

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

Buckling Analysis of Sandwich Composite Cylinders: Approach and Lessons Learned

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Outline

- **Finite element Modeling and Analysis Plan (MAP) for the analysis of composite sandwich cylinders**
- **Lessons learned from analysis of composite sandwich cylinder model**
 - Load plateau of perfect cylinder model
 - Effect of shell element offset & boundary conditions
- **Summary**



Modeling and Analysis Plan (MAP)

- Design parameters
- Application of boundary and load conditions
- Facesheet material system
- Element type and mesh convergence
- Evaluation of damping coefficients & analysis parameters
- Model check
- Imperfection sensitivity analysis

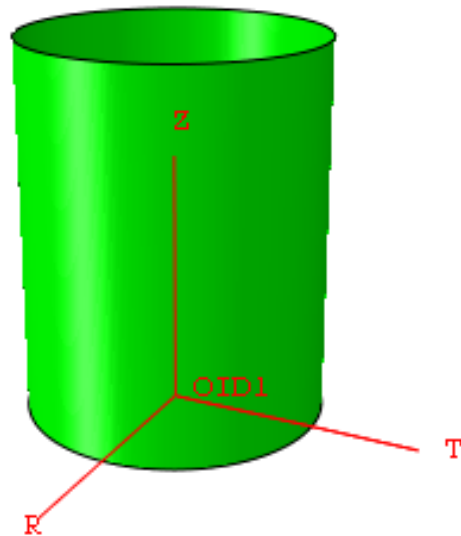
Explain model check

Finite Element Model: Coordinate Systems

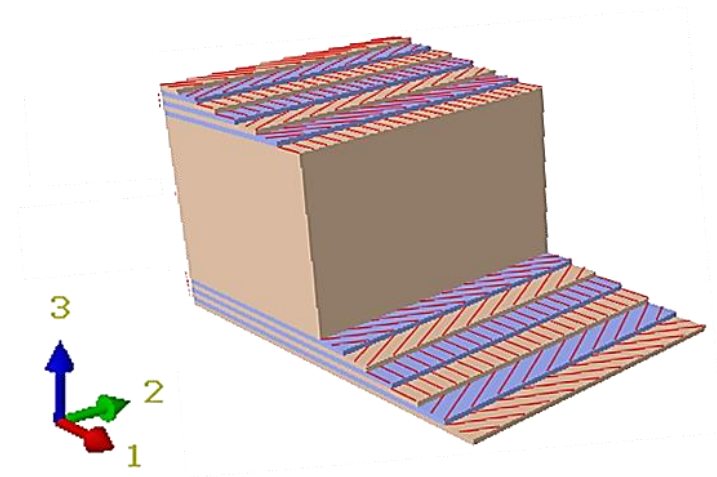


- Coordinate systems

Global (Cylindrical)



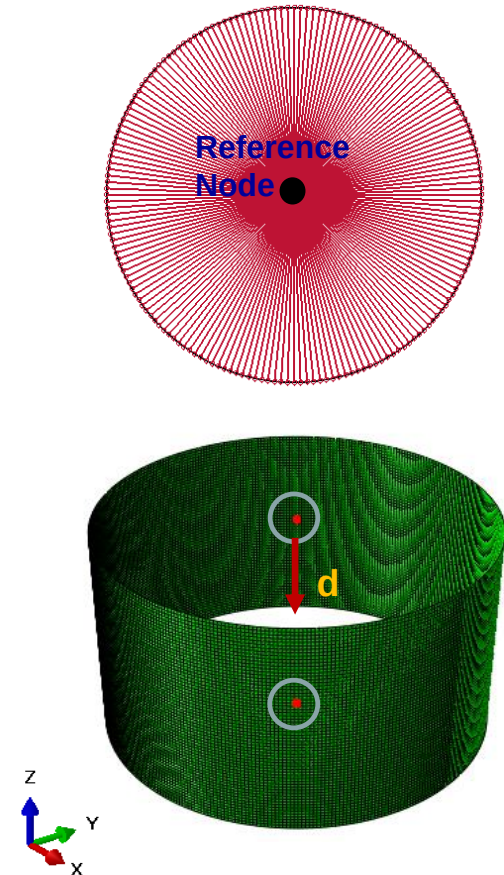
Material



Finite Element Model: Model Setup



- **Application of boundary and load conditions**
 - Top and bottom nodes are connected to reference nodes by kinematic couplings
 - Degrees of freedom connected to reference nodes
 - $u, v, w, \theta_x, \text{ \& } \theta_z$
 - Top reference node
 - $u, v, \theta_y, \theta_x \text{ \& } \theta_z = 0$
 - $w = d$ (applied displacement)
 - Bottom reference node
 - $u, v, w, \theta_y, \theta_x \text{ \& } \theta_z = 0$
 - Loading and boundary conditions are applied to reference nodes





Design Parameters

- **Design parameters**
 - Geometry
 - Diameter: 331 in.
 - Length: 90 in., 180 in., 331 in.
 - Facesheet
 - Three layups (graphite-epoxy)
 - Quasi-isotropic: $[\pm 45/90/0]_s$
 - Axially stiff: $[\pm 45/90/0/0]_s$
 - Fabric: $[45_f/0_f/0_f]_s$
 - Material: IM7/8552 Unidirectional tape
 - Core
 - Several core thicknesses
 - 3.1 pcf aluminum honeycomb
 - 0.5 in., 0.75 in., 1.0 in.
- **Analysis types (ABAQUS implicit analysis)**
 - Linear buckling analysis
 - Nonlinear static analysis
 - Transient dynamic analysis

**Explanation of each analysis type,
why is it important to run all three?**

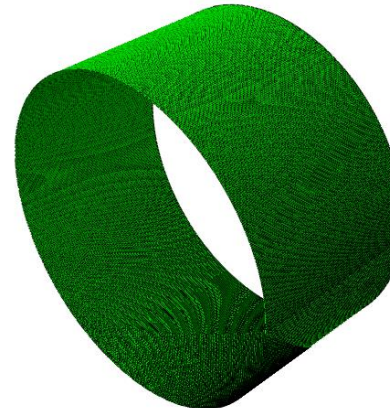
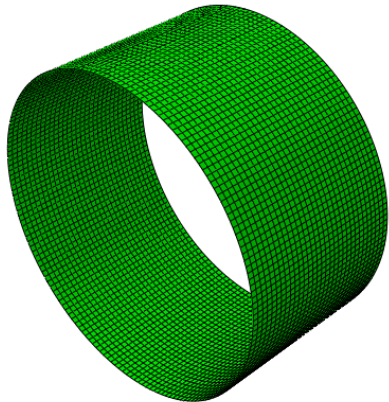
Finite Element Type and Mesh Convergence Study



2.0 Degree mesh:
of elements 31 axial,
180 circumferential

1.0 Degree mesh:
of elements 62 axial,
360 circumferential

0.5 Degree mesh:
of elements 124 axial,
720 circumferential



Shell element types

- S4
- S4R
- S4R5
- S8R
- S8R5

Problem size of 1.0 degree mesh

Element types	S4	S4R	S4R5	S8R	S8R5
Total number of elements	22,320	22,320	22,320	22,320	22,320
Number of nodes	22,682	22,682	22,682	67,682	67,682
Active degrees of freedom for node	6	6	5	6	5

	Full integration	Reduced integration
First order interpolation S4		
Second order interpolation S8		

Evaluation of Damping Coefficients & Step Time Parameter



- Material damping coefficients Rayleigh mass proportional (alpha) and Rayleigh stiffness (beta)

$$\alpha = 2\pi f \xi \quad \beta = \frac{\xi}{2\pi f}$$

f = Natural frequency of FE model
 ξ = Damping coefficient

- Nonlinear transient dynamic step definition

*Step, nlgeom=YES, inc=1000

*DYNAMIC, APPLICATION=QUASI-STATIC, INCREMENTATION=CONSERVATIVE,
INITIAL=NO, **ALPHA**= -0.05 (structural damping parameter)

initial step size, total pseudo time, minimum step size, maximum step size

1, 1800, 0.001, 20

Finite Element Type and Mesh Convergence Study



Element type and size study matrix for linear bifurcation analysis
(Quasi-isotropic facesheet with 0.5 in. core)

	Abaqus element type			
No of Elements	S4	S4R	S4R5	S8R5
0.5 degree	2.325 E+6	2.325 E+6	2.325 E+6	2.326 E+6
1.0 degree	2.341 E+6	2.335 E+6	2.331 E+6	2.327 E+6
2.0 degree	2.403 E+6	2.352 E+6	2.341 E+6	2.329 E+6

Linear and nonlinear peak loads of the model

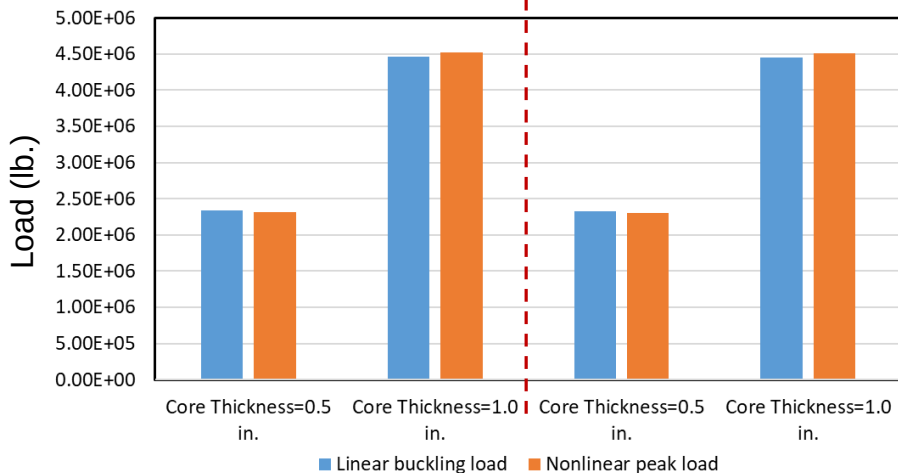
Quasi-isotropic facesheets

Axially stiff facesheets

What mesh density did we go with?

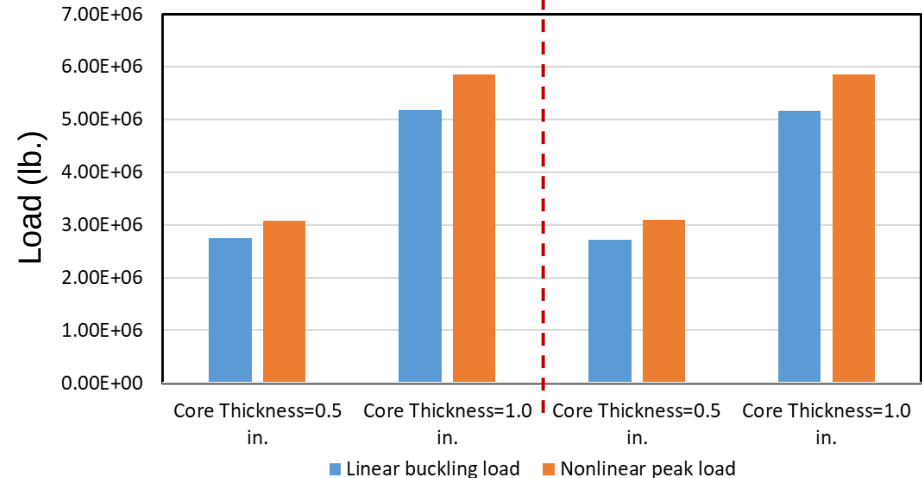
1.0 Degree mesh

0.5 Degree mesh



1.0 Degree mesh

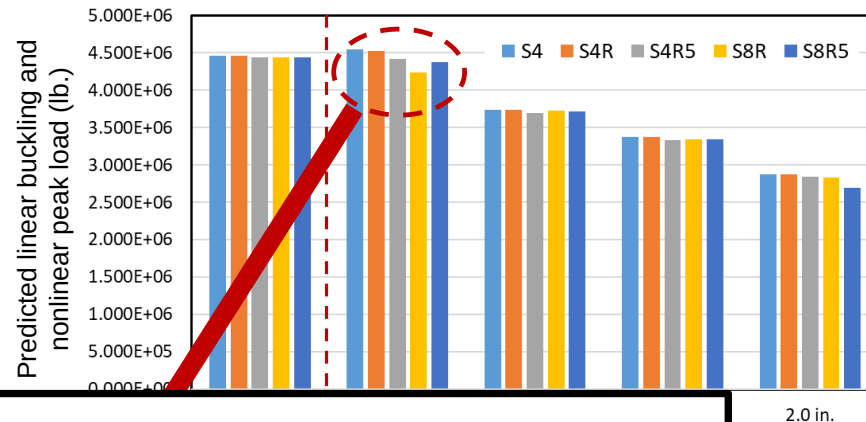
0.5 Degree mesh



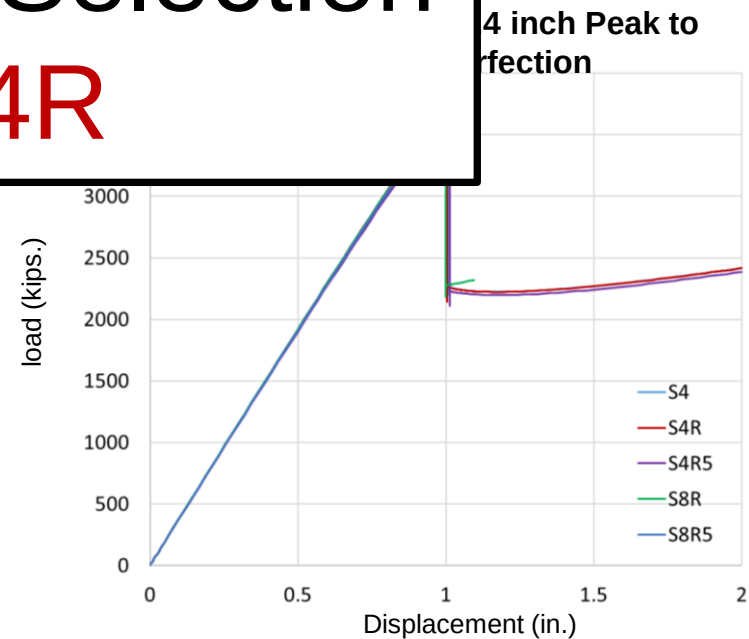
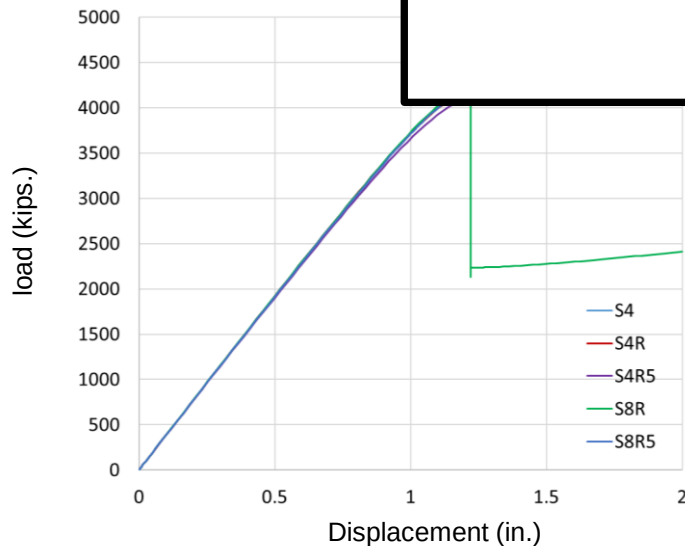
Nonlinear Analysis Of Composite Sandwich Cylinders



Element type and
imperfection study matrix for
nonlinear analysis
(Quasi-isotropic facesheet
with 1.0 in. core thickness)



Element Selection
S4R



Finite Element Model of Composite Sandwich Cylinders



- Element type : S4R
- Mesh: 1 degree mesh (62 axial, 360 circumferential)
- End condition: kinematic coupling
- Mass dampin **Delete? Repetitive**

Mass Dam
α
13.5

information.

The alpha and beta factors are dependent on the natural frequency of the structure so I don't think it is appropriate to give specific values.

- Structural dam -0.05, default
- Nonlinear an

*Step, nlgeom=YES, inc=10uu

*DYNAMIC, APPLICATION=QUASI-STATIC, INCREMENTATION=CONSERVATIVE, ALPHA=-0.05

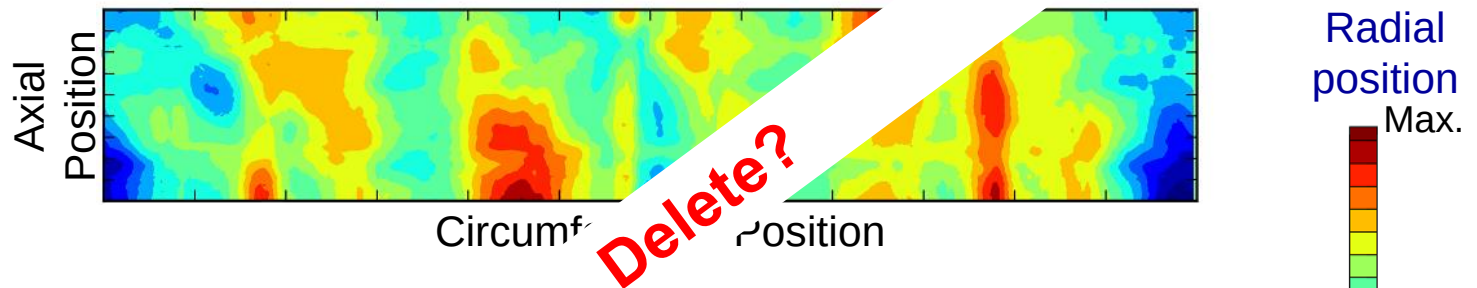
** initial step size, total pseudo time, minimum step size, maximum step size

1, 1800, 0.001, 20

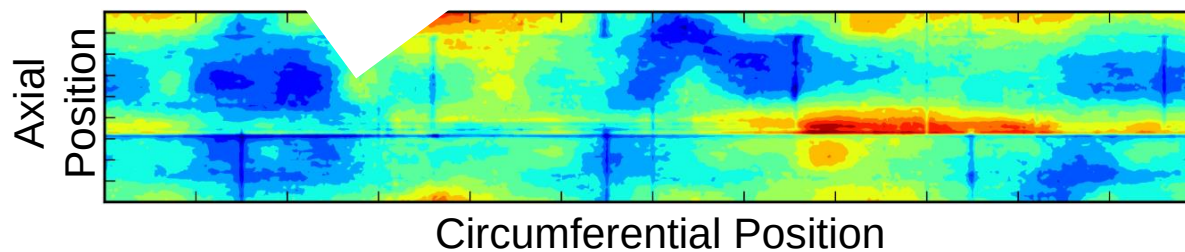
Geometric Imperfection Input

Vary magnitude of measured test structure geometry

CTA8.1 test article



CF⁺ fabrication tool



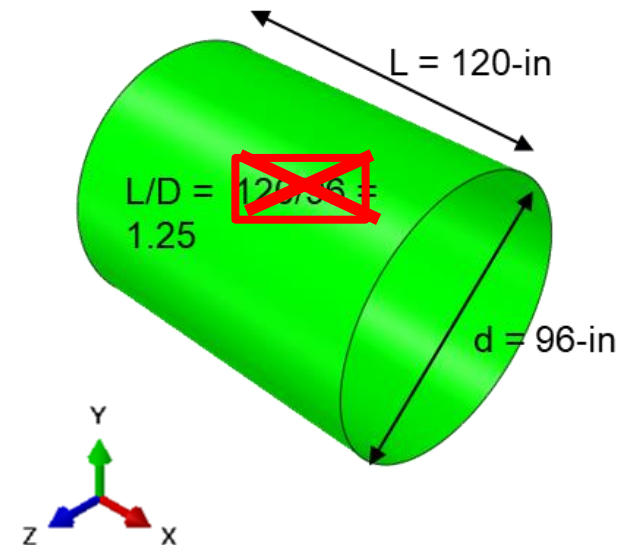


Lessons Learned from Analysis of Composite Sandwich Cylinder Model: Load Plateau of Perfect Cylinder Model

Nonlinear Analysis of 8-ft-diameter Test Article

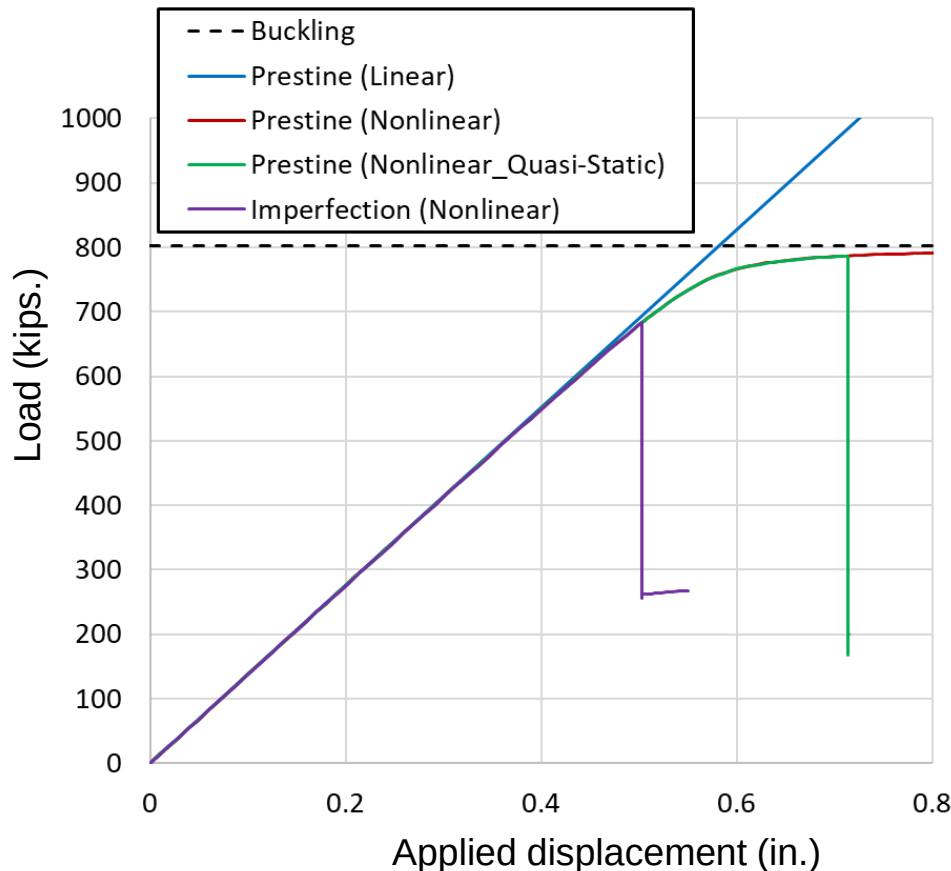


- **CTA8.2 geometry and mesh**
 - Number of elements: 36,240 (120 axial, 302 circumferential)
 - Number of nodes: 37,148 (approx. 1.0 in. $\times$ 1.0 in.)
 - Element type: S4R
- **Facesheet layup**
[60/-60/0/0/-60/90]_T
- **Ply thickness = 0.0057 in.**
- **Core thickness = 0.2 in.**
- **Total thickness = 0.2684 in.**



Load Plateau of Perfect Cylinder Model

Abaqus Nonlinear static vs. Nonlinear quasi-static dynamic (Simply support, Displacement control)



- Nonlinear Analysis

- Step 1.

- Total displacement (time) = 1.0
 - Increment (uniform) = 0.01 (1% total)
 - NEGATIVE EIGENVALUES (Applied end shortening = 0.53 in. and reaction force = 714 kips)
 - Failure to obtain solution at 0.82 in. end

- Nonlinear Analysis

- Step 1. Static Analysis

- Total displacement (time) = 0.5
 - Increment (uniform) = 0.01

- Step 2. Transient Dynamics

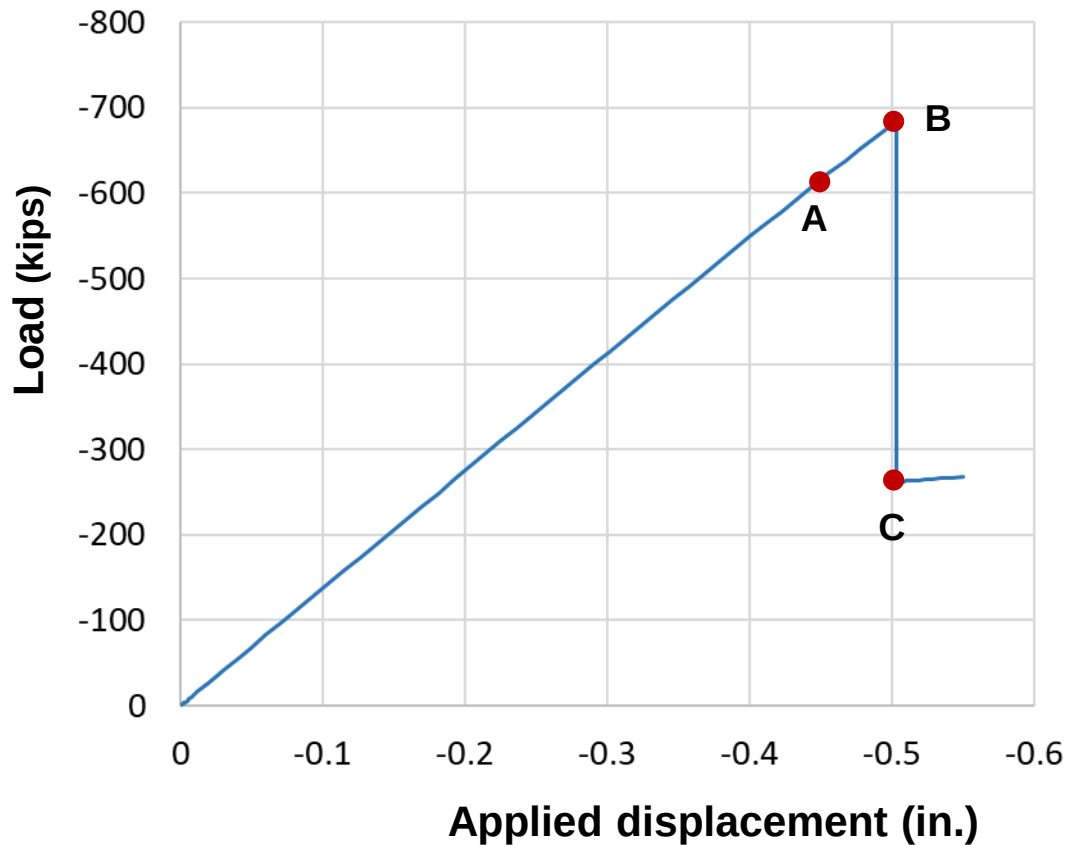
- Total time = 1000.0-sec
 - Initial time increment = 1.0 sec
 - Max time increment = 20.0 sec
 - Min time increment = 1.0E-6 sec
 - NEGATIVE EIGENVALUES (applied end shortening = 0.52-in and reaction force = 707 kips)
 - Peak load = 787 kips

Too much information?

Response of Imperfect Cylinder

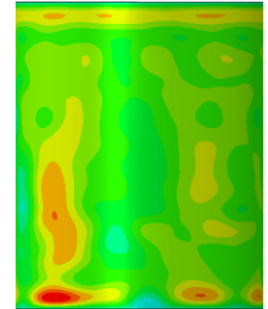


Nonlinear static analysis

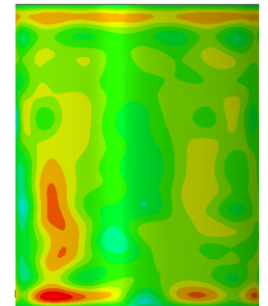


Radial Displacement

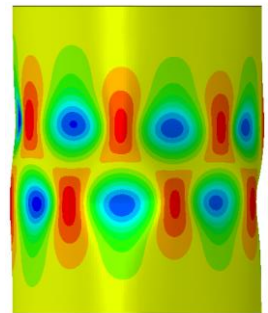
A
90% of peak load



B
Peak load

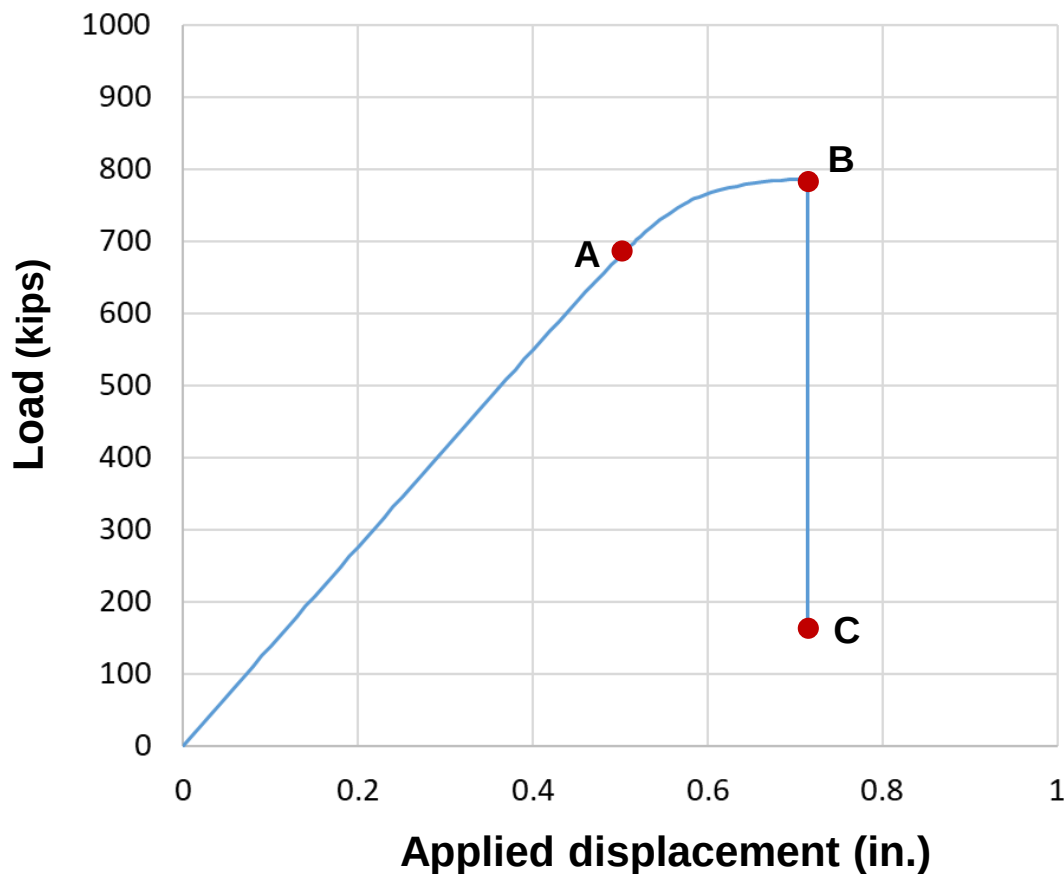


C
Postbuckling



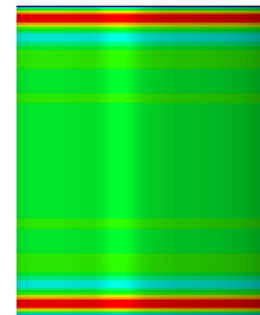
Response of Perfect Cylinder

Transient dynamic analysis

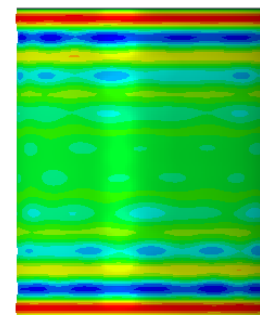


Radial Displacement

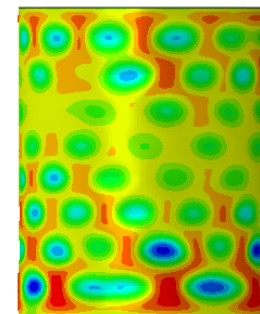
A
90% of peak load



B
Peak load

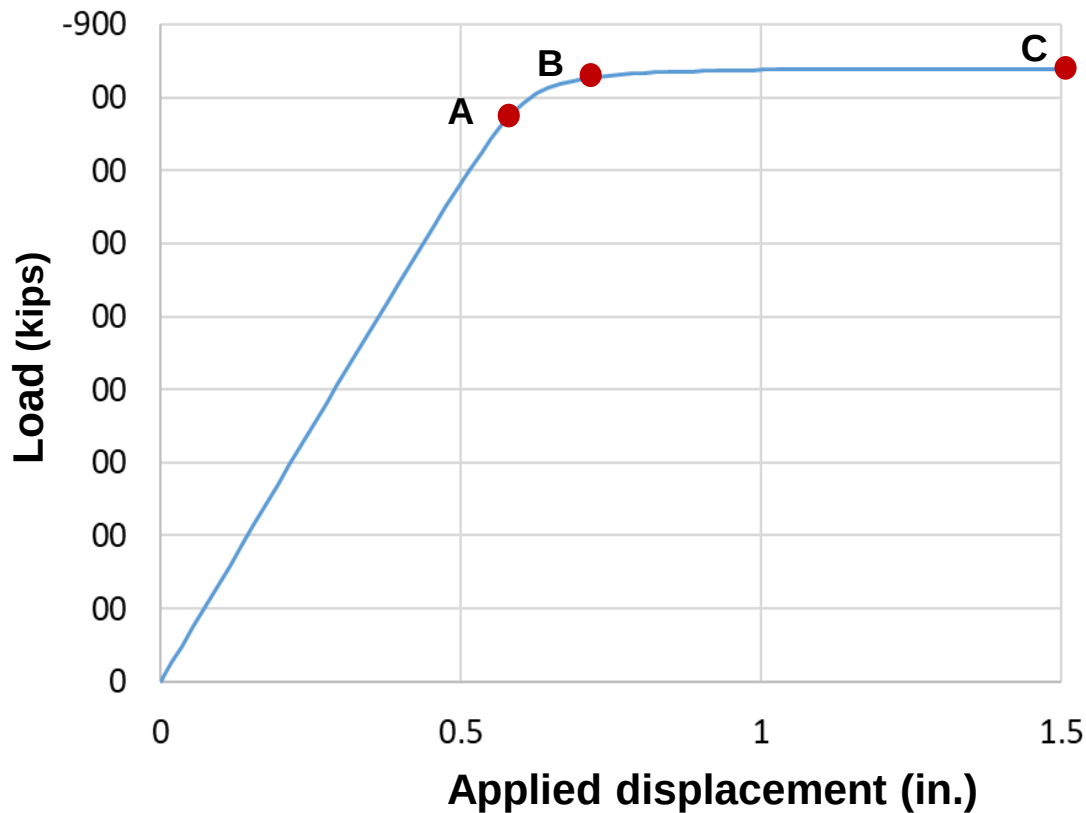


C
Postbuckling



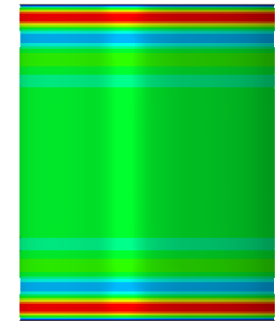
Response of Perfect Cylinder

Nonlinear static analysis

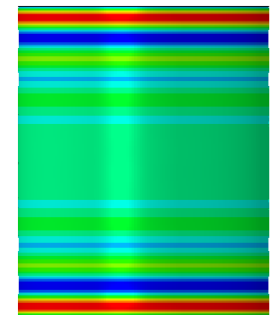


Radial Displacement

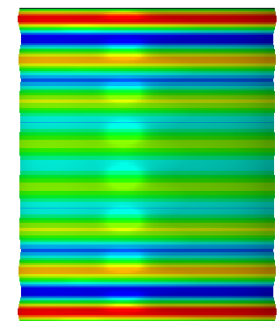
A
Negative
eigenvalues
warning



B
Peak load



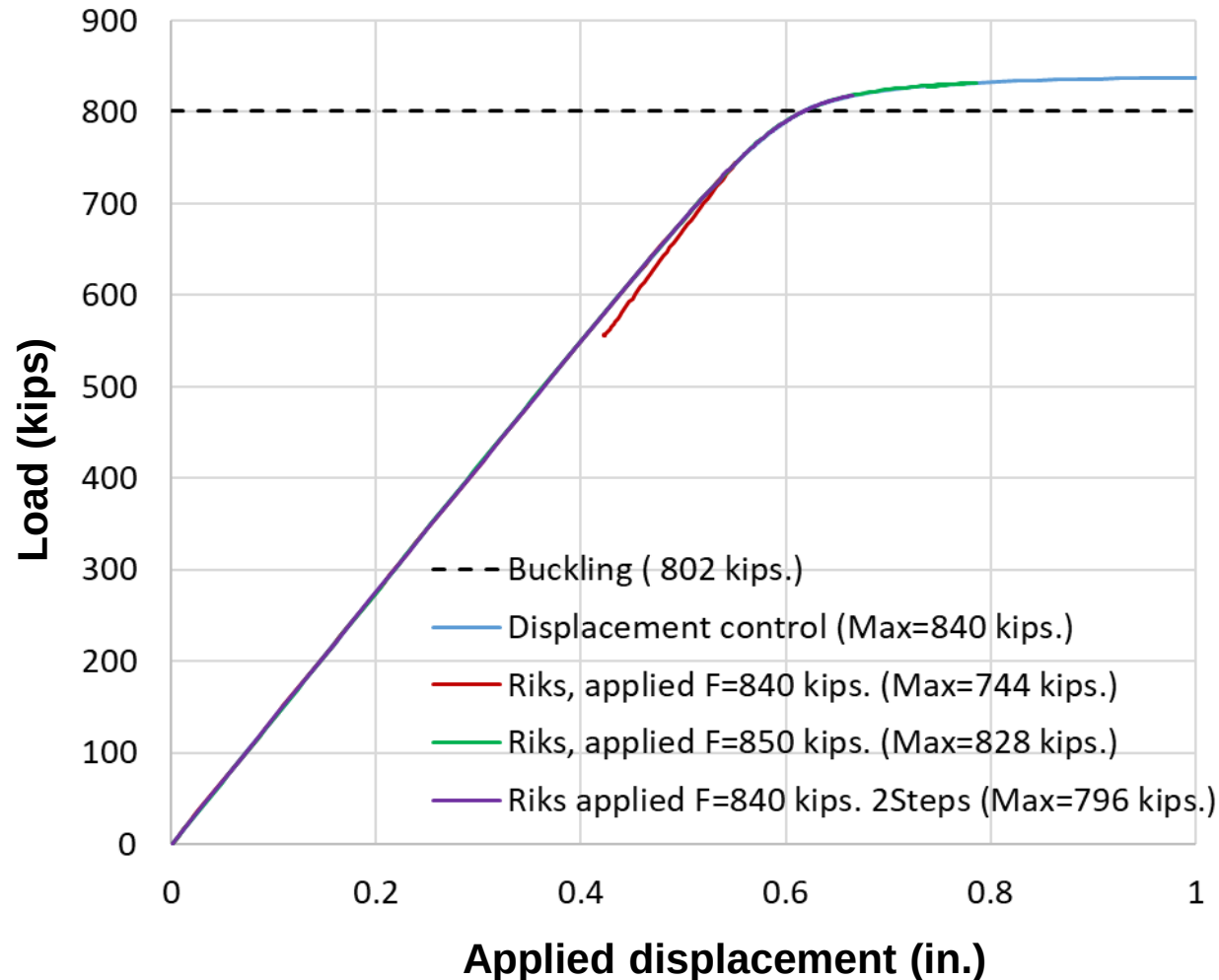
C
Plateau





Response of Perfect Cylinder Model

Force control, different applied force, Riks method



Abaqus Convergence Tolerance Parameters



- ***CONTROLS**

- **Reset solution controls. (Total 52 parameters)**
- **Typical analysis definition**

```
*STEP, NAME=Step 1, NLGEOM, INC=200
**
*STATIC
0.01, .1, 1E-4, 0.05
```

- **Modify convergence parameters in input file**

```
*CONTROLS, PARAMETERS=LINE SEARCH
5, 1, 0.0001, 0.25, 0.1
**
*CONTROLS, PARAMETER=FIELD, FIELD=GLOBAL
, , , , , , ,
**
*CONTROLS, PARAMETER=TIME INCREMENTATION
4, 8, 9, 16, 10, 4, 50, 5 , 50 , 50
Second line (optional)
Third line (optional)
**
```



- **Summarize load plateau lessons learned**

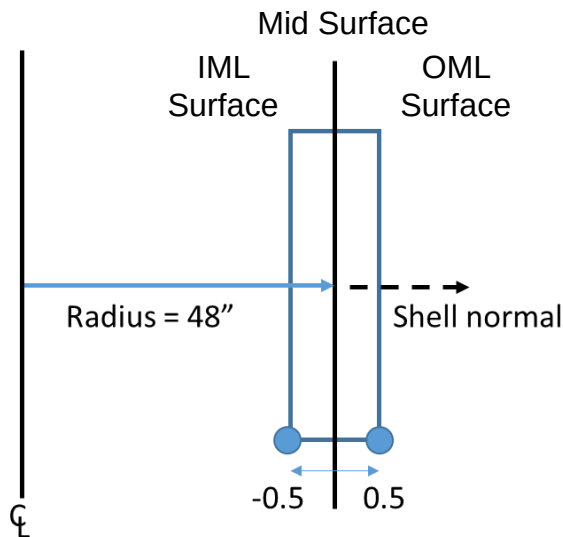


Lessons Learned from Analysis of Composite Sandwich Cylinder Model: Effect of Offset and Boundary Condition

Linear Buckling Analysis of Perfect Composite Cylinder



Perfect composite cylinder model



Kinematic coupling	Offset	Abaqus, P_{cr} lb	% diff from mid
Simply Supported Boundary Condition	0.5 (OML)	8.505E+05	0.432
	0.4	8.497E+05	0.337
	0.3	8.490E+05	0.252
	0.2	8.483E+05	0.177
	0.1	8.477E+05	0.099
	0.0 (Mid)	8.470E+05	0.000
	-0.1	8.463E+05	0.350
	-0.2	8.456E+05	0.872
	-0.3	8.449E+05	1.140
	-0.4	8.442E+05	1.218
	-0.5 (IML)	8.435E+05	1.179

Replace with bar chart?

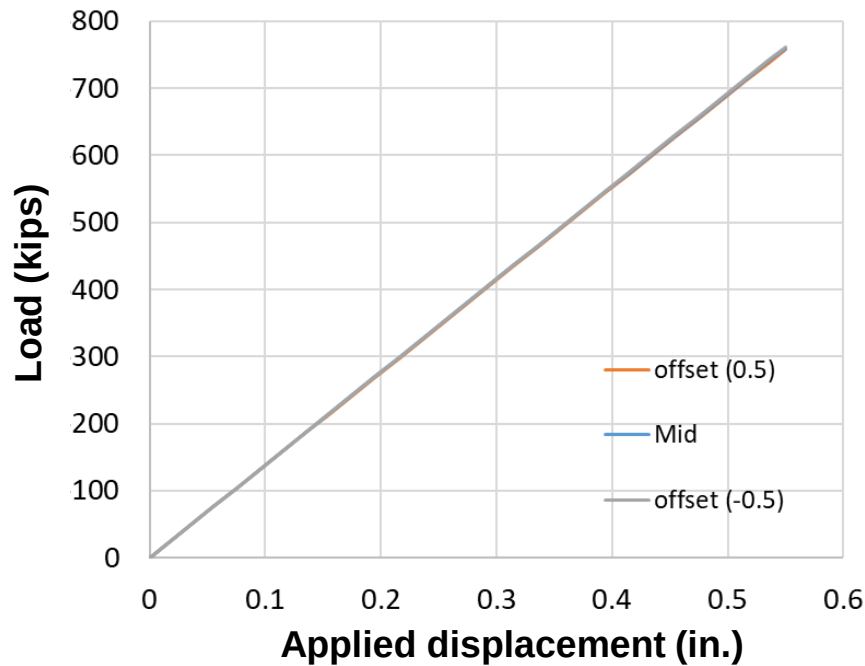
Kinematic coupling	Offset	Abaqus, P_{cr} lb	% diff from mid
Clamped Boundary Condition	0.5 (OML)	8.533E+05	0.377
	0.4	8.525E+05	0.279
	0.3	8.517E+05	0.194
	0.2	8.511E+05	0.119
	0.1	8.506E+05	0.054
	0.0 (Mid)	8.501E+05	0.000
	-0.1	8.497E+05	0.042
	-0.2	8.495E+05	0.075
	-0.3	8.493E+05	0.096
	-0.4	8.492E+05	0.107
	-0.5 (IML)	8.492E+05	0.108

Nonlinear Analysis of Perfect Composite Cylinder

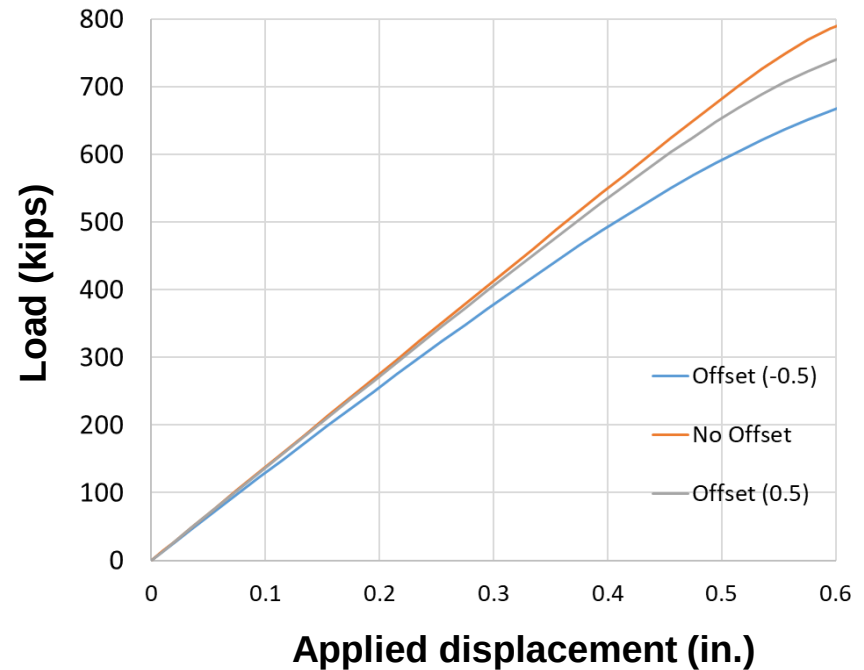


Load vs. applied displacement response of perfect composite cylinder

Clamped boundary condition



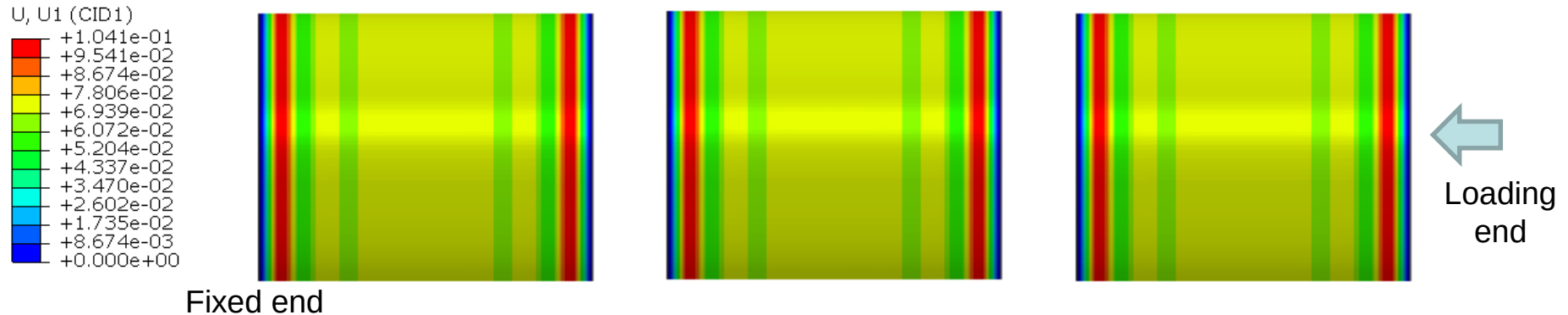
Simply supported boundary condition



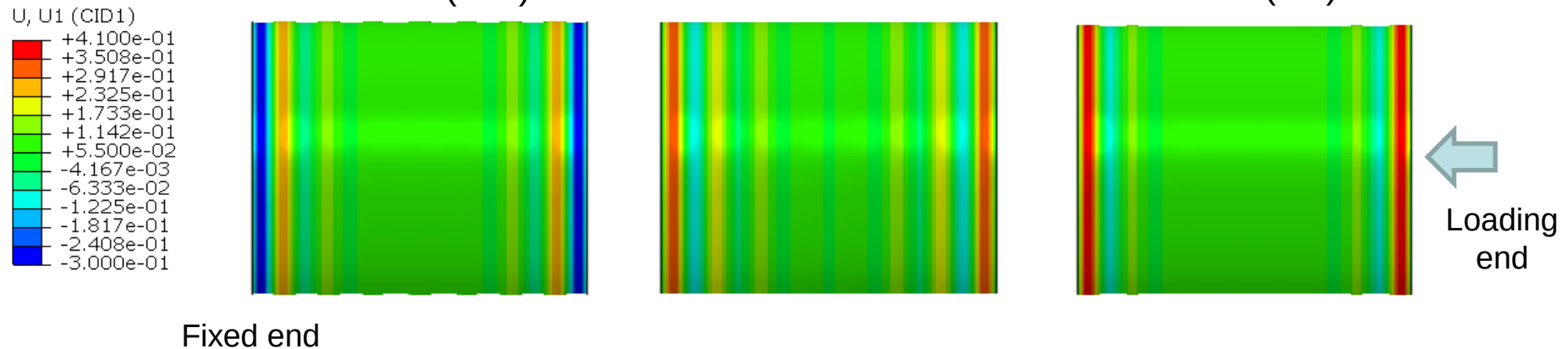
Nonlinear Analysis of Perfect Composite Cylinder (Radial displacement)



Clamped condition (applied displacement = 0.55 in.)



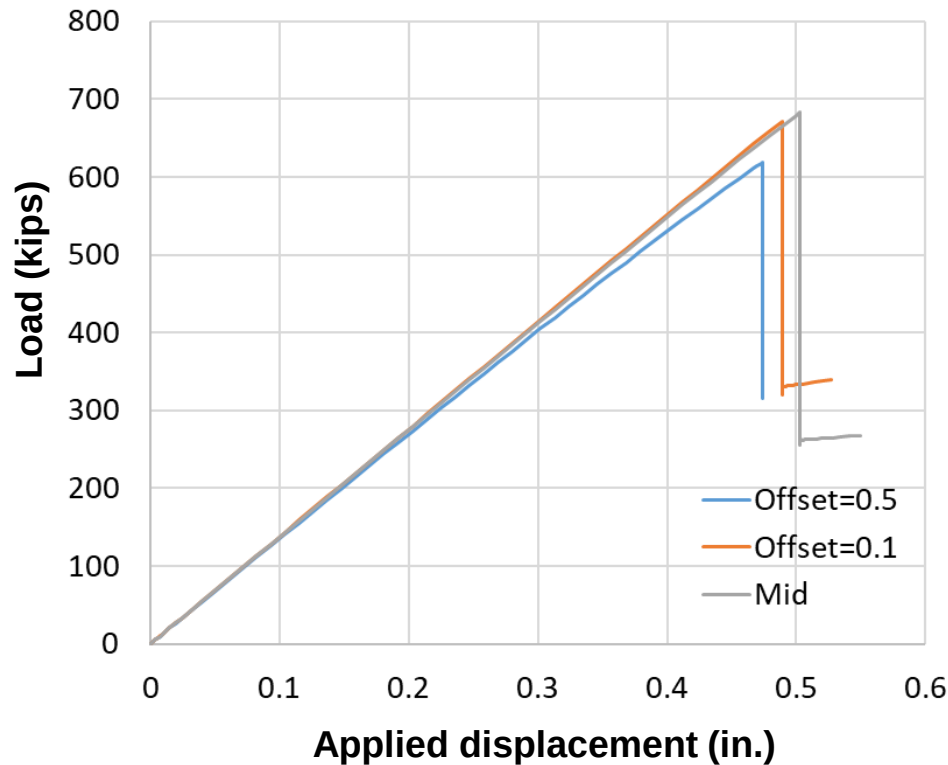
Simply support condition (applied displacement = 0.55 in.)



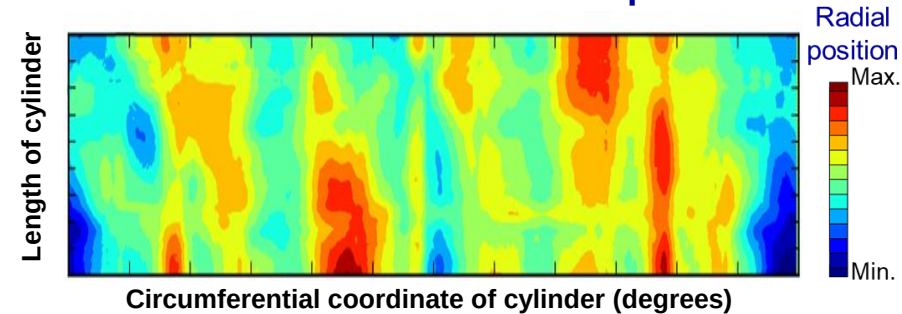
Load vs. Displacement Response of Composite Cylinder Model



Simply supported boundary condition



CTA8.1 test article nominal amplitude





- **Summarize offsets and boundary conditions lessons learned**



Concluding Remarks

- **Modeling and Analysis Plan (MAP) for composite sandwich cylinders was drafted and finite element models were developed and executed utilizing MAP**
- **The nonlinear and postbuckling responses are sensitive to the nonlinear convergence criteria and user inputs**
- **The prediction of the global response of the composite cylinder model is sensitive to boundary conditions, shell element offset, and initial imperfection shape of the cylinder**



Discussion and Questions
