Improved Characterization of Ceramic Matrix Composites for Flight Vehicles

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Outline

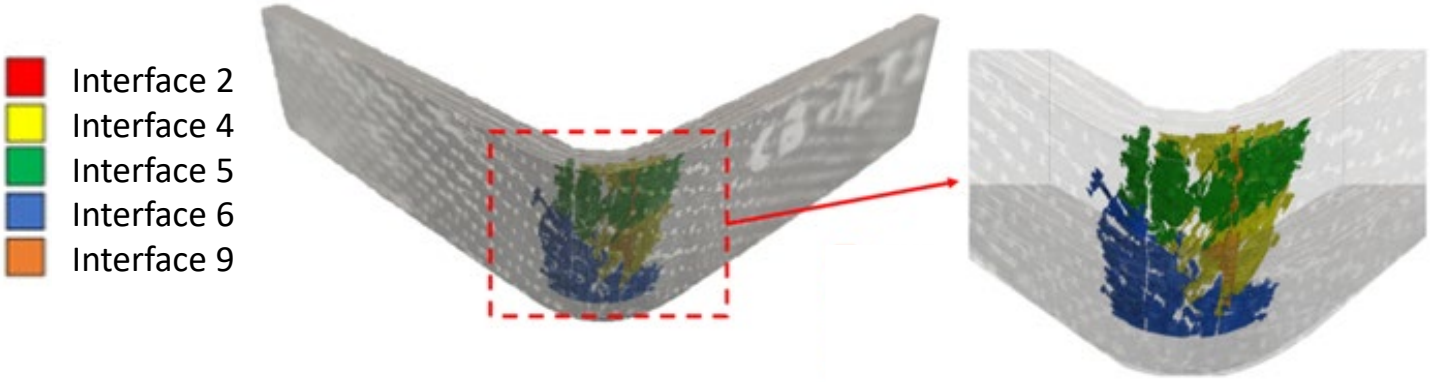
- Introduction
- Current Research Focus
- Collaboration Ideas

Using Non-Destructive Evaluation for New Data

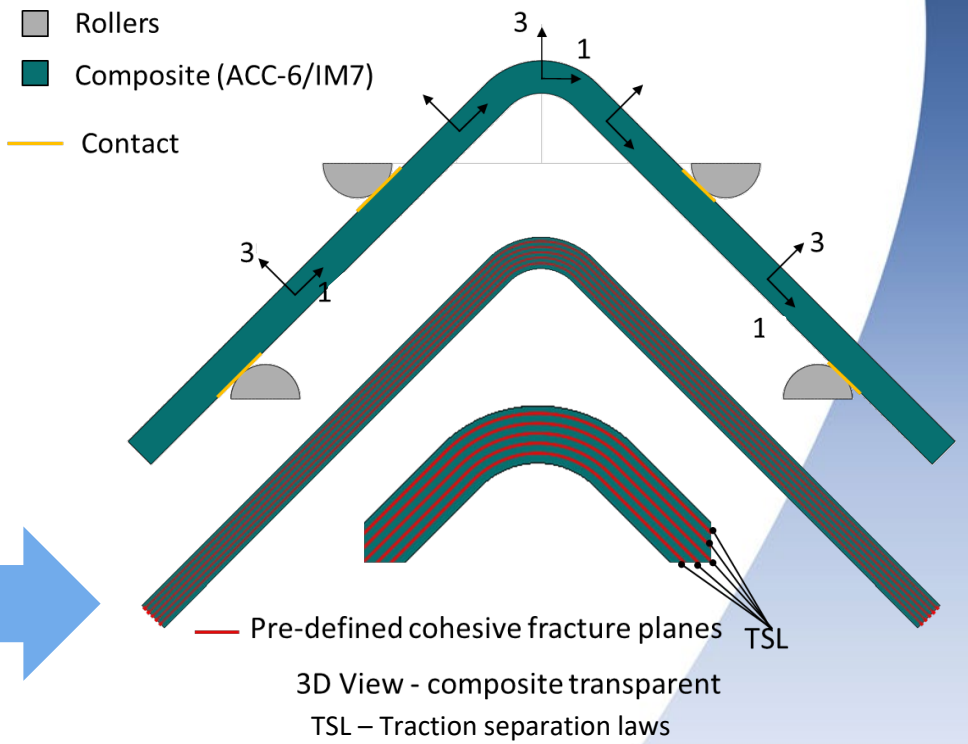
Research Focus

1. **Improved experimental data**
   - Improved simulation inputs, like pin displacement in all three directions
   - Able to measure linear and non-linear material behavior in 3-D
2. **Improved material simulation**

   New empirical measurements = new simulations



Per-ply damage (*in-situ*)



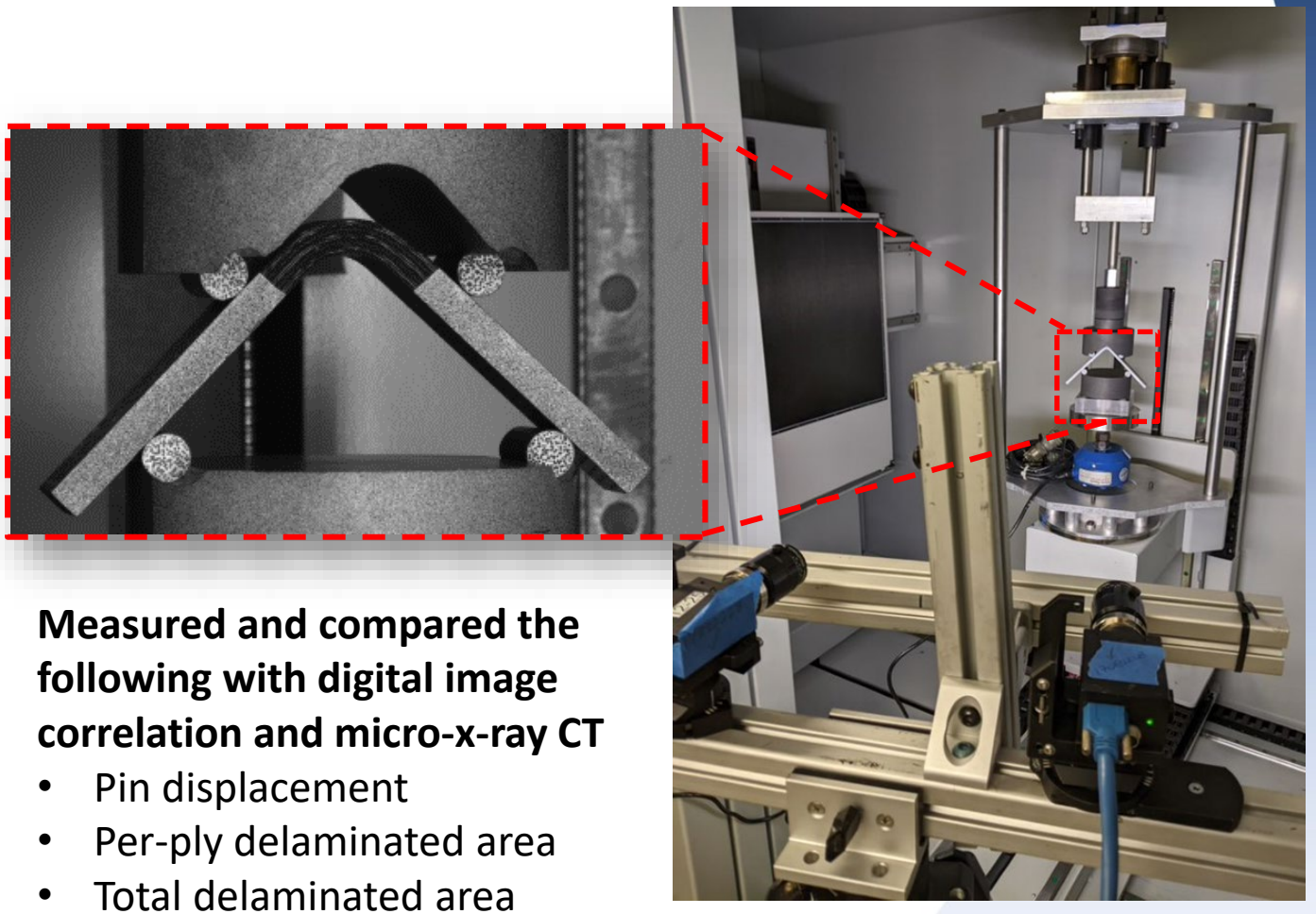
X-Ray Capability

North Star Imaging X-3000

- **System Capabilities**
  - X-ray Energies from 10 kV – 240 kV
  - Overall Maximum System Resolution: ~500 nm
  - 19.5 in Diameter x 24 in tall nominal part envelope
  - Typical scan resolution for a coupon size scan is approximately 8-20 um
  - Typical scan energies: 60kV & 180 µA

Detector

- **Perconel Elmer Detector**
  - Digital X-ray Detector Flat panel (DDA)
  - Dimensions
    - Standard: 16 in. W x 16 in. H
    - Vortex: 16 in. W x 24 in. H
    - MosaiX: 23.5 in. W X 38 In. H



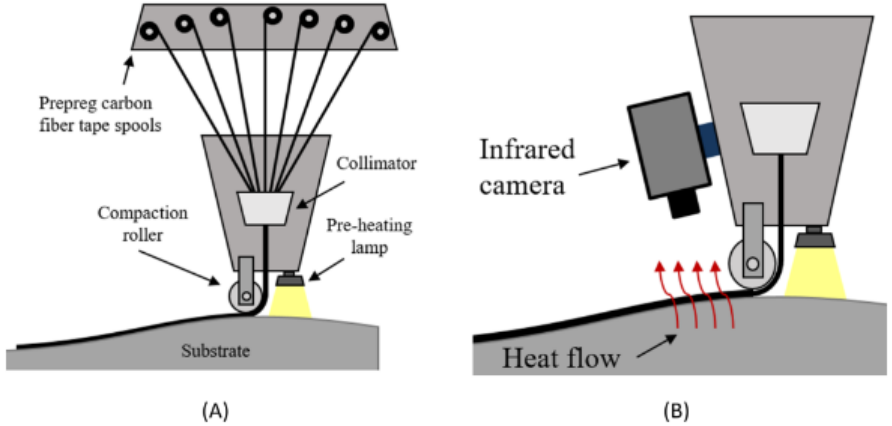
Measured and compared the following with digital image correlation and micro-x-ray CT

- Pin displacement
- Per-ply delaminated area
- Total delaminated area

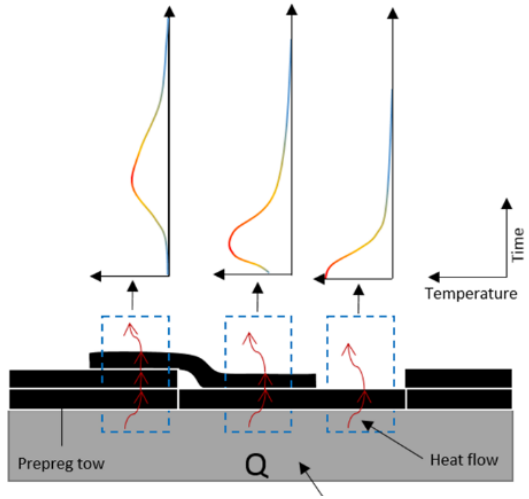
Other NASA Langley Capabilities

Other NDE Experience/Resources

- *In-Situ* Inspection System (ISTIS) for AFP
- Access to 4 other micro-x-ray CT machines
- Ultrasound
- Eddy Current
- Microwave
- Terahertz Imaging
- Fiber Optic Strain and Shape Sensing
- Nano and MEMS sensor fabrication
- Raman Spectroscopy
- Carbon Nano Sensors
- Computational NDE



A) Diagram of typical Advanced Fiber Placement (AFP) end effector
B) Diagram of thermal camera monitoring heat flow



A depiction of the effect of defects on the temperature profile when the substrate acts as a through transmission conductive heat source

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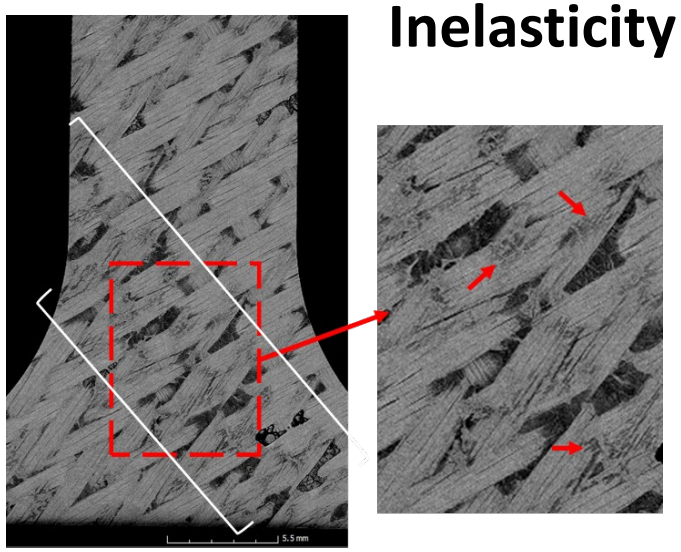
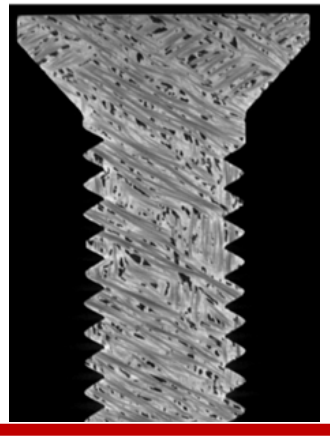
Research Focus Areas

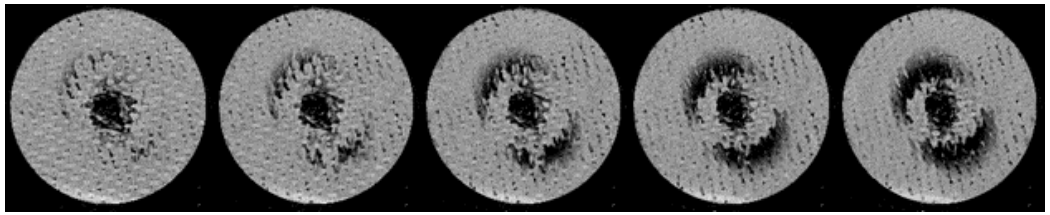
Inelasticity



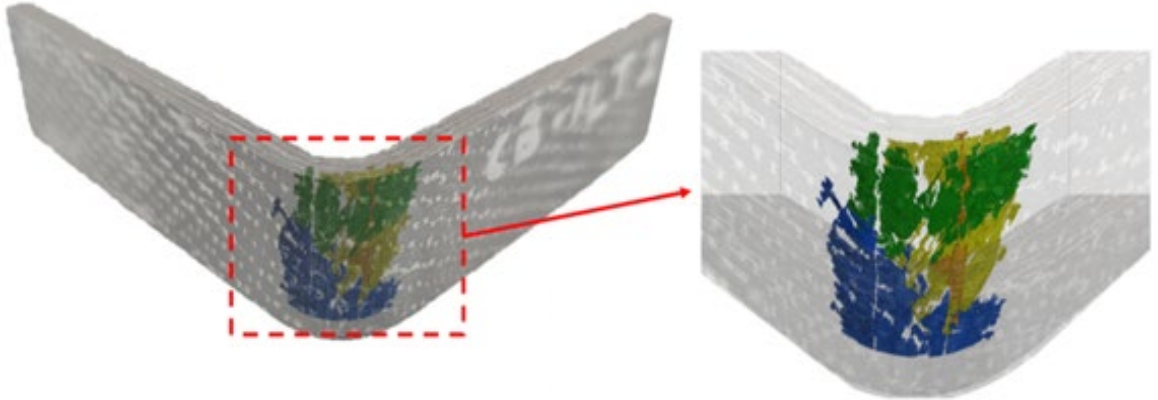
Fastener Thread QA



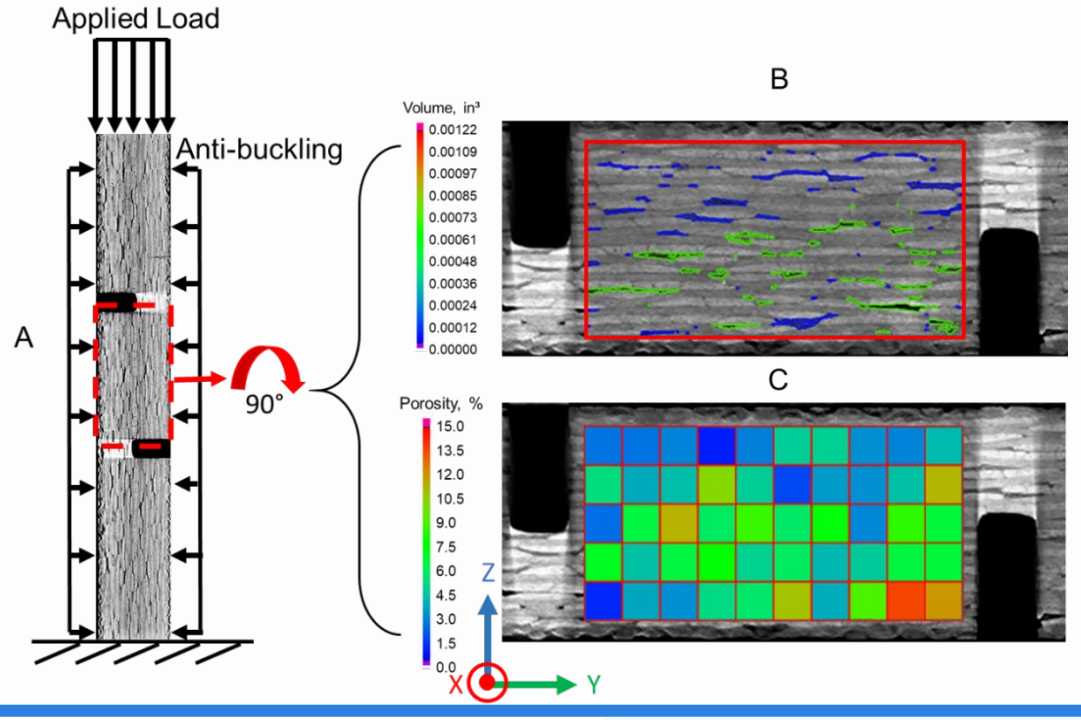
Hypervelocity Impact



Per-Ply Damage Characterization (*In-Situ*)



Relationship of Porosity on Material Strength



Validation of Numerical Simulations for In-situ Testing

Objective

- Utilize uncertainty quantification (UQ) to validate a model of damage in curved-beam interlaminar tension (CB-ILT) and asymmetric four-point-bend (A4PB)

Approach

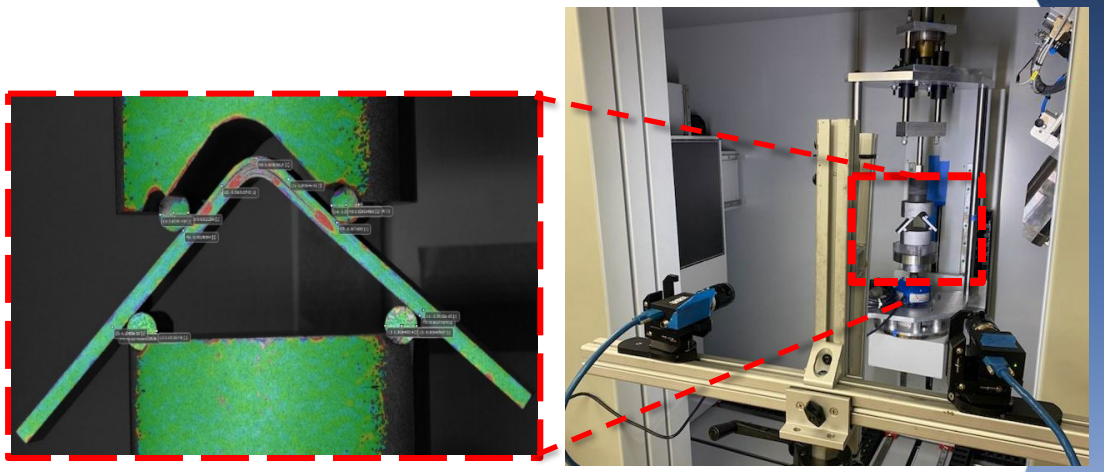
- Mechanically test CB-ILT and A4PB inside of a micro-x-ray computed tomography (CT) machine
- Use digital image correlation (DIC) to measure 2D rigid body motion
- Use micro-x-ray CT to measure 3D rigid body motion and damage

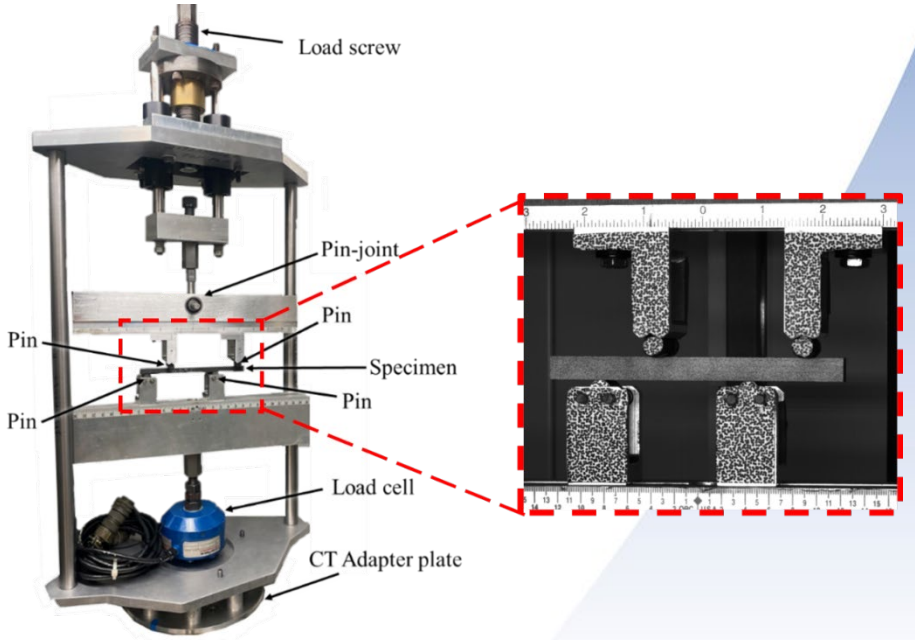
Accomplishments / Status

- Testing has been completed and UQ simulations are currently be conducted

New tool

- This material model quantifies uncertainty better than most others and, as such, can facilitate the study of complex failure modes in other CMC materials.

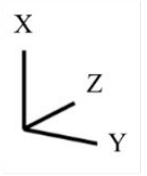


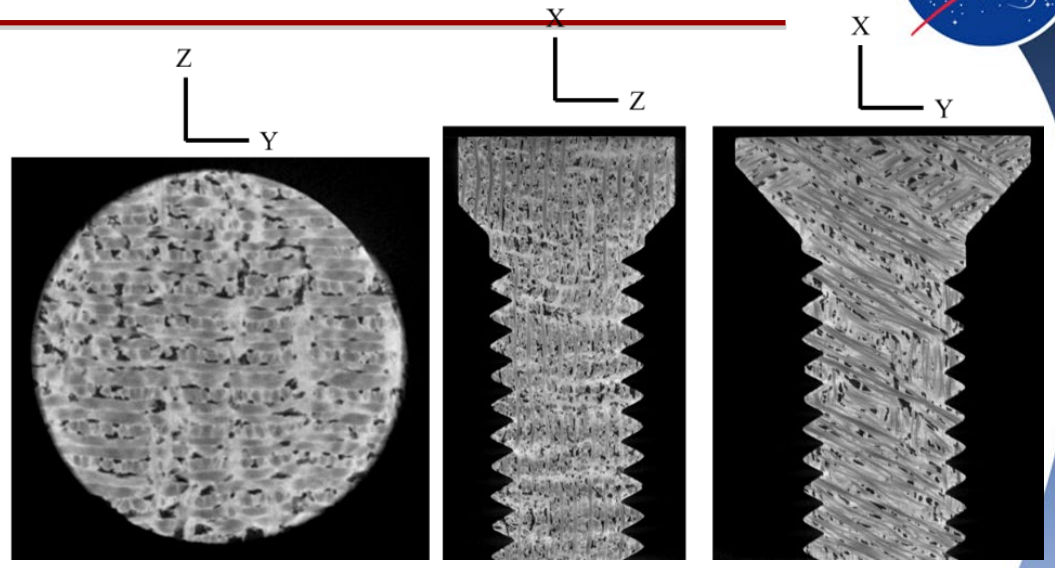


Fastener NDE Quality Assurance

Objective

- Provide the community with reference-style document summarizing fastener performance in composite joints to facilitate a more streamline joint design
- Tackle the last two remaining challenges for CMC fasteners:
  - Machine quality
  - Cost





CT scan of a CMC fastener

Approach

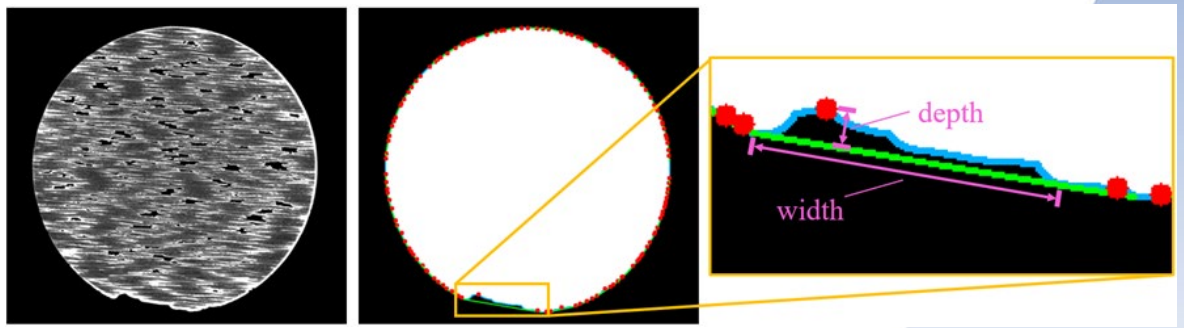
- Develop alternative fastener design that does not require the high labor costs associated with high-end machining
- Characterize the machine quality of the

Accomplishments / Status

- Published a code to quantify the thread quality from x-ray CT images

Plans

- Fabricate threaded fasteners that do not require post-heat treat machining
- Correlate quality of the quick fabrication with fastener tensile and shear properties



The DETECT software identifying and characterizing a defect from faster machining

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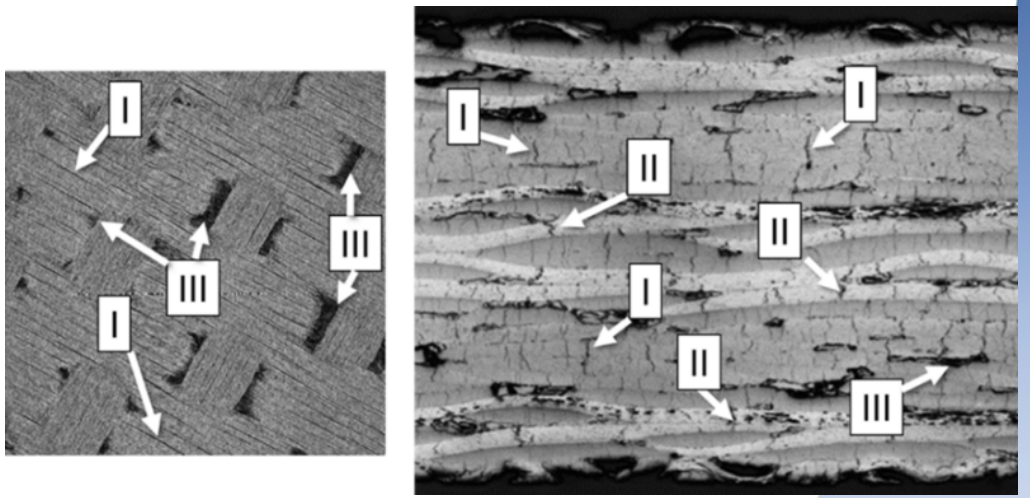
Two Project Ideas

1. **Allowable and Critical Damage Classification (ACDC)**
   - Project ACDC will determine:
     - The allowable damage that the design ultimate loads can be sustained
     - The critical damage threshold defines the state of damage that must be detectable to ensure that the structure possess adequate residual strength to sustain the design limit load
2. **Rapid Assessment of Material Properties (RAMP)**
   - RAMP Method will use computed tomography (CT) images of various as-built conditions of the CMC material and correlate internal features to material properties. To accomplish this, the project will use:
     - Micro-x-ray CT
     - Finite Element Modeling (FEM)
     - Deep Neural Network (DNN)
3. **In-situ Micro-x-ray CT at temperature**

Allowable and Critical Damage Classification

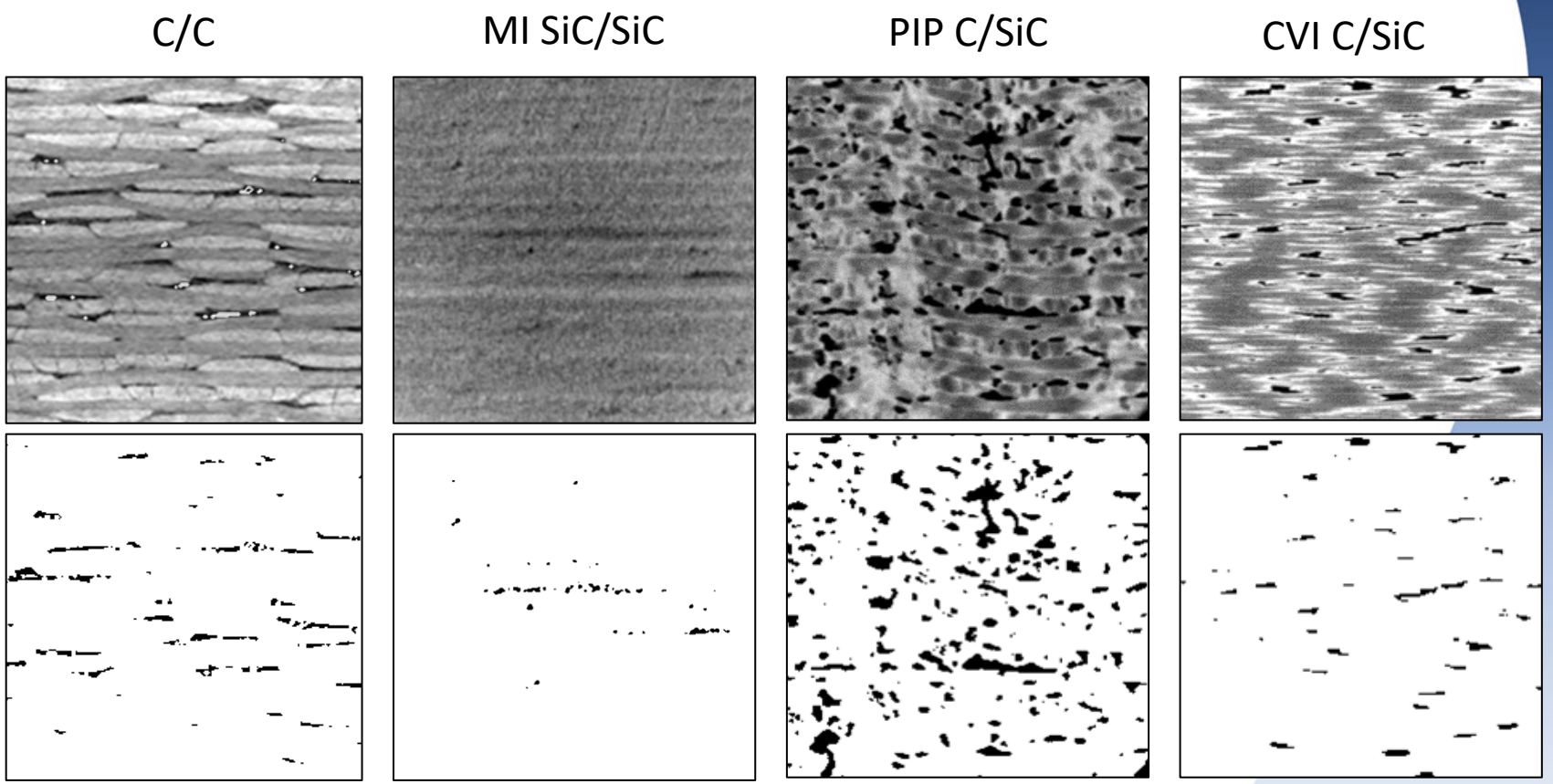
- **Goal**
  - Set the critical damage threshold for various CMCs
- **Objective**
  - Must determine what permits as allowable damage
    - The allowable damage that the design ultimate loads can be sustained
  - Must determine what the critical damage threshold
    - The critical damage threshold defines the state of damage that must be detectable to ensure that the structure possess adequate residual strength to sustain the design limit load
- **Approach**
  - Use in-situ micro-x-ray CT mechanical testing to measure damage growth for fracture critical components



Various features within C/C

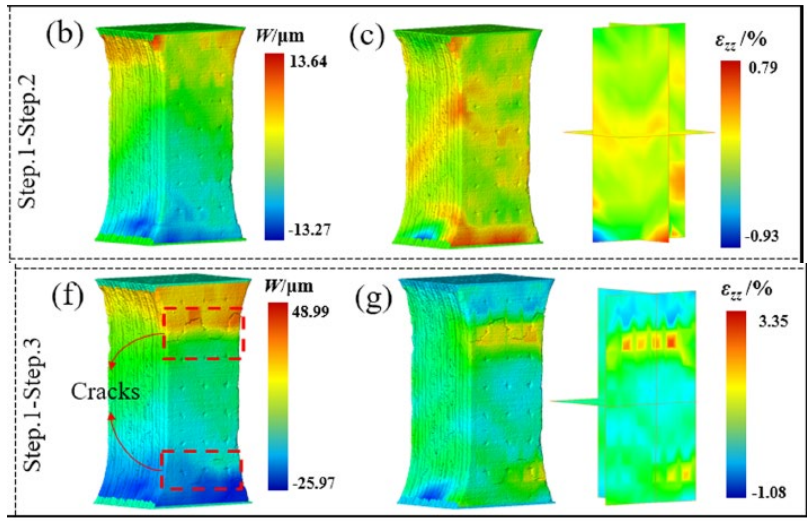
RAMP Method

- **Objective**
  - Correlate the inherent defects within the CMC to the material response
- **Approach**
  - Treat the material as homogenous with pores acting as defects
  - Establish the correlation of the distribution of porosity to the material properties by using micro-x-ray CT and finite element analysis (FEA)
- **Application**
  - Use deep neural networks (DNN) to predict the material properties of complex component by changing the pores distribution reflecting that component



Enable Digital Volume Correlation

- **Objective**
  - Increase the voxel resolution in CT scans to enable the use of digital volume correlation (DVC) to characterize material strength and strain
  - Eventually perform tests at elevated temperature
- **Purpose**
  - To further characterize ply-level behavior in both thermal protection systems and refractory composites
- **Approach**
  - Redesign current test stand to position the specimen closer to the X-ray Source
  - Perform a parametric study to optimize the best CT scan parameters, DVC software's, and reconstruction
- **Accomplishments / Status**
  - Initial DVC tests has begun
- **New Tool**
  - In progress



DVC of C/SiC compression test at 1000°C [1]

Furnace with mechanical loading and x-ray capabilities [2]

Guohao, Niu Et al., "Internal Damage Evolution Investigation of C/SiC Composites using In-Situ Tensile X-Ray Computed Tomography Testing and Digital Volume Correlation at 1000°C.", Beijing Institute of Technology, Beijing, PR China Composites: Part A 163, Oct. 2022. [1]

Rongqi Zhu Et al., "In-Situ Quantitative Tracking of Micro-crack Evolution behavior inside CMCs under load at high temperature" A deep learning method", Beijing Institute of Technology, Beijing, PR China, Acta Materialia 255, June 2023.[2]

Potential Collaboration

- Assess different segmentation techniques to determine the sensitivity of measure crack growth
  - Various image analysis with AI/ML
  - Semantic segmentation
  - Gray Scale segmentation
- Conduct a round robin of quantifying flaw size in different variants of C/C, C/SiC, C/C-SiC, and SiC/SiC
- Conduct a sensitivity study on various infield NDE techniques to determine the feasibility of detecting damage
- Conduct round robin test on anticipated critical components
  - Open hole tension
  - Mode-I and Mode-II fracture tests

Portable Shearography