Recent DIC Activities at NASA Langley Research Center

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AS&M, Inc.

iDICs 2019 Conference & Workshop

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Overview

- Introduction to the materials and structural testing at NASA Langley Research Center (LaRC)
- Acknowledgment of active DIC contributors and sponsors
- Examples of recent activities
  - Why are measurements being made?
  - What is requested to be measured?
  - What is needed to be measured?
  - What equipment is needed?
  - How will the equipment be used and test article prepared?
  - How will the data be processed and presented?

NASA LaRC James H. Starnes Structures Lab, B1148

Load Frame Test Machines

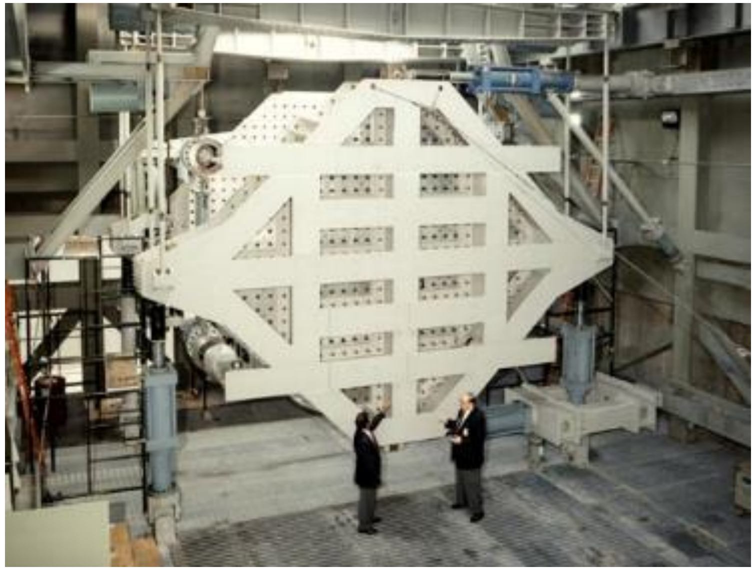
- Focus on large static and combined load tests
- ~ 40 Load Frames: 5,000 lbs. to 1,000,000 lbs.
- Environmental chambers: -320 to 600 F
- COLTS
    - Combined pressure, axial, torsion, shear loading
    - Test articles as large as 15 by 40 ft.


Backstop

B1148

1M lbs. Load Frame

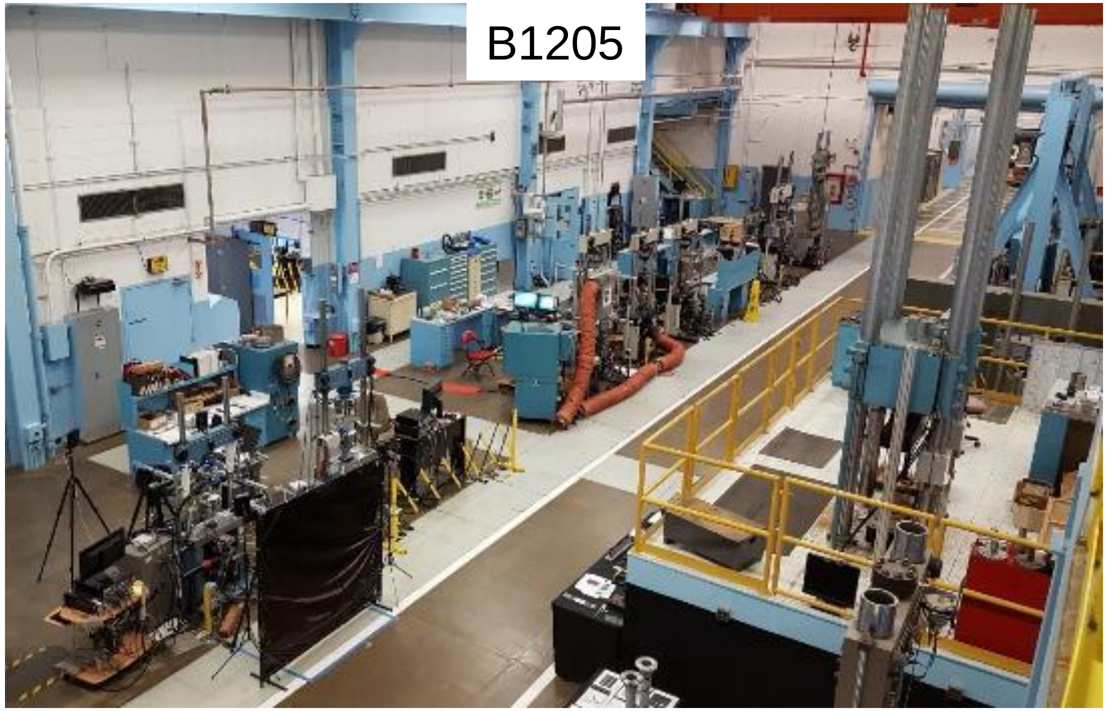
Combined Loads Test System (COLTS)



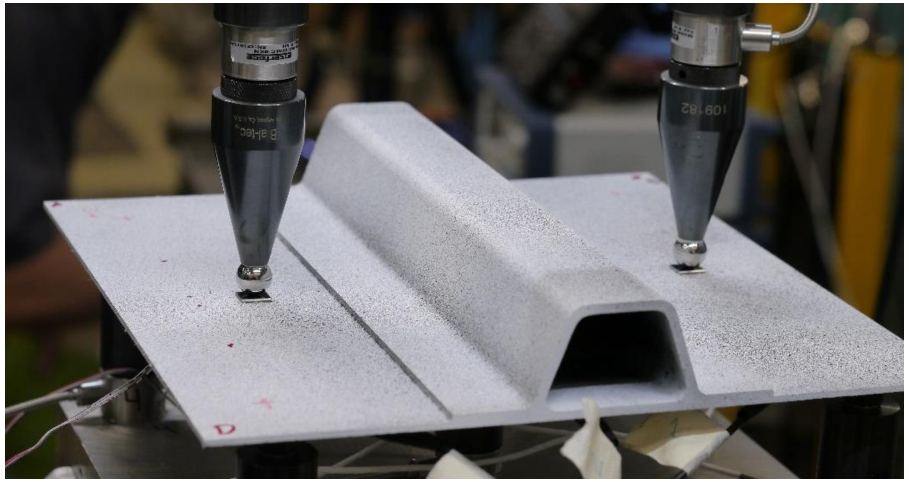
NASA LaRC Fatigue and Fracture Lab, B1205

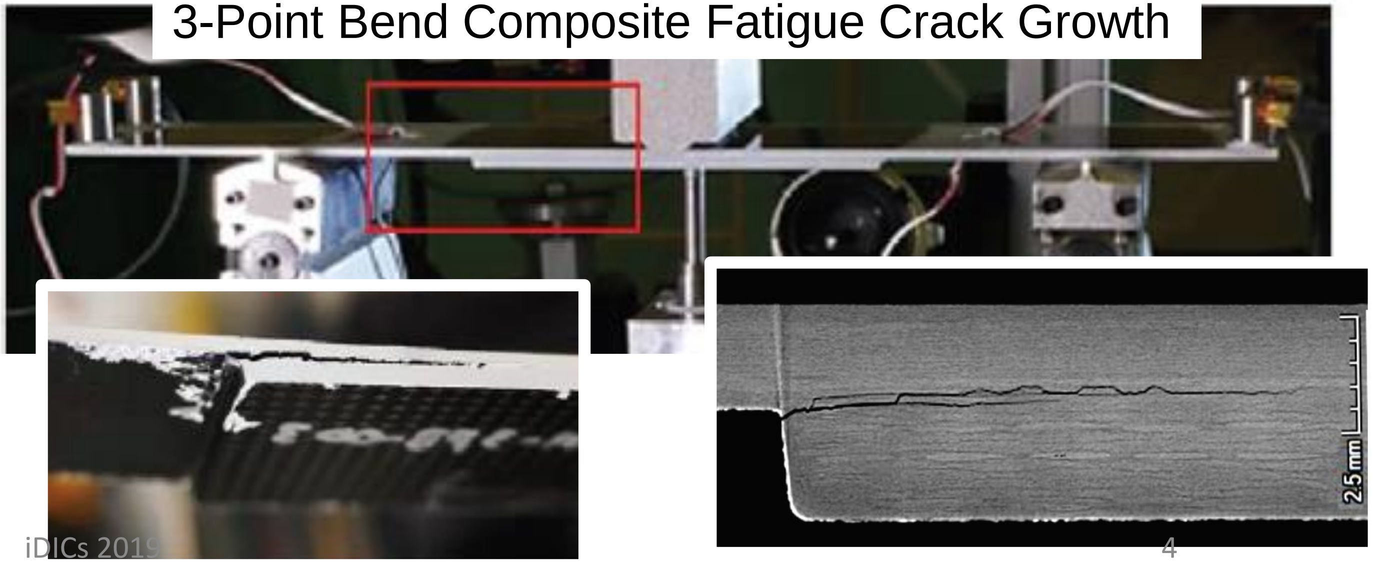
Load Frame Test Machines

- Focus on sub-component and material level tests
- Environmental Chambers: -320°F to 600°F
- Load Frames: 5,000 to 400,000 lbs.
- Cyclic and static loading


B1205

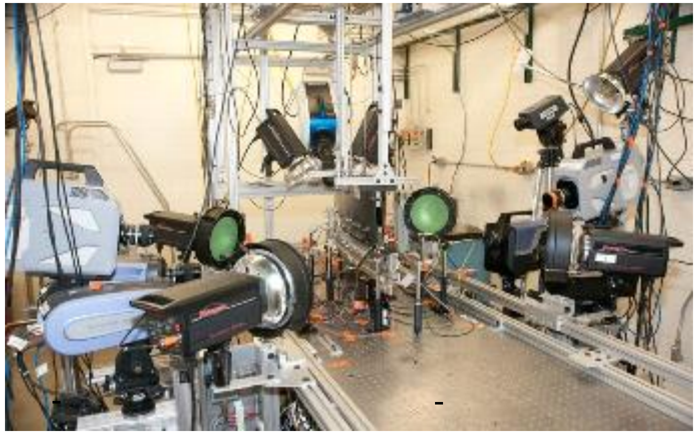

Tension/Torsion


Sub-component Level Testing


3-Point Bend Composite Fatigue Crack Growth

Other NASA and non-NASA Facilities Supported

NASA WSTF

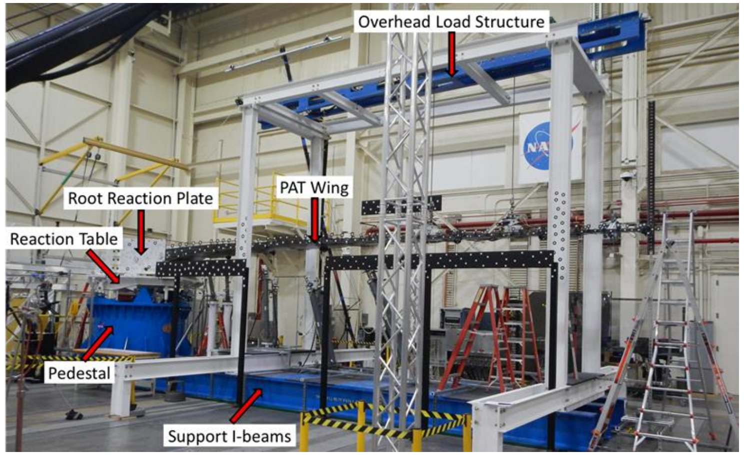


NASA MSFC

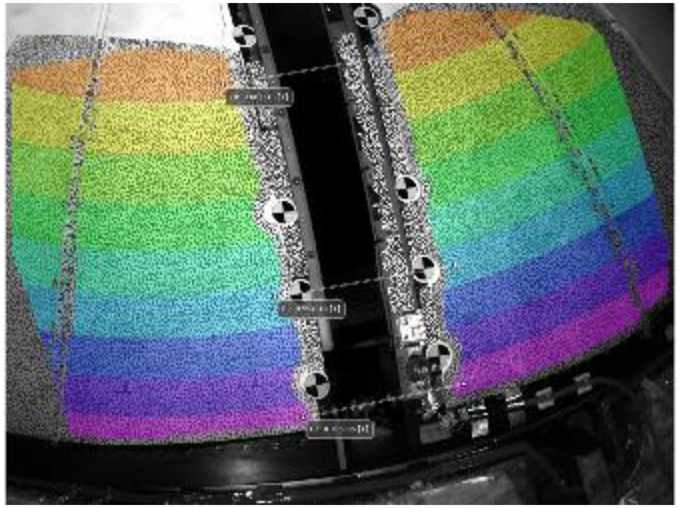
Lockheed-Denver (NASA JPL)

Cimarron-Huntsville (NASA LaRC)

NASA AFRC



California (for NASA WSTF)



How is DIC Used at NASA LaRC

- Material Characterization
  - Composite and metallic materials
  - Mostly room temperature with some work between -200F and +300F
  - Fatigue and fracture
  - Plastic response
  - Validation of damage models
- Structural Characterization
  - Aircraft and space flight sub-component, component, and full-scale
  - Impact of large structures
  - Validation of structural models
- Special Projects
  - Qualification of flight hardware
  - High-speed and vibration characterization
  - “Can you tell me what is going on with my …”

DIC Contributors and Sponsors

DIC Contributors

- Dave Dawicke, AS&M Inc.
- Nate Gardner, AS&M, Inc.
- Michael McNeill, STC

- Will Johnston, STC
- Justin Littell, LaRC
- Paul Leser, LaRC
- Patrick Leser, LaRC
- Jake Hochhalter, U. of Utah
- Geoff Bomarito, LaRC

DIC Summer Students

- Phillip Cragg, VaTech
- Dan Newall, U. of NH
- Cameron Underwood, VaTech
- Jonathan “Jonas” Merrill, U. of Utah

Sponsors

- Advanced Composite Project: Cheryl Rose, Wade Jackson, Andrew Bergan, Frank Leone, James Radcliff, Dawn Jegley (all LaRC)
- Shell Buckling Knockdown Factor (SBKF) Program: Mark Hilburger, Marc Schultz, Tom Haynie, Adam Przekop, Cyrus Kosztowny (all LaRC)
- NESC Assessments and Investigations
  - LaRC: Mike Kirsch, Clint Cragg, Sotiris Kellas, James Reeder, Pete Parker
  - WSTF: Jon Haas
  - GRC: Heather Hickman
  - KSC: Rick Russell
  - JPL: Lorie Grimes-Ledesma
- Other NASA
  - MSFC: Jeff Rayburn
  - JSC: Ian Juby, Mark Mcelroy
  - KSC: Dan Bell
  - LaRC: Robin Schlecht, David Sleight, Arun Satyanarayana, Tom Jones, Andrew Lovejoy, Steve Smith

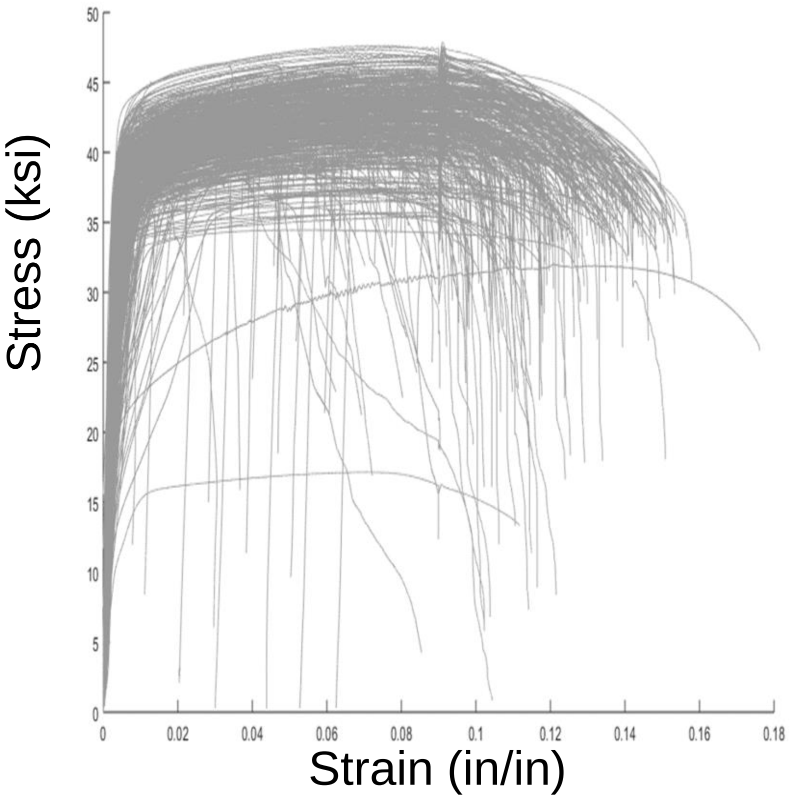
Example #1: Characterization of the Influence of Grain Structure

Problem:

- Standard tensile tests exhibited considerable scatter that resulted in design allowables that were too low to meet margins
- The processing of an aluminum flight hardware structure resulted in a microstructure with a wide variation in grain sizes
- The structure is loaded well beyond the elastic range
- Fracture control requirements also presented concerns with identifying critical locations for safe-life analyses

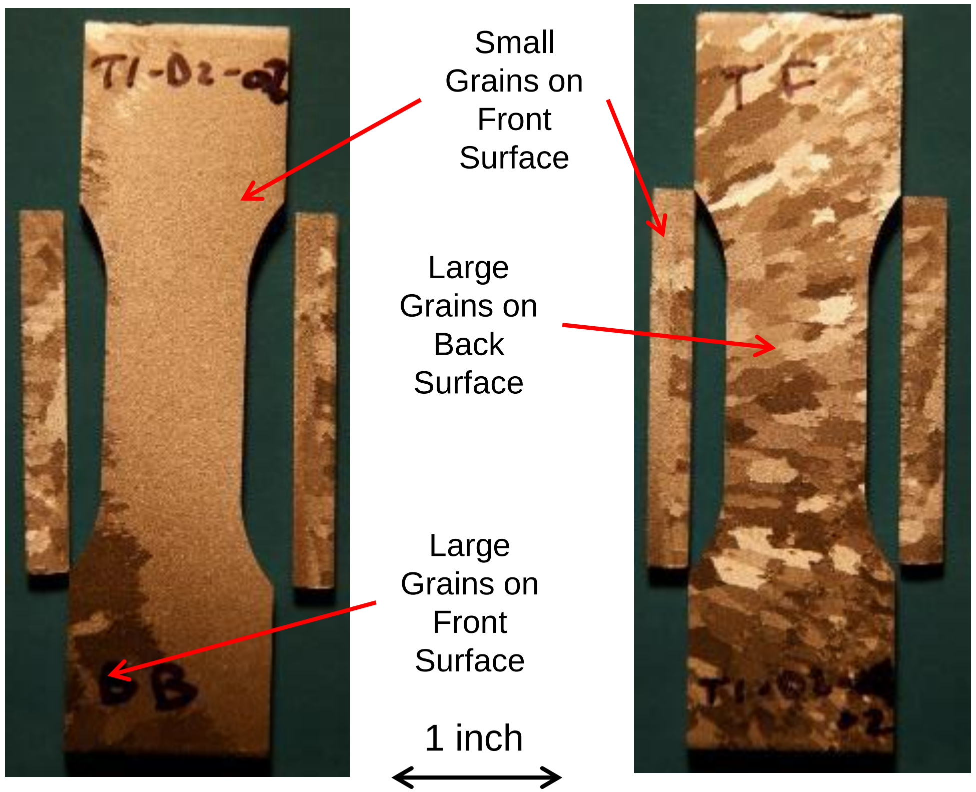
Goal:

- Identify root cause of scatter and influence of microstructure
- Collect data for validation of microstructural model



Front

Back



Small Grains on Front Surface

Large Grains on Back Surface

Large Grains on Front Surface

1 inch

Example #1: DIC Setup Solution

Hardware/Software:

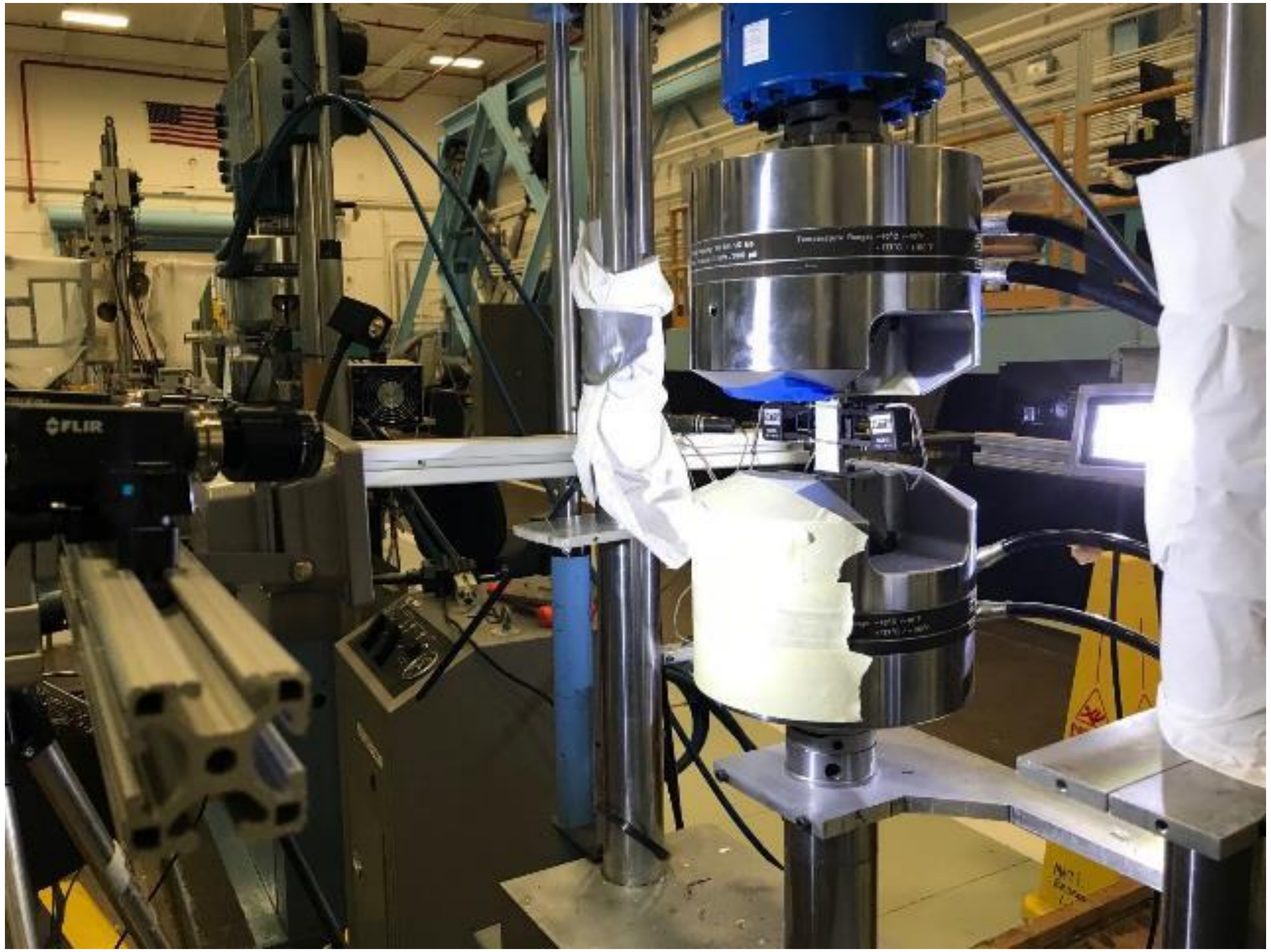
- Two pairs of cameras
  - 12MP FLIR Grasshopper 3 with 50mm lenses
  - Cameras on opposite sides of the test article
- Cameras supported with tripods and 80/20
- Software synced systems front and back
- VIC3D-8^{TM} with RealTime
- 20 kip servo-hydraulic load frame
- Aperture, exposure time, and lighting optimized

DIC Configuration:

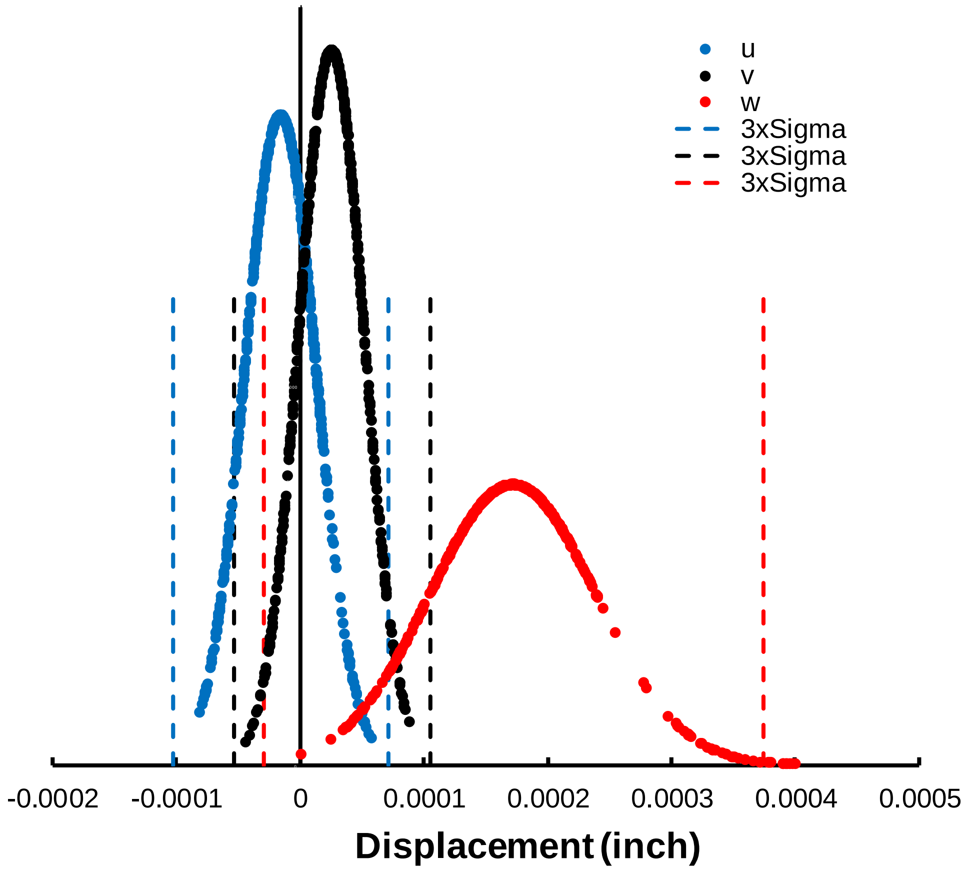
- AOI ~ 2.5 inch x 1.7 inch
- Pixel Resolution ~ 1700 pixels/inch
- Speckle Size ~ 0.002 inch (fine spray paint)
- Subset Size 29 pixels and Step Size 7 pixels
- Standoff Distance ~ 10 inches
- Camera Angle ~ 25-degrees
- Calibration grid: 14x10 4mm

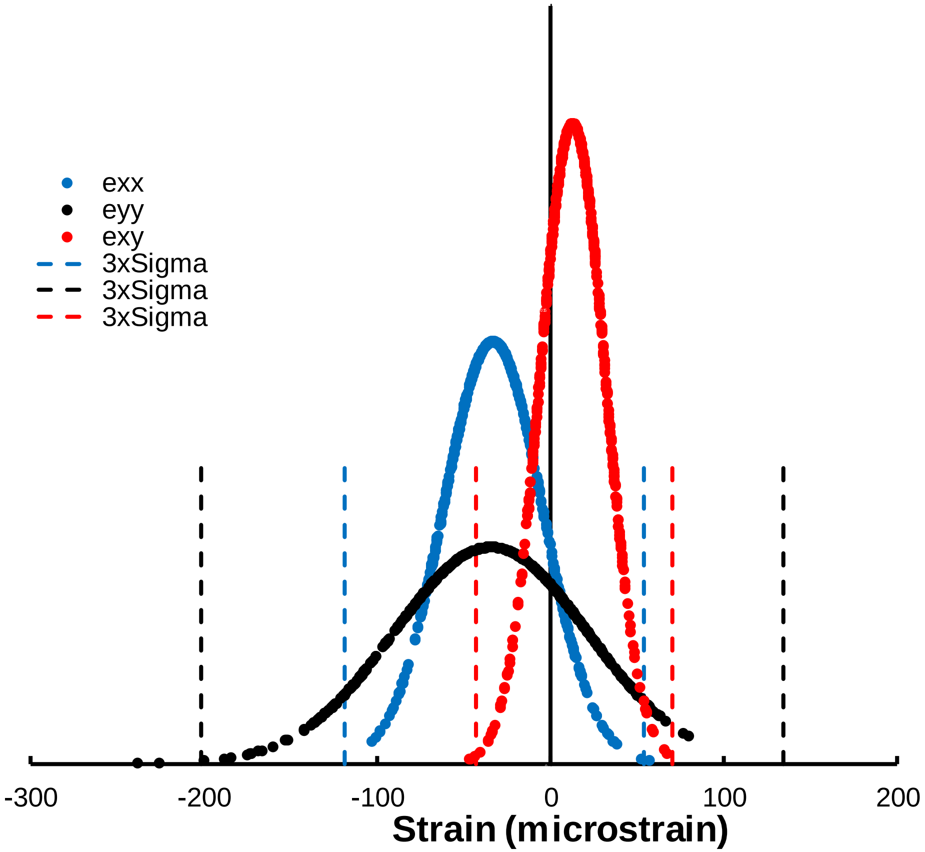
Issues

- Light glare from the load frame
- Narrow depth of field during calibration
- Front/back coordinate system alignment



Example #1: DIC Noise Floor

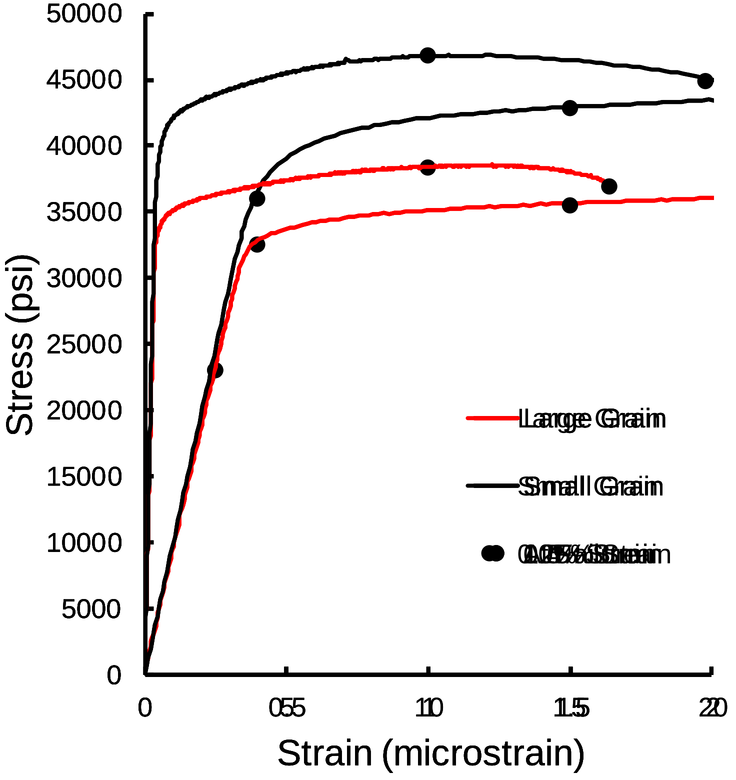


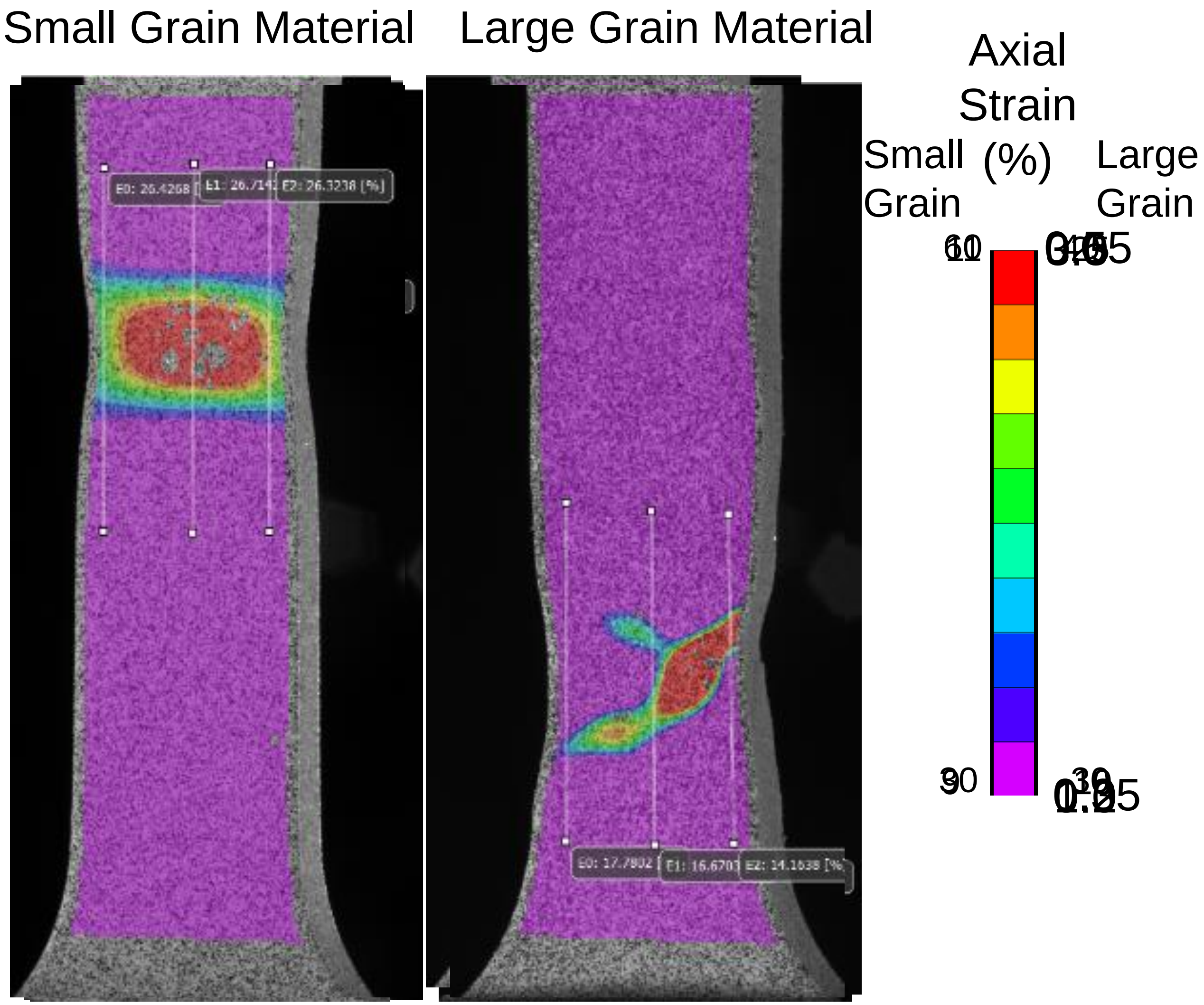


Ratio of Expected Signal to 3σ Noise
u: ~40
v: ~300
W: ~15

Ratio of Expected Signal to 3σ Noise
e_{xx}: ~100
e_{yy}: ~100
e_{xy}: ~50

Example #1: Strain Localization



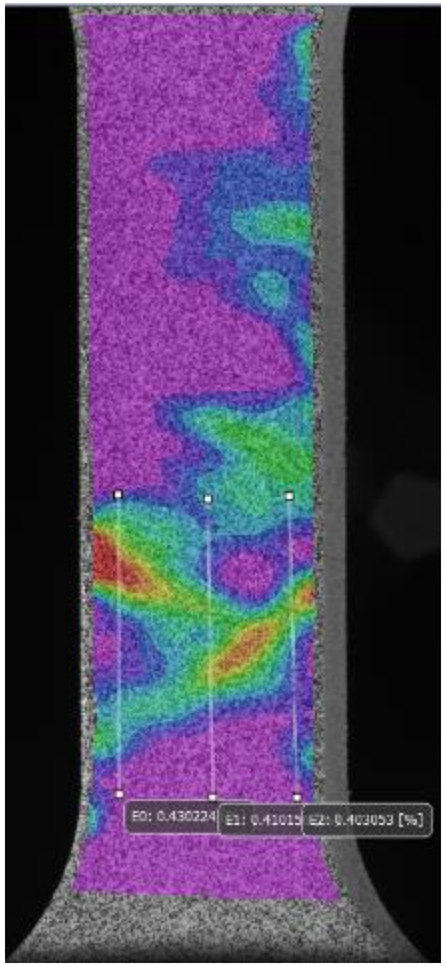

Small Grain Material

Large Grain Material

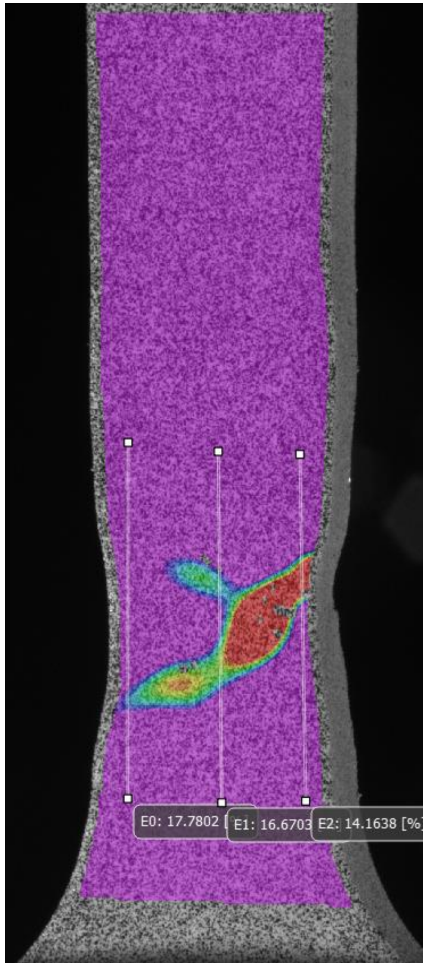
Axial Strain (%)

Example #1: Correlation of Localization to Grain Structure

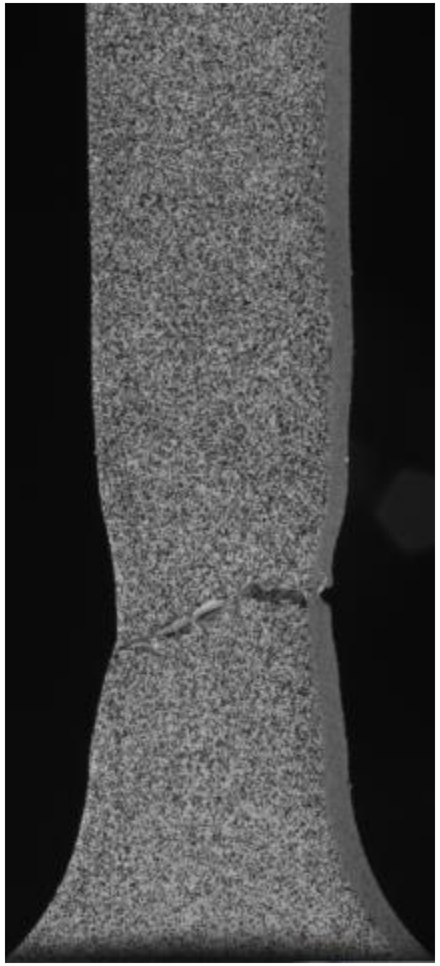
Localization at
0.4% Strain



Localization at
Failure



Fracture Path



20

EBSD with
Fracture Path

- EBSD: Electron Backscatter Diffraction
- EBSD identifies grains and grain orientation
- The localization occurred at or near grain boundaries
- Fracture followed the worst localization path
- Fracture also followed grain boundaries

Example #1: Findings and Ramifications

- The yield stress and elongation scatter was directly related to strain localization at grain boundaries
- The strain localization prevented the structure from being flight qualified for damage tolerance using existing qualification standards
  - The largest crack that could be missed by an NDE inspection will exist at the worst location
  - The cracked structure must survive 4 lifetimes of operational loading
- Risk was reduced by conducting coupon tests
  - The coupons were loaded to about 0.6% strain as measured by DIC in real-time
  - The region of strain localization was identified in each coupon and a notch was added along the grains in the high strain region
  - The notched coupons were precracked elastically to the NDE detectable size
  - The cracked coupons were cycled for 4 lifetimes

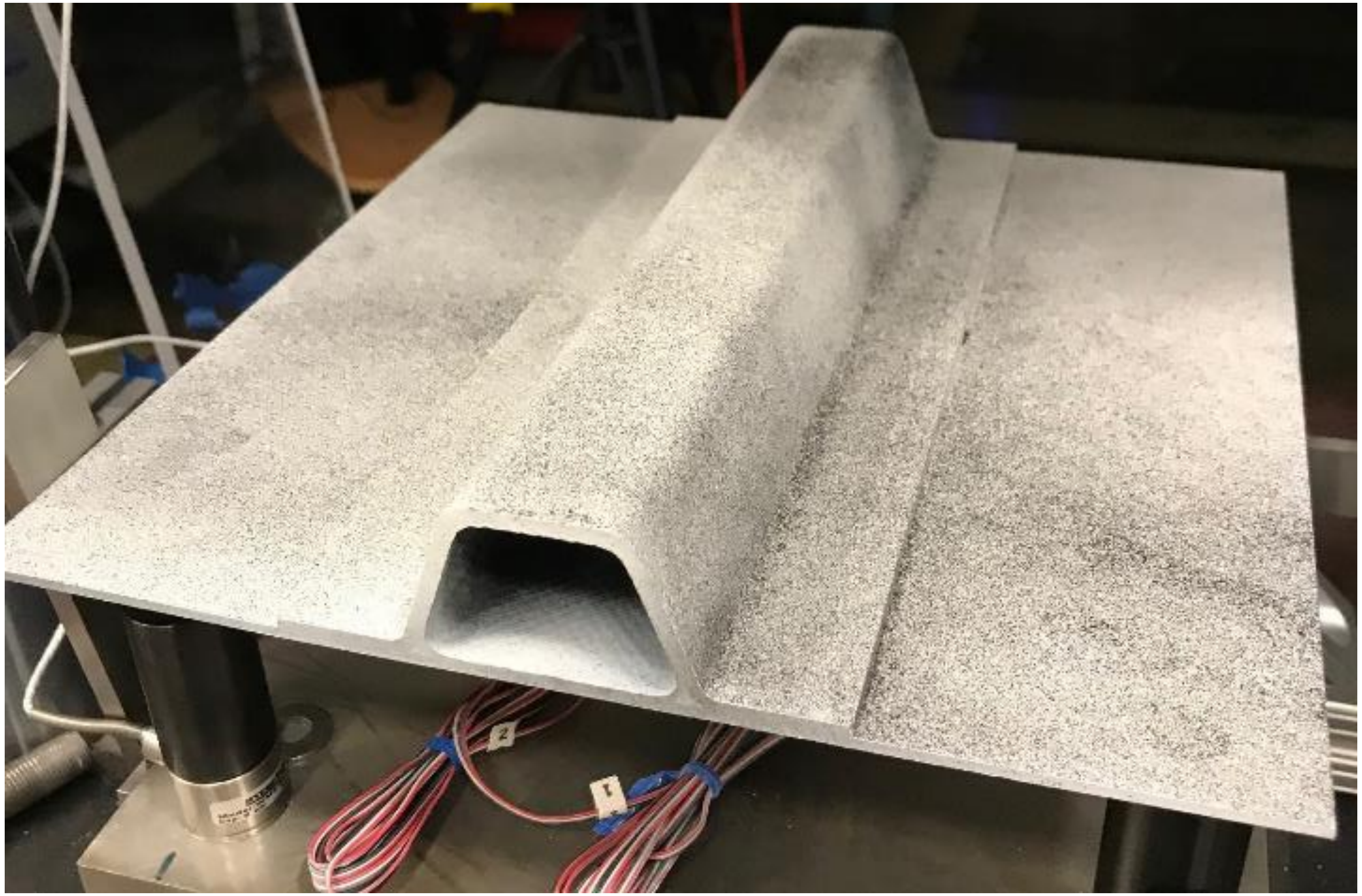
Example #2: Characterization of Cracks and Delaminations in Composite Materials

Problem:

- A single hat stiffened composite panel was tested in bending
- The validation of progressive damage models in composites requires the characterization of cracks and delaminations

Goals:

- Quantify when and were cracking first occurs
- Quantify when delaminations occur and measure the shape



Example #2: DIC Setup

Hardware/Software:

- Two pairs of cameras (left and right)
  - 12MP FLIR Grasshopper 3 with 50mm lenses
  - Overlapping AOI
- Cameras mounted on 80/20 above the test article
- Software synced systems left and right
- VIC3D-8^{TM} with RealTime
- 20 kip servo-hydraulic load frame
- Aperture, exposure time, and lighting optimized

DIC Configuration

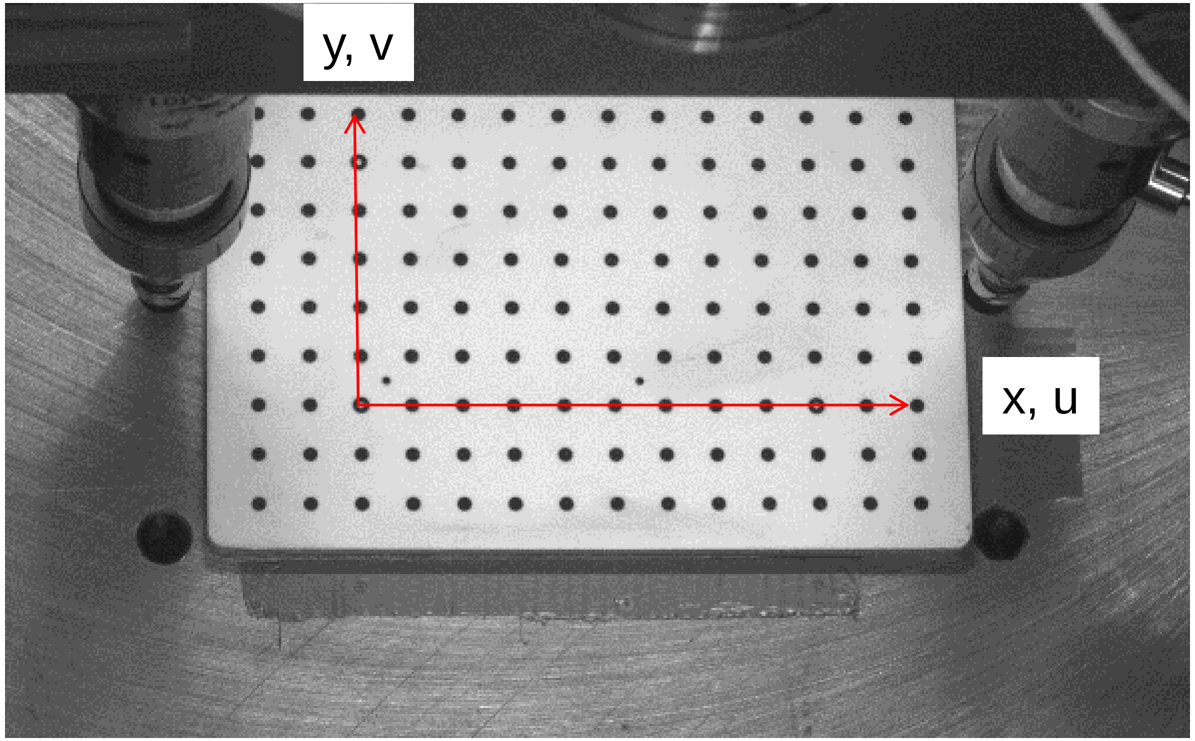
- AOI ~ 10 inch x 8.2 inch
- Pixel Resolution ~ 250 pixels/inch
- Speckle Size ~ 0.015 inch (spray paint)
- Subset Size 17 pixels and Step Size 3 pixels
- Standoff Distance ~ 50 inches
- Camera Angle ~ 10-degrees (limited optical access)
- Calibration grid: 14x10 10mm

Issues

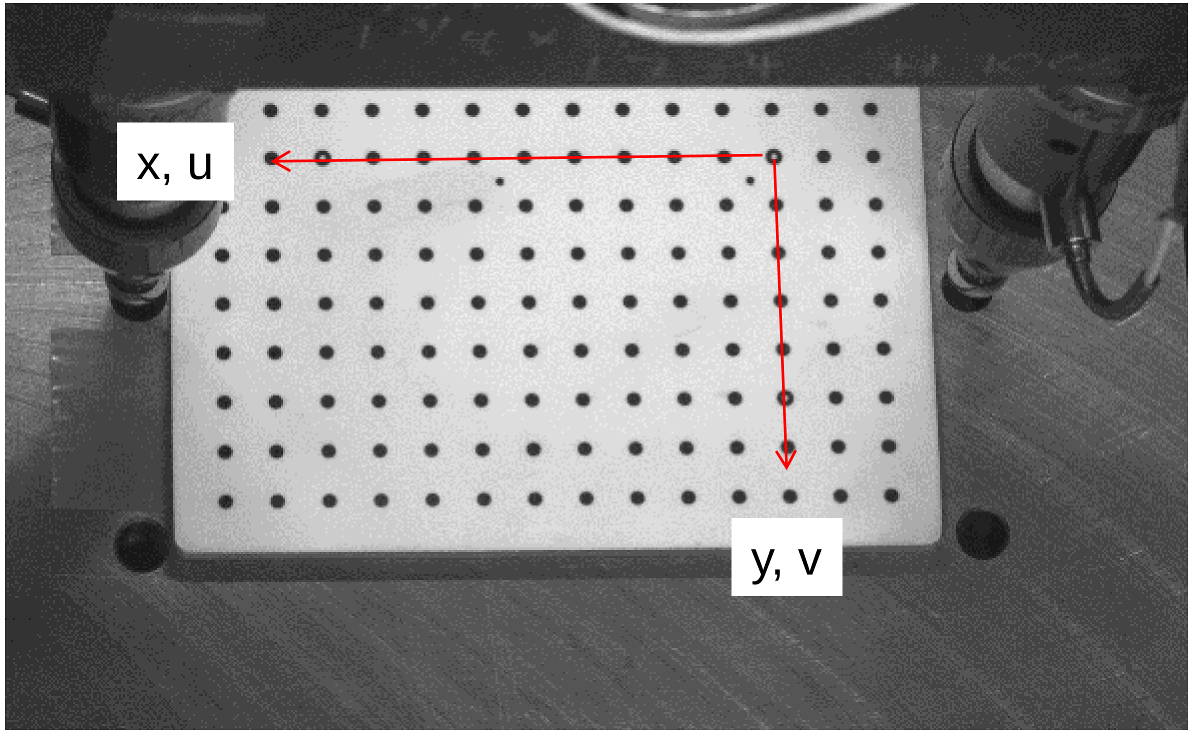
- Common coordinate system in both systems for multiple tests run over 18 months

Example #2: Common Coordinate System

Calibration Grid Viewed from Front Cameras



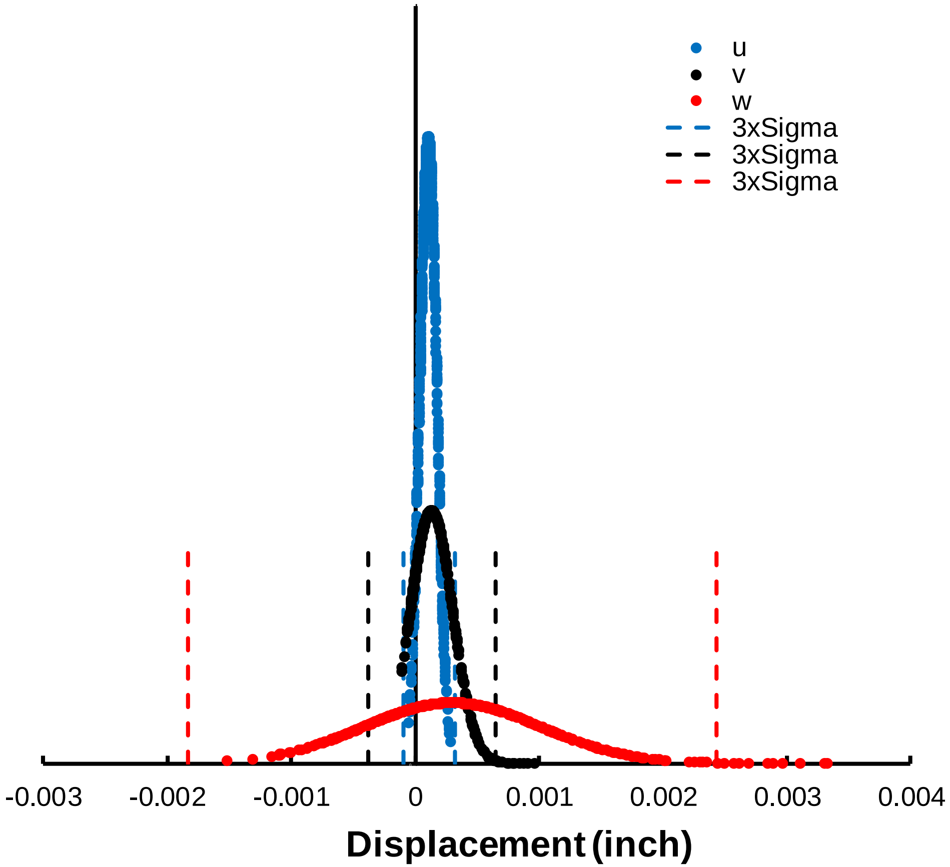
Calibration Grid Viewed from Back Cameras

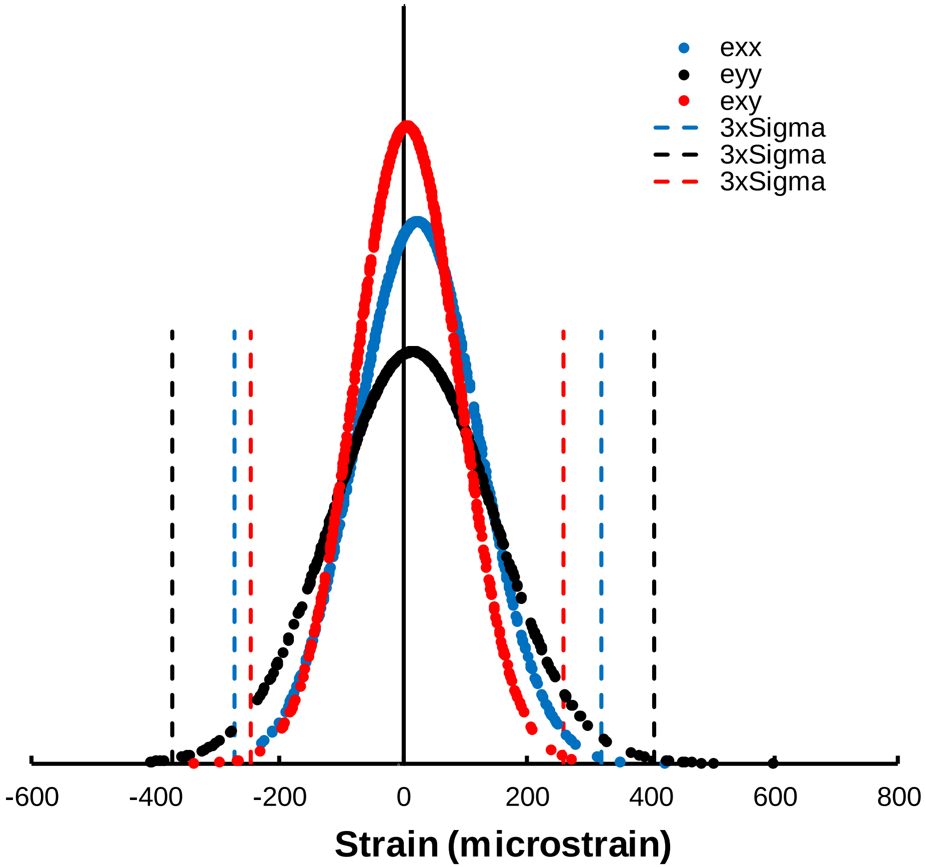


Coordinate System Approach

- Both pairs of cameras could view center section of the test article
- A calibration grid was placed at a marked location on the loading platform that within view of both pairs of cameras and a coordinate system defined
- This provided a quick method of defining a coordinate system that would always be aligned with the loading fixture

Example #2: DIC Noise Floor

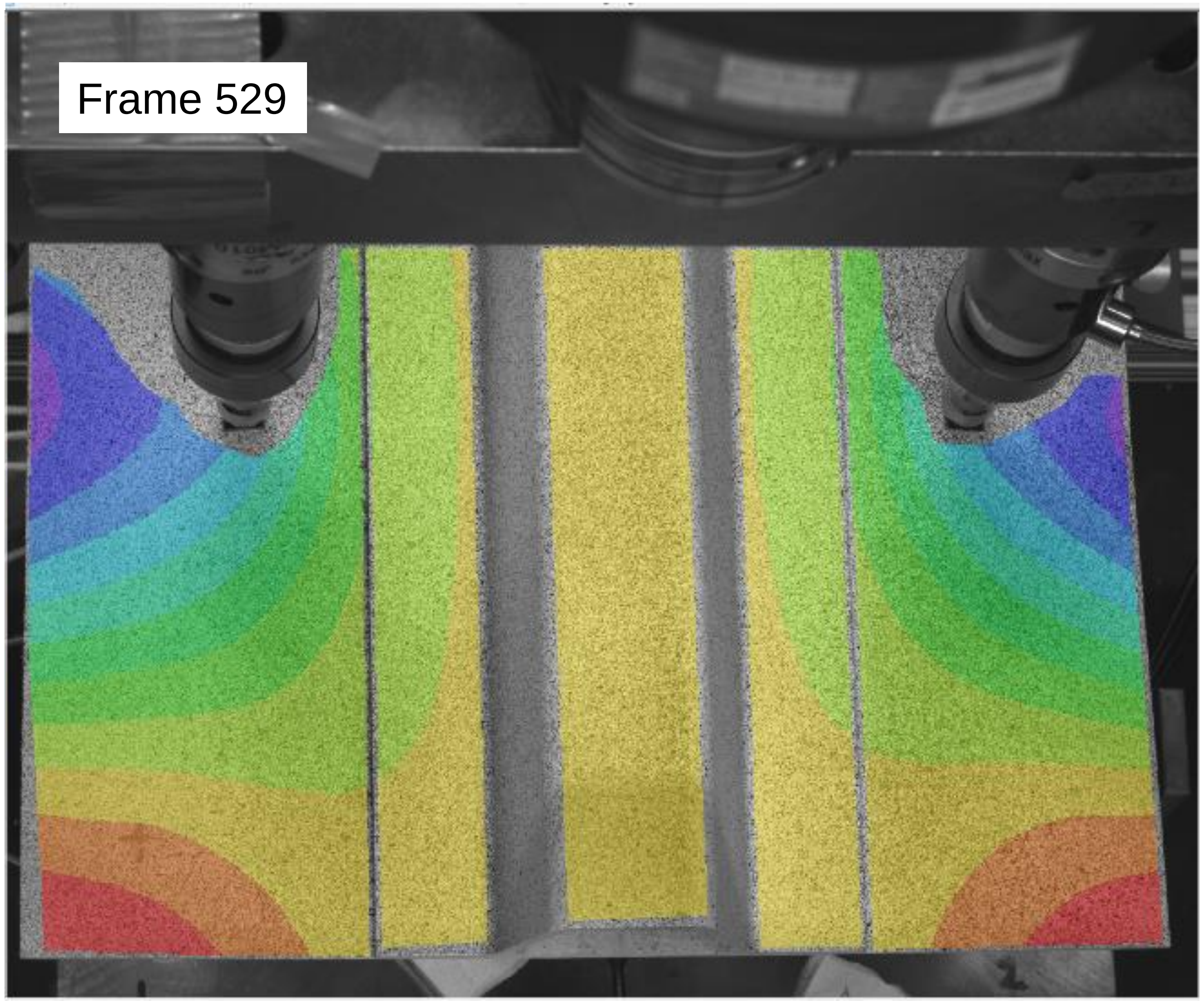


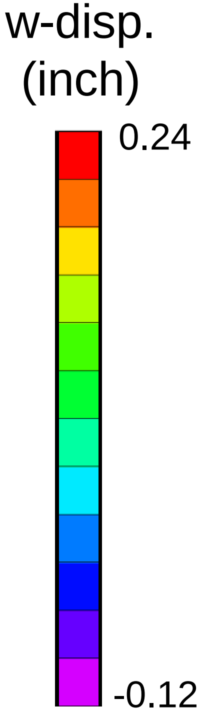


Ratio of Expected Signal to 3σ Noise
u: ~30
v: ~20
W: ~2

Ratio of Expected Signal to 3σ Noise
e_{xx}: ~15
e_{yy}: ~10
e_{xy}: ~12

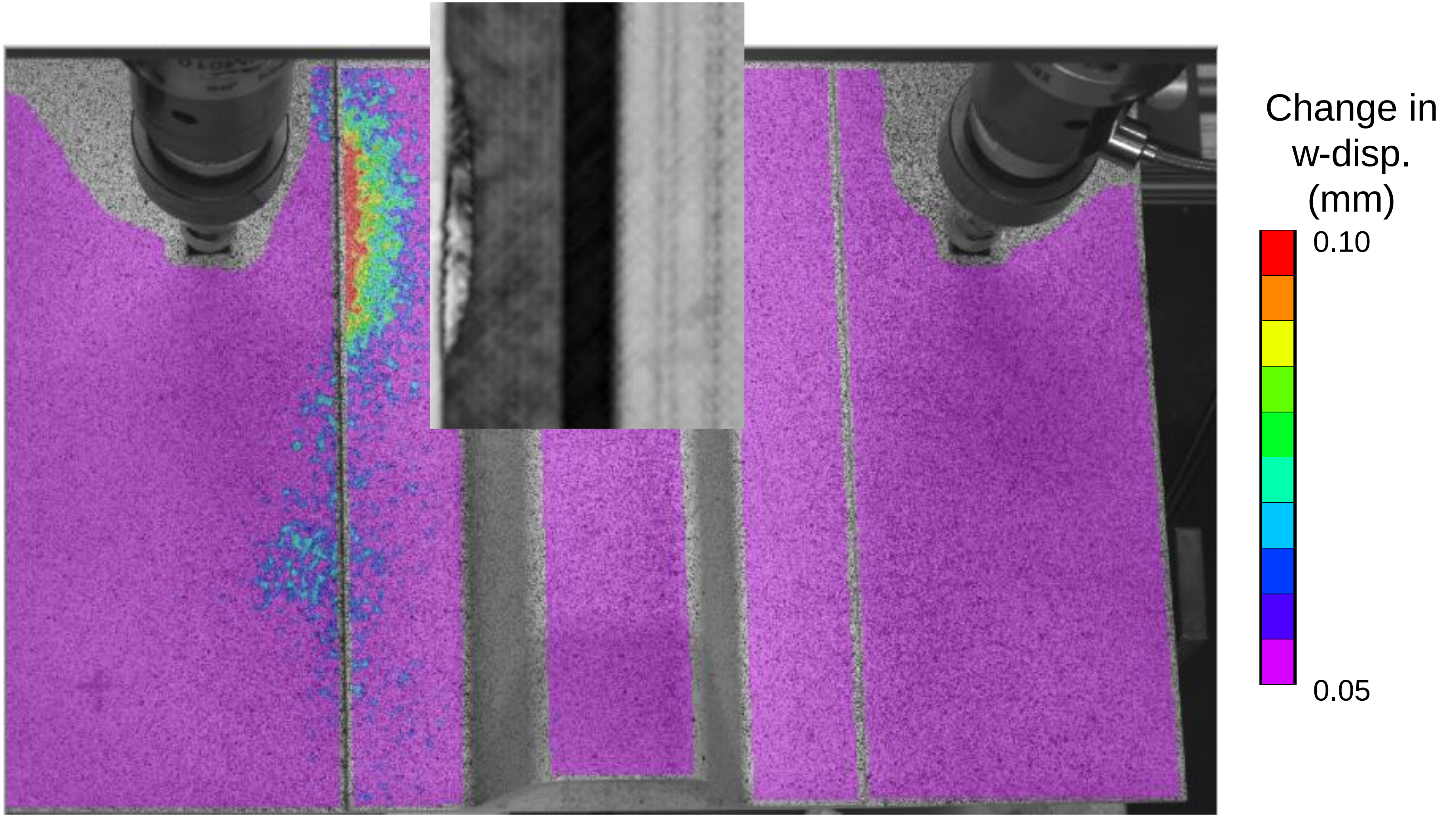
Example #2: Out-of-Plane Displacement Contours





Example #2: Characterizations of Delaminations

Frame 528 was used as a reference and the out-of-plane displacements shown below



Example #2: Findings and Ramifications

- The shape, displacement, and strain measurements from DIC were used to validate the structural analyses
- The DIC measurements were able to detect delaminations and quantify delamination size and growth
- The delamination measurements were validated with x-ray CT measurements that were performed at the end of loading cycles where delaminations were detected
- The delamination measurements were used to validate progressive damage models

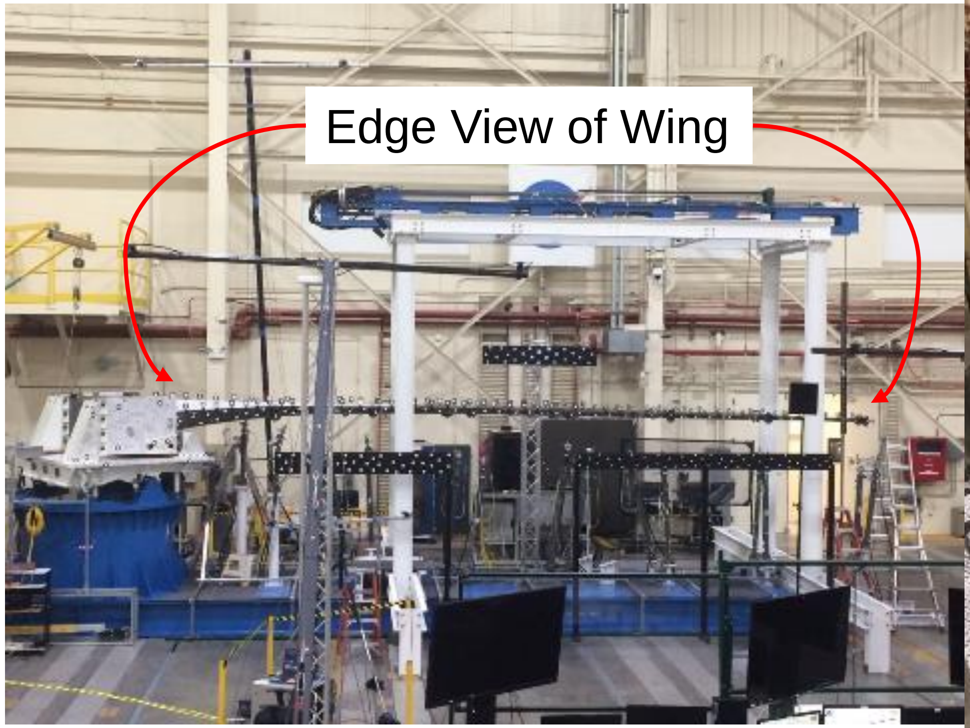
Example #3: AFRC Passive Aeroelastic Tailored (PAT) Wing Test

Problem:

- A full-scale composite wing (>40 feet) was tested in bending
- The characterization of wing deformations needed for validation of structural analyses and composite designs
- The rigidity of the boundary conditions was a concern, so characterization of support fixtures was required

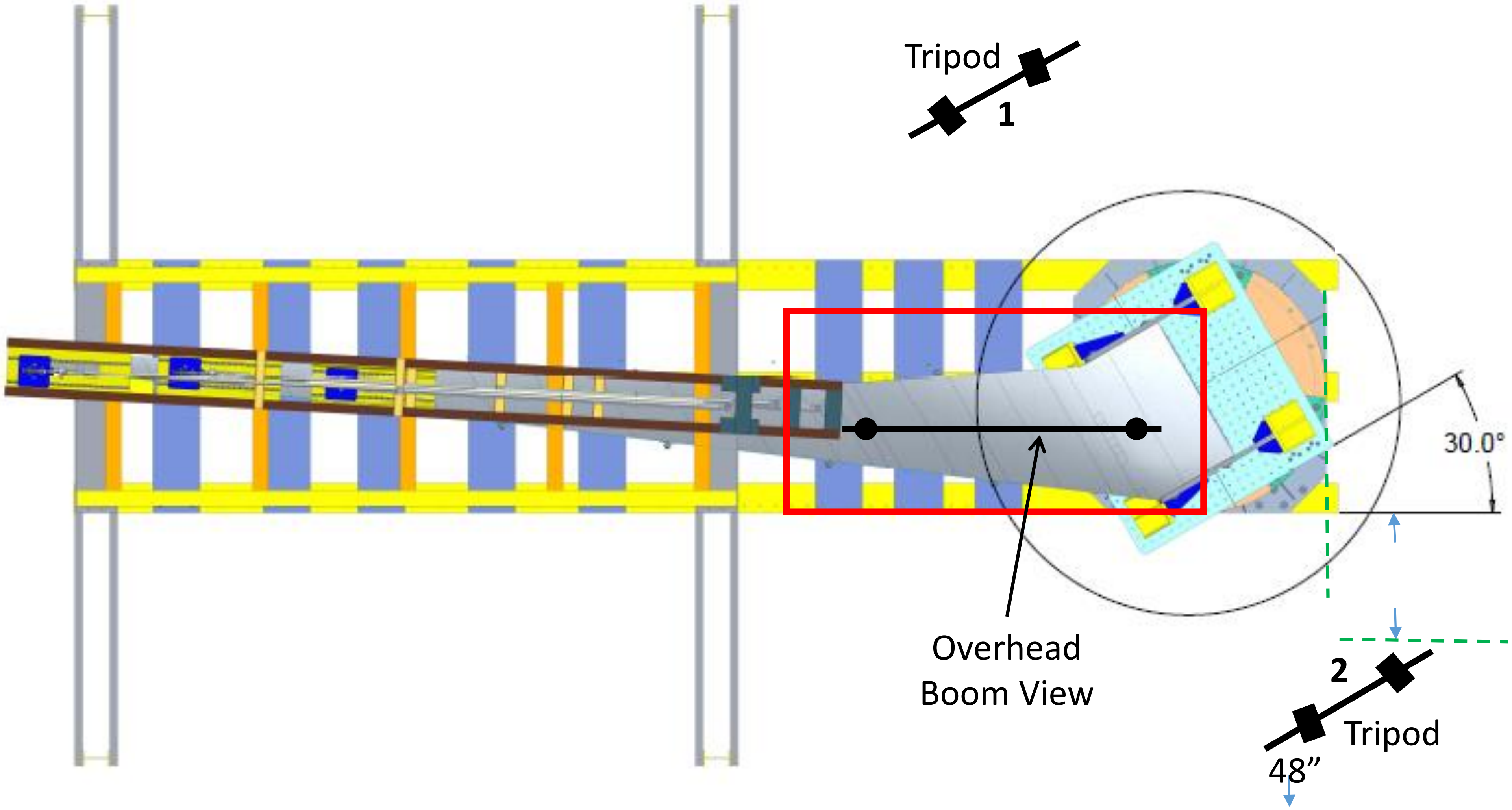
Goals:

- Quantify the wing deformations during upward and downward bending
- Quantify the support fixtures to establish the boundary conditions for the structural analyses


Edge View of Wing

Top View of Wing

Example #3: Initial DIC Camera Plan



Example #3: PAT Wing DIC Setup Top View

Hardware/Software:

- 30MP AVT cameras 28mm lenses suspended above the wing on a 36’ tall boom
- Hardware synced with a function generator
- VIC3D-8^{TM} with RealTime
- Aperture & exposure time optimized for ambient lighting

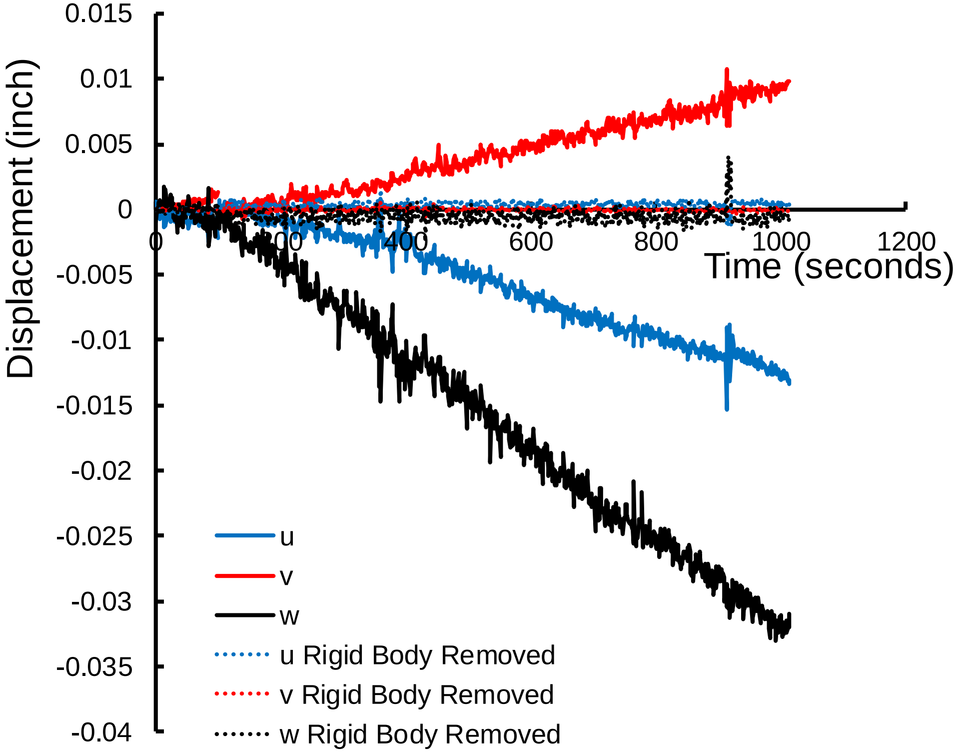
DIC Configuration:

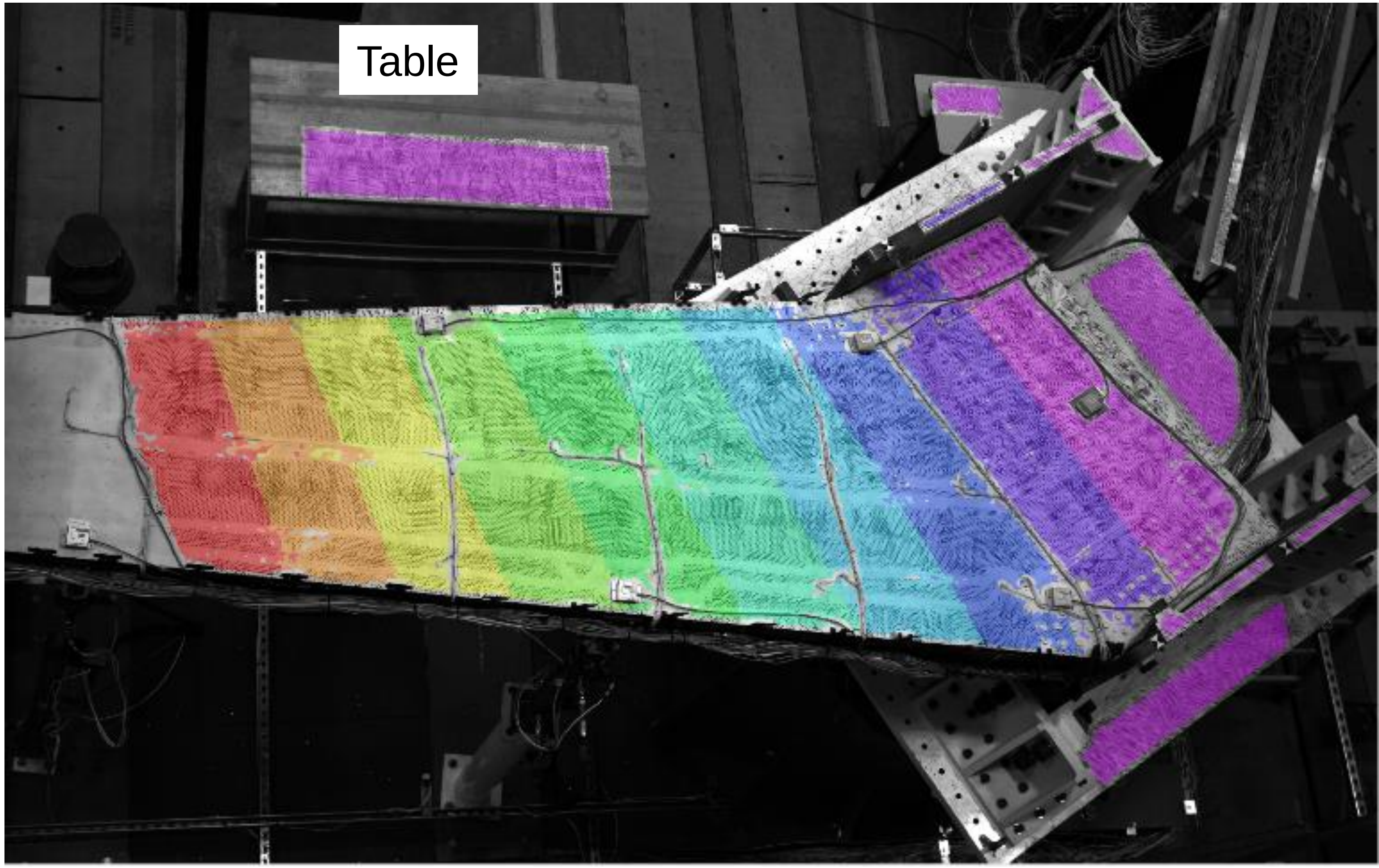
- AOI ~ 164 inch x 65 inch
- Pixel Resolution ~ 40 pixels/inch
- Speckle Size ~ 0.08 inch (ink stamp)
- Subset Size 41 pixels
- Step Size 7 pixels
- Standoff Distance ~ 22 feet
- Camera Angle ~ 20-degrees
- Calibration grid: 12x9 70mm

Issues:

- Travel logistics (i.e., make sure we have everything we need)
- Movement of the camera supports during the long duration test
- Fall and drop hazards

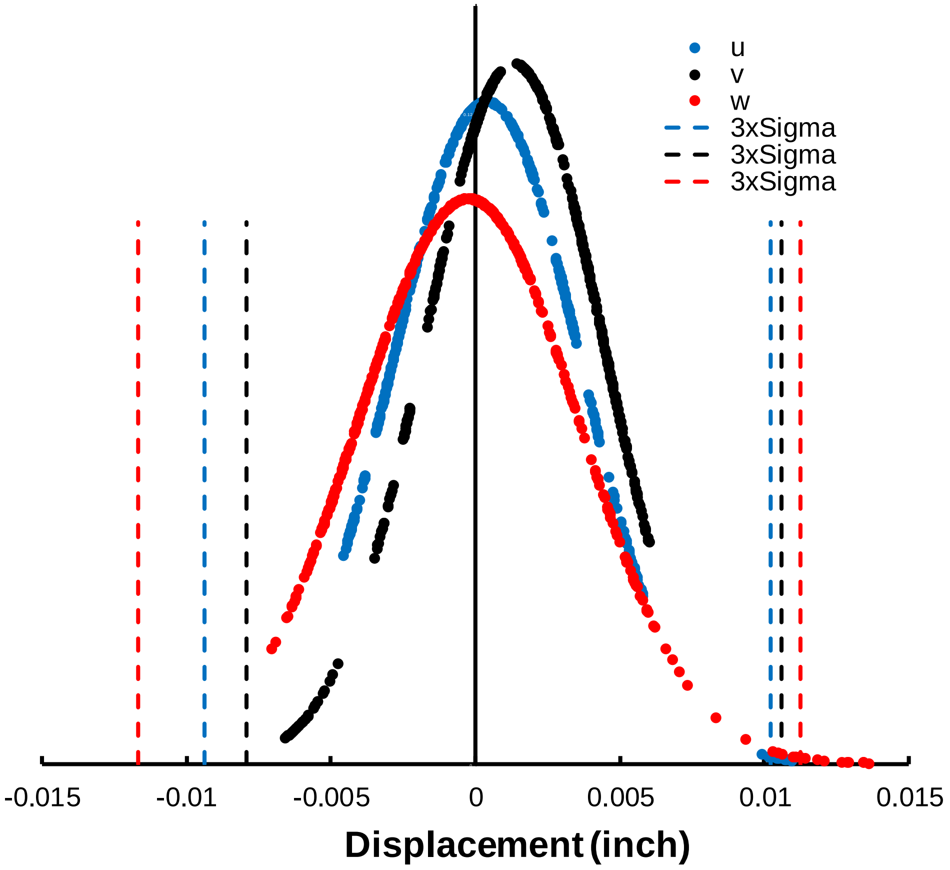
Example #3: Top View Rigid Body Motion



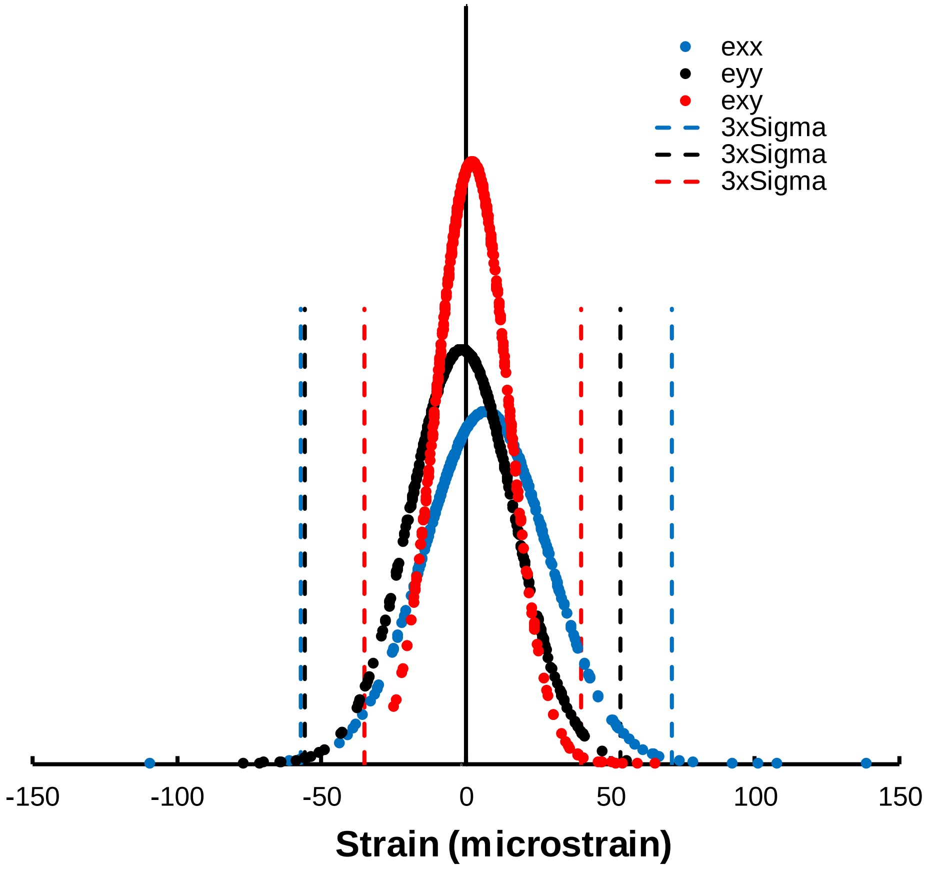


The boom supporting the top view cameras moved continuously during the tests (likely due to temperature changes during the test). A table was placed in the field of view (isolated from the test article and loading structure) and speckled. The table was used as a fixed point to remove rigid body motions.

Example #3: DIC Noise Floor for Top View

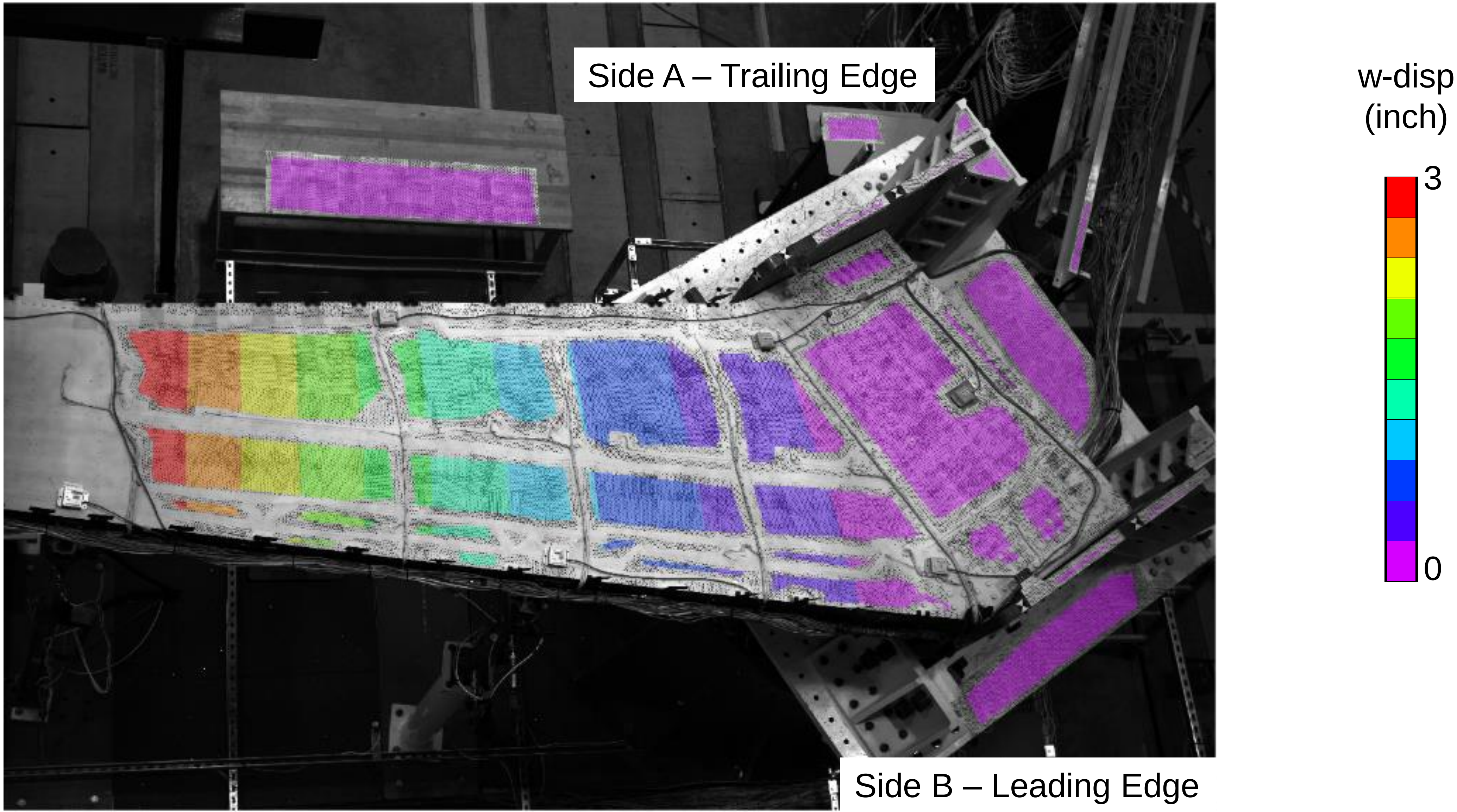


Ratio of Expected Signal to 3σ Noise
u: ~25
v: ~100
W: ~350



Ratio of Expected Signal to 3σ Noise
e_{xx}: ~15
e_{yy}: ~35
e_{xy}: ~25

Example #3: Top View Displacement (Rigid Body Motion Removed)



Example #3: PAT Wing DIC Setup Side View

Hardware/Software:

- 12MP FLIR Grasshopper 3 with 28mm lenses
  - Supported on tripods
  - Viewing the support structure
- Hardware synced with a function generator
- VIC3D-8^{TM} with RealTime
- Aperture & exposure time optimized for ambient lighting

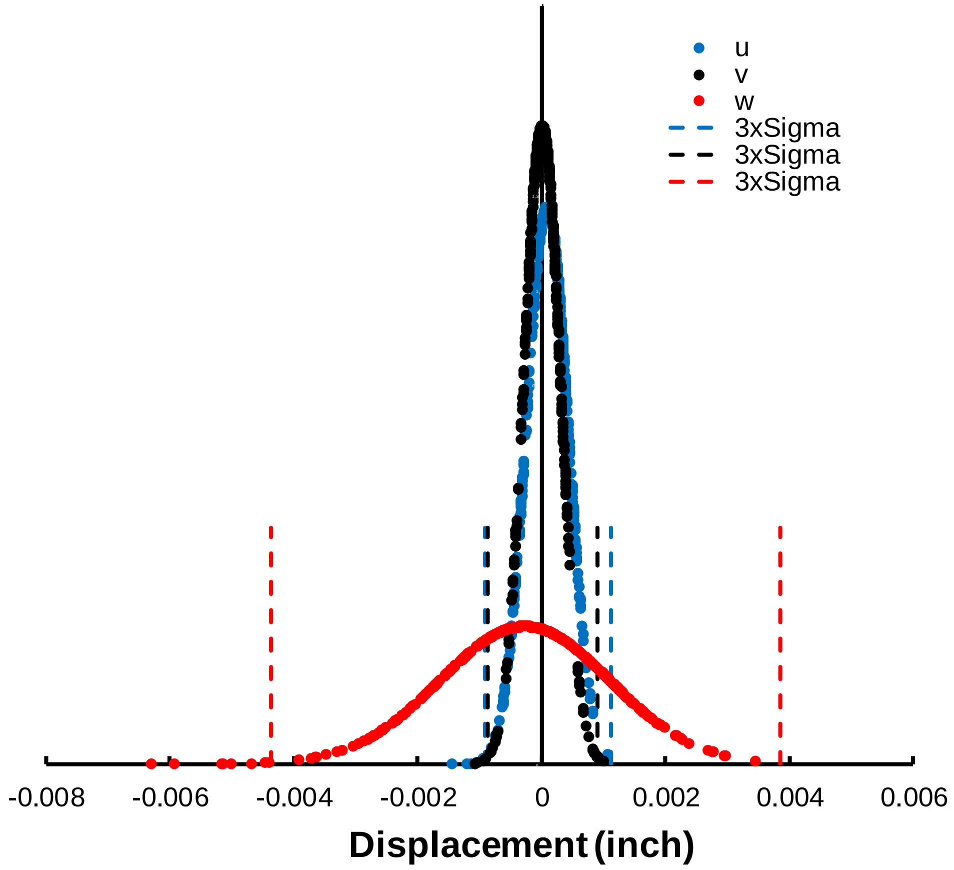
DIC Configuration:

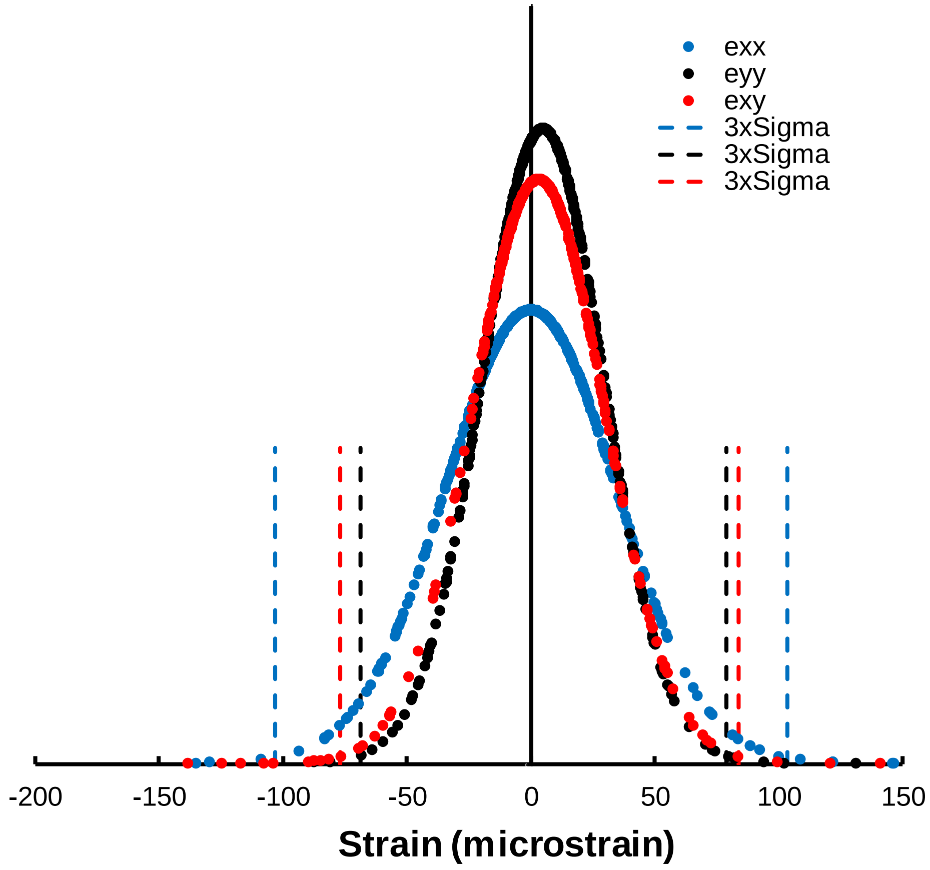
- AOI ~ 100 inch x 65 inch
- Pixel Resolution ~ 50 pixels/inch
- Speckle Size ~ 0.05 inch (ink stamp)
- Subset Size 29 pixels
- Step Size 7 pixels
- Standoff Distance ~ 18 feet
- Camera Angle ~ 18-degrees
- Calibration grid: 12x9 70mm

Issues:

- Speckling a large structure
- Obstructions for camera placement

Example #3: DIC Noise Floor for Side Views

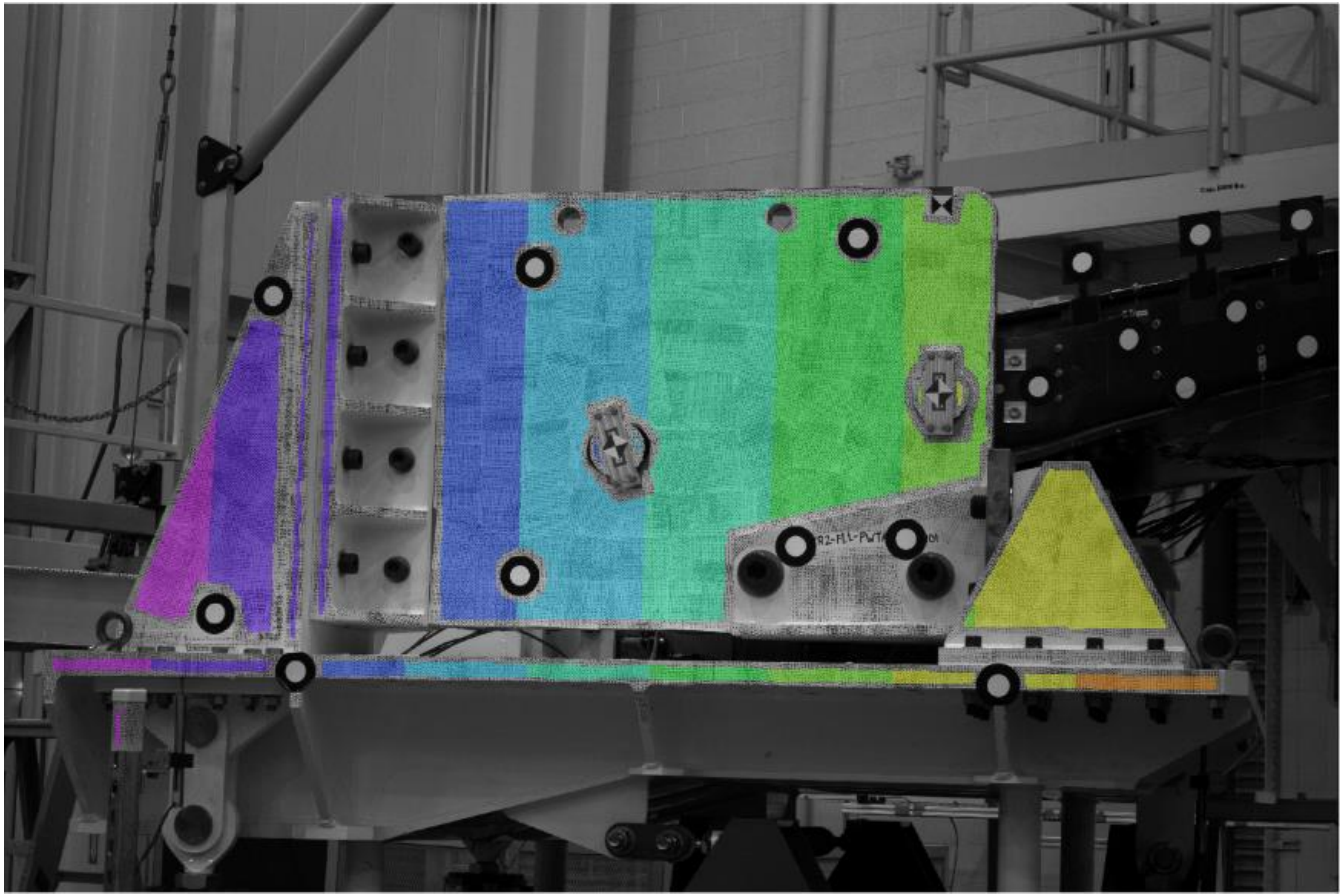




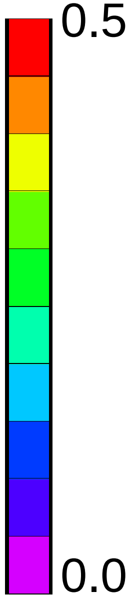
Ratio of Expected Signal to 3σ Noise
u: ~50
v: ~50
W: ~5

Ratio of Expected Signal to 3σ Noise
e_{xx}: ~2
e_{yy}: ~4
e_{xy}: ~4

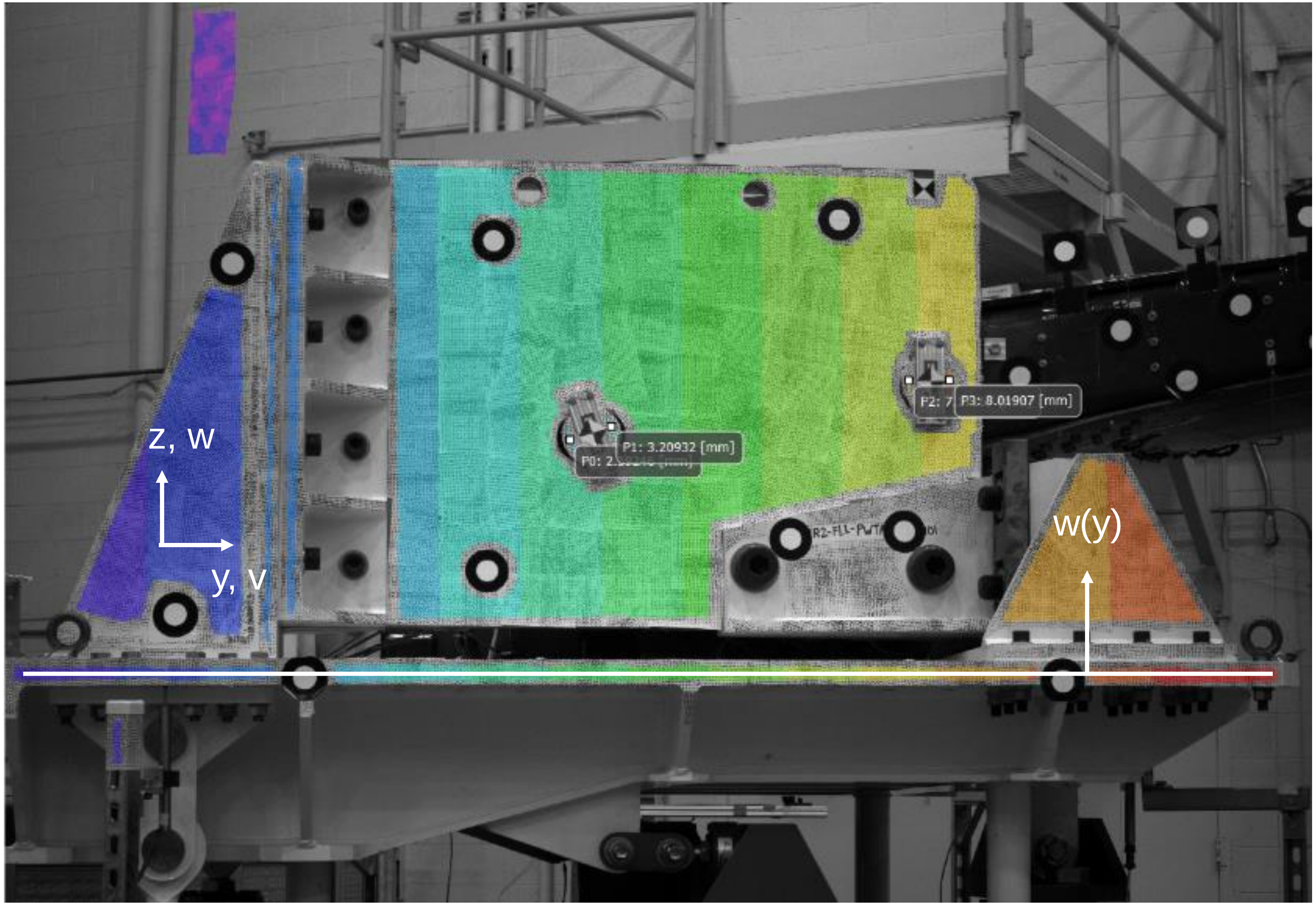
Example #3: Fixture Movement



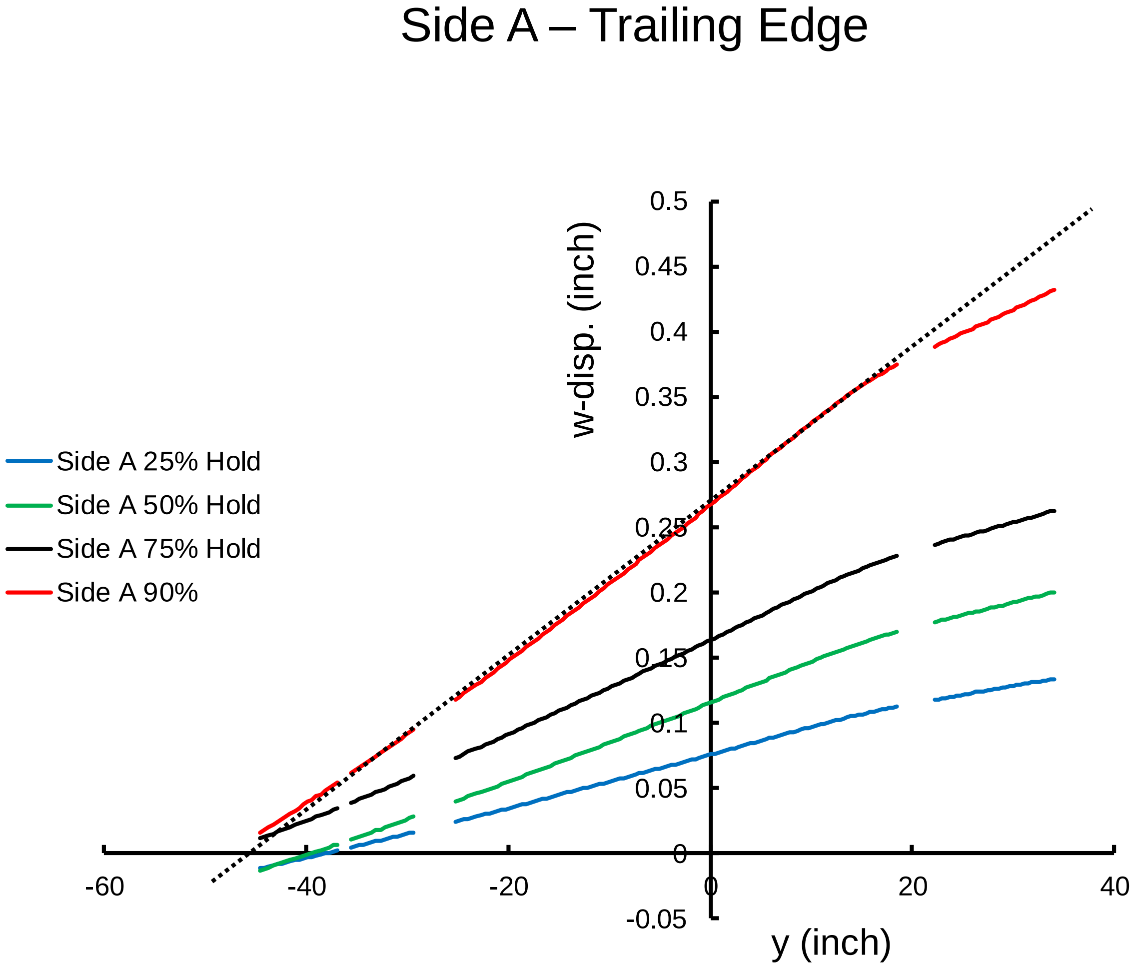
w-disp
(inch)

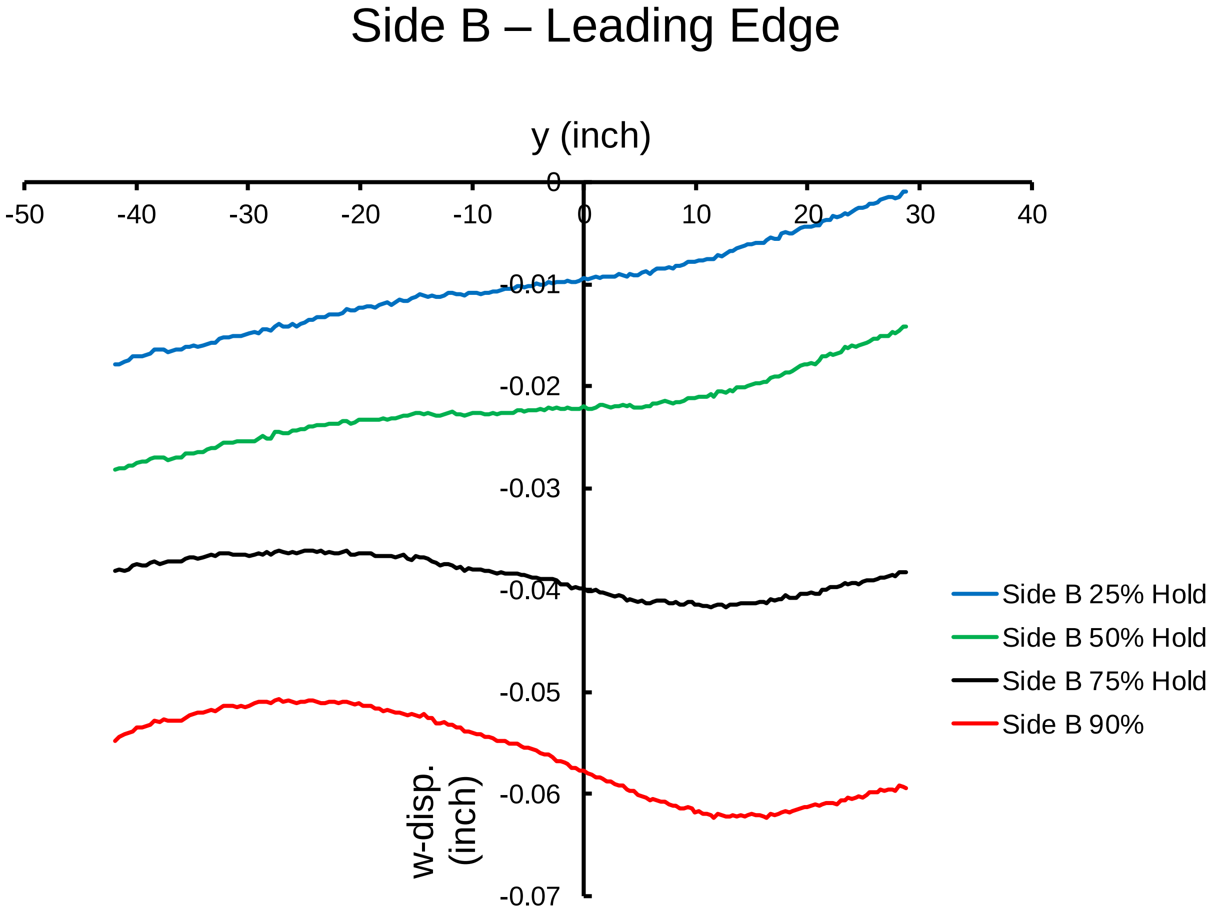


Example #3: Side Coordinate System

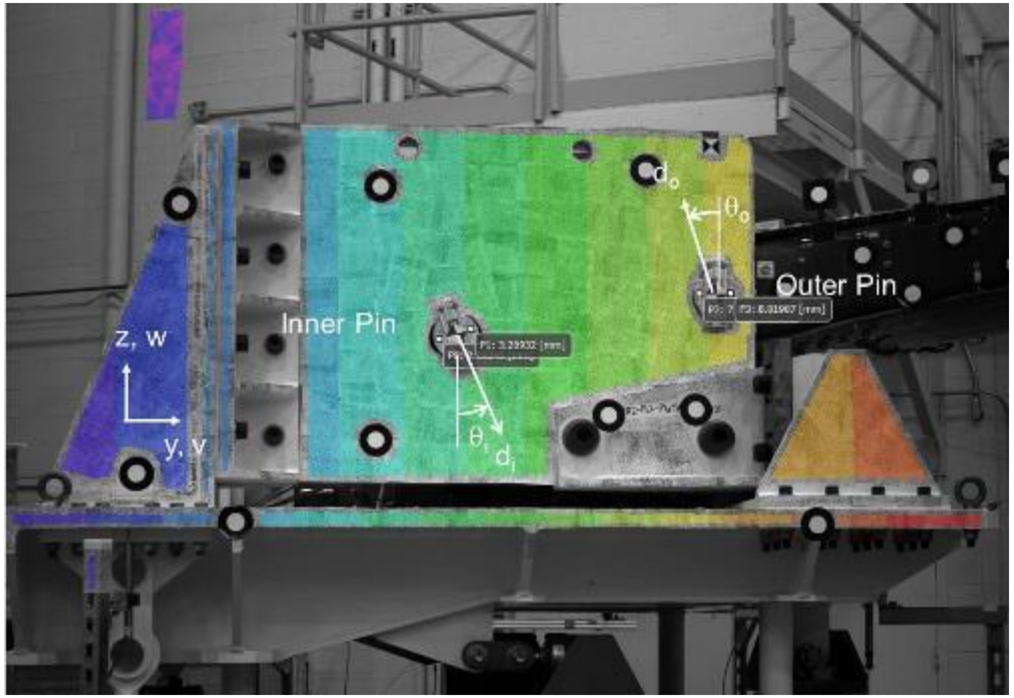


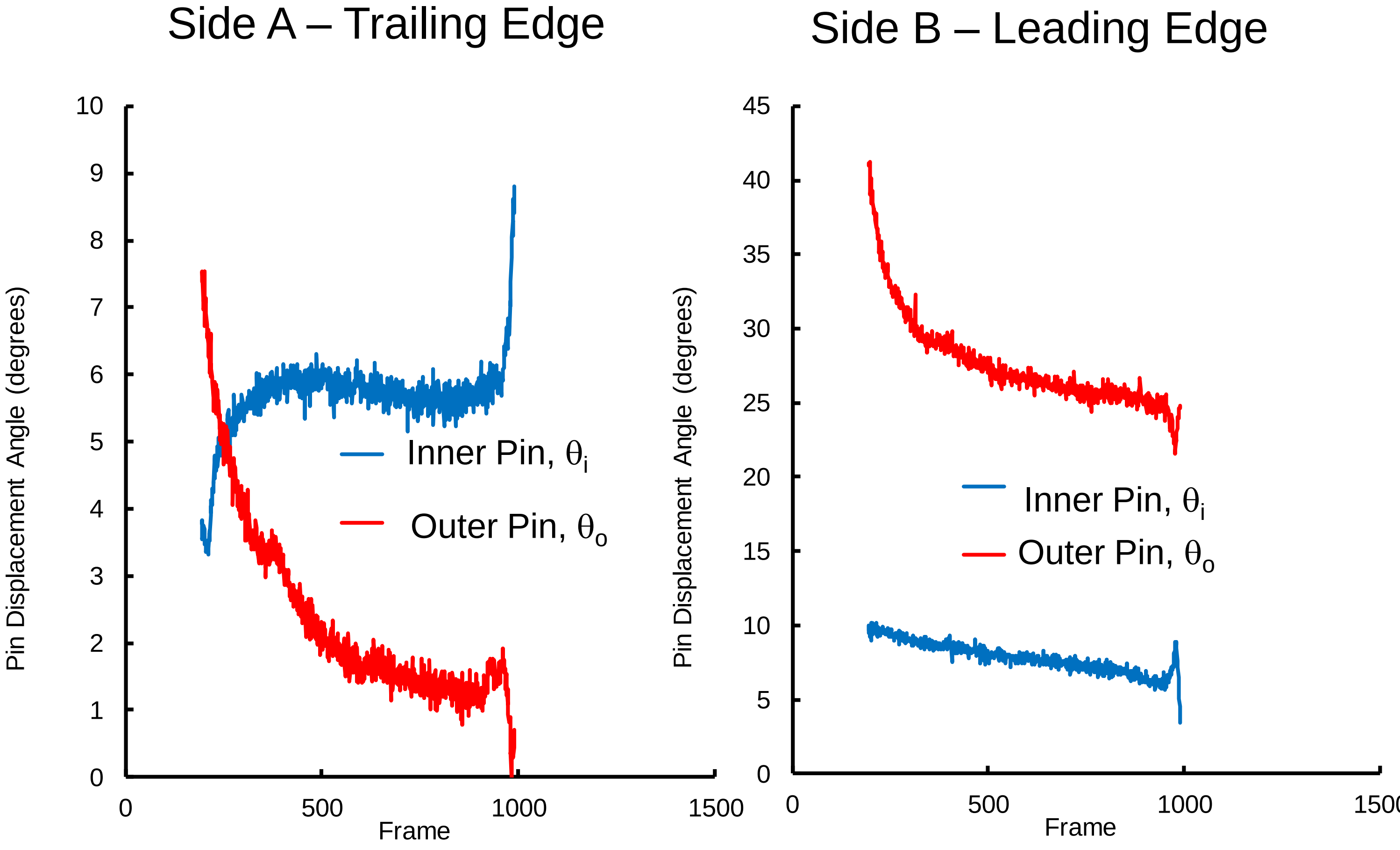
Example #3: Support Plate Deformations





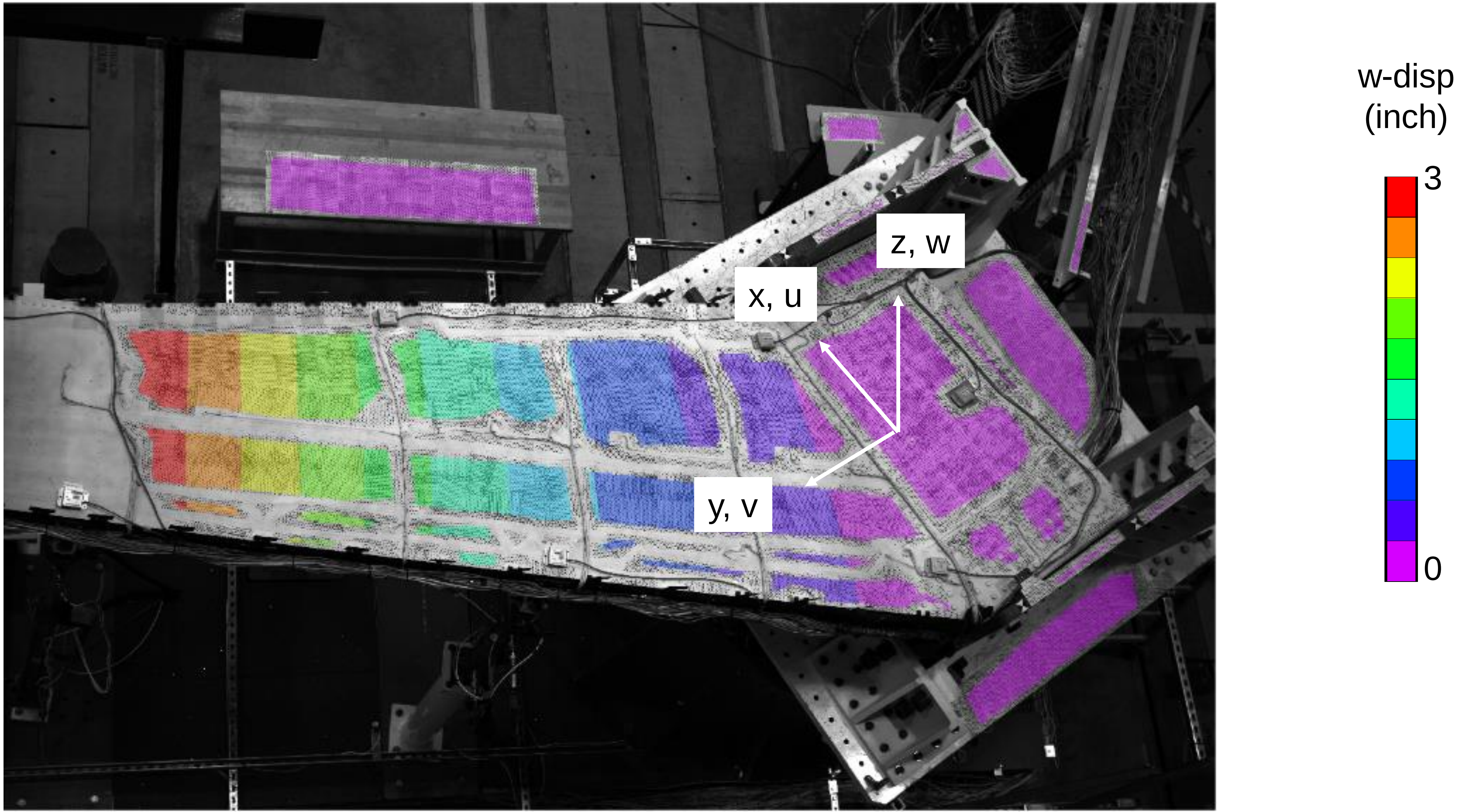
Example #3: Pin Movement




Side A – Trailing Edge

Side B – Leading Edge

Example #3: DIC Measurements



Example #3: Findings and Ramifications

- The top camera movement was larger than expected and accounted for by removing rigid body motion
- The pin rotation and plate deformation were unexpected
- The boundary conditions that were measured with DIC were incorporated into the finite element analyses
- The top surface displacements and strains were used to validate the finite element model

Example #4: Mars 2020 Heat Shield

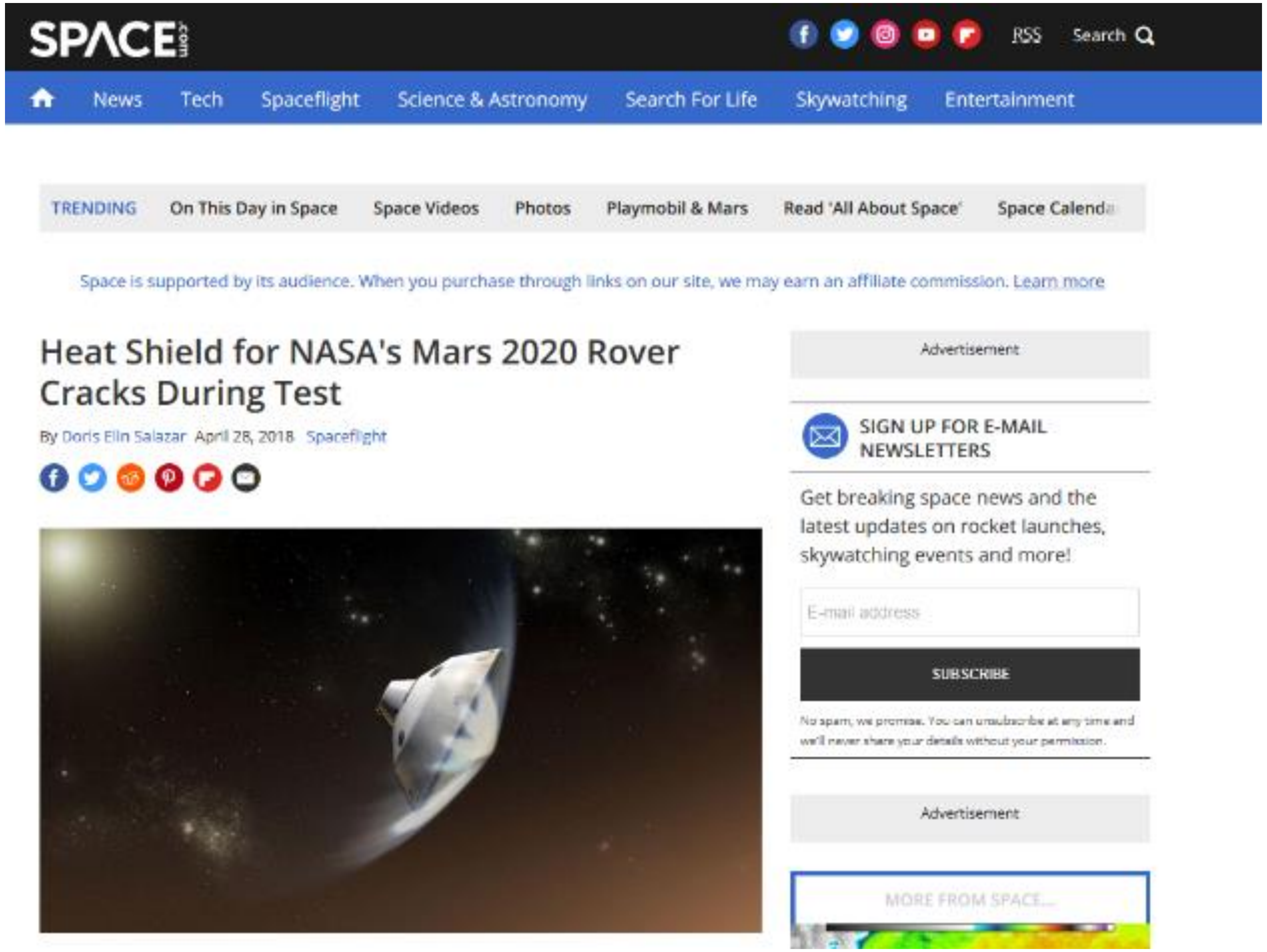
Problem:

- The Mars 2020 heat shield (flight hardware) is required to have a ground proof test to 120% of the entry, descent, and landing loads
- The first test performed in 2018 and the strain during loading was monitored with strain gages, but a fracture occurred away from the strain gages
- The heat shield was redesigned for testing in 2019
- A failure of the second proof test would likely cause a 2-year delay in the launch

Goals:

- Perform full-field characterization of the entire heat shield in real-time during the proof test loading to prevent fracture by identifying any regions of elevated strain
- Characterize the full-field strain distribution for validation of structural models

Space.com article from April 28, 2018



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Heat Shield for NASA's Mars 2020 Rover Cracks During Test

By Doris Elin Salazar April 28, 2018 Spaceflight

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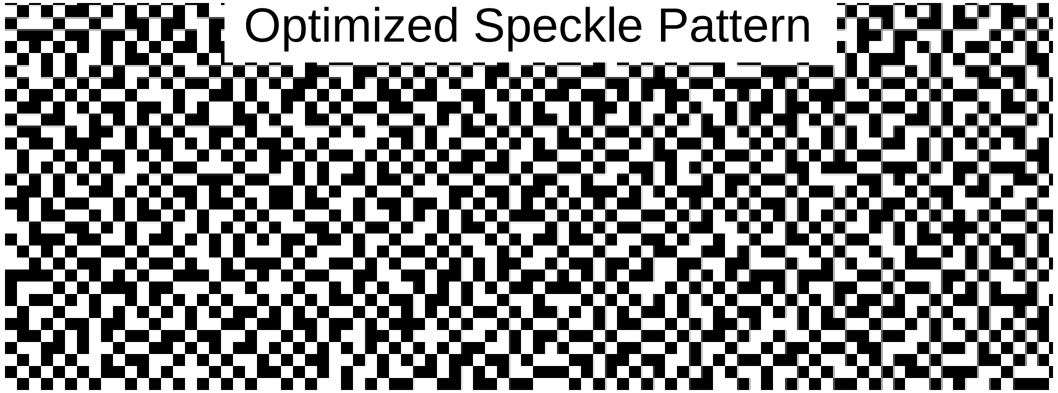
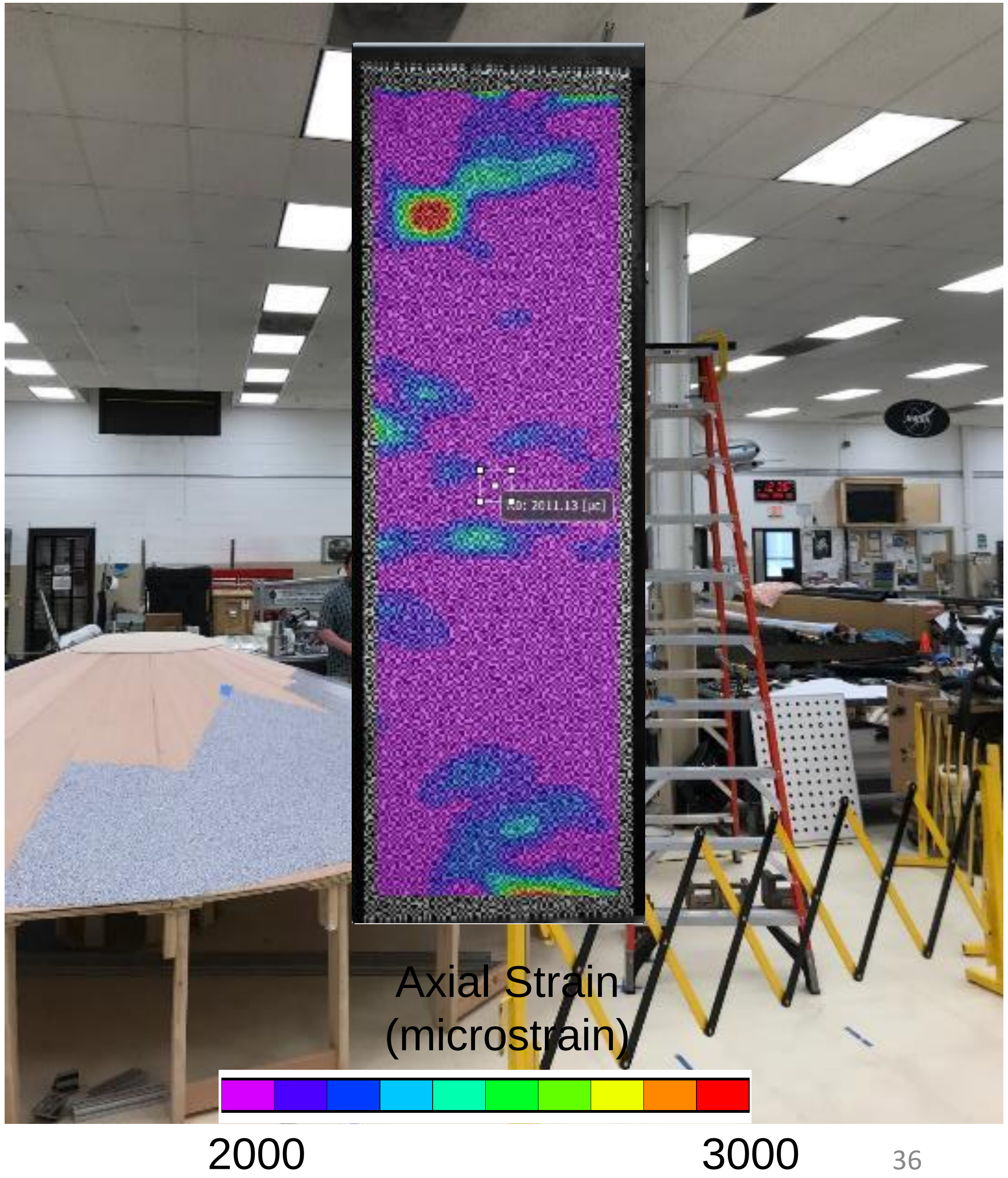
Example #4: DIC Preparations

- Selected and received approval to use a vinyl wrap (3M 1080) for use on the flight hardware
- Used an optimized speckle pattern (Bomarito, Hochhalter, Ruggles, and Cannon, “Increasing Accuracy and Precision of Digital Image Correlation Through Pattern Optimization,” Optics and Lasers in Engineering, Vol. 91, PP 73-85, April 2017)
- Conducted preliminary tests to demonstrate that the strain obtained from the vinyl wrap was representative of structure
- Developed a full-scale plywood mockup



Optimized Speckle Pattern



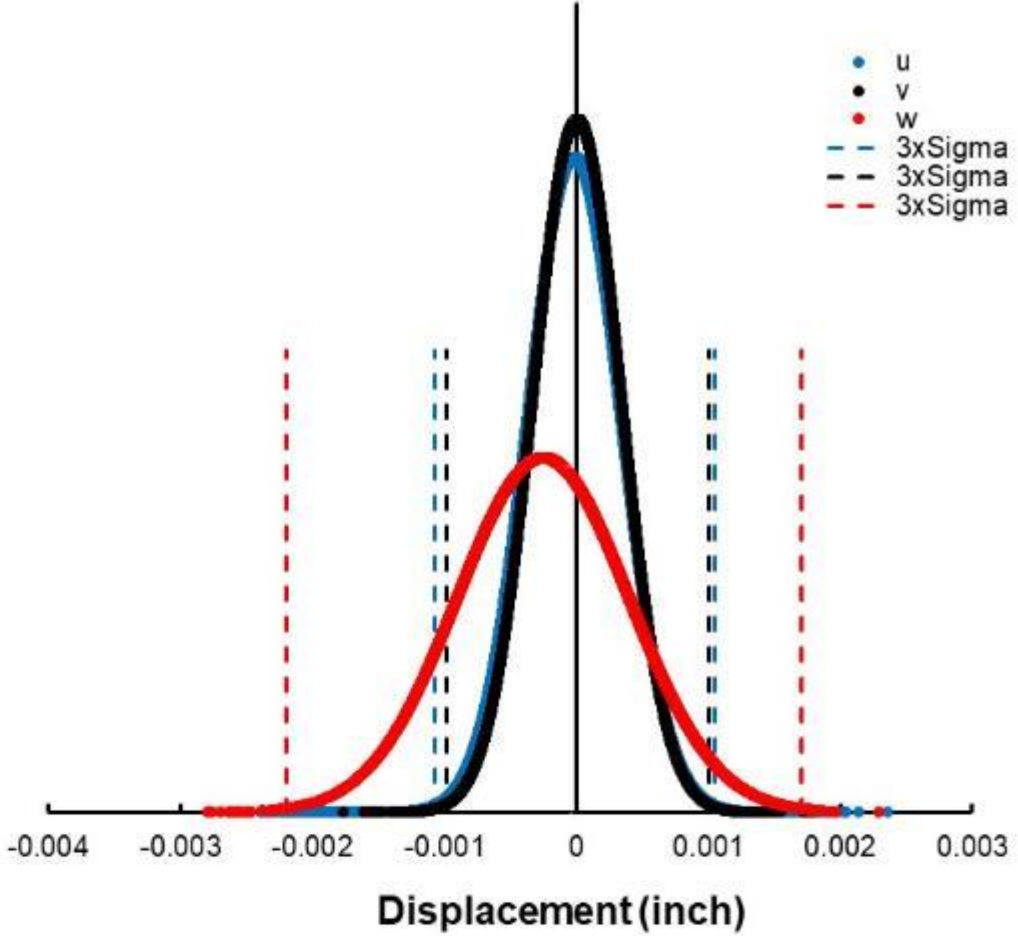
Example #4: DIC Setup

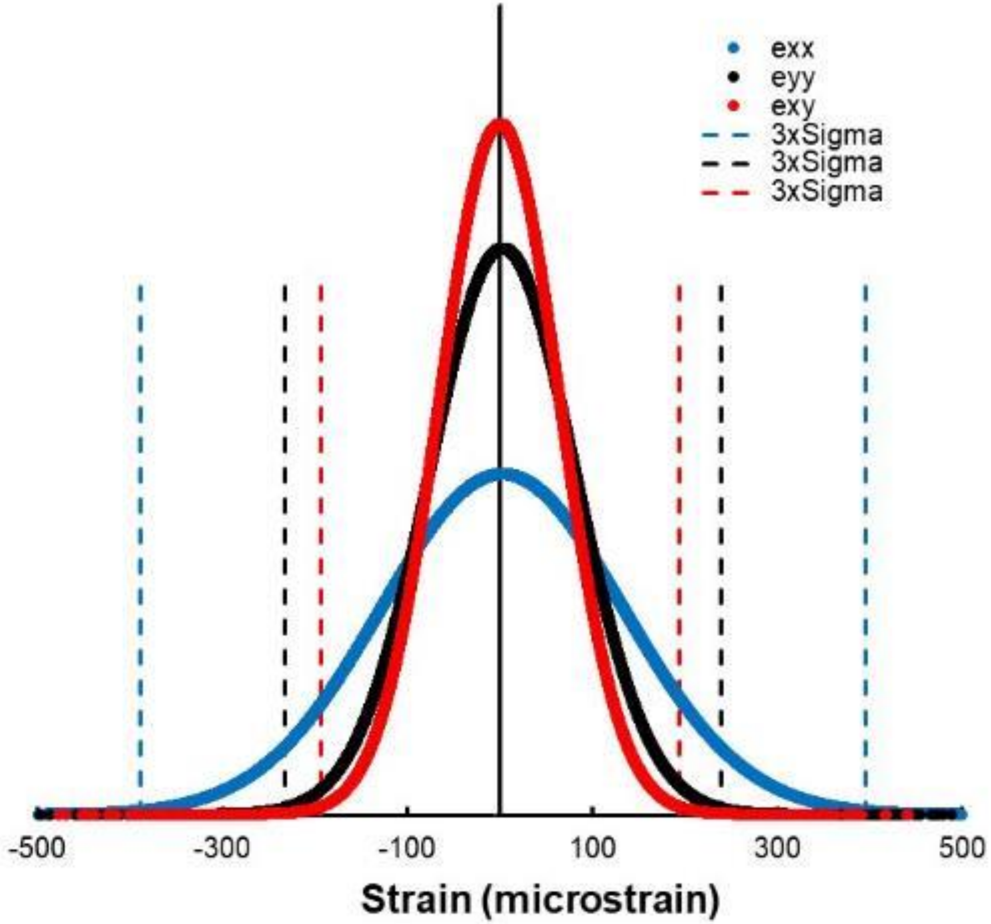
Hardware/Software:
- Three pairs of cameras (every 120-degrees)
  - 30MP AVT cameras 50mm lenses
  - Overlapping AOI
- Cameras mounted on 80/20 supported by ladders
- Hardware synced systems
- VIC3D-8^{TM} with RealTime
- Aperture, exposure time, and lighting optimized

DIC Configuration
- AOI ~ 176 inch x 117 inch
- Pixel Resolution ~ 36 pixels/inch
- Speckle Size ~ 0.1 inch (printed on vinyl)
- Subset Size 29 pixels and Step Size 7 pixels
- Standoff Distance ~ 15 feet
- Camera Angle ~ 22-degrees
- Calibration grid: 12x9 70mm

Issues
- Travel logistics (i.e., make sure we have everything we need)
- Flight hardware (i.e., surface must be returned to pristine condition)
- Real-time monitoring (i.e., ~1 second refresh) during loading
- High strain resolution (< 100 microstrain)
- Limited floor space
- Drop hazards (one of a kind flight hardware)

Example #4: DIC Noise Floor for Side Views



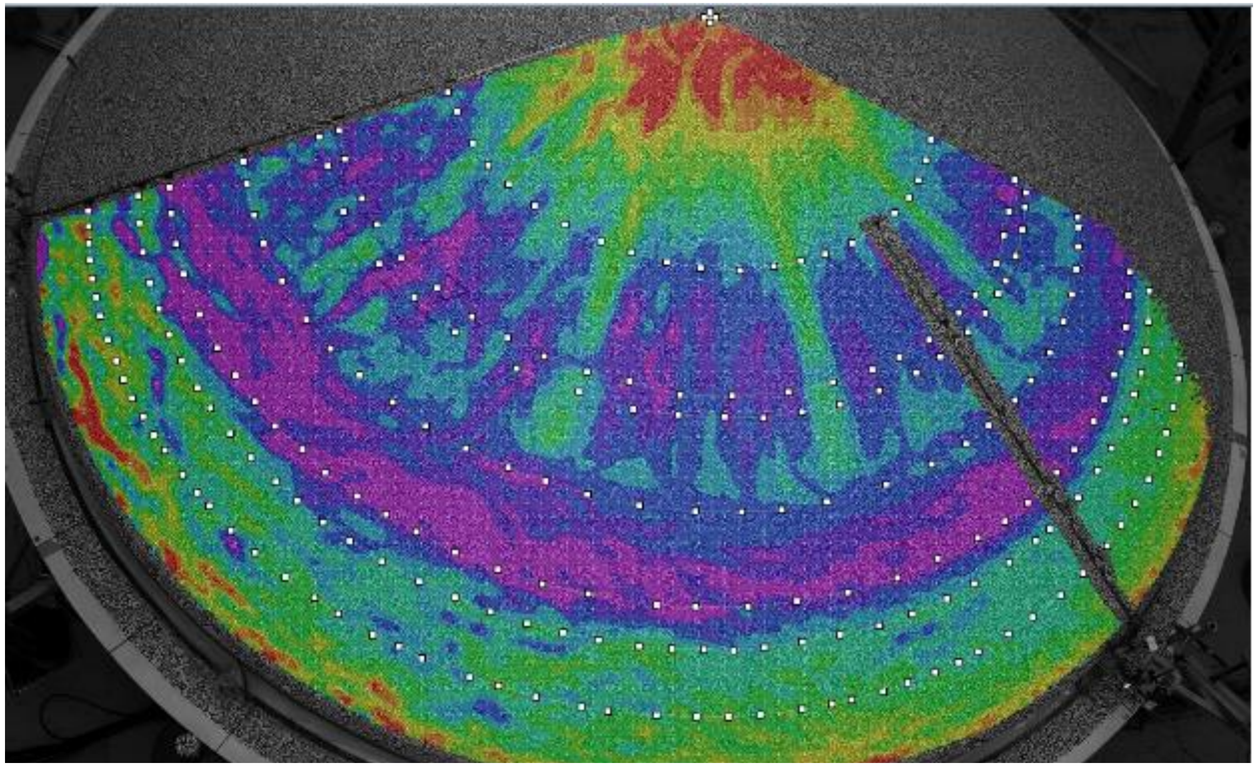


Ratio of Expected Signal to 3σ Noise
u: ~70
v: ~70
W: ~200

Ratio of Expected Signal to 3σ Noise
e_{xx}: ~6
e_{yy}: ~6
e_{xy}: ~4

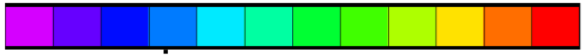
Example #4: DIC and Strain Gage Locations

Min Principal Strains

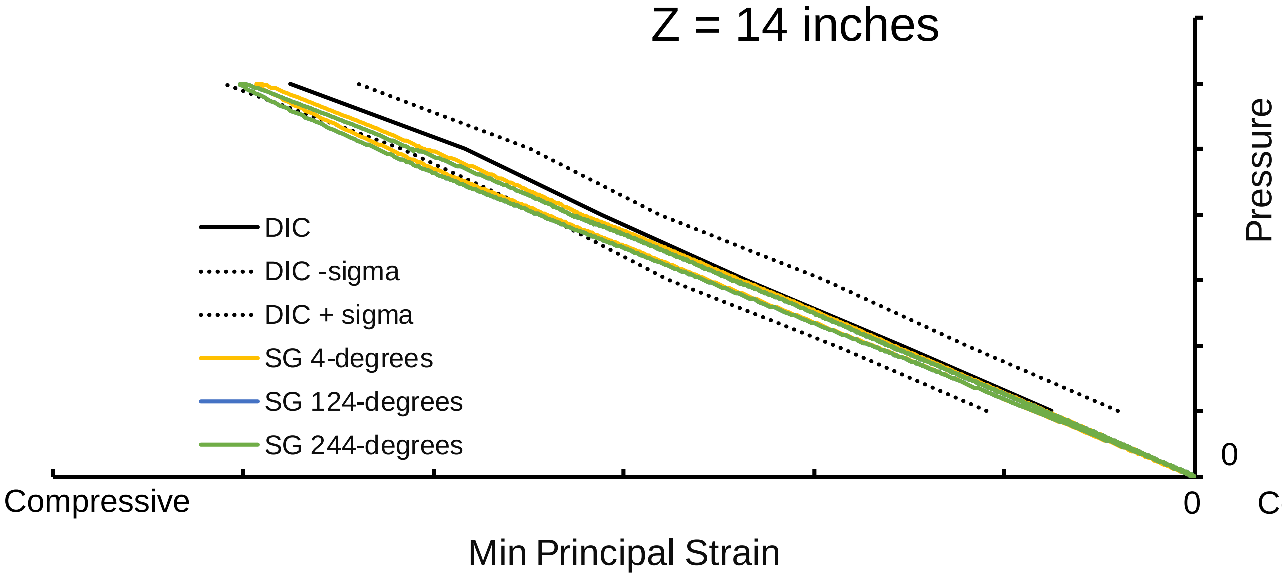


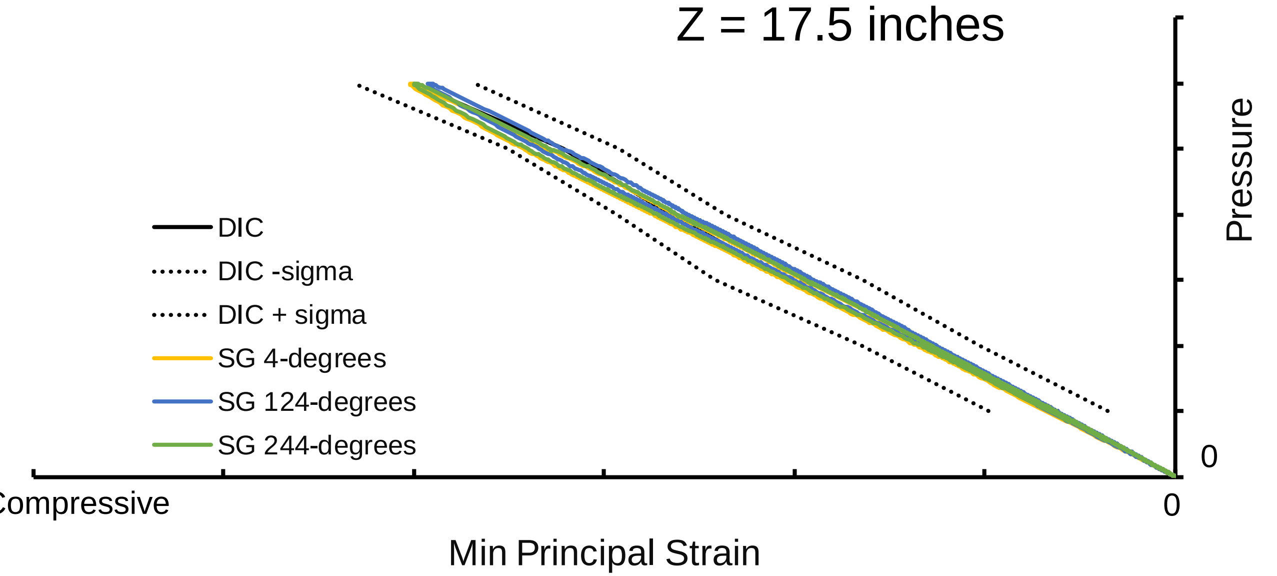
DIC Strain Extracted the Strain Gage Height for 360-degrees

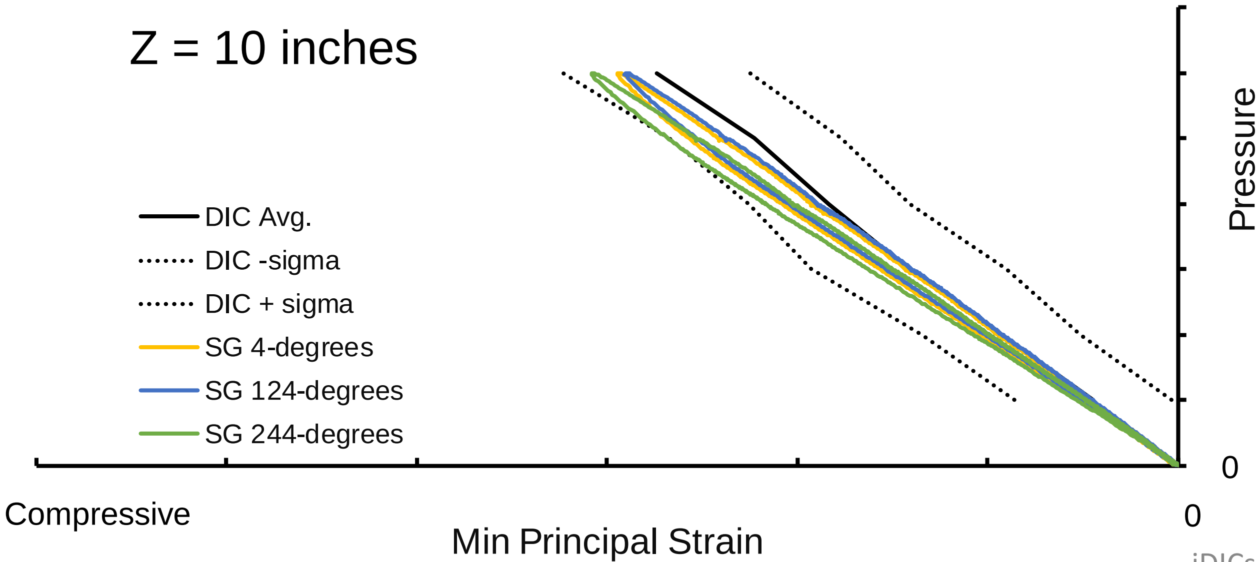
e_1
(microstrain)

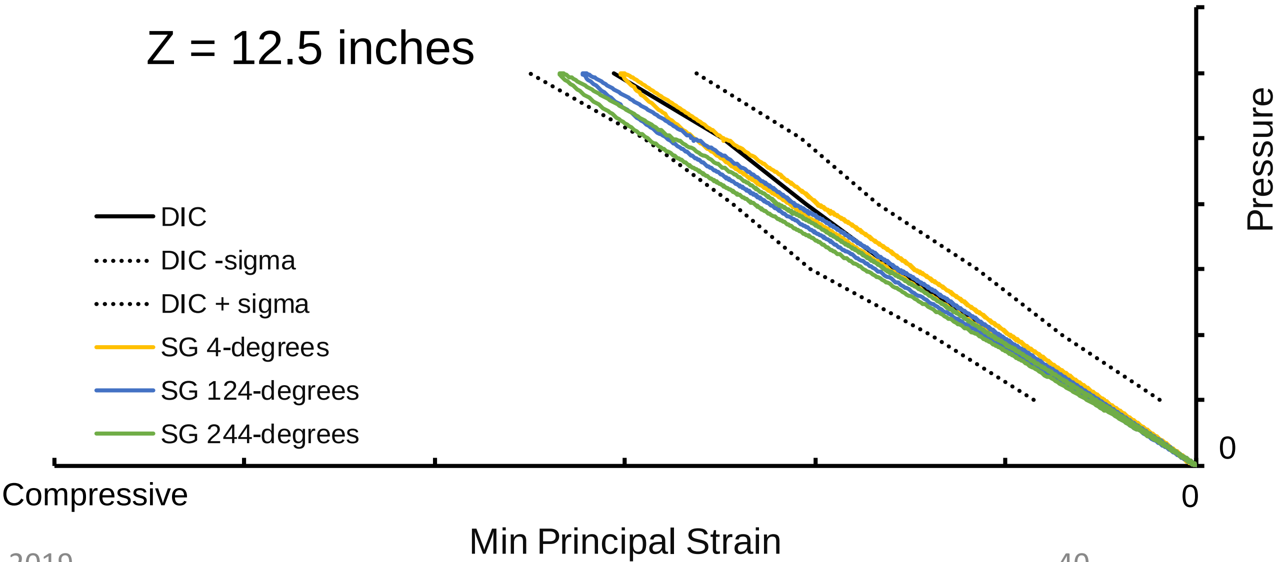


Example #4: DIC and Strain Gage Comparisons (4 Lowest Gage Locations)

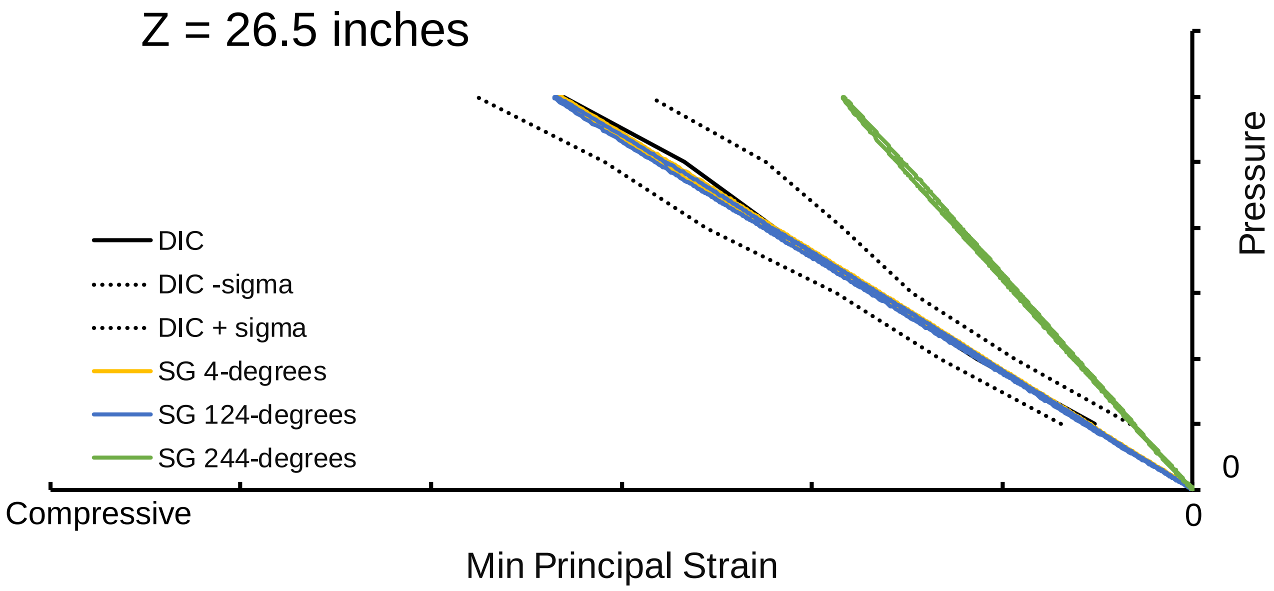

Z = 14 inches

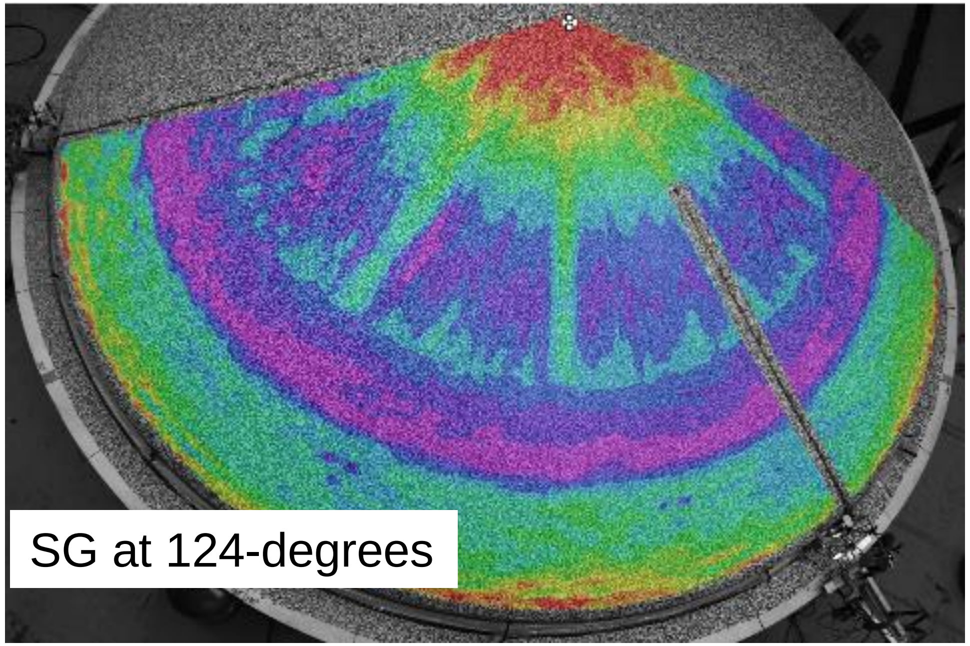

Z = 17.5 inches

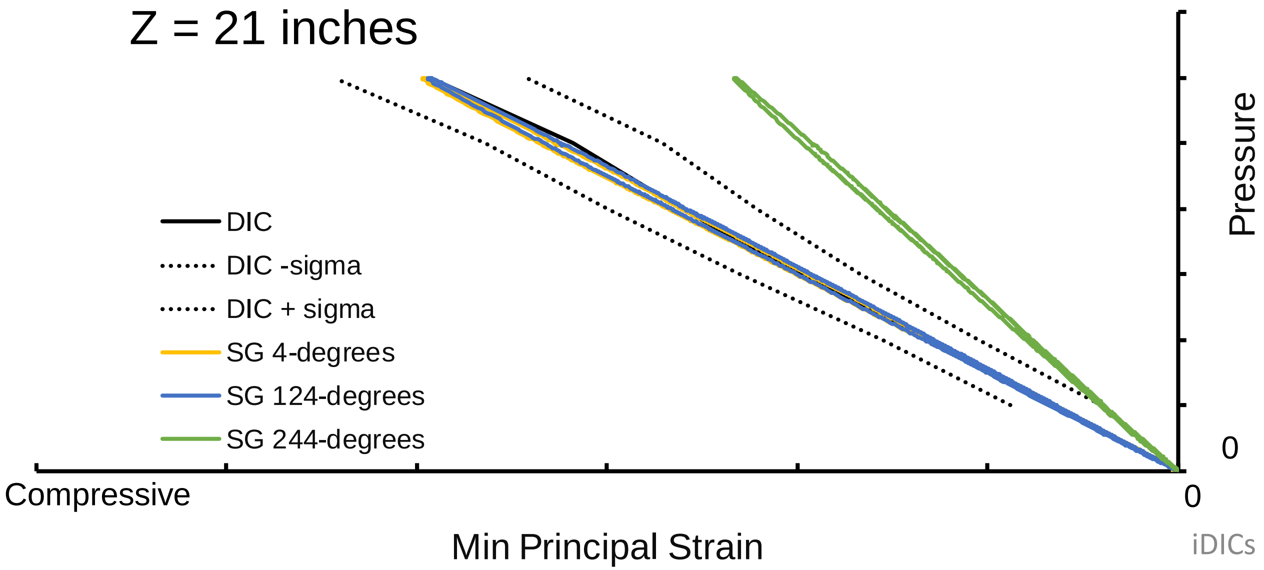

Z = 10 inches

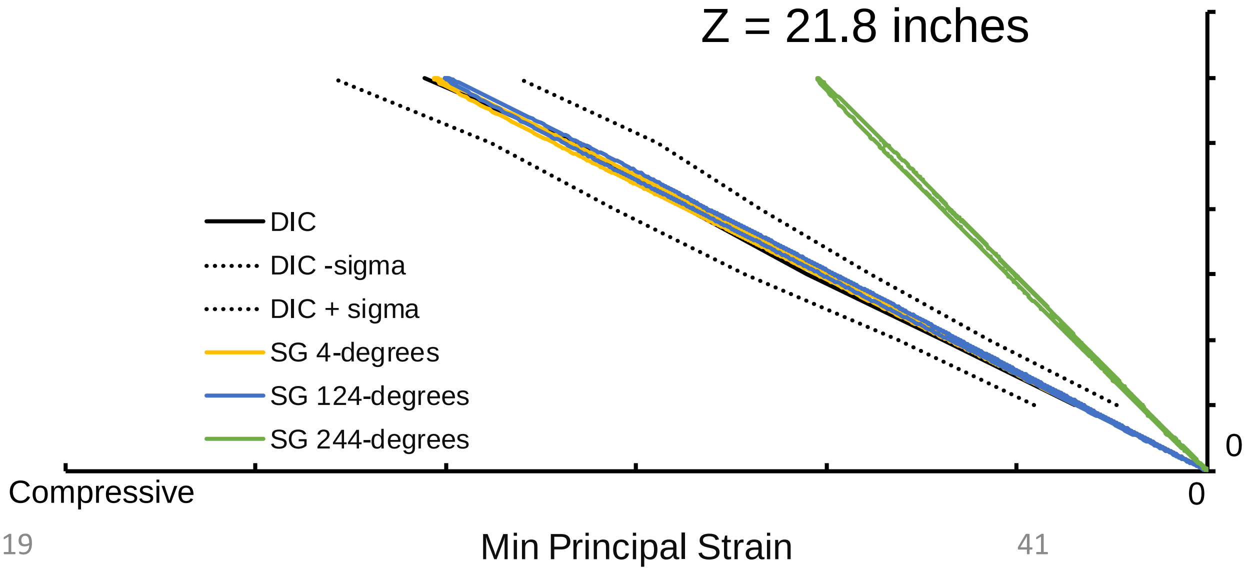

Z = 12.5 inches

Example #4: DIC and Strain Gage Comparisons (3 Highest Gage Locations)


Z = 26.5 inches

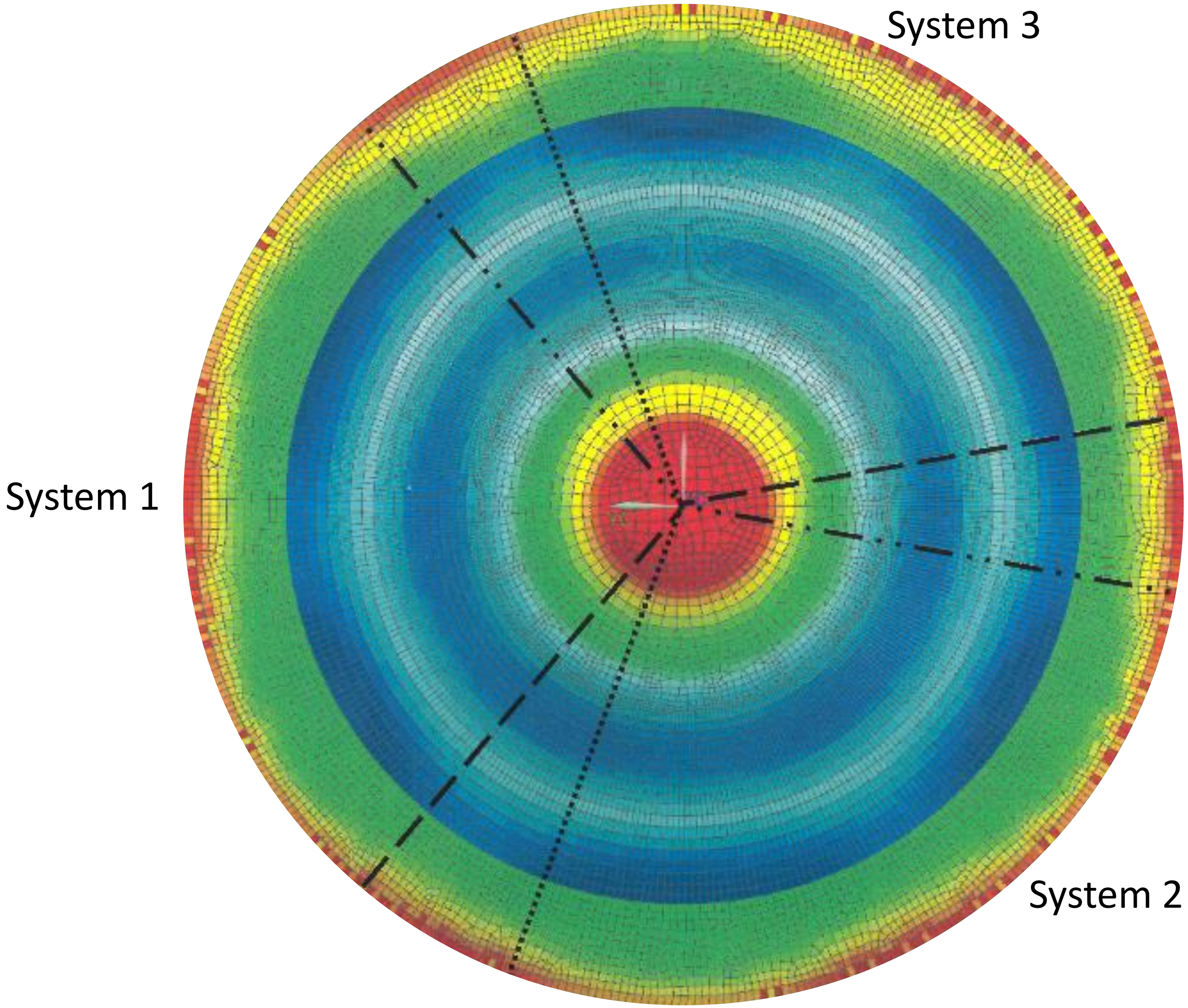

SG at 124-degrees


Z = 21 inches

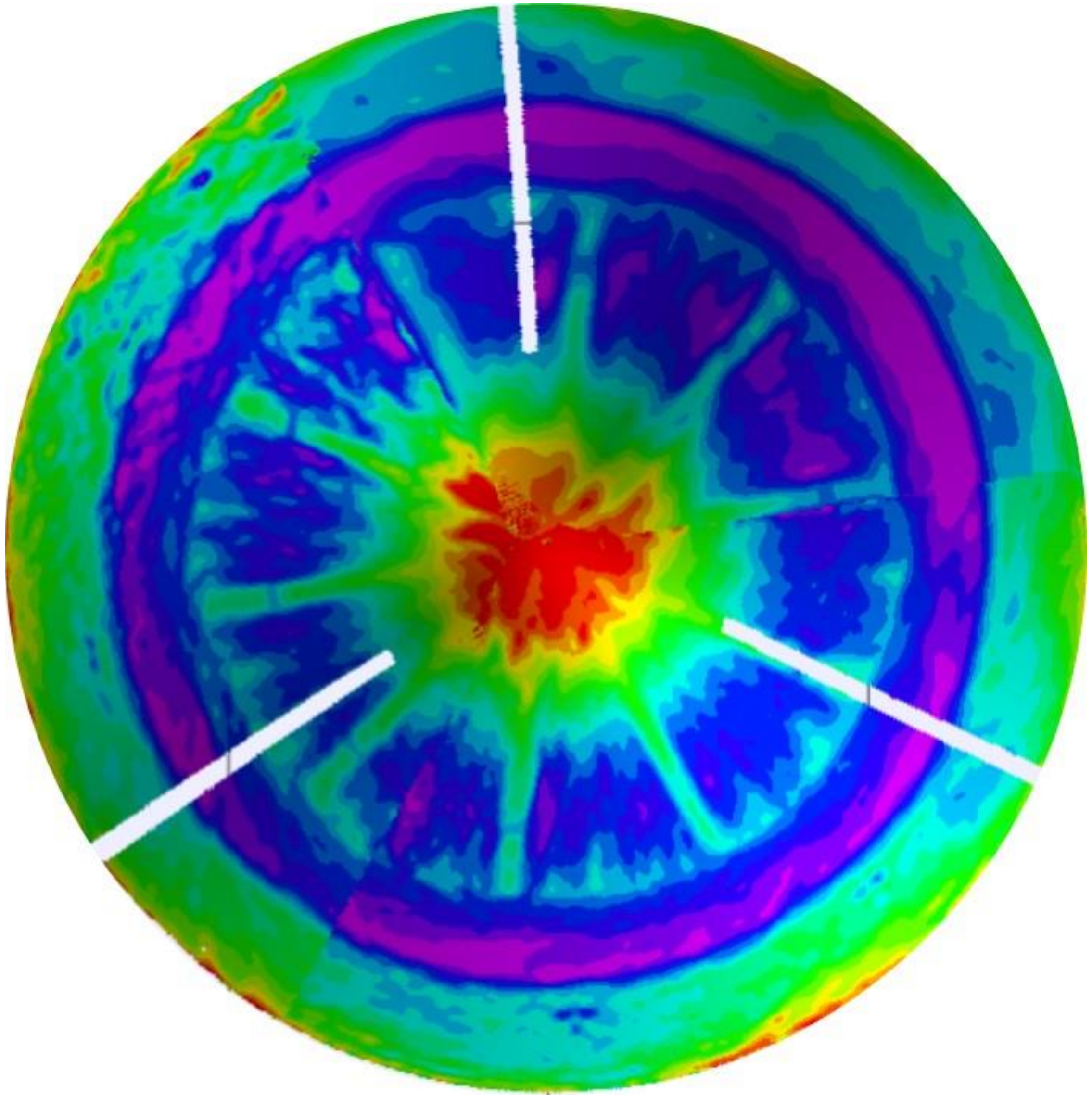

Z = 21.8 inches

Example #4: Stitched DIC and Analysis Predictions at a Constant Pressure

Analysis Minimum Principal Strains

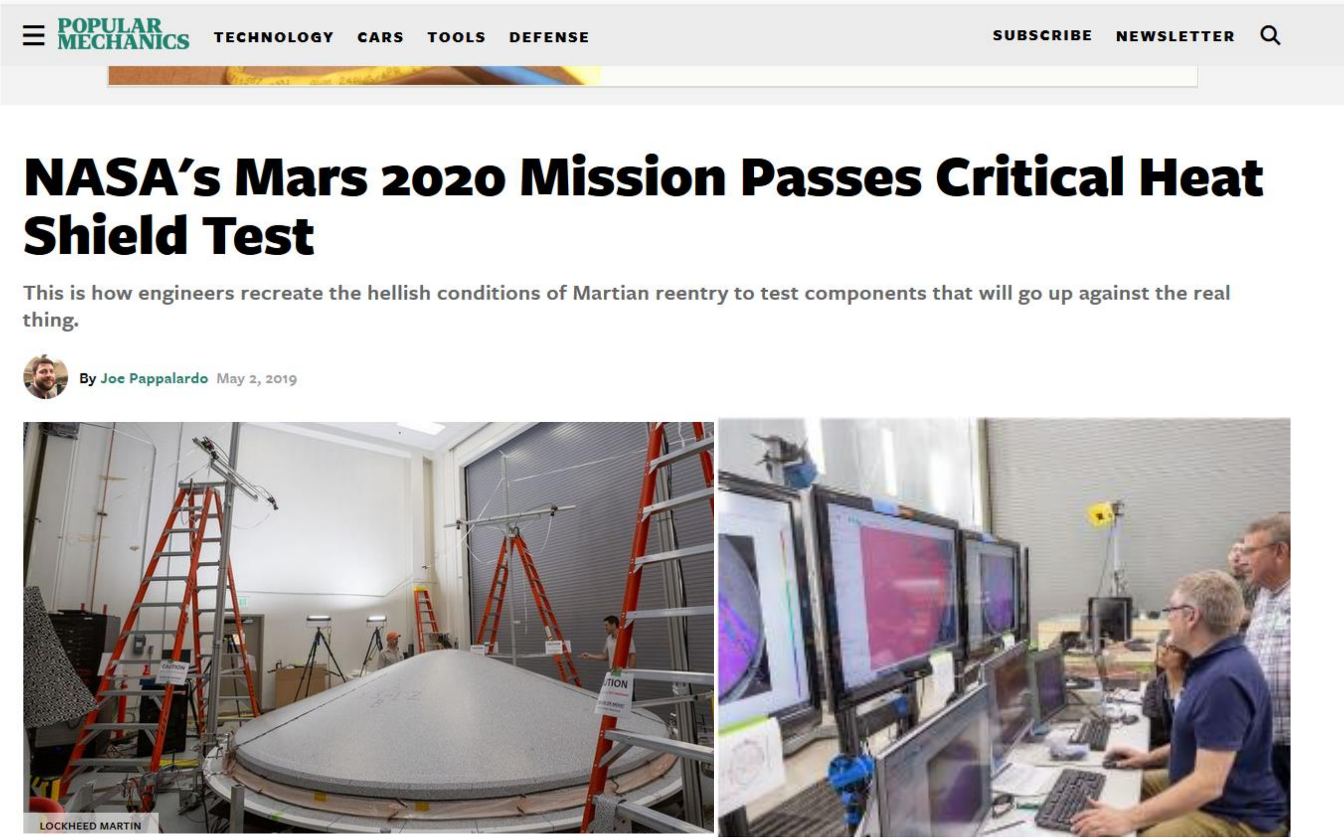


DIC Minimum Principal Strains



Example #4: Findings and Ramifications

- The Mars 2020 Heat Shield passed the 120% qualification test without fracture or strains that exceed prediction limits
- The vinyl was removed and the Heat Shield is being prepared for launch in August 2020
- The DIC strain and displacement measurements were in good agreement with independent point measurements
- The full-field strain measurements were extracted at FEA node points for direct comparison with analytical predictions



NASA's Mars 2020 Mission Passes Critical Heat Shield Test

This is how engineers recreate the hellish conditions of Martian reentry to test components that will go up against the real thing.

By Joe Pappalardo May 2, 2019

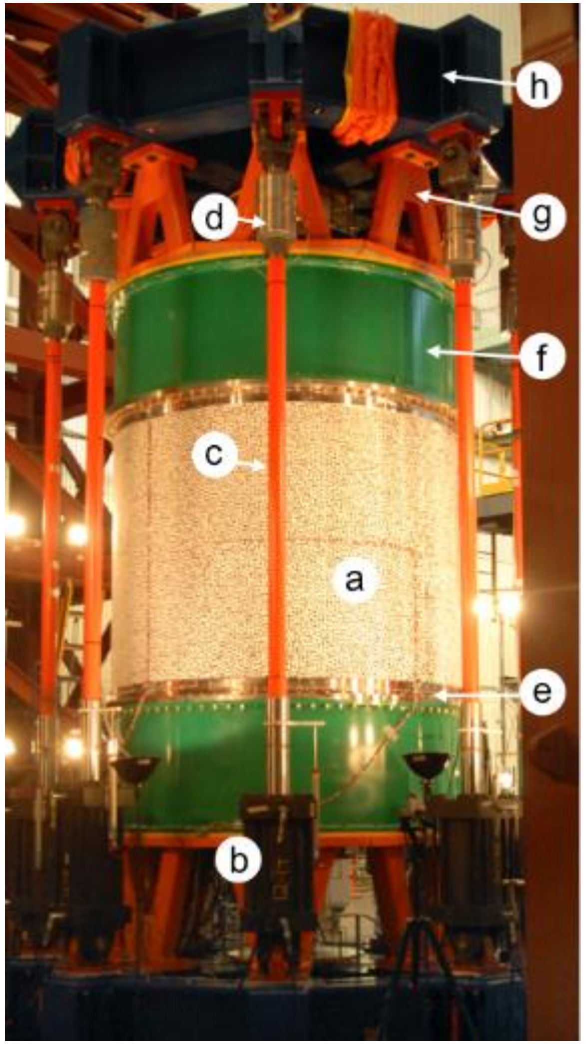
Example #5: Characterization of Buckling Behavior in a Large, Integrally Stiffened Metallic Cylinder

Problem:

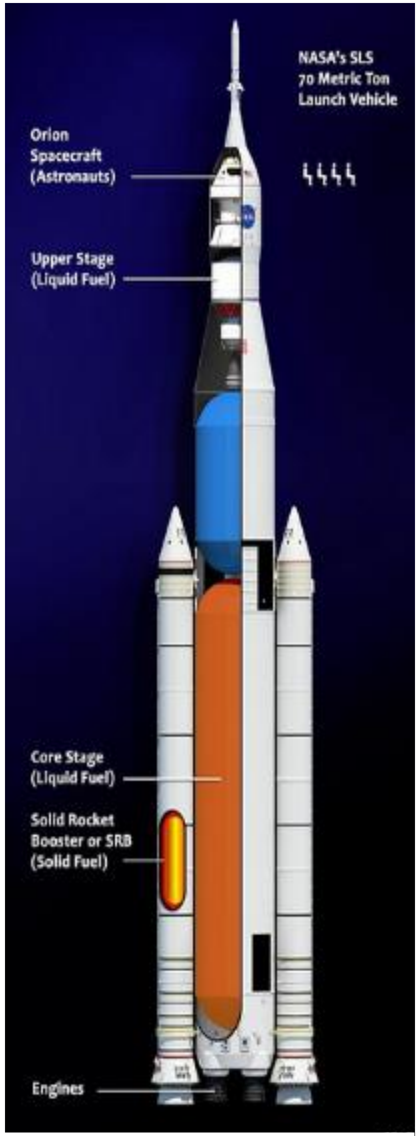
- Cylinder buckling is the primary design driver in launch vehicle designs
- Overly conservative design factors can result in overweight structures
- The buckling behavior is strongly influenced by the shape and imperfections
- The imperfections and shape may change during initialization

Goals:

- Obtain test data to develop and validate high-fidelity buckling simulations and design guidelines
- Characterize the installed shape and imperfections
- Characterize loading boundary conditions



(a)	Test Article (8' dia.)
(b)	Hydraulic Actuator
(c)	Loading Rod
(d)	Load Cell
(e)	Attachment Ring
(f)	Load Introduction Cylinder
(g)	Load Strut
(h)	Loading Spider



www.nasa.gov/sls

Example #5: DIC Setup

Hardware/Software:

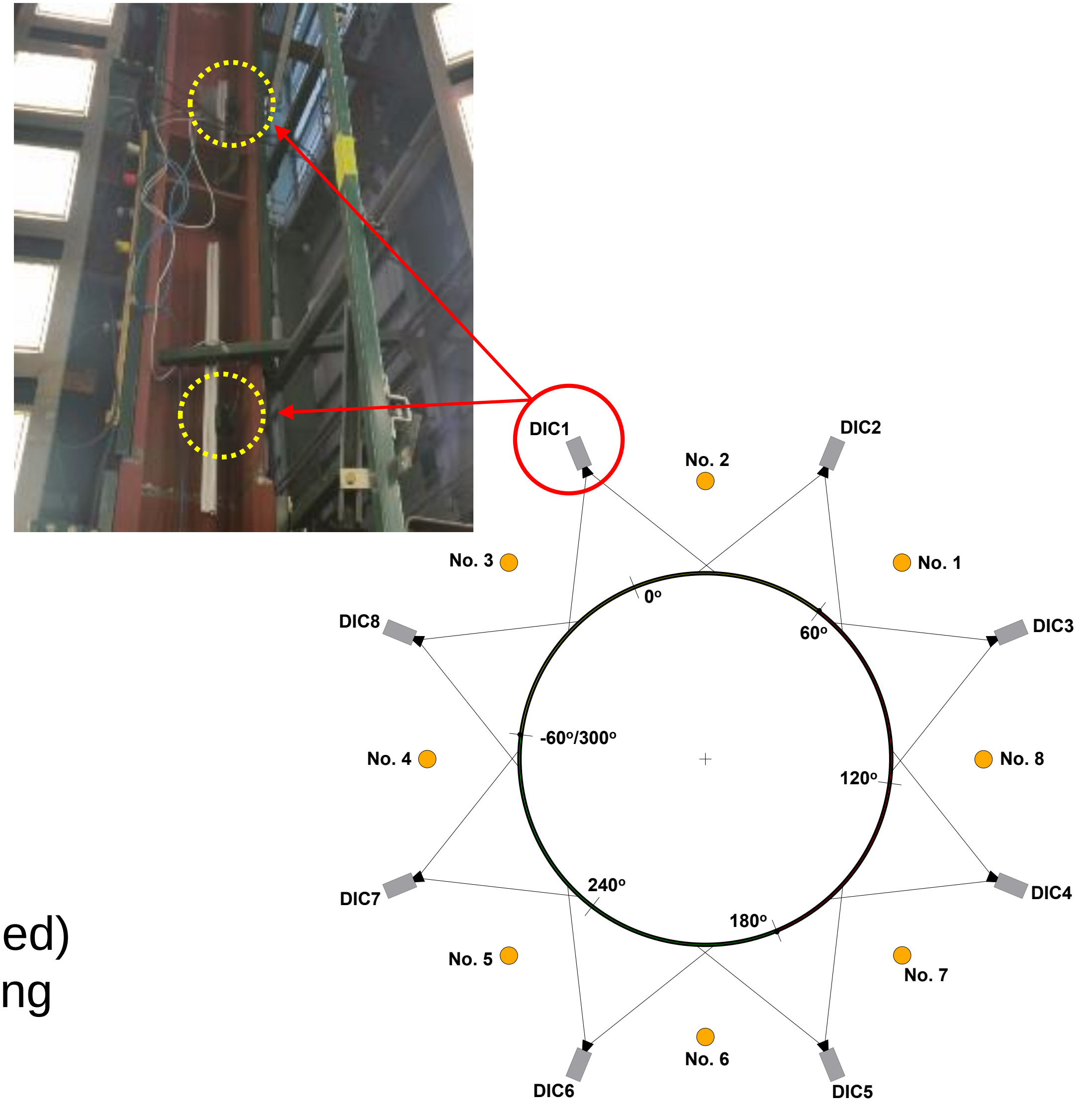
- Eight pairs of cameras (every 45-degrees)
  - 5MP FLIR Grasshopper with 6 and 8mm lenses
  - Overlapping AOI (~15-degrees)
- Cameras mounted on existing building frame
- Hardware synced systems
- VIC3D-8^{TM} with RealTime
- Aperture, exposure time, and lighting optimized

DIC Configuration

- AOI ~ 84 inch x 70 inch
- Pixel Resolution ~ 30 pixels/inch
- Speckle Size ~ 0.5 inch (painted with vinyl stencils)
- Subset Size 35 pixels and Step Size 7 pixels
- Standoff Distance ~ 6 to 10 feet
- Camera Angle ~ 25 to 30-degrees
- Calibration grid: 14x10 56mm

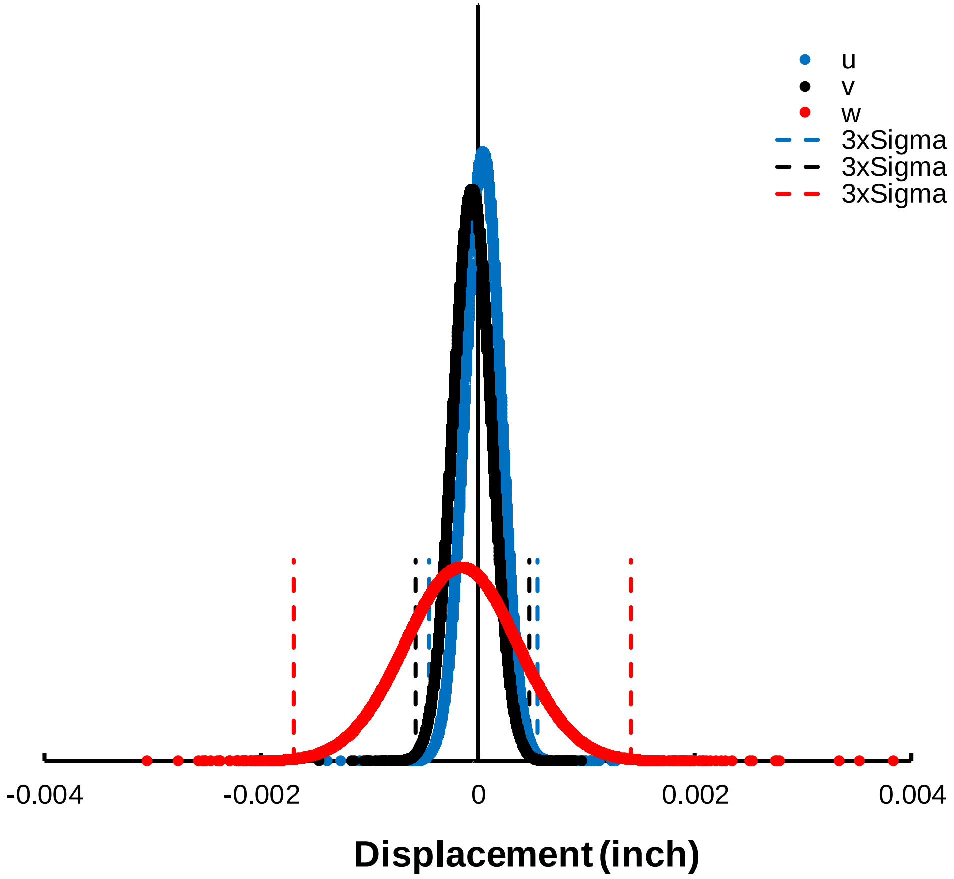
Issues

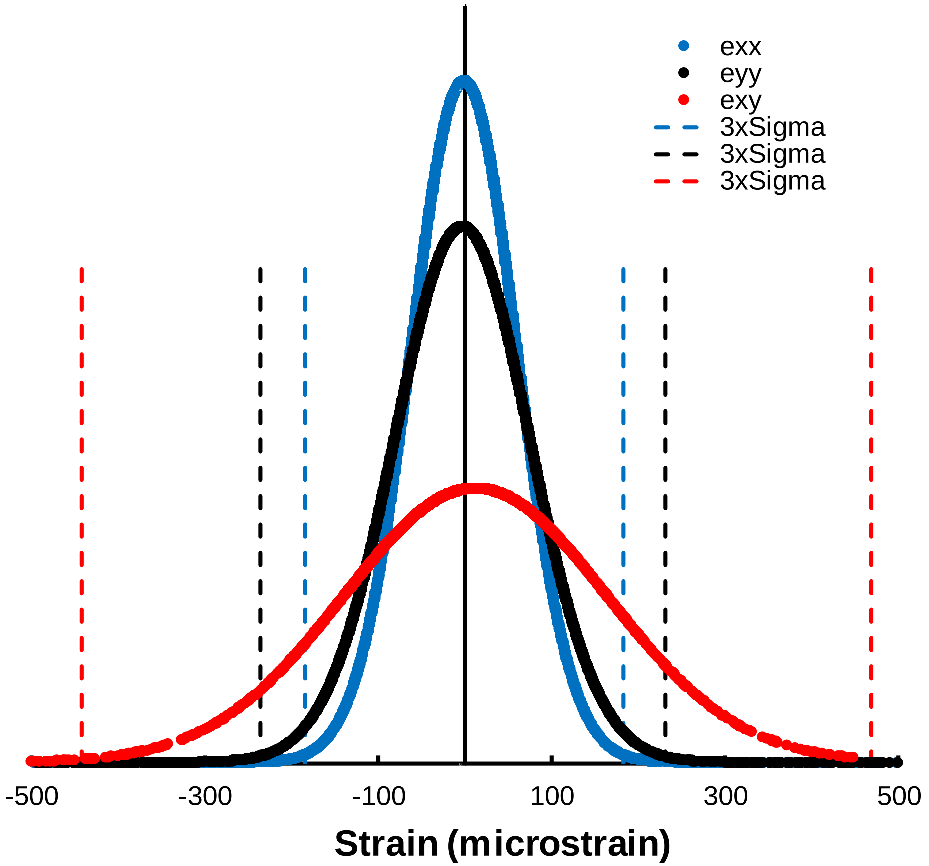
- Travel logistics (i.e., make sure we have everything we need)
- Real-time monitoring (i.e., ~5 second refresh) during loading
- Syncing multiple systems



Top-view of low-speed DIC system layout

Example #5: Typical DIC Noise Floor





Ratio of Expected Signal to 3σ Noise

u: ~100

v: ~400

W: ~40

Ratio of Expected Signal to 3σ Noise

e_{xx}: ~15

e_{yy}: ~5

e_{xy}: ~2

Example #5: DIC Operations

- Images acquired every five seconds [0.2 Hz]
- Set of images acquired at tare load for noise estimates [~ 50 images]
- Load line and pressure data recorded by DIC to synchronize with data acquisition system
- VIC-3D™ Real-time module used during testing
  - Each of the eight systems was monitored
  - DIC results compared to predictions in real-time to identify anomalies that could influence loading decisions

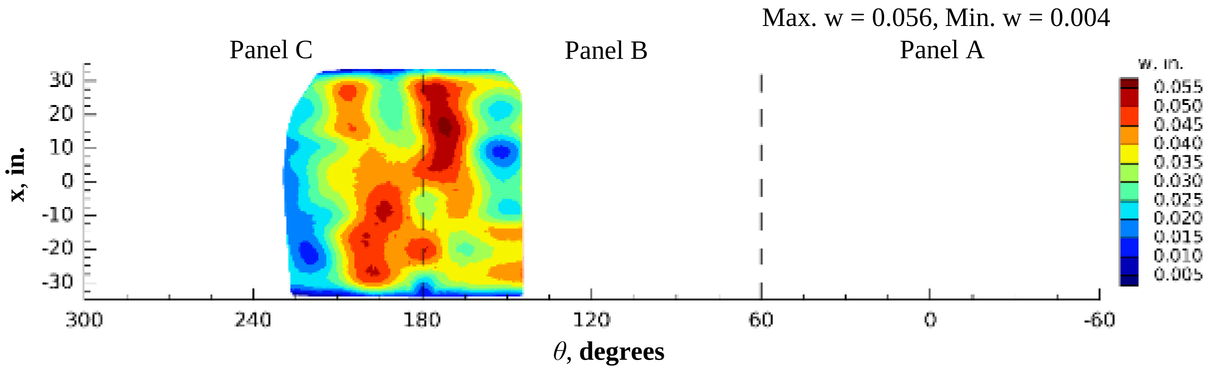
Control Room with VIC-3D™ Real-time Monitoring of each system

Example 5: DIC Results

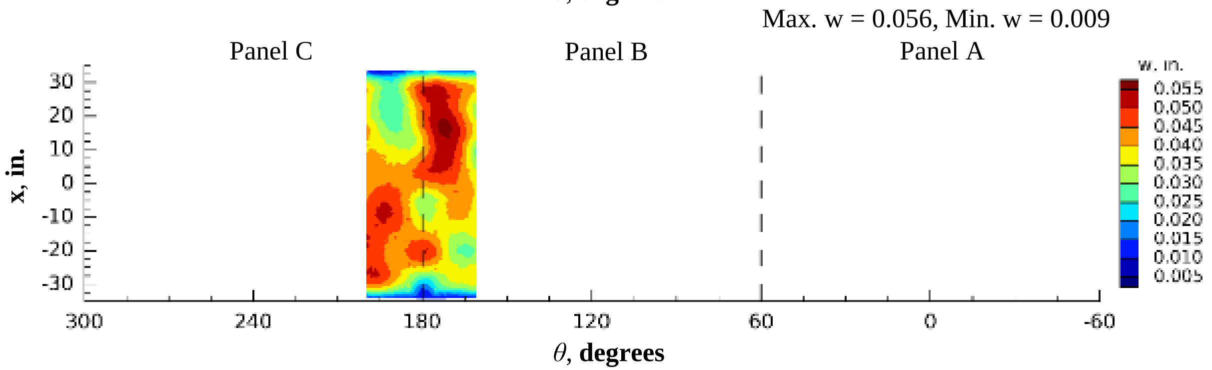
Thresholding locations correspond to points of intersection with adjacent uncertainty curves

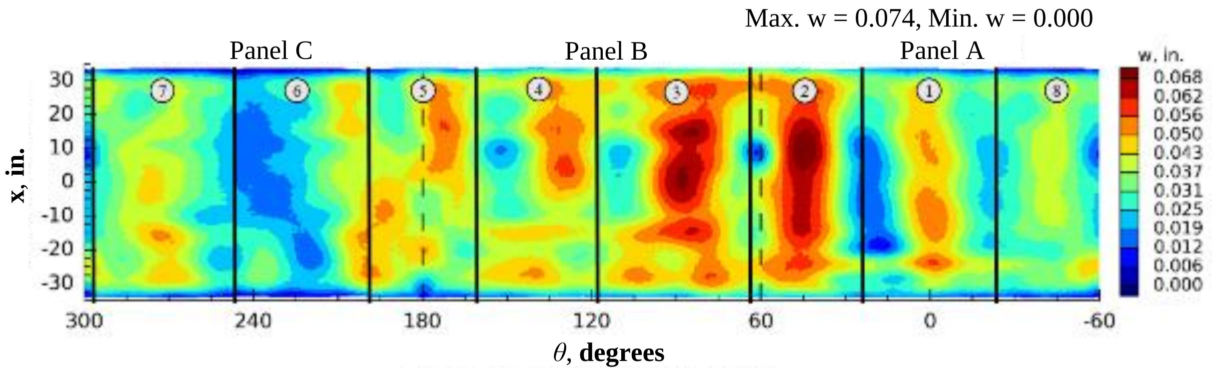
- Referred to as θ – thresholding
- DIC data outside these points was removed from data sets
- Minimizes measurement uncertainty in the assembled data
- Allows for an estimate of the displacement uncertainty
  - σ_{mag} = 0.001 inches
  - $3\sigma_{mag}$ = 0.003 inches (99.7% confidence interval)

System 5 without data thresholding



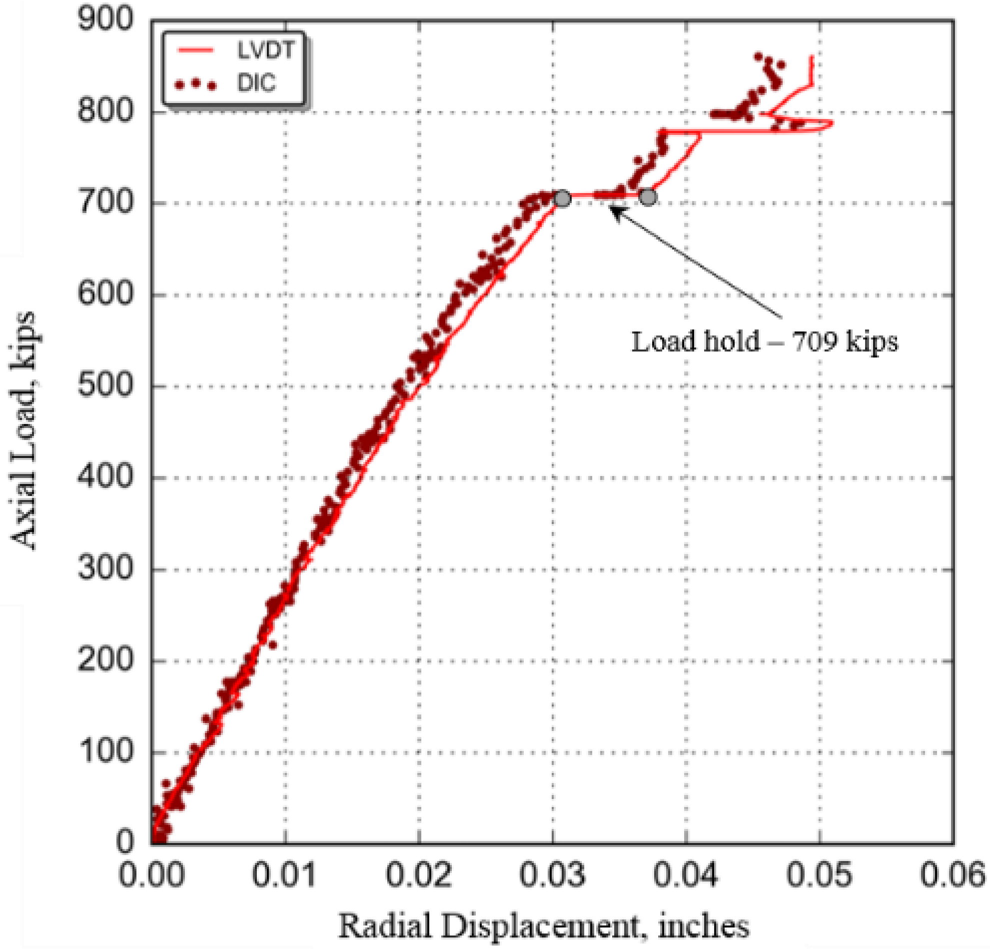
System 5 with data thresholding



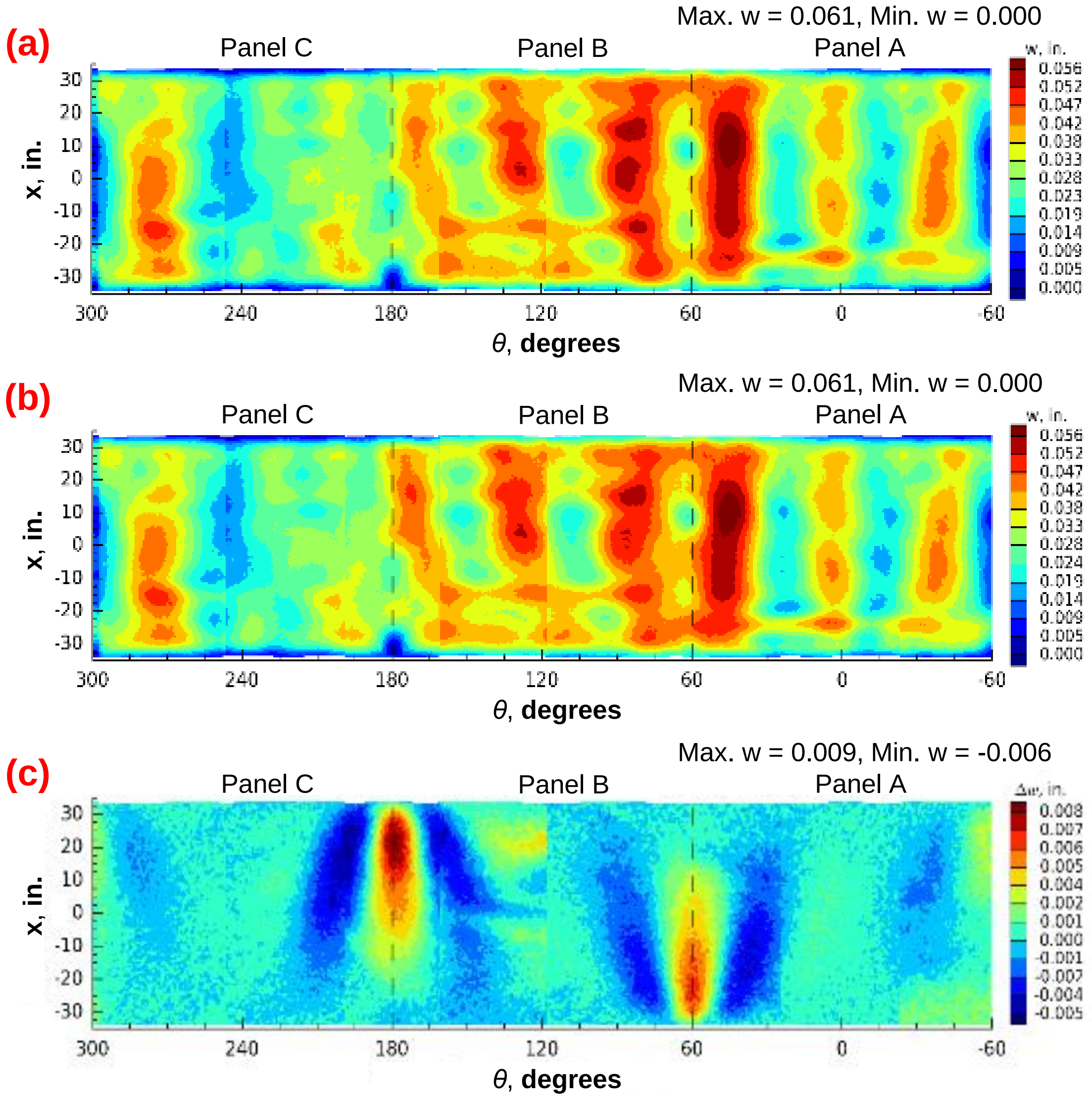


Example #5: Anomalous Behavior

Displacement jump observed during hold

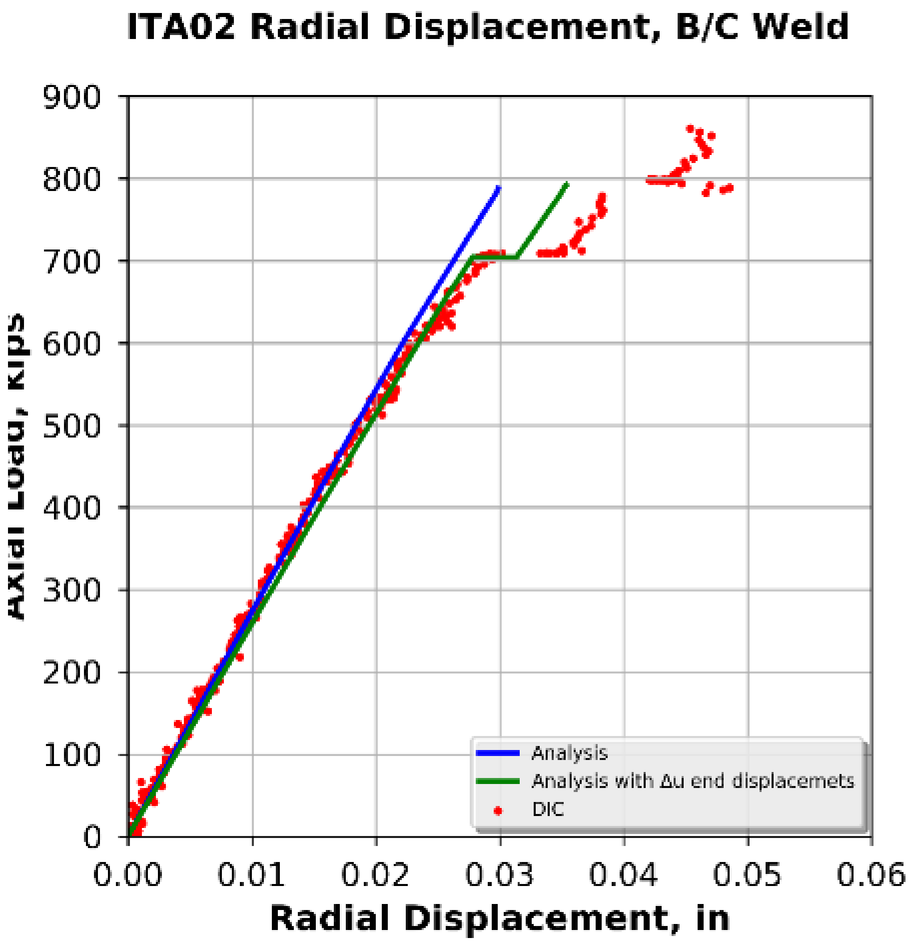


Subtraction of the out-of-plane (w) displacement at start (a) and end (b) of hold



Example #5: Using DIC Boundary Conditions in Analysis

- The DIC data indicated that the cylinder slipped at the stiffer weld region
- DIC characterized:
  - The extent of the slippage around the circumference
  - The magnitude of the slippage (axial displacement)
- DIC measurements were included as boundary conditions to the analysis at the hold load



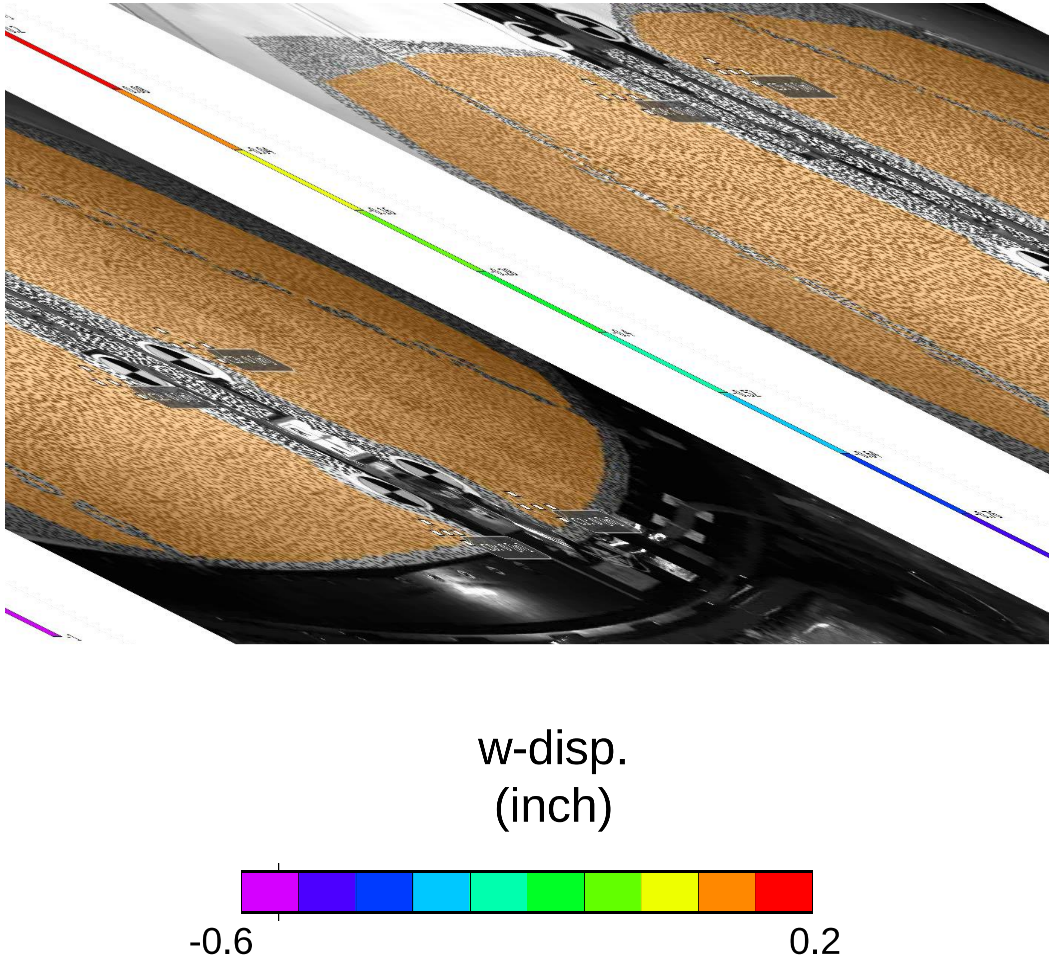
Example #5: Findings and Ramifications

- The “jump” in the LVDT displacements have been previously observed and attributed to “issues” with the LVDT
- The DIC measurements allowed the root cause to be determined and incorporated in the analysis as modified boundary conditions
- Additional studies were performed to understand the slippage and a new potting approach was developed for future tests

Additional Example #1: Ascent Cover Separation

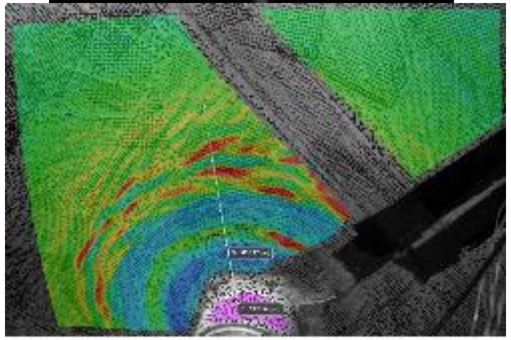
- The Ascent Cover protects the docking mechanism from aerodynamic loads during launch
- An explosive charge separates the two hemispheres and jettisons the cover away from the flight vehicle
- Testing was performed to evaluate rivet separation times and hemisphere velocities
- 2D DIC was used to characterize rivet separation times
- 3D DIC was used to characterize oscillations during separation

Separation at 5000 fps



Additional Example #2: COPV Deformations

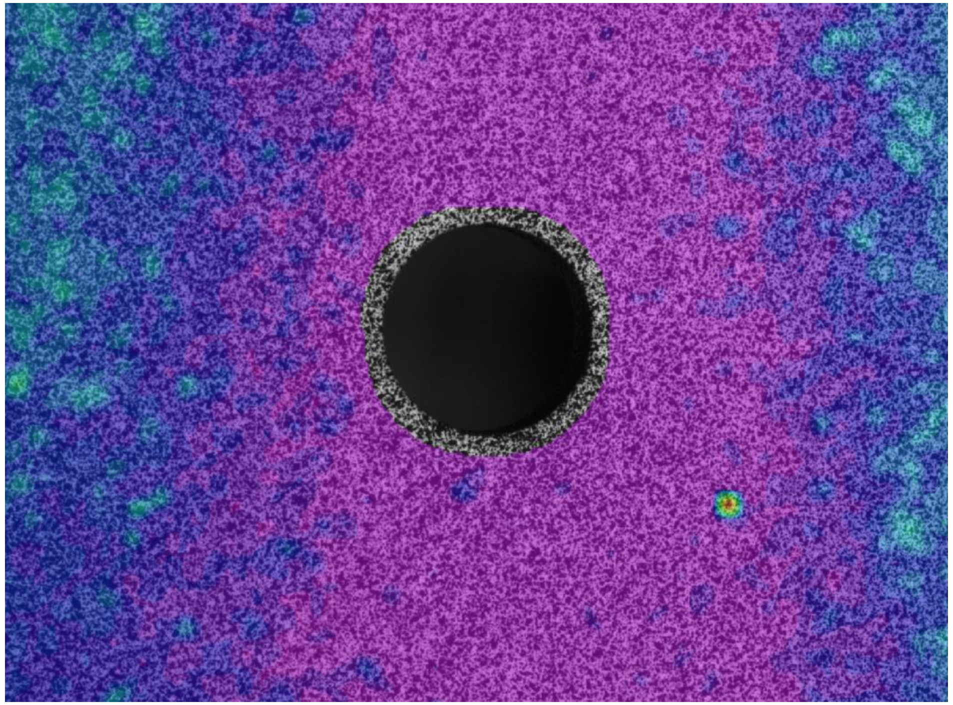
- Composite Overwrapped Pressure Vessels (COPVs) contain pressurized gases or liquids and are used on nearly all space flight vehicles
- A COPV consists of a metallic liner that acts as a barrier and a composite overwrap for strength
- Multiple 3D DIC systems are used to characterize:
  - Hoop and axial strains
  - Tank elongations
  - Volume change estimates
  - Complex strain fields in the dome regions
  - Localized deformations
  - Liner composite delaminations



Additional Example #3: Crack Growth in Composite Materials

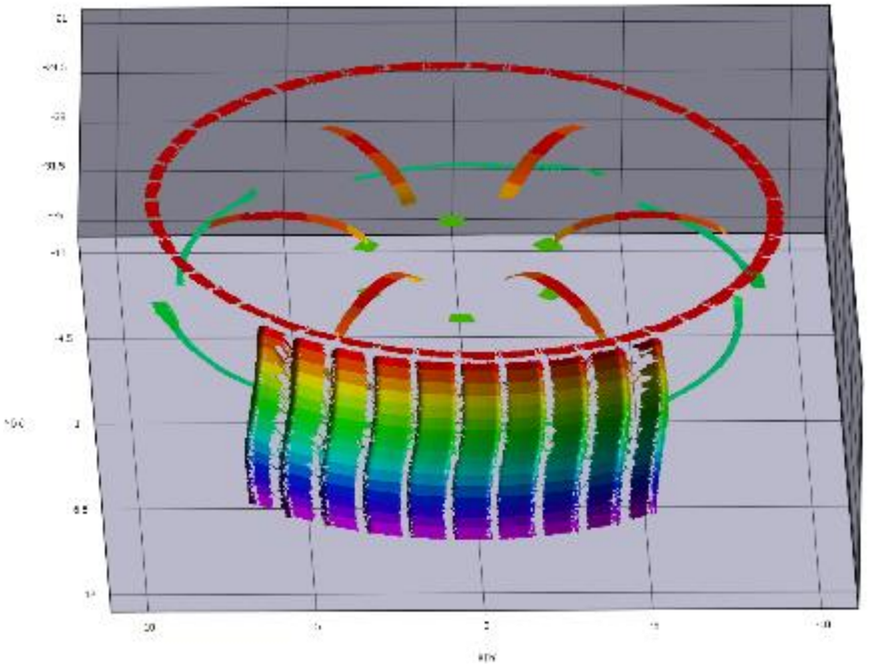
- The Advanced Composite Project is developing methods for predicting progressive damage in composite materials
- Tests were conducted on open hole tension coupons to develop data on crack nucleation and propagation
- DIC was used to determine:
  - The load that cracks initiated
  - The rate that cracks propagated
  - Local crack parameters (e.g., crack opening displacement)

Crack growth in an open hole tension composite test coupon (45° outer plies)



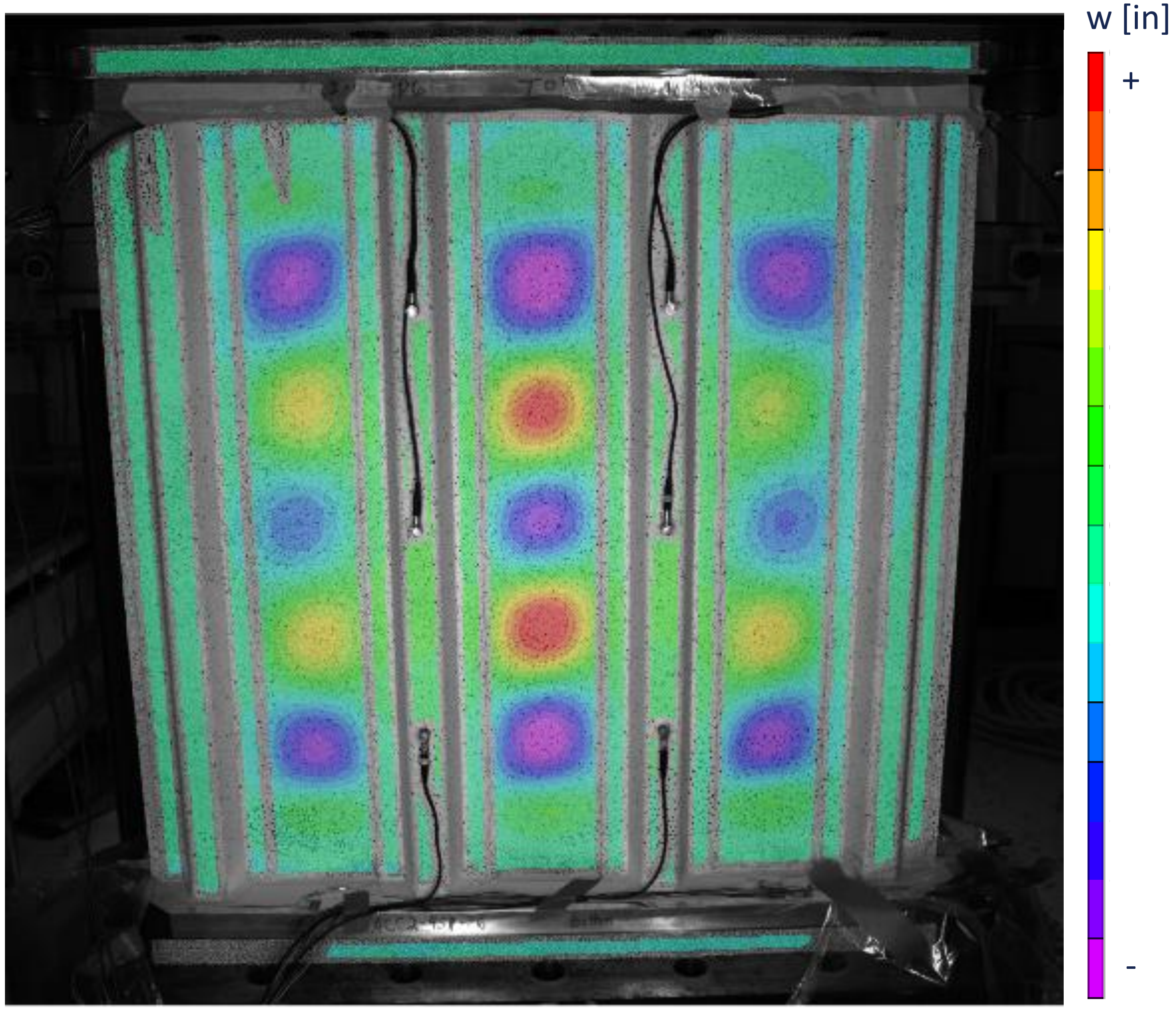
Additional Example #4: Mars 2020 Rover Wheels

- The Mars 2020 Rover wheels will be tested to simulate landing loads
  - Validation of models
  - Evaluate peak strains relative to design margins
- Testing of a full-scale 3D printed mockup was performed to determine requirements
- Flight hardware tests will be performed in Oct-Nov 2019



Additional Example #5: Composite Panel Buckling

- The Advanced Composite Project (ACP) is developing tools to reduce certification time for composite materials and structures
- High fidelity computational methods are being developed for strength and life predictions
- Tests are being conducted to validate the computational tools



Out-of-plane displacement [w] of 4-stringer at max load

Lessons Learned

- Boundary conditions need to be considered in any structural test
  - Rigid conditions are usually not rigid
  - Analyses with incorrect boundary condition assumptions can be right for the wrong reason or right, but not know it because the analysis does not agree with the test measurements
- Complex tests, especially at remote locations and on a tight schedule, require planning
  - Mockups are extremely useful when traveling to remote locations
  - Build DIC setup with the mockup, then pack for shipping
- Understand the noise floor relative to the magnitude of the quantities being measured
- Follow iDICs “Good Practices Guide for Digital Image Correlation” for documenting results