

A large, detailed image of the Moon's surface, showing craters and lunar features, occupies the upper left portion of the slide. The background of the entire slide is a deep blue gradient, transitioning to a lighter blue and white horizon line at the bottom, suggesting a view from space.

6th Shell Buckling Knockdown Factor Project Workshop: Day 2

*NASA Marshall Space Flight Center
Huntsville, AL
June 4, 2019*

Workshop Agenda:

Day 2



8:00-8:10AM	Assemble and welcome
8:10-8:40AM	First Large-Scale Composite Cylinder Test and Analysis
8:40-9:50AM	Large-Scale Sandwich Cylinder Test-Article Design and Analysis
9:50-10:25AM	Manufacturing Process Development for Composite Sandwich Structures at NASA MSFC
10:25-10:45AM	Structured Light Support of SBKF
10:45-11:15AM	Processing and Implementing Geometric Imperfections into Analyses
11:15-12:00PM	Discussion
12:00PM	Dismiss

A large, detailed image of the Moon's surface, showing craters and lunar features, occupies the upper left portion of the slide. The background of the entire slide is a deep blue gradient, transitioning from a lighter blue at the bottom to a darker blue at the top, with a thin white line representing the Earth's horizon at the very bottom.

First Large-Scale Composite Cylinder Test and Analysis

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Huntsville, AL*

June 5, 2019

Testing Levels

- **Coupon**
 - Shell property testing
 - Transverse shear stiffness
- **Panel**
 - Out-of-plane deformations
 - Effects of joints
 - Effects of damage
- **Subscale cylinders**
 - 8-ft diameter
 - Validate analysis approach



Subscale Cylinder Testing (8-ft diameter)



Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

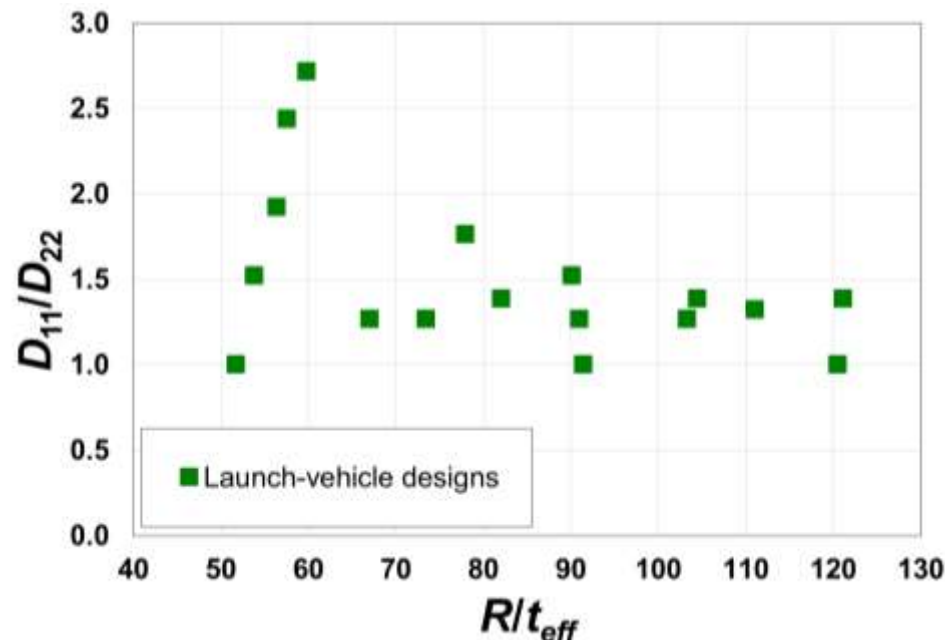
- Calculate design-space parameters for launch-vehicle components

R = radius

t_{eff} = effective thickness, $\sqrt[4]{144 \frac{D_{11}D_{22}}{A_{11}A_{22}}}$

D_{11} = axial bending stiffness

D_{22} = circumferential bending stiffness

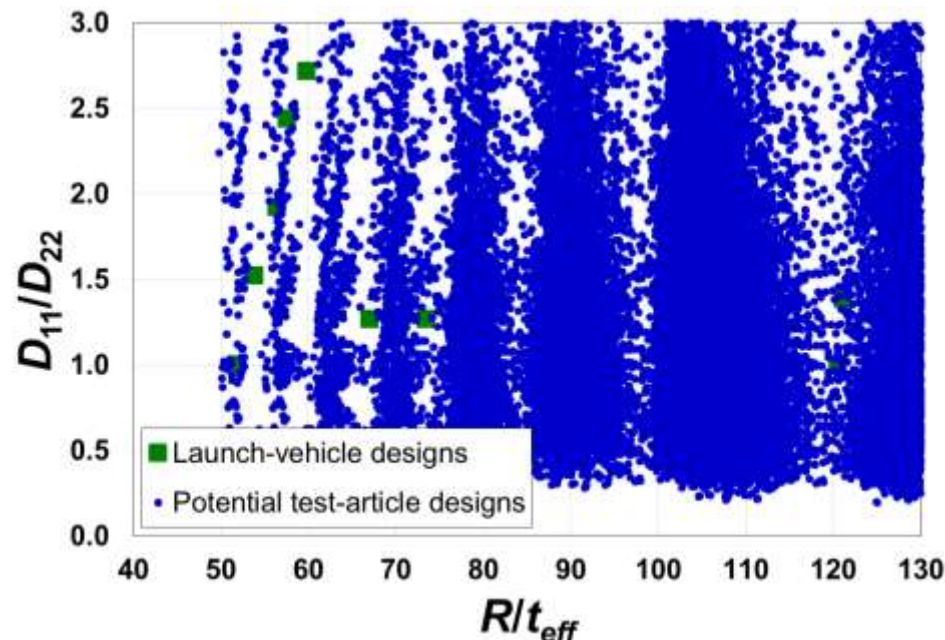


Subscale Cylinder Testing (8-ft diameter)



Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

- Calculate design-space parameters for launch-vehicle components
- Generate possible 8-ft-diameter subscale designs
 - Variables: number of plies, ply angle, core thickness

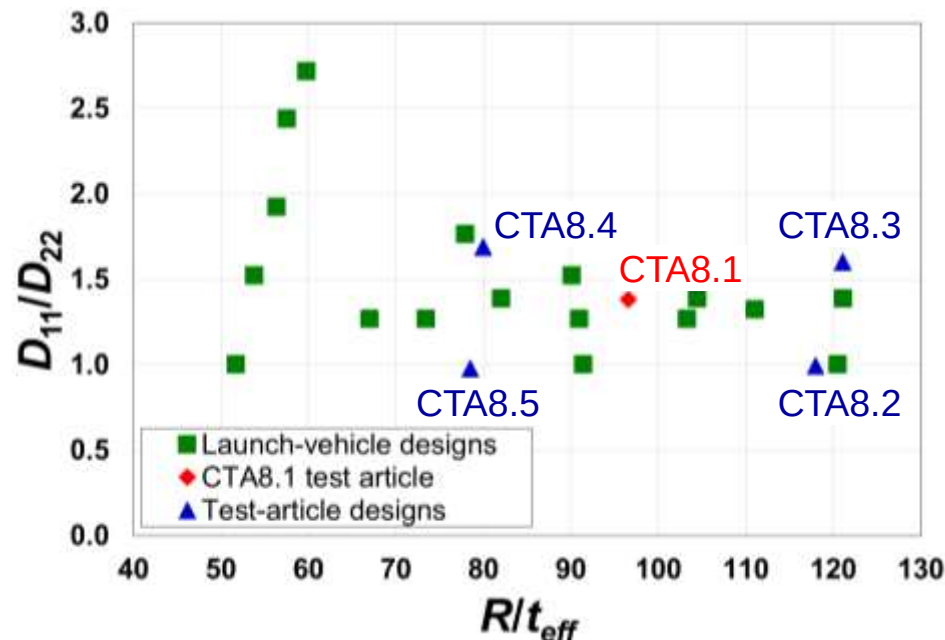


Subscale Cylinder Testing (8-ft diameter)

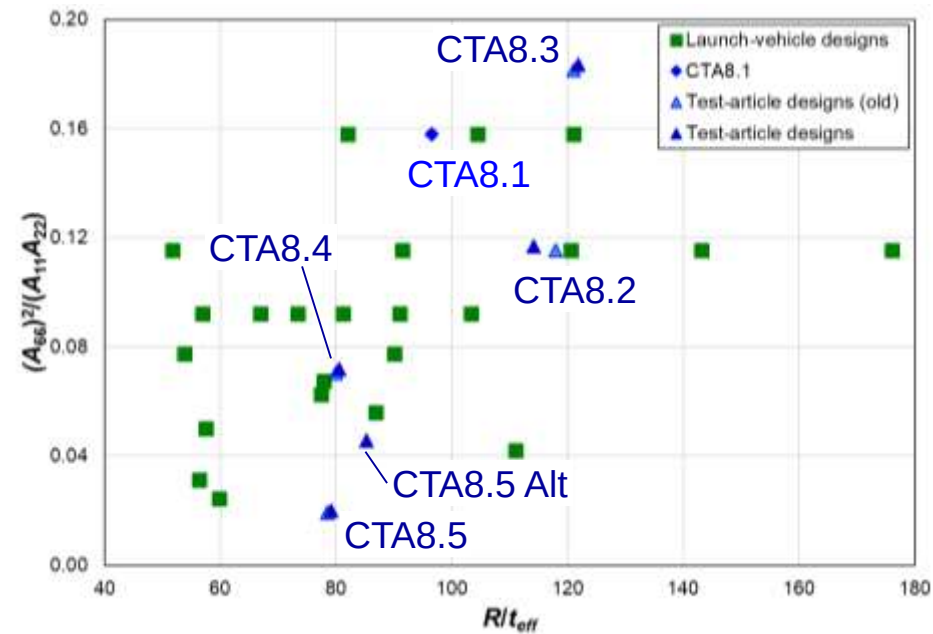
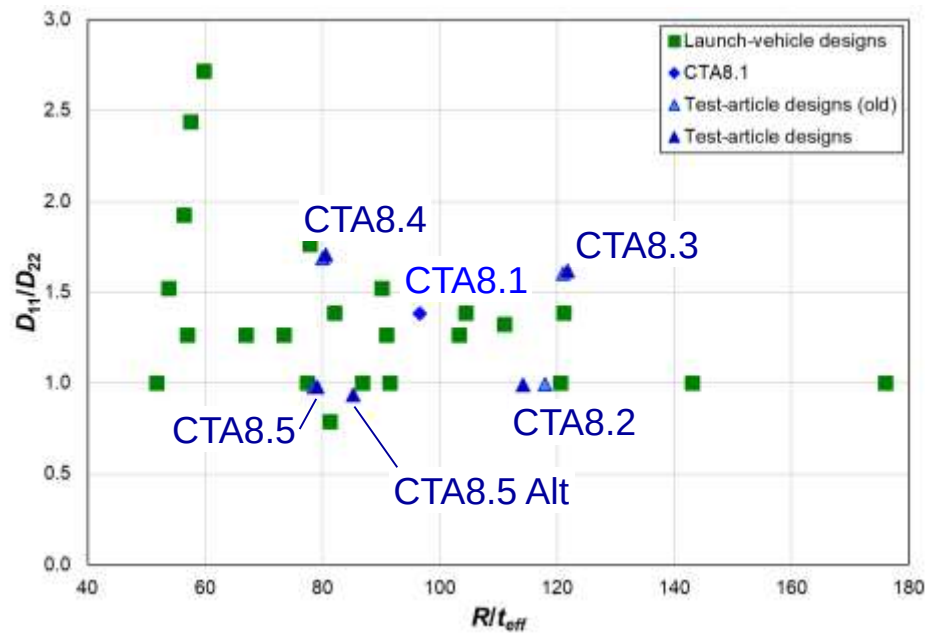


Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

- Calculate design-space parameters for launch-vehicle components
- Select subscale designs
 - Criteria: buckling critical, failure load, design space, etc.
 - Five test article designs selected as minimum number to bound design space and validate analysis methods



Modified (Final) Test-Article Designs



First Large-Scale Test Article (CTA8.1)



- **Construction**

- 8-ft-dia. honeycomb-core sandwich composite cylinder
- Single piece (unsegmented)
 - Core: 0.25-in. Korex honeycomb
 - Facesheets: 7-ply IM7/MTM45, $[\pm 45/0/90]_s$

- **Fabrication**

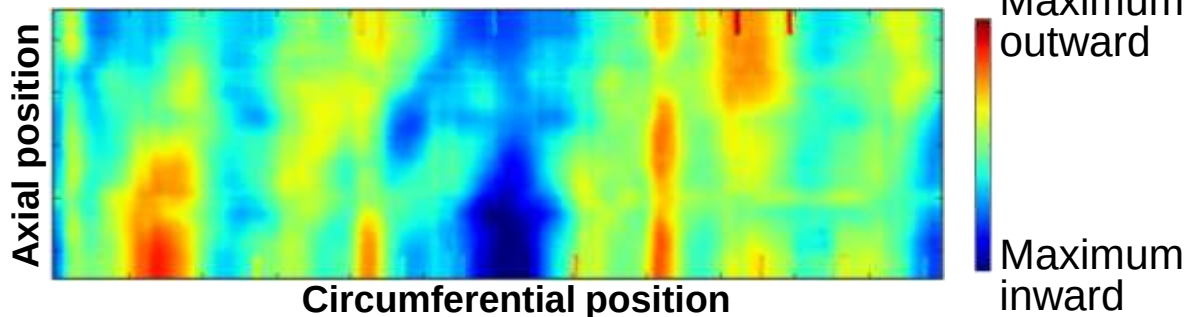
- Built by Northrop Grumman under collaborative agreement
- Manufacturing development unit
- Out-of-autoclave
 - **Material properties not well known**
 - Posttest material characterization



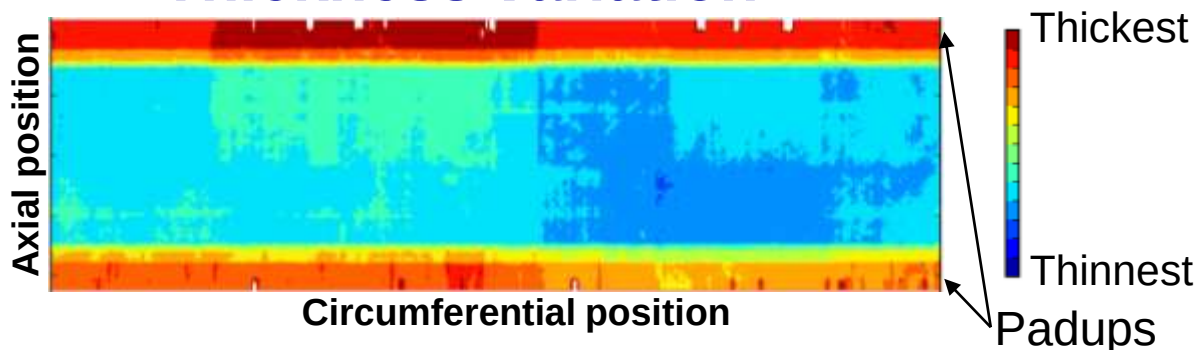
Structured Light Scanning Geometry Measurement



- Photogrammetric technique to measure three-dimensional (3-D) shapes
 - Inside and outside
- Radial imperfection

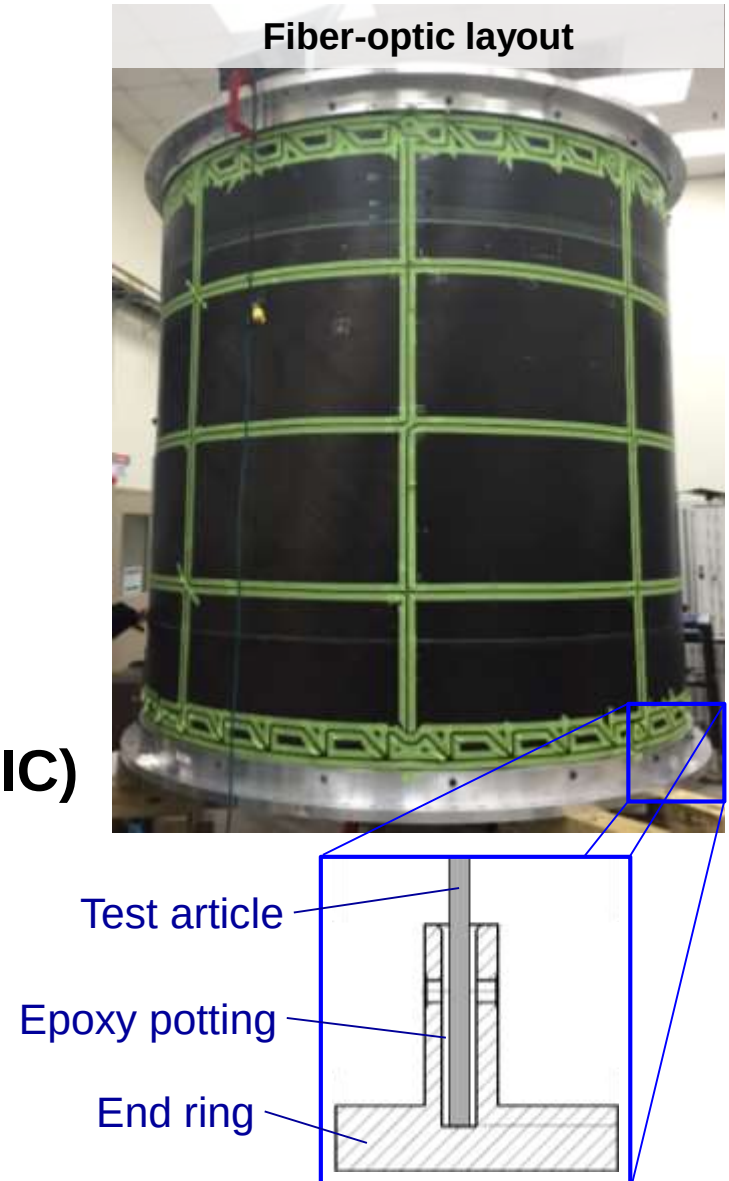


- Thickness variation

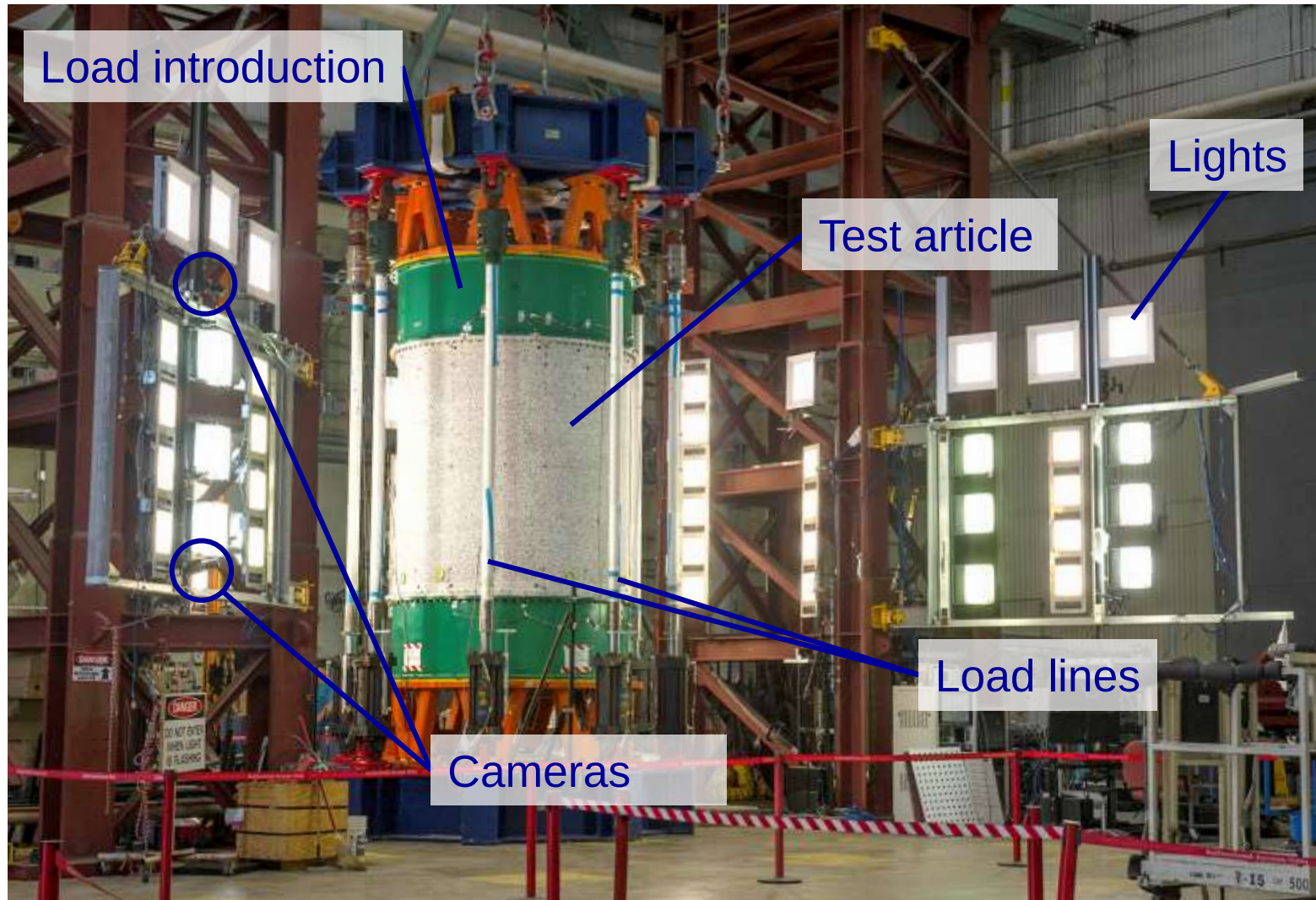


Testing and Instrumentation

- **Test conditions**
 - Subcritical axial compression and combined loading cases
 - **Axial compression** to failure
- **Instrumentation**
 - ~300 electrical strain and displacement sensors
 - 3-D digital image correlation (DIC)
 - Eight low-speed systems
 - Six high-speed systems
 - 16,000 fiber-optic strain sensing positions

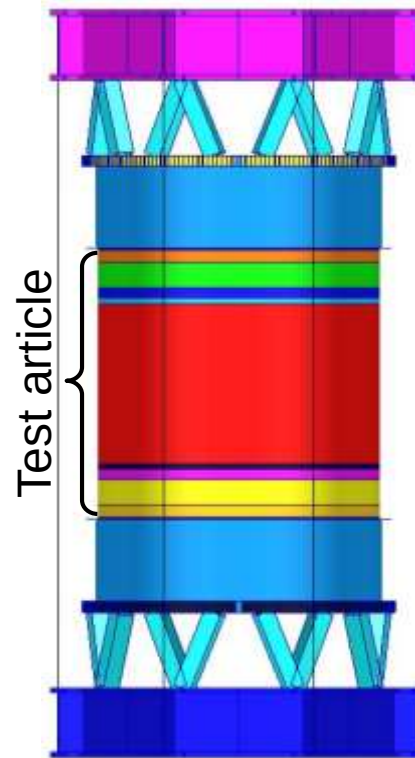


Test Setup

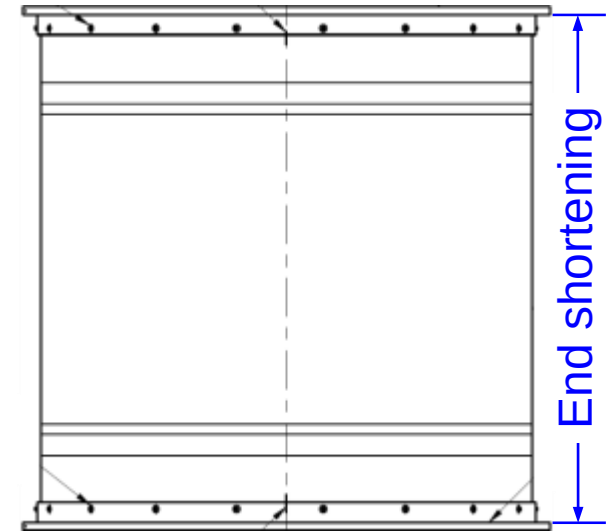
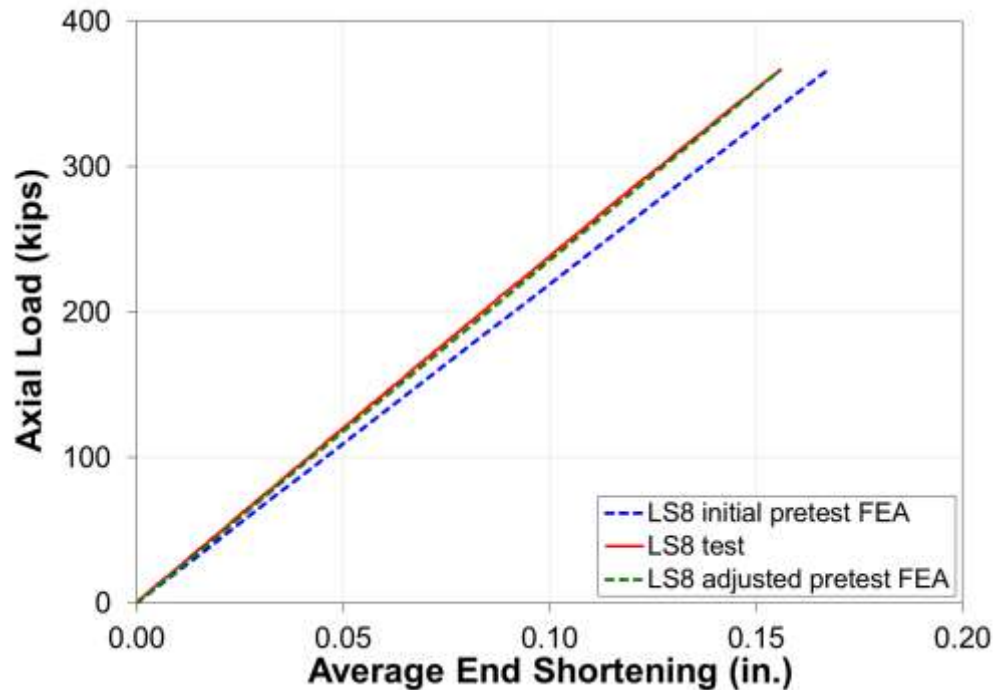


Analysis Approach

- Test article and testing hardware
 - Abaqus **shell** and **beam** elements
 - 156,960 elements
- Geometrically nonlinear transient analysis
 - Measured **radial** and **thickness** imperfections included



Subcritical Compression



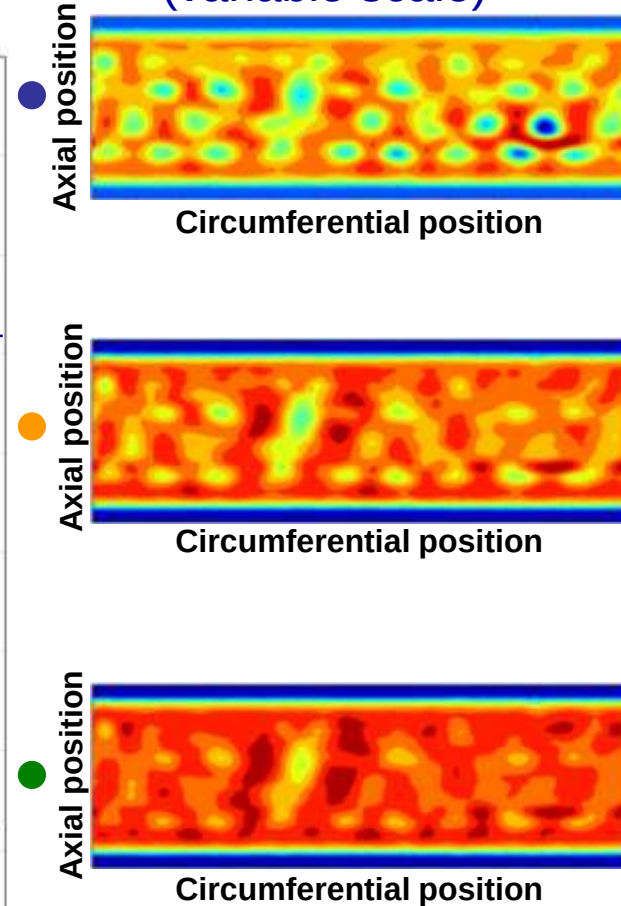
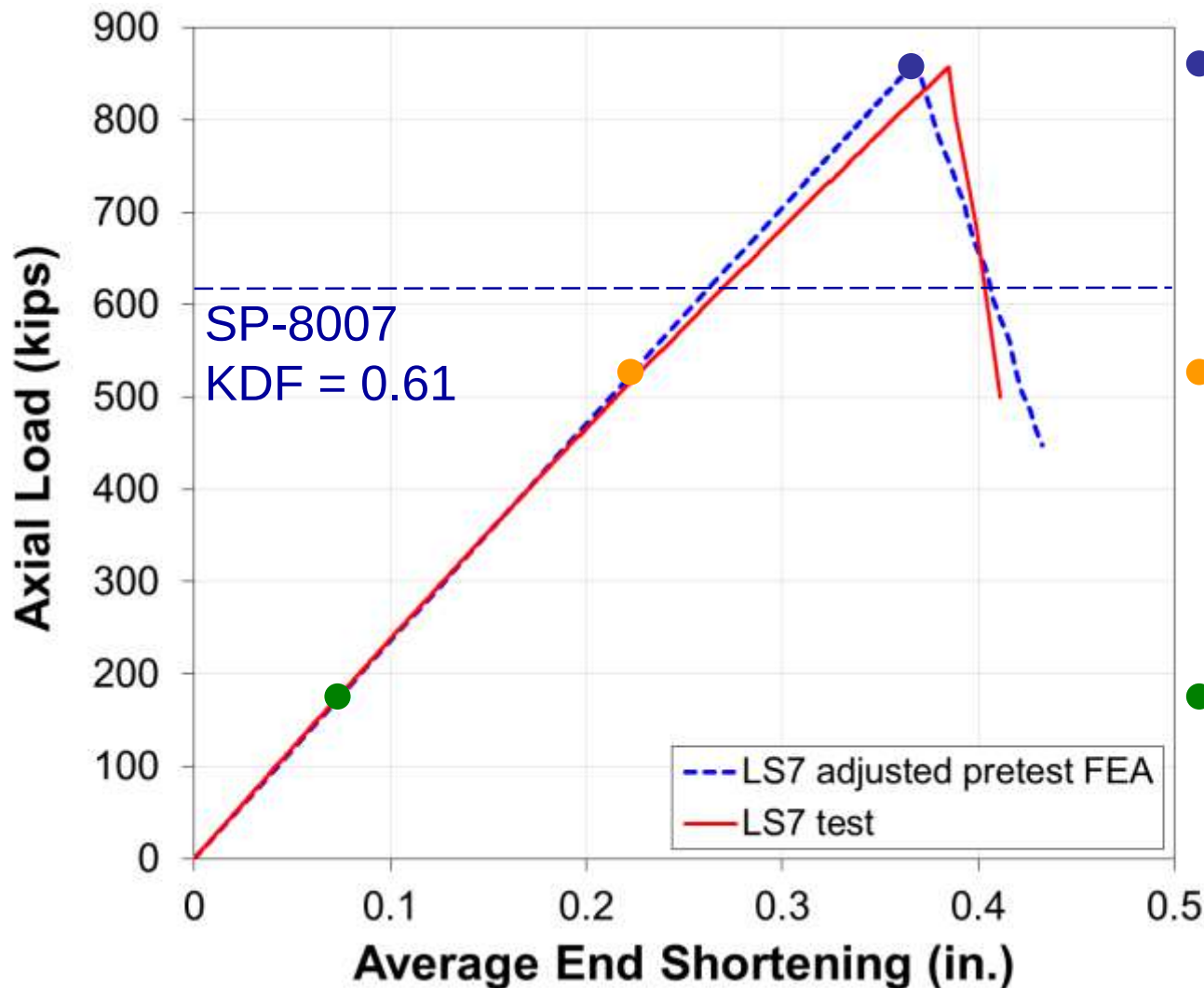
- **Significant difference in axial stiffness**
 - End shortening measured at end rings
 - Manufacturing demo—uncertain material properties
 - Ply extensional stiffnesses increased by 8.7% to match test data

Test-Analysis Correlation: End Shortening

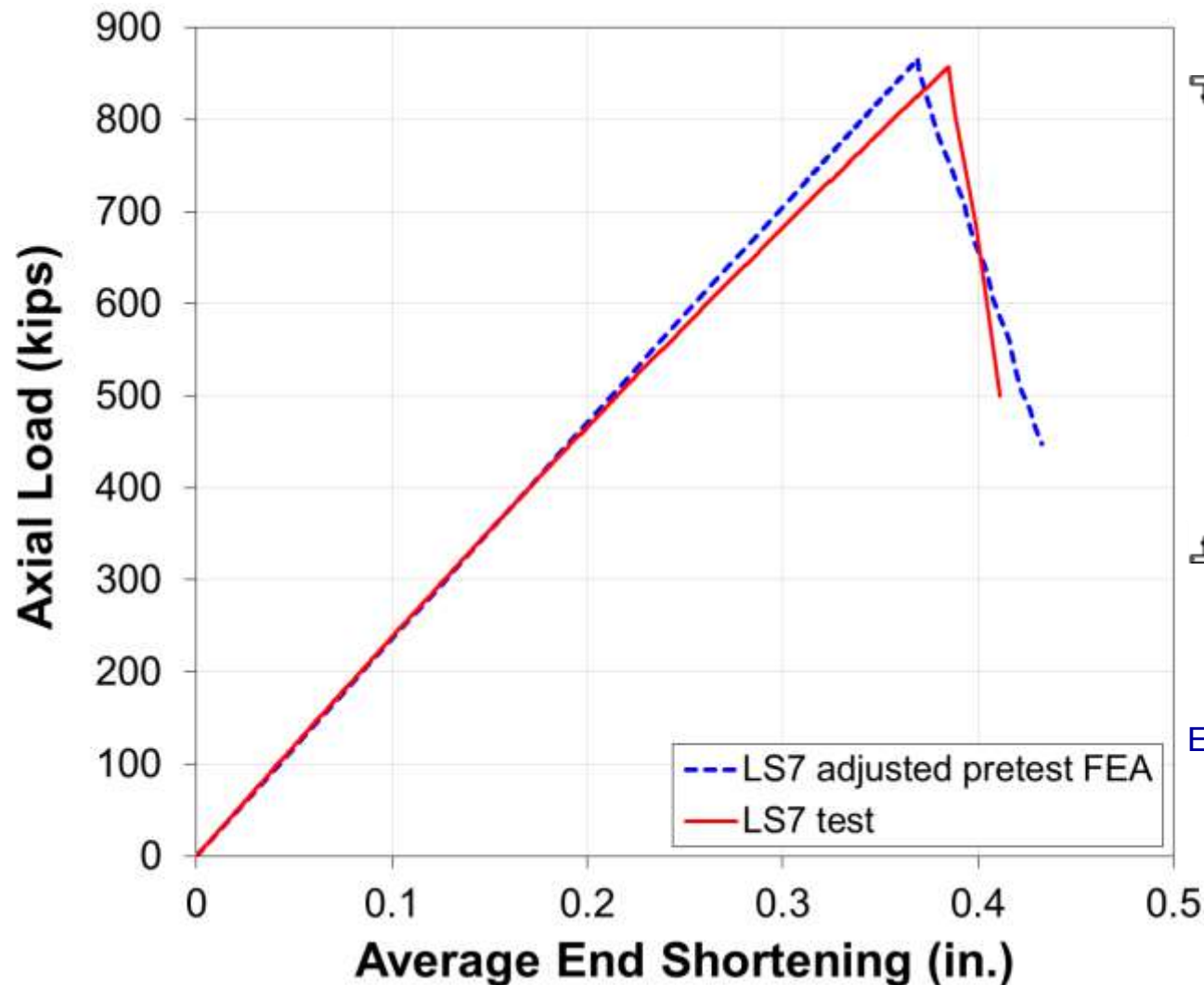


$P_{bif} = 984.9$ kips

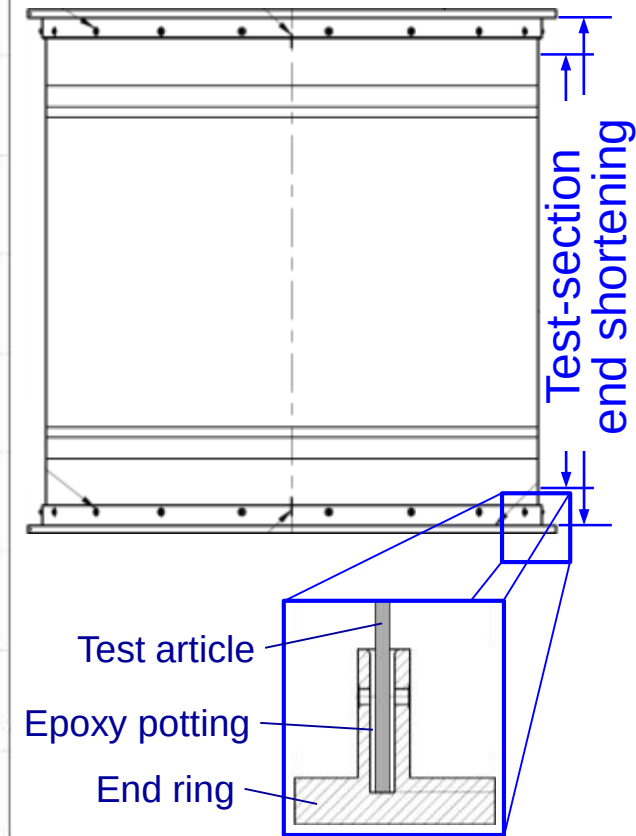
Predicted radial deformation
(variable scale)



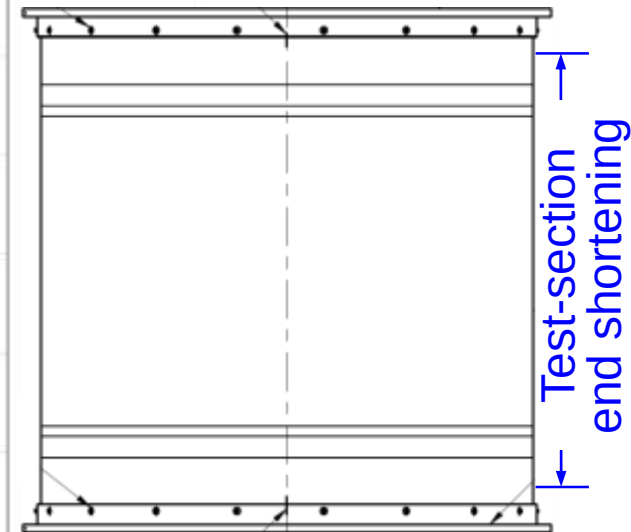
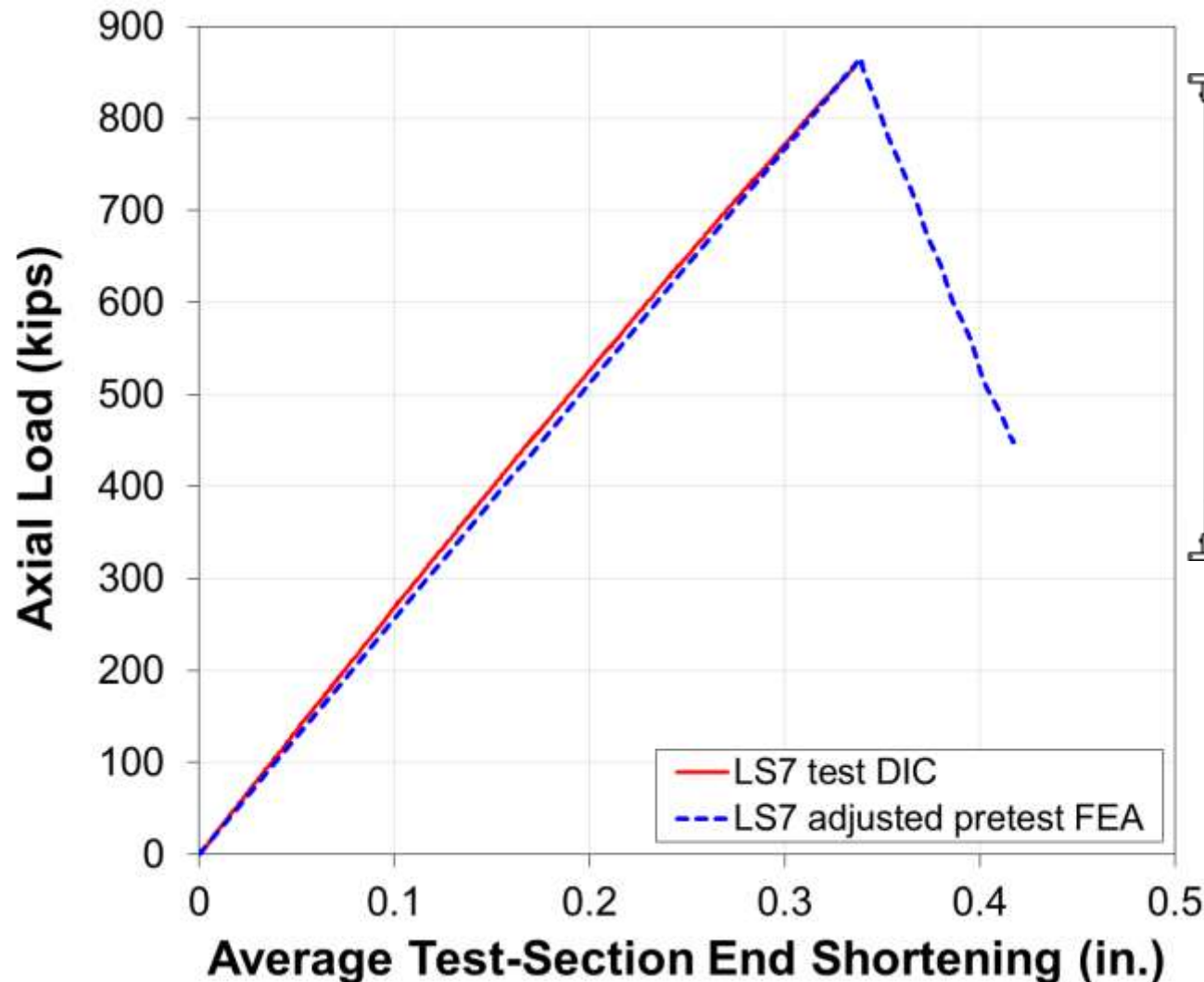
Test-Analysis Correlation: End Shortening



Slipping in end rings occurred



Test-Analysis Correlation: Test-Section End Shortening



Material Testing

- **Measured stiffness**
 - Sectioned barrel and performed edgewise compression testing
 - Ply thickness 9.2% greater than assumed
 - Nonlinear ply stiffnesses calculated
- **Material nonlinearity**
 - Though often ignored in analysis, fiber-reinforced composites can show material nonlinearity

Compression specimen

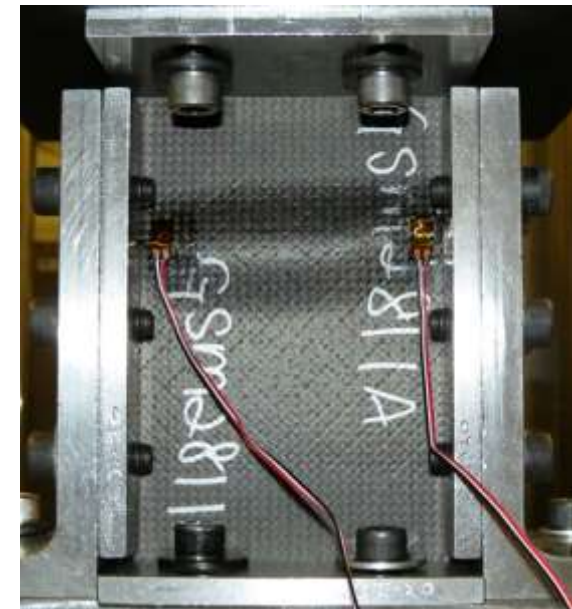
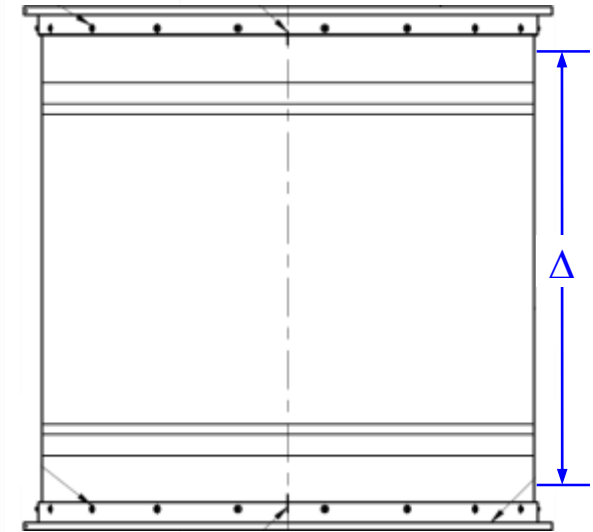
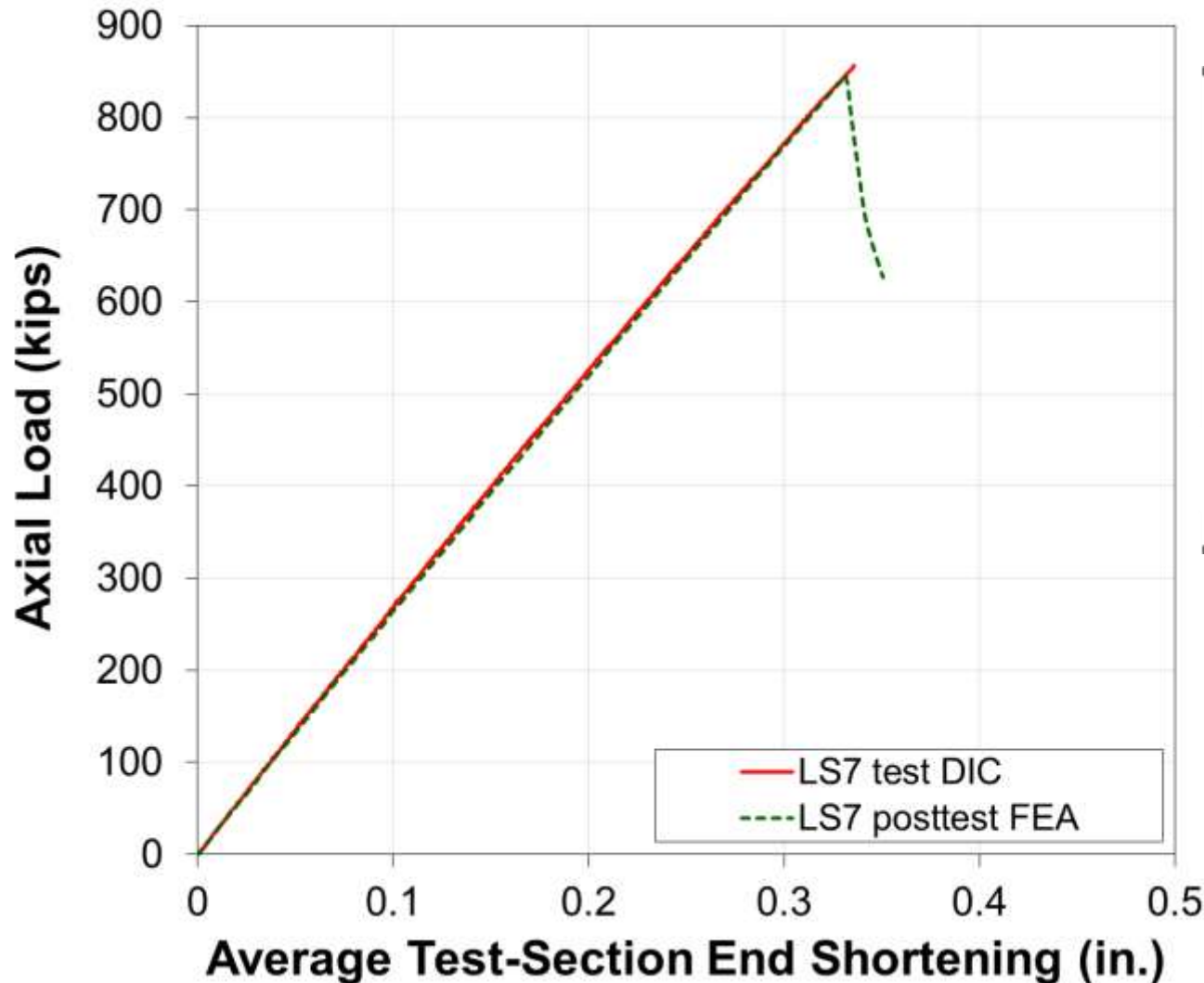


Photo: NIAR

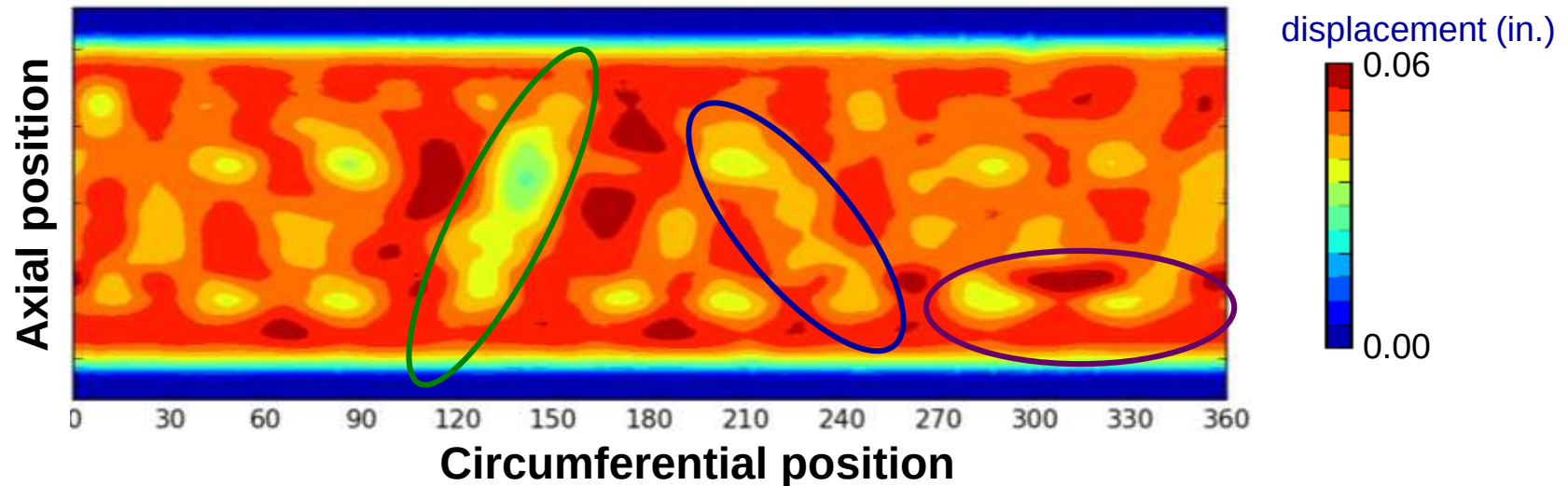
Test-Analysis Correlation: Test-Section End Shortening



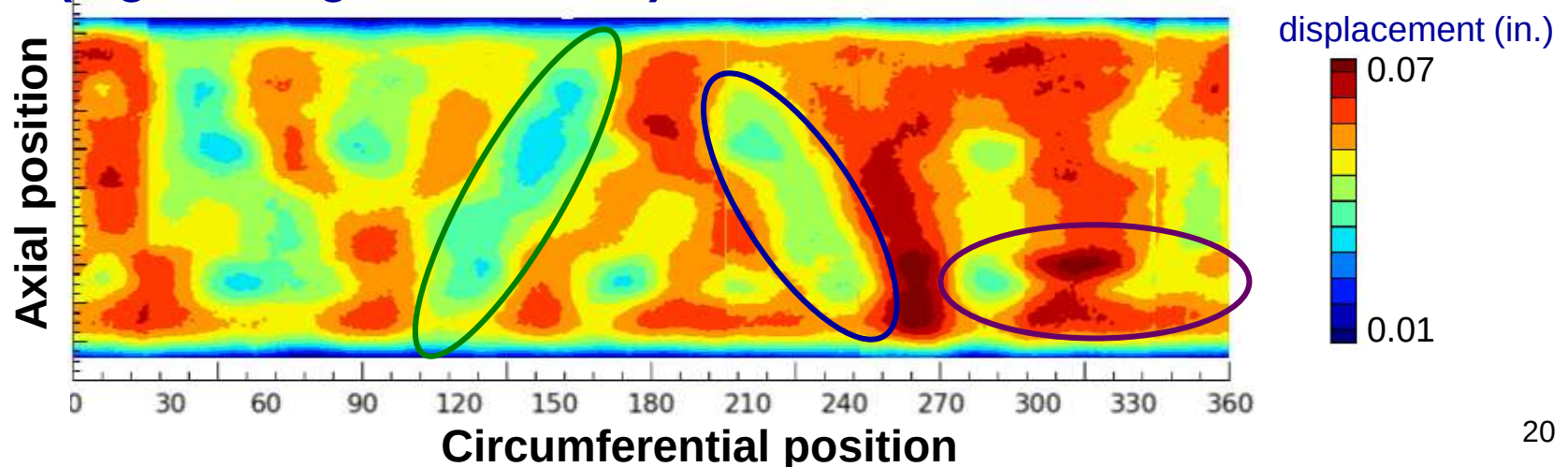
Test-Analysis Correlation: Radial Deformation, 458 kips



Adjusted pretest prediction



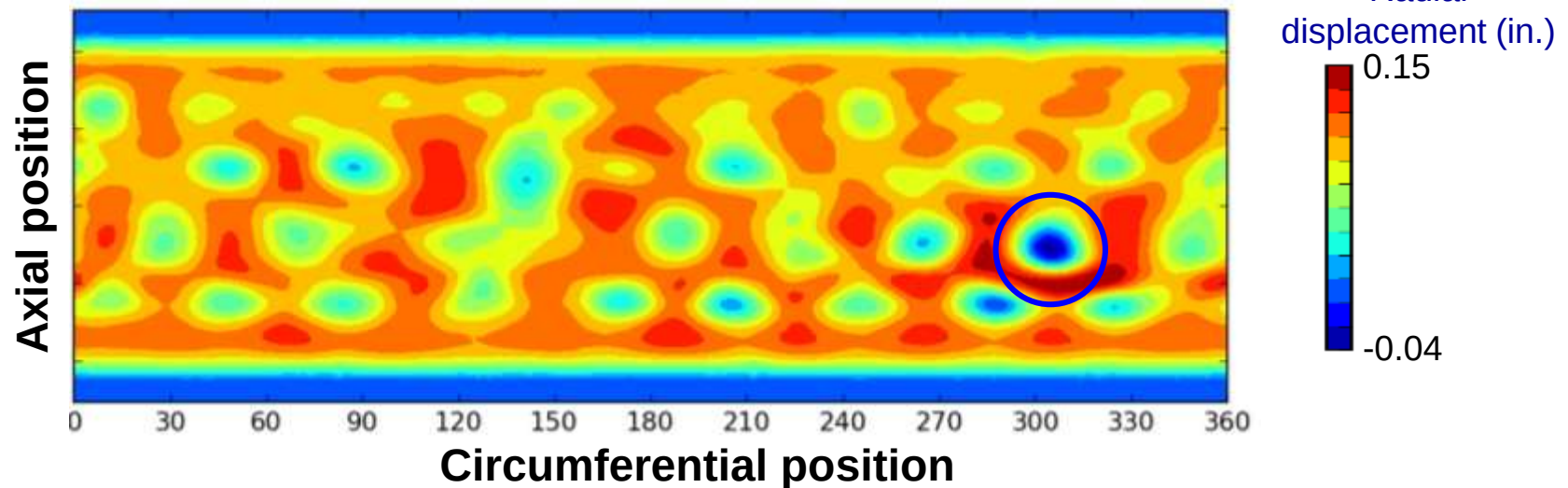
Test (digital image correlation)



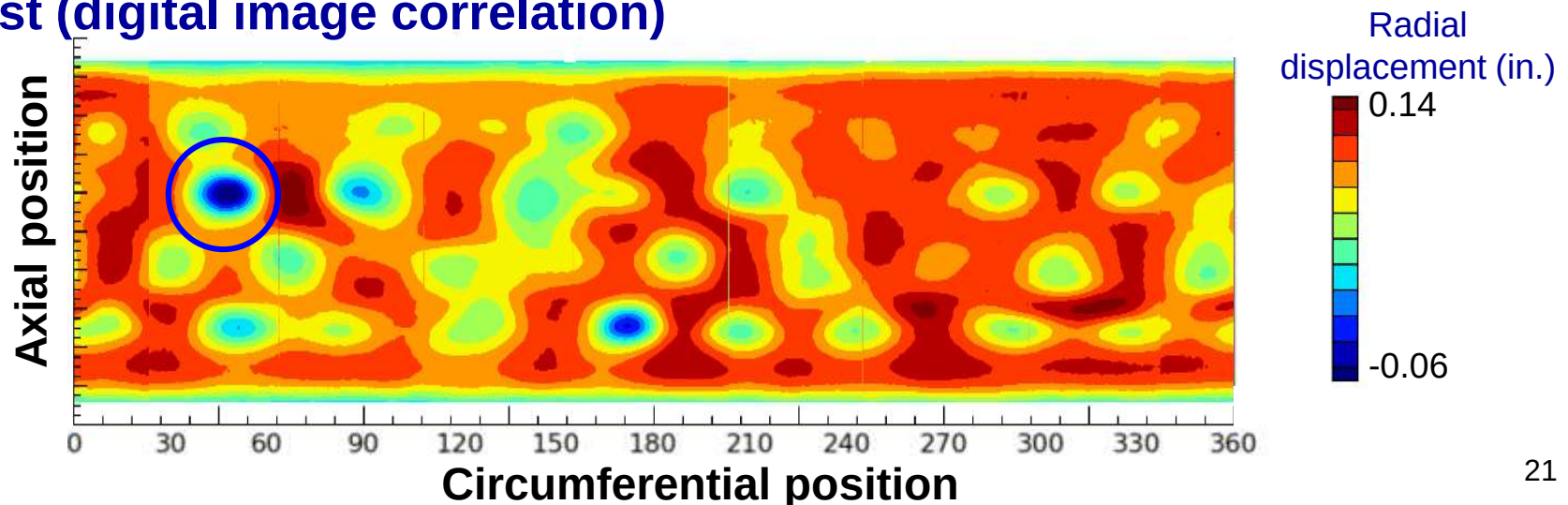
Test-Analysis Correlation: Radial Deformation, at Failure



Adjusted pretest prediction



Test (digital image correlation)



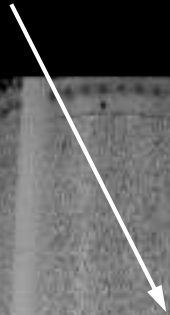
Failure Event: Standard-Rate Video



Failure Event: High-Speed Video (~10,000 fps)



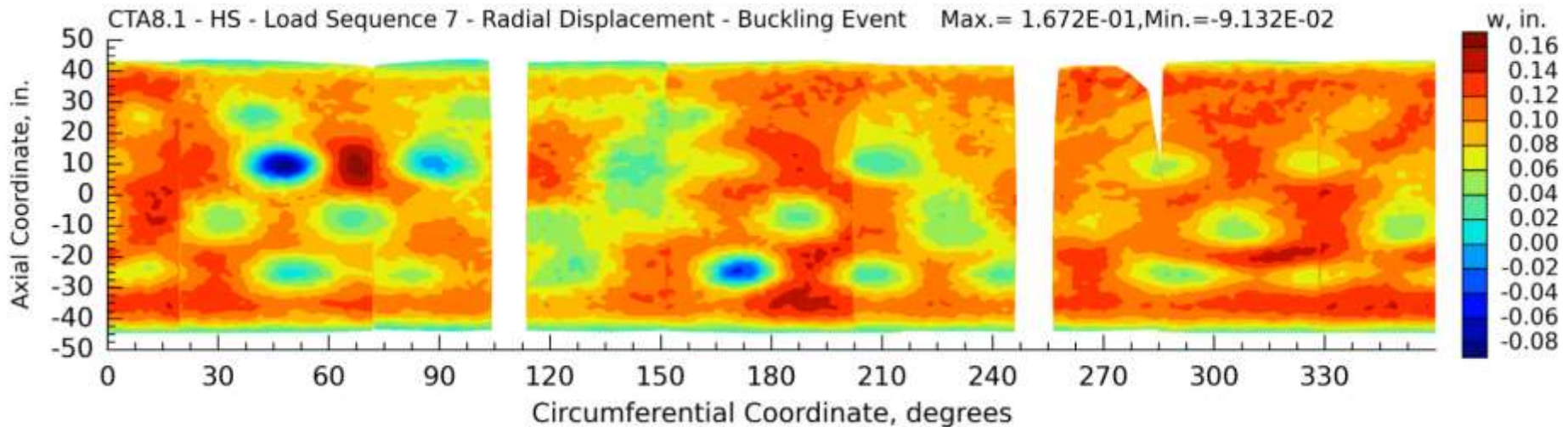
Initiation



Failure Event: High-Speed Digital Image Correlation



Radial deformation (~10,000 fps)



Axial strains were measured to be well below failure strains at buckling initiation

Test-Analysis Correlation: Summary



- **Character of prebuckling response predicted well**
- **Buckling load predicted well with measured material properties**
- **Nonlinearity in experimental response explained by combination of slipping in end rings and material nonlinearity**
- **Location of buckling initiation site not predicted correctly**

Nonuniform Loading Sensitivity Study



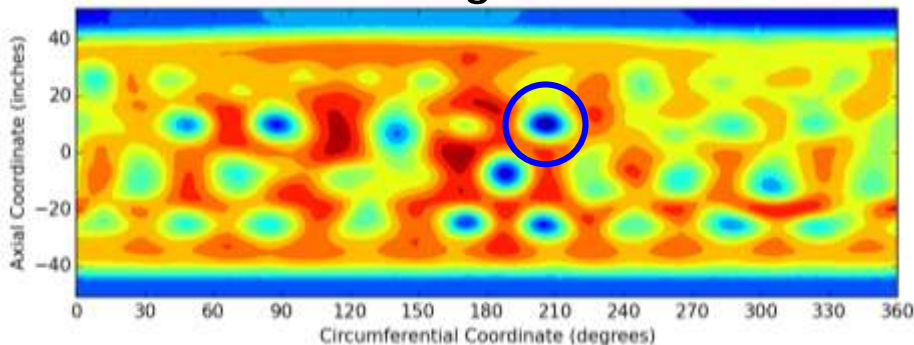
- **Difference in location of buckling initiation site between analysis and test could be due to loading nonuniformities**
 - Interface tolerances between test article and rings
 - Settling in end rings
 - Small amount of applied bending during test
- **Investigated numerically: axial compression with slight applied bending moment**
 - Bending moments giving 1%, 2%, and 3% variation in line loads around the circumference
 - Bending toward the direction measured in test (135°) and toward the test buckling initiation site (45°)

Nonuniform Loading Sensitivity Study

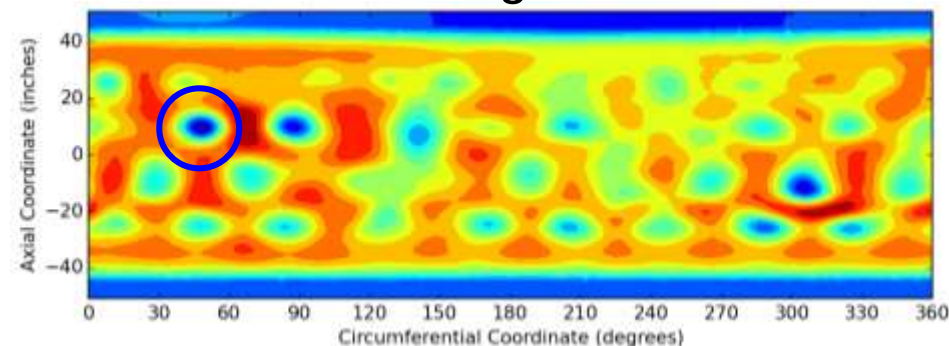


- Predicted buckling loads changed very little for all bending cases
 - All within 1.4% of experimental buckling load
- Predicted buckling initiation site:
 - The 1% and 2% bending cases did not change the predicted location
 - The 3% bending cases changed the predicted location

3% bending toward 135°



3% bending toward 45°





Concluding Remarks

- **First large-scale composite shell test completed with very good agreement between test and analysis**
- **Inclusion of material nonlinearity in analysis improved correlation**
- **Predicted location of buckling initiation site changed with small loading imperfections**



Questions?