



Shell Buckling Knockdown Factor Project: Test and analysis of a large-scale sandwich composite cylinder

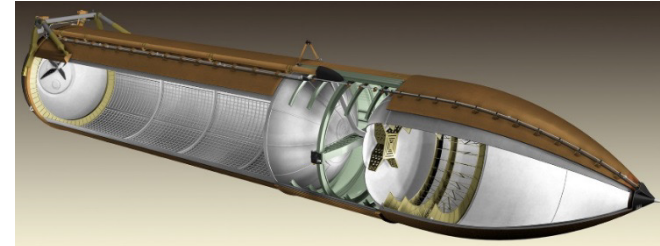
Michelle Tillotson Rudd
NASA Marshall Space Flight Center

University of California- San Diego
November 08, 2021



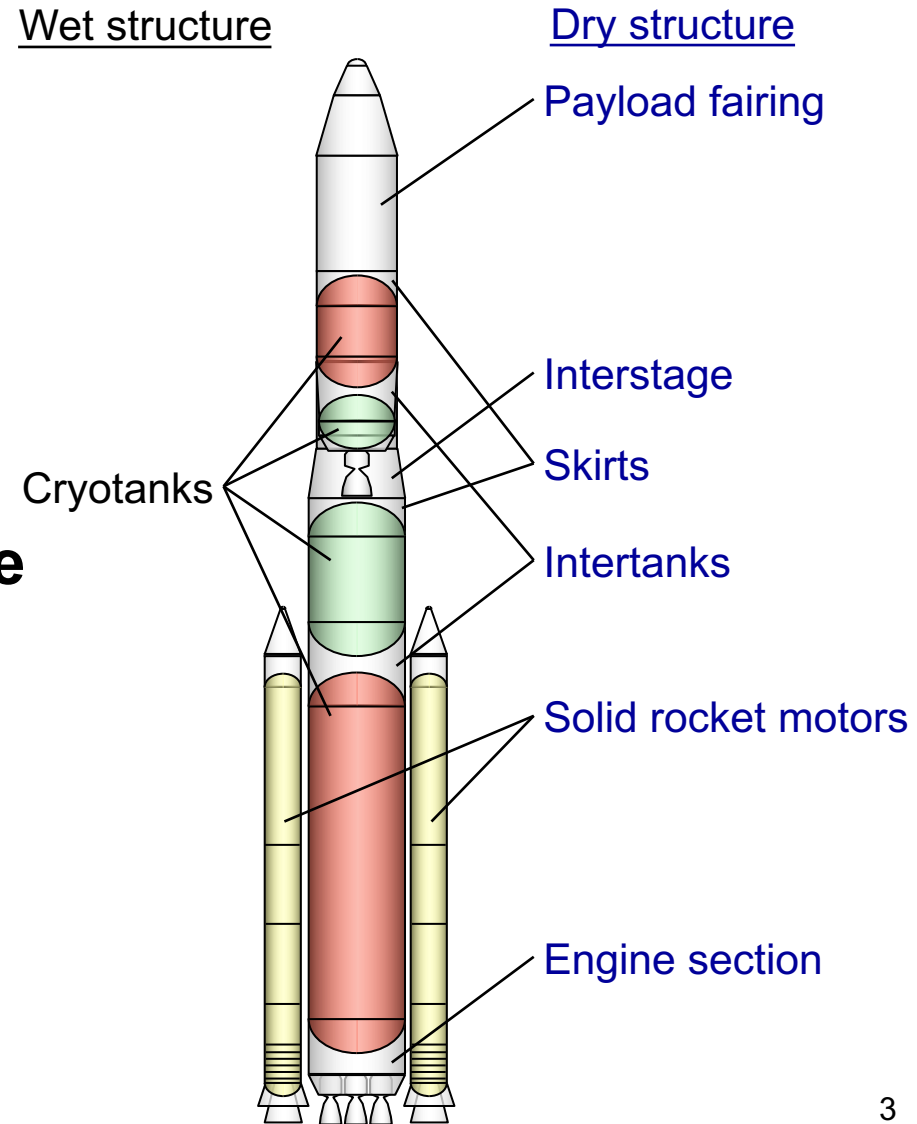
NASA Launch-Vehicle Shell Structures

- **Traditionally, metals have been used for most launch-vehicle primary shell structure**
 - Tanks
 - Integrally stiffened orthogrid or isogrid, etc.
 - Dry structure
 - Fastened hat stiffeners, etc.
- **More recently, composites have been gaining wider acceptance for primary structure**
 - Potential gains (mass, thermal, cost, etc.)
 - Most commonly have sandwich construction
 - Most often considered for dry structures



Launch-Vehicle Shell Structures

- **Cylindrical shells**
 - Significant portion of launch-vehicle structure
- **Buckling**
 - Often a controlling failure mode during design
 - Empirical buckling loads are often **significantly less** than theoretical predictions

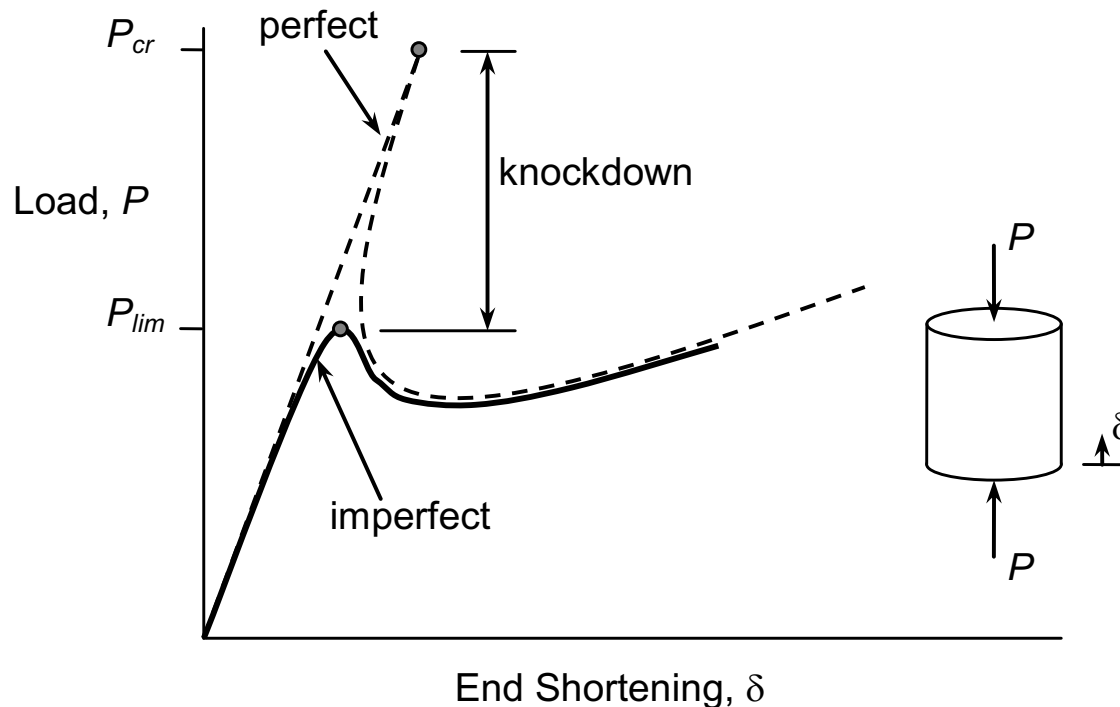




Empirical Shell Buckling Design Approach



- Standard practice is to predict the buckling load of an idealized perfect cylinder and apply an empirical *buckling knockdown factor (KDF)* to account for differences between test and analysis
- Differences between test and analysis primarily attributed to initial *geometric imperfections* in the shell wall (i.e., out-of-roundness)





NASA SP-8007: Buckling of Thin-Walled Circular Cylinders



- Most commonly used source of empirical buckling knockdown factors for cylindrical shells
- Pedigree of test articles and test data (1920s-1960s) used to develop the knockdown factors is difficult to assess
- Most test-article designs not relevant to modern launch-vehicle constructions and material systems
 - Limited data for stiffened cylinders
 - No data for composite cylinders
- Generally thought to be overly conservative—this can lead to a large weight penalty



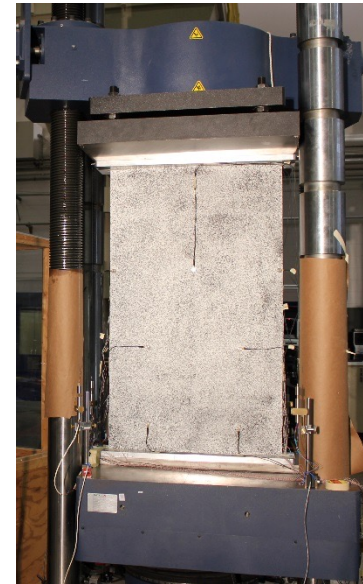
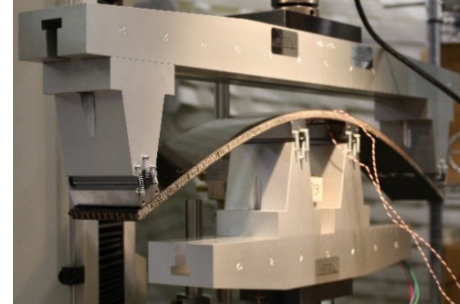
Shell Buckling Knockdown Factor Project: Composite Structures



- **Objective: Develop new analysis-based buckling knockdown factors (KDFs) for composite launch-vehicle structures**
- **Scope**
 - Sandwich-composite cylinders
 - Acreage designs
 - Axial compression
- **Approach**
 - **Analysis-based** knockdown factor development and validation
 - Develop and assess various knockdown factor prediction methodologies
 - Targeted **validation testing** at coupon, panel, and cylinder levels
 - Relevant subscale test-article designs that span the launch-vehicle design space
 - State-of-the-art manufacturing, testing, and measurement techniques
 - Implementation of new knockdown factors
 - Engage the user community to review and refine a technology development and implementation plan
 - **Domestic and International collaborations**

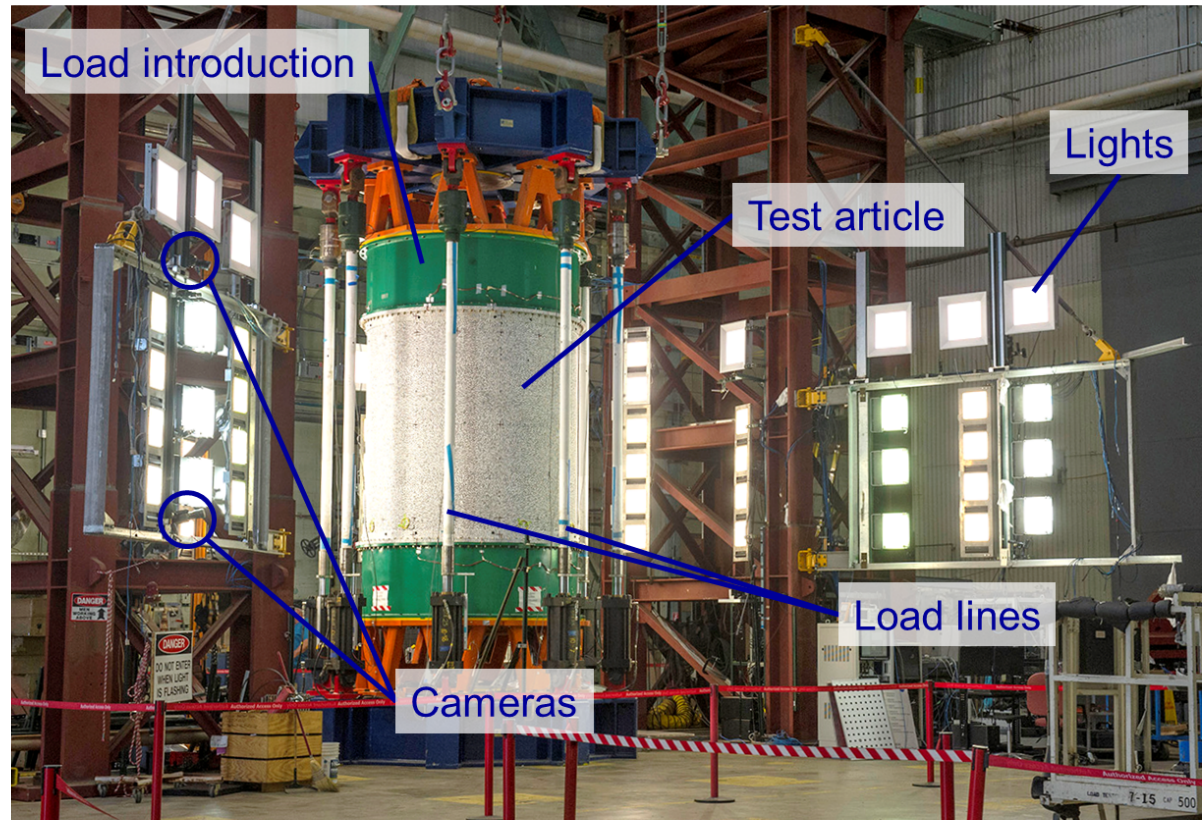
Validation Testing Levels

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



For subscale cylinder testing

- **Test articles**
 - 8-ft diameter
 - Lengths up to 12-ft
- **Loading**
 - Uniform compression up to 1.5×10^6 lbf
 - Combined compression and bending





Shell Buckling Research at NASA

Test-Article Design Example



Test-Article Design Example: Design Requirements



- **Test-article first failure mode under axial compression should be global buckling**
 - Desire to have **factor of 1.4 (Failure Index* below 0.71)** between global buckling and all other failure modes
 - Buckling should occur within facility load limits (1.5×10^6 lbf)
- **Test-article shell design should be in desired design space (“thin,” axially stiff, etc.)**
- **Design should follow best practices for aerospace composite design and fabrication**
- **Test article to be fabricated at MSFC using automated fiber placement**

$$^* \text{Failure Index} = \frac{P_{cr}^{FEA \text{ Perfect}}}{P_{fail}}$$



Test-Article Design Example: Analyses



- **Closed-form “hand” calculations**
- **Finite element analysis: shell models**
- **Finite element analysis: axisymmetric models**
- **Finite element analysis: global-local models**



Test Article Design

Closed-Form Calculations

Closed-Form Calculations for Preliminary Design

- **Global buckling load, P_{cr}**

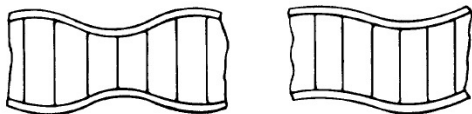
$$P_{cr} = 4\pi R t_f \phi \sigma_{cr}^{rc} \left(1 - \frac{1}{2} \frac{\phi \sigma_{cr}^{rc f} t_f t_c}{G_{xz} h^2} \right)$$

- **Axial strain at buckling, ε_{cr}**

$$\varepsilon_{cr} = \frac{P_{cr}}{4\pi R t_f \bar{E}_x}$$

- **Sandwich failures**

- **Facesheet wrinkling, P_{FW}**



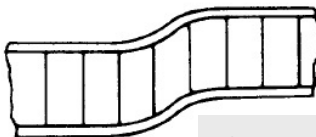
$$P_{FW} = 4\pi R t_f \sqrt{\frac{2 t_f}{3 t_c} \frac{E_c \sqrt{\bar{E}_x \bar{E}_y}}{1 - \bar{\nu}_{xy} \bar{\nu}_{yx}}}$$

- **Facesheet dimpling, P_{FD}**



$$P_{FD} = 4\pi R t_f \frac{2 \sqrt{\bar{E}_x \bar{E}_y}}{1 - \bar{\nu}_{xy} \bar{\nu}_{yx}} \left(\frac{t_f}{d} \right)^2$$

- **Core shear instability, P_{CS}**



$$P_{CS} = 4\pi R t_f \frac{G_{xz} t_c}{2 t_f}$$

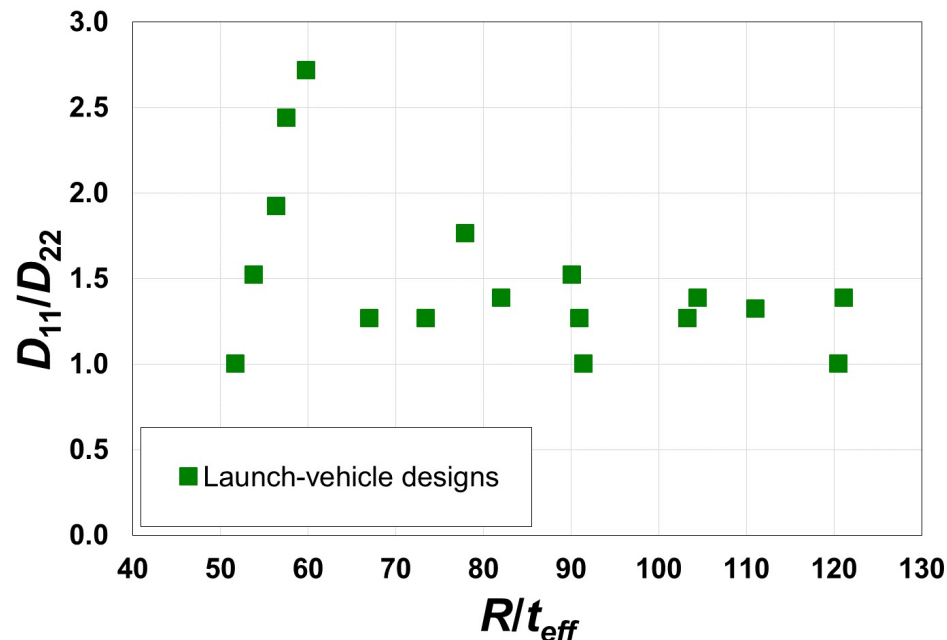


Subscale Cylinder Testing (8-ft diameter)



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

- Calculate design-space parameters for launch-vehicle components



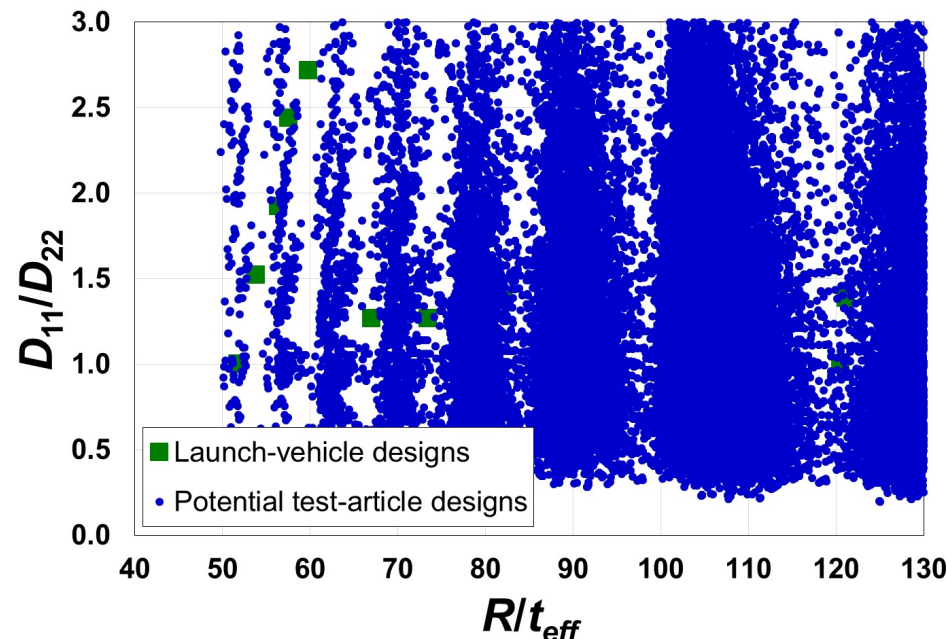


Subscale Cylinder Testing (8-ft diameter)



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



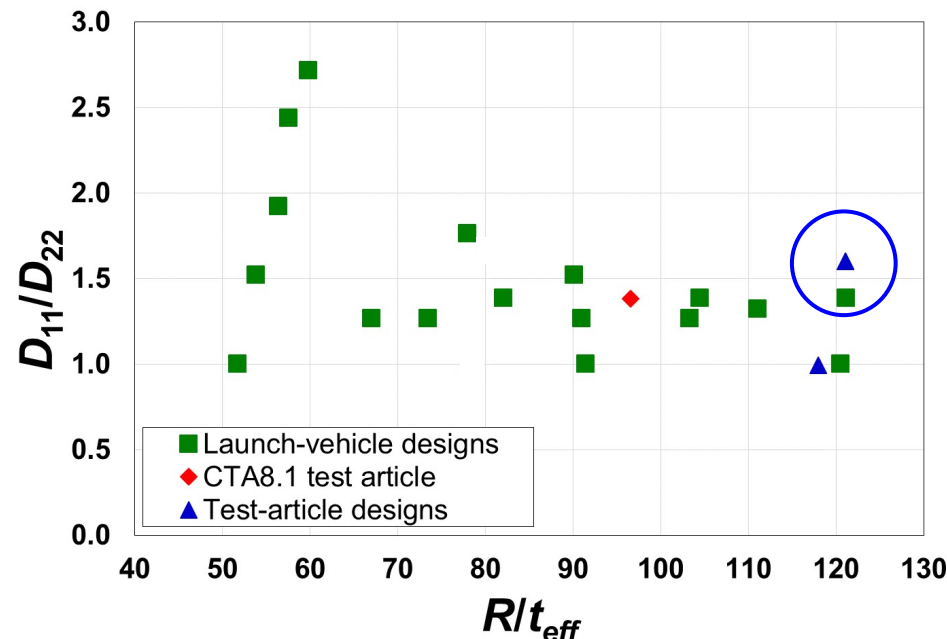


Subscale Cylinder Testing (8-ft diameter)



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

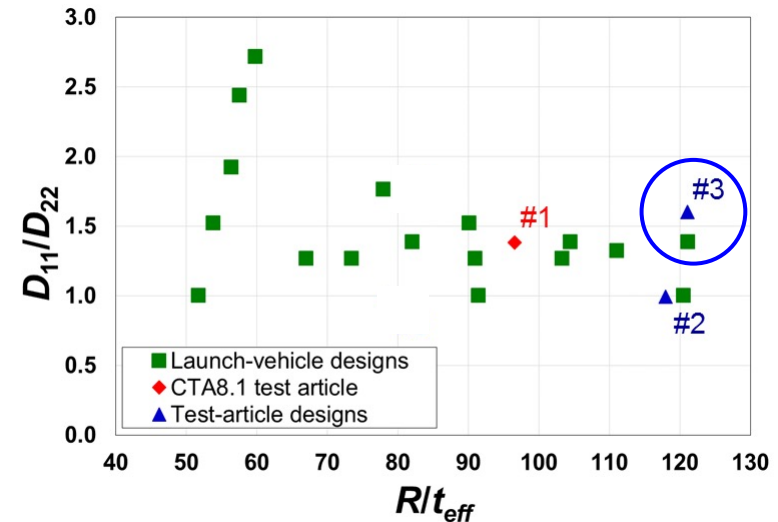
- Calculate design-space parameters for launch-vehicle components
- Select subscale designs
 - Criteria: buckling critical, failure load, design space, etc.
 - Five test-article designs selected as minimum number to validate analysis methods



Selected Design

• Faces

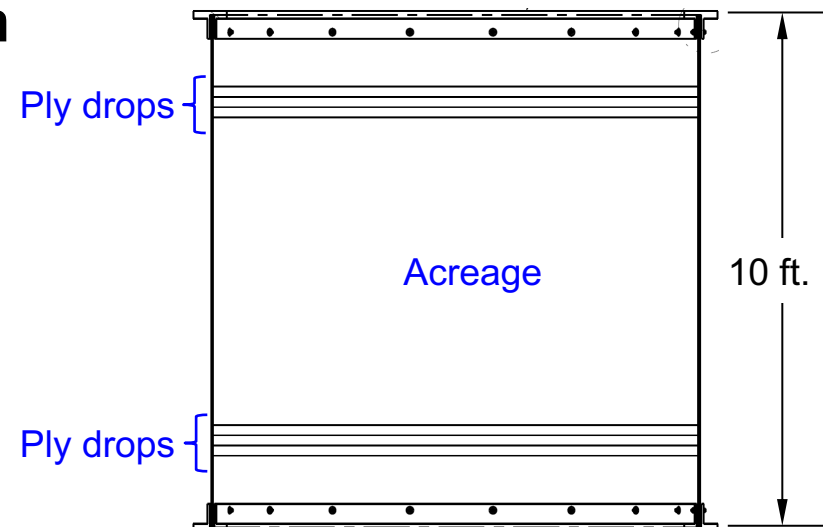
- 5-ply axially stiff facesheets: $[\pm 30/\overline{90}]_s$
- Padups: four interleaved ± 45 plies/face dropped at 14 in., 16 in., 18 in., and 20 in.



• Core

- Acreage: 3.1 pcf aluminum honeycomb
- End 10 in.: 8.1 pcf aluminum honeycomb
- Thickness: 0.2 in.

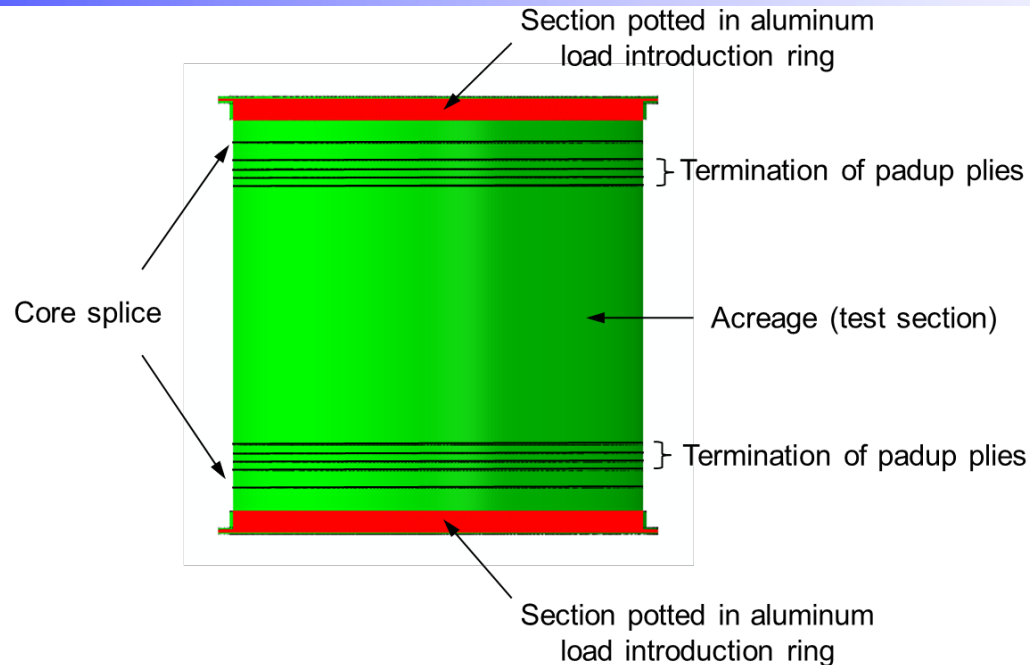
- To be tested in axial compression to failure





Test Article Design

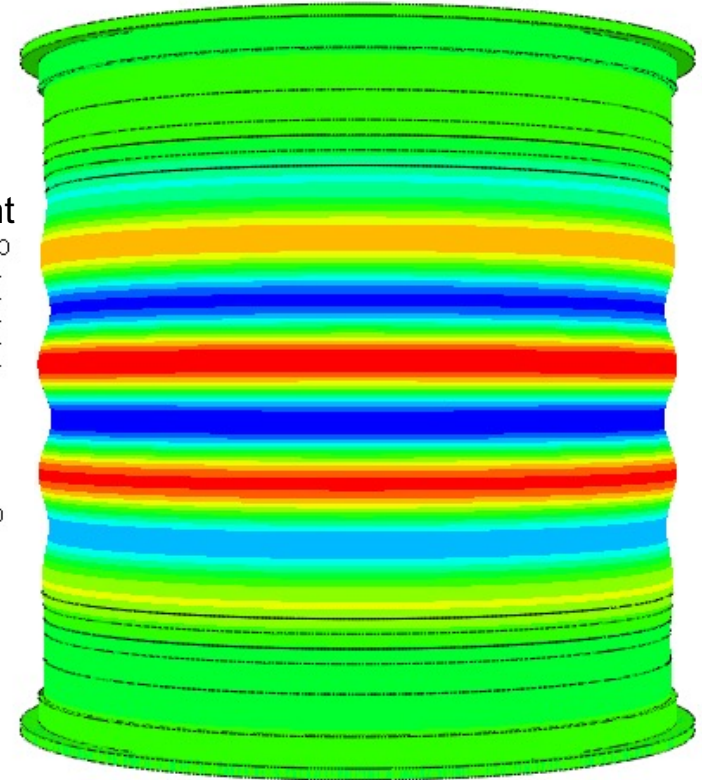
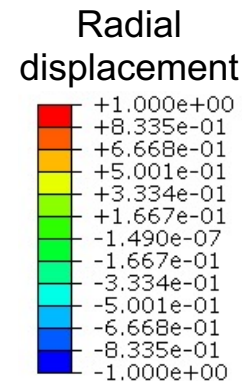
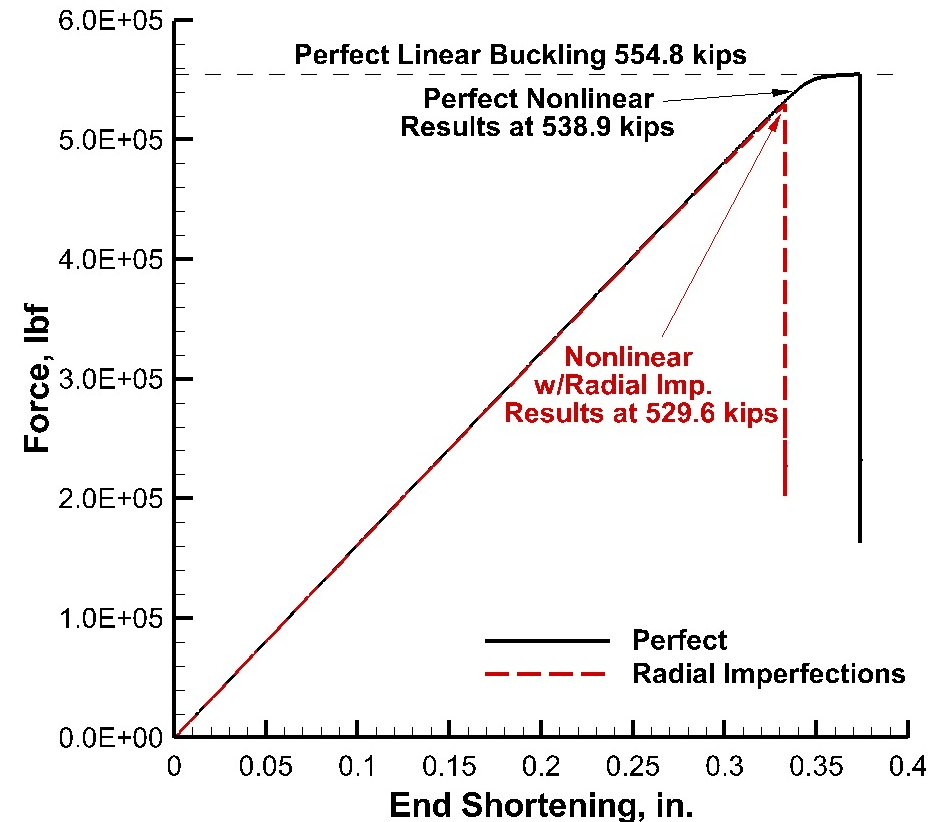
Finite Element Analysis: Shell Model



- **Model**
 - Approximately 154,000 shell elements (S4R)
 - Element size: 0.5 in. in the axial direction by 0.5-degree (approximately 10 mm) in the circumferential direction
 - Problem size: approximately 932,000 degrees-of-freedom
- **Analyses**
 - Linear buckling
 - Nonlinear transient buckling (perfect and imperfect geometries)

Characteristic Loads and Linear Buckling

Load versus end shortening



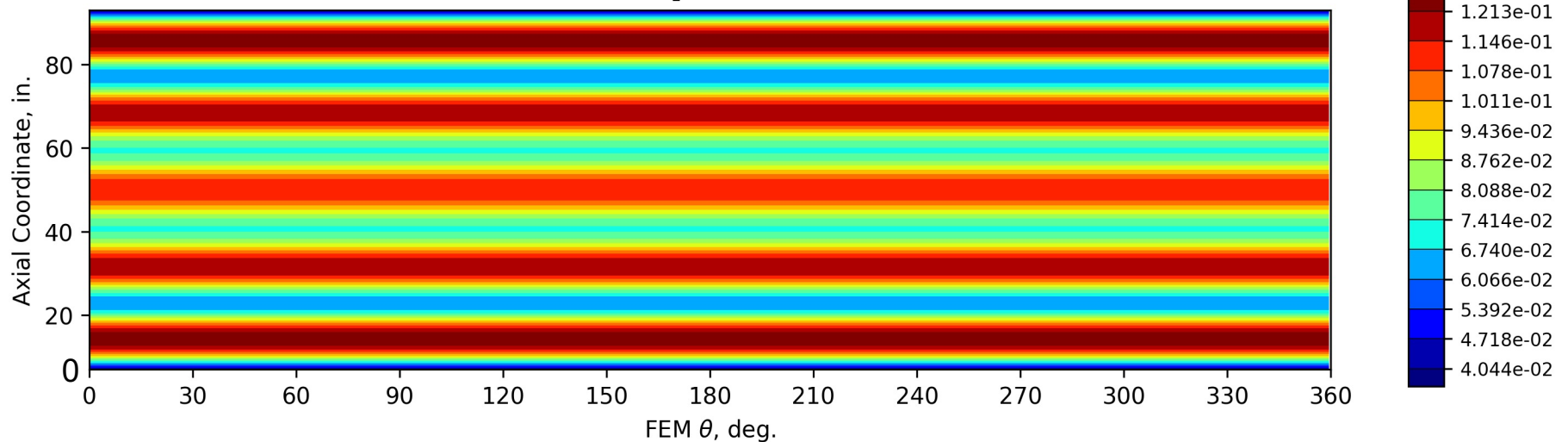
**Radial displacement,
fundamental mode,
554.8 kips**



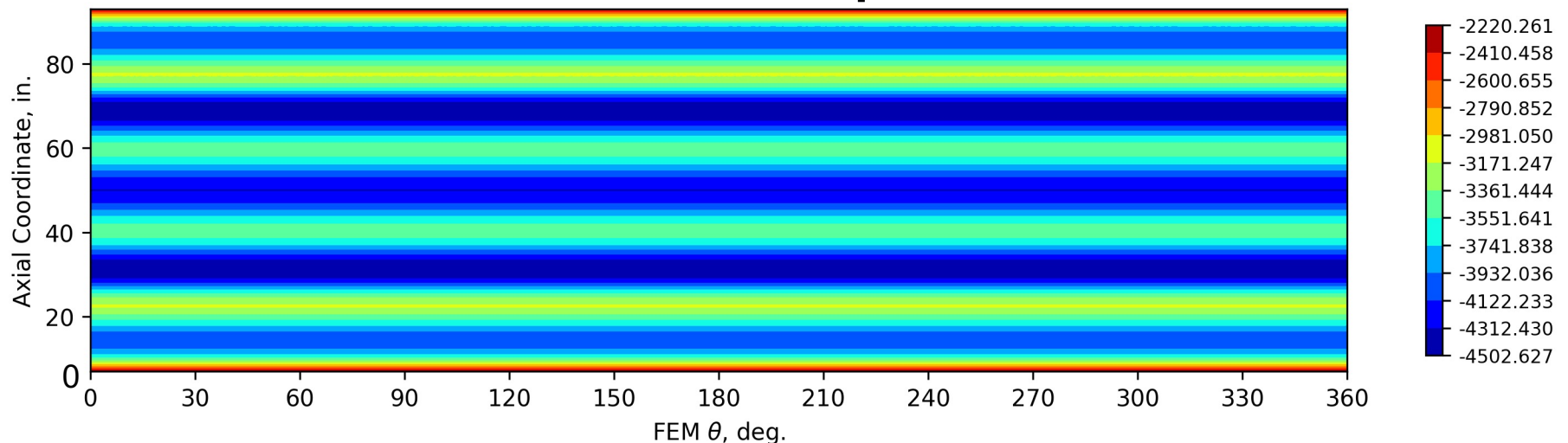
Nonlinear Analysis at 538.9 kips Perfect Geometry



Radial Displacement, mm



Axial Strain, $\mu\epsilon$

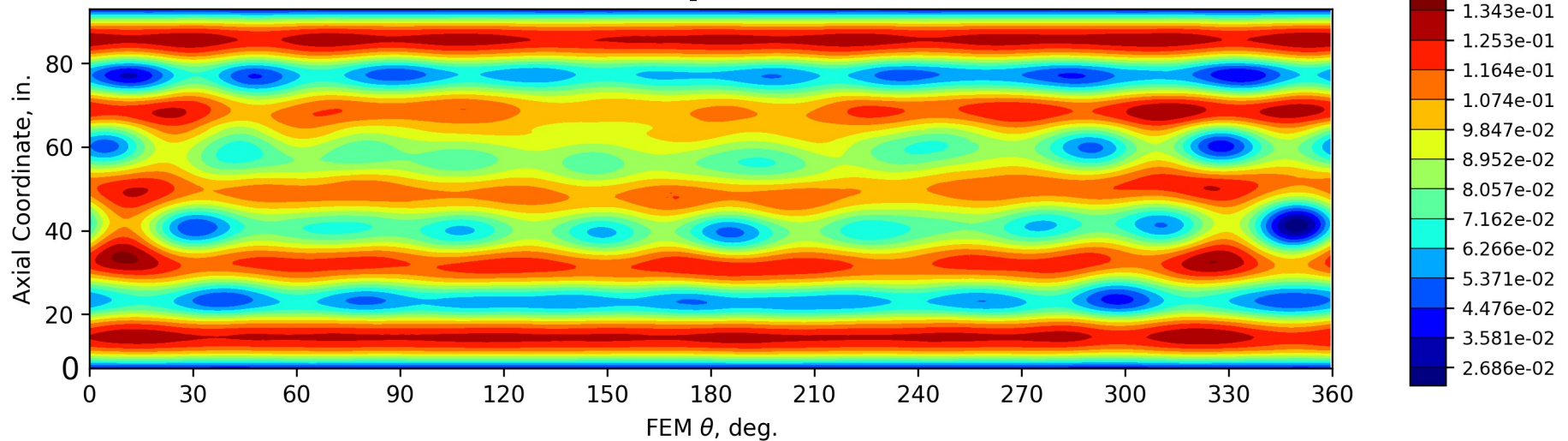




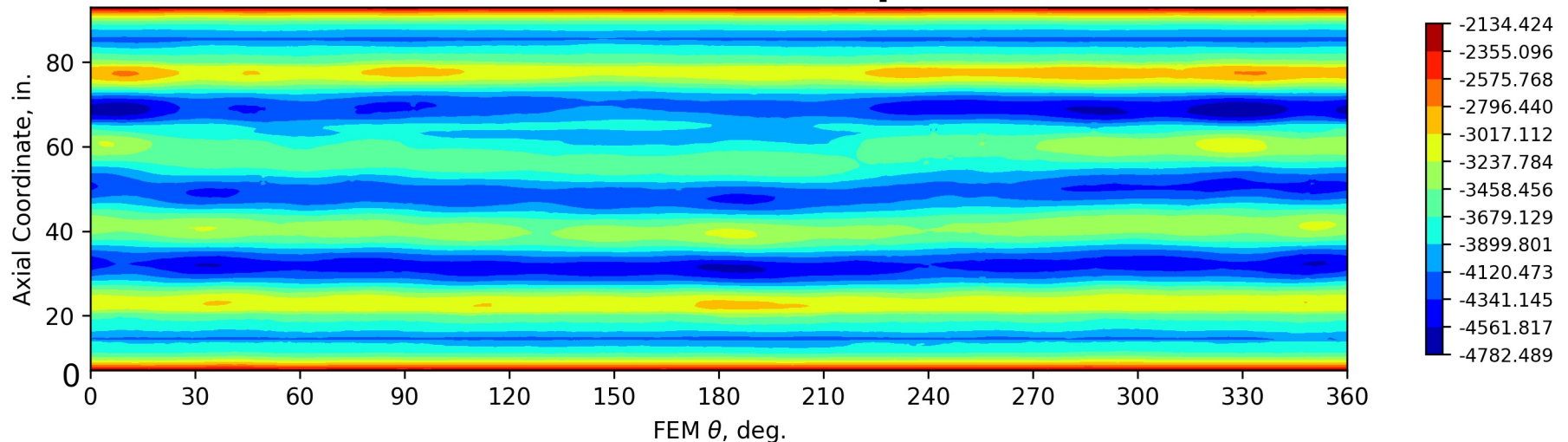
Nonlinear Analysis at 529.6 kips Geometry with Radial Imperfections



Radial Displacement, mm



Axial Strain, $\mu\epsilon$





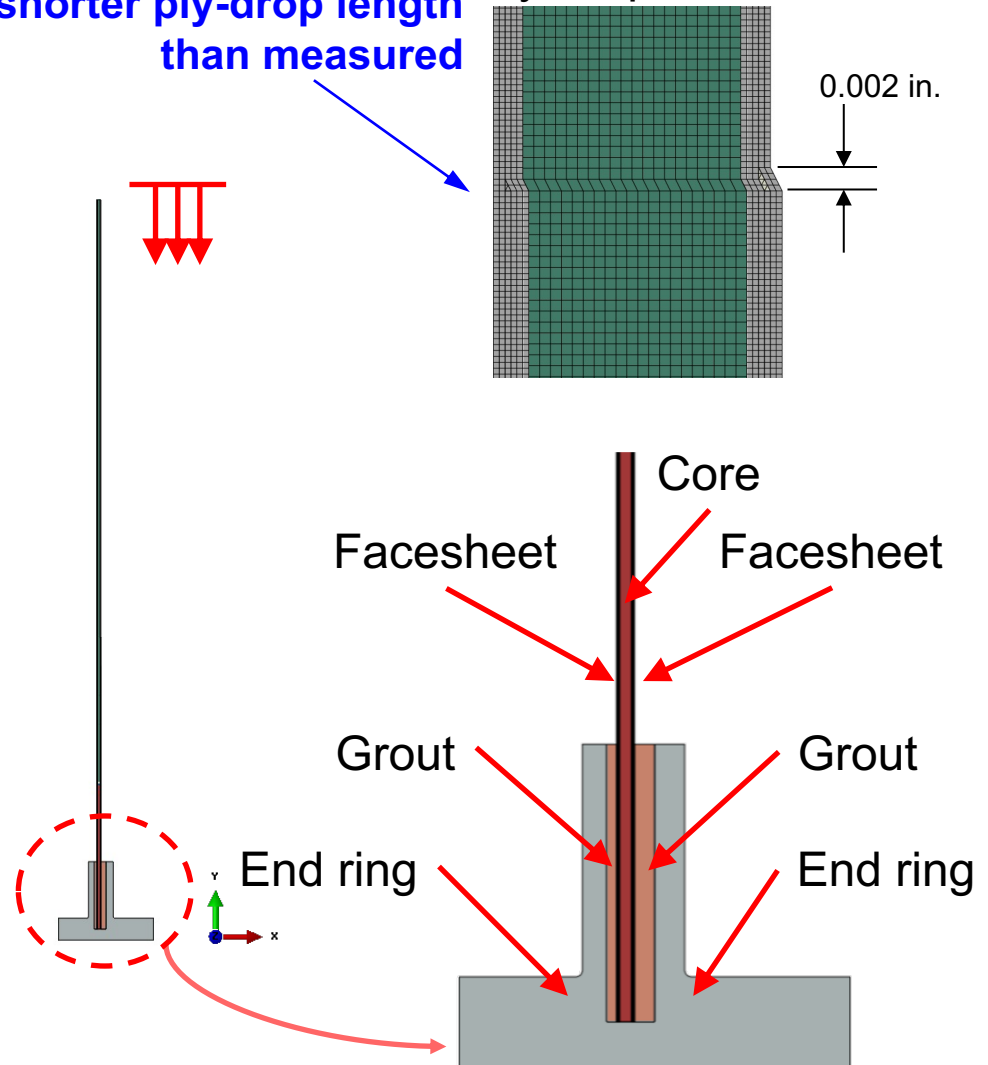
Test Article Design

Finite Element Analysis: Axisymmetric Model

- **Half-cylinder-height model**
 - Applied displacement at midlength
 - Midlength constrained from rotating
- **Abaqus CAX4 elements**
 - Fully integrated
 - Axisymmetric continuum formulation
- **Individual plies modeled**
 - Ply drops modeled as wedges
 - Wedges have same properties as terminating ply
- **Model metrics**
 - 220,000 elements
 - 685,000 DOFs
- **Static solver**
 - Geometrically nonlinear
 - Linear-elastic material

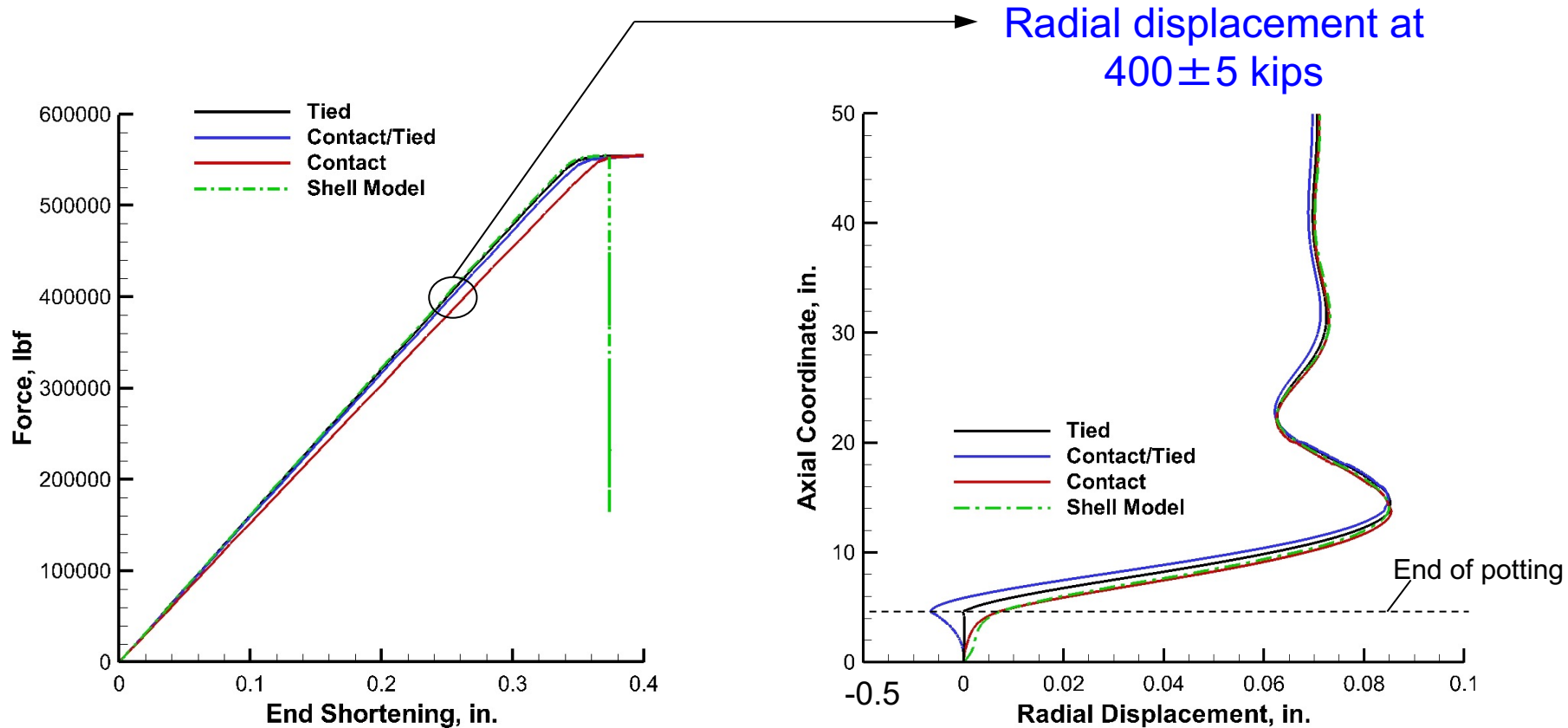
Much shorter ply-drop length than measured

Ply-drop detail



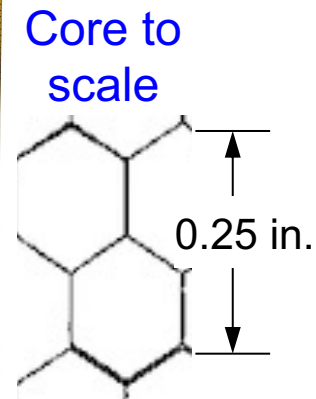
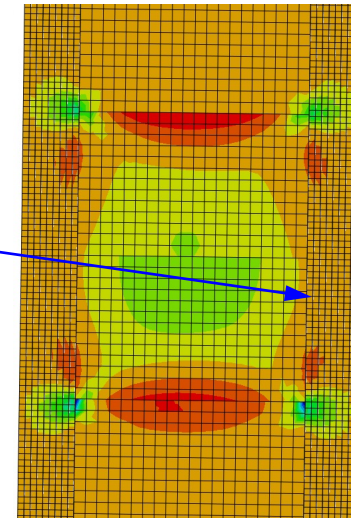
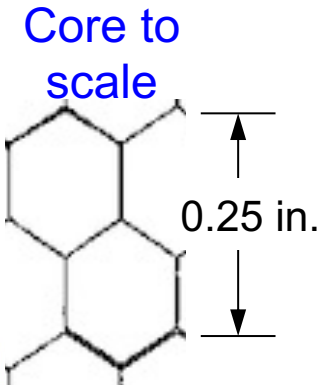
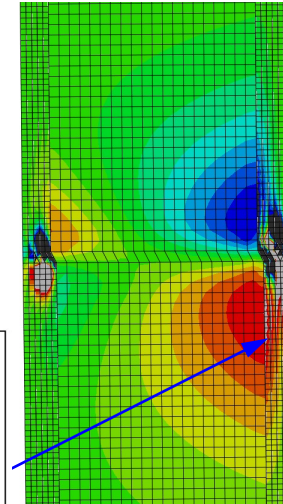
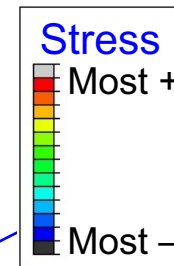
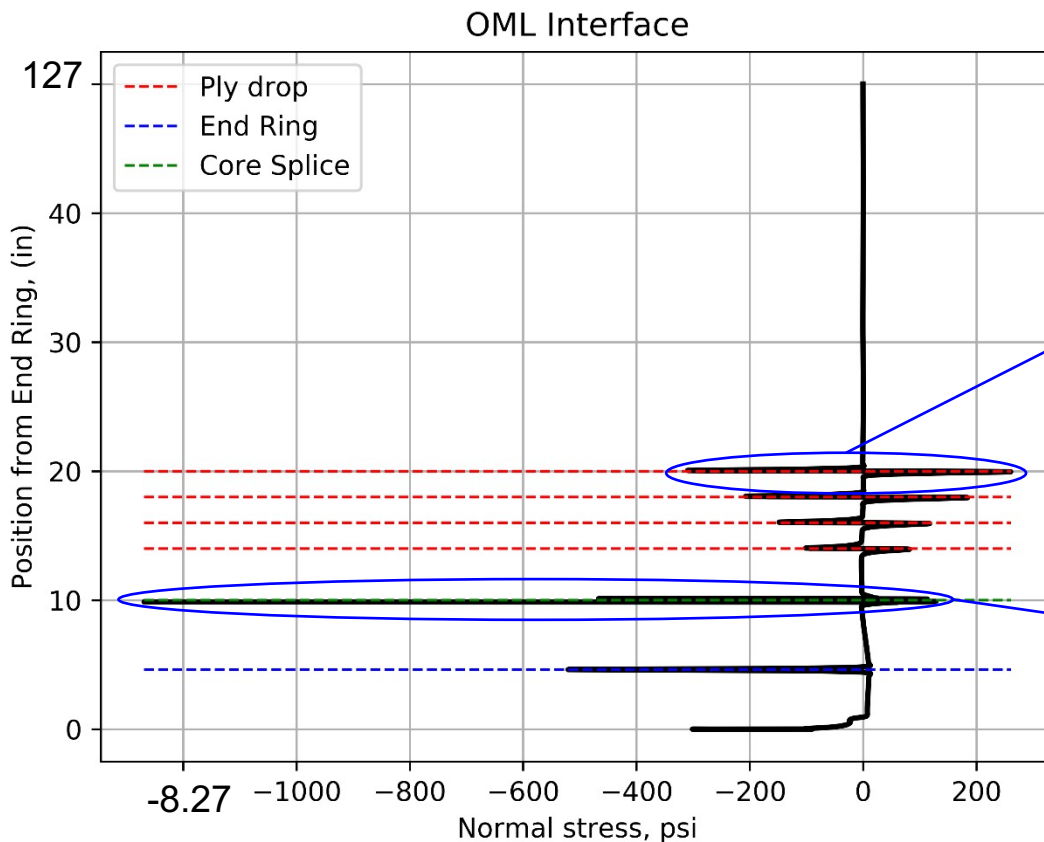
Axisymmetric Analysis

Comparison with perfect-geometry shell model



Axisymmetric FEA Analysis: Core-to-Facesheet Interface Stresses

Axisymmetric model, 535 kips



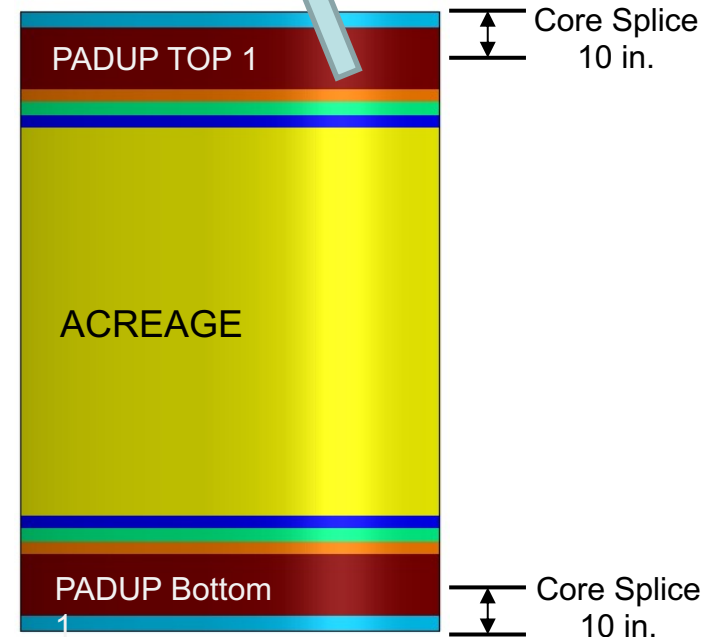
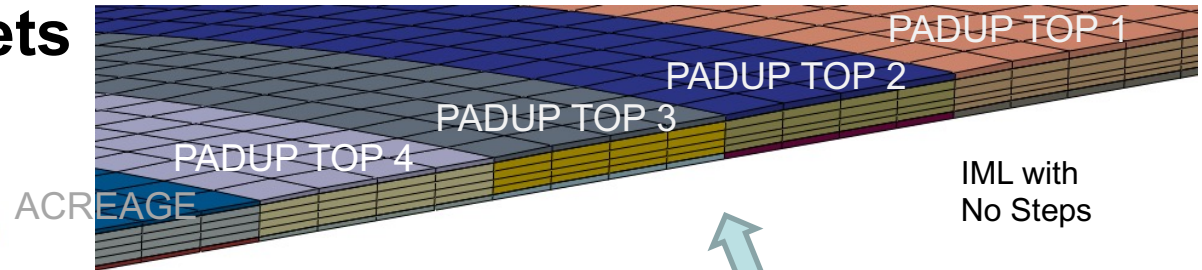
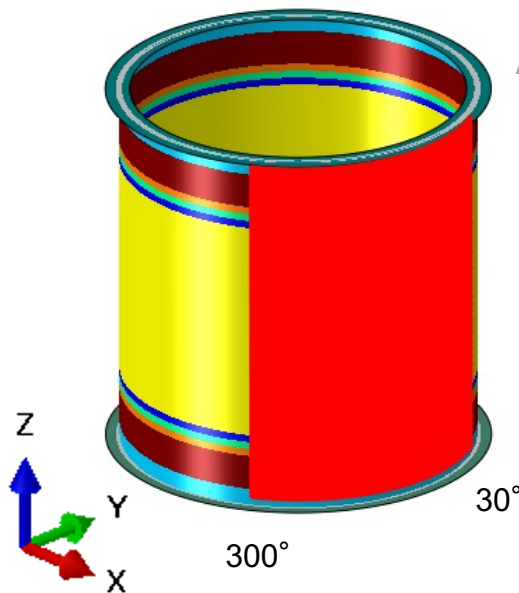


Test Article Design

Finite Element Analysis: Global-Local Model

Finite Element Analysis: Global-Local Analysis

**Solid elements in core, continuum shell
elements in facesheets**



Two Global Models

- Perfect mesh model
- Radial imperfection mesh model



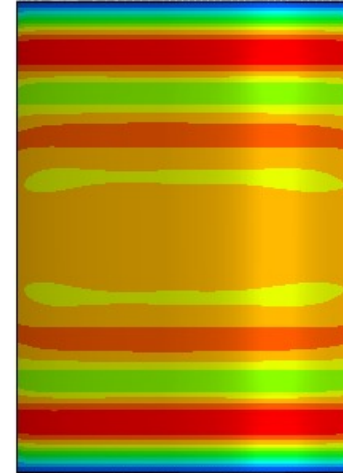
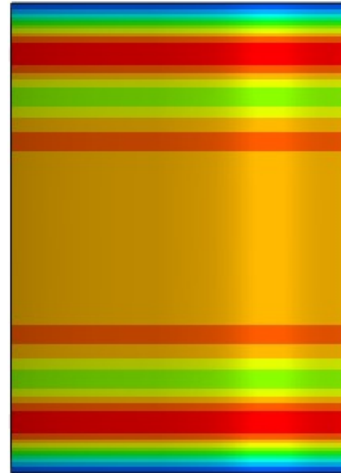
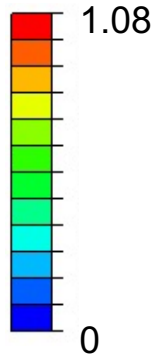
Finite Element Analysis Results: Global-Local Analysis



Global Shell Model

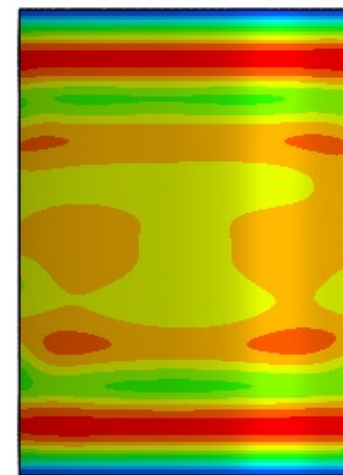
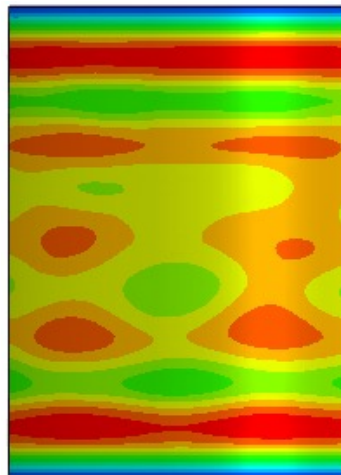
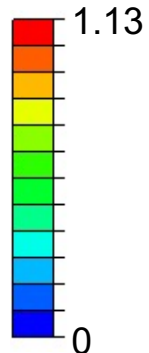
Local Solid Model

Radial
displacement (in.)



Perfect,
472 kips

Radial
displacement (in.)



With radial
imperfection,
480 kips

Analysis	Failures interrogated	Advantages	Limitations
Closed-form (hand calculations)	• Linear global buckling (for initial down select) • Facesheet wrinkling • Facesheet dimpling • Shear crimping	• Quickly assess many designs • Calculate otherwise difficult-to-predict failure loads	• Linear only • Perfect geometry only • Simple, uniform shell only
FEA shell	• Global buckling • Facesheet strength failures	• Linear/nonlinear analyses • Can easily include measured radial and thickness imperfections • Pretest buckling predictions	• Cannot capture core crush or shear failures • Cannot capture end conditions in great detail
FEA axisymmetric	• Global buckling • Smeared-core strength failures (crush, shear) • Core-to-facesheet interface stresses • Facesheet strength failures	• Linear or nonlinear analyses • Interrogate facesheet and core response in detail (high mesh density) for low computational cost • Investigate effects of various end conditions • Captures closed-cylinder response	• May not capture minimum buckling mode • Cannot include realistic geometric imperfections • Composite layup approximated • Smeared-core assumption
FEA global-local	• Global buckling • Smeared-core strength failures (crush, shear) • Core-to-facesheet interface stresses • Facesheet strength failures	• Interrogate the effects of nonaxisymmetric deformations on core stresses/strength failures • Can properly model composite layup • Computationally efficient • Can include nonaxisymmetric imperfections	• Difficult to model end conditions in detail • Smeared-core assumption • Results may not be accurate near edges of local model • Difficult to capture thickness imperfections



Shell Buckling Research at NASA

Test and Analysis Correlation

First Large-Scale Test Article

- **Construction**

- 8-ft-dia. honeycomb-core sandwich composite cylinder
- Single piece (unsegmented)
 - Core: 6.4-mm Korex honeycomb
 - Facesheets: 7-ply $[\pm 45/0/90]_s$

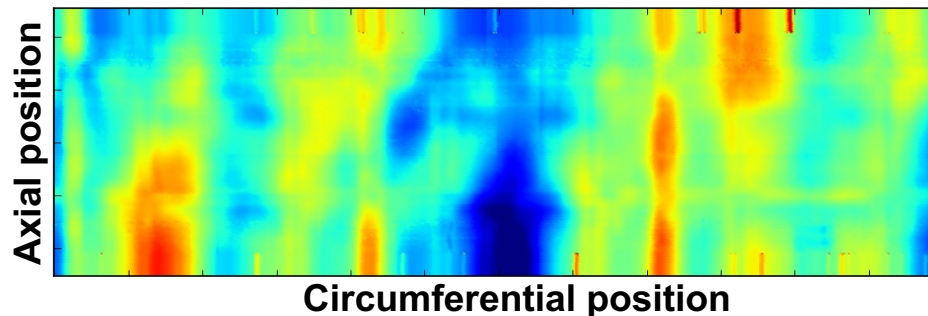
- **Fabrication**

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

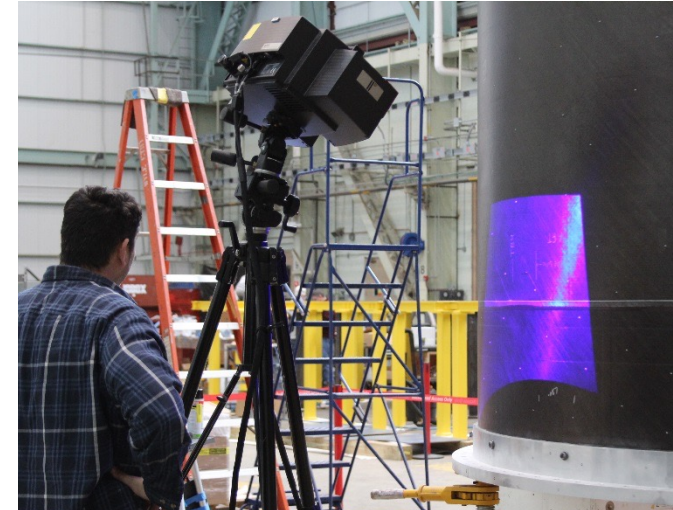
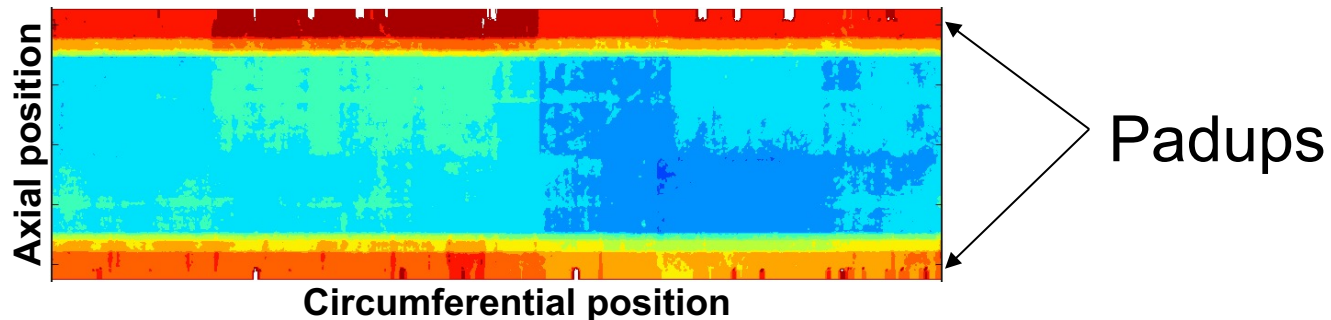


Structured Light Scanning Geometry Measurement

- Photogrammetric technique to measure 3-D shapes
 - Inside and outside
- Radial variation

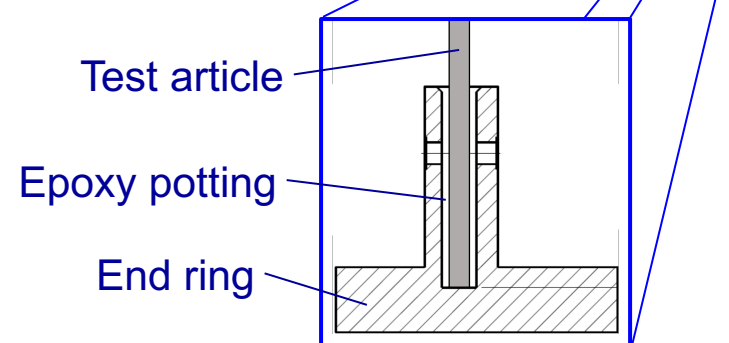
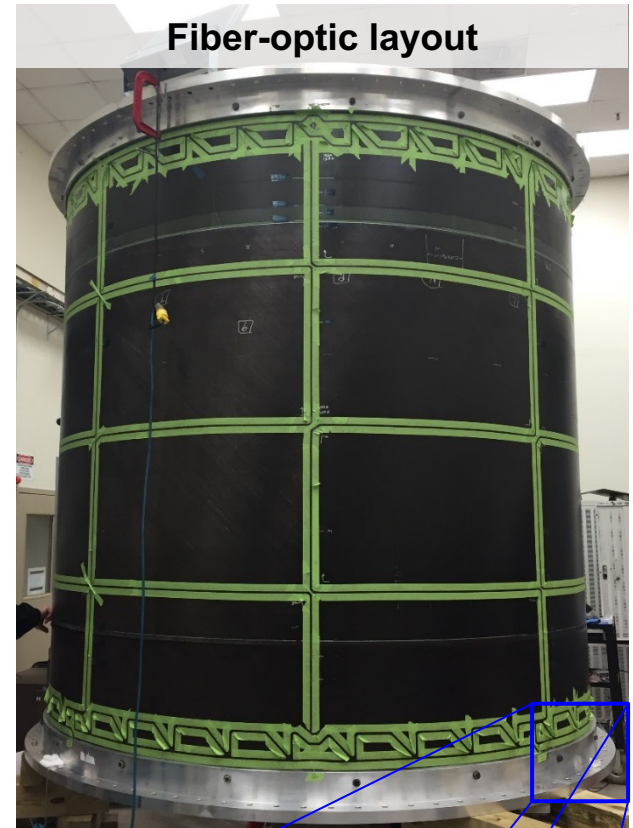


- Thickness variation

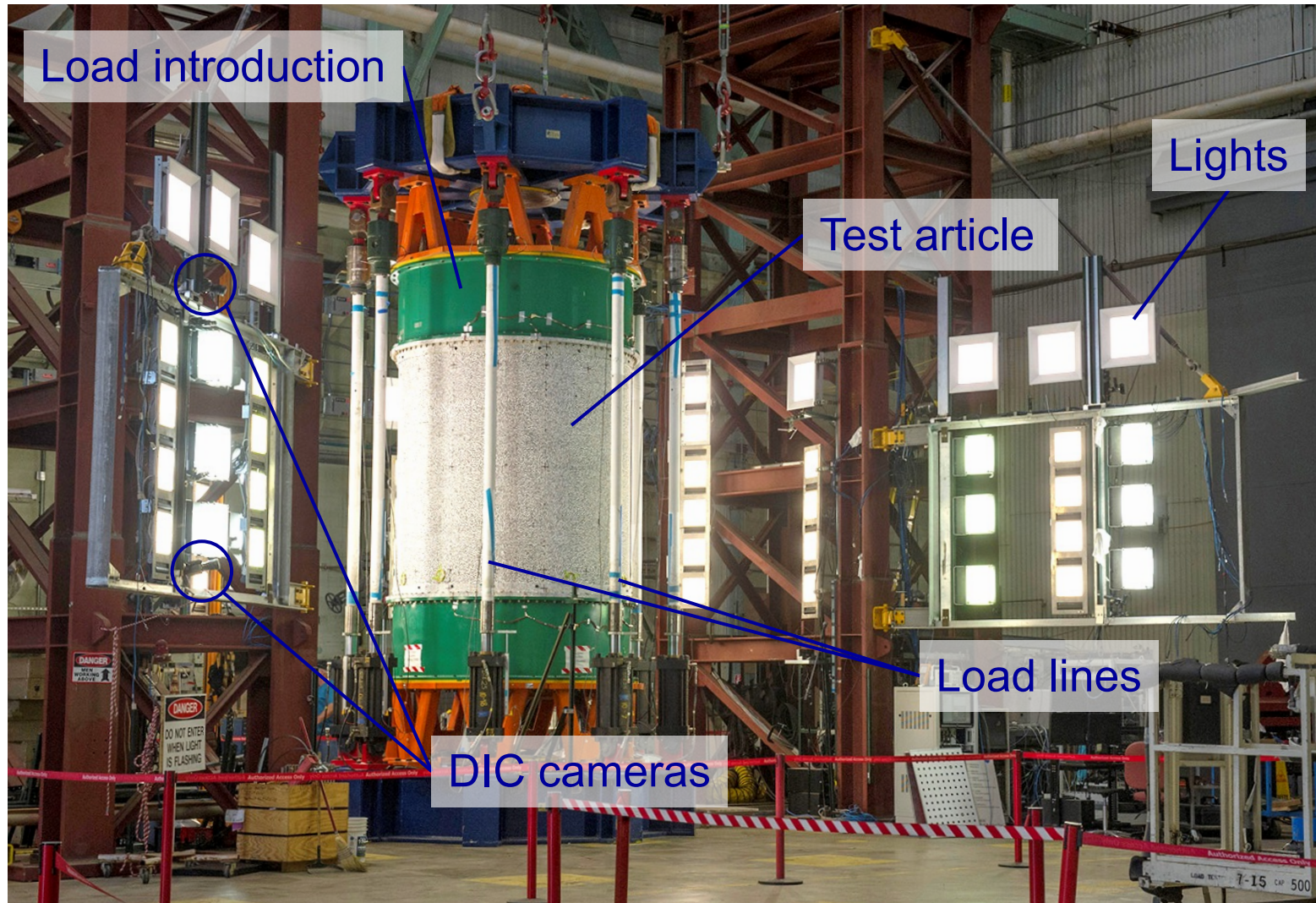


Testing and Instrumentation

- **Test conditions**
 - Subcritical axial compression and combined loading cases
 - **Axial compression** to failure
- **Instrumentation**
 - 300 electrical strain and displacement sensors
 - Digital image correlation (DIC)
 - Low speed and high speed
 - 16,000 fiber-optic strain sensors

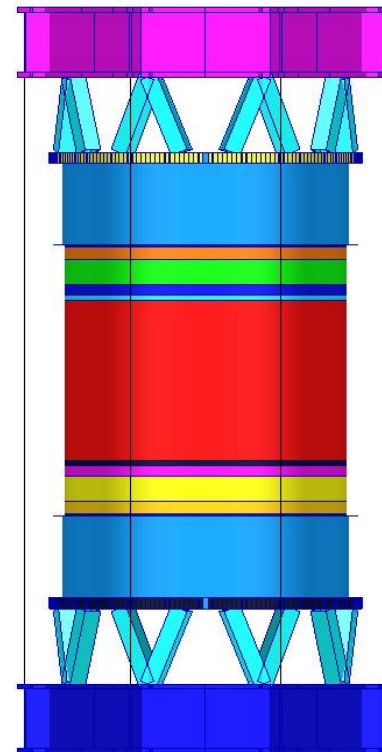


Test Setup

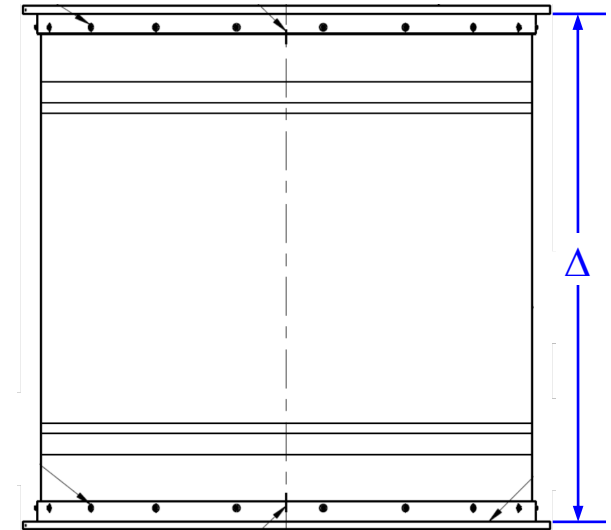
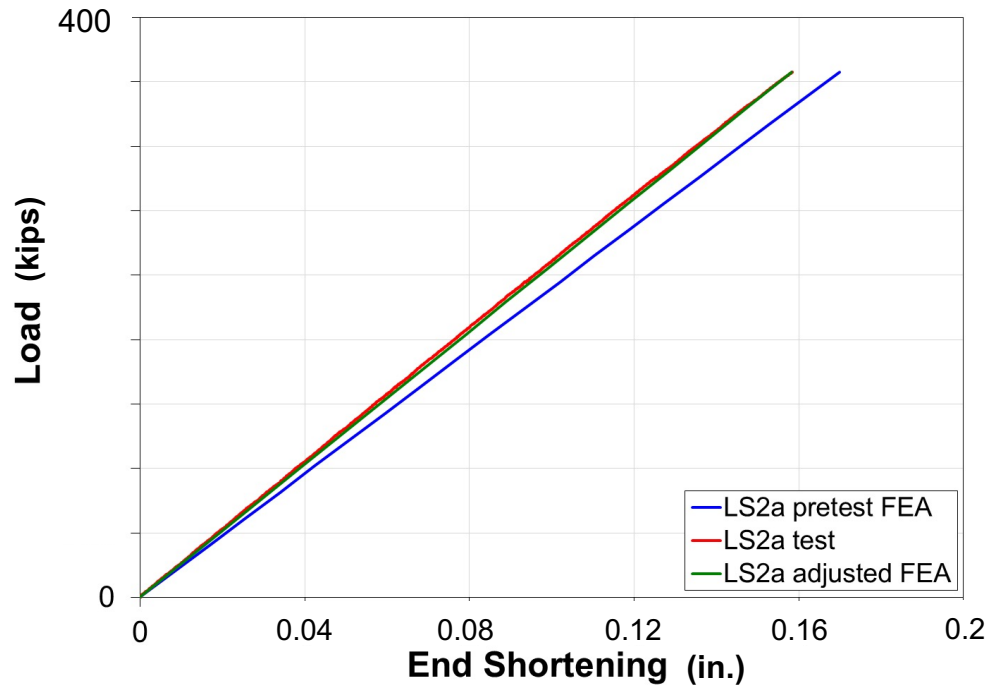


Analysis Approach

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



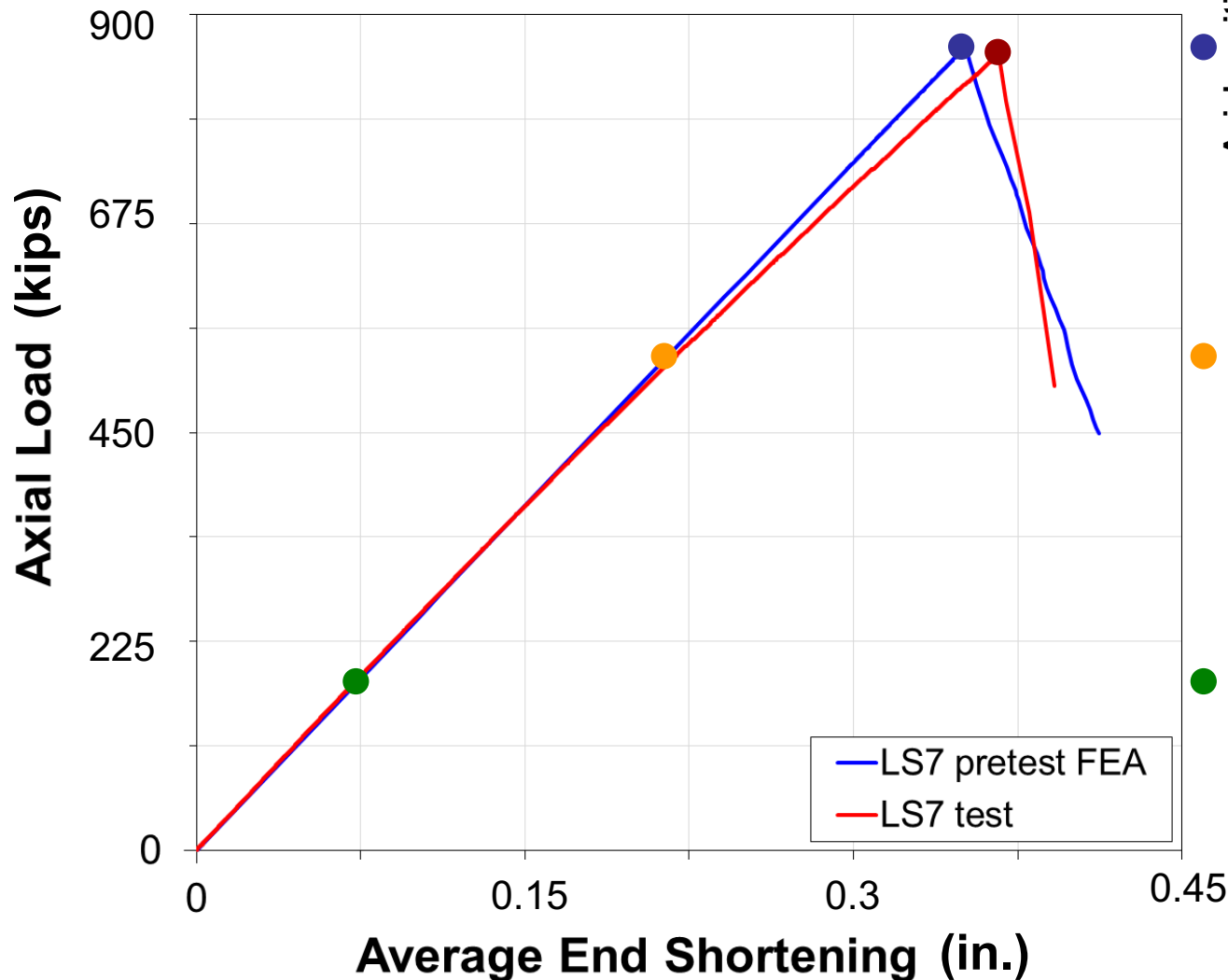
Subcritical Compression



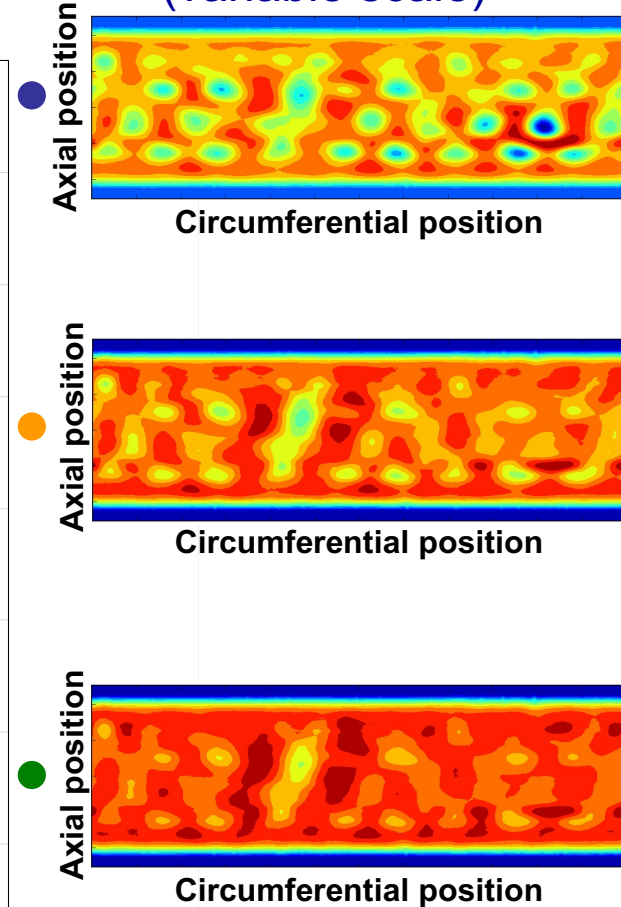
- **Significant difference in axial stiffness**
 - Measured at end rings
 - Manufacturing demo—uncertain material properties
 - Ply extensional stiffnesses increased by 8.7%



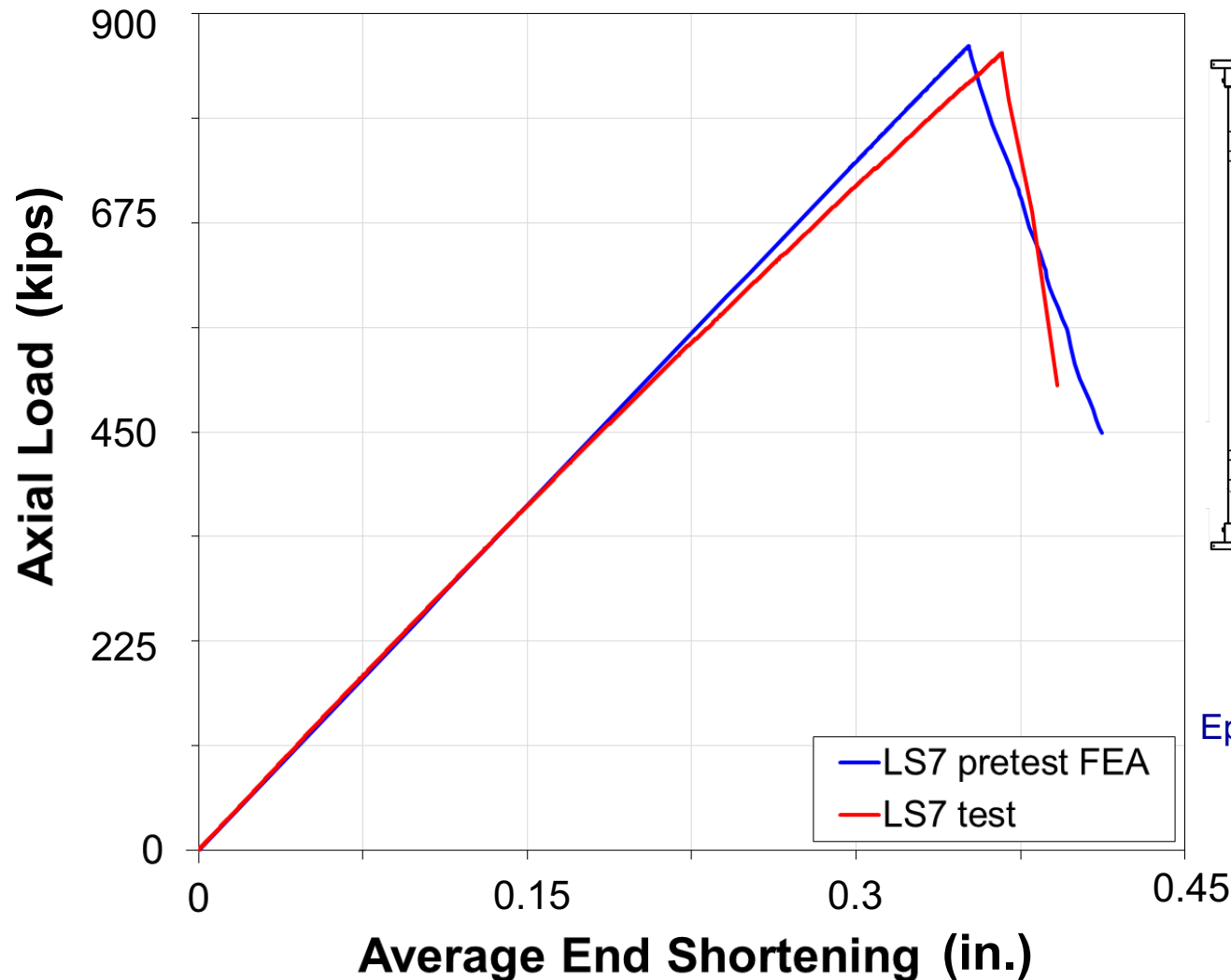
Test and Analysis Correlation: End Shortening



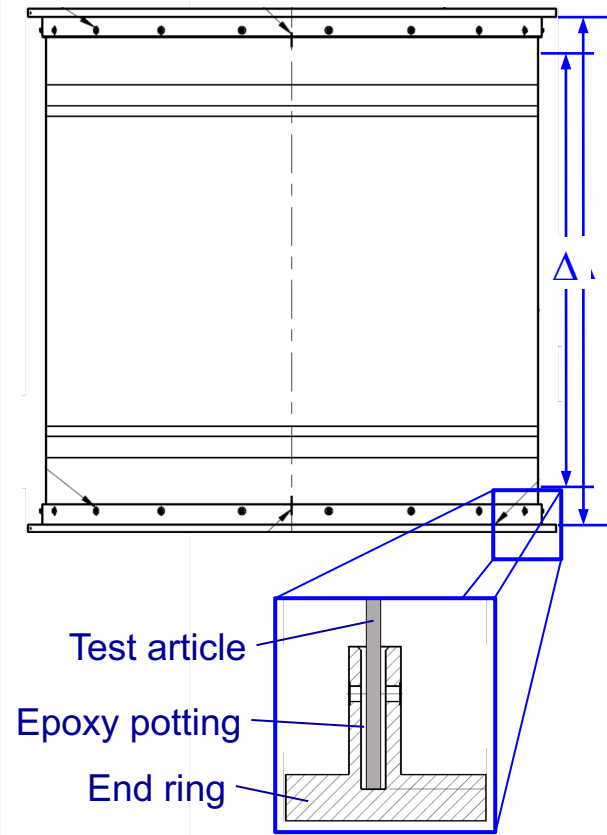
Predicted radial deformation
(variable scale)



Test and Analysis Correlation: End Shortening

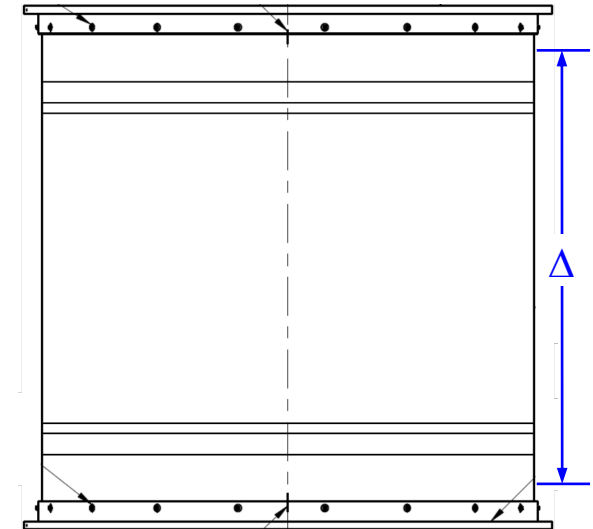
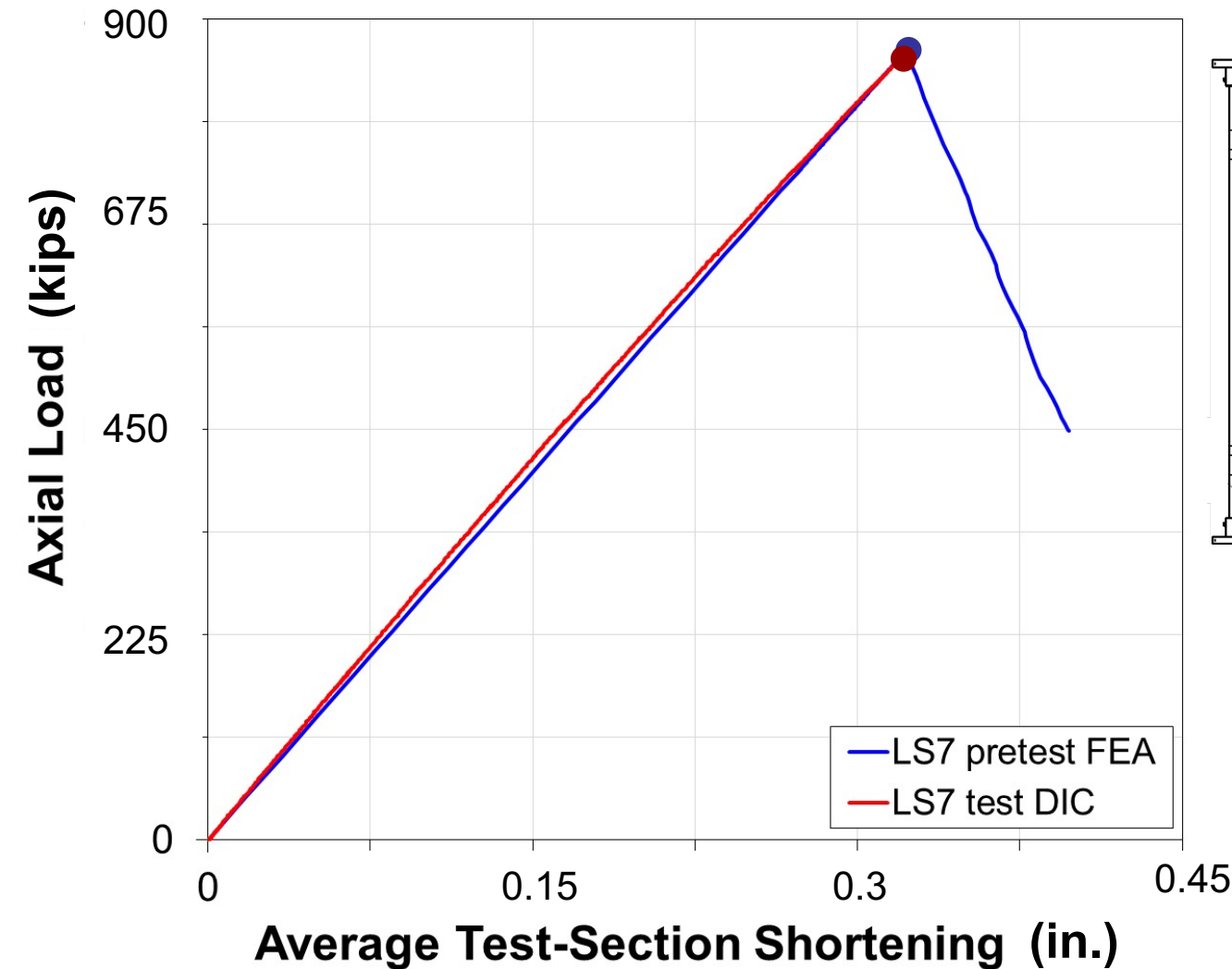


Slipping in end rings occurred





Test and Analysis Correlation: Test-Section End Shortening



- **Material nonlinearity**

- Though often ignored in analysis, it is known that fiber-reinforced composites can show material nonlinearity

- **Measured stiffness**

- Sectioned barrel and performed edgewise compression testing
- Ply thickness 9.2% greater than assumed
- Nonlinear ply stiffnesses calculated

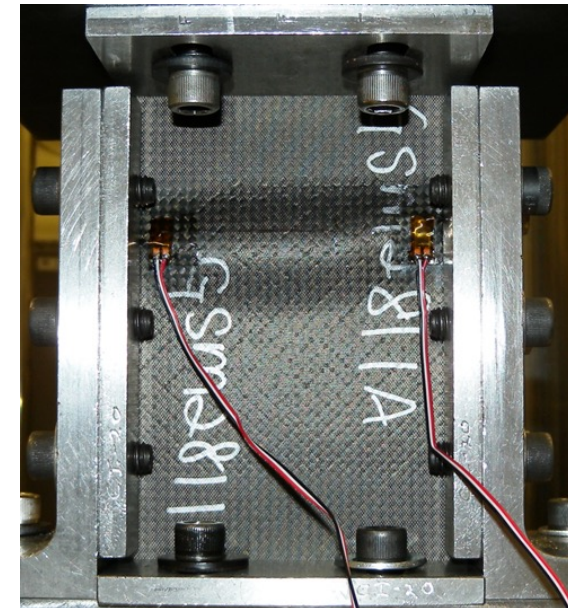
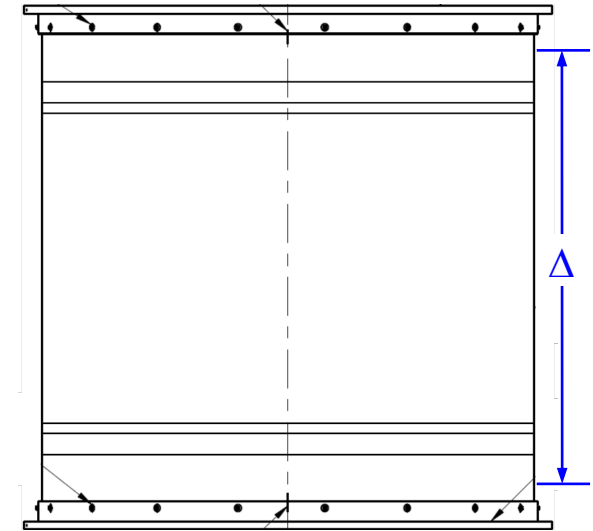
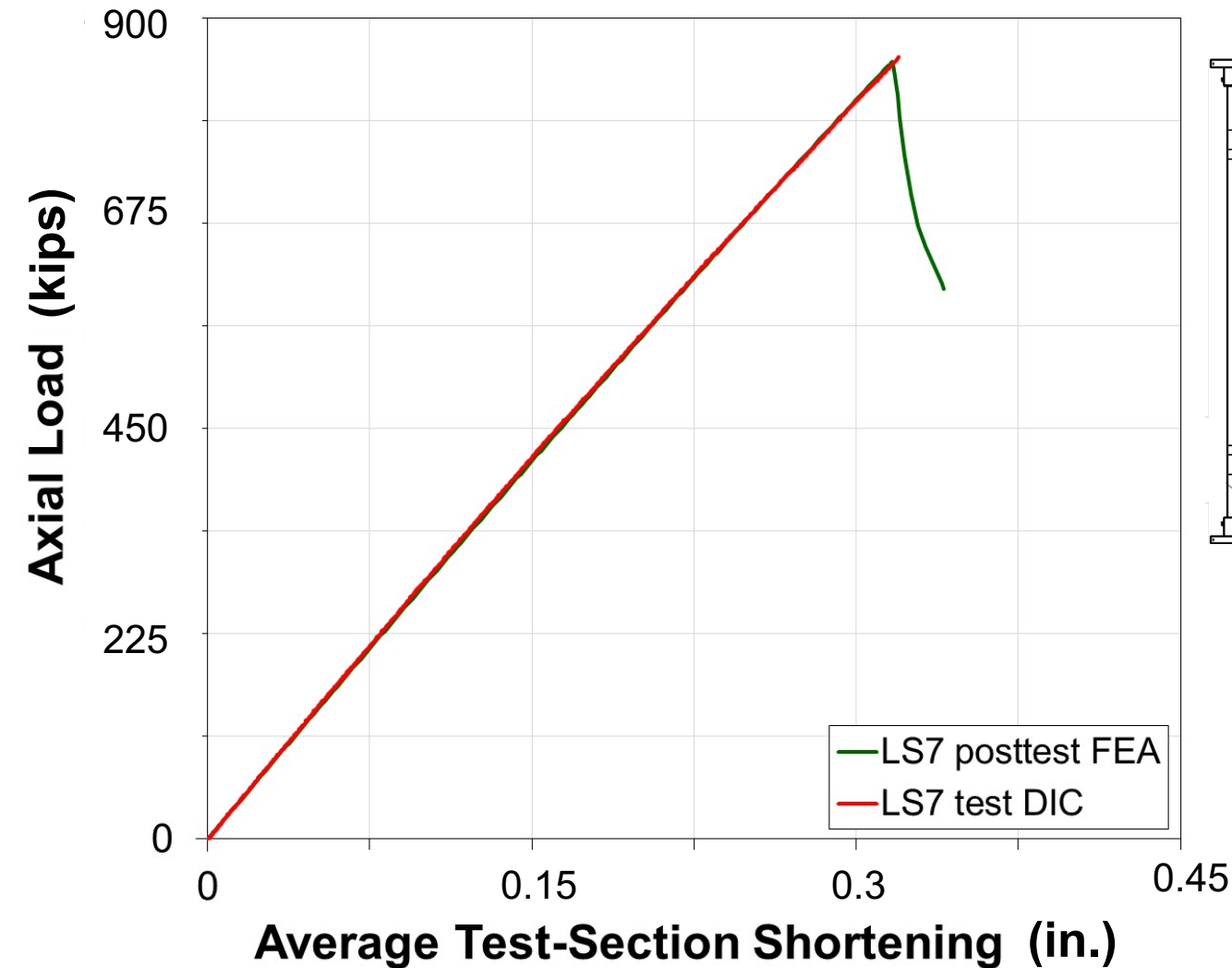


Photo: NIAR



Test and Analysis Correlation: Test-Section End Shortening

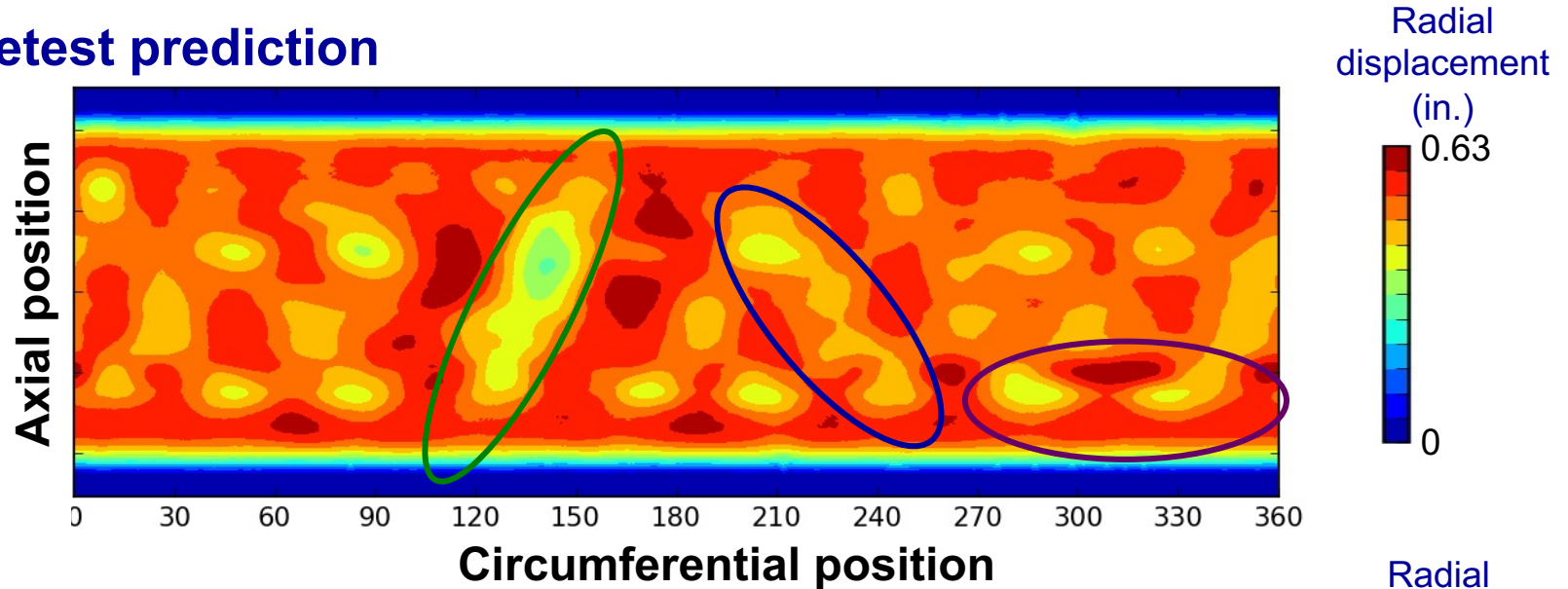




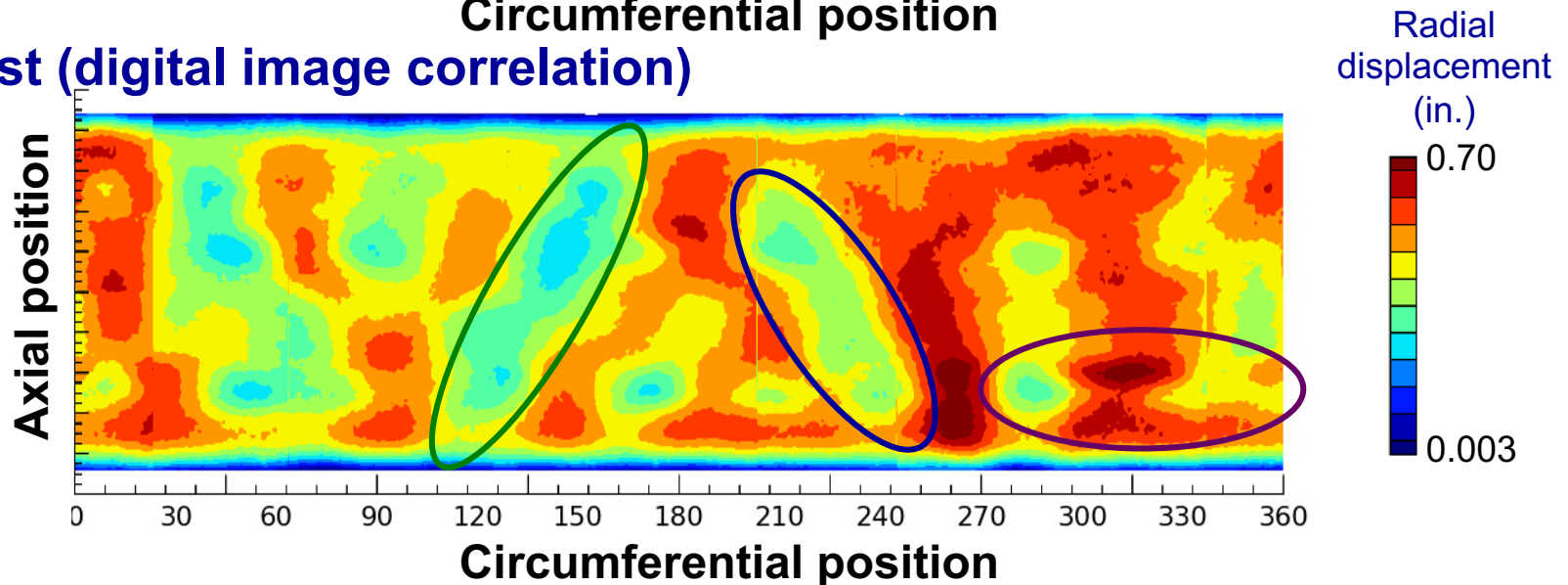
Test and Analysis Correlation: Radial Deformation, 458 kips



Pretest prediction

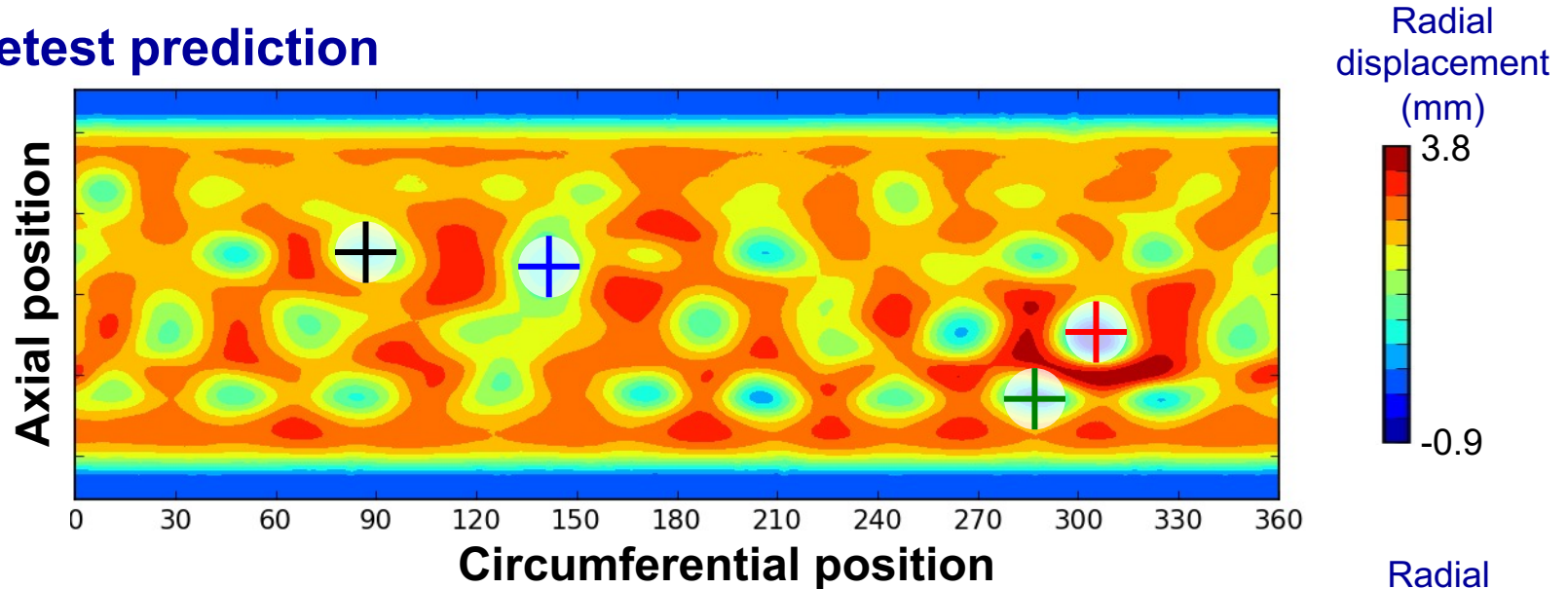


Test (digital image correlation)

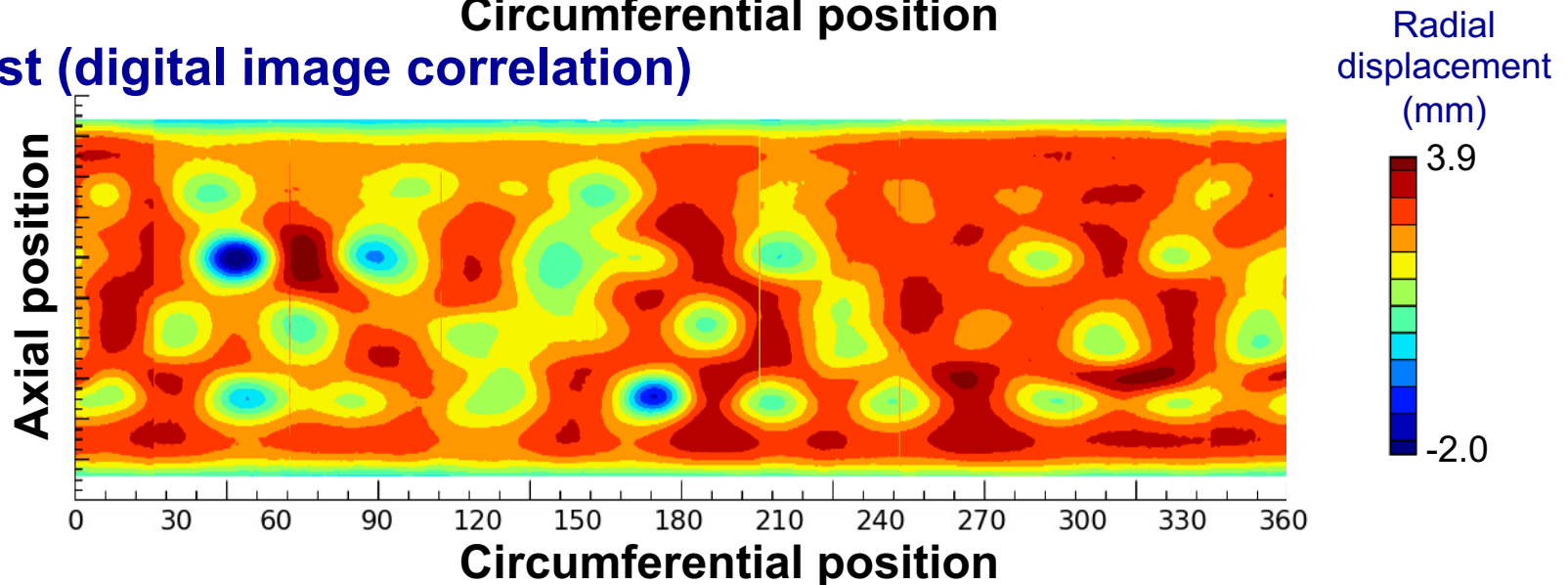


Test and Analysis Correlation: Radial Deformation, at Failure

Pretest prediction

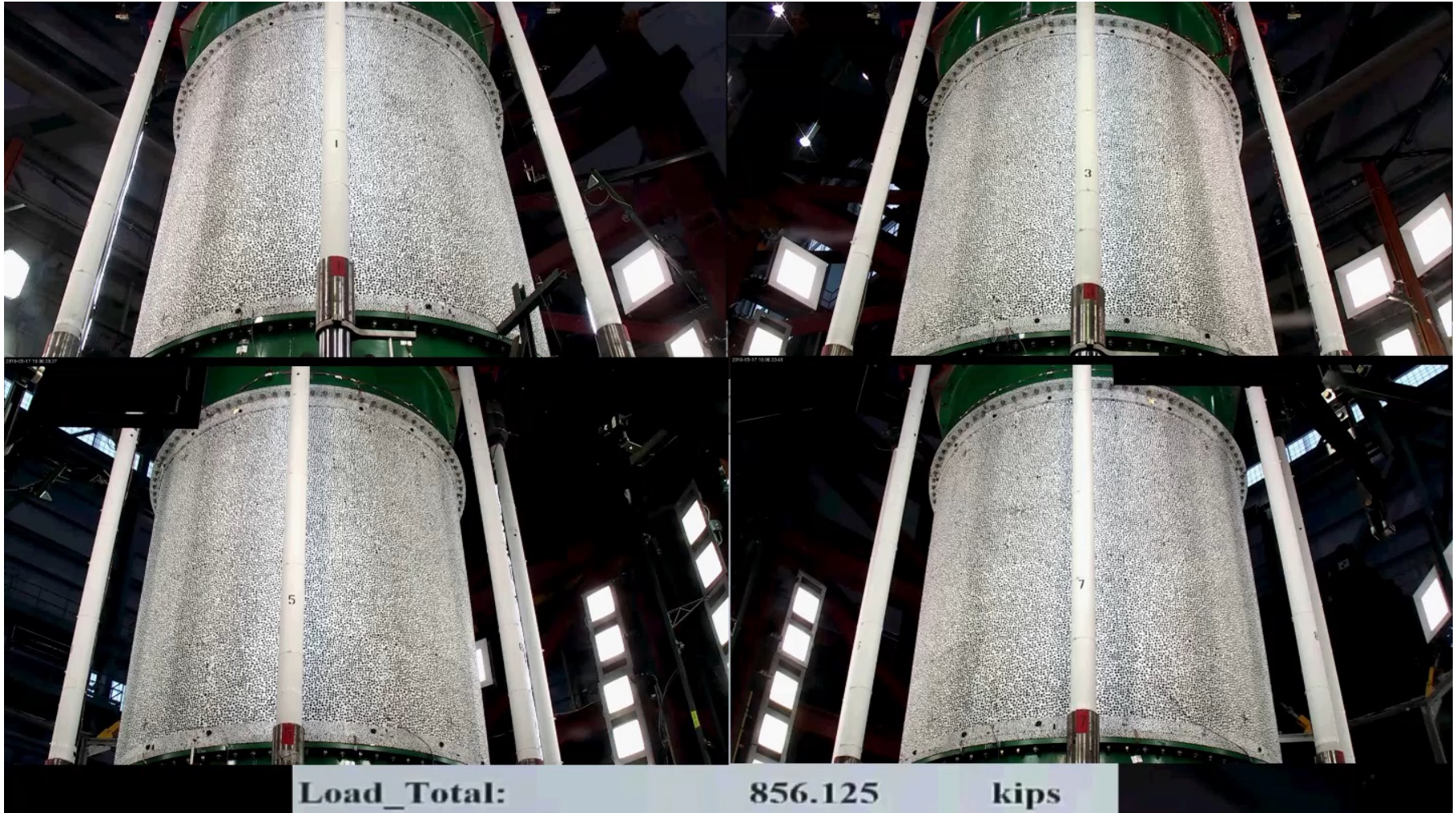


Test (digital image correlation)





Failure Event: Standard-Rate Video





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



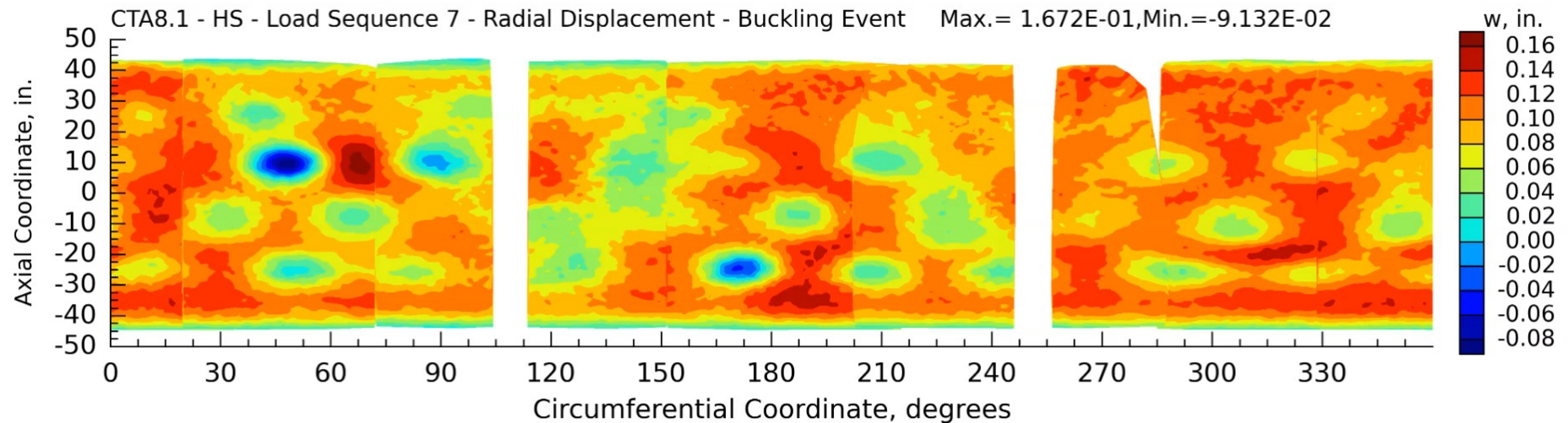


Failure Event:

High-Speed Digital Image Correlation



Radial deformation (~10,000 fps)





Concluding Remarks

- **High-fidelity models can represent physical response very well, but need good understanding of test article and test conditions**
 - **SBKF predicted the buckling load within 1 %, 1.5%, and 7% of three 8-ft diameter test articles**
- **Understand the analysis tools advantages and limitations**



Acknowledgements

- **Dr. Marc Schultz, LaRC**
- **Dr. Mark Hilburger, LaRC**
- **Clint Cragg, NESC**
- **Shell Buckling Knockdown
Factor Project Team**



Questions?

