

Large-Scale Sandwich Composite Cylinder Buckling: Test and Analysis

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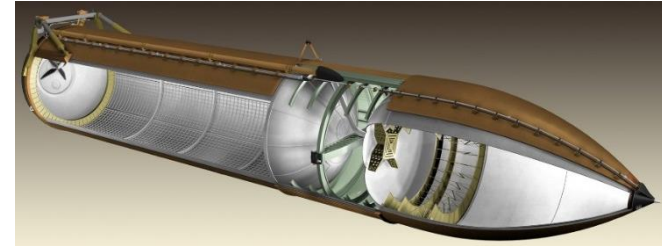
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NASA Launch-Vehicle Shell Structures

- **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 in the Space Launch System (SLS) vehicle**
 - Potential gains (mass, thermal, cost, etc.)
 - Most commonly have sandwich construction
 - Most often considered for dry structures

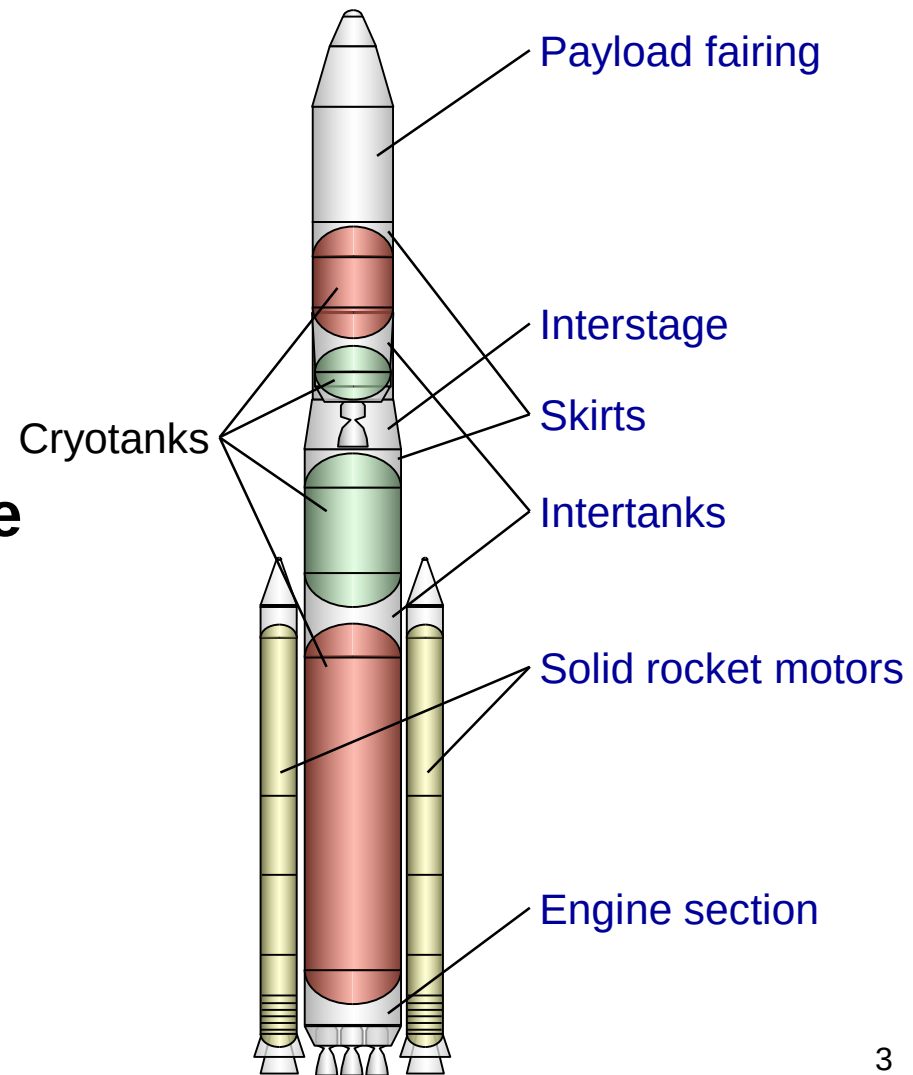


Launch-Vehicle Shell Structures

- **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

Wet structure

Dry structure

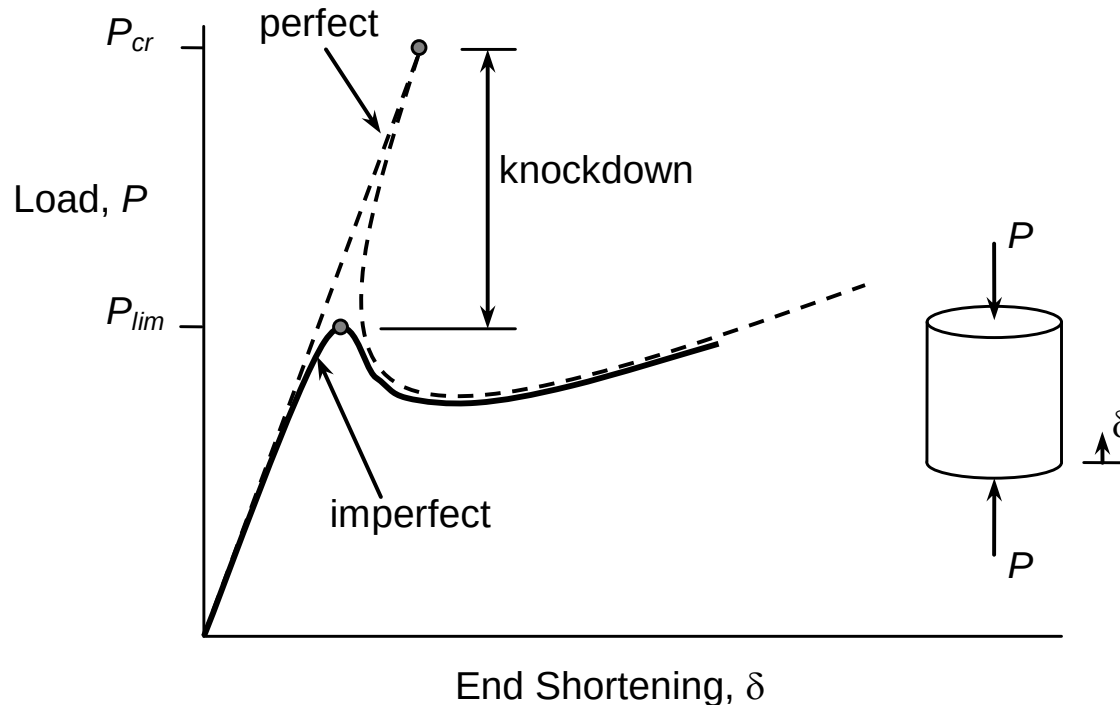




Empirical Shell-Buckling Design Approach



- 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 (SBKF)



- **NASA Engineering and Safety Center (NESC) assessment**
 - 2007 – Present
- **Objective**
 - To develop and validate new analysis-based shell buckling knockdown factors and design guidelines for stability-critical launch-vehicle structures
 - Metallic cryotank and dry structures
 - Composite dry structures
- **Expected outcome**
 - Reduce structural mass and mass-growth potential
 - Enable new structural configurations
 - Increase buckling knockdown factor fidelity to improve design trades and reduce design cycle time/redesigns



Shell Buckling Knockdown Factor Project (SBKF)



- **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

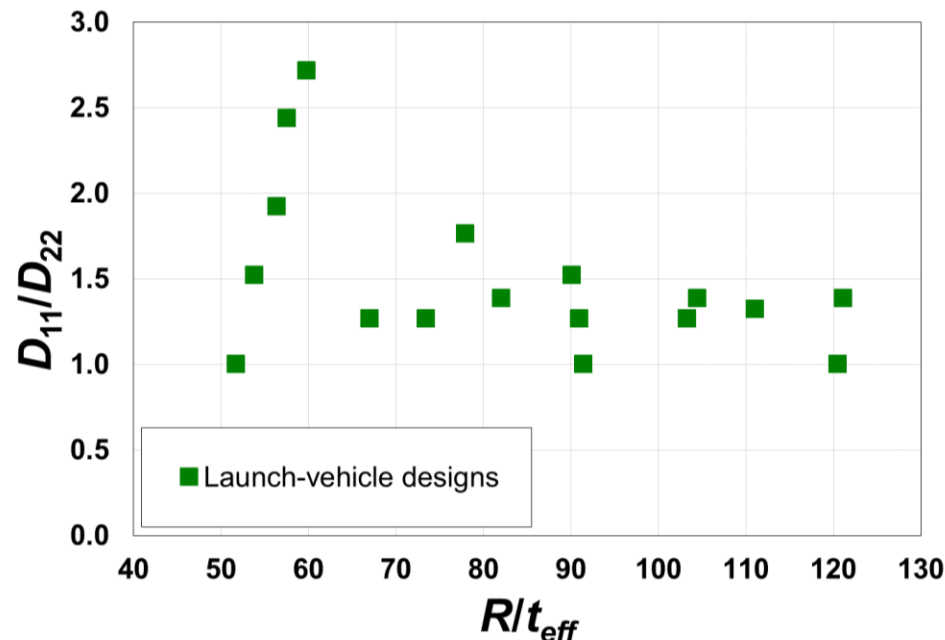


Subscale Cylinder Testing (2.4-m diameter)



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

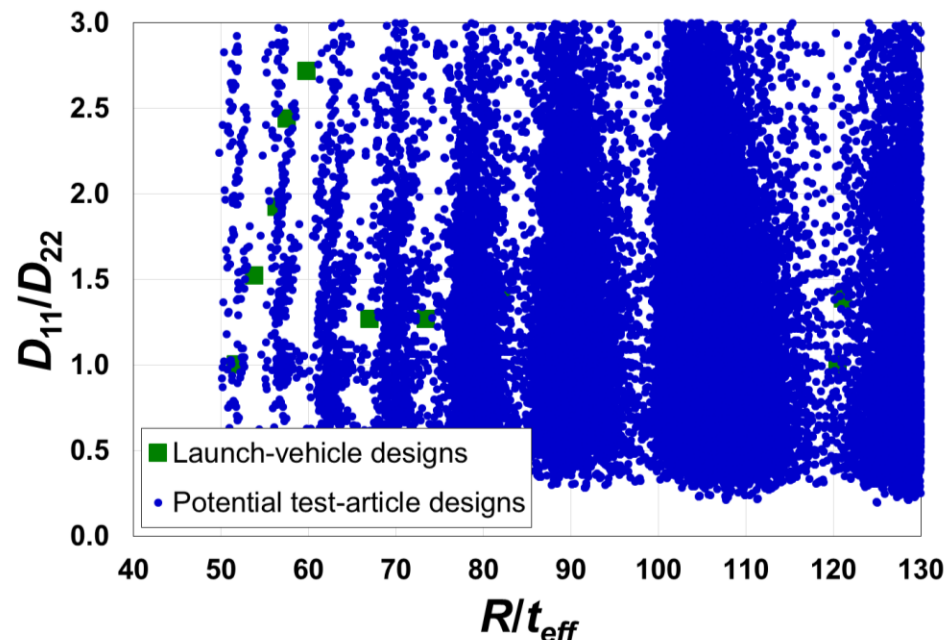
- Calculate design-space parameters for launch-vehicle components



Subscale Cylinder Testing (2.4-m diameter)

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

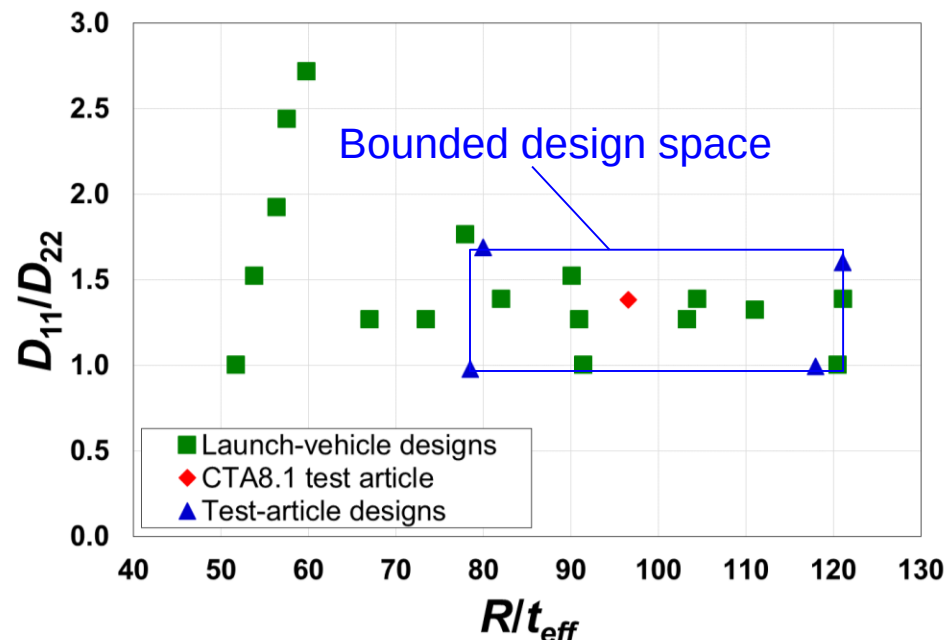
- Calculate design-space parameters for launch-vehicle components
- Generate possible 2.4-m-diameter subscale designs
 - Criteria: buckling critical, failure load, etc.
 - Variables: number of plies, ply angle, core thickness



Subscale Cylinder Testing (2.4-m 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 2.4-m-diameter subscale designs
- Select subscale designs that span the design space
 - Five test article designs selected as minimum number to validate analysis methods



First Large-Scale Test Article

- **Construction**

- 8-ft-dia. honeycomb-core sandwich composite cylinder
- Single piece (unsegmented)
 - 6.4-mm core, 7-ply facesheets
 - IM7/MTM45 facesheets
 - Korex core

- **Fabrication**

- Built by Northrop Grumman under nonreimbursable agreement
- Manufacturing development unit
- Out-of-autoclave
 - Poorly characterized material properties





Nondestructive Inspection (NDI) and Repairs



- **Flash thermography**

- Indication: several void-like indications in bond between padups and acreage
- Repair: padups replaced

- **Vacuum shearography**

- Indication: 250-mm x 380-mm delamination in bond between padup and acreage
- Repair: typical scarf repair



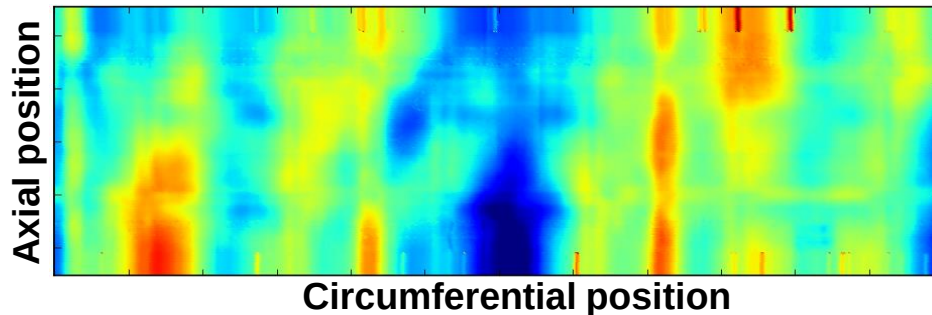
- **Visual inspection**

- Indication: dry fiber on in a number of locations on FWD end of IML acreage
- Repair: room-temperature-cure adhesive applied to affected region

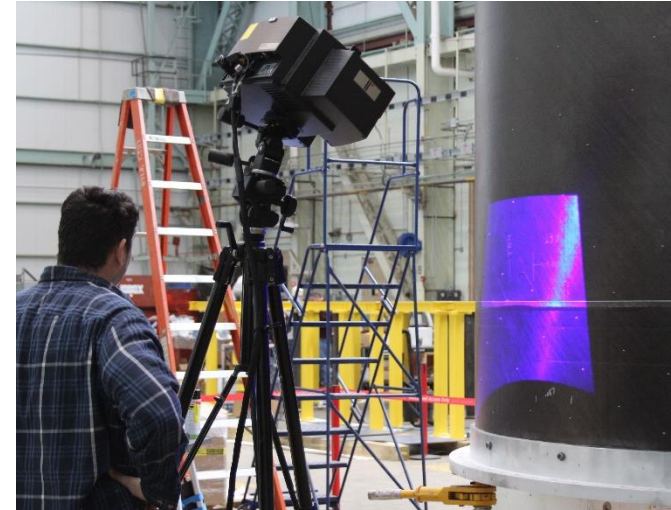
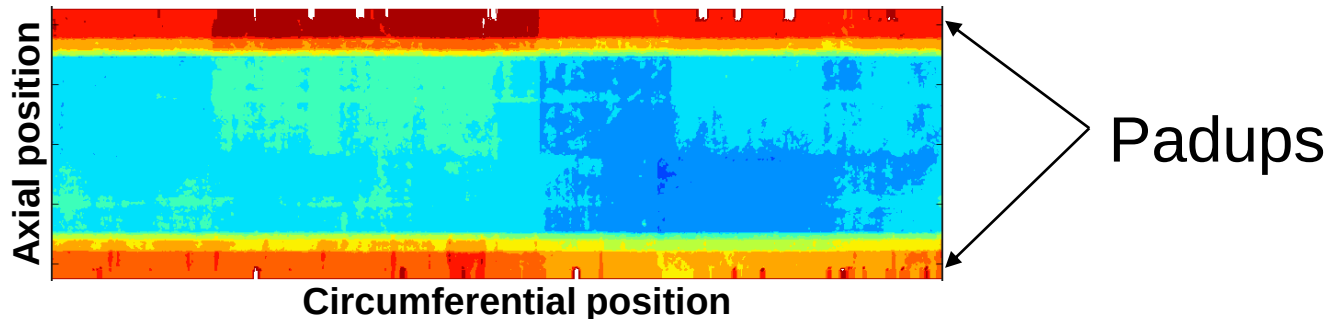
- **Structured light geometry measurement**

Structured Light Scanning

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

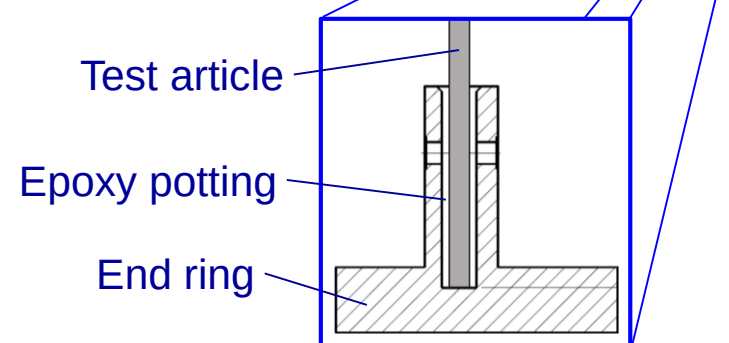
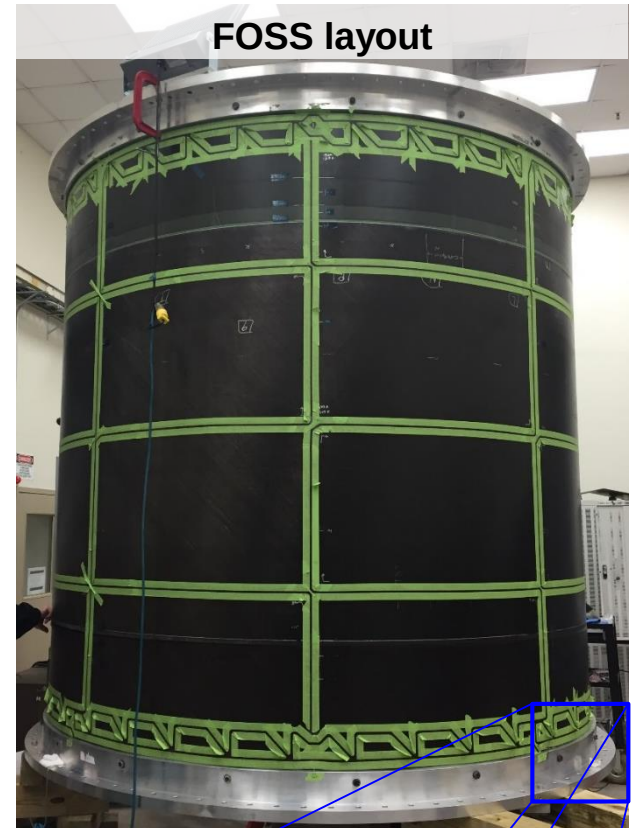


- Thickness variation

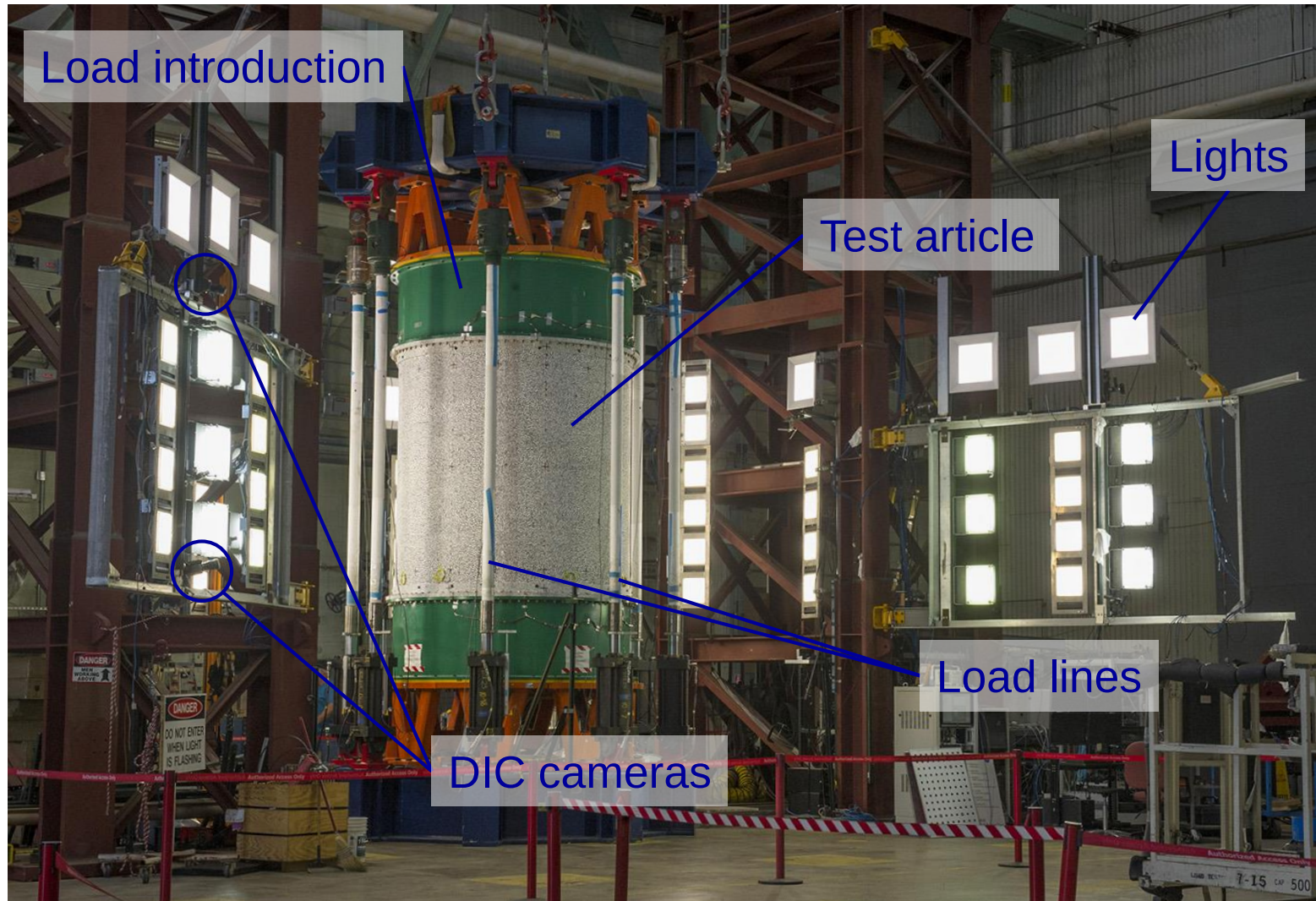


Testing and Instrumentation

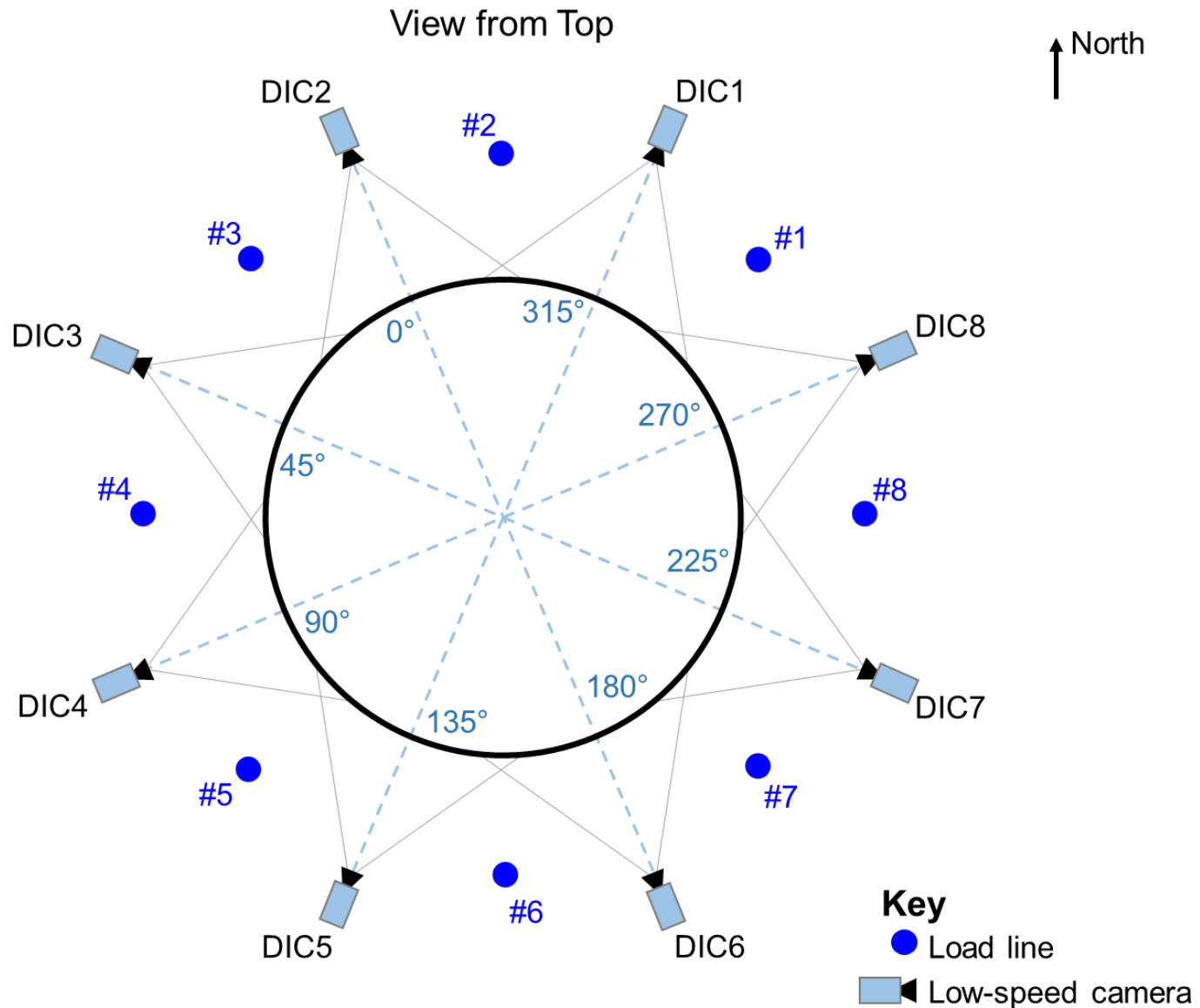
- **Test conditions**
 - Subcritical axial compression and combined loading cases
 - **Axial compression** to failure
- **Instrumentation**
 - 300 electrical strain and displacement sensors
 - Digital image correlation (DIC)
 - Low speed and high speed
 - 16,000 fiber-optic strain sensors (FOSS)



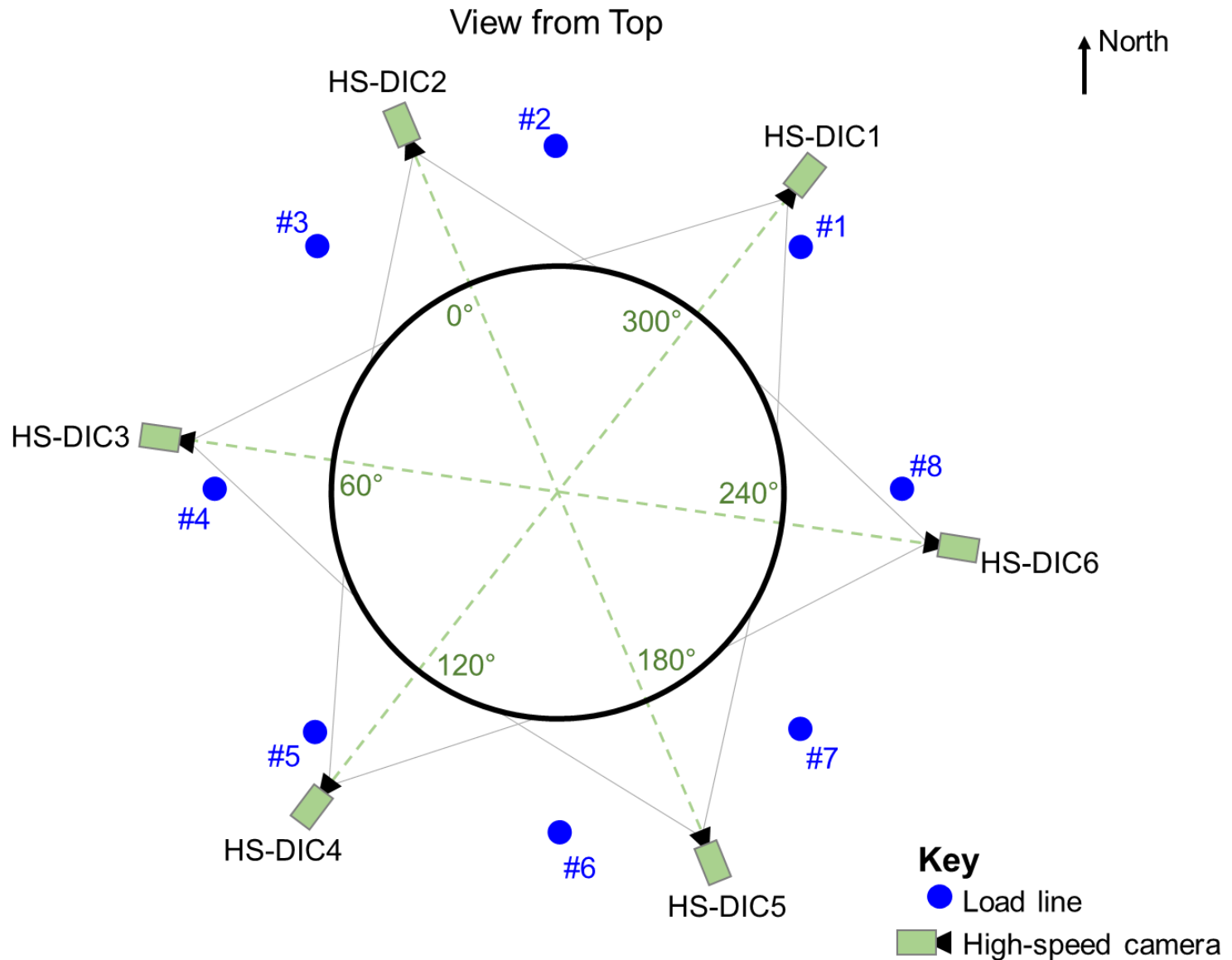
Test Setup



Low-Speed Digital Image Correlation

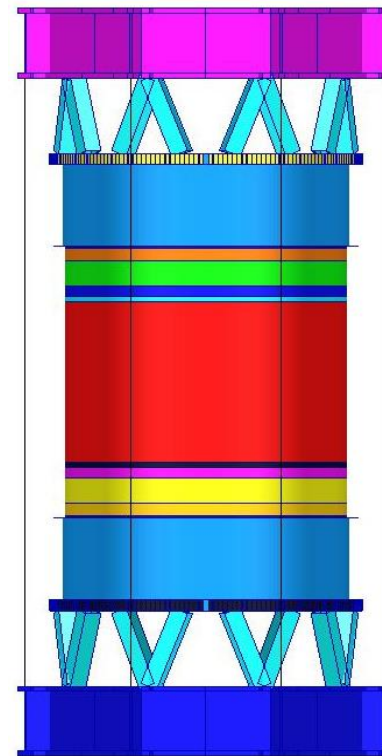


High-Speed Digital Image Correlation

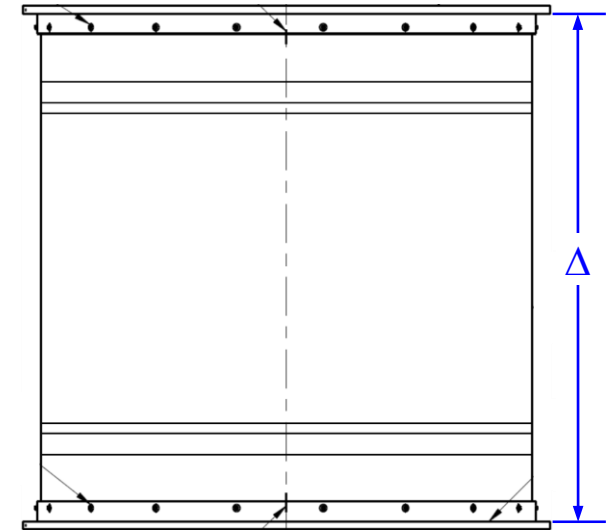
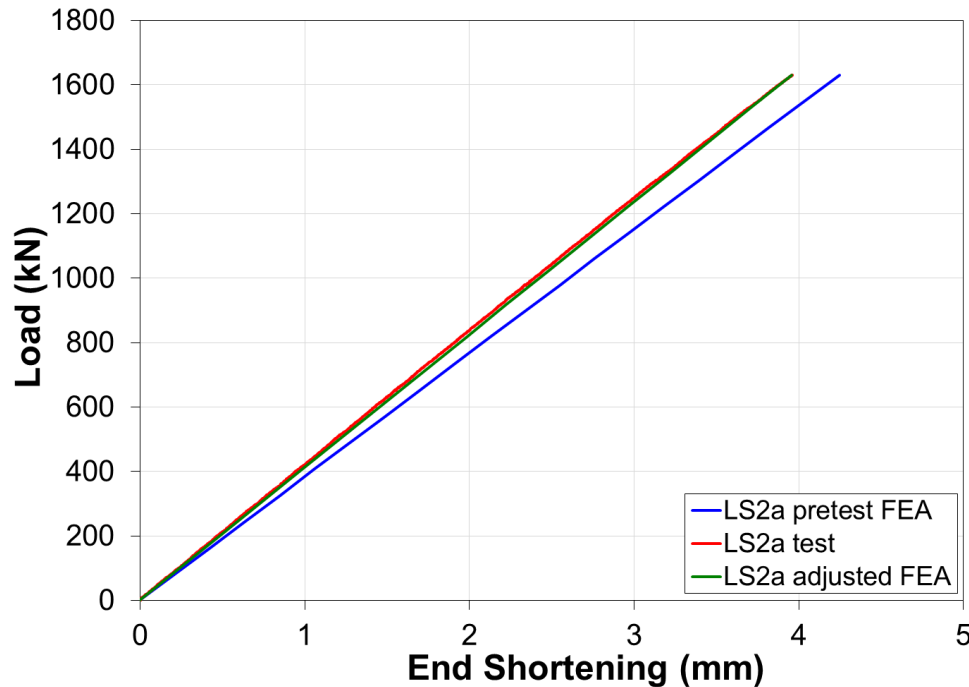


Analysis Approach

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

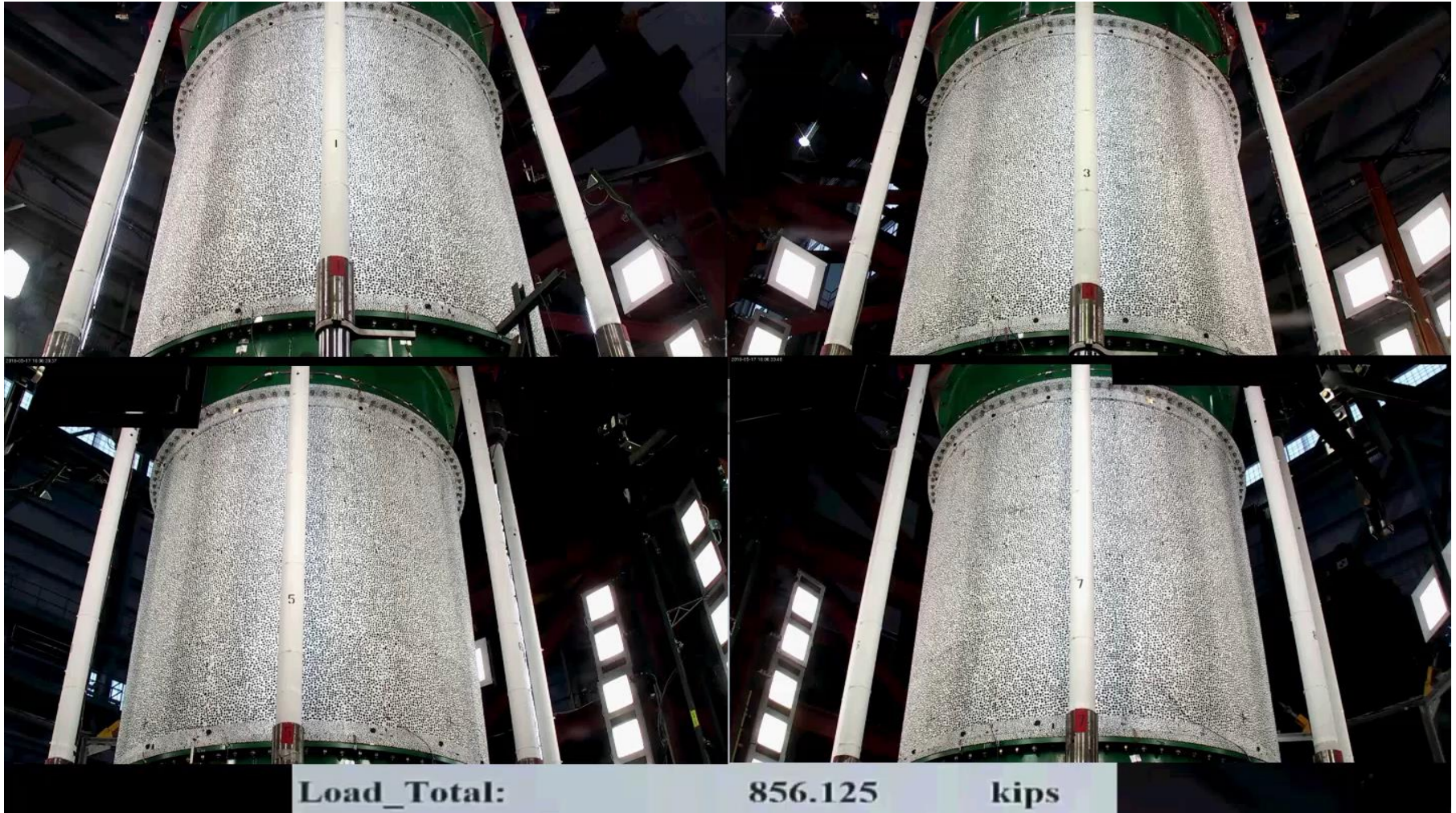


Test-Analysis Correlation: Subcritical Compression



- **Significant difference in axial stiffness**
 - Measured at end rings
 - Manufacturing demo—uncertain material properties
 - Ply stiffnesses modified
- **Good agreement with radial deformations**

Real-Time Video

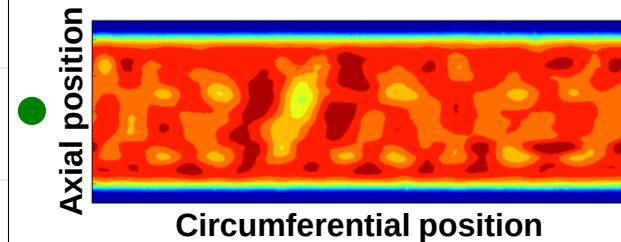
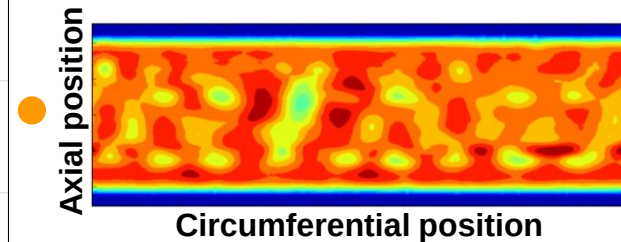
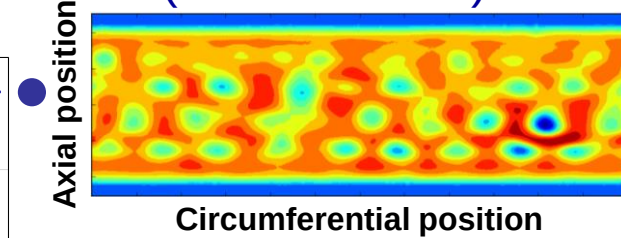
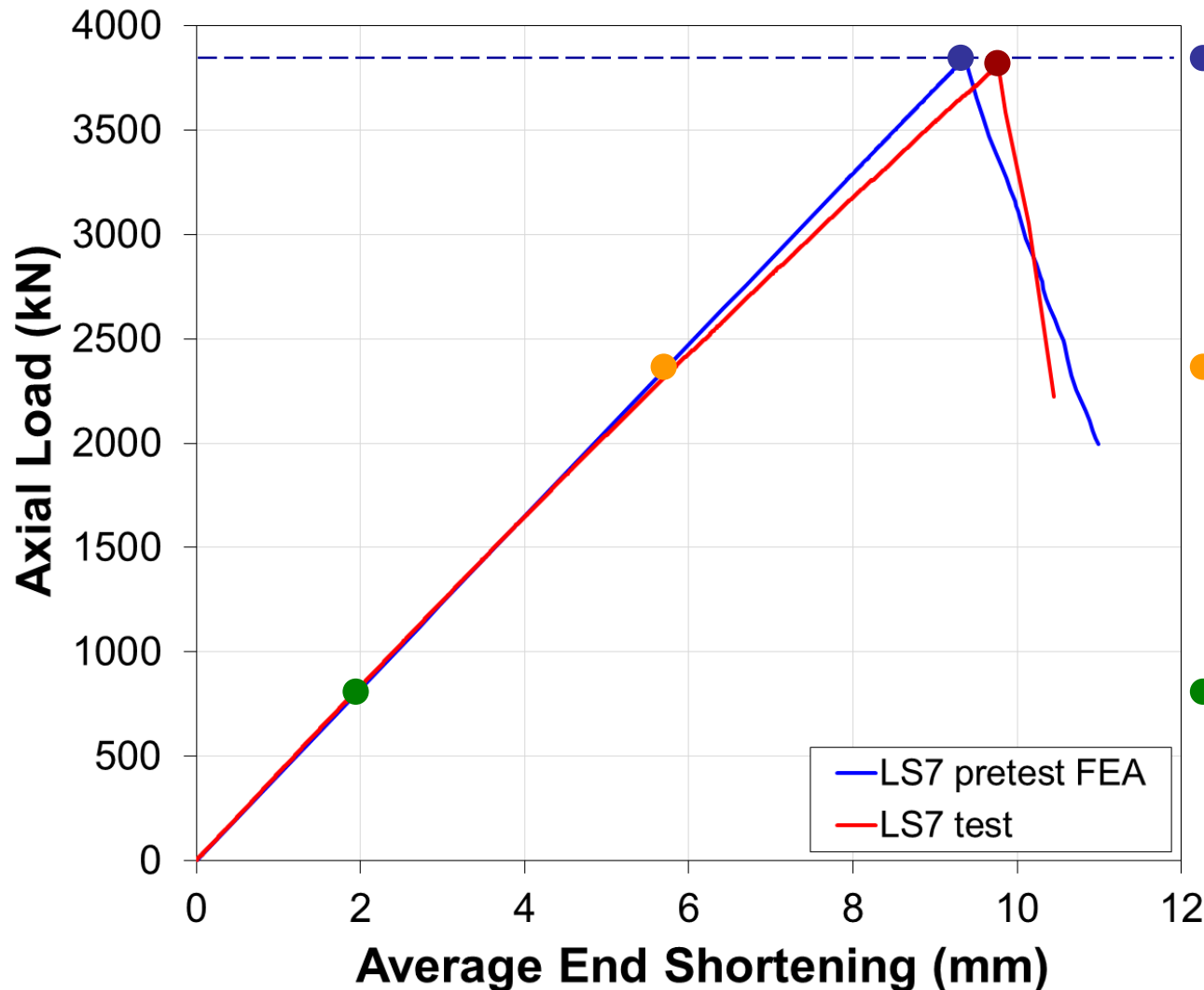


High-Speed Video ~10,000 fps

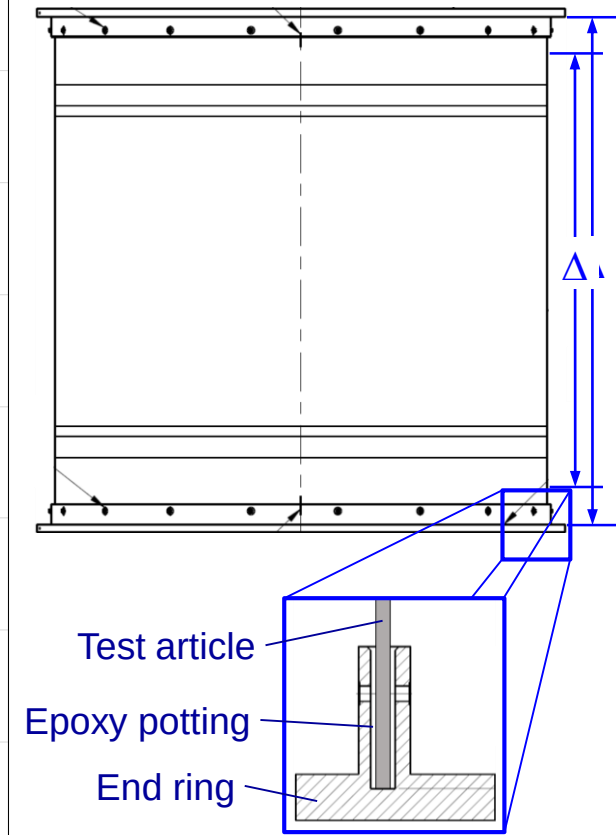
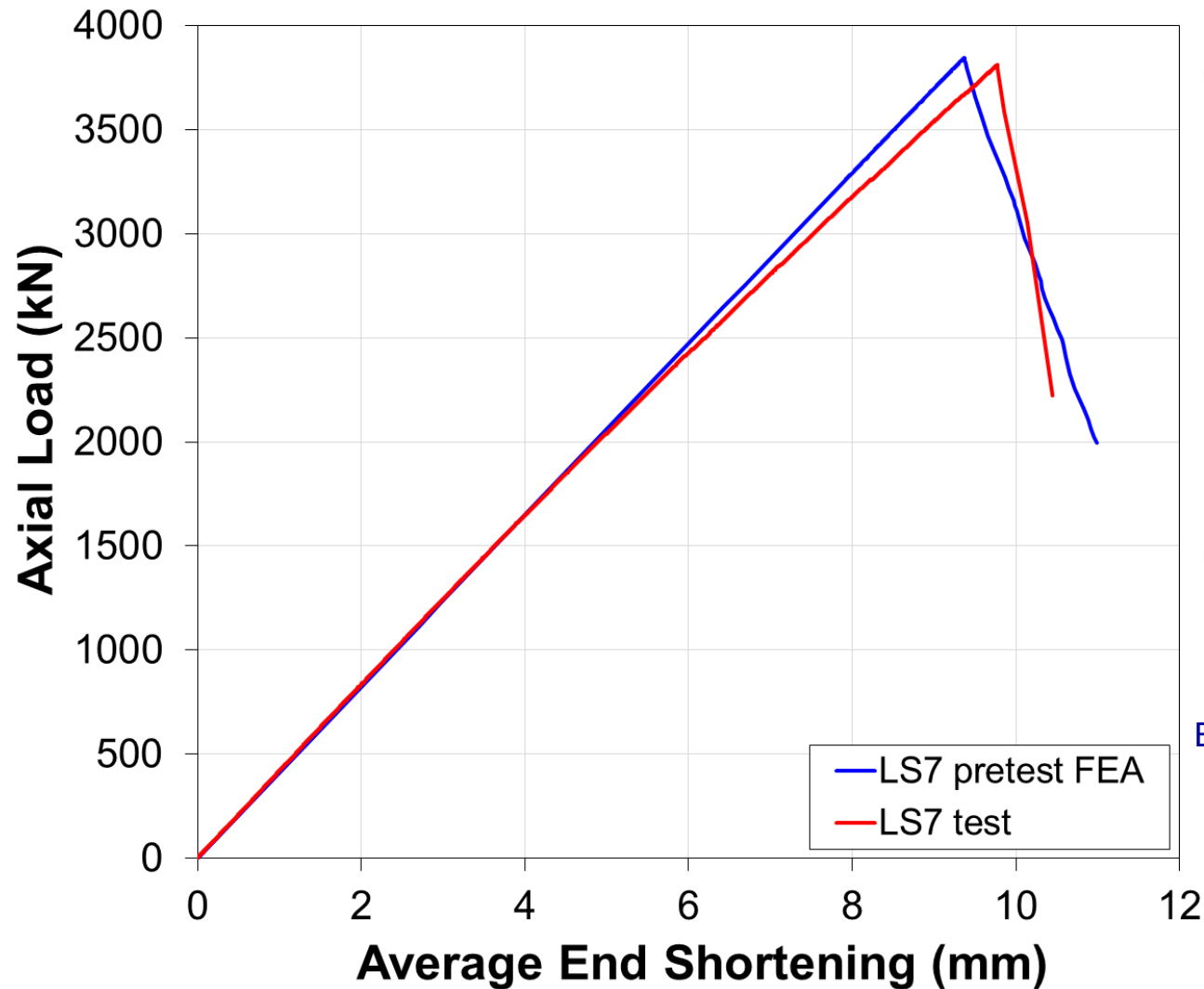


Test-Analysis Correlation: End Shortening

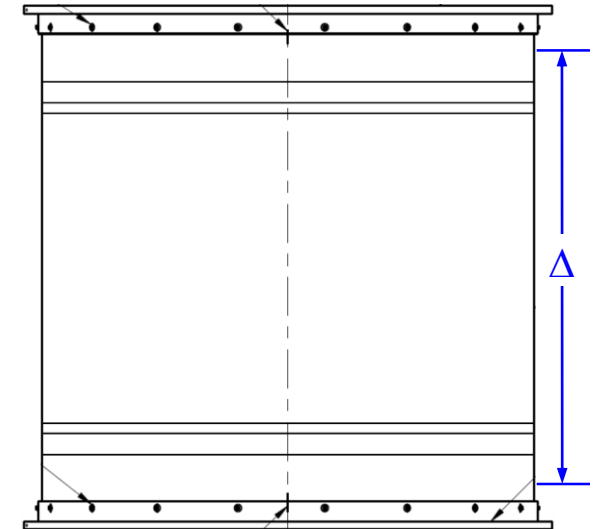
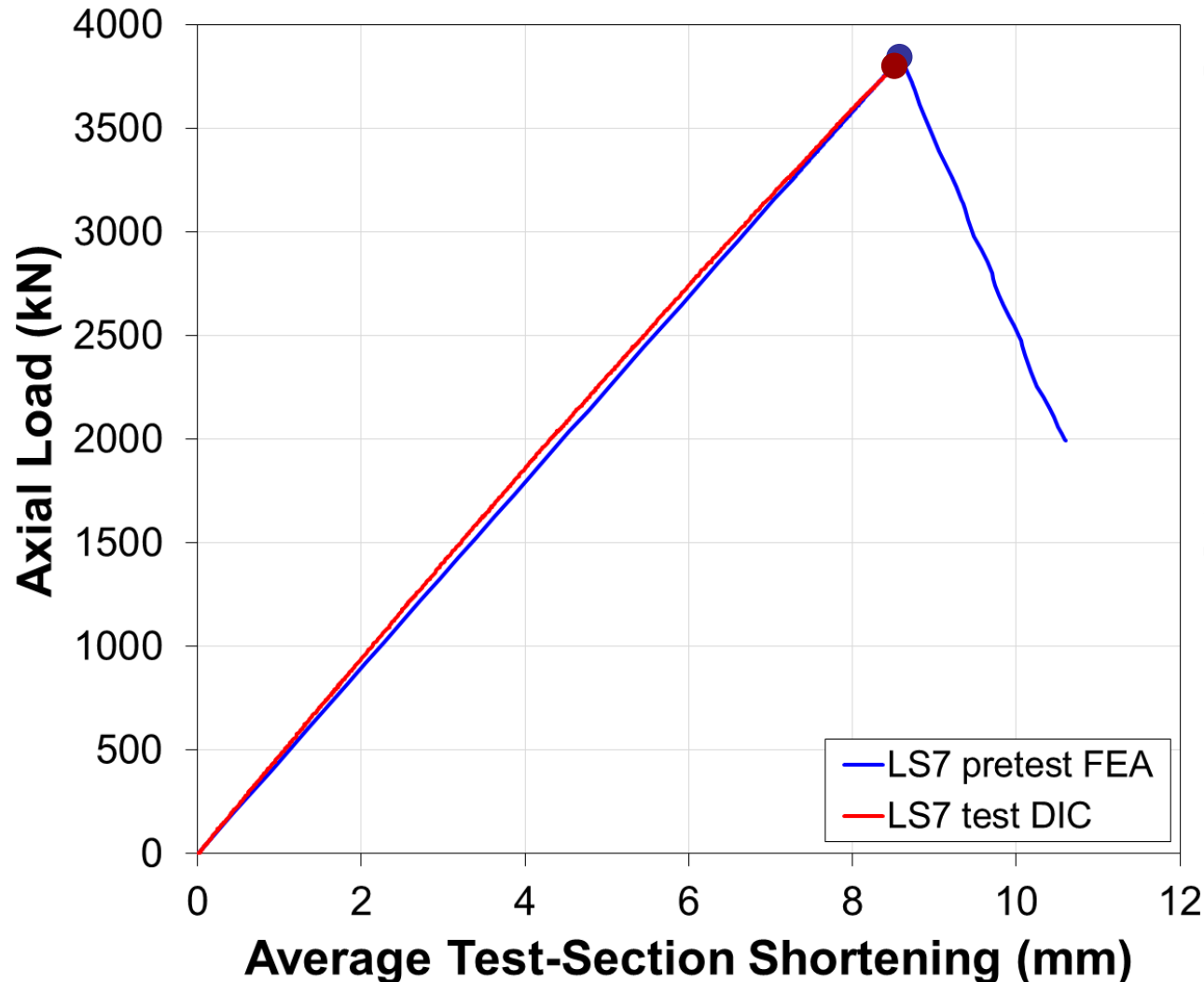
Predicted radial deformation
(variable scale)



Test-Analysis Correlation: End Shortening



Test-Analysis Correlation: Test-Section End Shortening

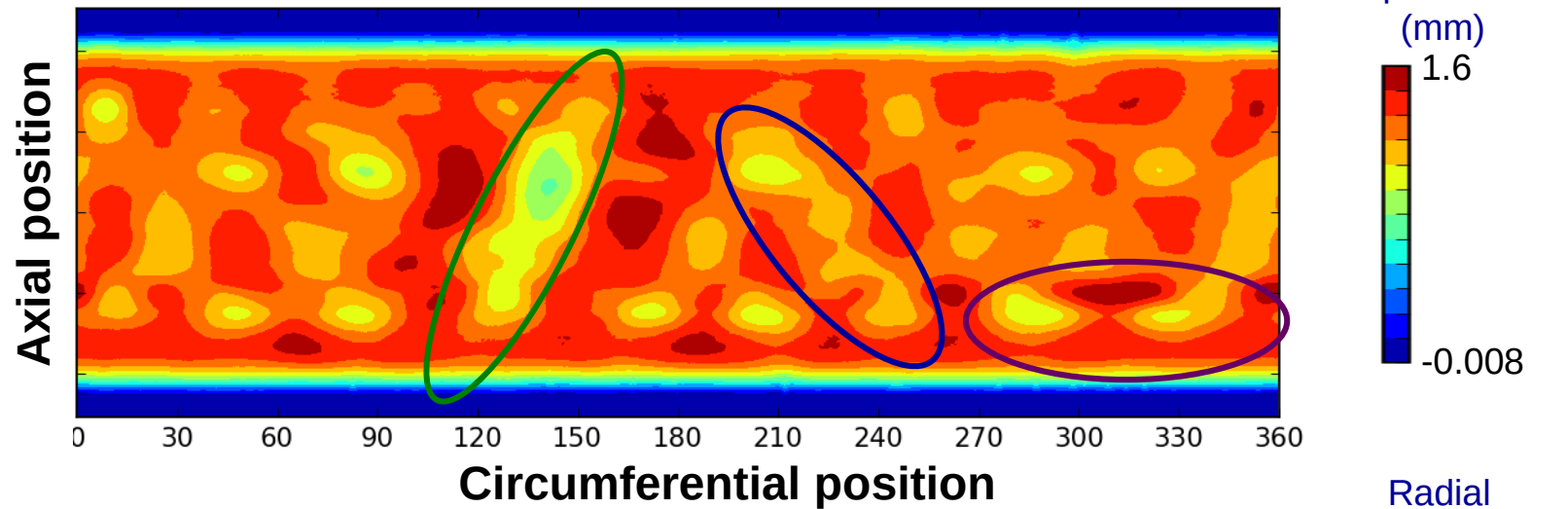




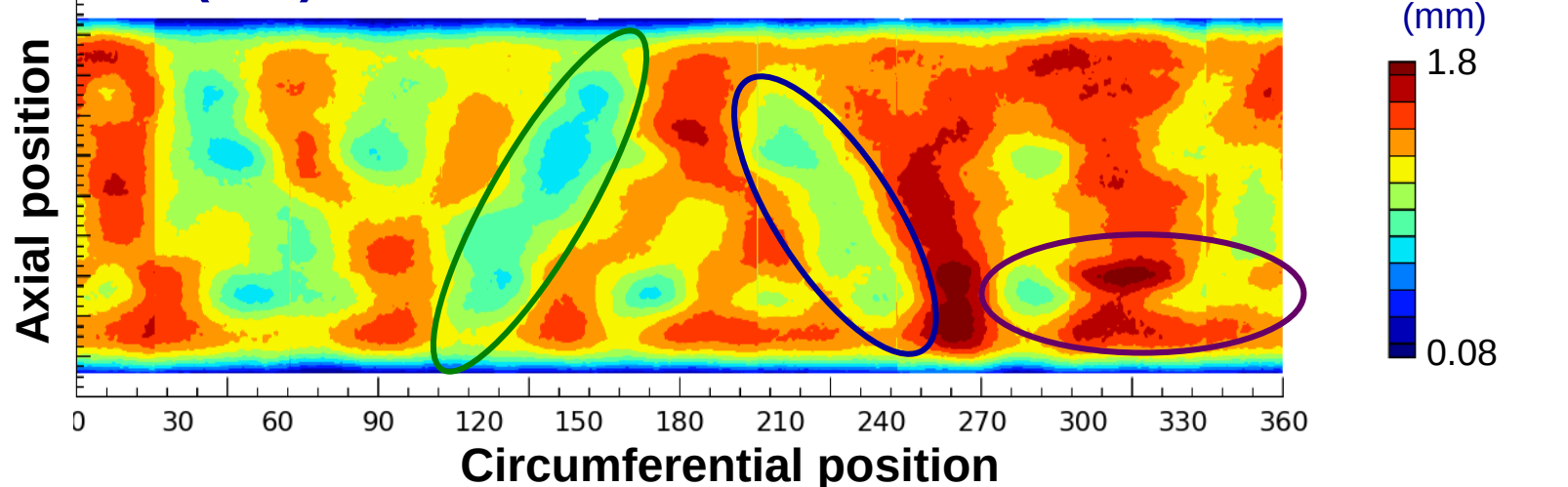
Test-Analysis Correlation: Radial Deformation, 458.2 kips



Pretest prediction



Test (DIC)

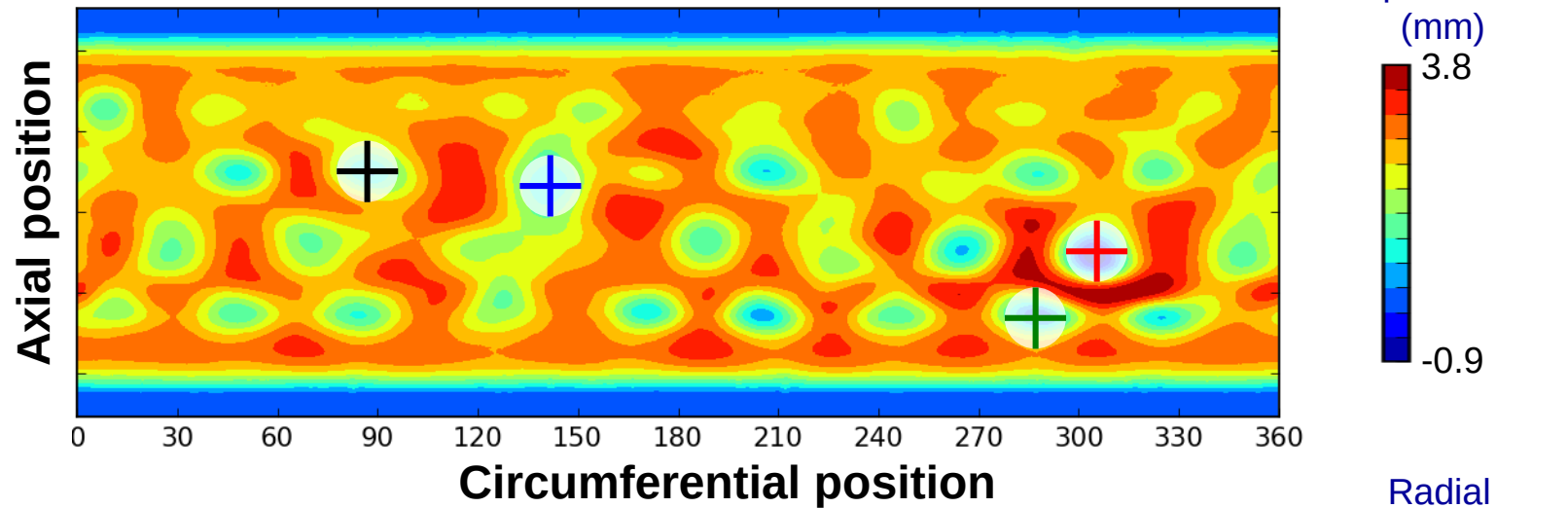




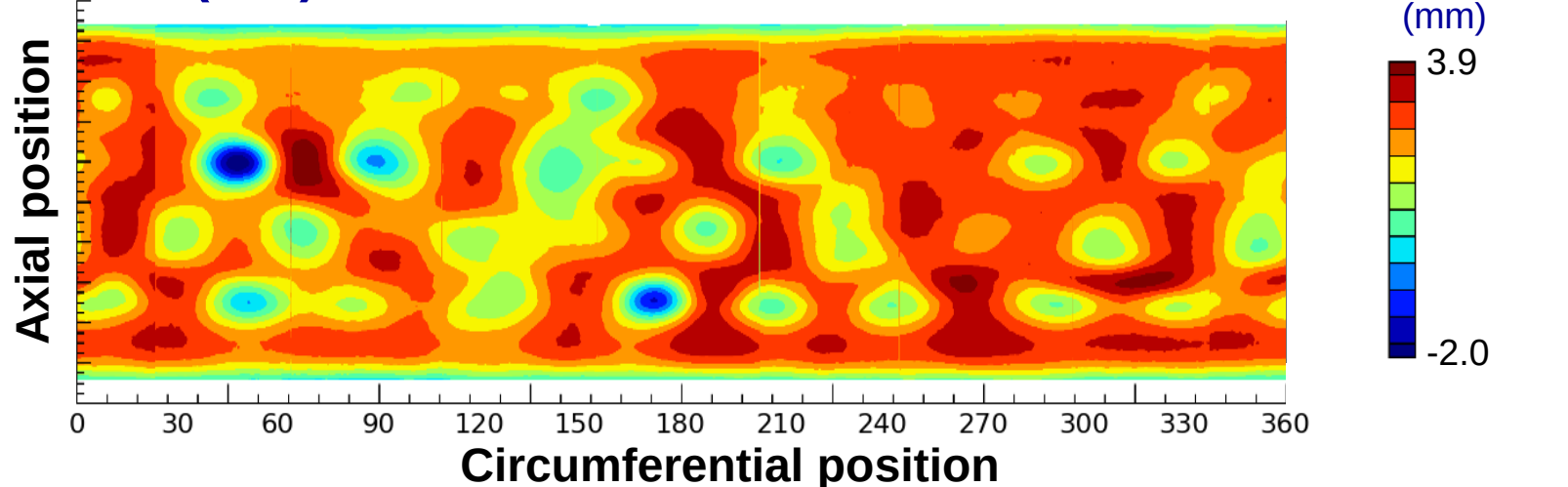
Test-Analysis Correlation: Radial Deformation, 458.2 kips



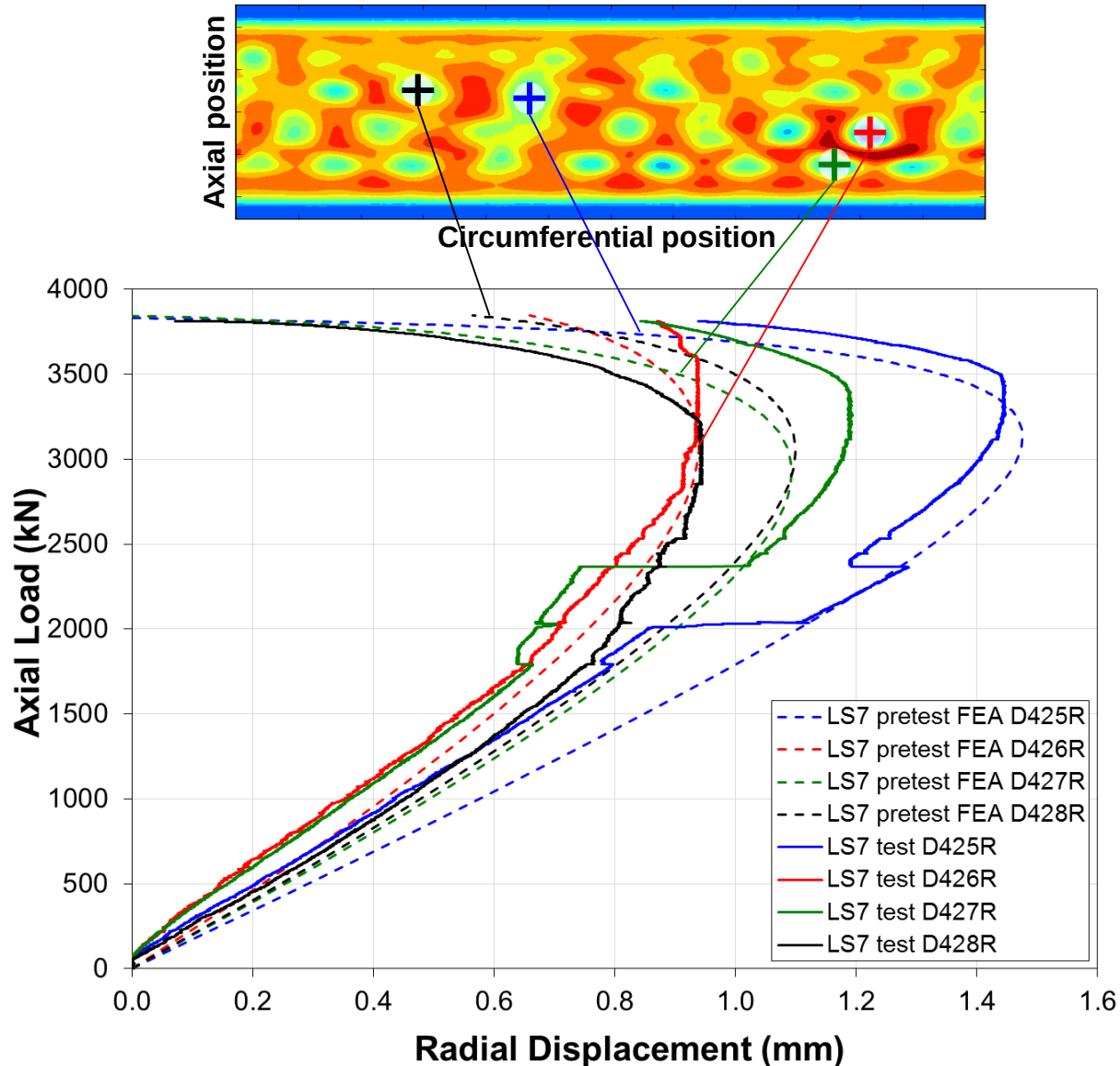
Pretest prediction



Test (DIC)

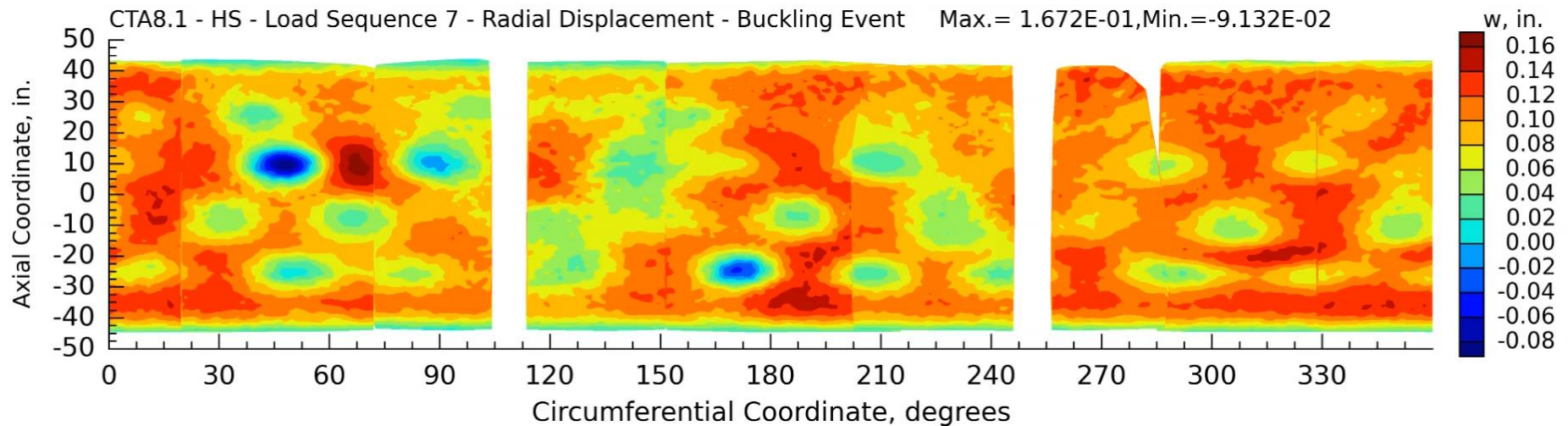


Test-Analysis Correlation: Radial Displacement



High-Speed DIC: Radial Deformation

Images taken at ~10,000 fps



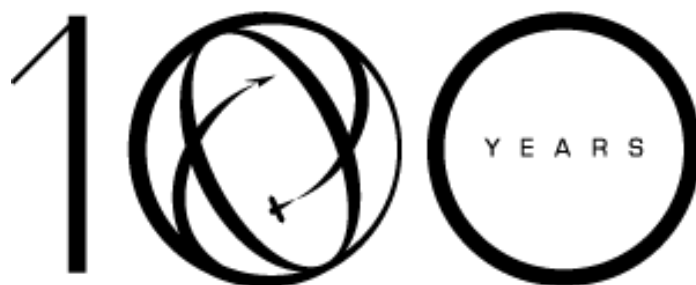


Concluding Remarks

- Sandwich composite shell structures are increasingly being considered for launch-vehicle primary structures
- NASA is developing new analysis-based buckling design guidelines for sandwich composite shell structures
- Large-scale test series for analysis validation
- First large-scale composite shell test recently completed with excellent agreement between test and analysis
 - Predicted and measured failure load and end shortening at failure both within 1%



C E L E B R A T I N G

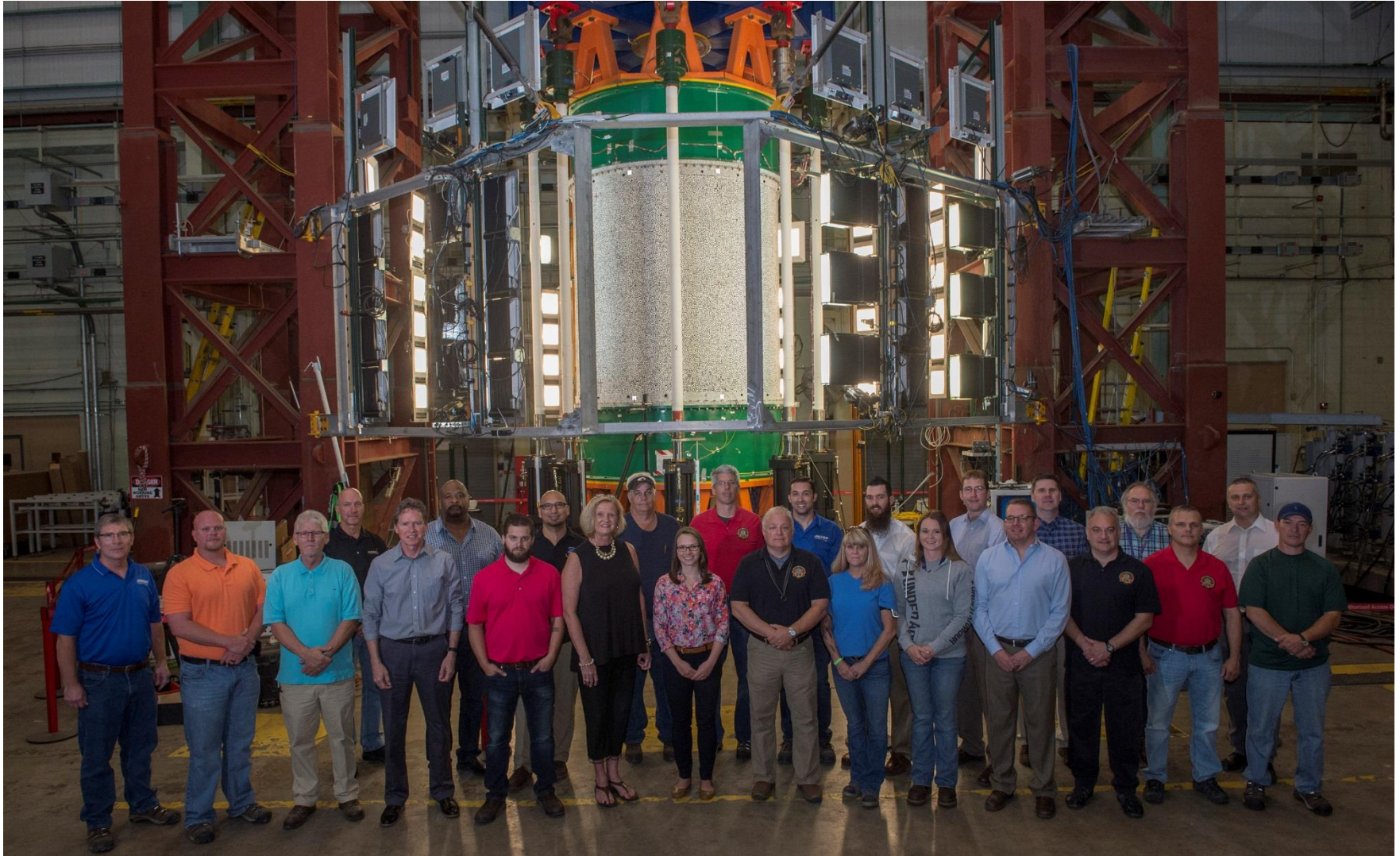


NASA Langley Research Center 1917-2017

Questions?



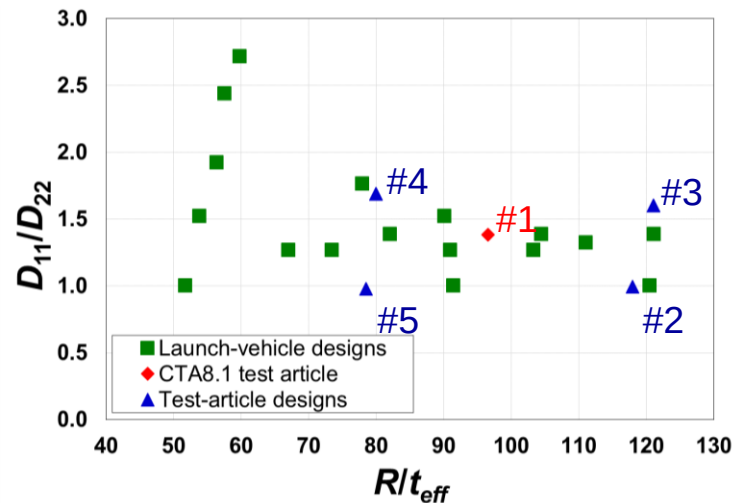
Questions?





Backup

Selected Test-Article Designs



- **Design #1 (tested)**

- Facesheet: 7 plies,* $D_{11}/D_{22} = 1.38$
- Core: 4.5 pcf Korex honeycomb, 6.4-mm thick

- **Design #2**

- Facesheet: 6 plies* quasi-isotropic, $D_{11}/D_{22} = 0.99$
- Core: 3.1 pcf aluminum honeycomb, 5.1-mm thick

- **Design #3**

- Facesheet: 5 plies,* $D_{11}/D_{22} = 1.60$
- Core: 3.1 pcf aluminum honeycomb, 5.1-mm thick

- **Design #4**

- Facesheet: 8 plies,* $D_{11}/D_{22} = 1.69$
- Core: 3.1 pcf aluminum honeycomb, 7.6-mm thick

- **Design #5**

- Facesheet: 9 plies,* $D_{11}/D_{22} = 0.98$
- Core: 3.1 pcf aluminum honeycomb, 7.6-mm thick

*Ply thickness: 0.14 mm