Structural Design and Analysis Considerations

Michelle Tillotson Rudd

NASA Marshall Space Flight Center

Delft University of Technology
Delft, The Netherlands

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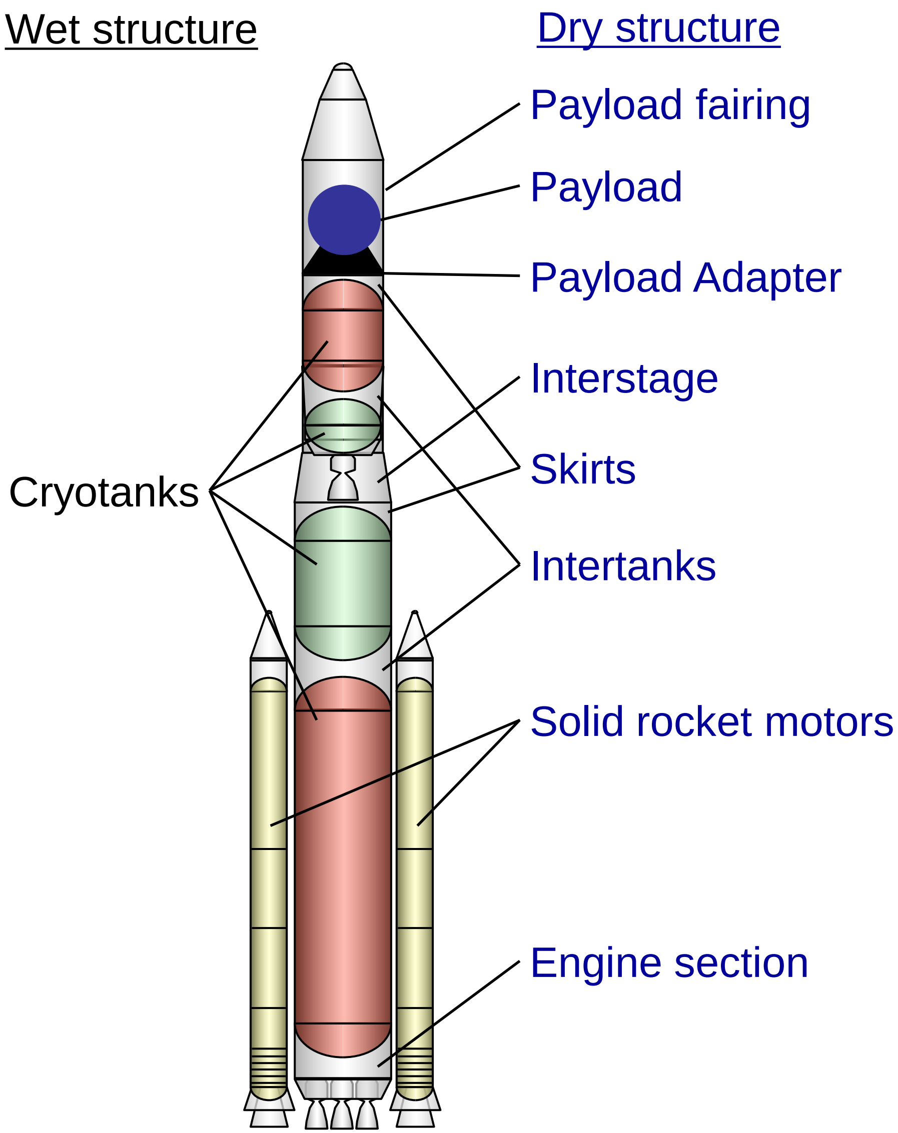
Outline

- **Part One**
  - **Mechanical Design Considerations**
  - **Structural Assessment: Analysis and Test**
- **Break**
- **Part Two**
  - **Shell buckling research at NASA**
    - **Background**
    - **Test-article design example**
    - **Large-scale testing**

Mechanical Design Considerations

Launch, Test

Typical Launch Vehicle

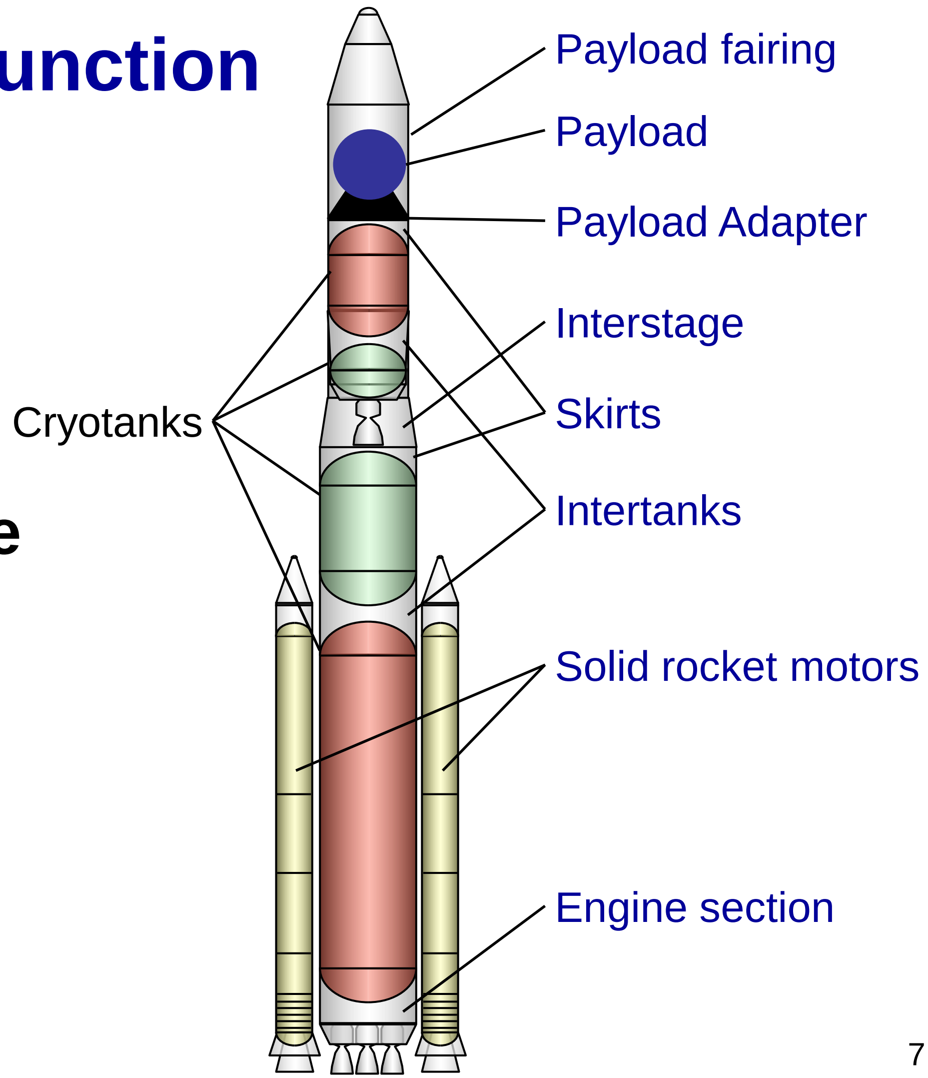


Structural Design Considerations

- Primary Function
- Loads and Environments
- Material Selection
- Structural Configuration
- Fabrication and Assembly
- Geometric Constraints and Interfaces
- Structural Integrity

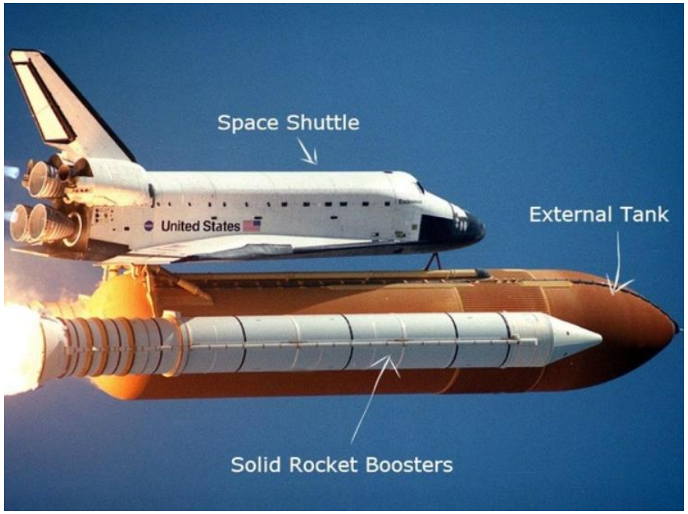
Structural Design Considerations: Primary Function

- **Determine primary function**
  - Primary structure
  - Secondary structure
  - Propellant tank
  - Mechanism
  - Aerodynamic surface
  - Insulation
  - Etc.



Structural Design Considerations: Loads and Environments

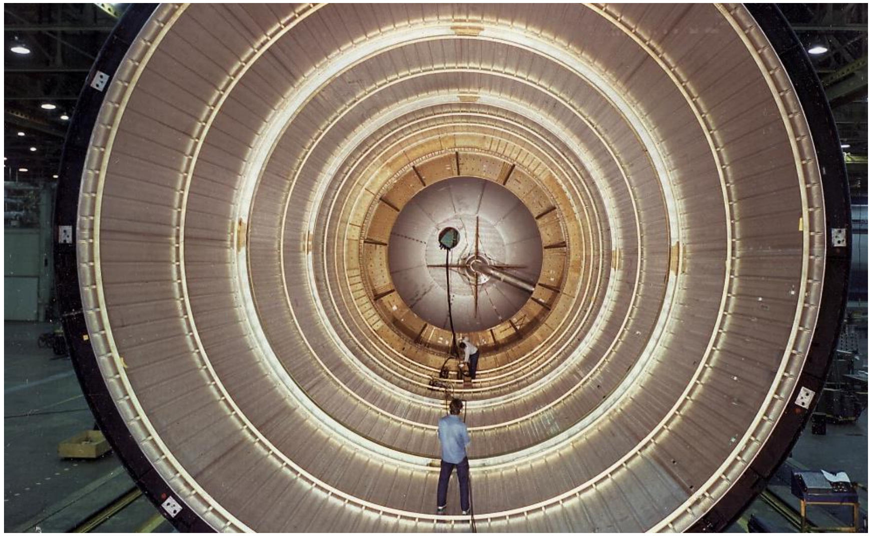
- Aerodynamic loads
- Aeroheating
- Shock and vibration
- In-space environments
- Cryogenic storage
- Transportation and lifting



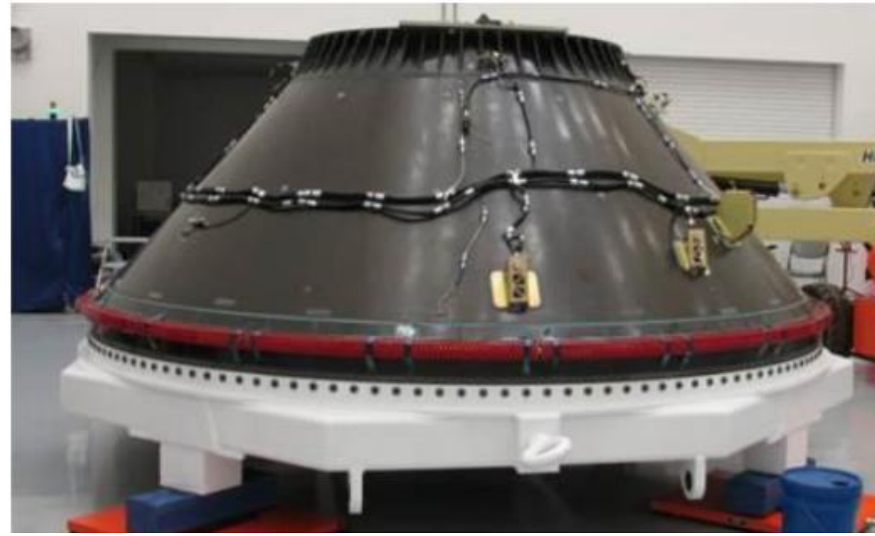
Shuttle

Saturn V, Dynamic Test Stand

Structural Design Considerations: Material Selection

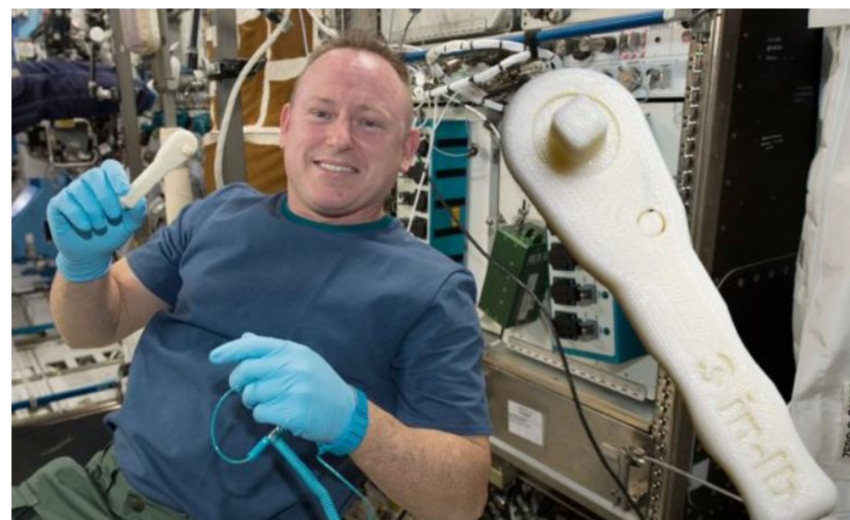


Metallic Propellant Tank



Composite Payload Adapter

Cork Thermal Protection System

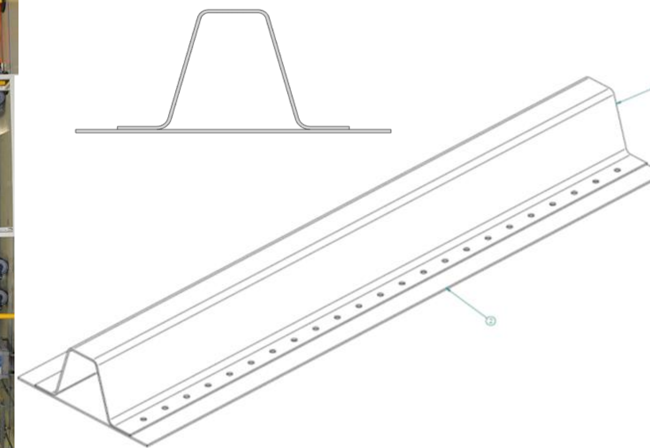


3D Printed Plastic

Structural Design Considerations: Structural Configuration

- **Monocoque/ solid laminate**
- **Truss**
- **Stiffened skin**
- **Skin stringer**
- **Sandwich**

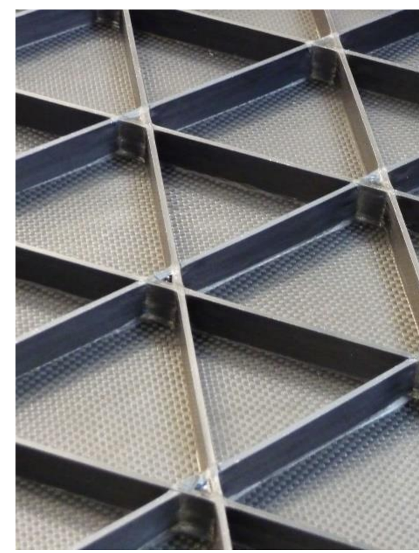
Second stage



Hat stiffened stringer

Payload fairing

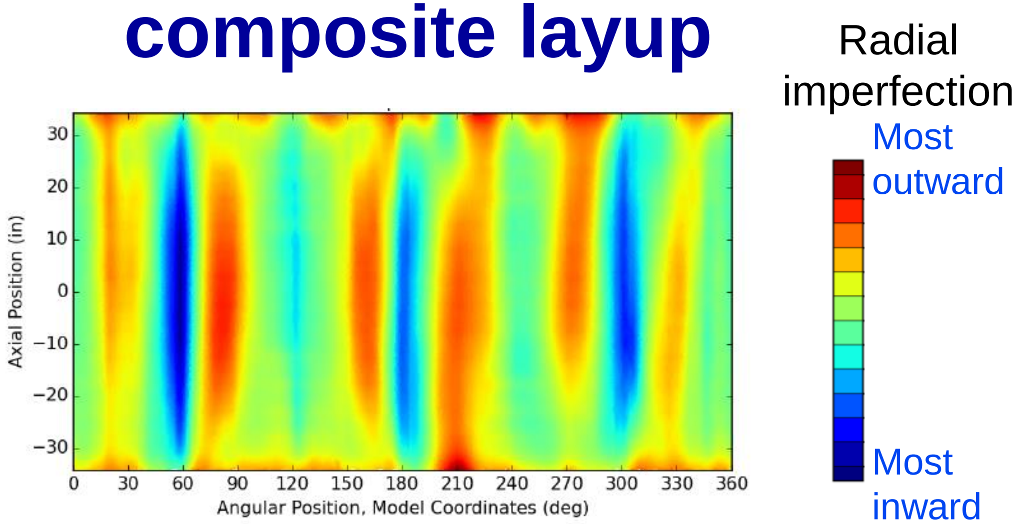
Metallic orthogrid



Composite isogrid

Structural Design Considerations: Fabrication and Assembly

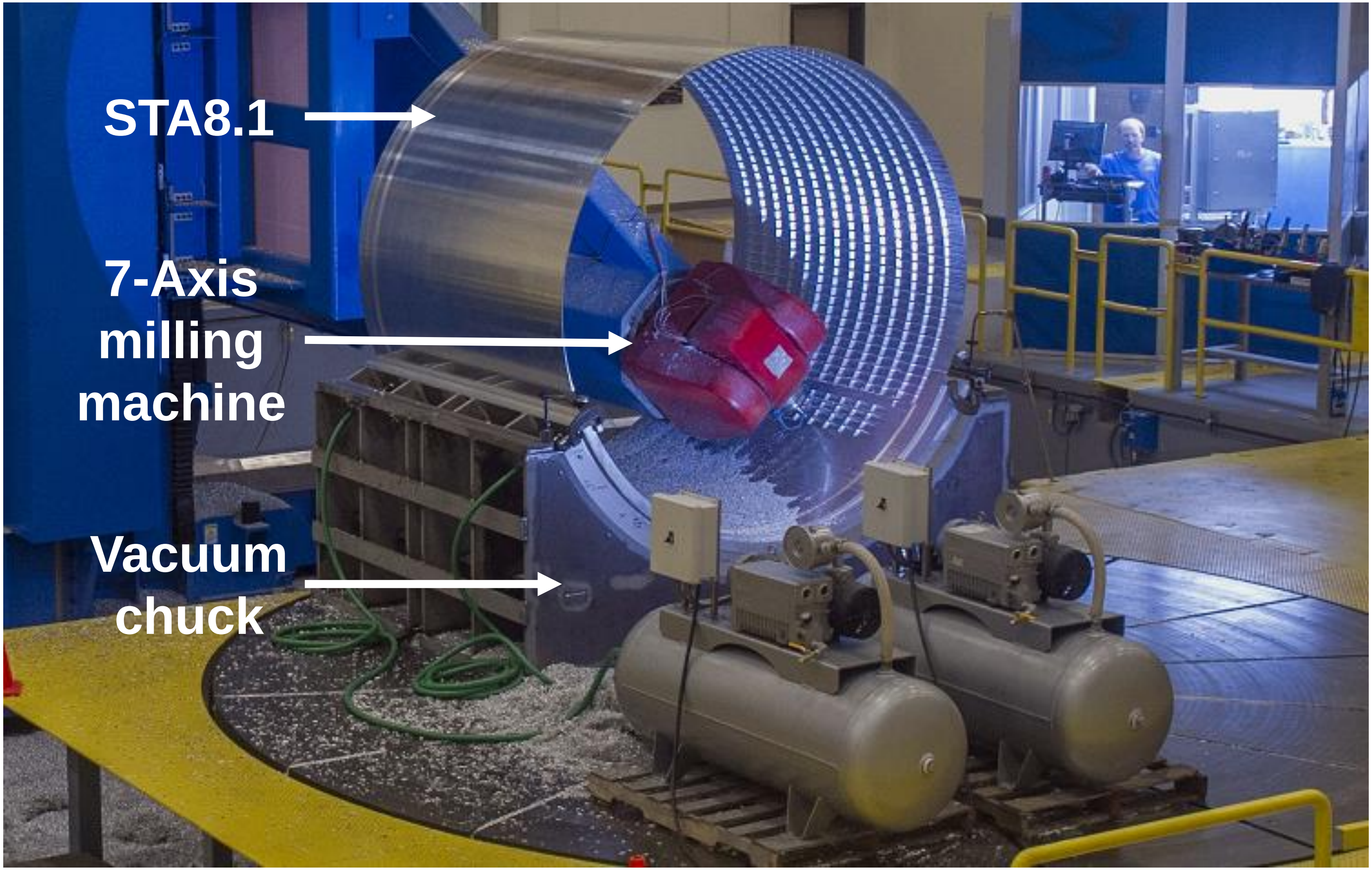
- **Precision-machined pieces**
- **Post-machined assembly**
- **Joint design**
  - **Rivet/Bolt/Weld/Bond**
- **Filament wound or composite layup**



Shrinkage due to welding

Launch Vehicle Stage Adapter

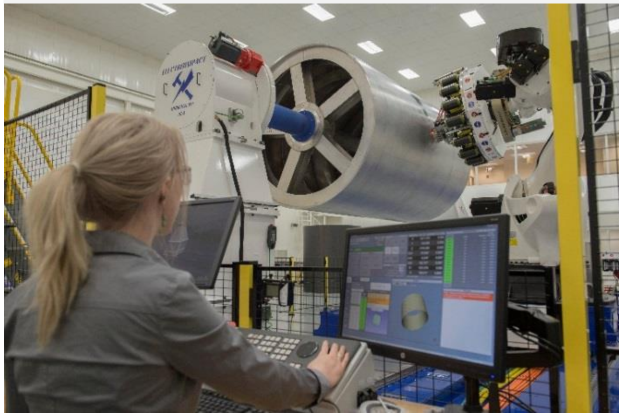
Structural Design Considerations: Fabrication and Assembly



Fabrication was performed at Marshall Space Flight Center (MSFC)

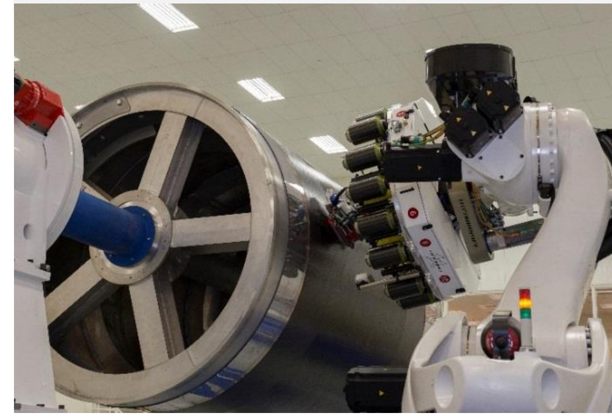
Structural Design Considerations: Fabrication and Assembly

Fiber place inner facesheet



Apply core

Fiber place outer facesheet



Autoclave cure

Remove from tool

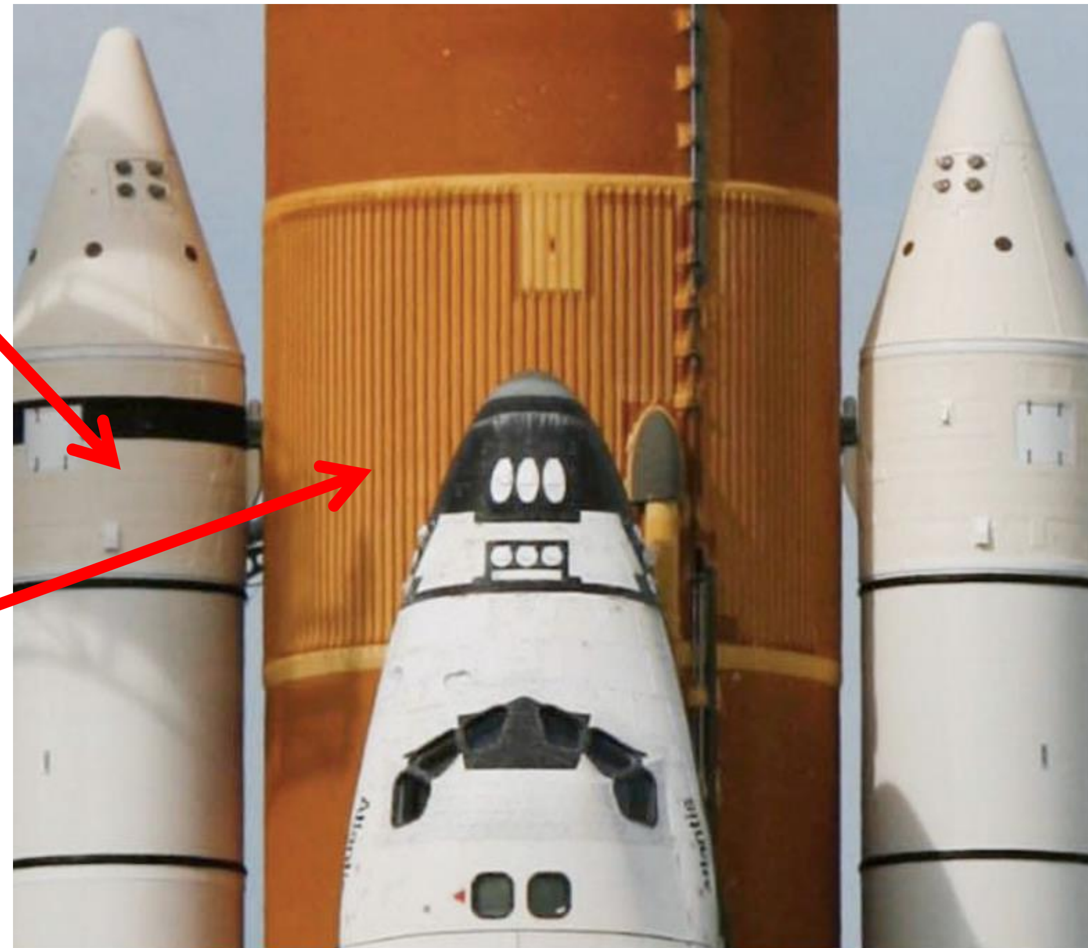
Trim

Fabrication was performed at MSFC

Structural Design Considerations: Geometric Constraints and Interfaces

Solid Rocket Boosters (SRB)

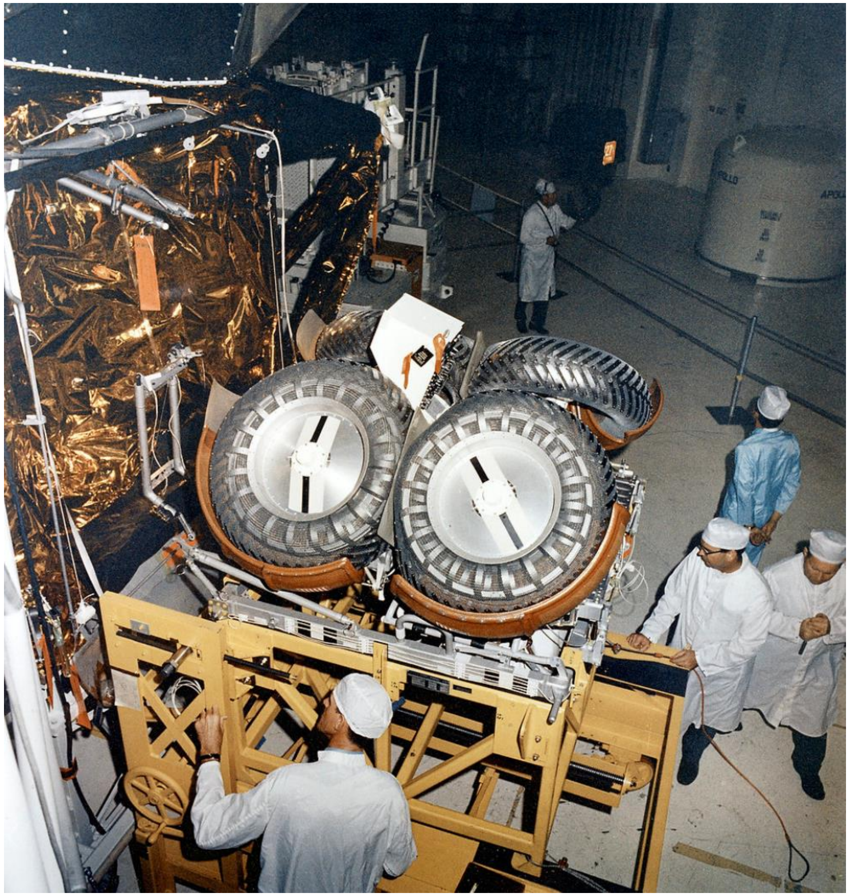
External Tanks (ET) Thrust Beam



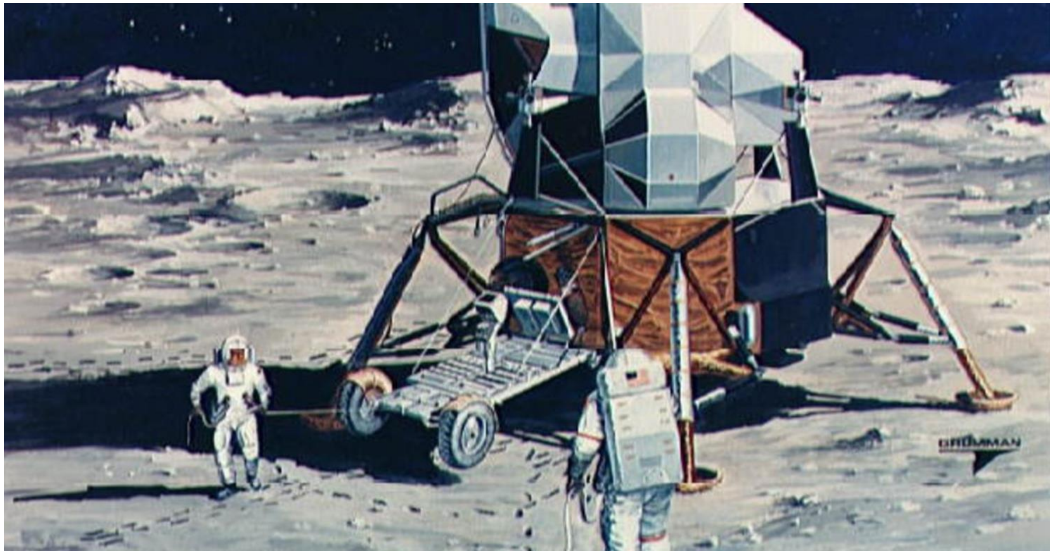
NASA Shuttle,
Intertank/SRB Attachment

Structural Design Considerations: Geometric Constraints and Interfaces

Apollo Era Lunar Rover



Lunar Rover Stowed

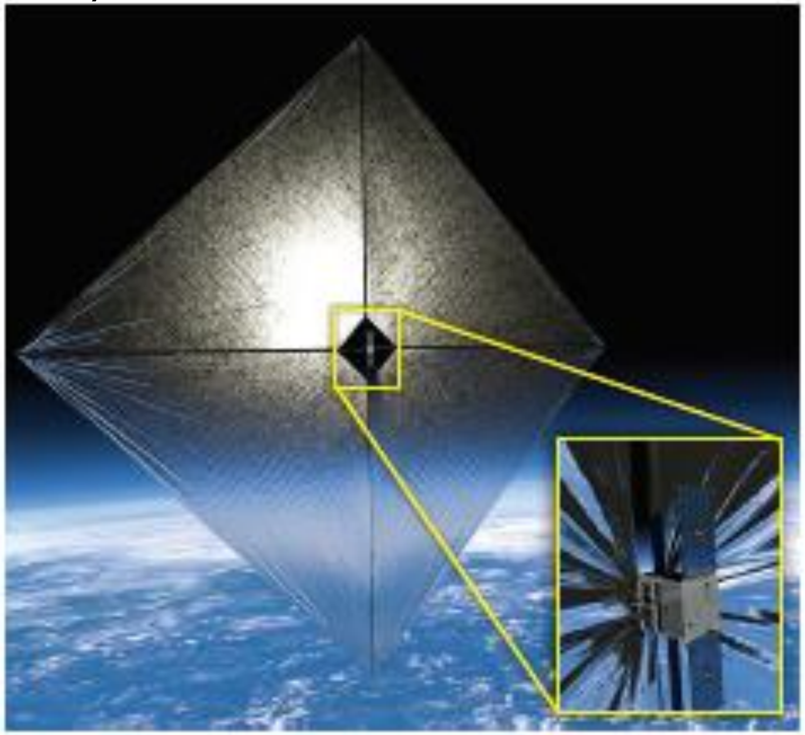


Lunar Rover Deployed

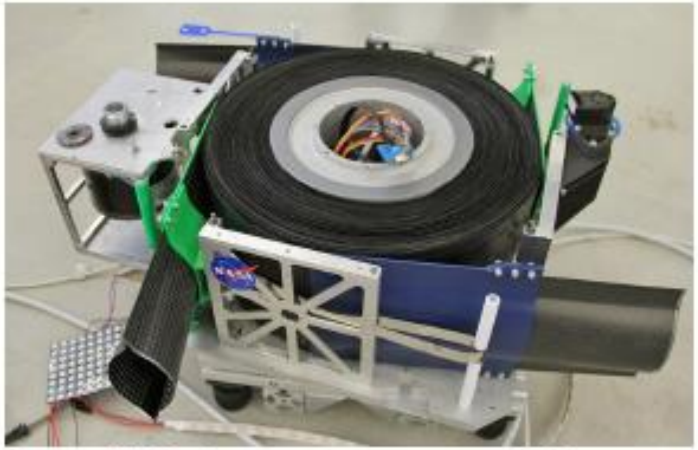
Structural Design Considerations: Geometric Constraints and Interfaces

NASA/DLR Deployable Composite Booms (DCB)

2,000-m^2-class solar sail

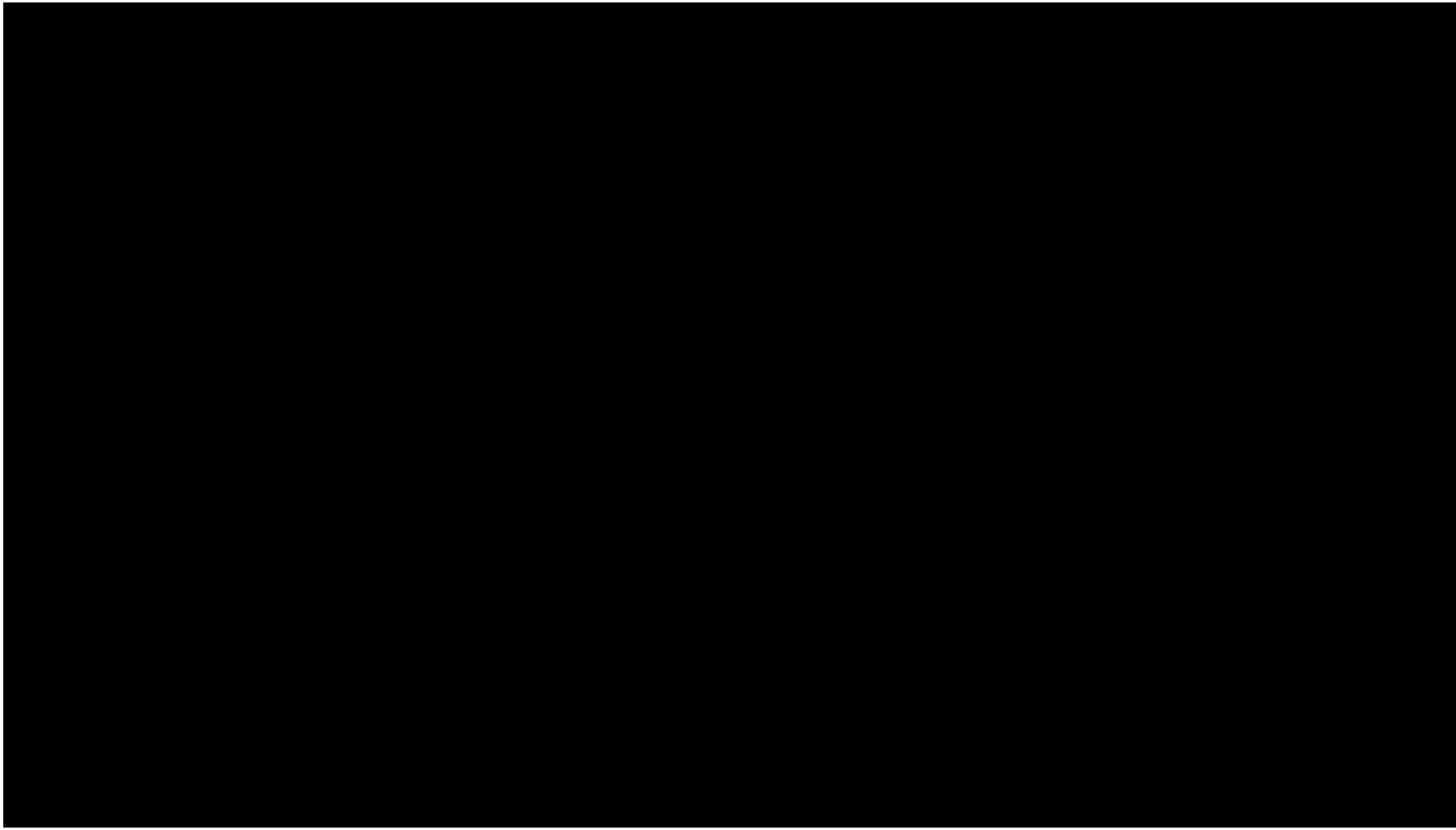


54.5-ft (16.6-m) boom partially coiled on a 7-in. (18-cm) diameter spool.



Four 54.5-ft (16.6-m) booms co-wrapped inside the DLR-developed deployment mechanism (top plate removed).

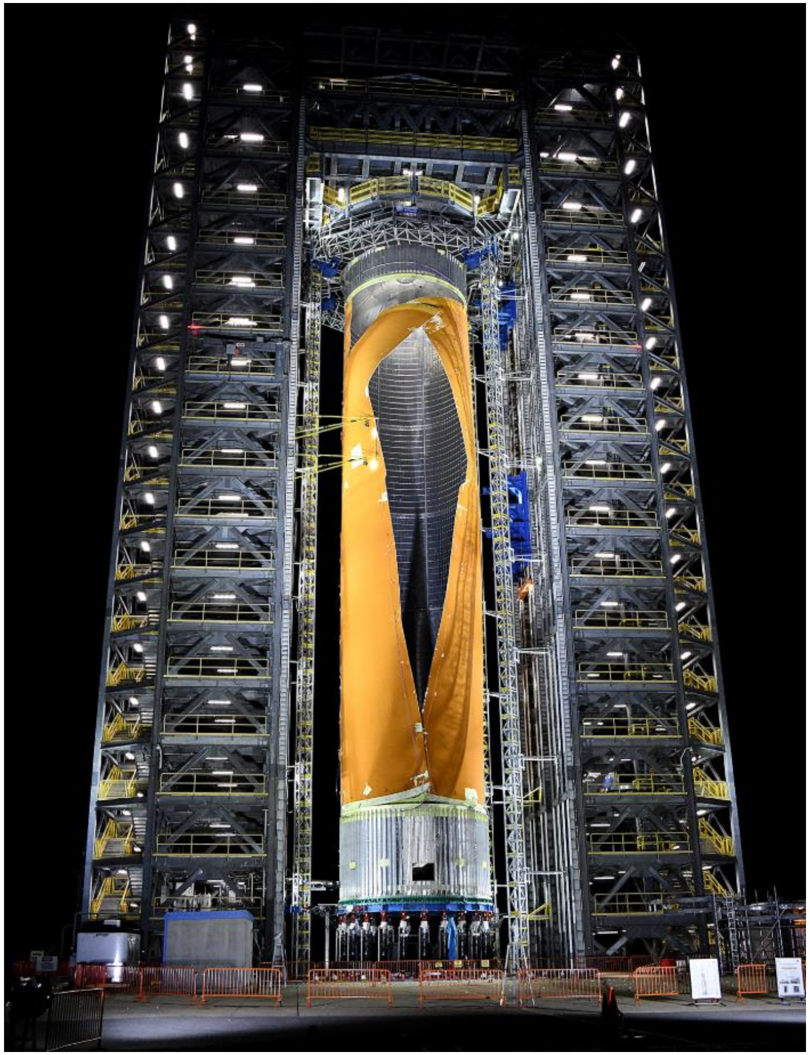
Structural Design Considerations: Structural Integrity



Structural Design Considerations: Structural Integrity

- **Strength**
- **Stability**
- **Frequency**
- **Fracture and fatigue**
- **Damage Tolerance**

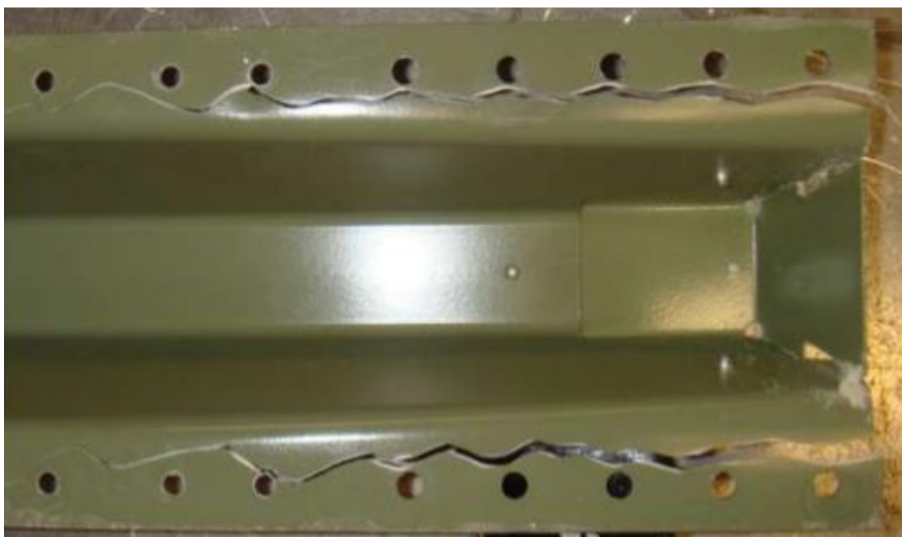
Each material and structural system has different failure modes



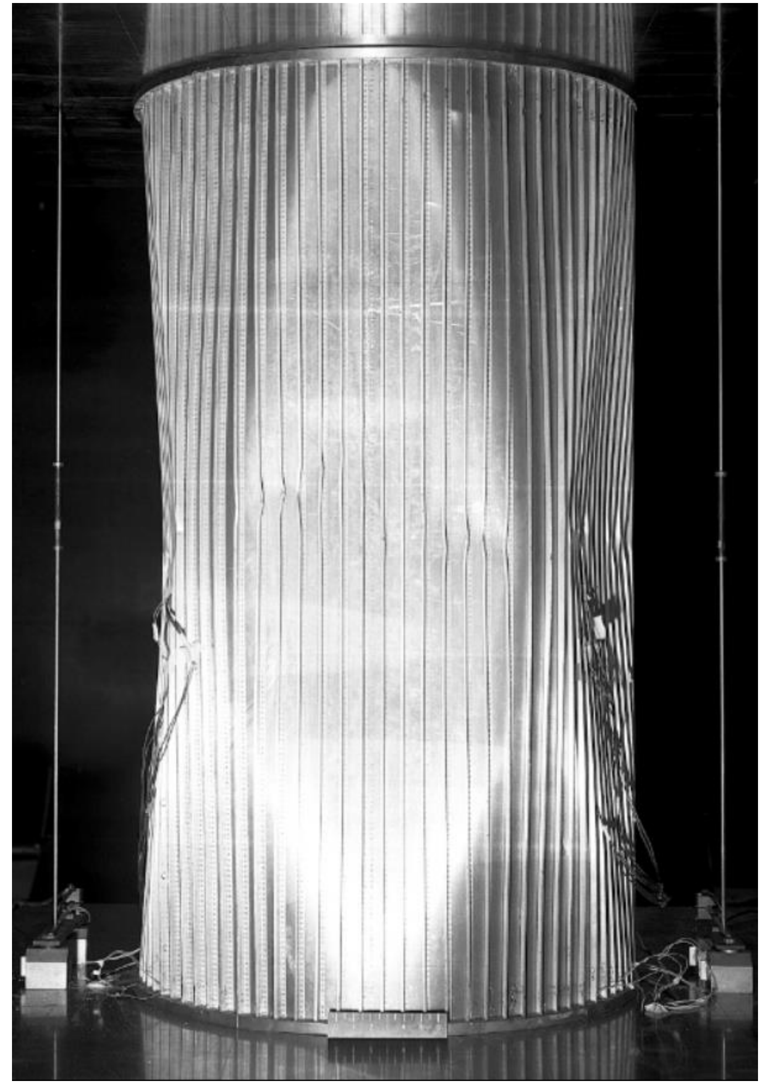
NASA Space Launch System (SLS) Hydrogen Tank after test to failure at MSFC

Structural Design Considerations: Structural Integrity

Local buckling

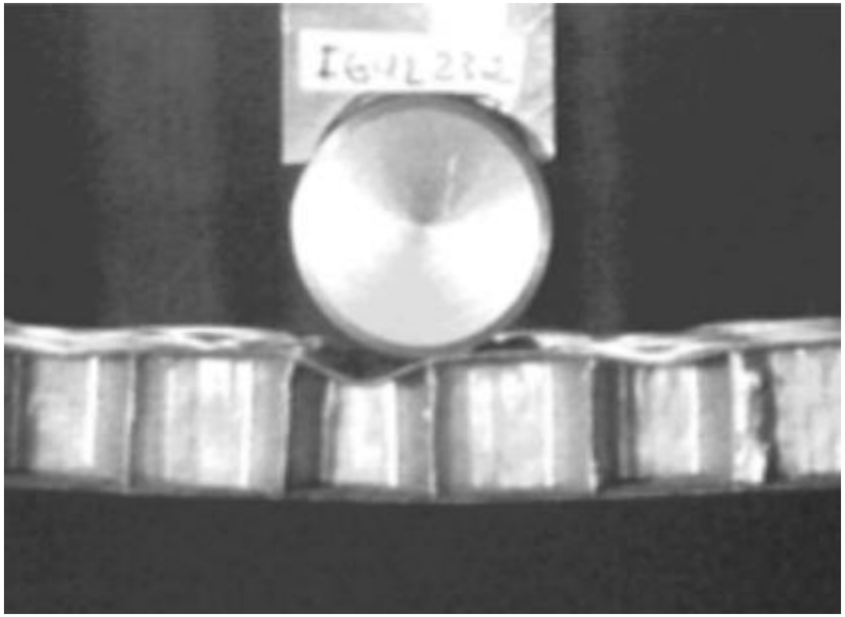


Material failure

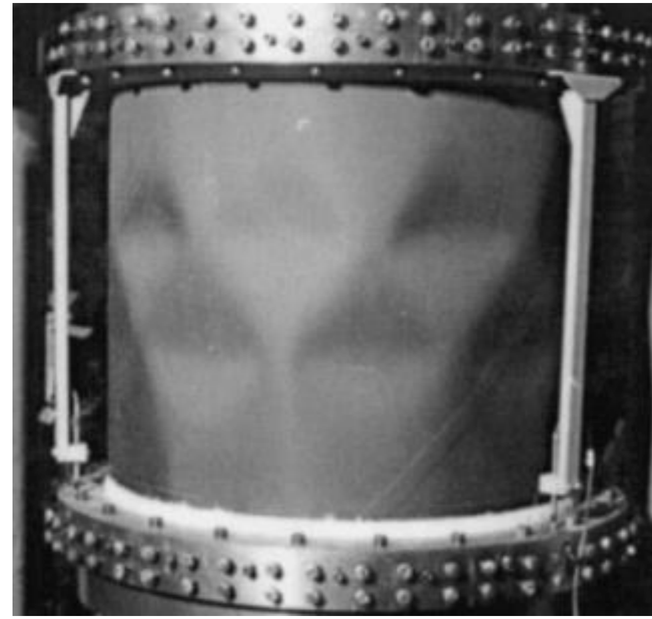


Global Buckling

Structural Design Considerations: Structural Integrity



Local buckling (facesheet dimpling)



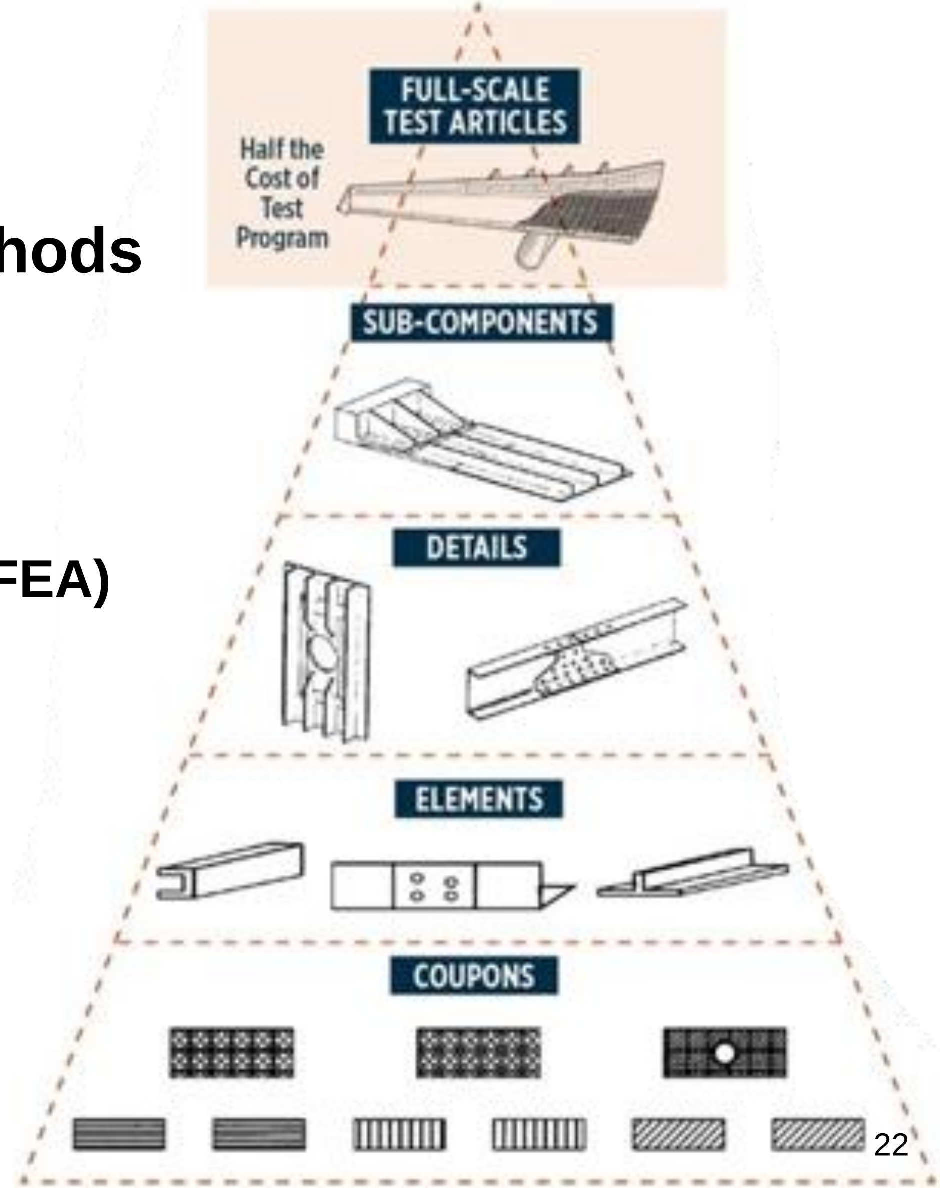
Global buckling

Material failures

Structural Assessment

Structural Assessment

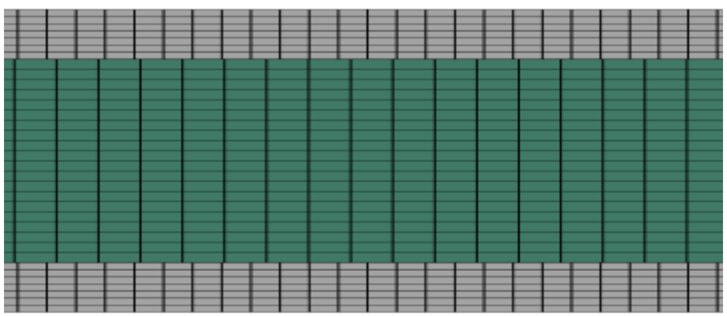
- **Analysis**
  - Classical analytical methods
    - Hand calculations
    - Closed-form solutions
  - Numerical methods
    - Finite element analyses (FEA)
- **Testing**
  - Building block

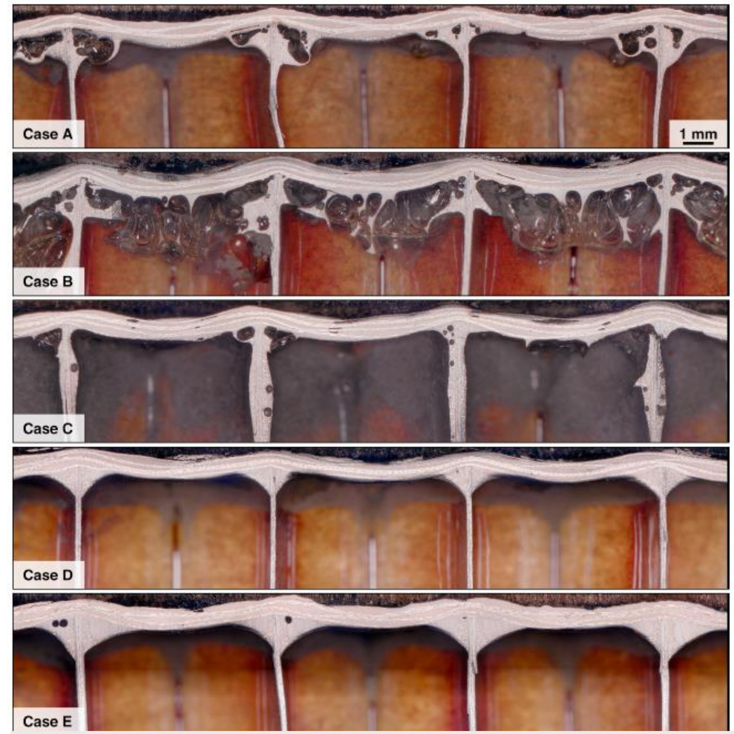


Some Common Simplifications in Structural Analysis

- **Continuum assumption**
- **Boundary conditions**
- **Uniformity/lack of design details**
- **Perfect or nominal**
- **“Smeared” shell or plate**
- **Linear material properties**
- **Geometrically linear response**
- **Assumed form of displacements, stresses, strains, etc.**
- **Transverse shear response: nondeformable, first- or second-order, etc.**

Honeycomb-Core Sandwich Composite

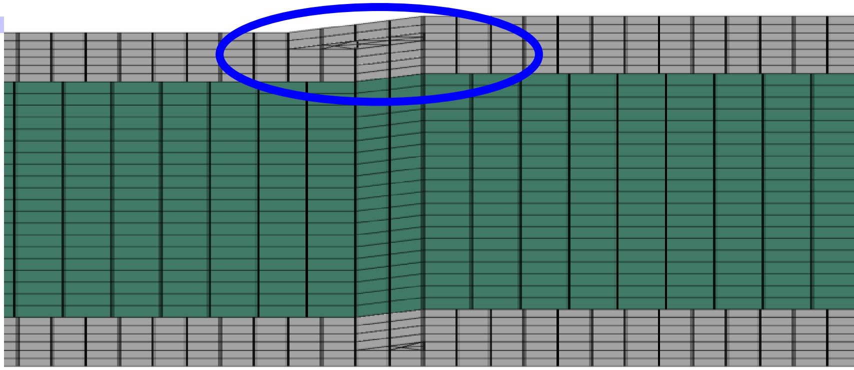




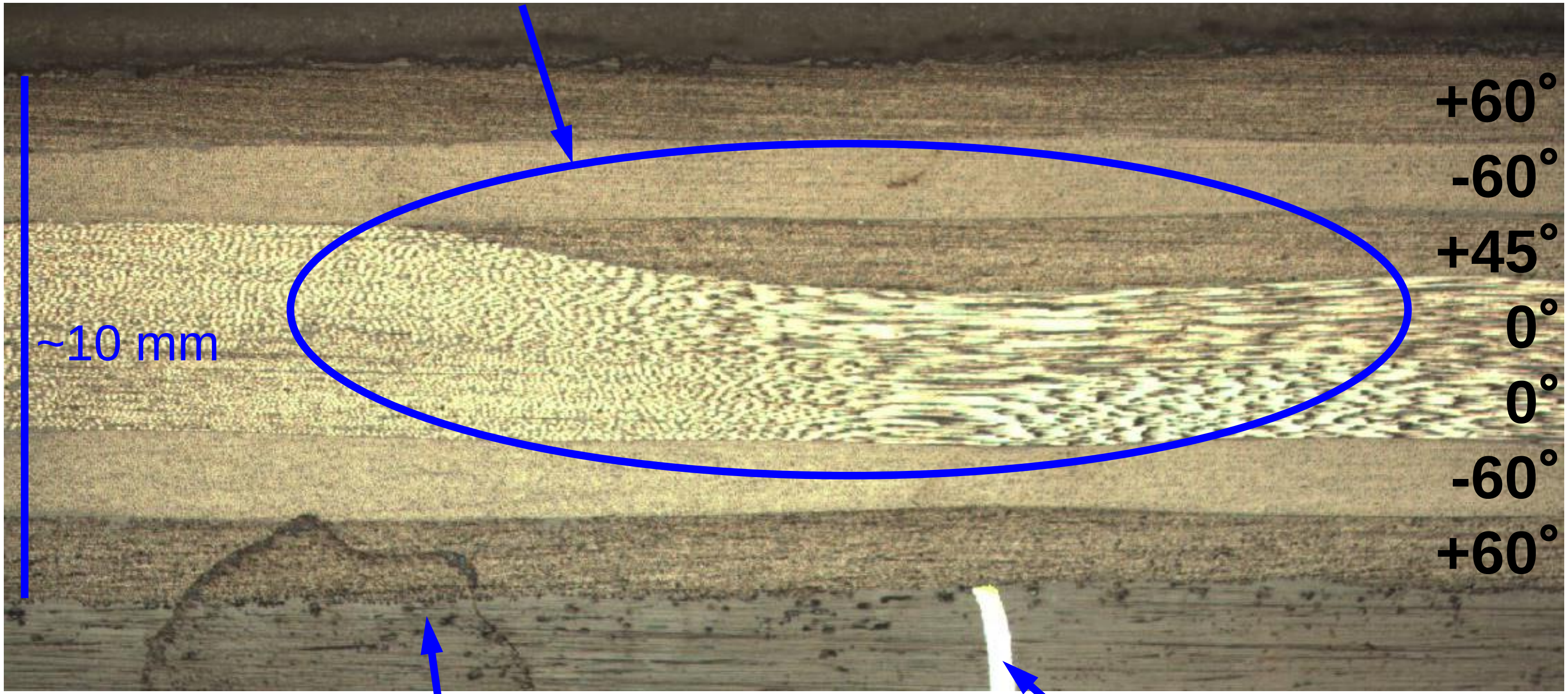
Anders, et al., 2019

Centea, et al., 2018

Honeycomb-Core Sandwich Composite: Ply Drop



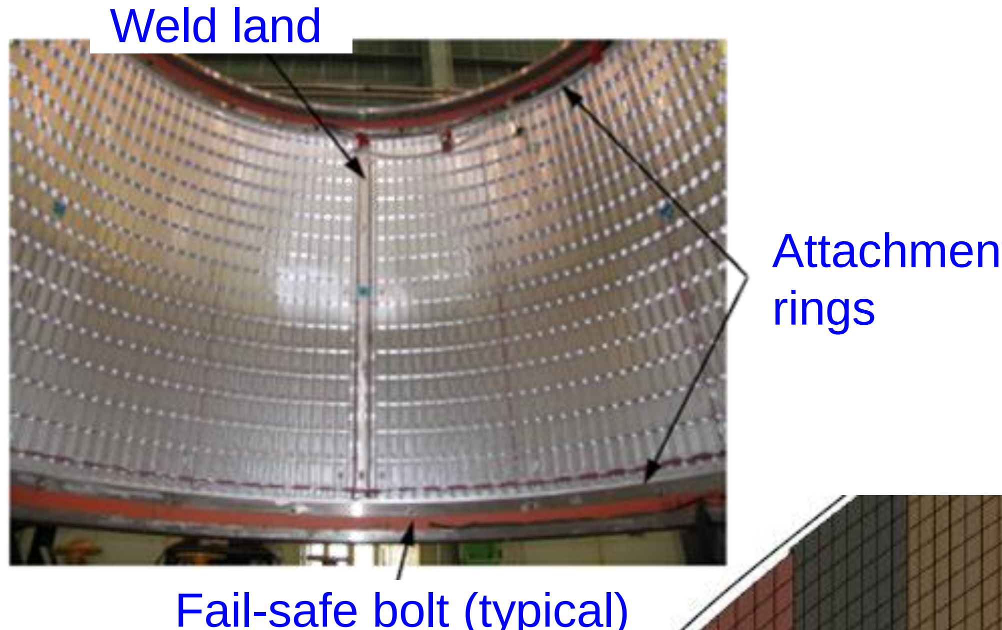
Redistribution of plies around ply drop

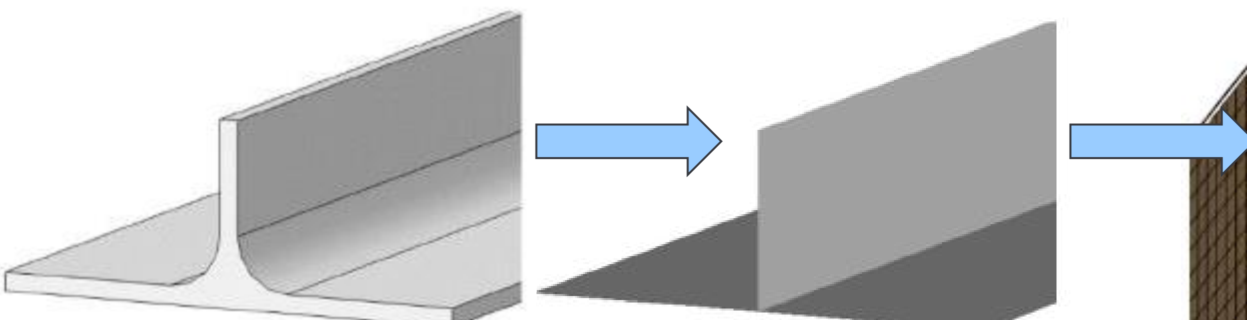


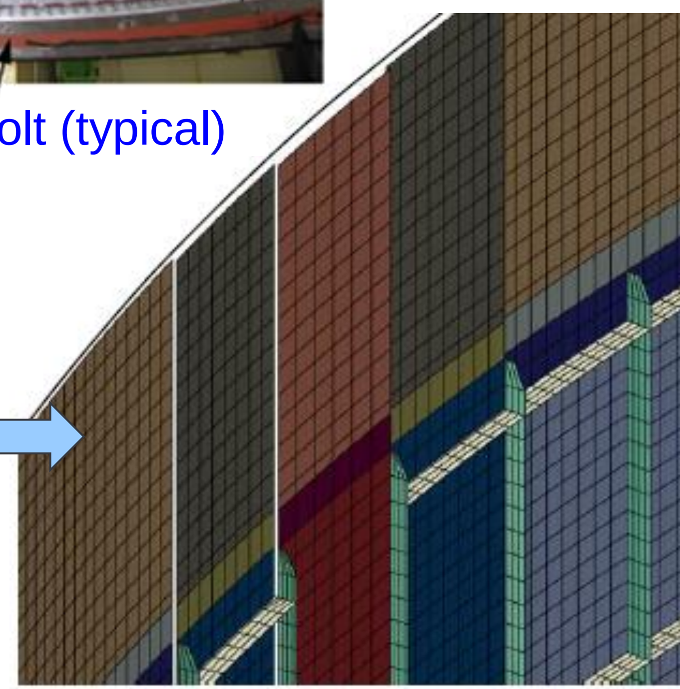
Little evidence of draping

Core cell wall

Integrally Stiffened Metallic Shell







Garcia, et al., 2019

Structural Analysis

"All models are wrong,
but some are useful."
– George E. P. Box

Short Break

Outline

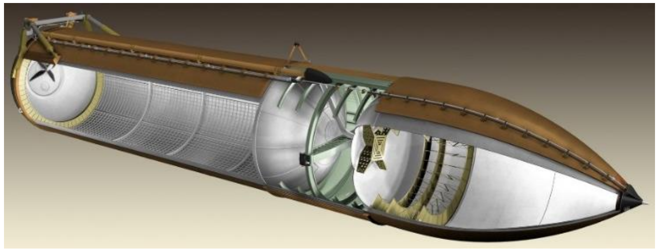
- Part One
  - Mechanical Design Considerations
  - Structural Assessment: Analysis and Test
- Break
- Part Two
  - Shell buckling research at NASA
    - Background
    - Test-article design example
    - Large-scale testing

Shell Buckling Research at NASA

Background

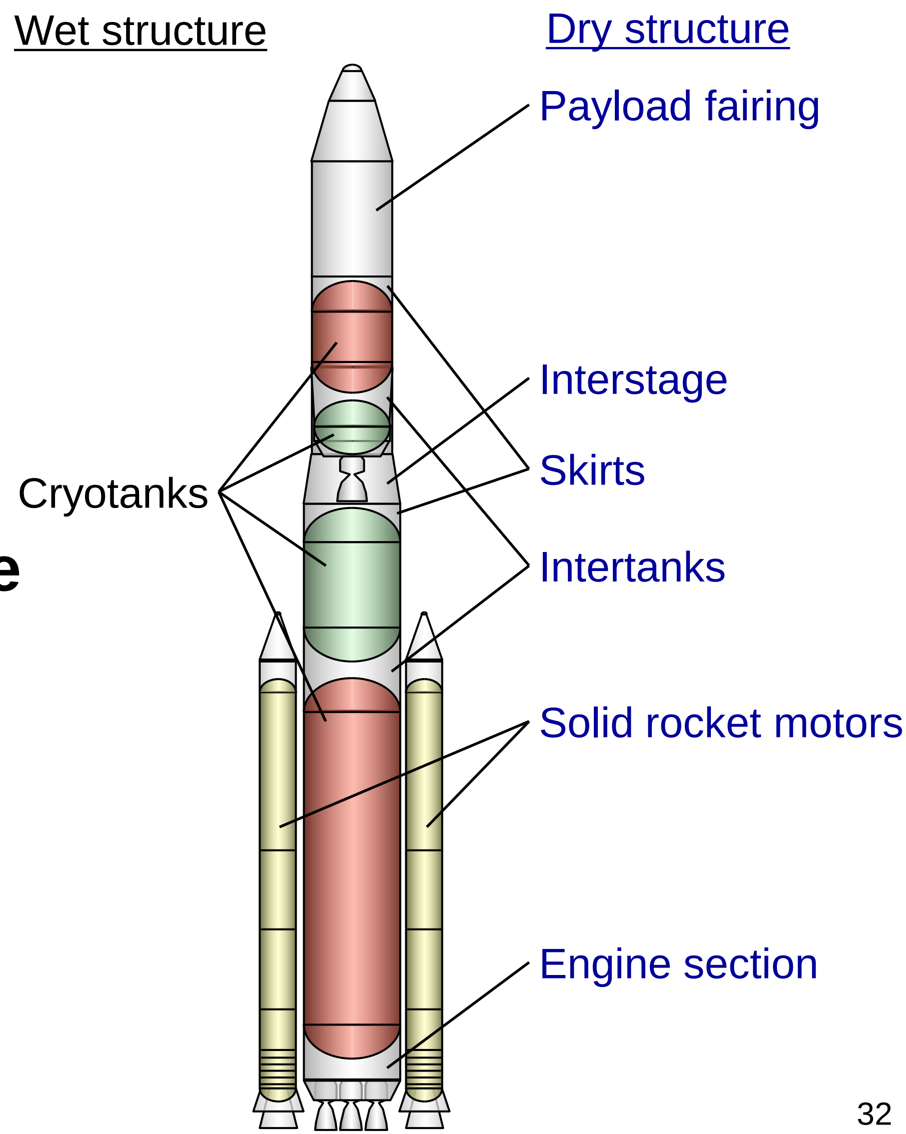
NASA Launch-Vehicle Shell Structures

- **Traditionally, metals have been used for most launch-vehicle primary shell structure**
  - **Tanks**
    - **Integrally stiffened orthogrid or isogrid, etc.**
  - **Dry 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**



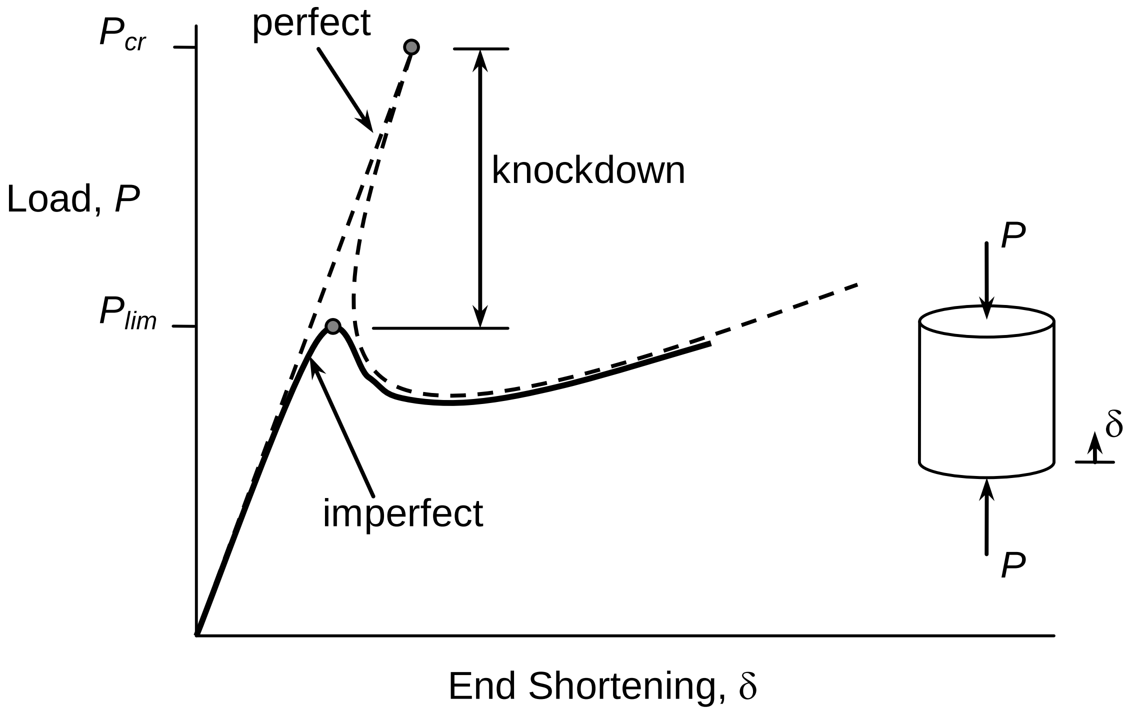
Launch-Vehicle Shell Structures

- **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

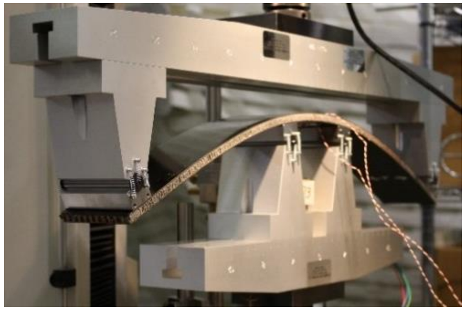
- Most commonly used source of empirical buckling knockdown factors for cylindrical shells
- Pedigree of test articles and test data (1920s-1960s) used to develop the knockdown factors is difficult to assess
- Most test-article designs not relevant to modern launch-vehicle constructions and material 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

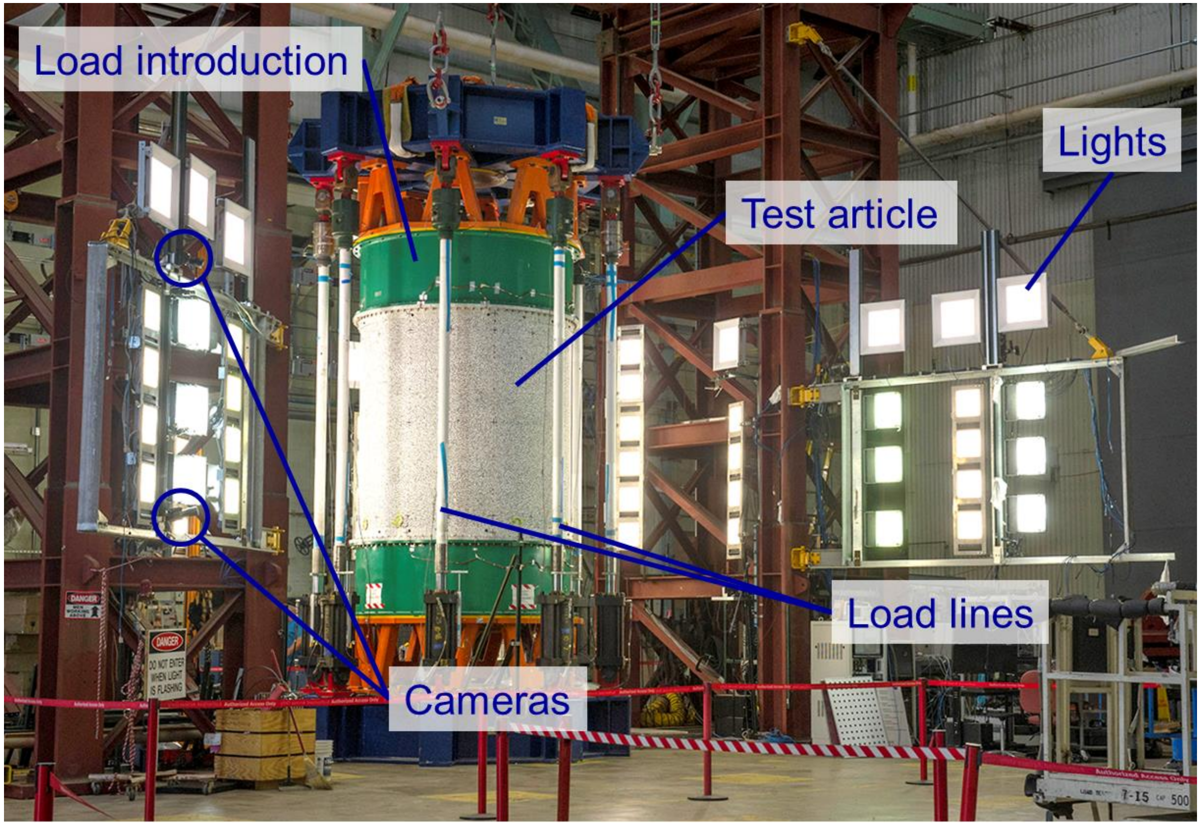
- **Subscale cylinders**
  - 2.4-m diameter
  - Validate analysis approach

MSFC Purpose-Built Test Facility

For subscale cylinder testing

- **Test articles**
  - 2.4-m diameter
  - Lengths up to 3 m

- **Loading**
  - Uniform compression up to 7000 kN
  - 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**

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

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

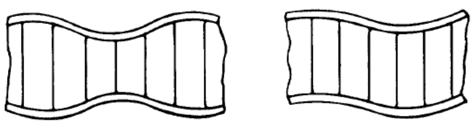
- **Global buckling load, P_{cr}**

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

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

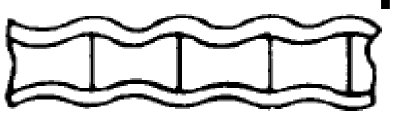
$$\varepsilon_{cr} = \frac{P_{cr}}{4\pi R\, t_f\, \bar{E}_x}$$

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



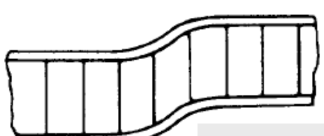
$$P_{FW} = 4\pi R t_f \sqrt{\frac{2}{3}\frac{t_f}{t_c}\frac{E_C\sqrt{\bar{E}_x \bar{E}_y}}{1-\bar{\nu}_{xy}\bar{\nu}_{yx}}}$$

  - **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}**



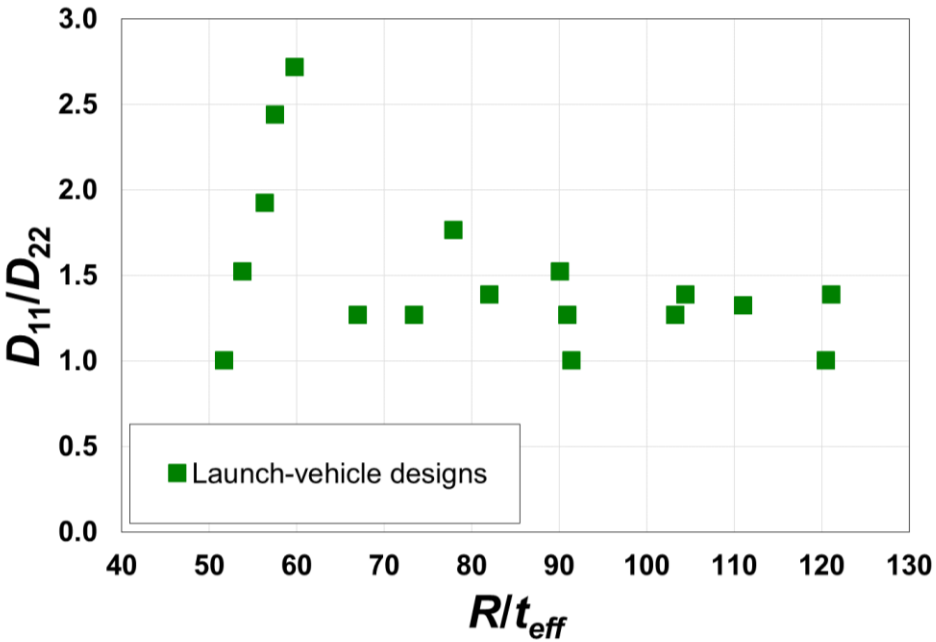
$$P_{CS} = 4\pi R\, t_f \frac{G_{xz}\, t_c}{2 t_f}$$

Sullins, et al., 1969

Subscale Cylinder Testing (2.4-m diameter)

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

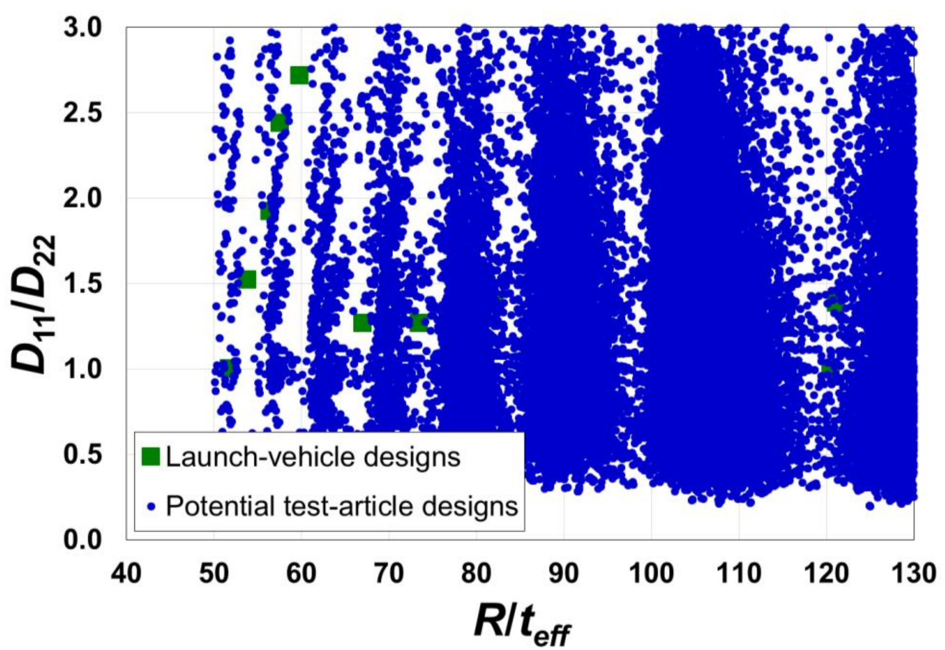
- Calculate design-space parameters for launch-vehicle components



Subscale Cylinder Testing (2.4-m diameter)

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

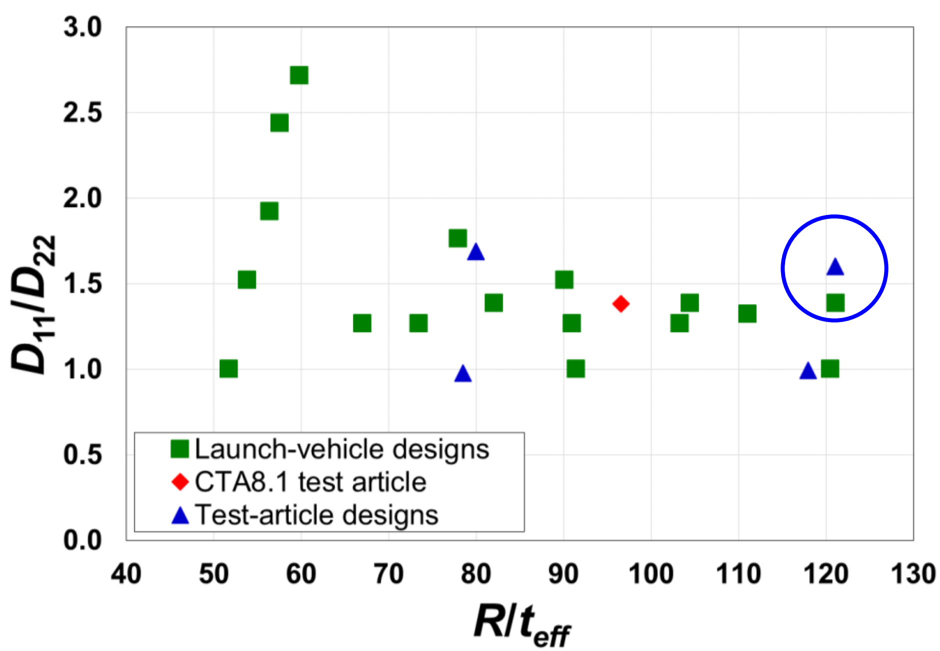
- Calculate design-space parameters for launch-vehicle components
- Generate possible 2.4-m-diameter subscale designs
  - Variables: number of plies, ply angle, core thickness



Subscale Cylinder Testing (2.4-m diameter)

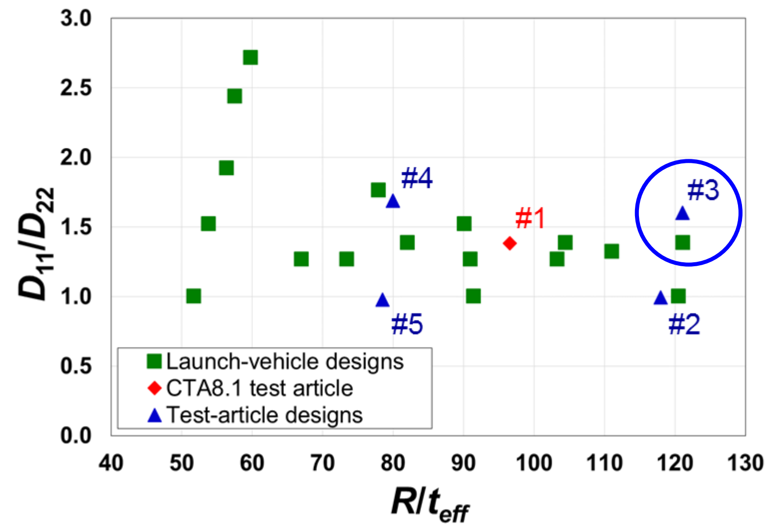
Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

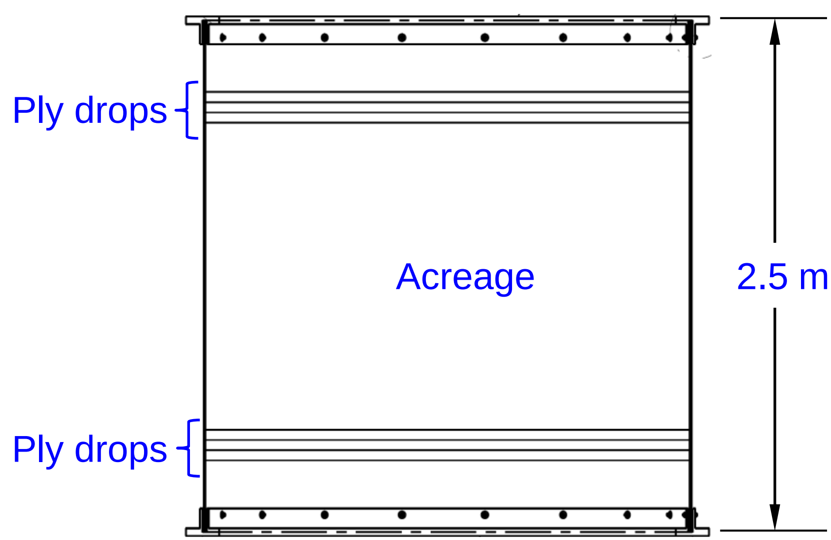
- Calculate design-space parameters for launch-vehicle components
- Select subscale designs
  - Criteria: buckling critical, failure load, design space, etc.
  - Five test-article designs selected as minimum number to validate analysis methods



Selected Design

- **Faces**
  - **5-ply axially stiff facesheets: $[\pm 30/\overline{90}]_s$**
  - **Padups: four interleaved ±45 plies/face dropped at 35 cm, 40 cm, 46 cm, and 51 cm**
- **Core**
  - **Acreage: 50 kg/m³ aluminum honeycomb**
  - **End 25 cm: 130 kg/m³ aluminum honeycomb**
  - **Thickness: 5 mm**
- **To be tested in axial compression to failure**

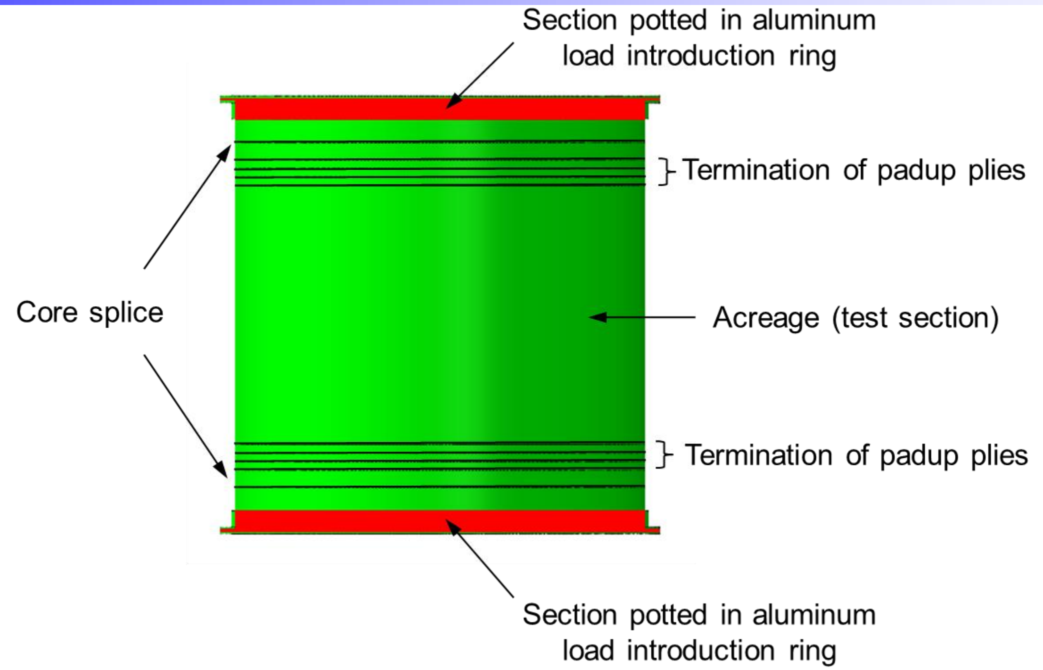




Test Article Design

Finite Element Analysis: Shell Model

Finite Element Shell Model

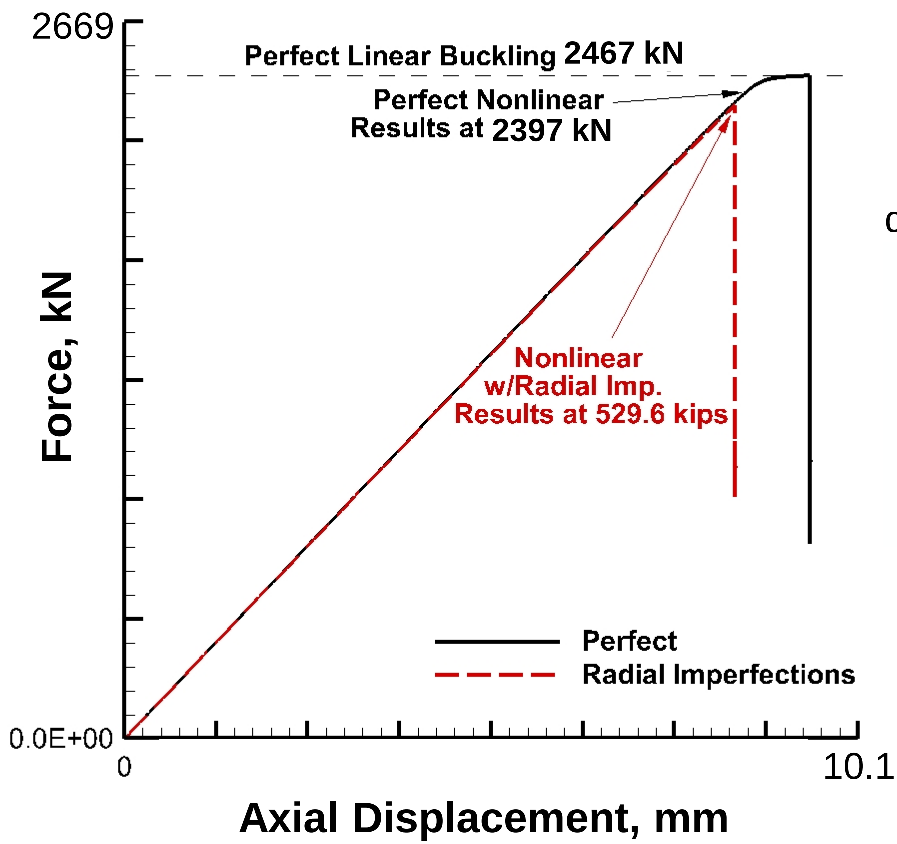


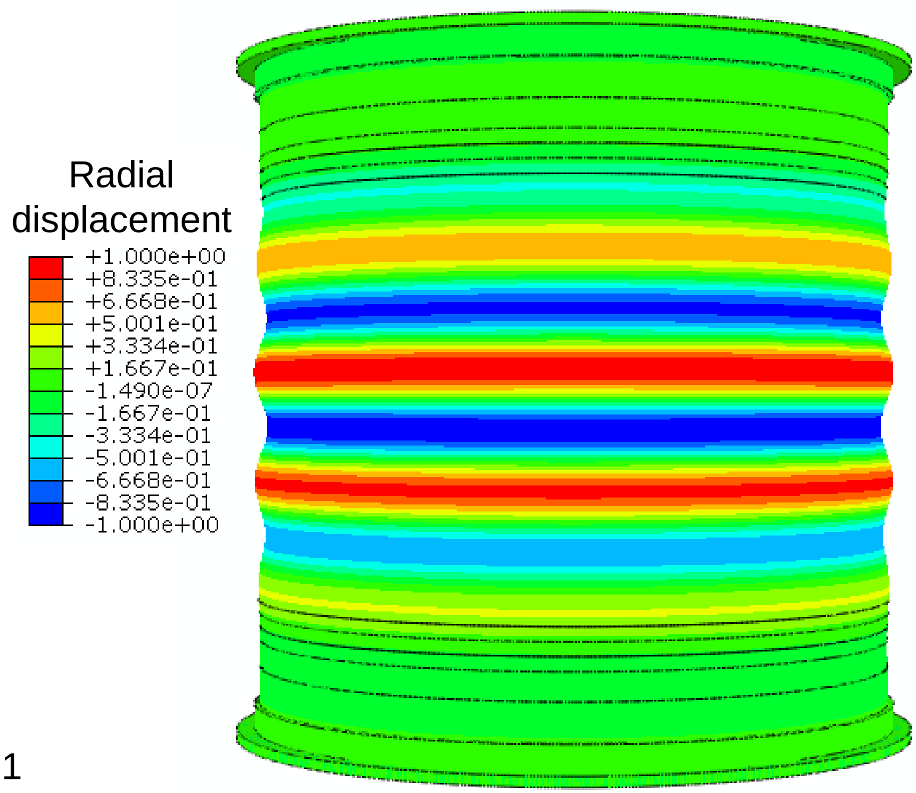
- **Model**
  - **Approximately 154,000 shell elements (S4R)**
  - **Element size: 13 mm in the axial direction by 0.5-degree (approximately 10 mm) in the circumferential direction**
  - **Problem size: approximately 932,000 degrees-of-freedom**

- **Analyses**
  - **Linear buckling**
  - **Nonlinear transient buckling (perfect and imperfect geometries)**

Characteristic Loads and Linear Buckling

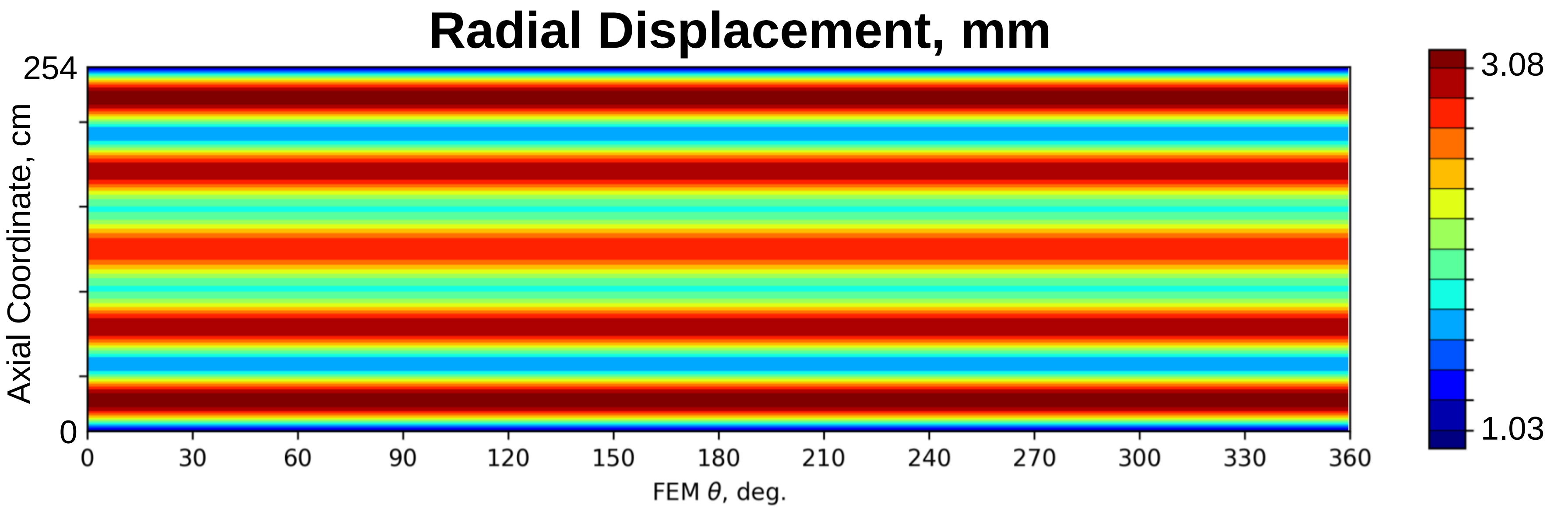
Load versus end shortening

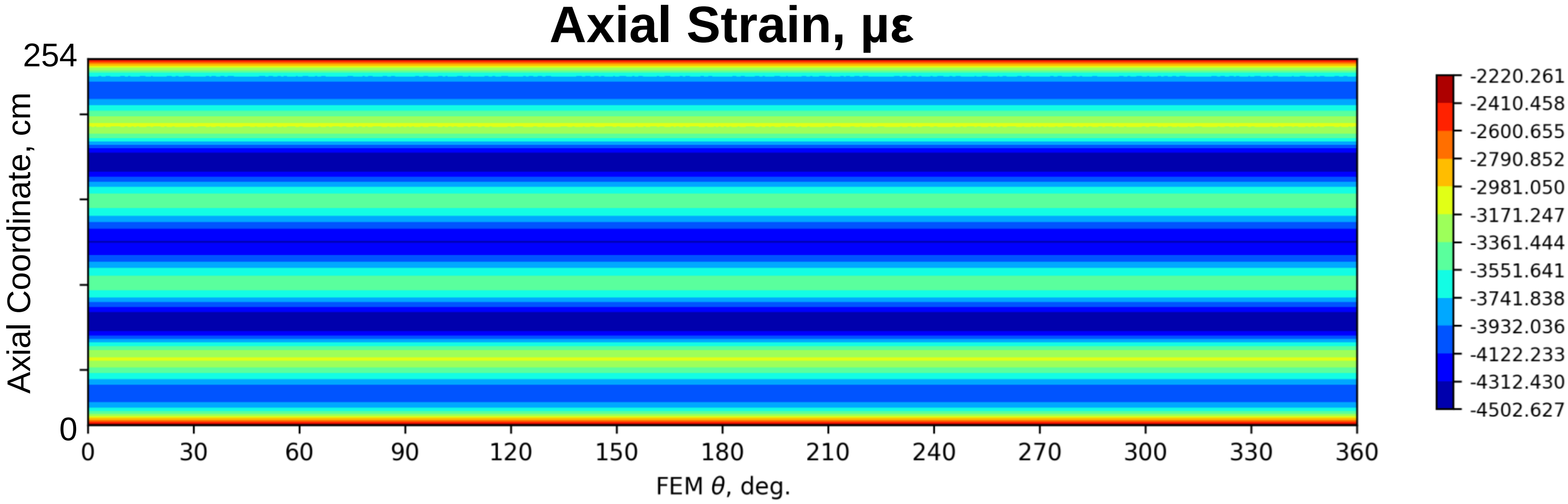




Radial displacement, fundamental mode, 2467 kN

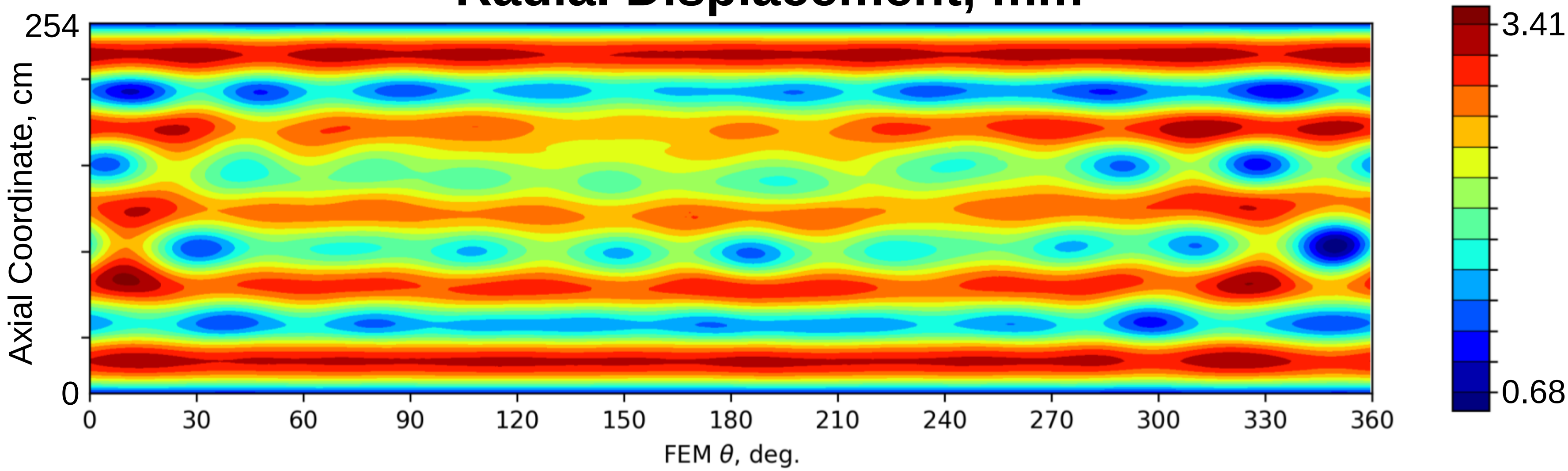
Nonlinear Analysis at 2397 kN
Perfect Geometry



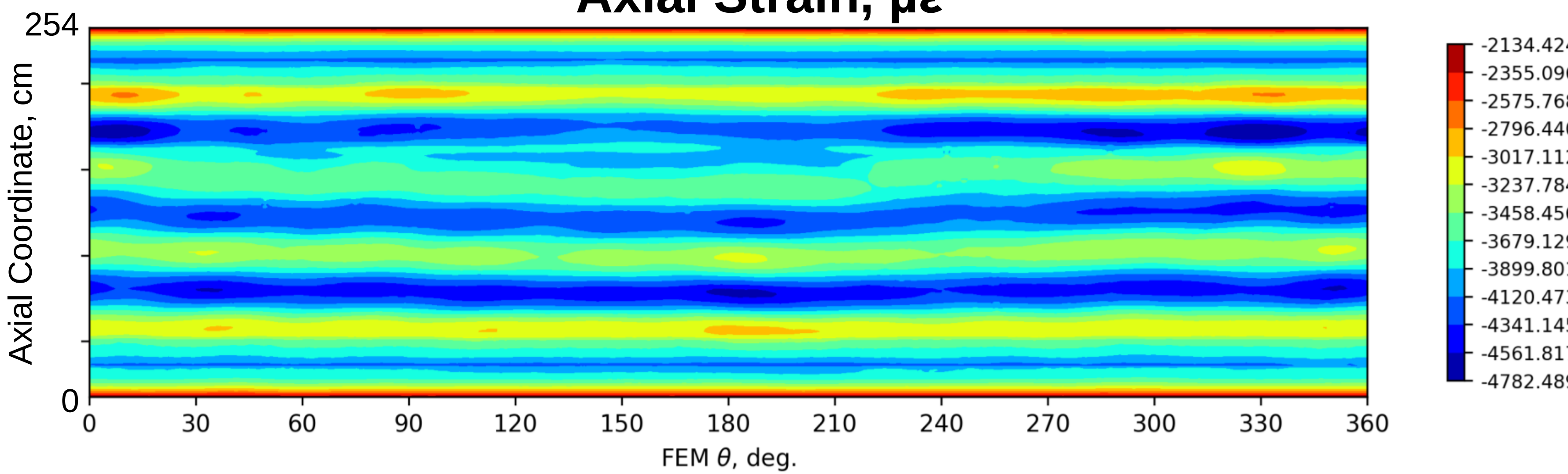


Nonlinear Analysis at 2356 kN
Geometry with Radial Imperfections

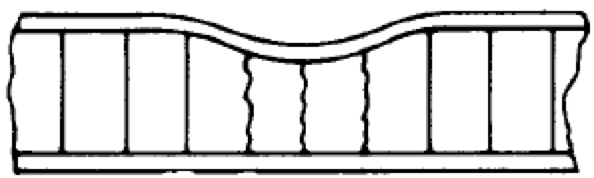
Radial Displacement, mm



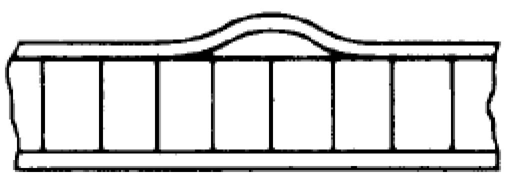
Axial Strain, με



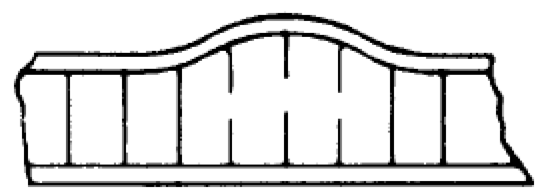
Additional Sandwich Composite Failure Modes



Core crushing



Core-to-facesheet separation



Core tensile failure

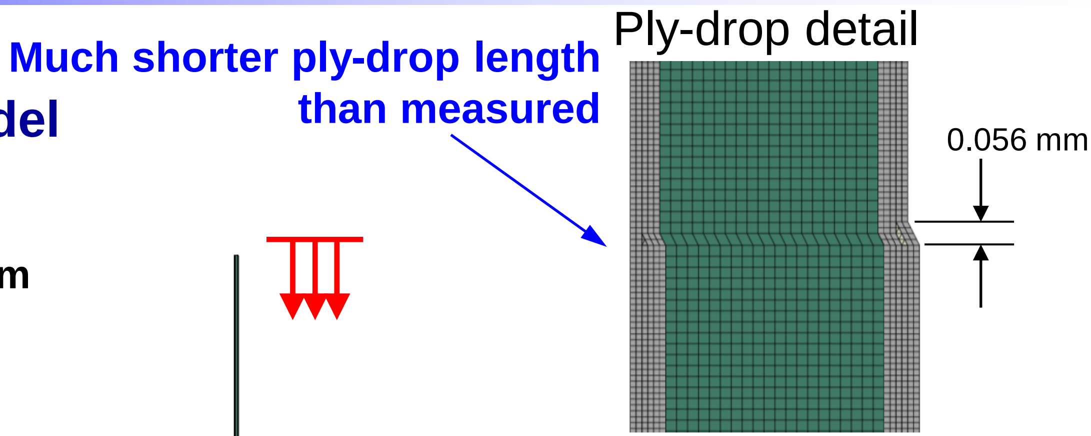
Sullins, et al., 1969

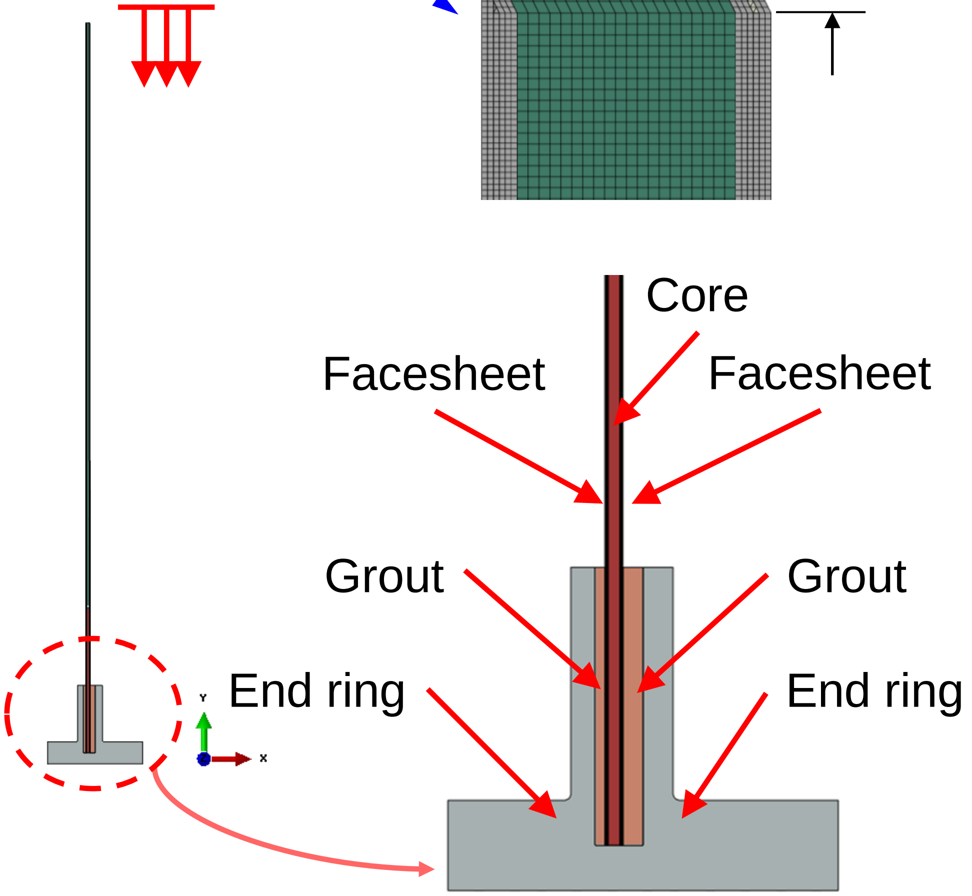
Test Article Design

Finite Element Analysis: Axisymmetric Model

Axisymmetric FEA Analysis: Model

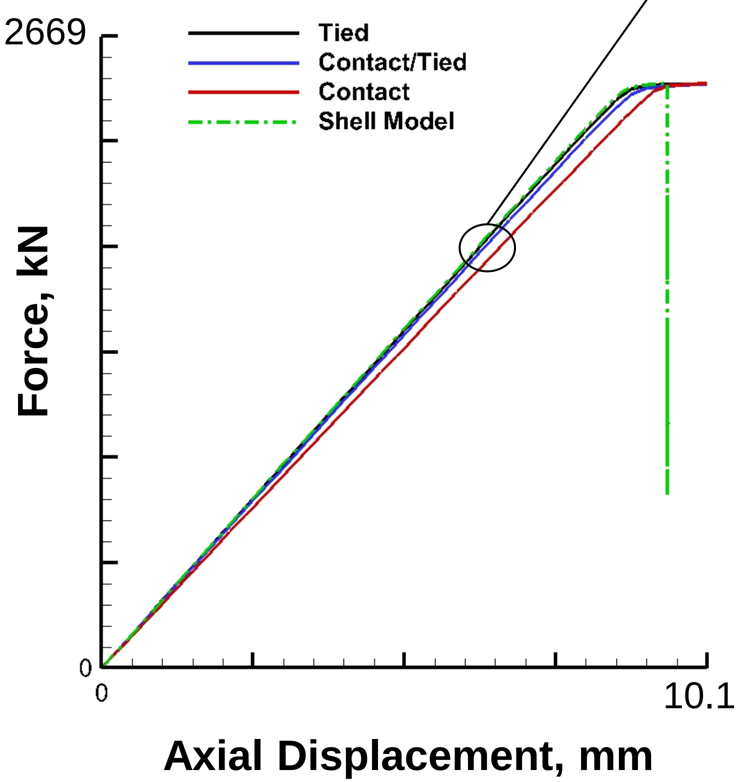
- **Half-cylinder-height model**
  - Applied displacement at midlength
  - Midlength constrained from rotating
- **Abaqus CAX4 elements**
  - Fully integrated
  - Axisymmetric continuum formulation
- **Individual plies modeled**
  - Ply drops modeled as wedges
  - Wedges have same properties as terminating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

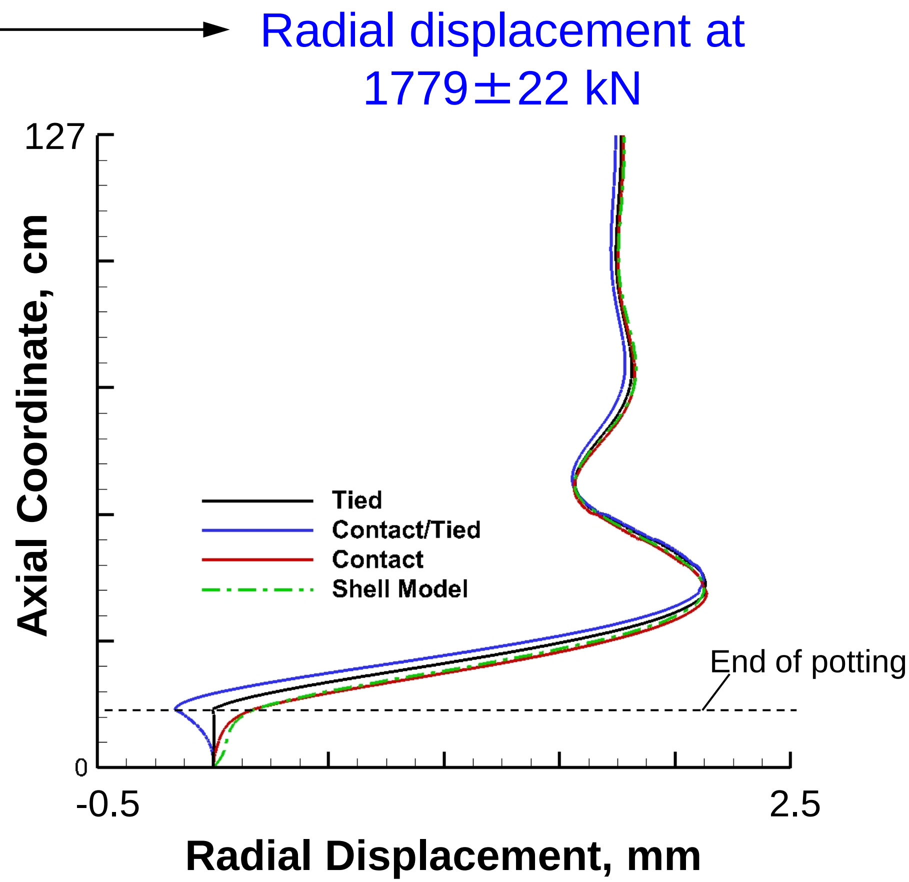




Axisymmetric Analysis

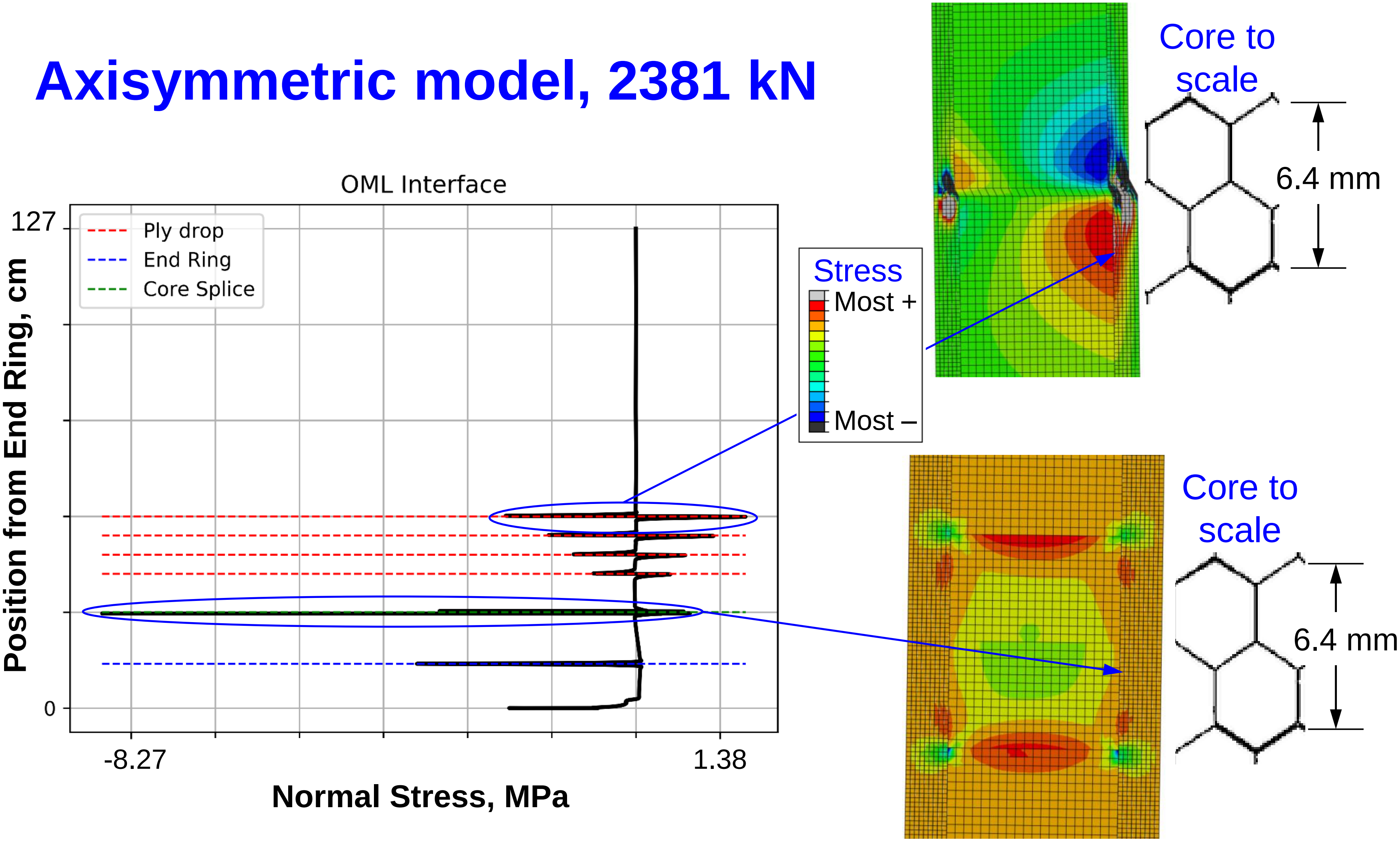
Comparison with perfect-geometry shell model





Axisymmetric FEA Analysis: Core-to-Facesheet Interface Stresses

Axisymmetric model, 2381 kN

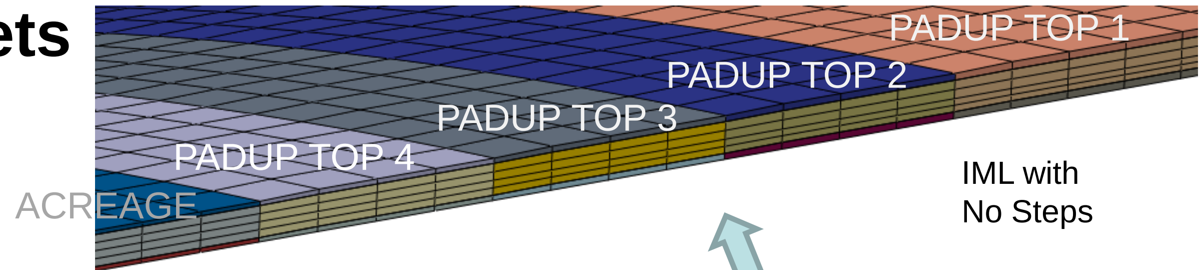


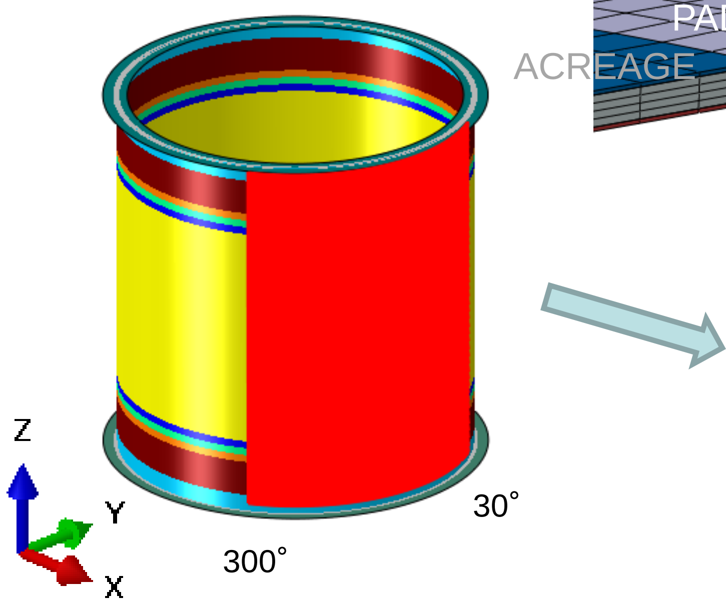
Test Article Design

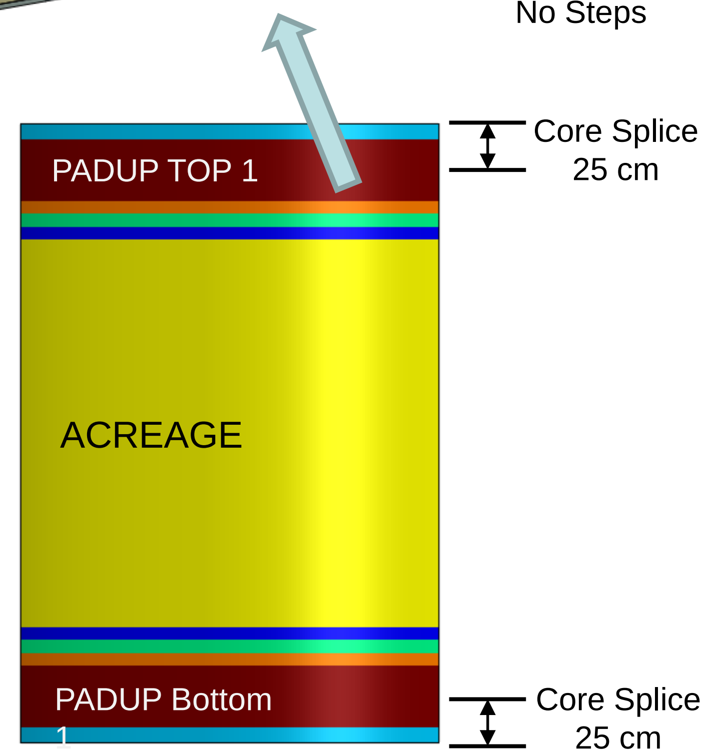
Finite Element Analysis:
Global-Local Model

Finite Element Analysis: Global-Local Analysis

Solid elements in core, continuum shell elements in facesheets





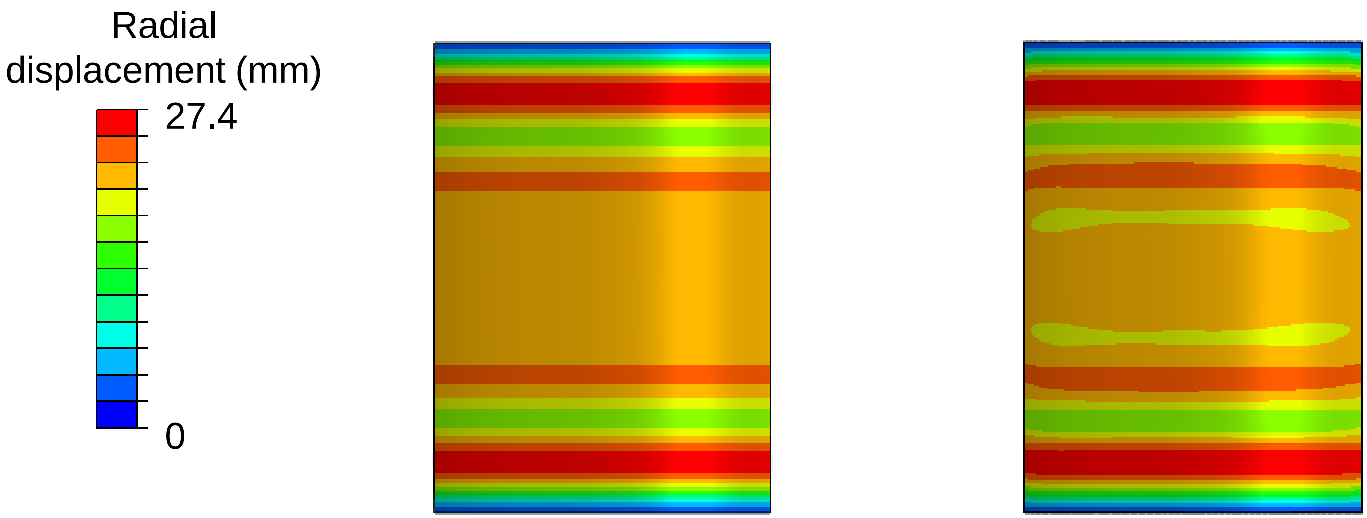


Two Global Models

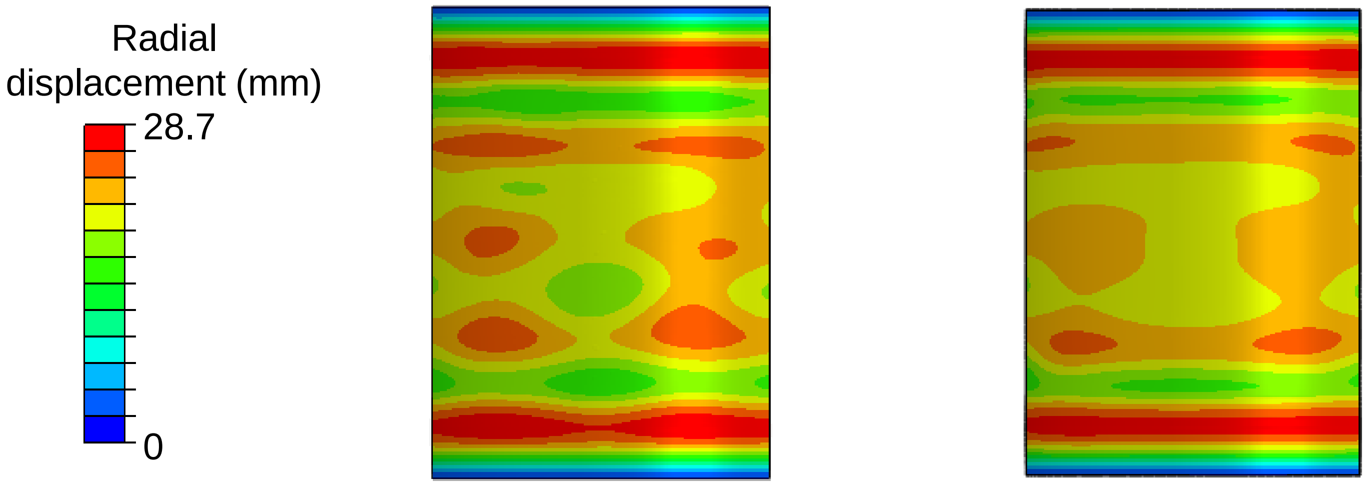
- Perfect mesh model
- Radial imperfection mesh model

Finite Element Analysis Results: Global-Local Analysis

Global Shell Model | Local Solid Model



Perfect, 2144 kN



With radial imperfection, 2135 kN

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

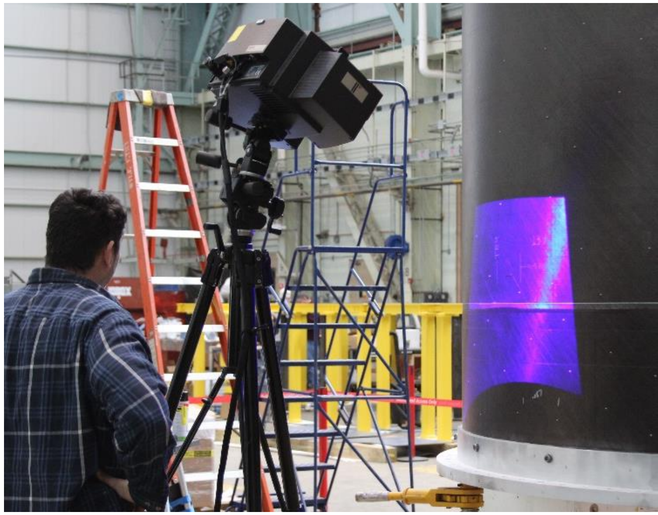
Shell Buckling Research at NASA

Test and Analysis Correlation

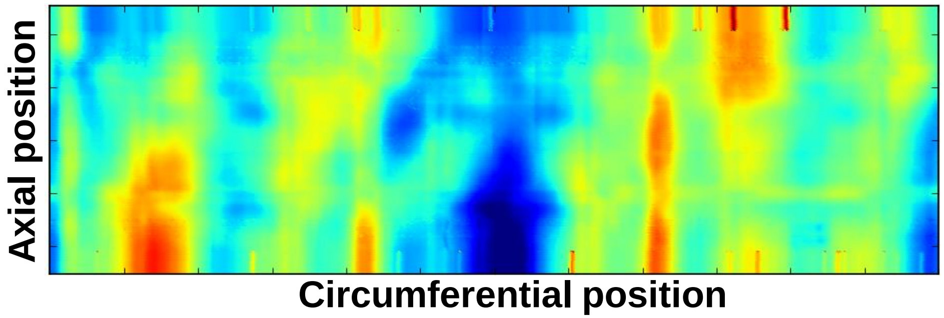
First Large-Scale Test Article

- **Construction**
  - 2.4-m-dia. honeycomb-core sandwich composite cylinder
  - Single piece (unsegmented)
    - Core: 6.4-mm Korex honeycomb
    - Facesheets: 7-ply $[\pm 45/0/\overline{90}]_s$
- **Fabrication**
  - Built by Northrop Grumman under collaborative agreement
  - Manufacturing development unit
  - Out-of-autoclave
    - Material properties not well known

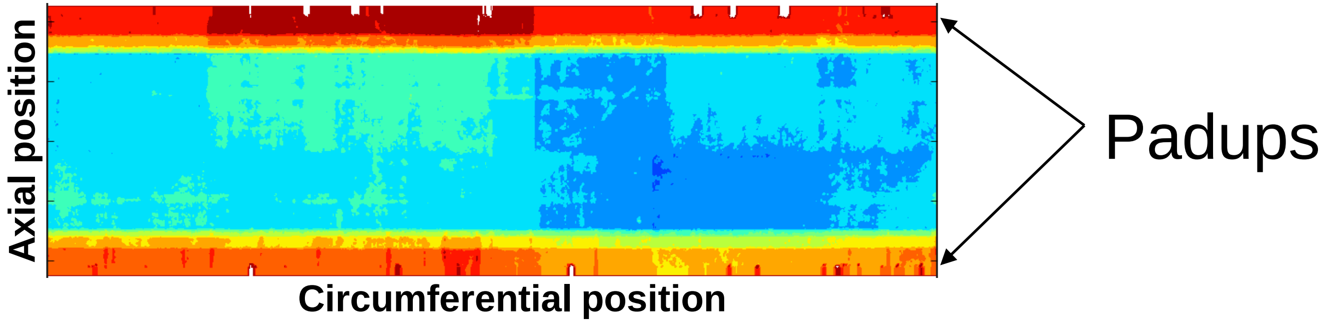
Structured Light Scanning Geometry Measurement



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

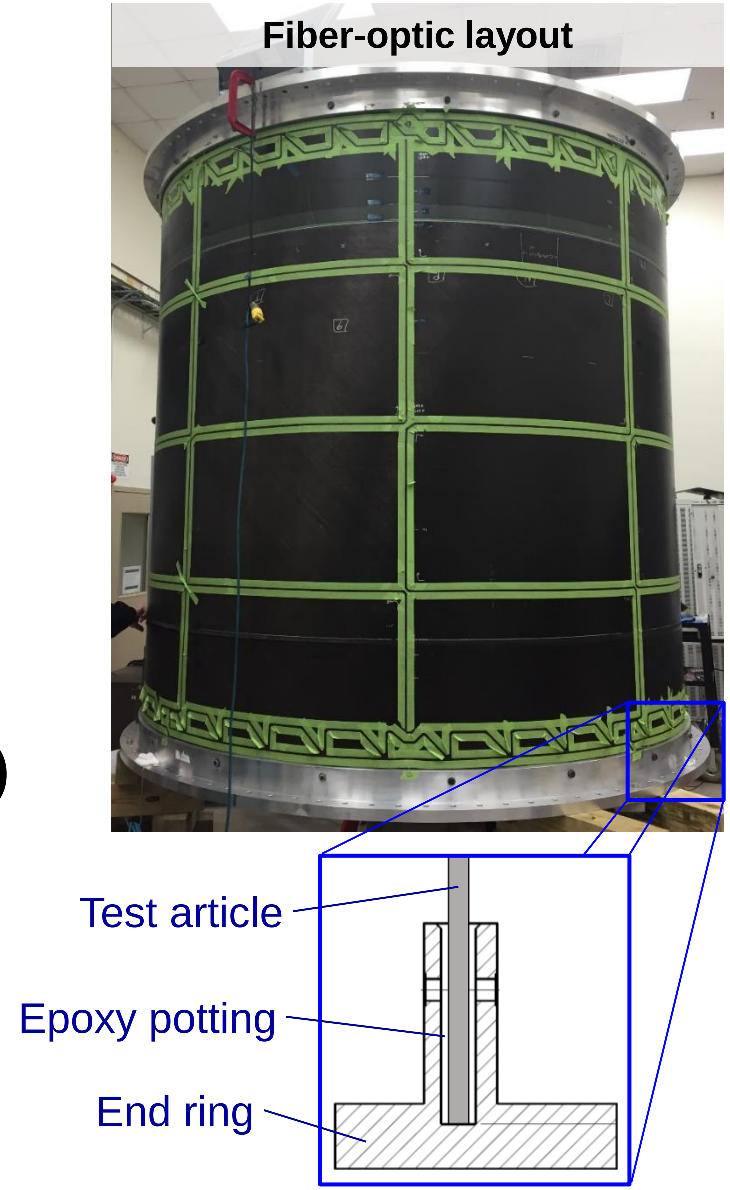


- **Thickness variation**

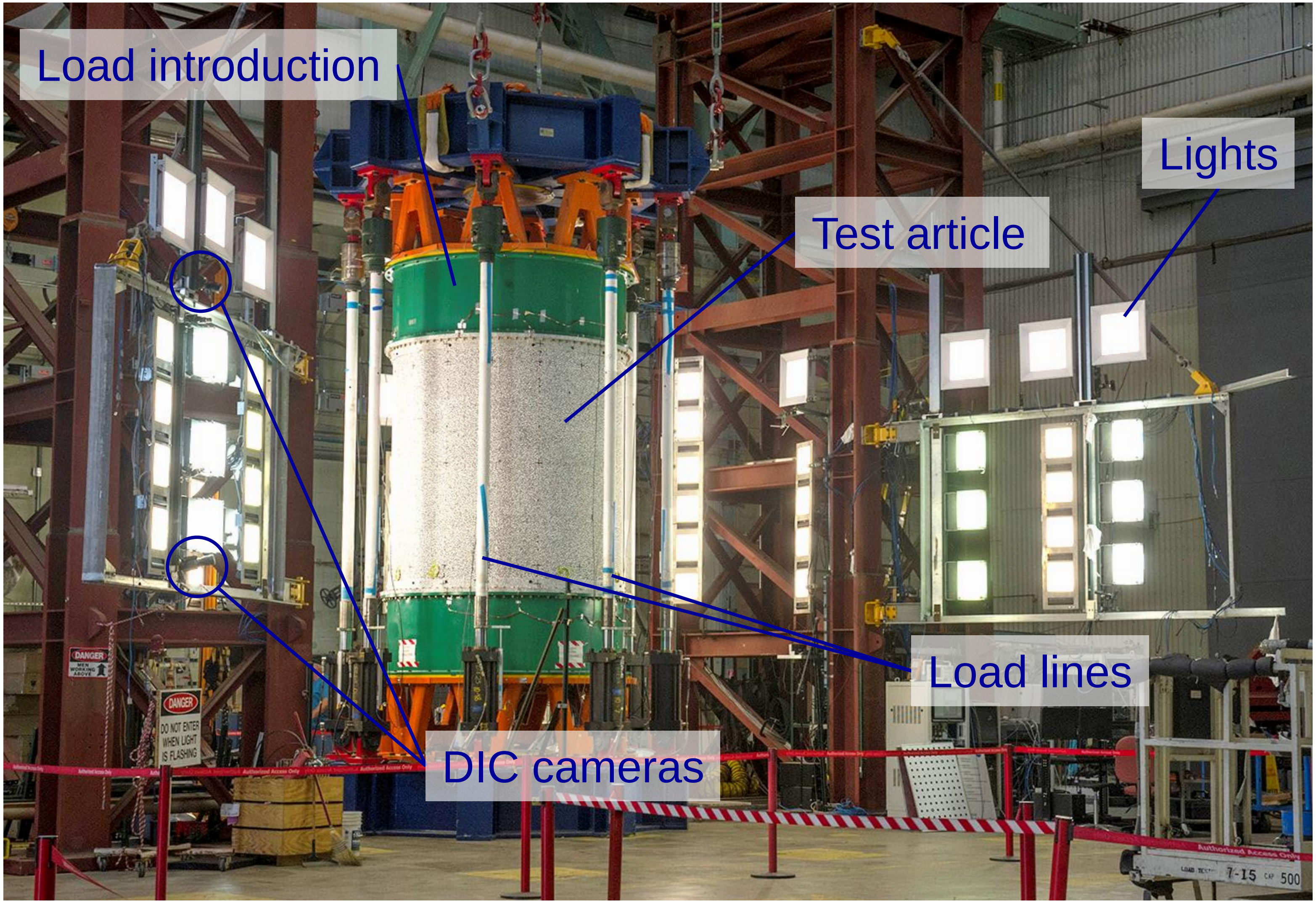


Testing and Instrumentation

- **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



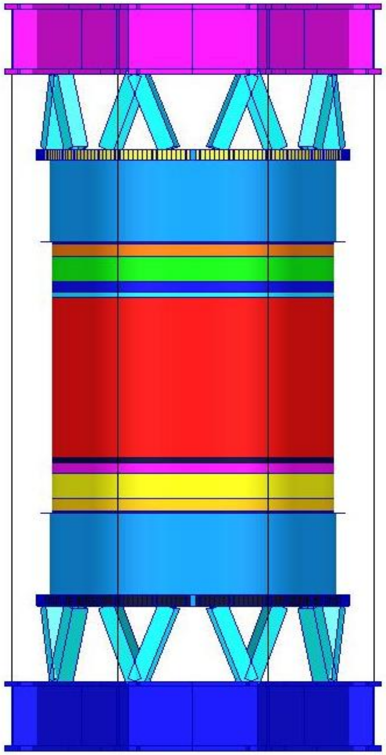
Test Setup



Load introduction
Lights
Test article
Load lines
DIC cameras

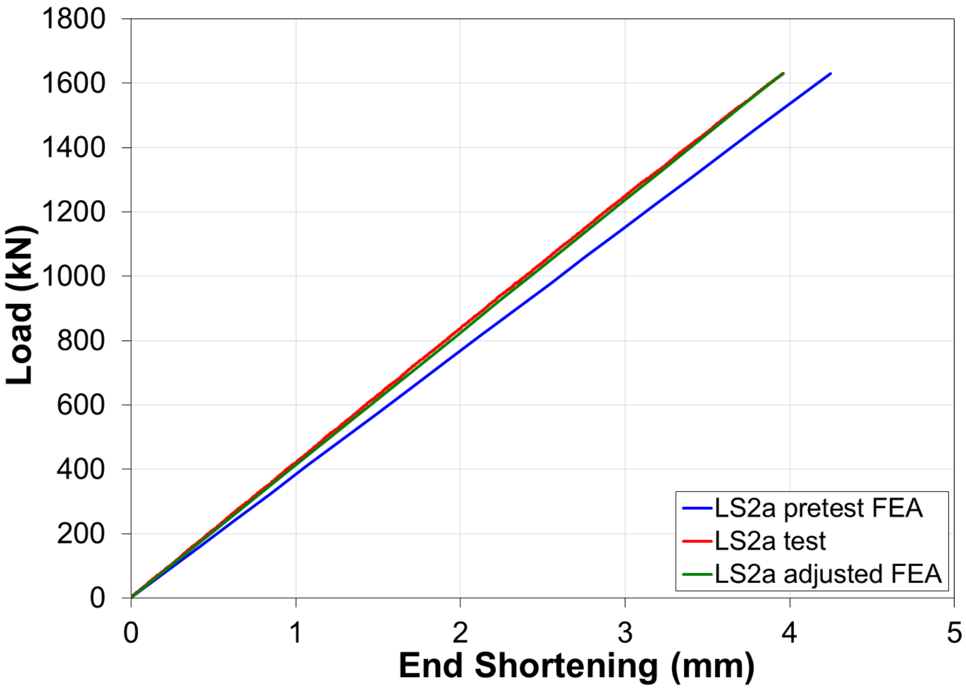
Analysis Approach

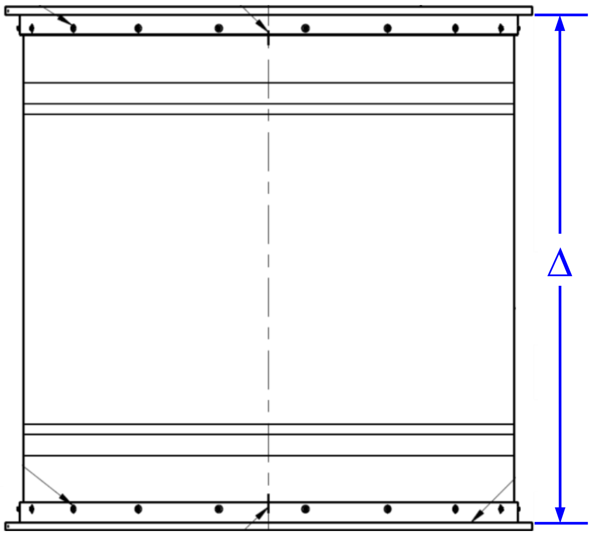
- **Test article and testing hardware**
  - **Abaqus shell and beam elements**
  - **156,960 elements**



- **Geometrically nonlinear transient analysis**
  - **Radial and thickness variations included**

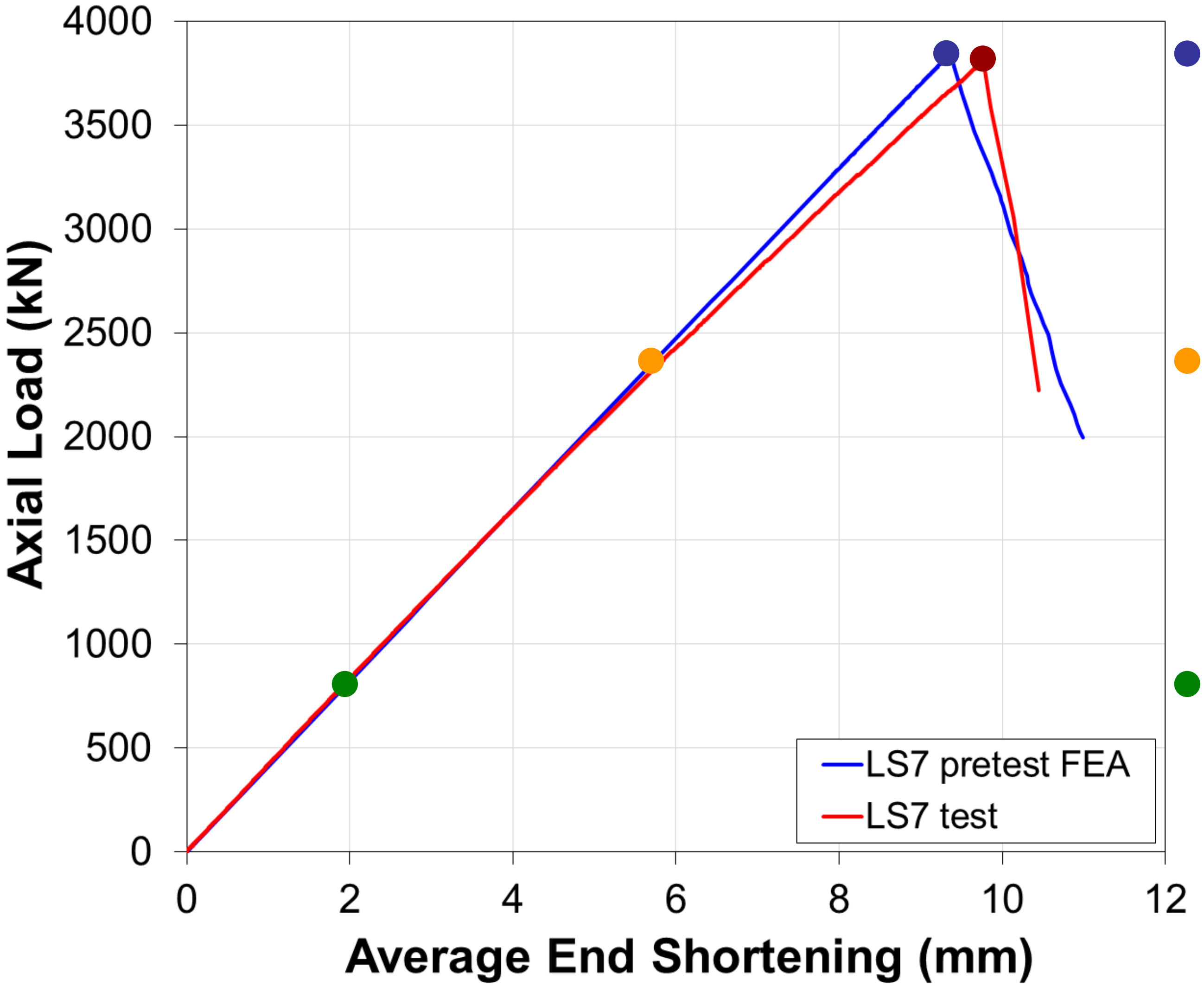
Subcritical Compression



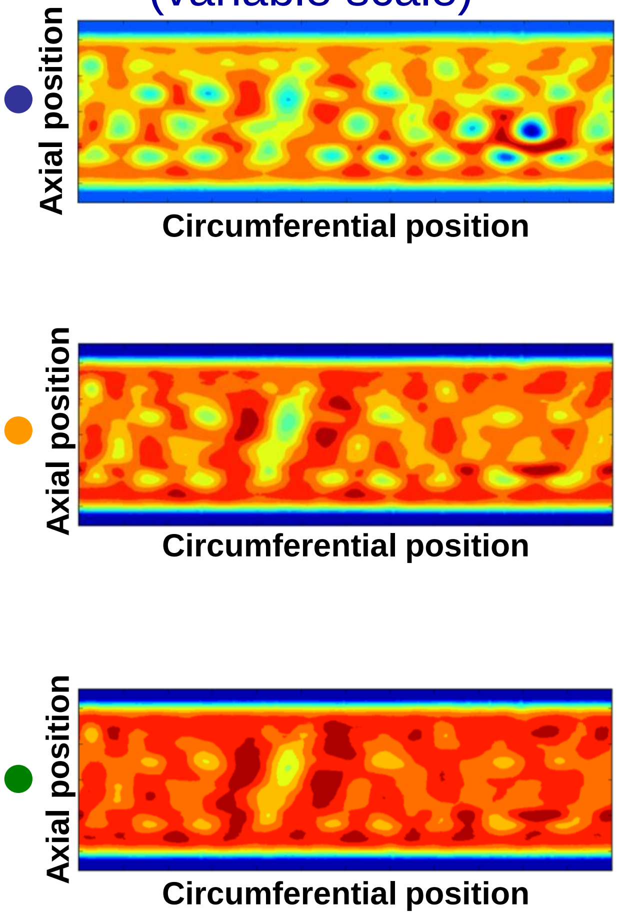


- **Significant difference in axial stiffness**
  - **Measured at end rings**
  - **Manufacturing demo—uncertain material properties**
  - **Ply extensional stiffnesses increased by 8.7%**

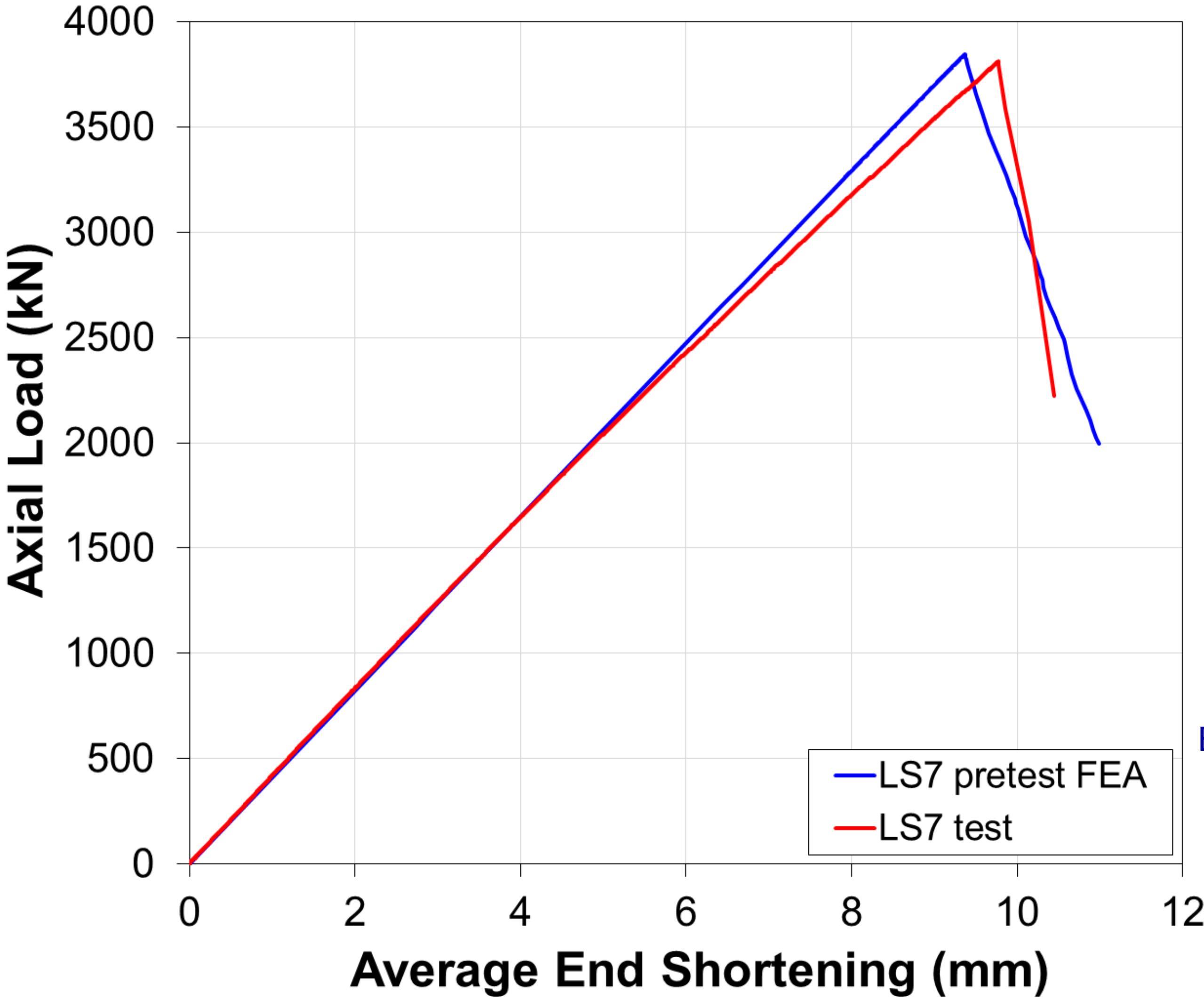
Test and Analysis Correlation: End Shortening



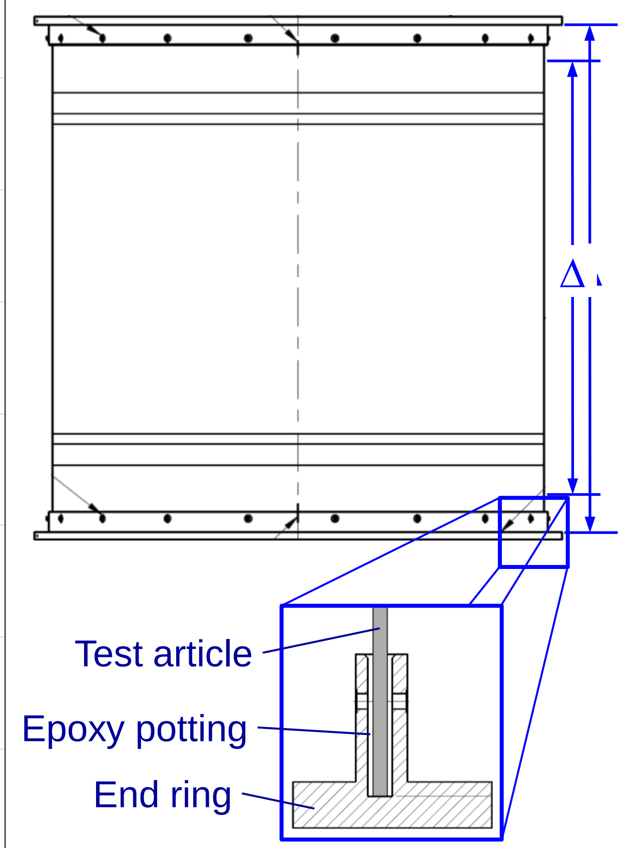
Predicted radial deformation (variable scale)



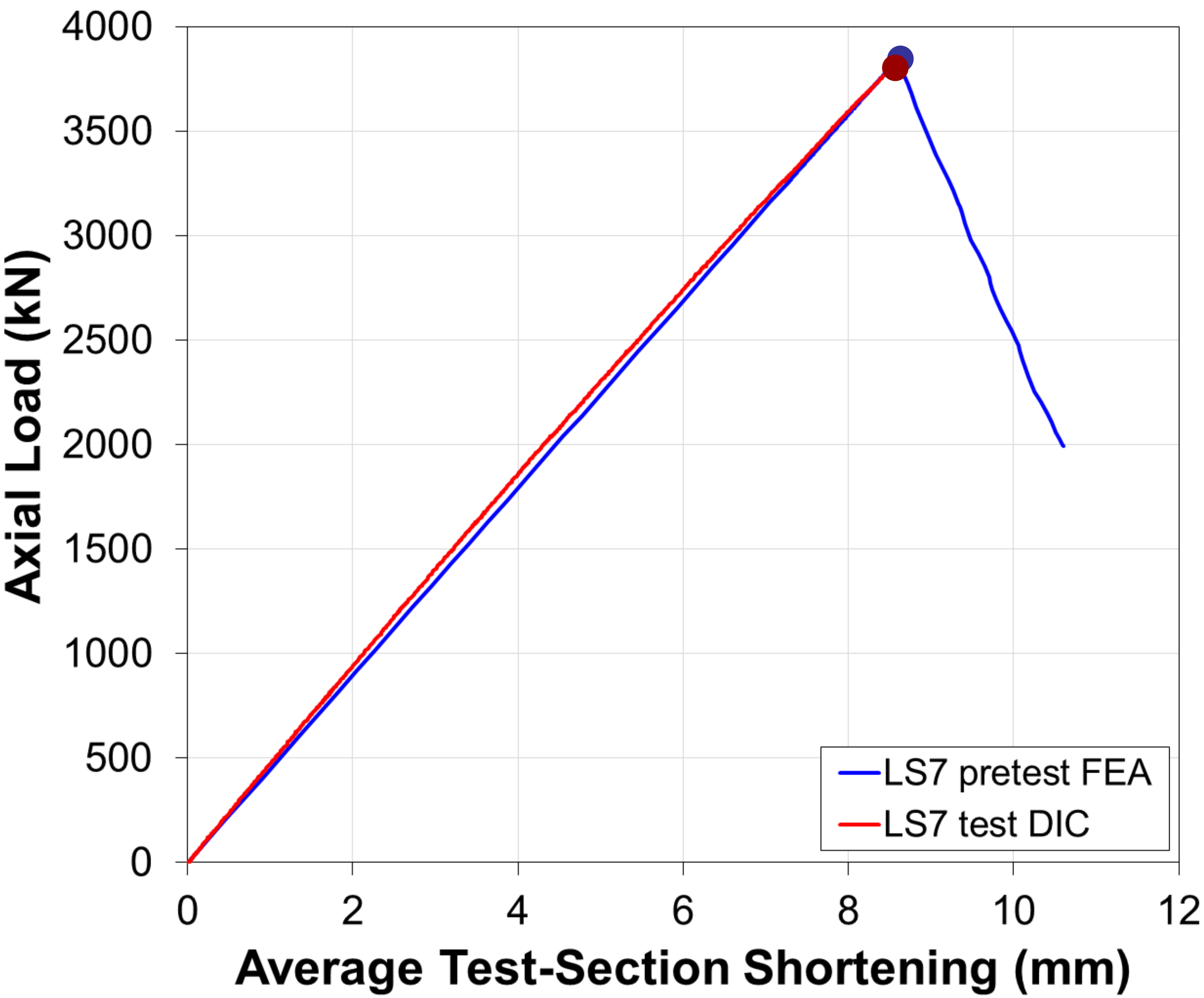
Test and Analysis Correlation: End Shortening

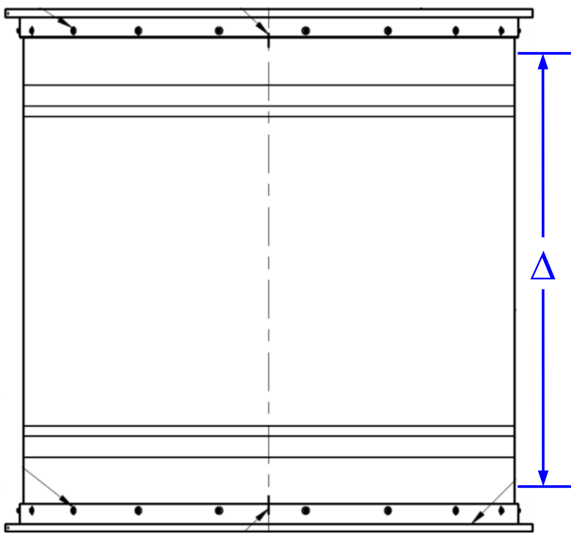


Slipping in end rings occurred



Test and Analysis Correlation: Test-Section End Shortening





Material Testing

- **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

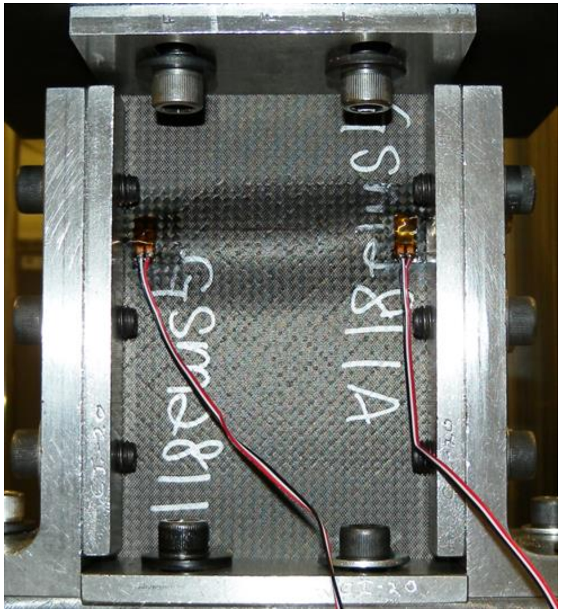
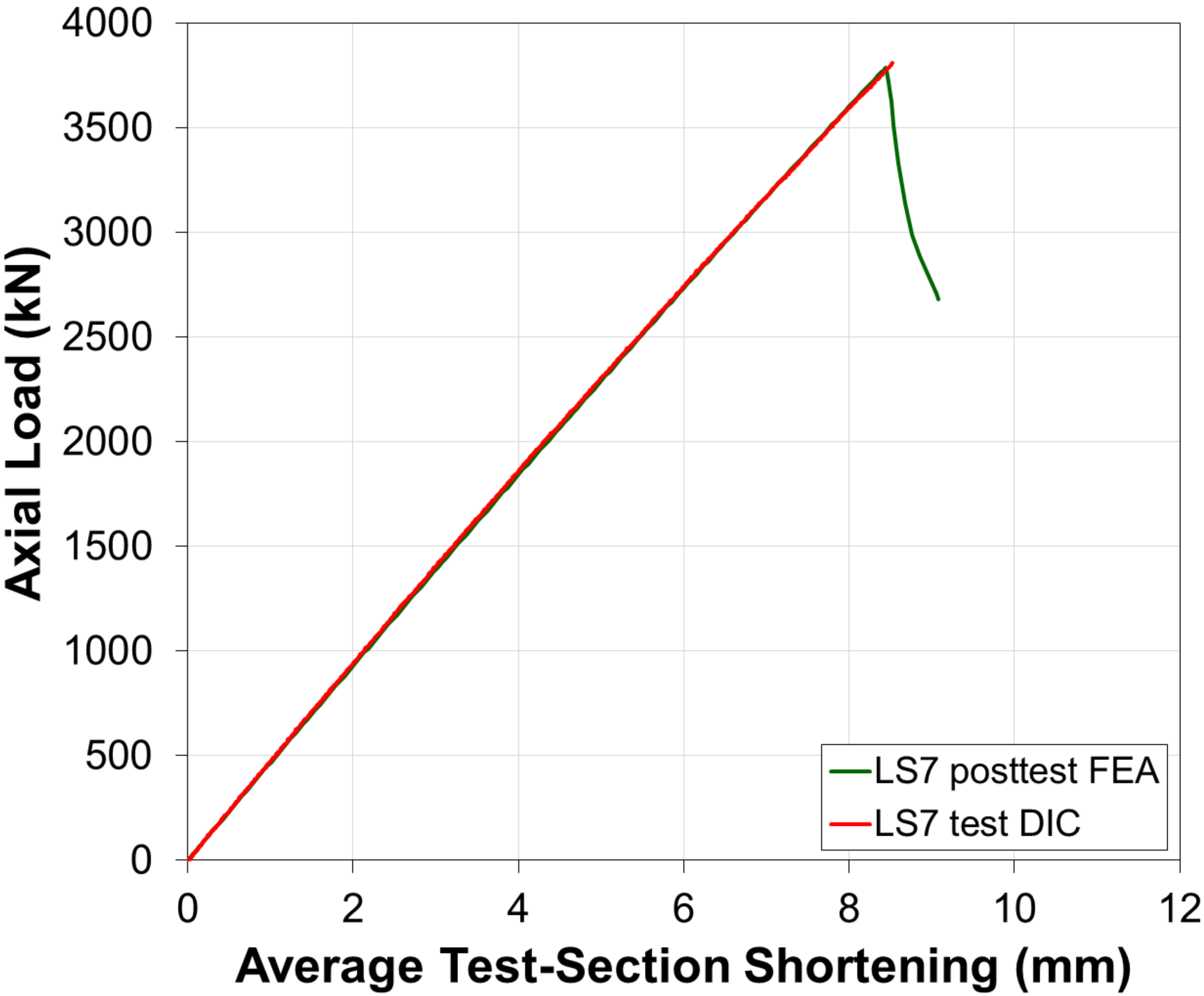
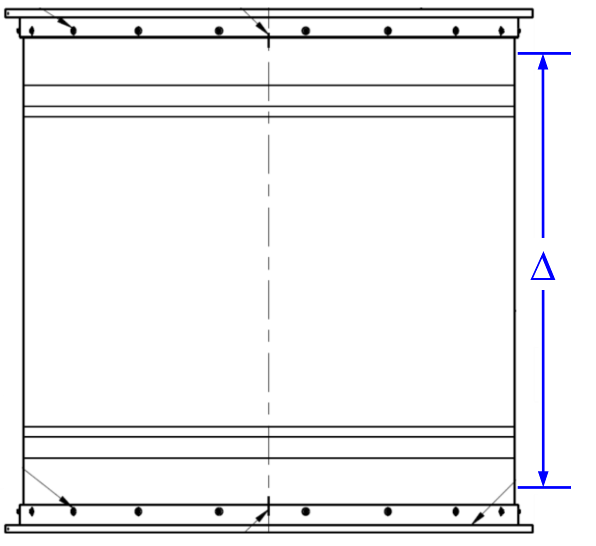


Photo: NIAR

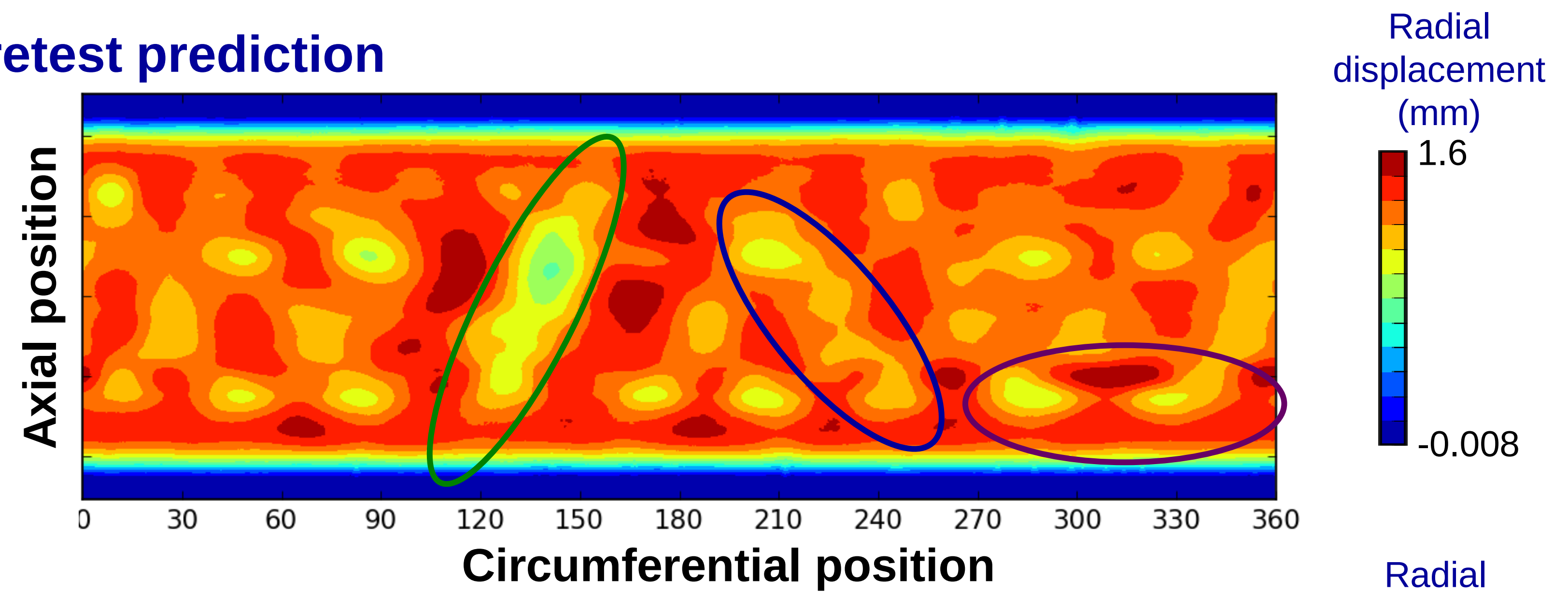
Test and Analysis Correlation: Test-Section End Shortening



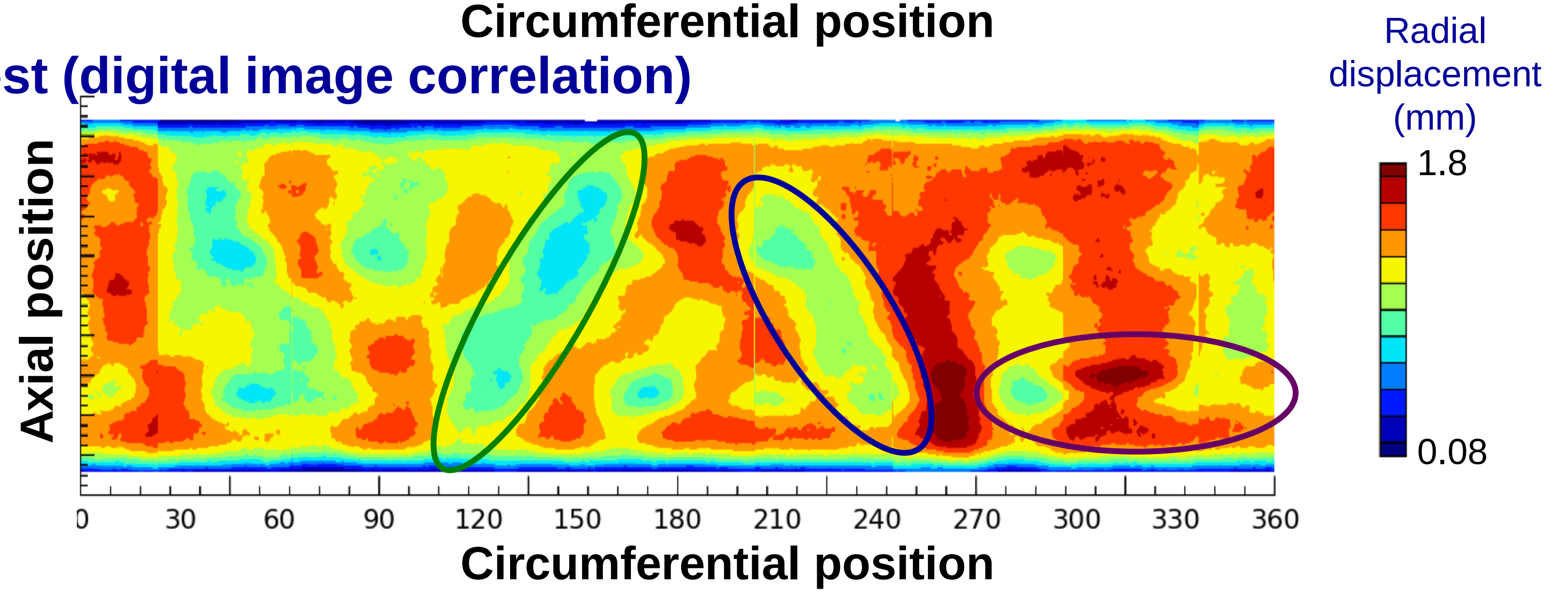


Test and Analysis Correlation: Radial Deformation, 2038 kN

Pretest prediction

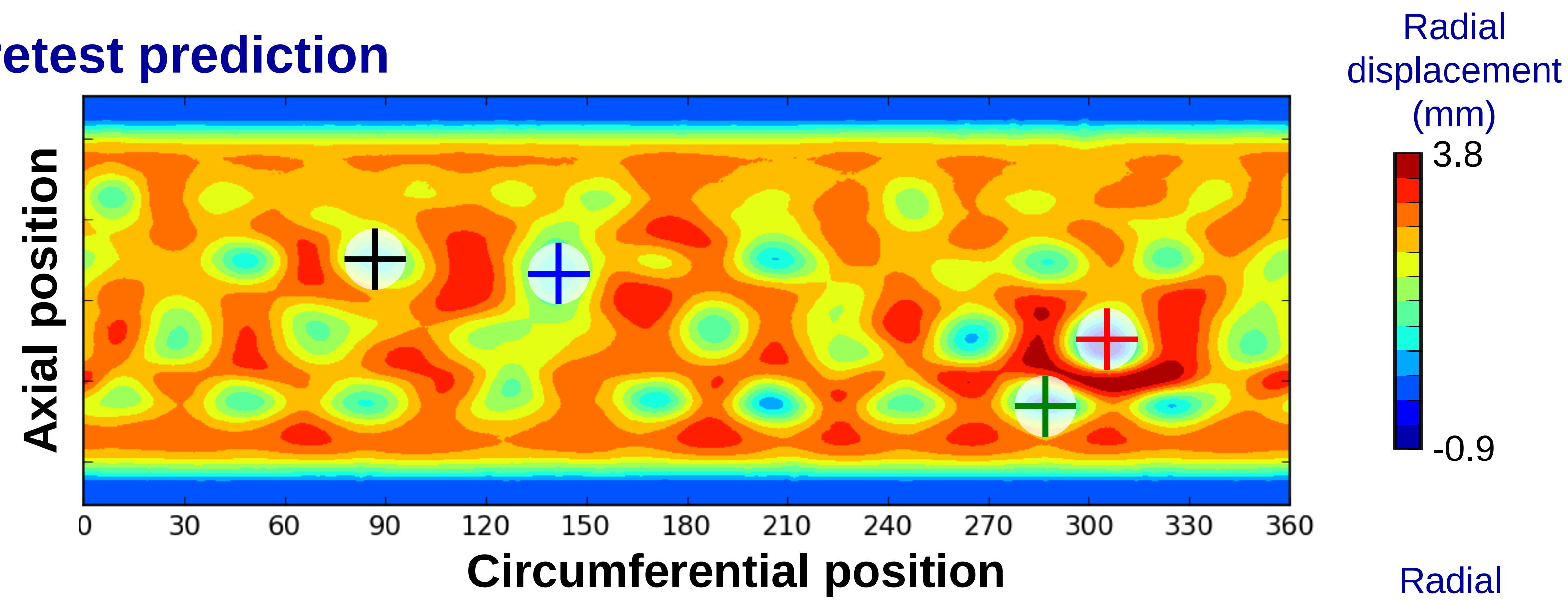


Test (digital image correlation)

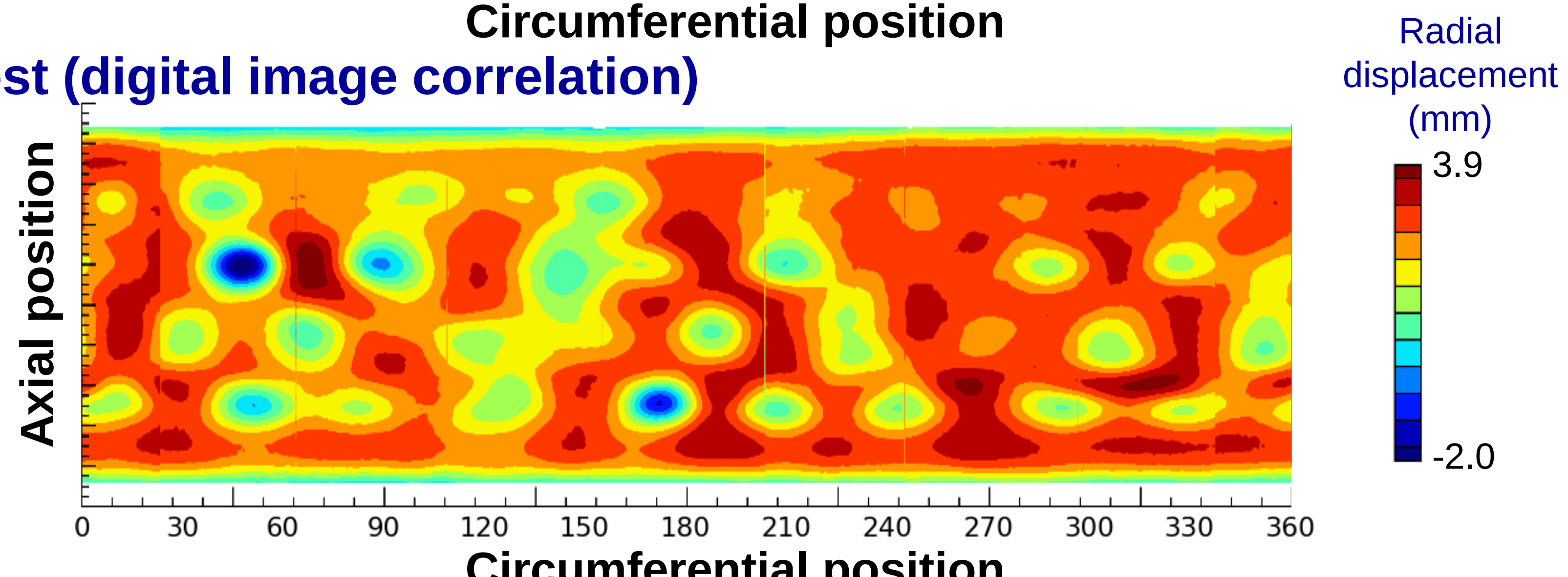


Test and Analysis Correlation: Radial Deformation, at Failure

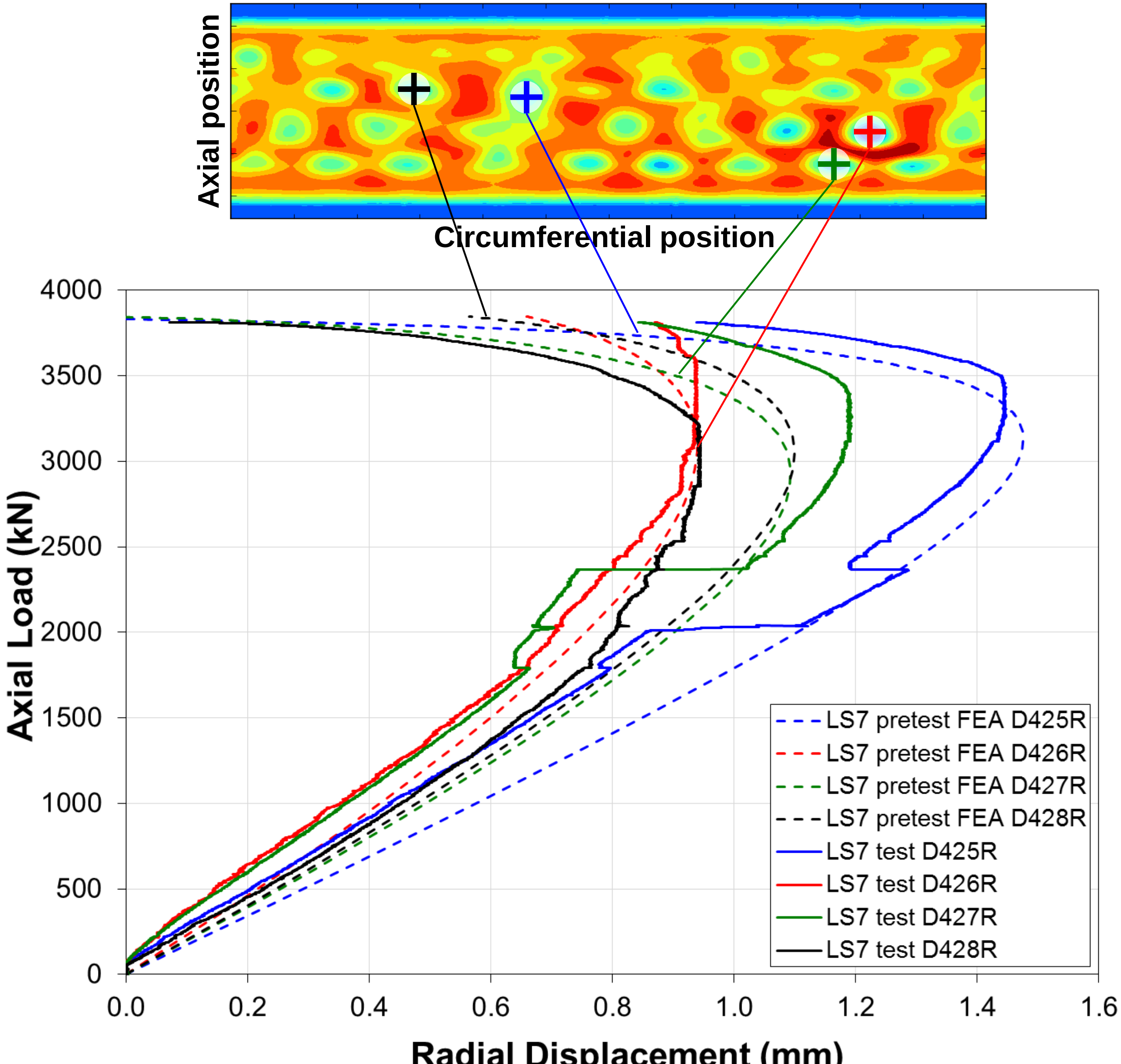
Pretest prediction



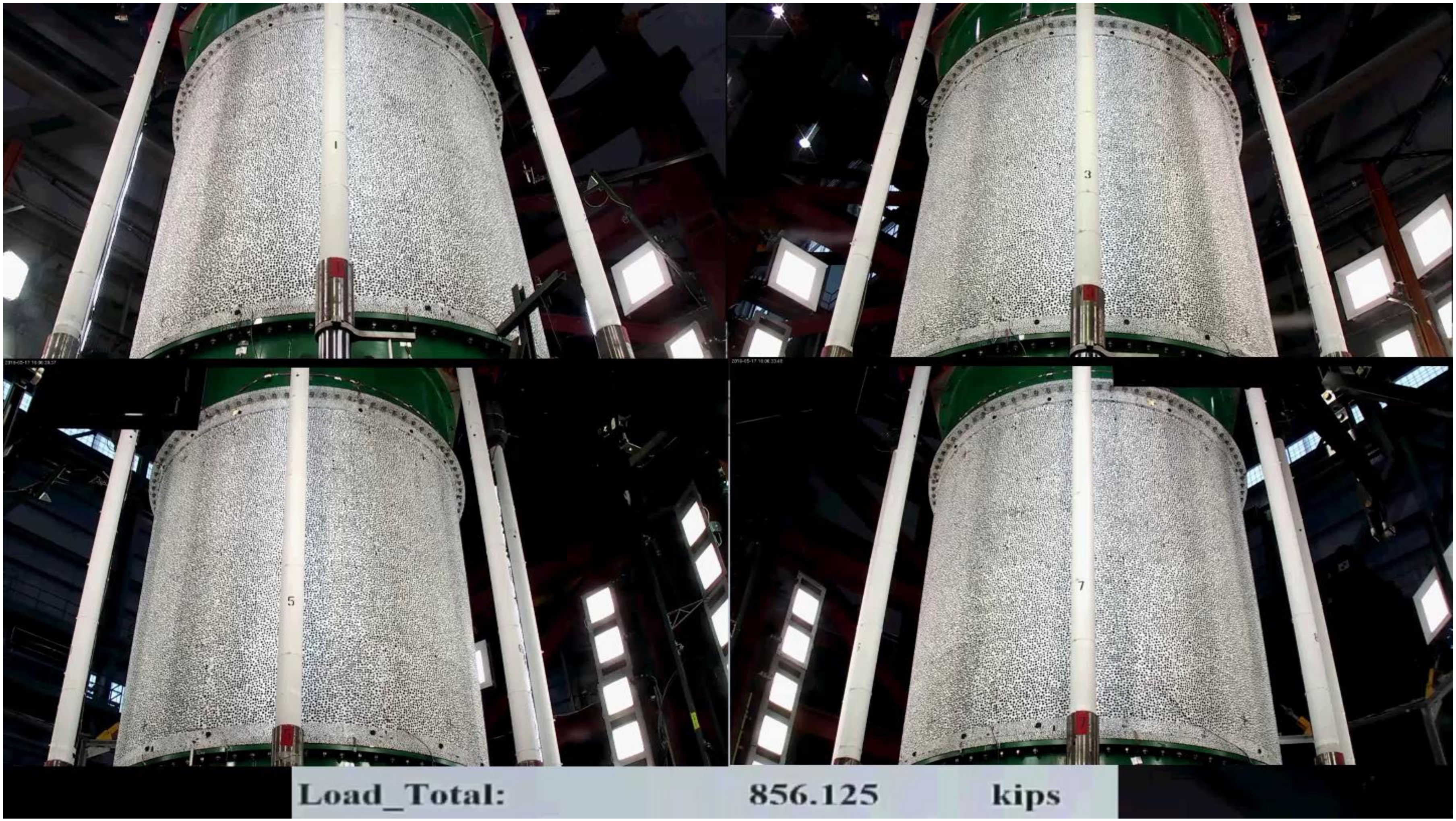
Test (digital image correlation)



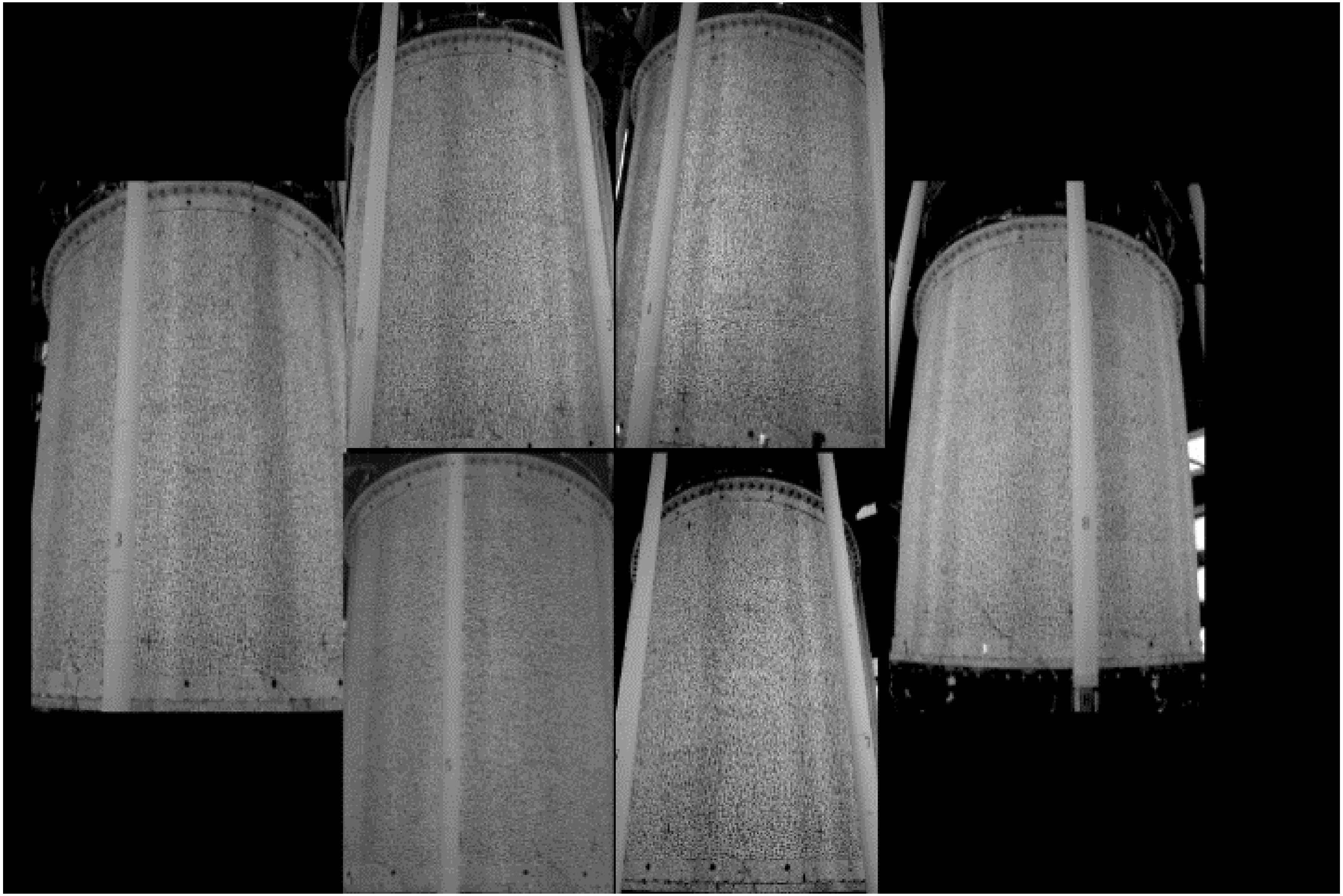
Test and Analysis Correlation: Radial Displacement



Failure Event:
Standard-Rate Video

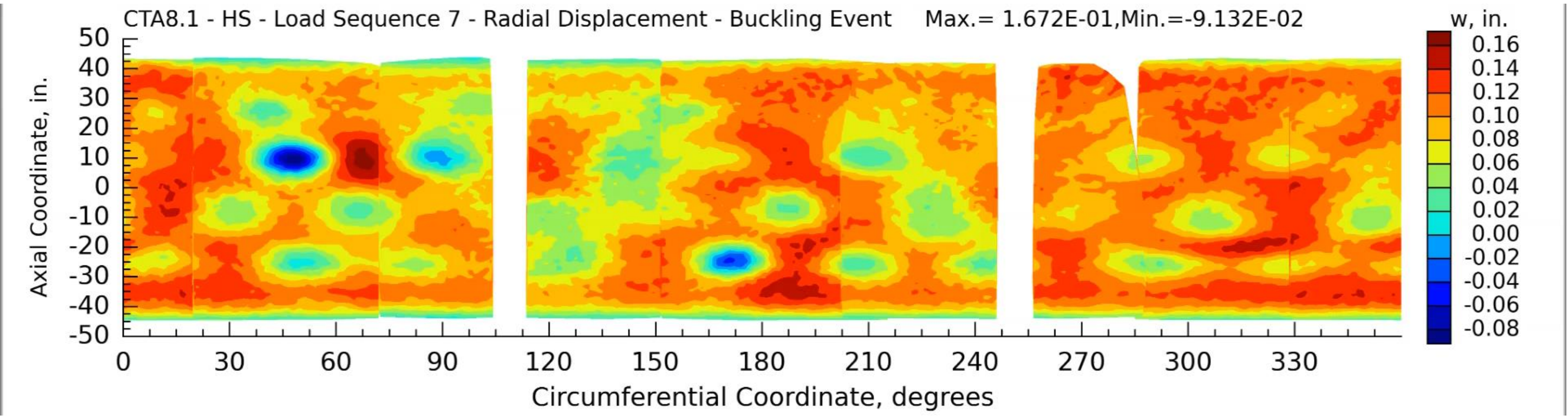


Failure Event: High-Speed Video (~10,000 fps)



Failure Event: High-Speed Digital Image Correlation

Radial deformation (~10,000 fps)



Concluding Remarks

- **Structural design considerations**
  - Numerous and potentially conflicting
  - Need to work with other groups, i.e., loads, aerodynamics, guidance and navigation, etc.
- **Structural assessment**
  - Analysis
  - Test
- **Design**
  - May require different analysis methods at different stages of design or to interrogate different potential failure modes
- **Test and analysis correlation**
  - High-fidelity models can represent physical response very well, but need good understanding of test article and test conditions

Acknowledgements

- Dr. Marc Shultz, MSFC
- Dr. Mark Hilburger, LaRC
- Tiffany Lockett, MSFC
- Rob Wingate, MSFC
- Mark Balzer, JPL
- Jeff Norris, MSFC
- Clint Cragg, NESC
- Shell Buckling Knockdown Factor Project Team

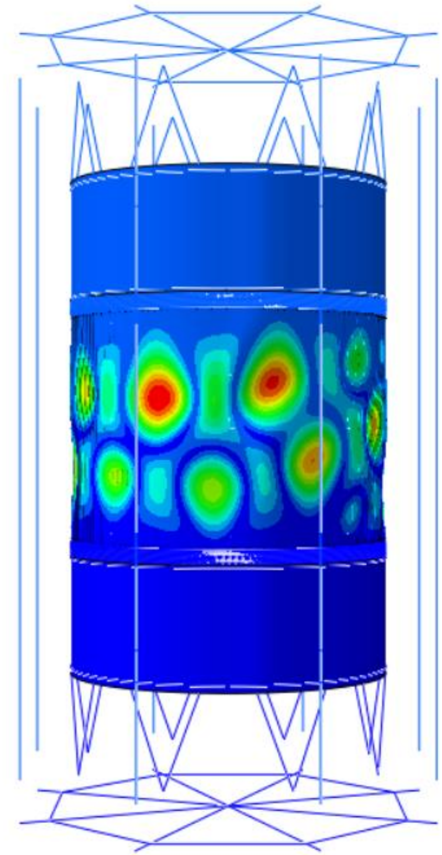
Questions?

Backup

Structural Design Considerations: Finite Element Modeling

- Finite element models are idealizations and assumptions
- Majority of analyses are not designed to predict failure, but to ensure the part will not fail

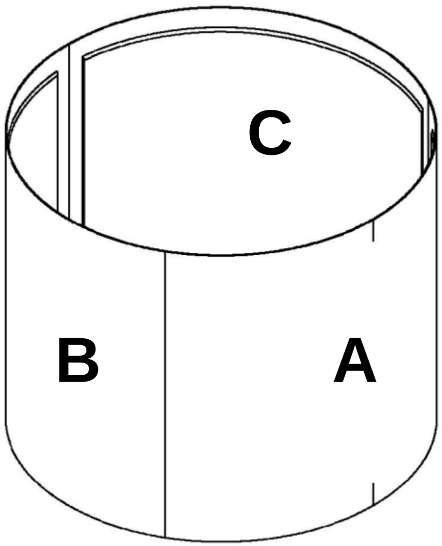
Test article in test stand

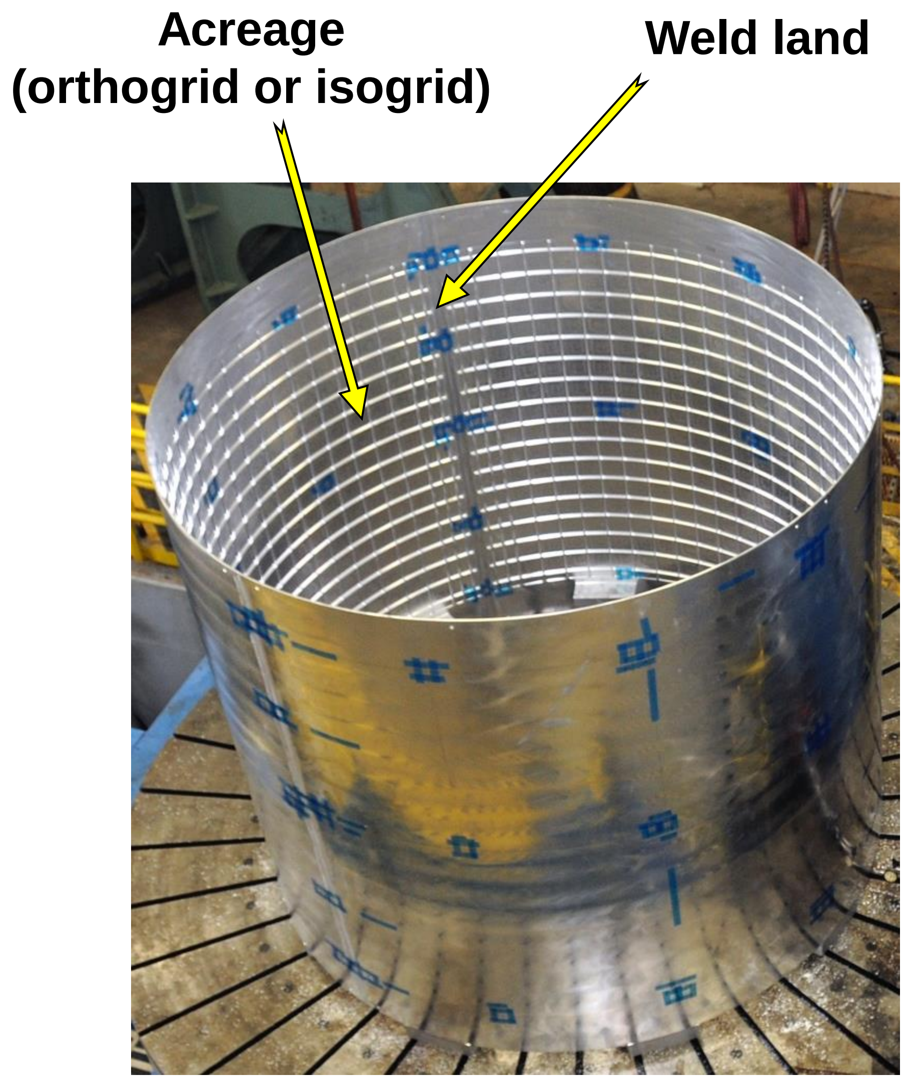


FEM of test article in test stand

Structural Design Considerations: Finite Element Modeling

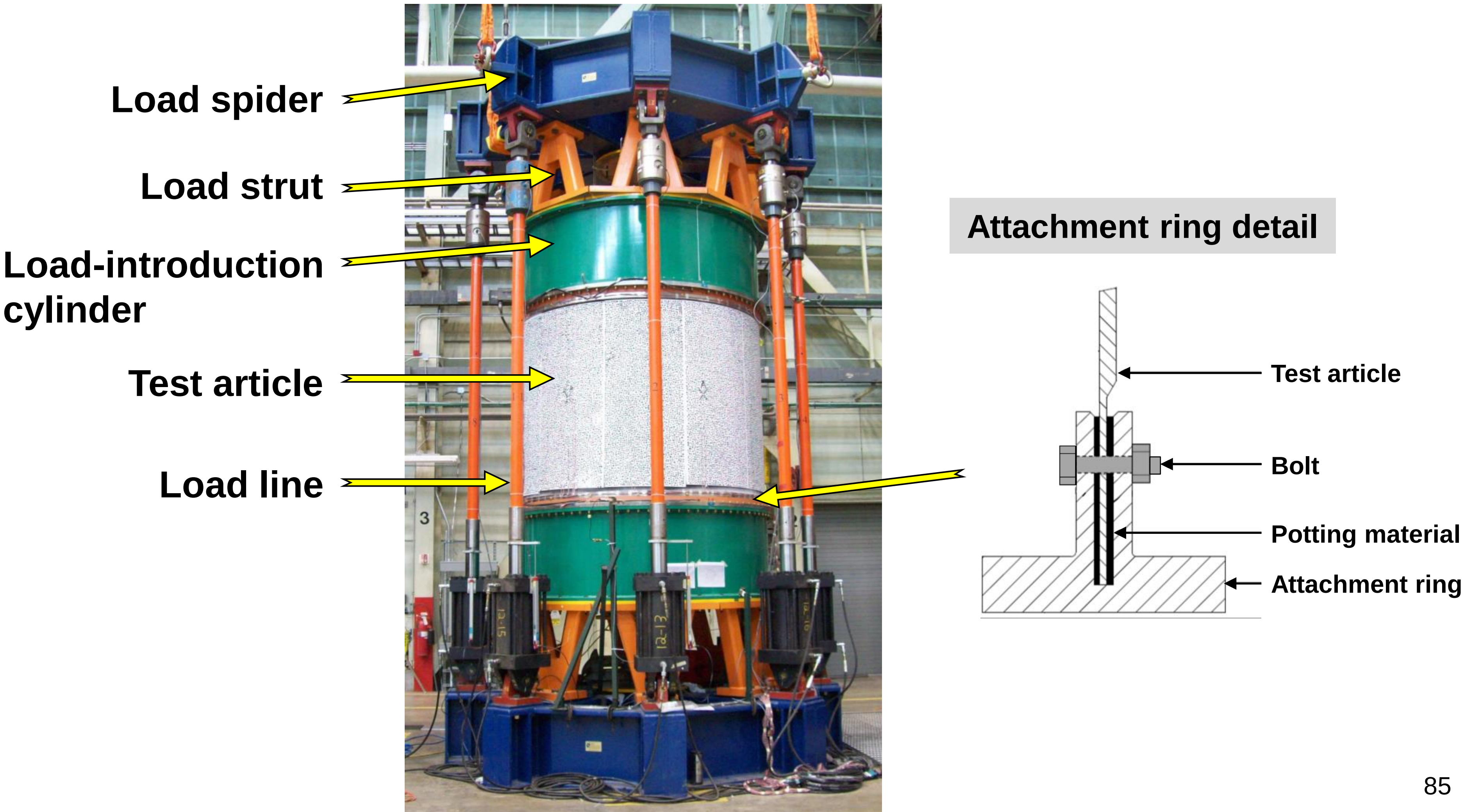
- **Shell Buckling Knockdown Factor test article, TA07**
  - 2.4-m diameter
  - 2-m length
- **3-panel construction**
  - Axial friction stir welds





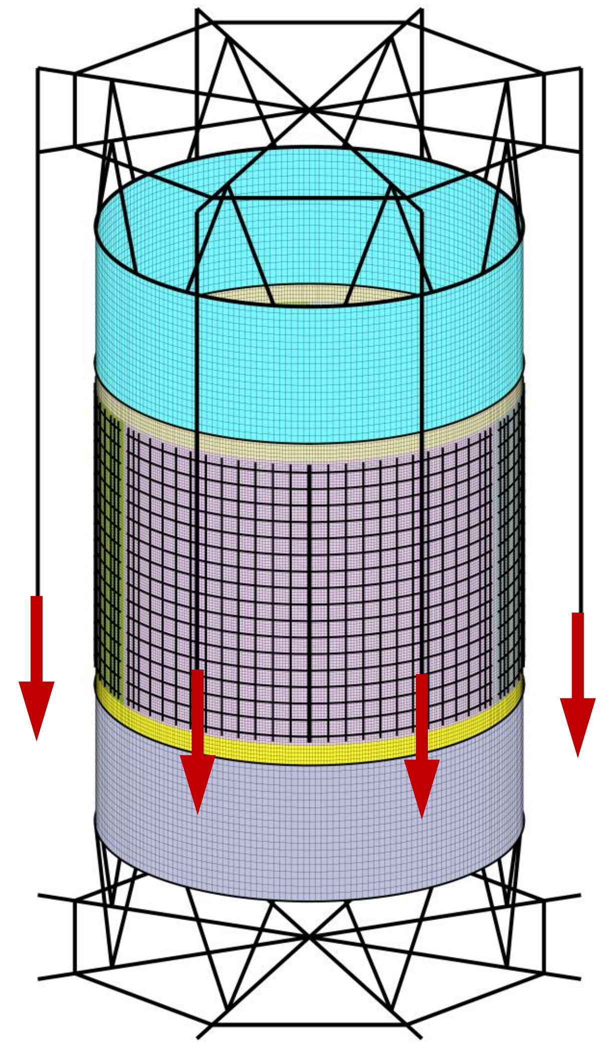
Structural Design Considerations: Finite Element Modeling

2.4-ft-Diameter Cylinder Buckling Test Facility



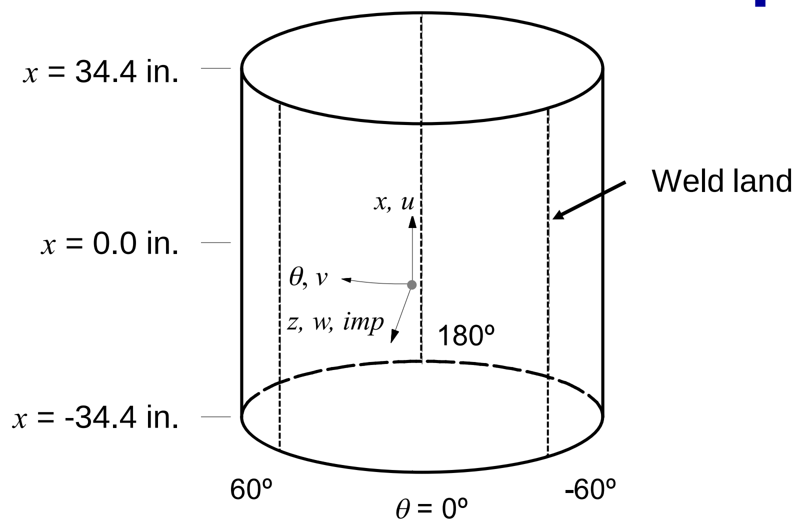
Mechanical Design Considerations: Finite Element Modeling

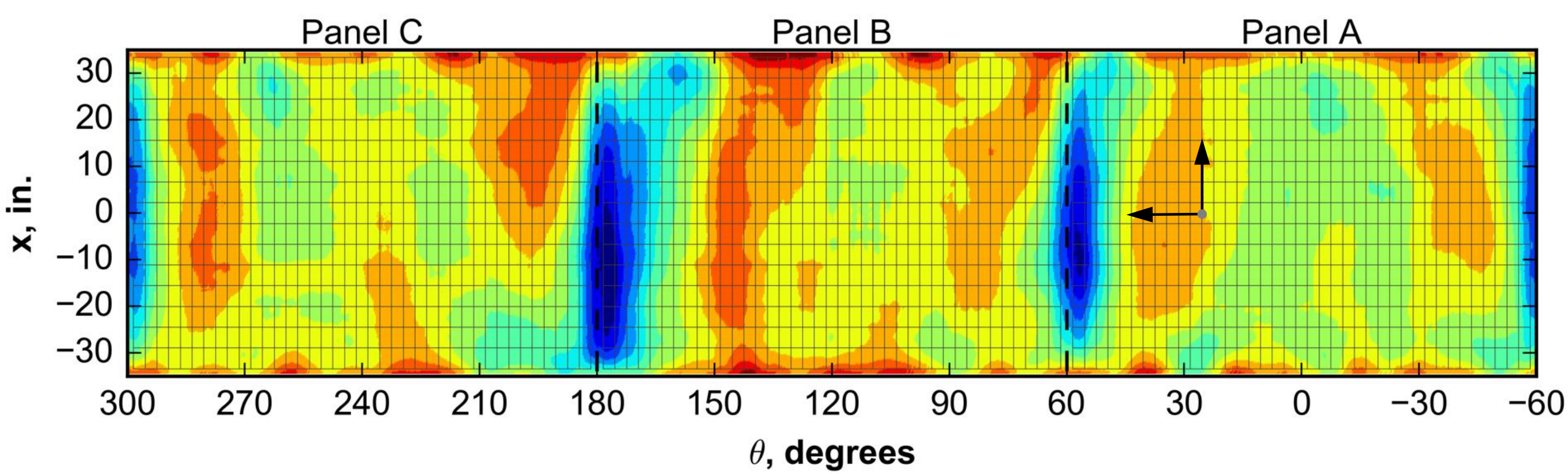
- **Modeled using Abaqus finite-element software**
  - **Shell and beam elements**
  - **Nominal geometry and material properties**
  - **Measured shell-wall geometric imperfections included**
- **Buckling response predicted using geometrically nonlinear transient analysis**



Structural Design Considerations: Finite Element Modeling

Measured Geometric Radial Imperfection





Structural Design Considerations: Finite Element Modeling

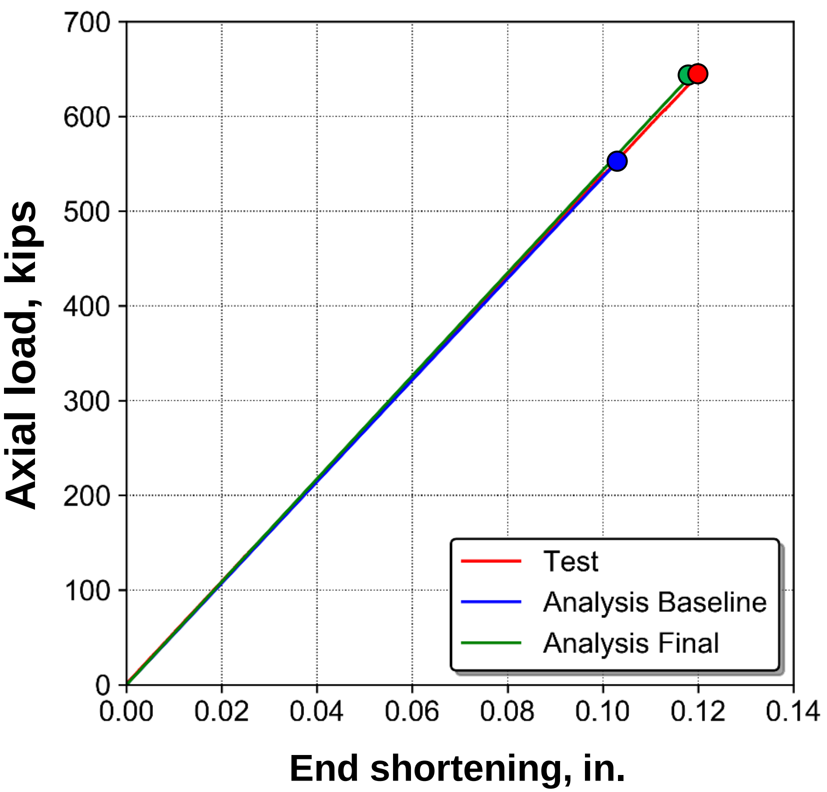
- **Hand Calculations: 1483 kN**
  - **Smeared stiffness**
  - **Perfect geometry**
  - **SP-8007 knockdown factor (0.495)**
- **Pretest Predictions (FEM): 2424 kN**
  - **Stiffeners and weldlands**
  - **Geometric radial imperfections**
- **Test: 2869 kN**
  - **Unknown unknowns**

48% difference between hand calculations and test
15% difference between pretest predictions (FEM) and test

Structural Design Considerations: Finite Element Modeling

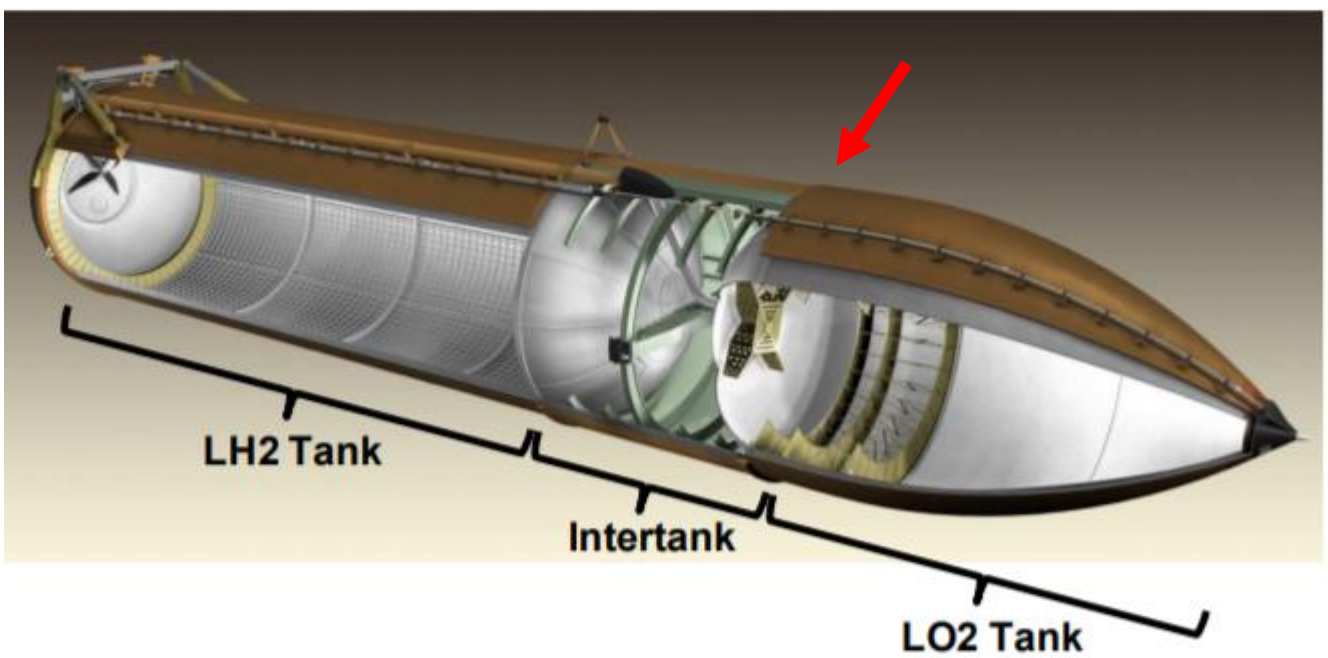
- **Post test model refinement predicted buckling load to within 1% of measured**
- **Effects of individual refinements**
  - **Material stiffnesses (1.3%)**
  - **Skin and stiffener dimensions (7.8%)**
  - **Stiffener fillet representation (4.2%)**
  - **Geometric imperfection (4.5%)**
  - **Attachment ring modeling (< 1%)**
  - **Loading imperfection (-1.8%)**

Load versus end shortening

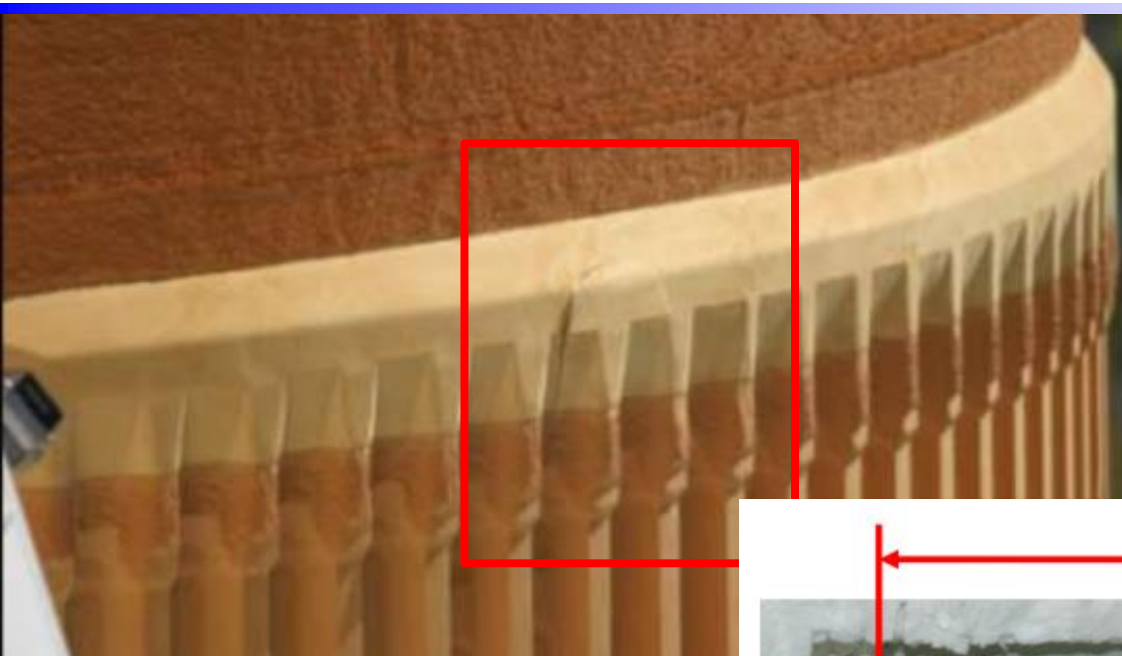


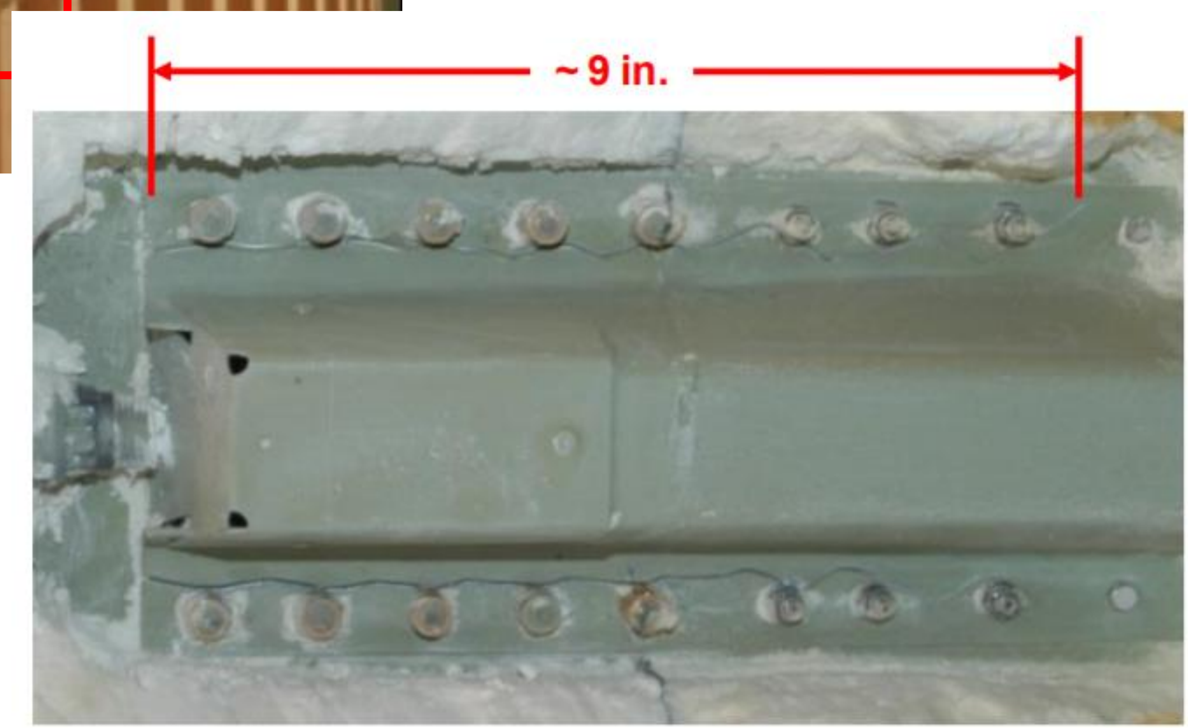
Structural Design Considerations: Finite Element Modeling

- **Cracks in the STS-133 Intertank stringers of the External Tank**
- **Crack suspected to occur during filling the tank with cryogenic propellant**

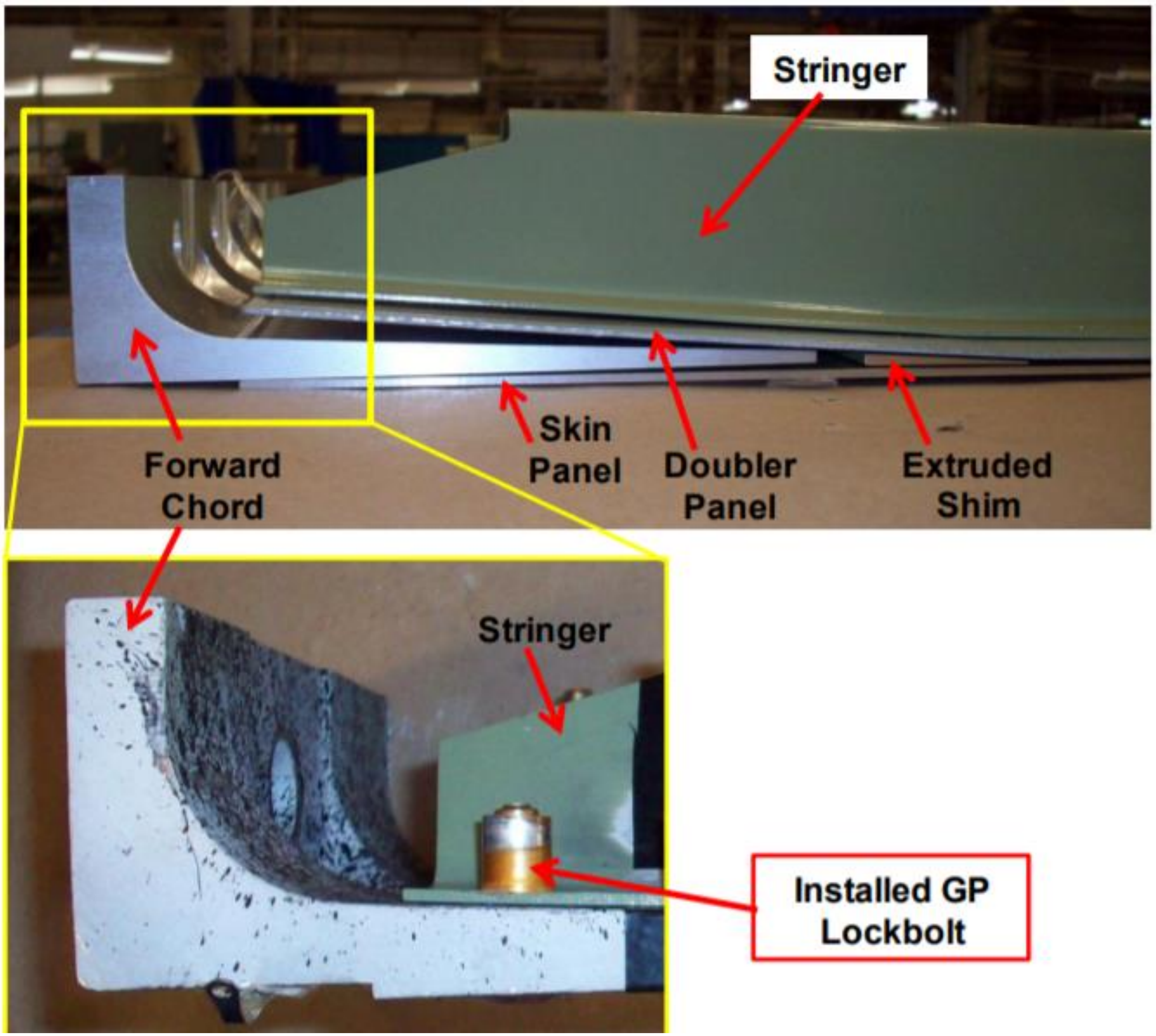


Structural Design Considerations: Finite Element Modeling



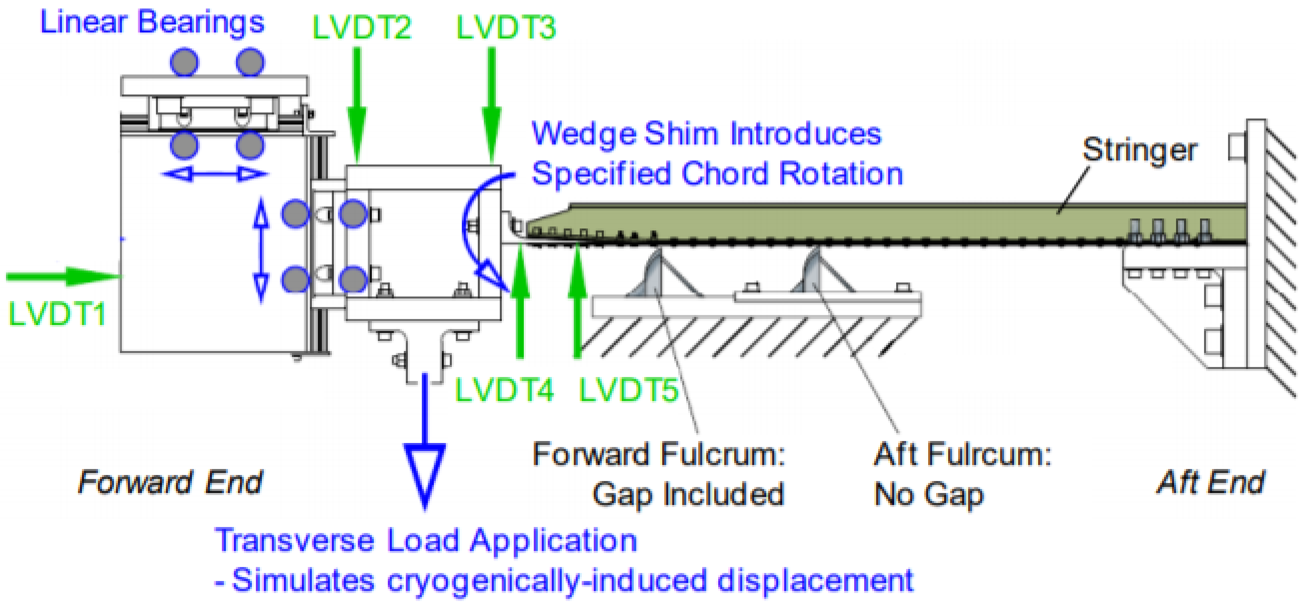


Structural Design Considerations: Finite Element Modeling

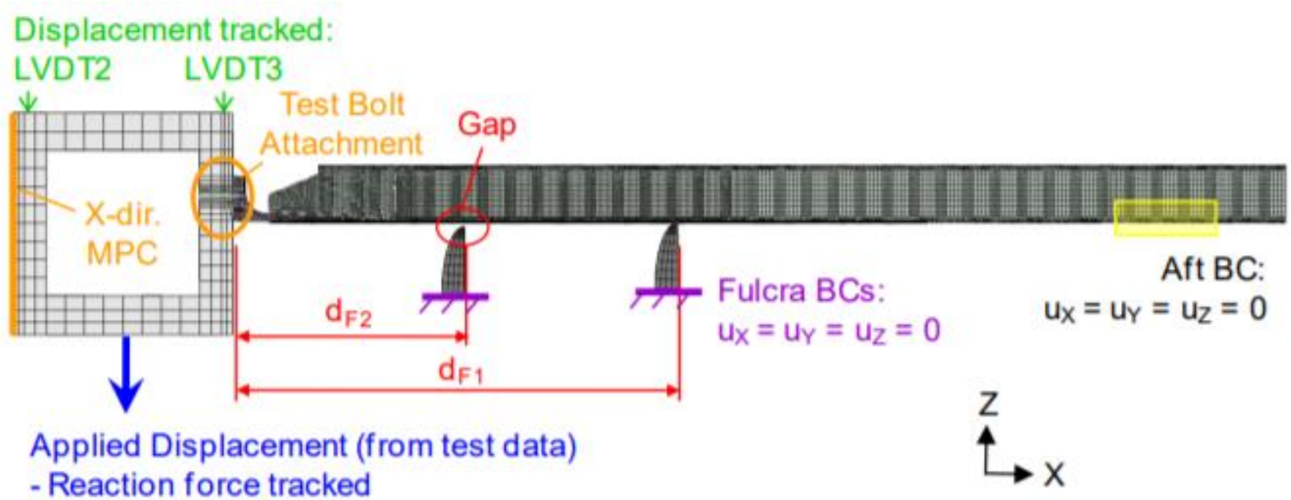


Structural Design Considerations: Finite Element Modeling

Test

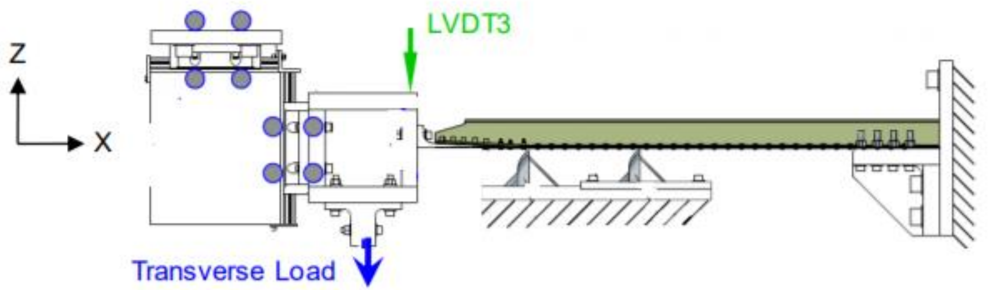


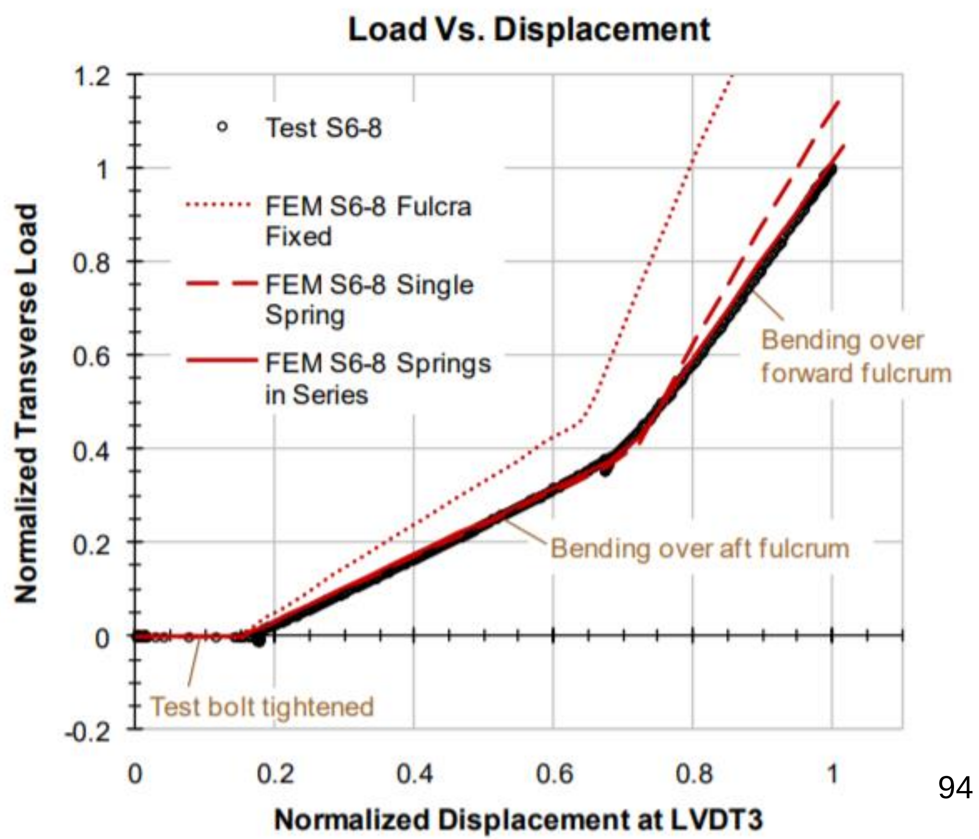
Finite Element Model



Structural Design Considerations: Finite Element Modeling

- **Boundary conditions lead to difference in test and analysis**
- **Large test fixtures were not as rigid as they appeared**






IDEAL PLANES
OR WHAT CAN HAPPEN IF ONE OF THE TEAM GETS ALL THEIR OWN WAY!
FUSELAGE GROUP
WEIGHTS GROUP
MECHANICAL CONTROLS GROUP
COMPUTER AIDED DESIGN GROUP
HYDRAULICS GROUP
PRODUCTION ENGINEERING GROUP
MAINTENANCE GROUP
EQUIPMENT GROUP
ARMAMENT GROUP
WING GROUP
AVIONICS GROUP
AERODYNAMICS GROUP
EMPENNAGE GROUP
POWERPLANT GROUP
STRESS GROUP

Design Considerations

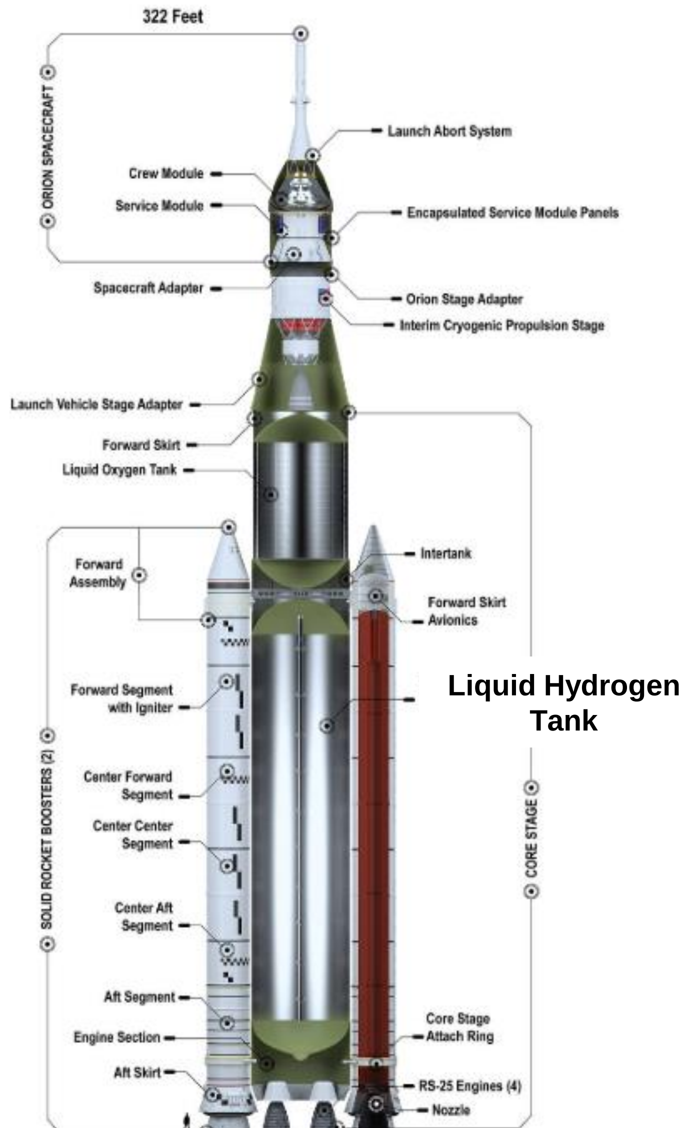
1. Functionality
2. Strength/stress
3. Distortion/deflection/stiffness
4. Wear
5. Corrosion
6. Safety
7. Reliability
8. Manufacturability
9. Utility
10. Cost
11. Friction
12. Weight
13. Life
14. Noise
15. Styling
16. Shape
17. Size
18. Control
19. Thermal properties
20. Surface
21. Lubrication
22. Marketability
23. Maintenance
24. Volume
25. Liability
26. Remanufacturing/resource recovery

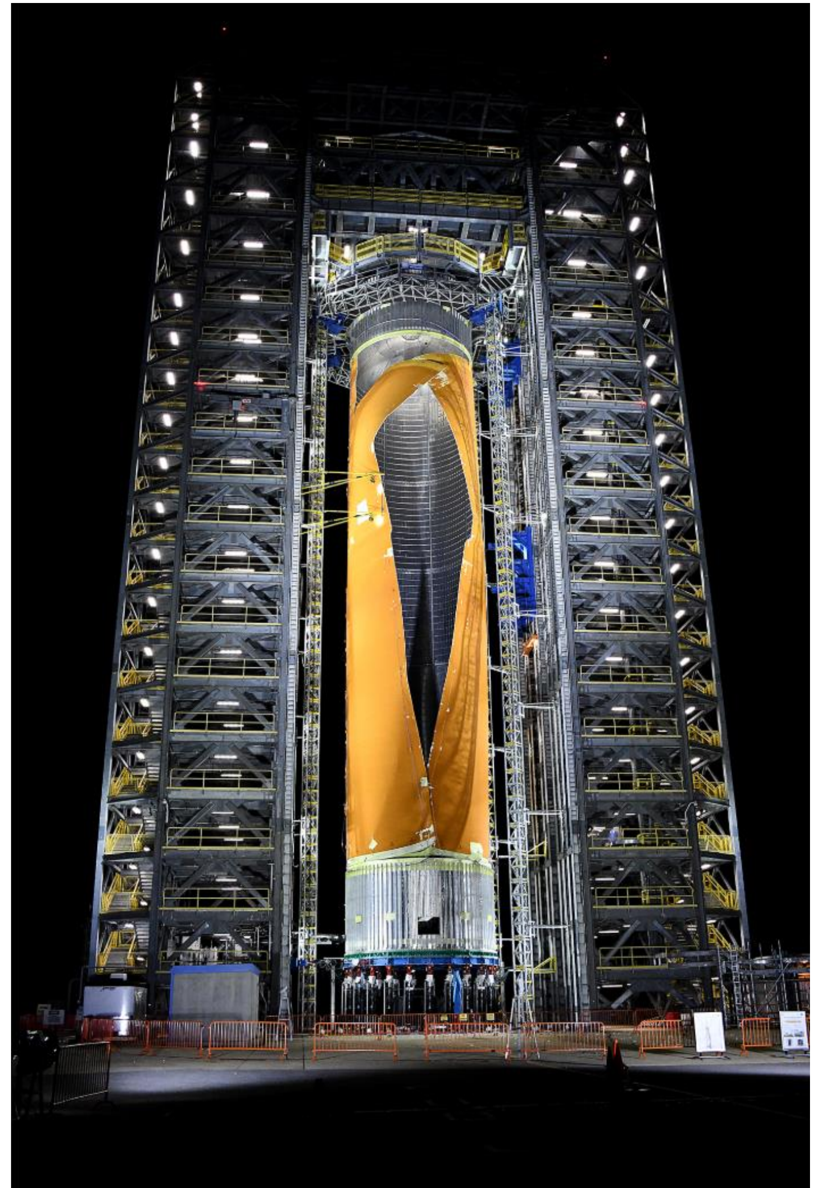
Ref: Shigley' Mechanical Engineering Design, 9th ed.

Mechanical Design Considerations

- **Functionality**
  - Designing for ease of assembly, testing, and installation
    - Assembly, what will you need access to prior to launch, does a welded joint need to be a bolted one?
    - Cutout sizes determined by Human Factors

NASA's SLS LH2 Buckling Test



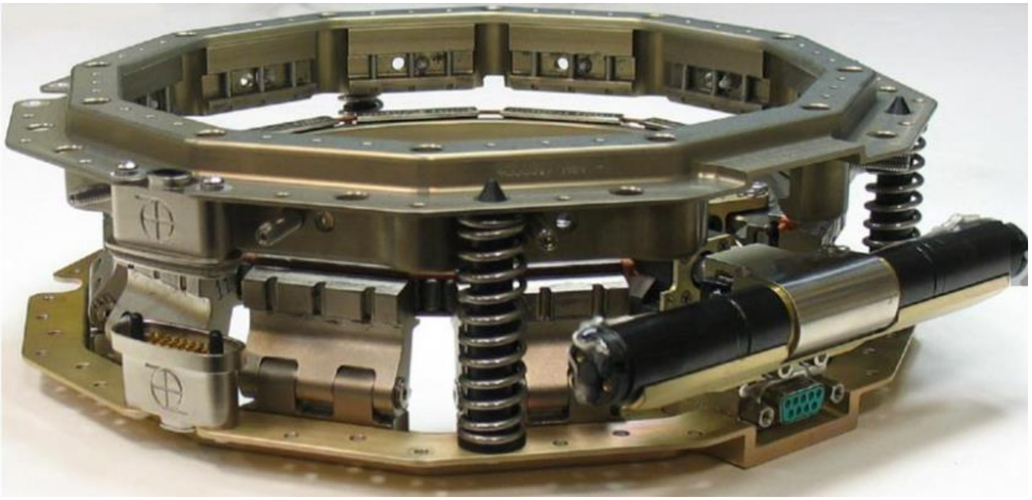


Program Considerations

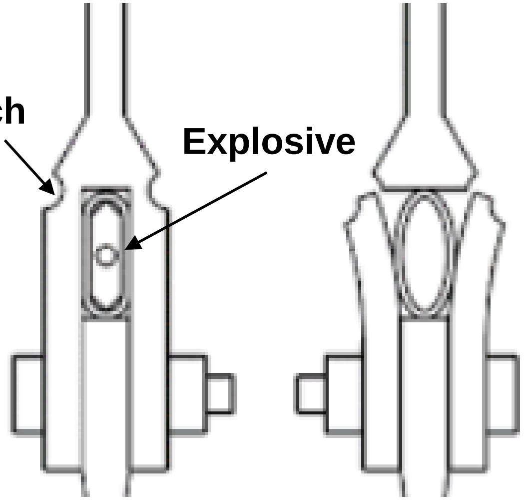
- Capability vs. “requirement” negotiations
  - Trades among all subsystems to get best/cheapest system
  - Risk/cost/performance trades with customer
- Margin management of design resources
  - Packaging volume, Dynamic/static clearances, structural strength, mass, mechanism force/torque, motor and pyro control circuit quantities
- Larger structure margin vs. more structural test; subsystem vs. system testing
  - Risk/cost/schedule/mass trade offs
- Trade offs of simplicity vs. performance
  - Manufacturing and assembly

Mechanical Design Considerations

- **Mechanisms**
  - Electric vs. Spring Motors, Linear vs. Rotating Action, Articulation Geometry
  - Latches, Pyro Devices, Wet vs. Dry Lube, Rolling vs. Sliding Interfaces



Planetary Systems Separation System



Frangible Joint Separation System

Closed-Form Failure Predictions

FEA buckling load from shell analysis for perfect cylinder, $P_{cr}^{FEA\ Perfect}$ = 2467 kN

Critical closed-form calculated loads

	Facesheet Wrinkling	Facesheet Dimpling	Shear Crimping
Load (kN)	4849	21,396	12,055
Failure Index	0.51	0.12	0.20

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

Shell FEA Analysis: Facesheet Measures

	Perfect, 2397 kN (before plateau)			Radial Imperfection, 2356 kN		
Measure	**Axial Strain (με)**	**Hoop Strain (με)**	**Tsai-Hill Index**	**Axial Strain (με)**	**Hoop Strain (με)**	**Tsai-Hill Index**
Value	-4503	2652	0.379	-4782	2825	0.405
Failure Index	0.57‡	0.15^	0.53**	0.60‡	0.16^	0.57**

Observation

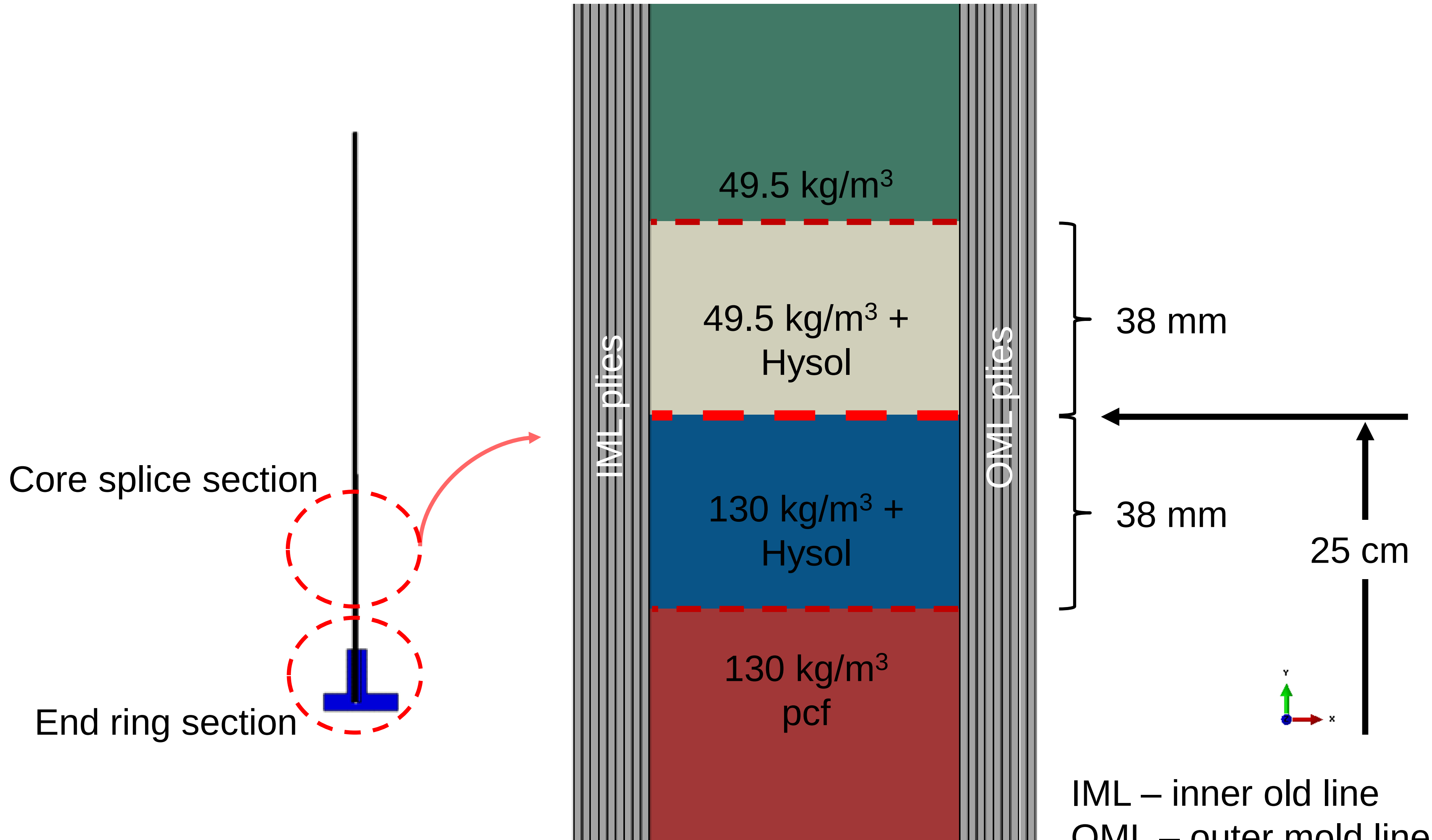
– **Reasonable axial strains and Tsai-Hill index that satisfy design requirements**

‡Axial-strain failure index = $\varepsilon_{FEA\ axial}$/-7926 με

^Hoop-strain failure index = $\varepsilon_{FEA\ hoop}$/17,400 με

**Co-cure failure index = (Tsai-Hill Index)/0.71

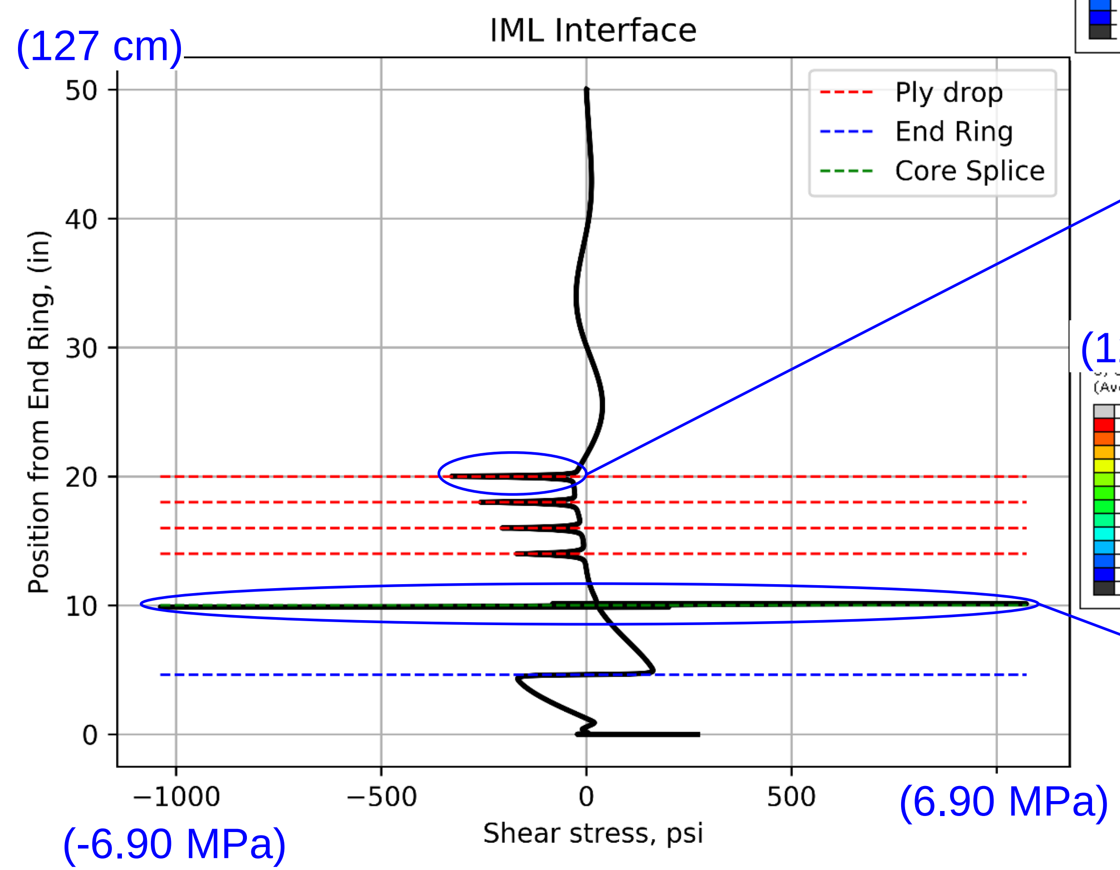
Axisymmetric FEA Analysis: Core-Splice Detail

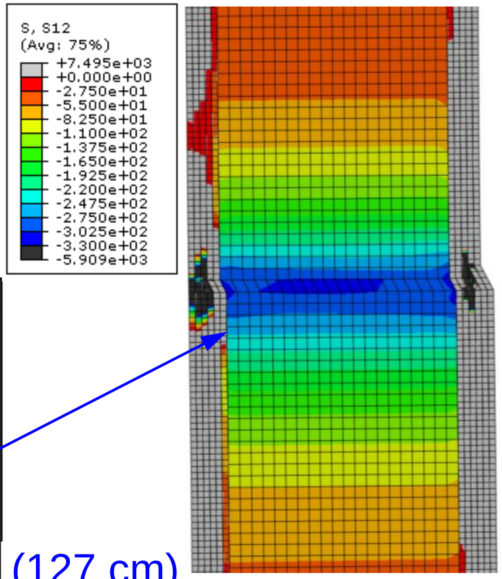


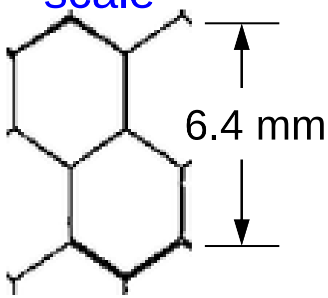
IML – inner old line
OML – outer mold line

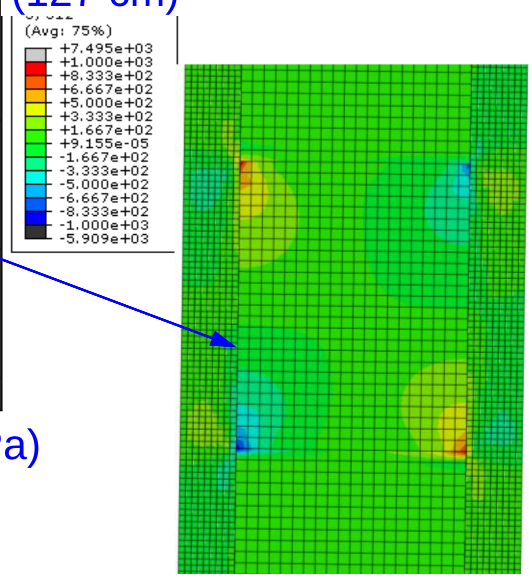
Axisymmetric FEA Analysis: Core-to-Facesheet Interface Stresses

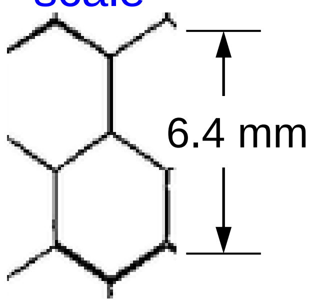
Axisymmetric model: sliding, no fillet, 2381 kN





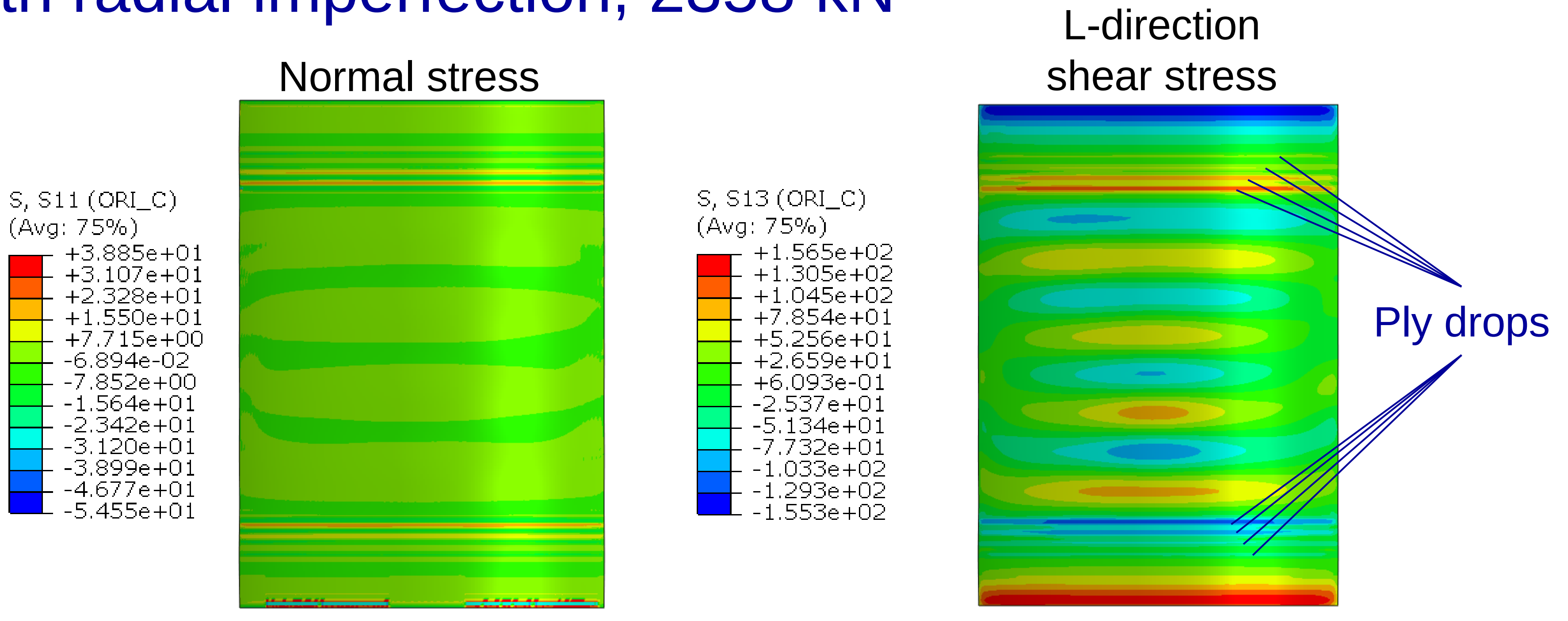






Finite Element Analysis Results: Global-Local Analysis

With radial imperfection, 2358 kN*



*the peak load