



On the Development of Buckling Design Recommendations for Launch-Vehicle Shell Structures

Sandwich Composite
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Agenda

- **Background**
- **NESC Shell Buckling Knockdown Factor Project (SBKF)**
- **Development of Composite Buckling Design Recommendations**
- **Composite Large-Scale Validation Testing and Test-Analysis Correlation**
- **An Update on Integrally Stiffened Metallic Shells**
- **Concluding Remarks**



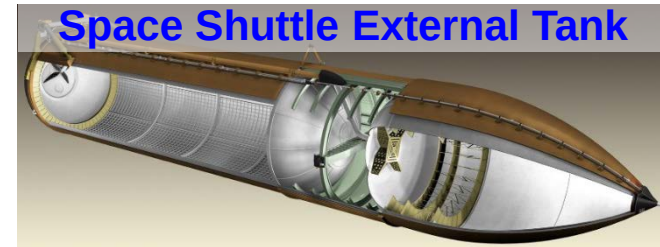
Background



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 structures
 - Fastened hat stiffeners, etc.
- More recently, composites have been gaining wider acceptance within NASA for primary structure
 - Potential benefits (mass, thermal, cost, etc.)
 - Most often considered for dry structures
 - Most commonly have **sandwich** construction



Strong, stiff faces

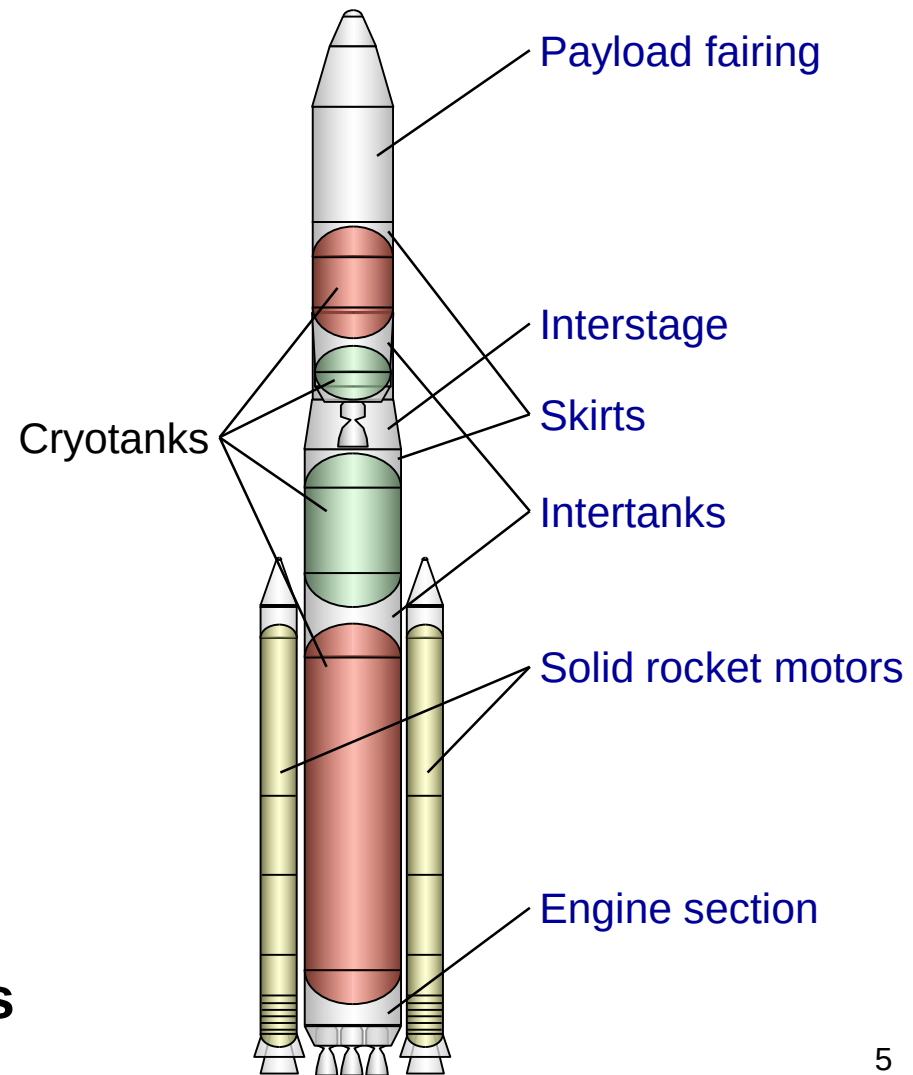
Lightweight core

Launch-Vehicle Shell Structures

- **Cylindrical shells**
 - Significant portion of launch-vehicle structure
- **Buckling**
 - Loss of structural stability accompanied by a change in equilibrium state
 - Often a controlling failure mode during design
 - Empirical buckling loads are often **significantly less** than theoretical predictions

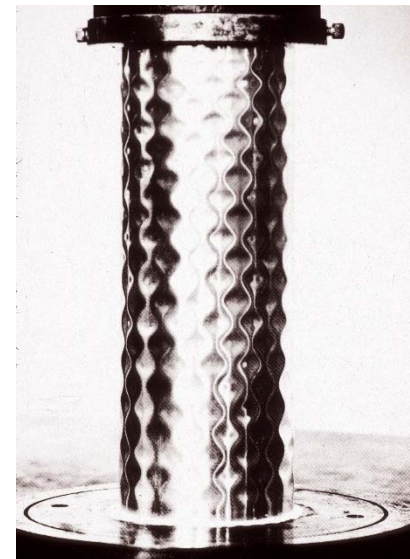
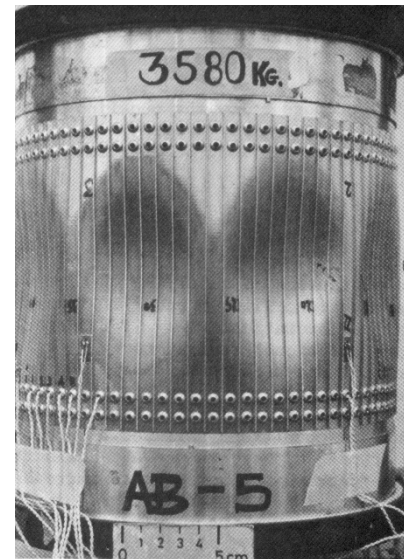
Wet structure

Dry structure



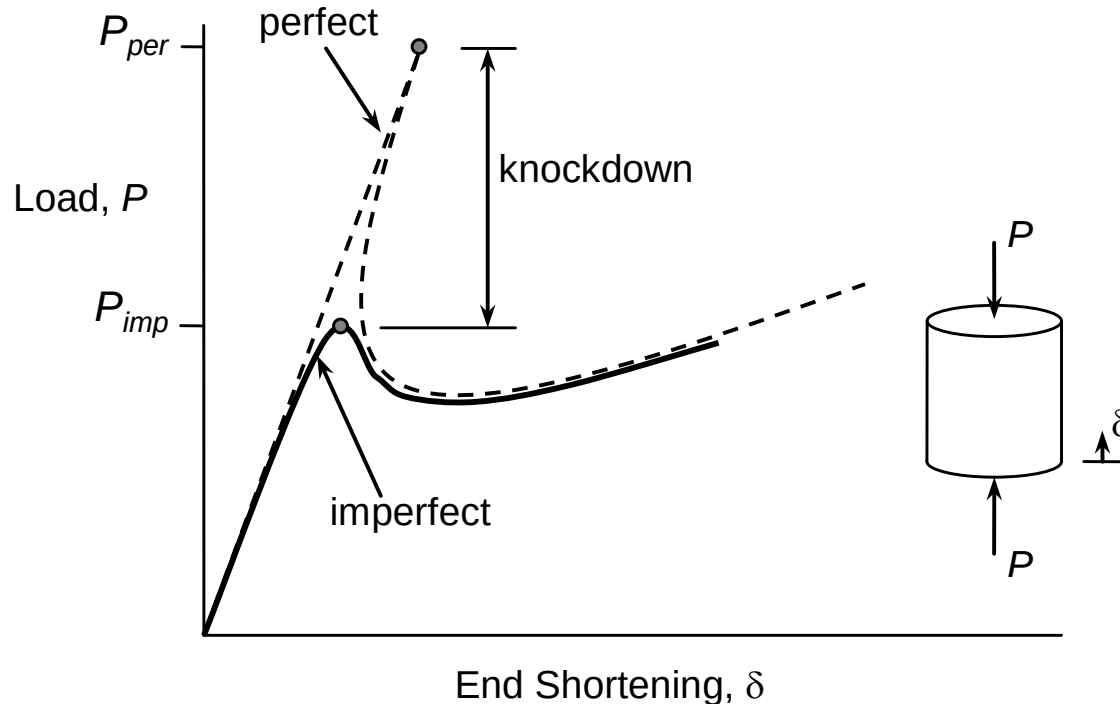
Shell Buckling Background

- Large amount of cylinder testing occurred in the 1920s-1960s to help understand shell buckling
 - Motivated by **catastrophic failures** of grain silos, water towers, wine tanks...later, missiles and launch vehicles
 - Significant **scatter** in the buckling loads that were typically **less than** theoretical predictions
- Analysis tools and theories of the day could not predict behavior
- Empirical design guidelines were developed



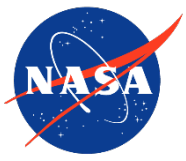
Empirical Shell-Buckling Design Approach

- Differences between test and analysis primarily attributed to initial *geometric imperfections* in the shell wall (i.e., out-of-roundness)
- 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 ideal response





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*
- Last revised in 1968

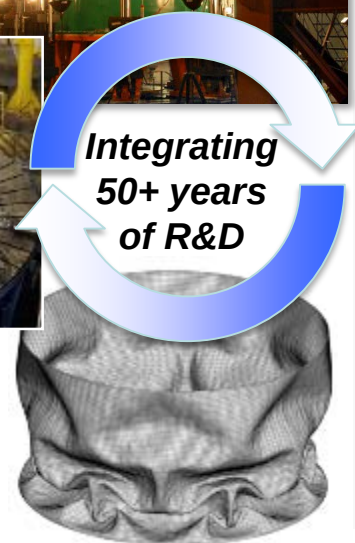
Developing New Design Factors

- Several things have happened since the 1960s to enable the development of new knockdown factors
 - **Understanding** of buckling and imperfection sensitivity (Koiter, Babcock, Arbocz)
 - Improved **manufacturing** processes that result in less variability in the as-built structure
 - Improved **analysis**, **metrology**, and **testing** technologies

Large-scale fabrication and testing

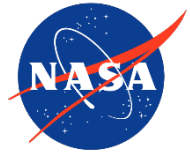


High-fidelity physics-based simulations



*Integrating
50+ years
of R&D*





NESC Shell Buckling Knockdown Factor Project (SBKF)



NESC 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 structure
 - Composite dry structure
- **Expected Outcomes**
 - Reduce **structural mass** and mass-growth
 - Estimated **5% to 20%** mass savings for metallic tanks
 - **Demonstrated 5% to 8%** mass savings
 - Estimated **4% to 20%** mass savings for sandwich composite dry structures*
 - Enable new structural configurations
 - Increase **knockdown fidelity** to improve design trades and reduce design cycle time/redesigns

Approach

- **Develop and validate high-fidelity shell buckling analysis methods**
 - High-fidelity finite element models serve as **analysis-based virtual tests** to generate design data
- **Targeted *validation testing* at coupon, panel, and cylinder levels**
 - Relevant **subscale test-article designs** over relevant design space
 - State-of-the-art **manufacturing**, **testing**, and **measurement** techniques
- **Develop and validate *analysis-based* knockdown factors to account for**
 - Initial geometric imperfections
 - Nonuniform loading
 - Modern launch-vehicle structural configurations (design space)
 - Modern launch-vehicle material systems
 - Combined mechanical and pressure loads
 - Joints
 - Thickness
- **Implementation of new knockdown factors**
 - Engage the user community to review and refine a technology development and implementation plan
 - Domestic and international collaborations

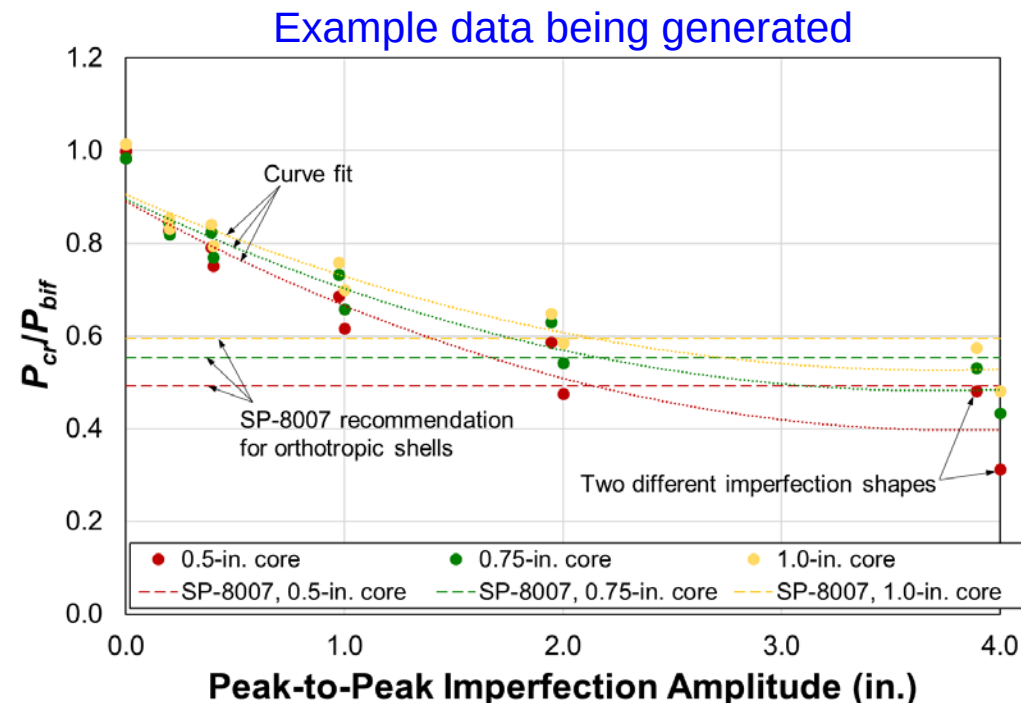




Development of Composite Buckling Design Recommendations

Composite Knockdown Factor Development

- Numerical parametric studies
 - Sandwich composite cylinders of different designs
 - Geometry, layup, etc.
- Realistic imperfections
 - Difficulty obtaining geometry measurements from large-scale shells
- Initial observations
 - Imperfection shape and magnitude can have significant influence
 - Very large imperfections necessary to reach SP-8007 levels
 - Thicker shells are less imperfection sensitive



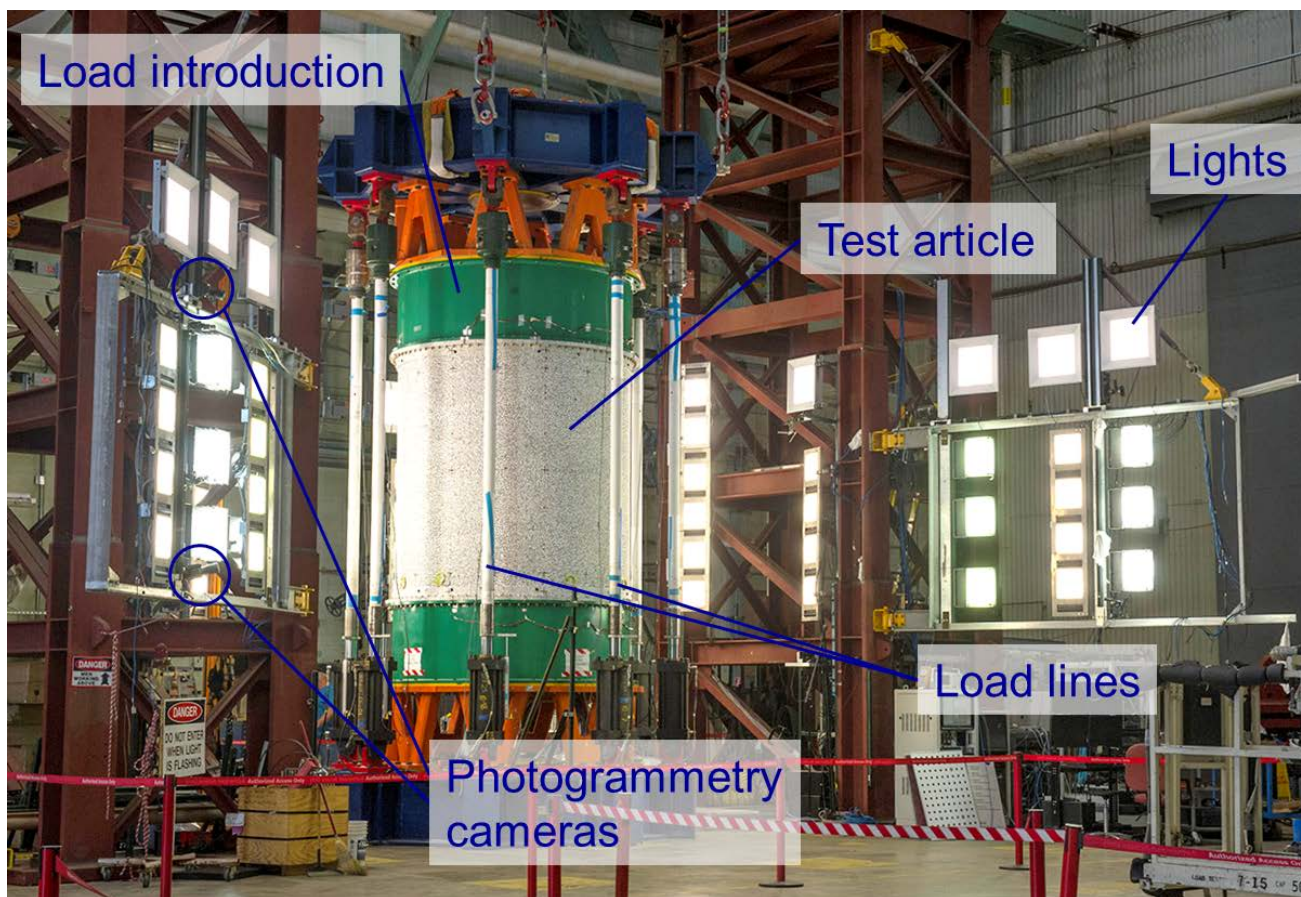
The challenge is in quantifying effects



Composite Large-Scale Validation Testing and Test-Analysis Correlation

Test facility

- For 8-ft diameter cylinders
- Up to 1.5×10^6 lb axial compression or combined loading



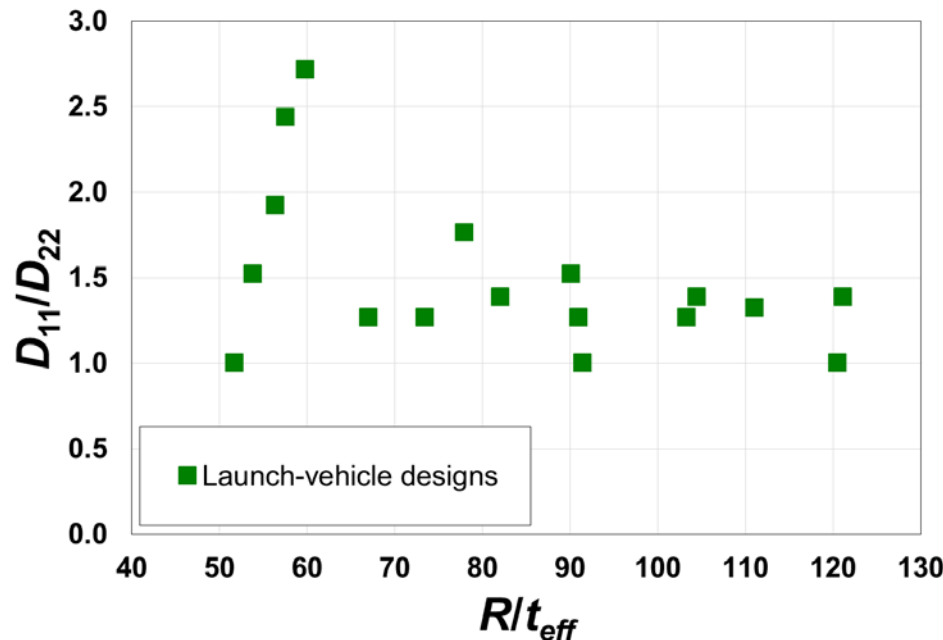


Validation Test-Article Design (8-ft diameter)



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

D_{11} = axial bending stiffness

D_{22} = circumferential bending stiffness

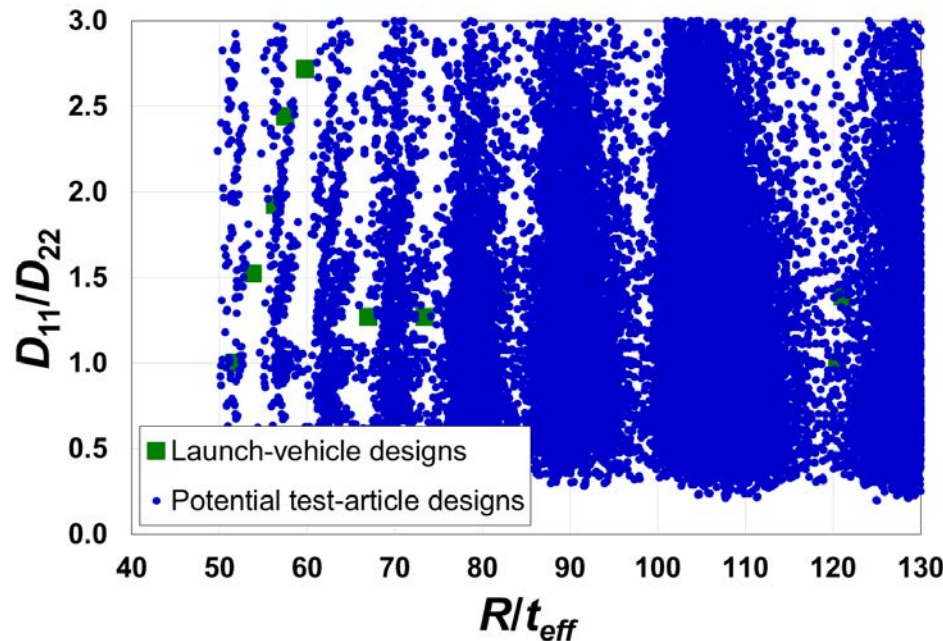


Validation Test-Article Design (8-ft diameter)



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 test-article designs
 - Variables: number of plies, ply angle, core thickness



R = radius

t_{eff} = effective thickness

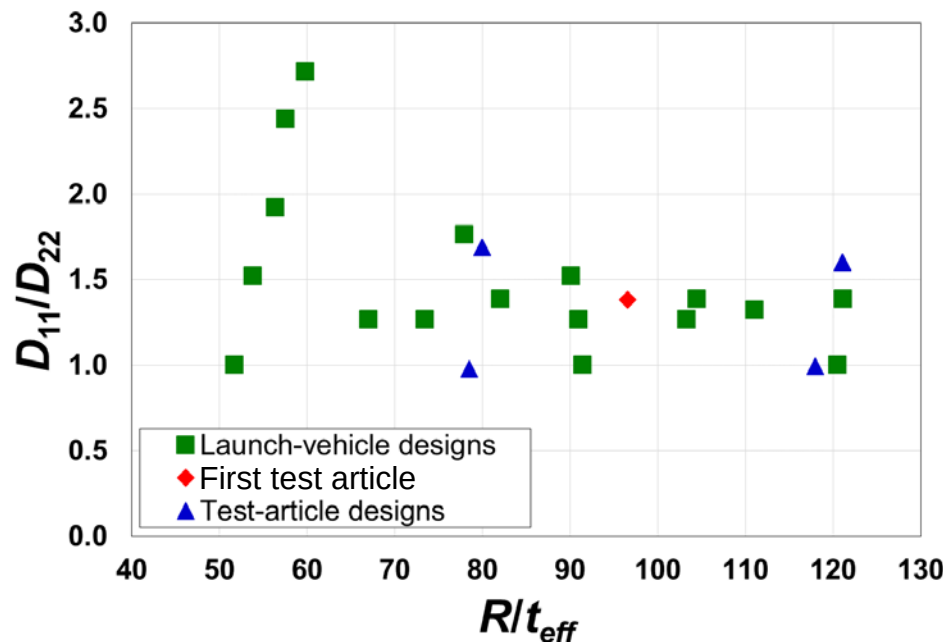
D_{11} = axial bending stiffness

D_{22} = circumferential bending stiffness

Validation Test-Article Design (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 test-article designs
 - Criteria: buckling critical, failure load, design space, etc.
 - Five test article designs selected as minimum number to validate analysis methods



R = radius

t_{eff} = effective thickness

D_{11} = axial bending stiffness

D_{22} = circumferential bending stiffness



First Large-Scale Composite Validation Test*



- **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 a collaborative agreement
- Manufacturing development unit
- Out-of-autoclave

- **Test conditions**

- Subcritical axial compression and combined loading cases
- **Axial compression** to failure

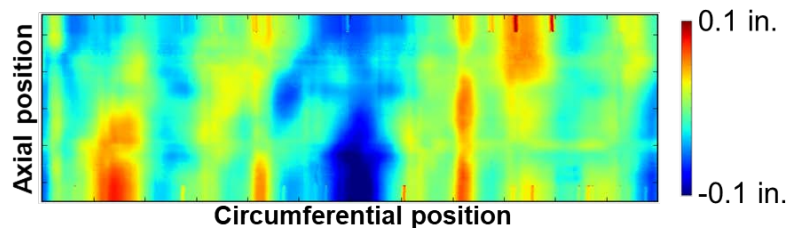


Finite Element Analysis Approach

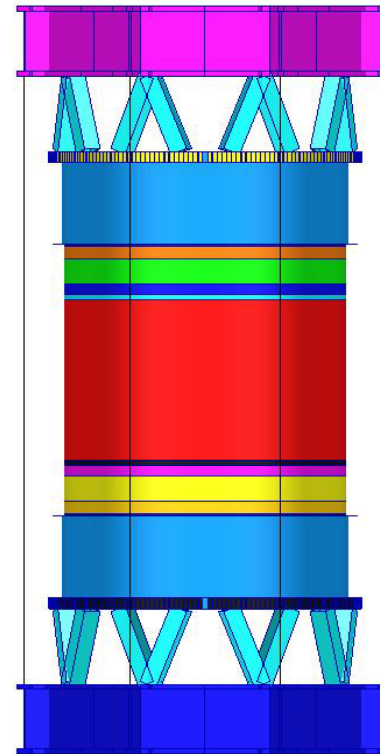
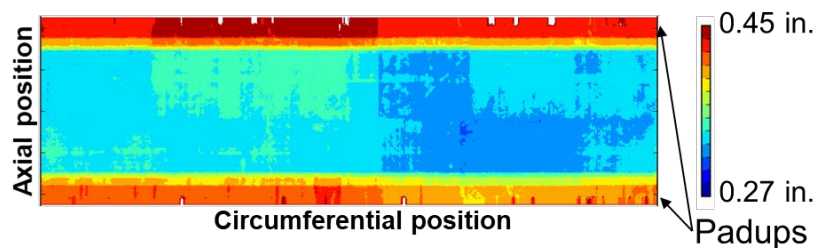
- **Test article and testing hardware**
 - Abaqus **shell** and **beam** elements
 - 156,960 elements

- **Geometrically nonlinear transient analysis**

- **Radial and thickness variations included**
- Radial variation



- Thickness variation





Failure Event: Standard-Rate Video

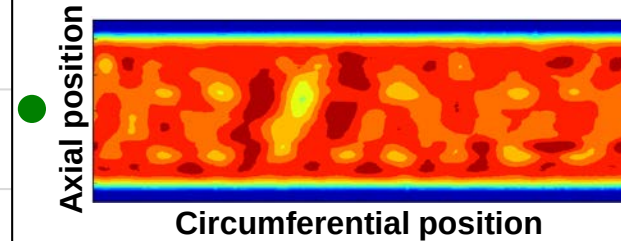
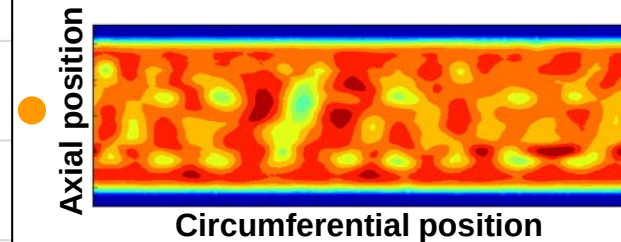
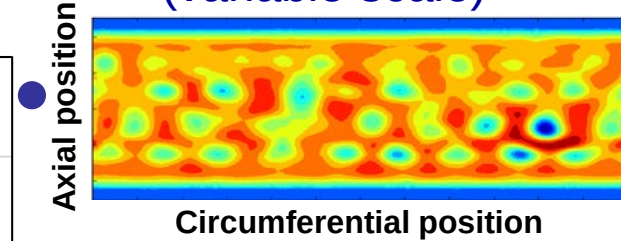
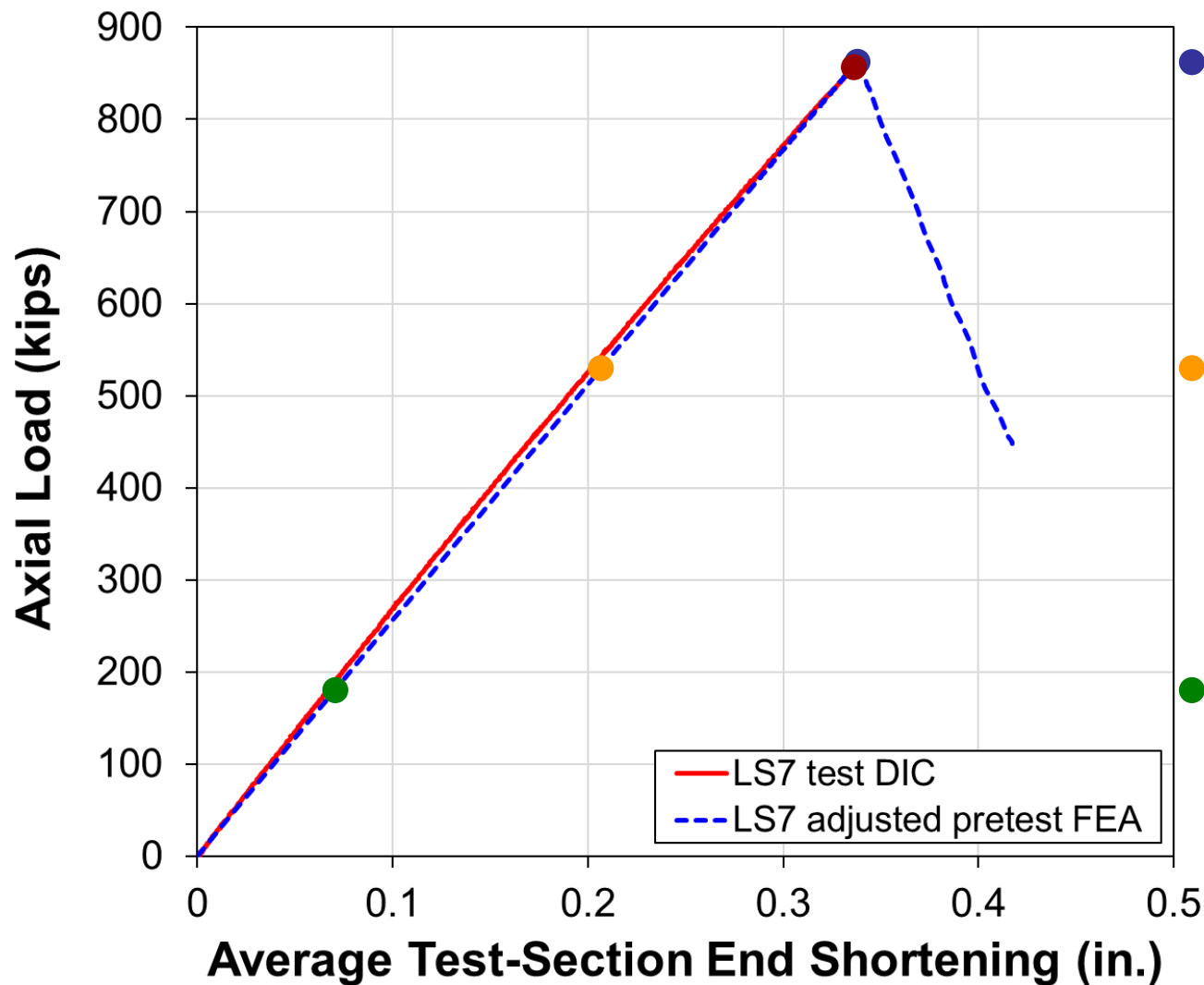




Test-Analysis Correlation: Test-Section Shortening



Predicted radial deformation
(variable scale)

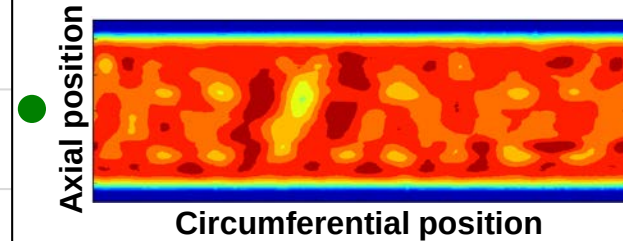
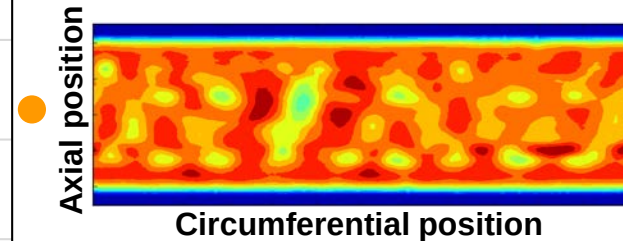
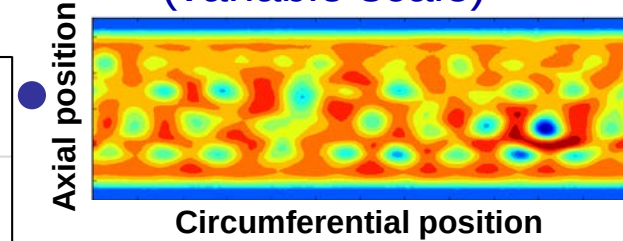
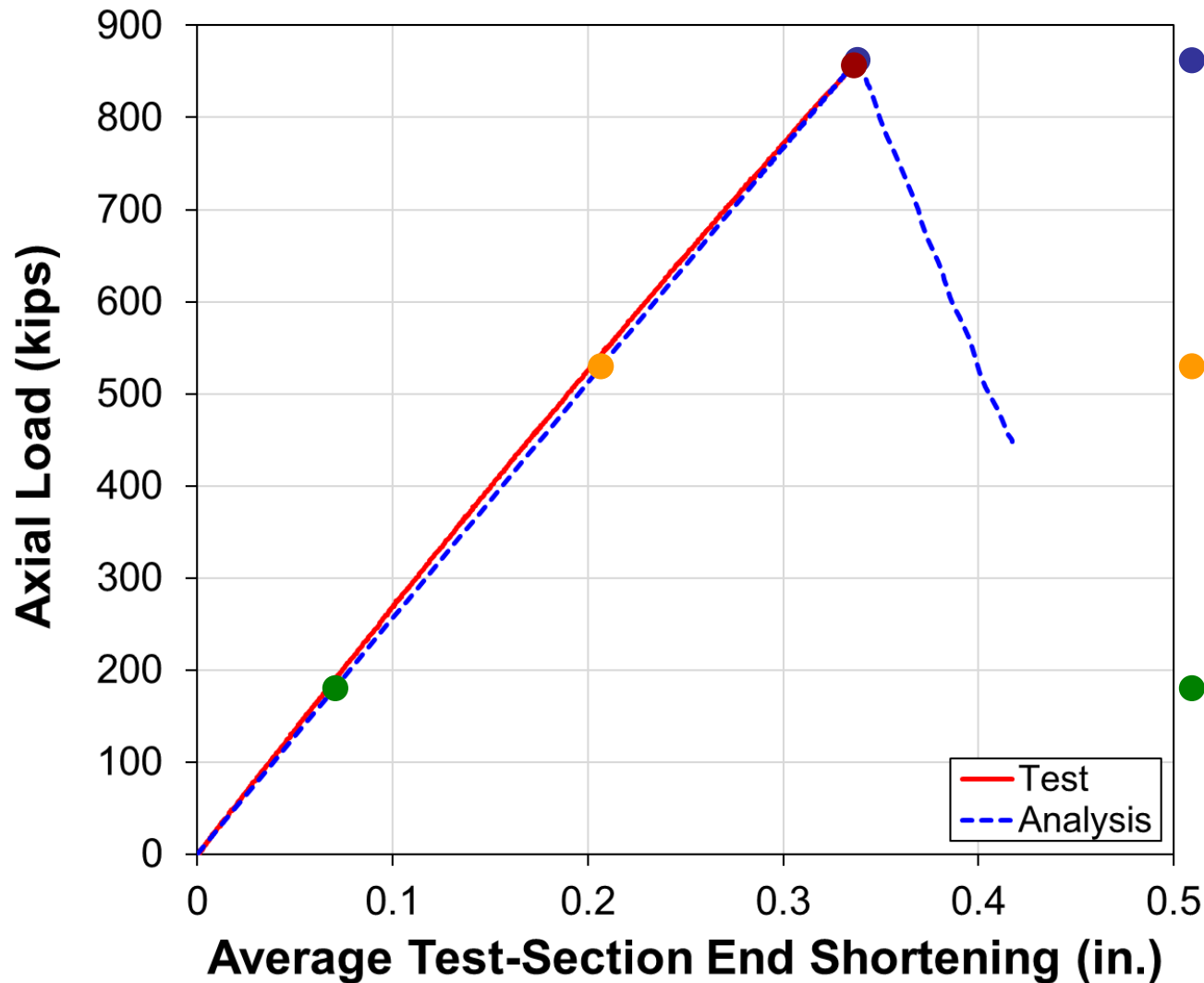




Test-Analysis Correlation: Test-Section Shortening



Predicted radial deformation
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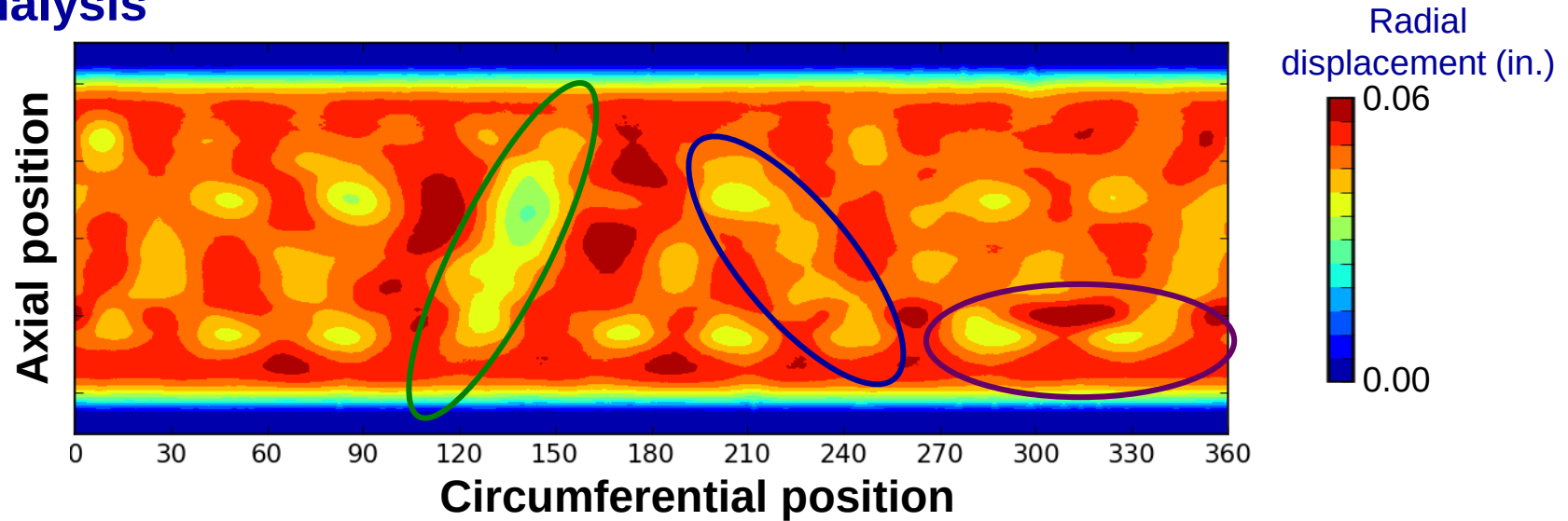




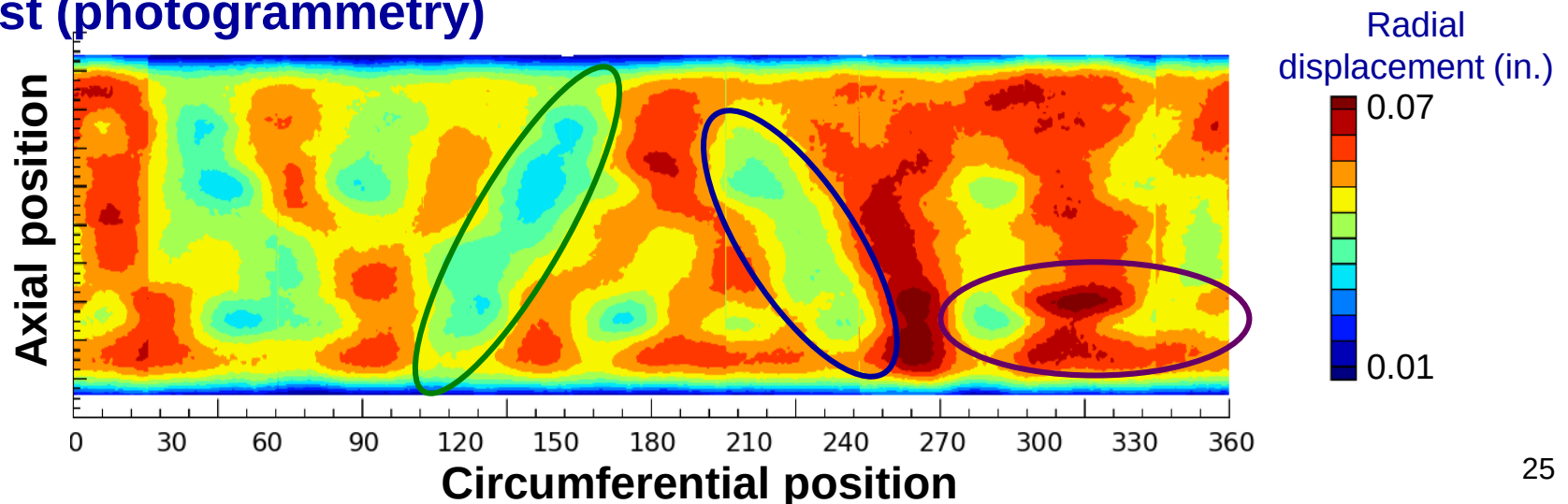
Test-Analysis Correlation: Radial Deformation, 458 kips



Analysis

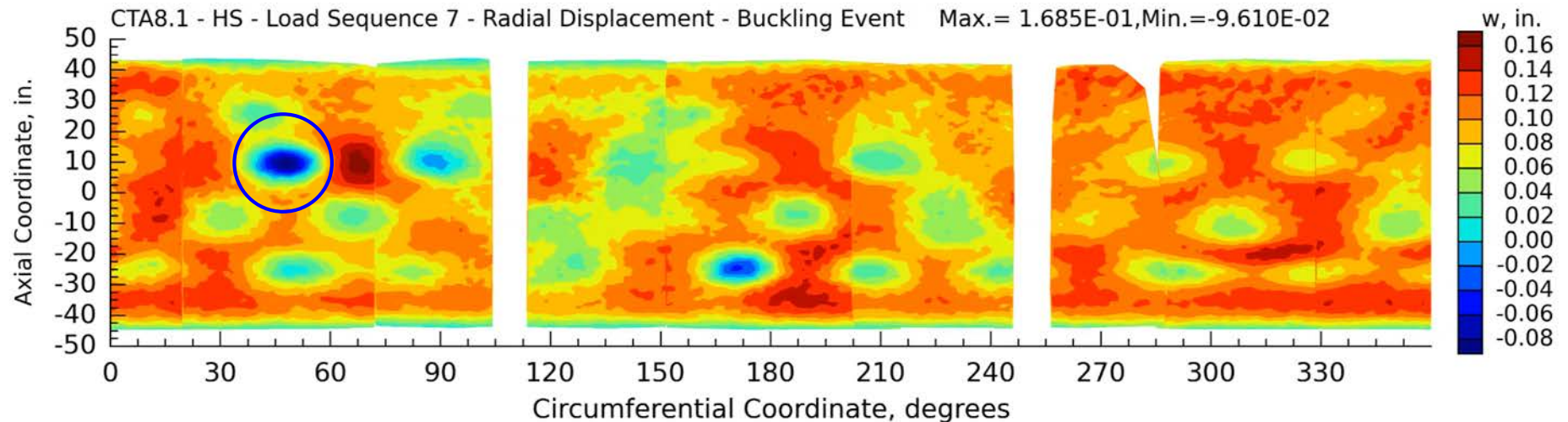


Test (photogrammetry)



Failure initiates as buckling before material failure

Radial deformation



- **Observations on test-analysis correlation**

- Good prebuckling agreement for stiffness and deformation pattern
- Good agreement on buckling load
- Buckling occurs prior to material failure



An Update on Integrally Stiffened Metallic Shells



Integrally Stiffened Metallic Shells



- Metallic for orthogrid- and isogrid-stiffened cylinders were initial focus of project
- Eight 8-ft-diameter and two 27.5-ft-diameter tests
- New knockdown factors were developed and provided to NASA Space Launch System (SLS):*
 - 2,000-3,000 lb (5%-8%) mass savings in the Core Stage tanks
 - Reduced material costs by \$300K-\$400K per launch
 - Reductions in design and analysis cycle time
 - Contributed significantly to on-time preliminary design review
- Updated SP-8007 is now complete and is currently undergoing internal review





Concluding Remarks

- **Buckling can be a critical failure mode for launch-vehicle shell structures**
- **Existing design guidelines are believed to be overly conservative and were not developed for modern constructions**
- **NESC is developing new analysis-based buckling design guidelines for stiffened metallic and sandwich composite shell structures**
 - **Large-scale test series for analysis validation**
 - **Good agreement between large-scale test and analysis**
- **Experience is being applied to current NASA development efforts**





Backup: Selected References

- Hilburger, et al., “Shell Buckling Design Criteria Based on Manufacturing Imperfection Signatures,” *AIAAJ*, vol. 44, no. 3, 2006.
- Lovejoy, et al., “Effects of Buckling-Knockdown Factor, Internal Pressure and Material on the Design of Stiffened Cylinders,” *51st Structures, Structural Dynamics and Materials Conference*, AIAA paper no. 2010-2778, 2010.
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