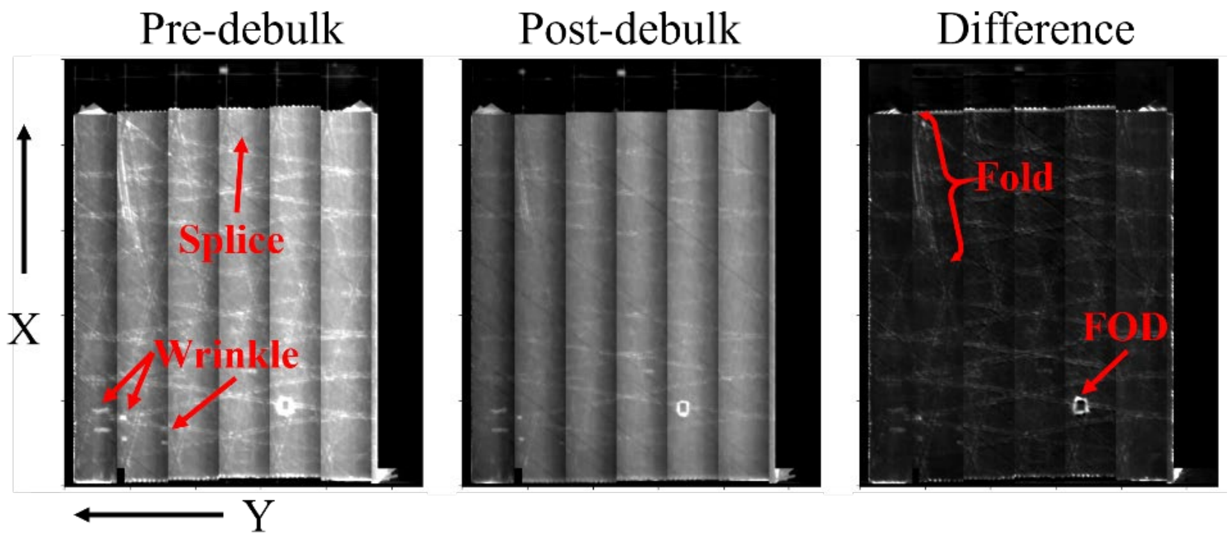
- Tow overlaps due to steering are apparent
- One void, removed after the second debulk, was observed

Inspection: Thermography

Panel-2, after 12th ply placement



Panel-2, after 24th ply placement



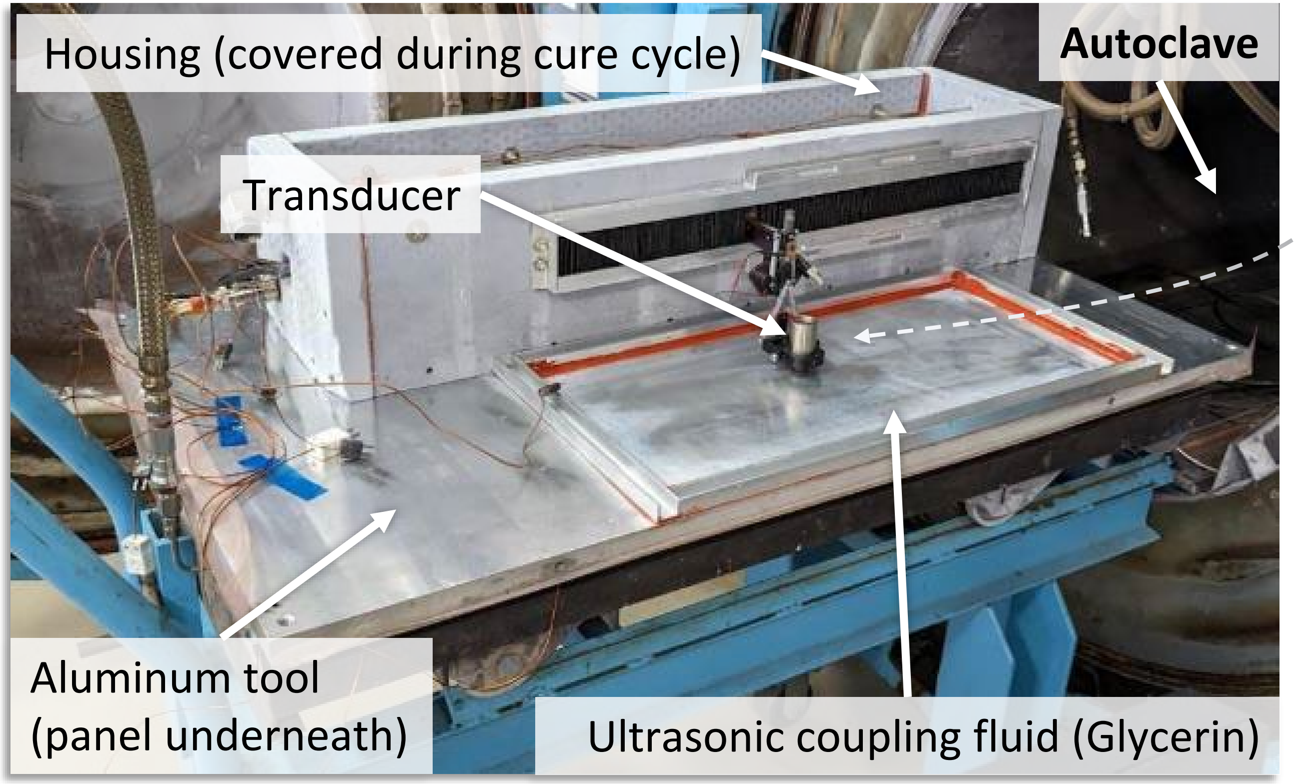
- Changes in brightness or intensity indicate how much heat flow occurred in the material
- Air gaps, thickness changes, or other interfaces may alter heat flow

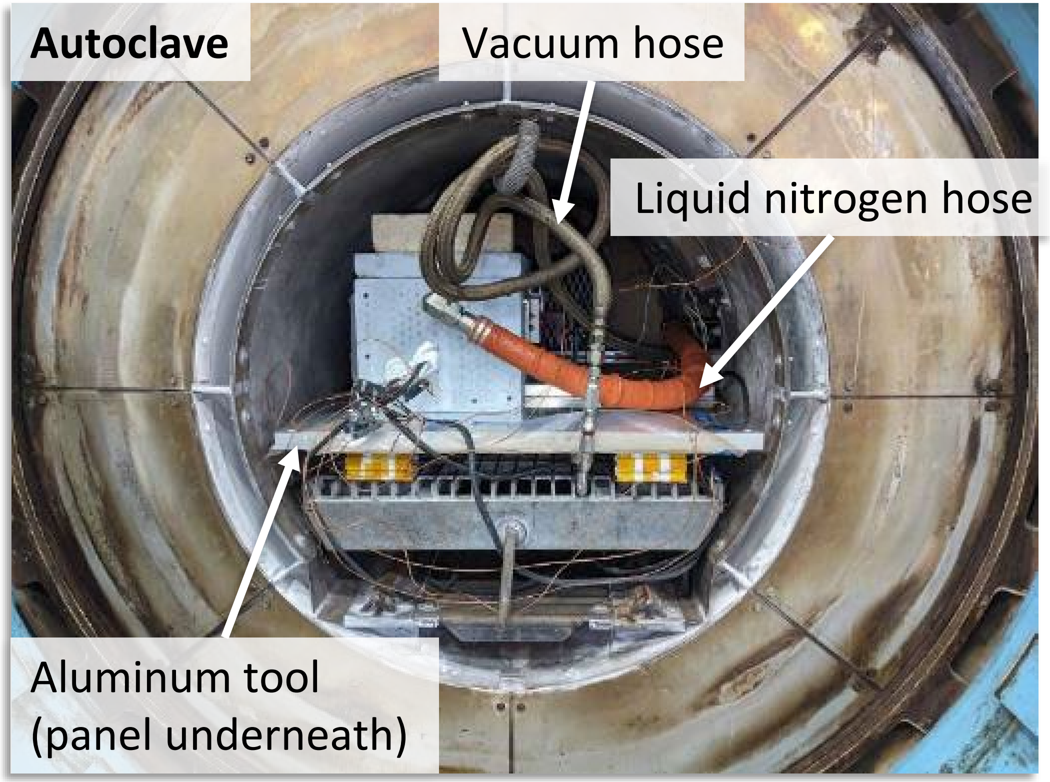
- Significant fiber bridging observed around FOD
- Twist, splice, wrinkle, overlaps, and folds were detected

Inspection: In-situ Cure UT

- Monitored cure process and fold defect

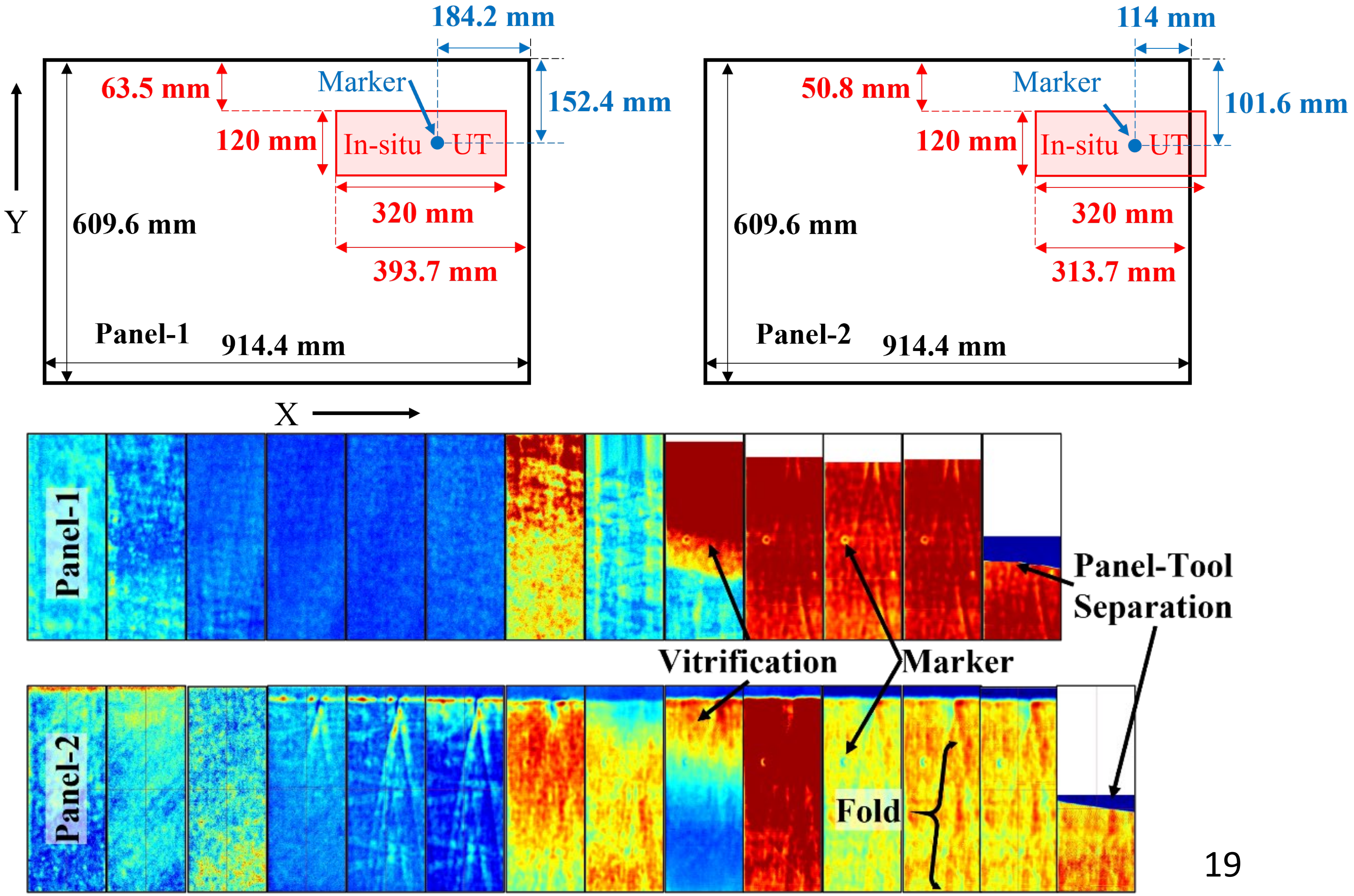
Cure monitoring transducer





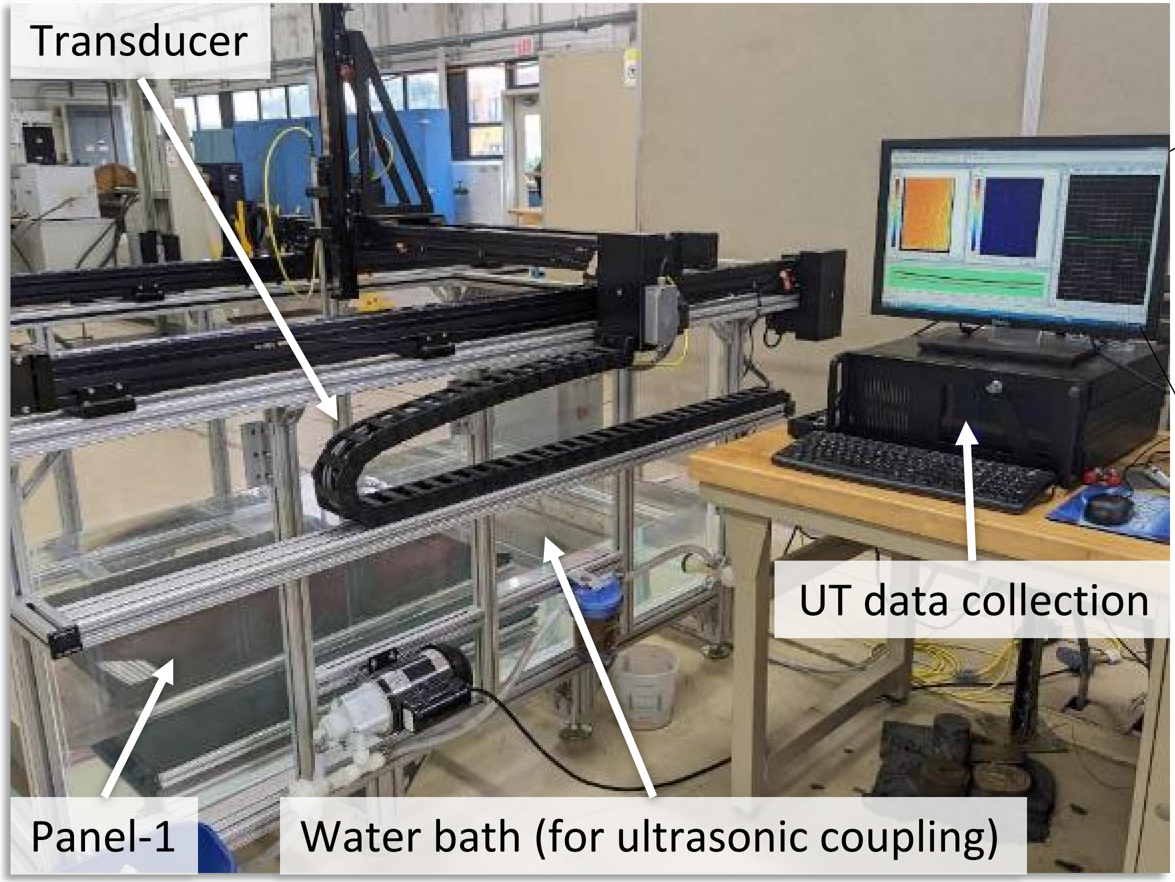
Inspection: In-situ Cure UT

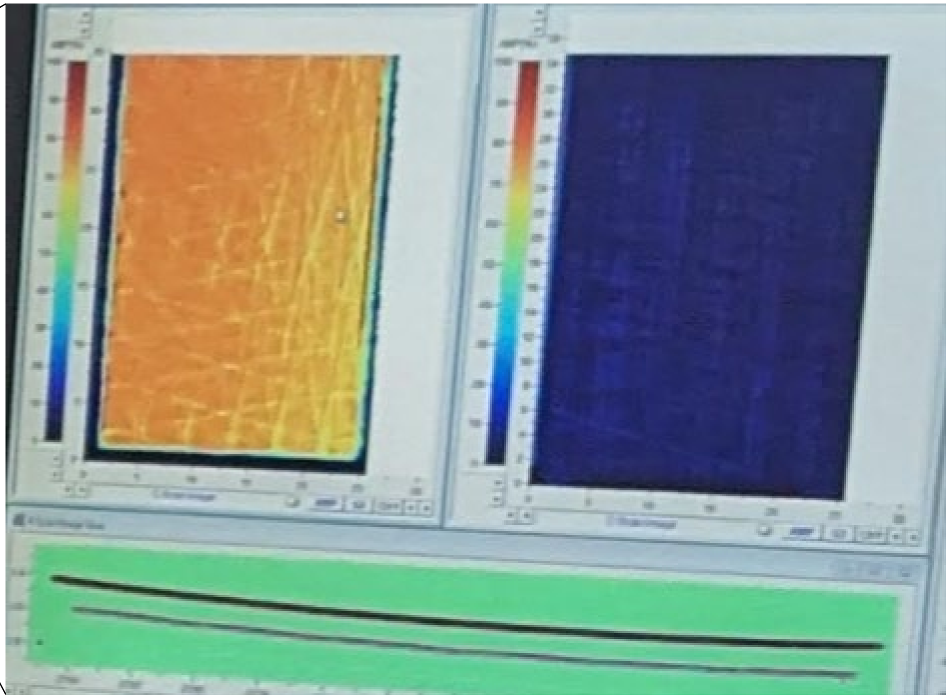
- A marker was placed on the bag-side panel surface to track with the UT system during cure
- Each scan took about 30 minutes
- No additional scans were performed after the panel separated from the tool during cool down
- Thermocouple data (not shown) was also collected at various locations



Inspection: Post-cure UT

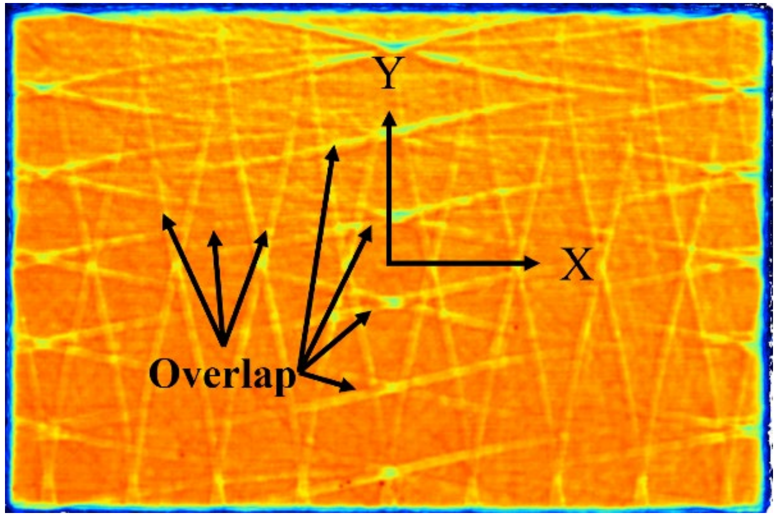
- Bag-side up and tool-side up scans with both 2.25 MHz and 10 MHz transducers were performed



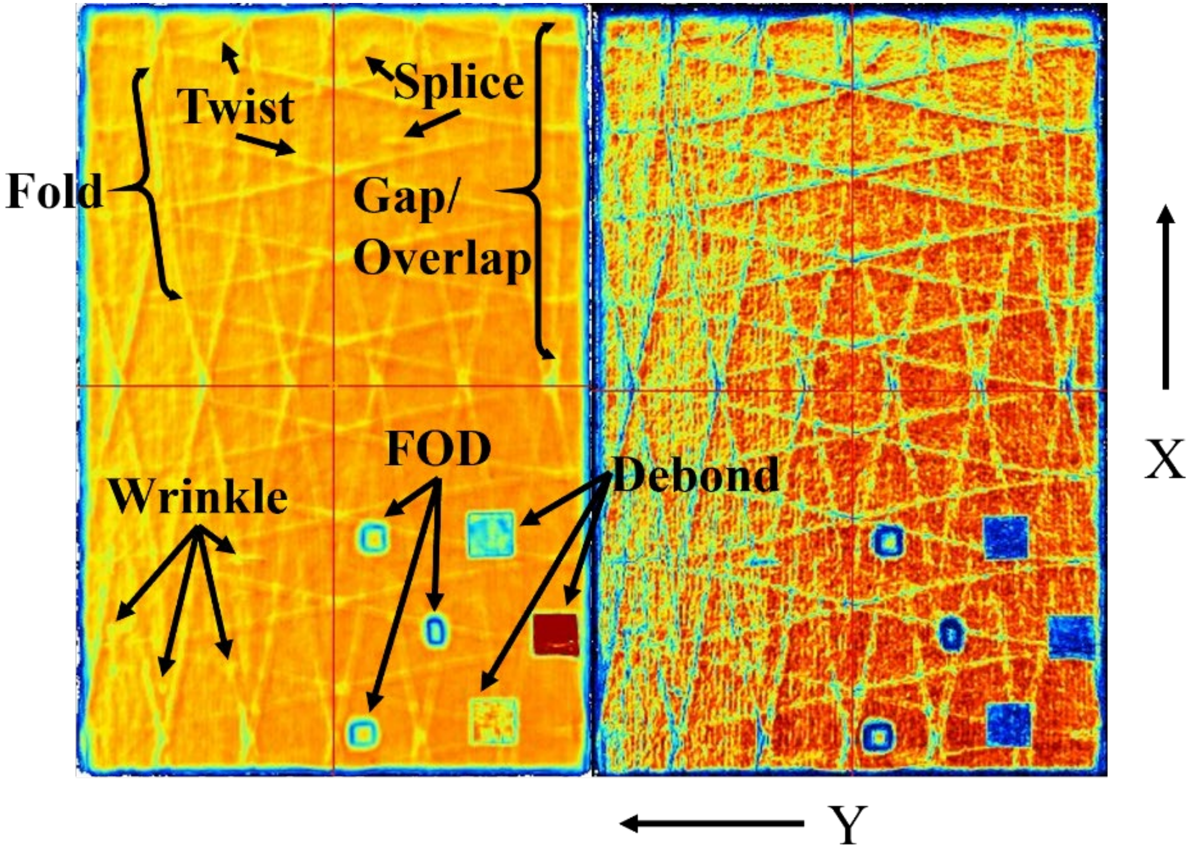


Results preview

Inspection: Post-cure UT

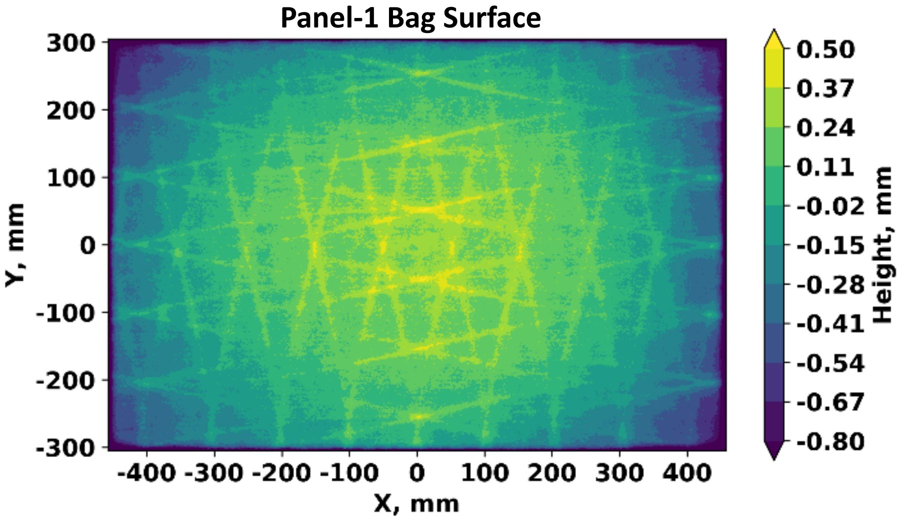


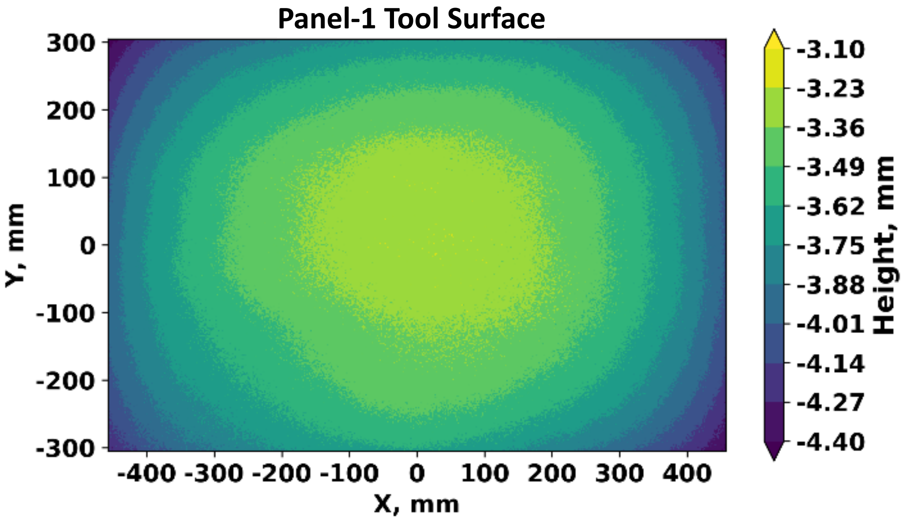
- Panel-1 2.25 MHz scan
- Changes in color indicate varying back-wall amplitude UT signal strength – a measure of signal attenuation and not strictly thickness
- Air gaps, thickness/contour changes, or other interfaces may alter UT signal attenuation

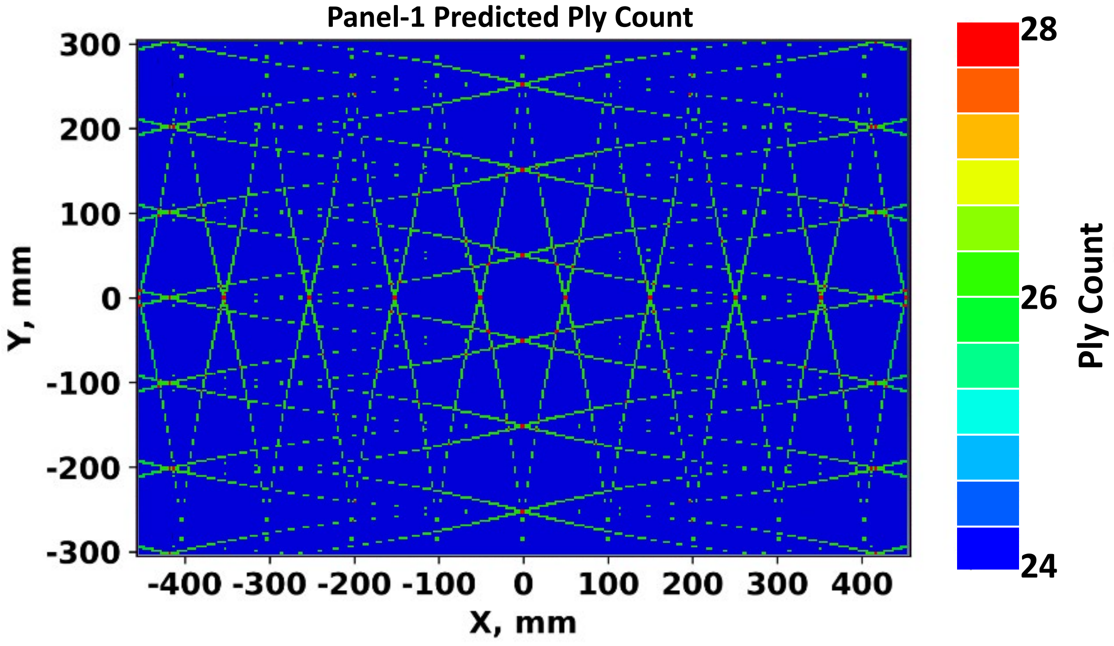


- Panel-2 2.25 MHz scan (left) and 10 MHz scan (right)
- All implemented defects were observed

Inspection: Structured Light Scanning



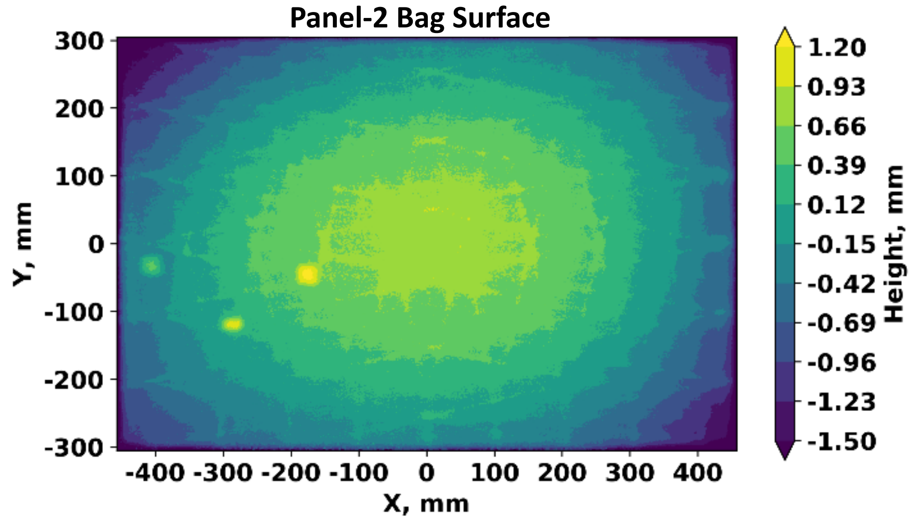


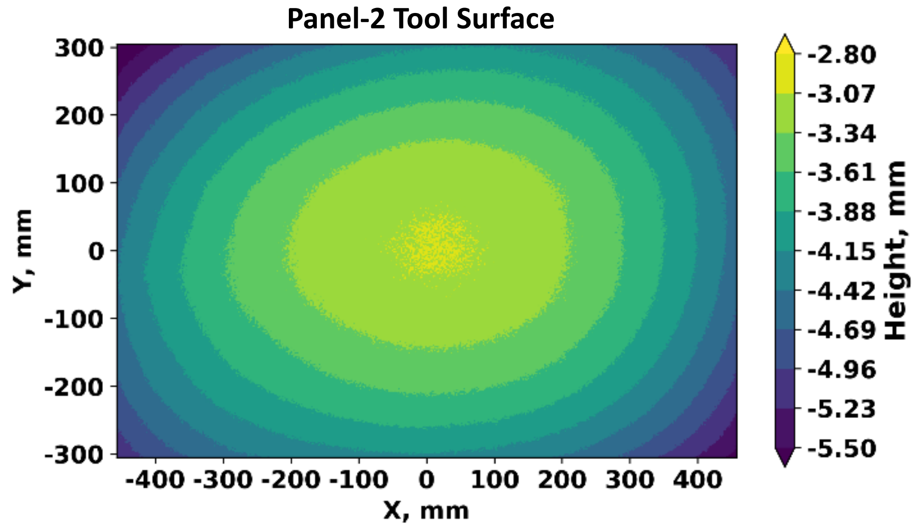


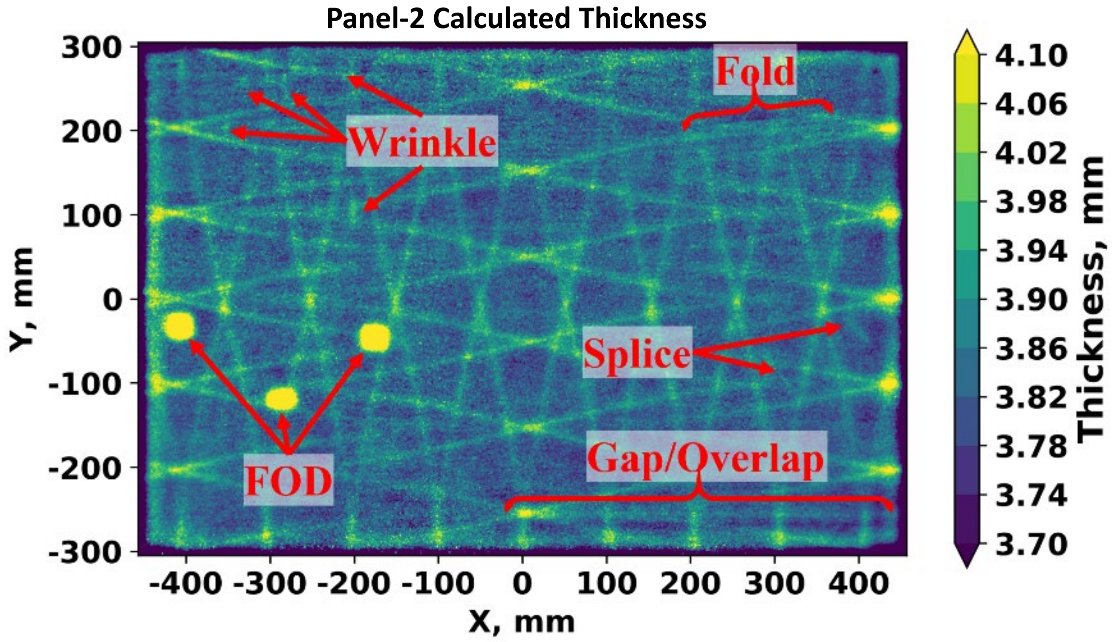
Bag surface – tool surface = calculated thickness

- Calculated thickness correlated well with ply count predictions

Inspection: Structured Light Scanning







Bag surface – tool surface = calculated thickness

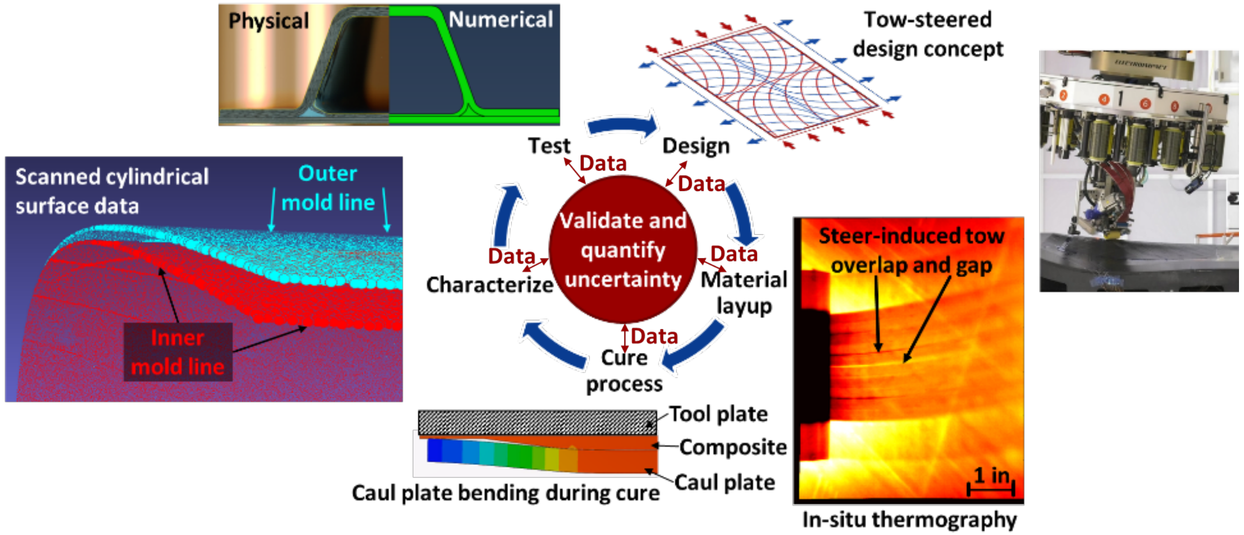
Inspection Summary

Defect	Defect detected by inspection system: Thermography	In-situ UT (2.25MHz)	Post-cure UT (2.25 MHz)	Post-cure UT (10 MHz)	Structured Light
Wrinkle	Yes	-	Yes	Yes	Yes
Fold	Yes	Yes	Yes	Yes	Yes
Twist	Yes	-	Yes	Yes	No
FOD	Yes	-	Yes	Yes	Yes
Debond	No	-	Yes	Yes	No
Gap/Overlap	Yes	-	Yes	Yes	Yes
Splice	Yes	-	Yes	Yes	Yes

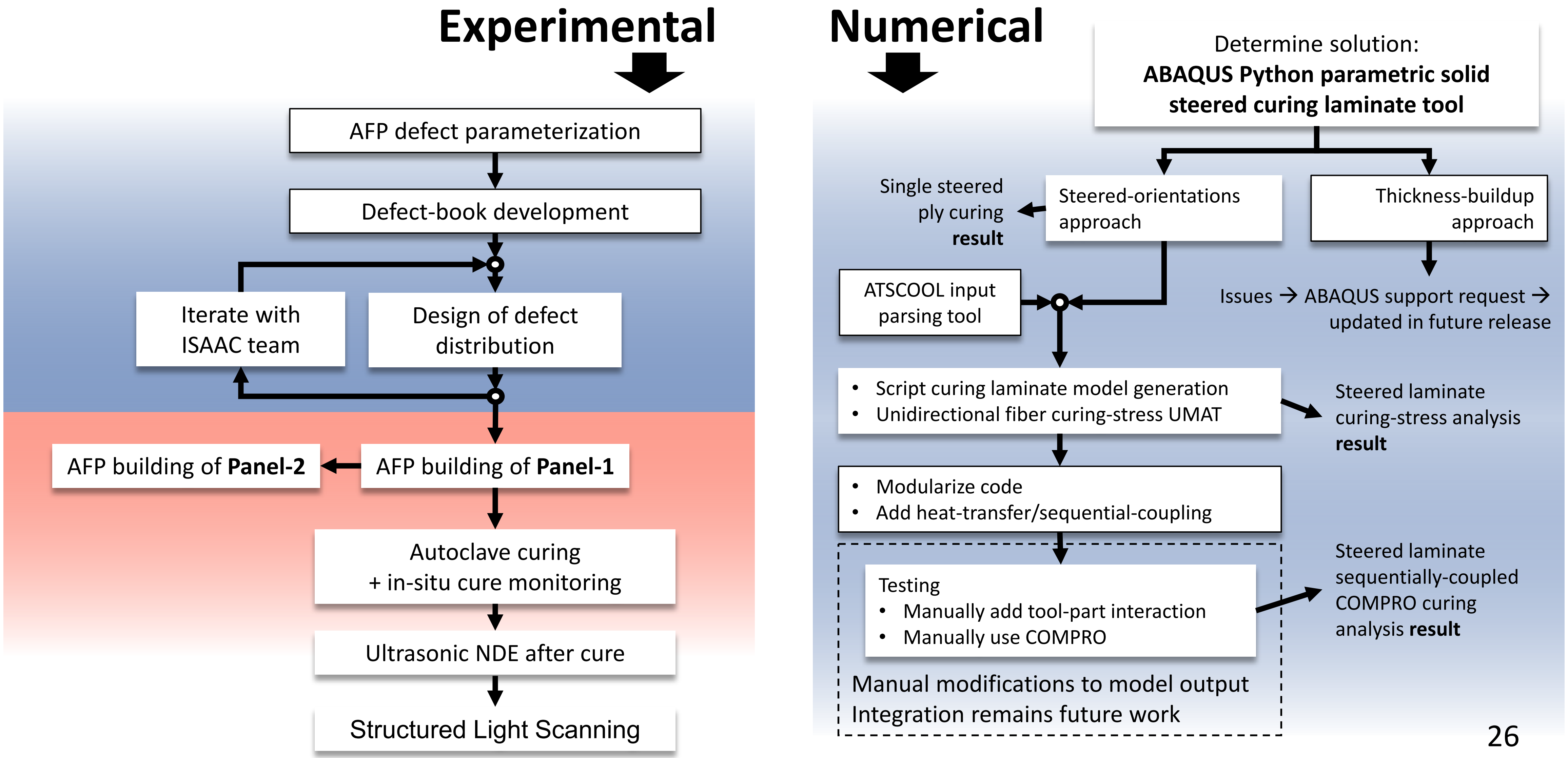
- Structured light was able to provide as-manufactured shape
- When real-time thermography is used, previous work has shown that detection of defects such as gaps, overlaps, folds, and splices is possible and repair may be conducted

Impact, or “So What?”

- Tow steered structures may enable the high-aspect ratio designs for AATT TTBW… but better data are needed
- Such complex structures can exhibit significant process-specific features
- Better understanding (and models) of the systems at work may reduce uncertainty

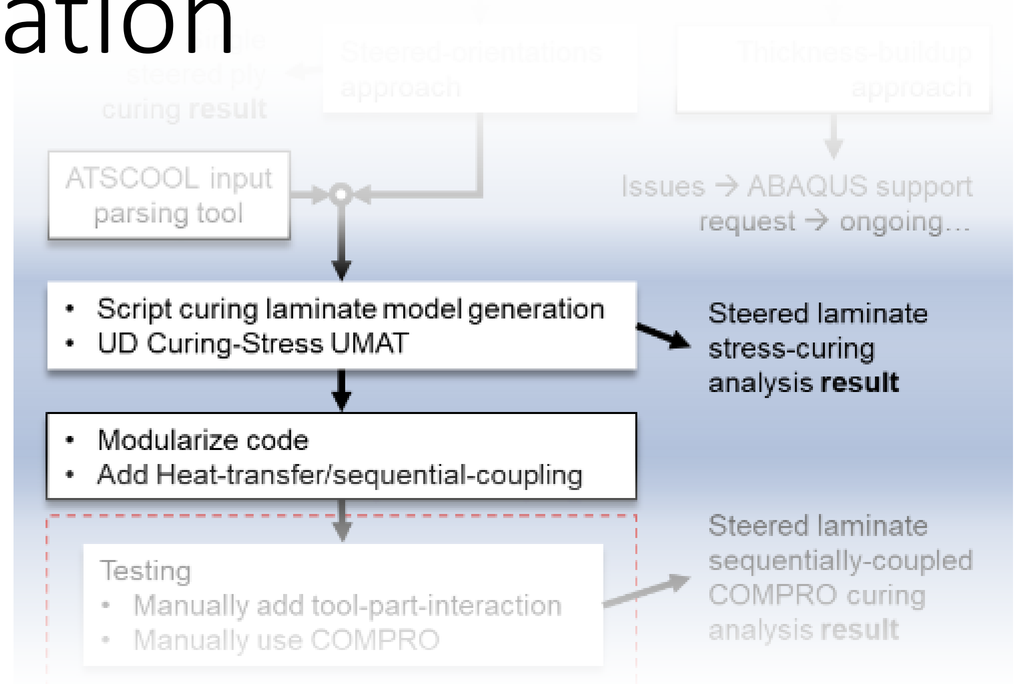


Initial Framework Effort



Initial Framework Demonstration

- Demonstration of process with a simpler tow-steered design



Input

- Stacking sequence, etc.
- Materials and processing parameters

↓

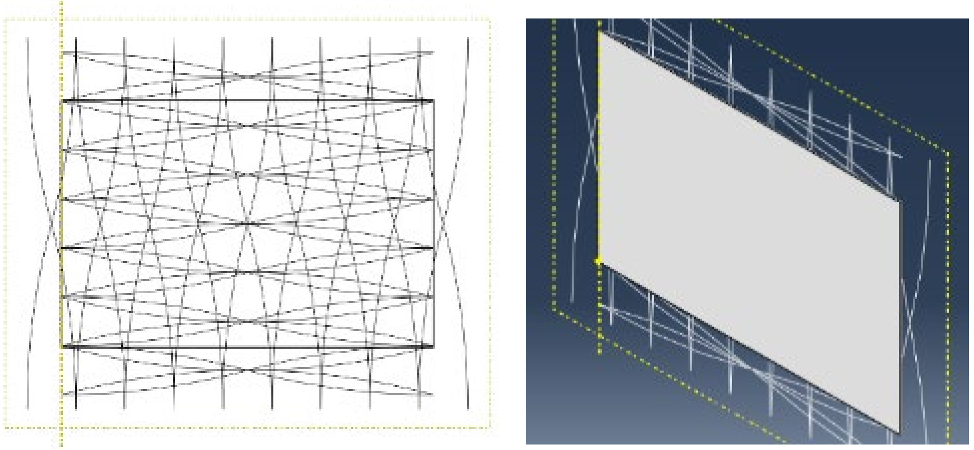
Steered Laminate Curing Tool

↓

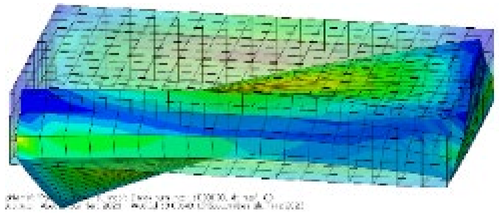
Output

- FEA curing input files

Orientation wires for all plies

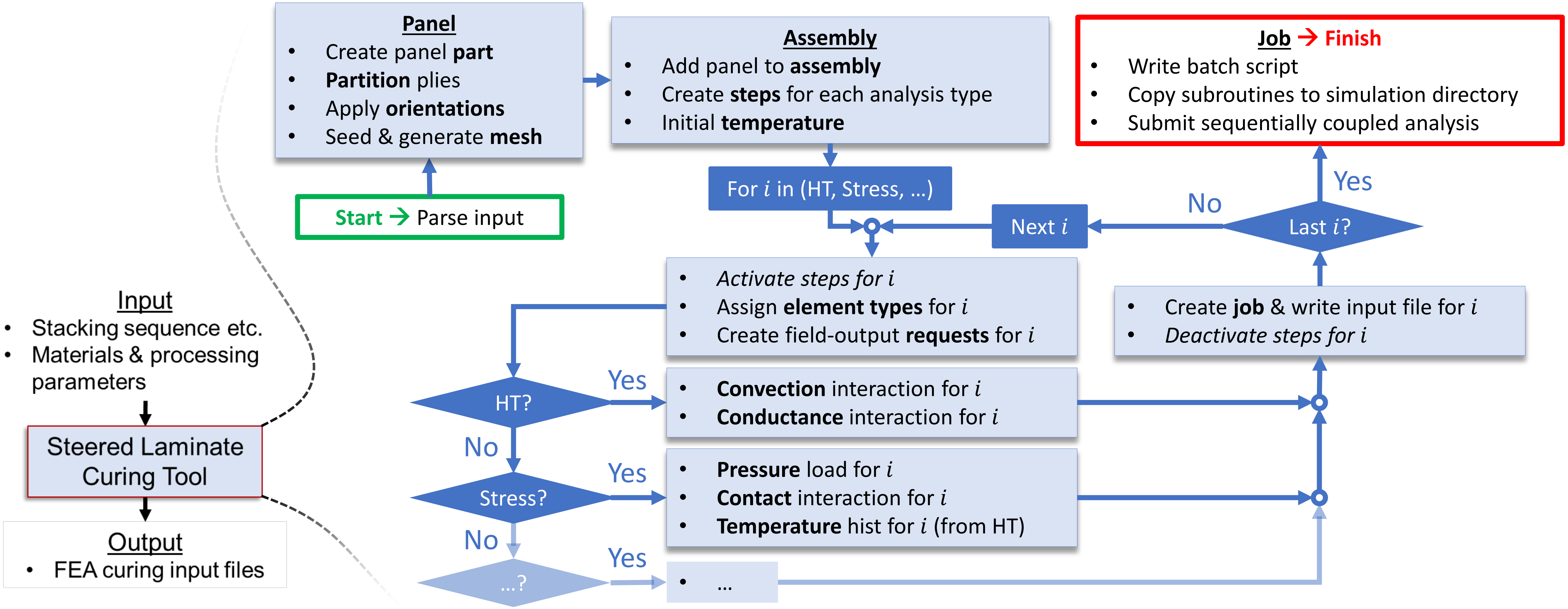


Simply unsymmetric 3-ply curing result



10x deformation scale

Flow-chart of Modularized Tool



Concluding Remarks

- Two tow-steered panels were fabricated; one as nominally pristine and the other with intentionally implemented defects common in carbon fiber reinforced polymer structures
- Four inspection systems were used throughout the fabrication process to determine whether defects could be detected
  - All defects were able to be identified using the post-cure UT system
  - Other systems generated data of interest in characterizing the state of the structure
- Collected data are being considered for inclusion in iterative design workflows and potential digital twin applications
- Many challenges remain in data integration, transfer, and validation

Acknowledgement to AATT TTBW for funding this work.

With appreciation to: Ryan Enos for the defect design and framework development, Erin Anderson, Alana Cardona, and Jake Tury for operating ISAAC, Peter Juarez and Elizabeth Gregory for collecting thermography data, Joshua Brown for collecting structured light data, and Tyler Hudson, Sean Britton, Wil Flores, Lloyd Jones, Kim Nguyen, and Hoa Luong, for UT inspections and autoclave operation.

Thank you