University of BRISTOL
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Nonlinear Buckling Analysis of Tow-Steered Composite Cylinders with Cutouts

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NASA Langley Research Center

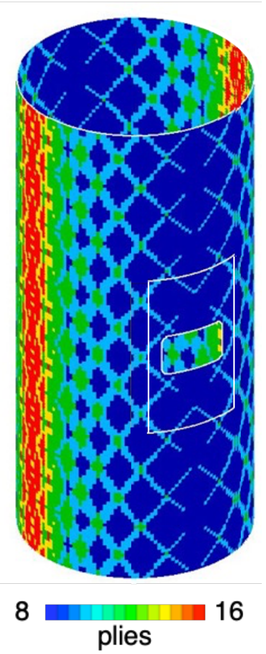
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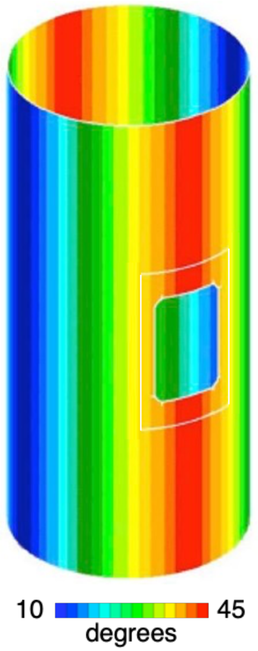
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Objectives

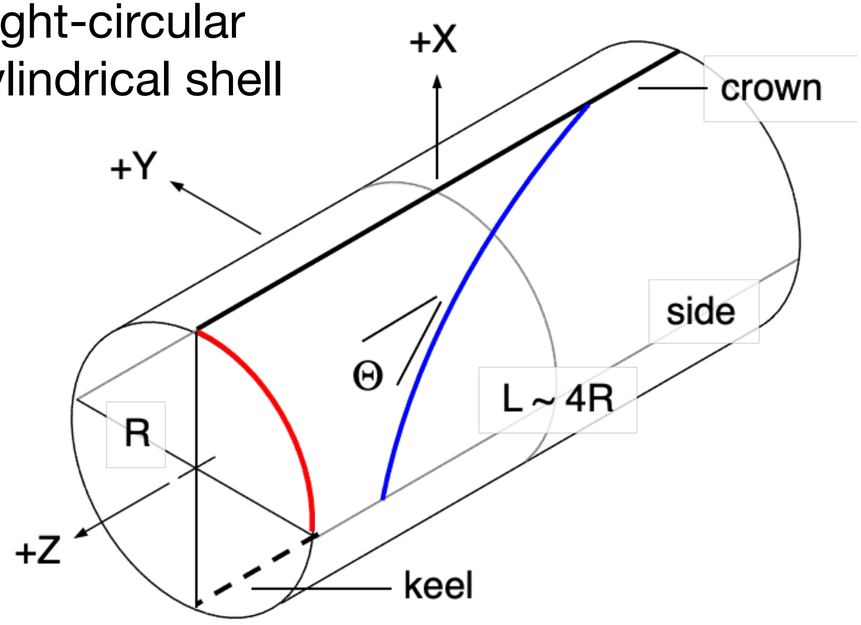
- Assess structural performance of four tow-steered composite shells with cutouts
  - Shells with and without tow overlaps (same layup)
  - Both small and large cutouts (serial tests)
- Apply geometrically nonlinear finite element analyses
  - Predict shell axial stiffness and buckling loads
  - Predict shell postbuckling response
- Compare modeled shell structural performance with compression test results
  - Shell prebuckling axial stiffness
  - Local and global buckling loads and deformations
  - Shell postbuckling deformations





Tow-Steered Shells

Right-circular cylindrical shell



Principal fiber path defined as a constant-radius **circular arc**

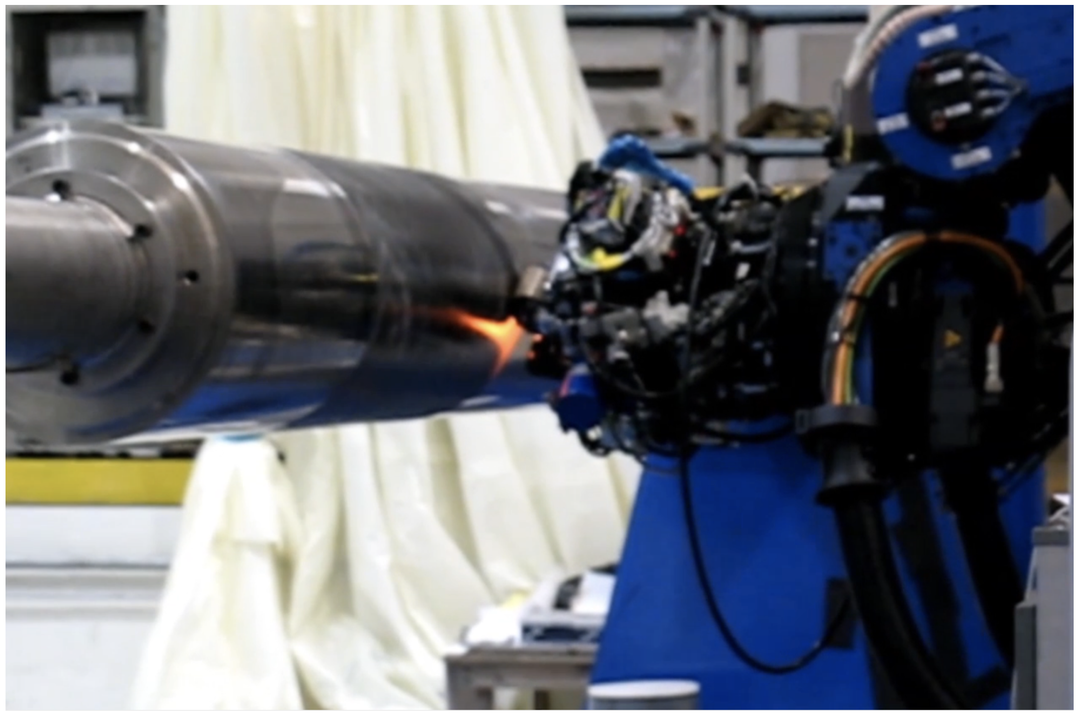
- Start angle Θ_0 on crown/keel
- End angle Θ_1 on sides

Arc width = mandrel circumference/4

Design laminate to replicate “I-beam” bending response:

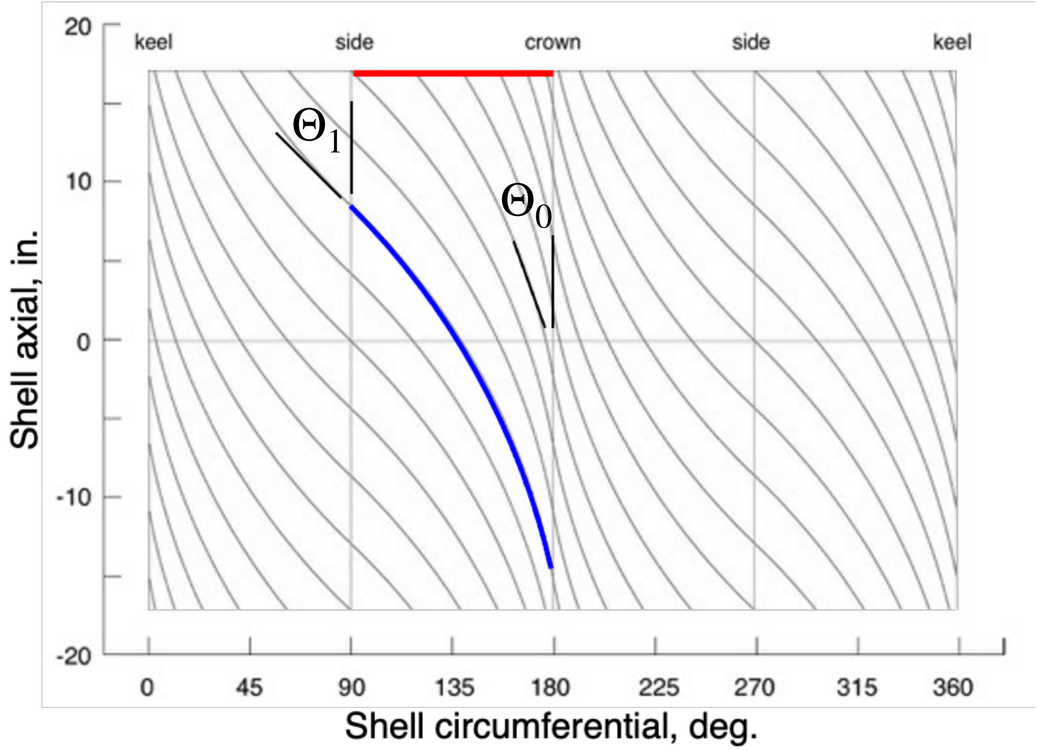
- Crown/keel carry axial compression/tension
- Sides carry shear loads

→ Circumferential angle variation



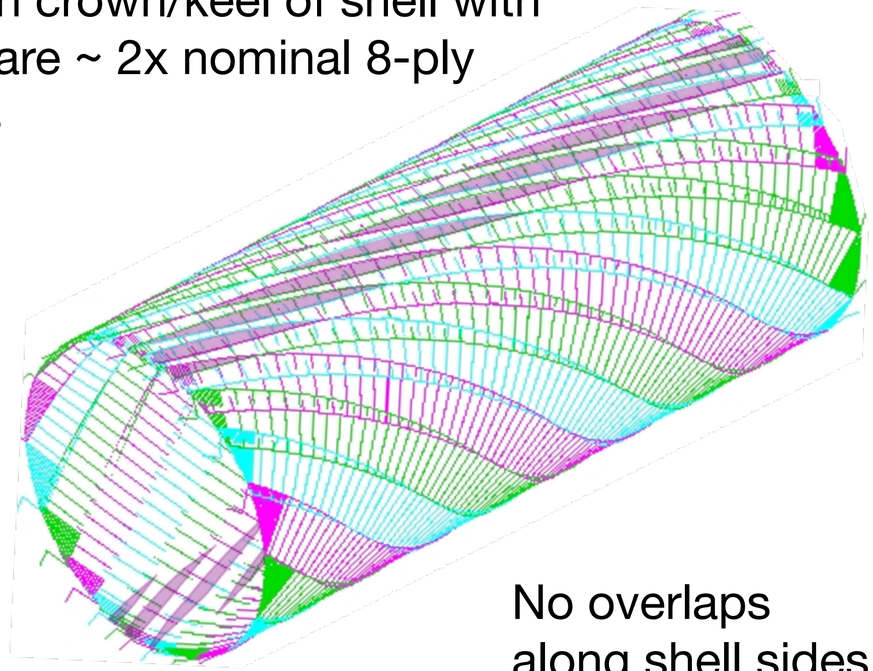
Fiber placement system has minimum steering radius → manufacturing constraint

Design for Manufacturing



- Continuous fiber angle variation from $\Theta_0 = 10$ deg on the shell crown/keel, to $\Theta_1 = 45$ deg on shell sides

- Layups on crown/keel of shell with overlaps are ~ 2x nominal 8-ply thickness



No overlaps along shell sides

- 22 steered courses required to cover 16.266 in. OD mandrel
- Nominal 8-ply $[\pm 45/\pm\Theta]_s$ layups
- Shells with (Shell A) and without (Shell B) tow overlaps fabricated (no cutout)

Description of Small Cutouts

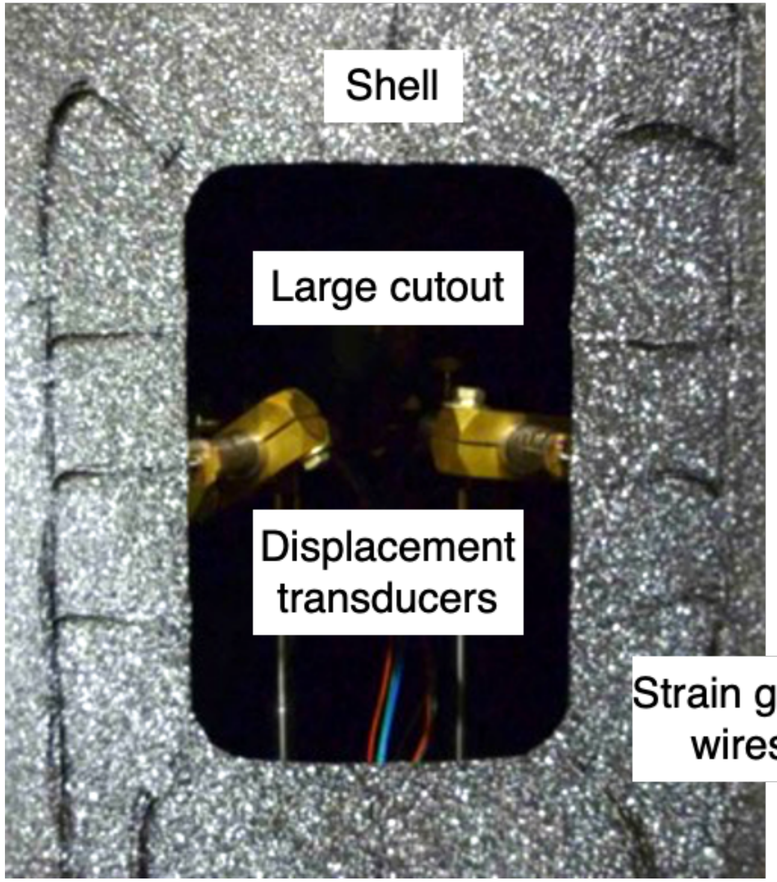
- Small cutouts scaled to represent passenger doors on commercial aircraft fuselage barrel
- Cutouts are 3 in. (axial) x 4.88 in. (circumferential) with 0.50 in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup ~ $[\pm 45]_{2s}$)
- 20 back-to-back strain gage pairs around cutout perimeter installed
- Full-field digital image correlation (DIC) applied



Shell with small cutout installed in test stand

Description of Large Cutouts

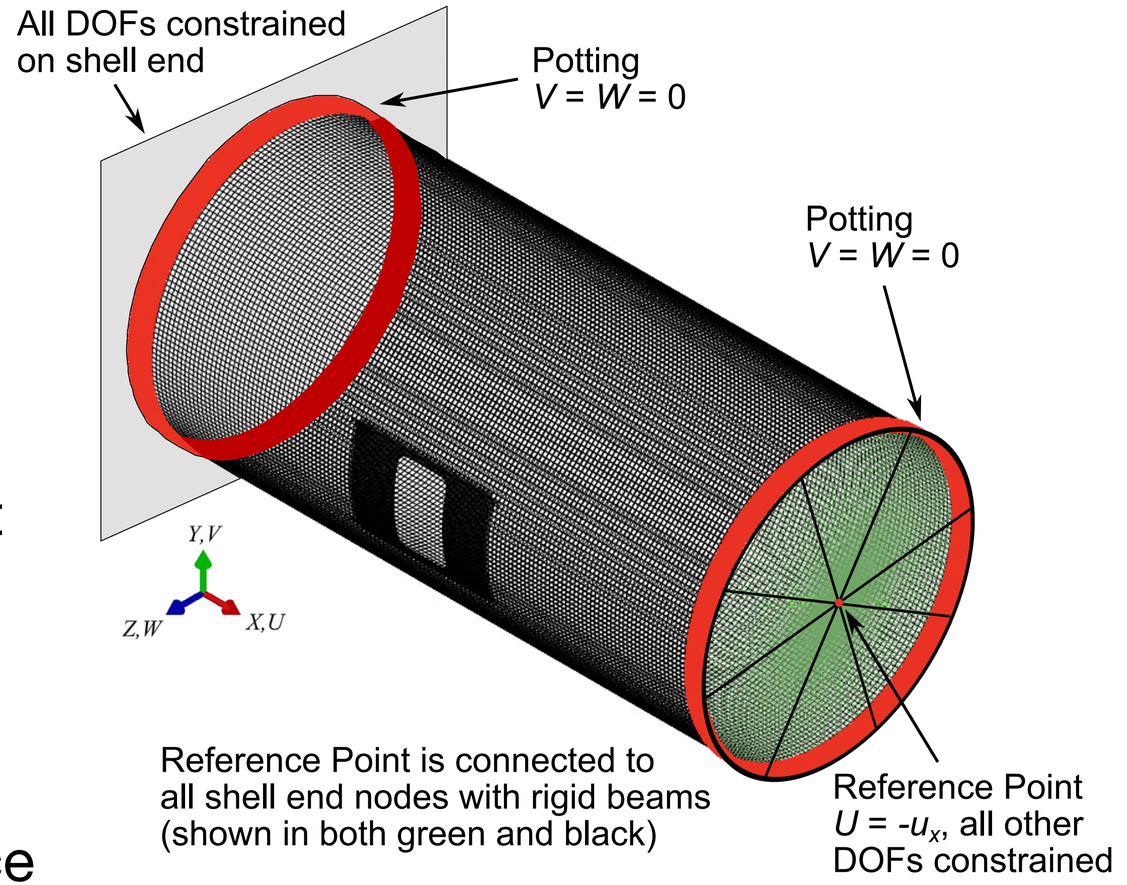
- Large cutouts scaled to represent cargo doors on commercial aircraft fuselage
- Cutouts dimensions are 8 in. (axial) x 5.25 in. (circumferential) with 0.75 in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup ~ $[\pm 45]_{2s}$)
- 24 back-to-back strain gage pairs around cutout perimeter installed
- 2 LVDTs centered on vertical edges to measure out-of-plane deflections around cutout



Detail of shell with large cutout

Finite Element Models

- ABAQUS analyses performed
  - Geometrically nonlinear analysis (implicit dynamic solver)
  - Axial end shortening applied to shell
- S4R elements used
  - 0.25 in.-square elements in acreage
  - Constant thickness and fibre angle per element
  - Measured IM7/8552 material properties and predicted laminate thickness
- Refined FE mesh around cutouts
  - 0.083 in.-square local refinement (convergence study)

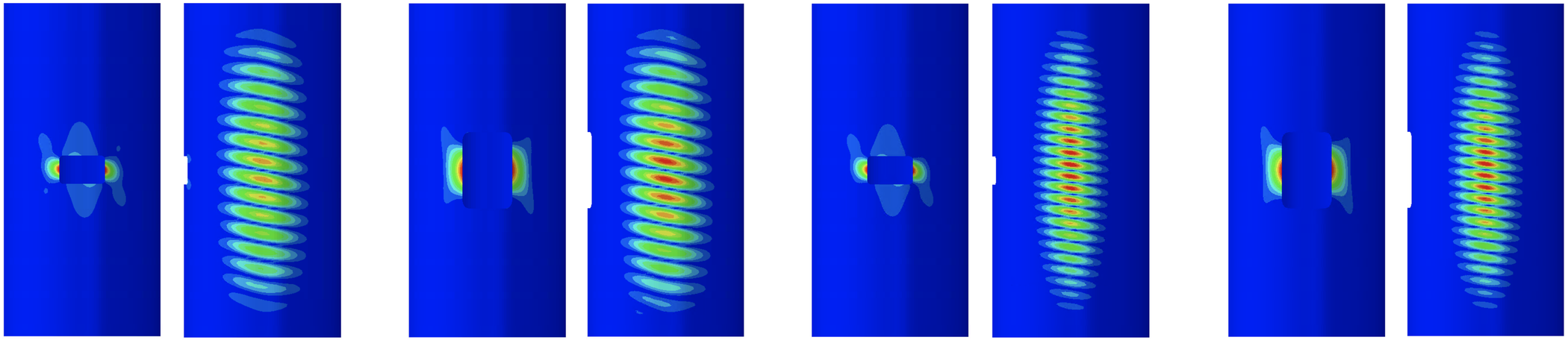


Results: Linear Eigenvalue Analysis

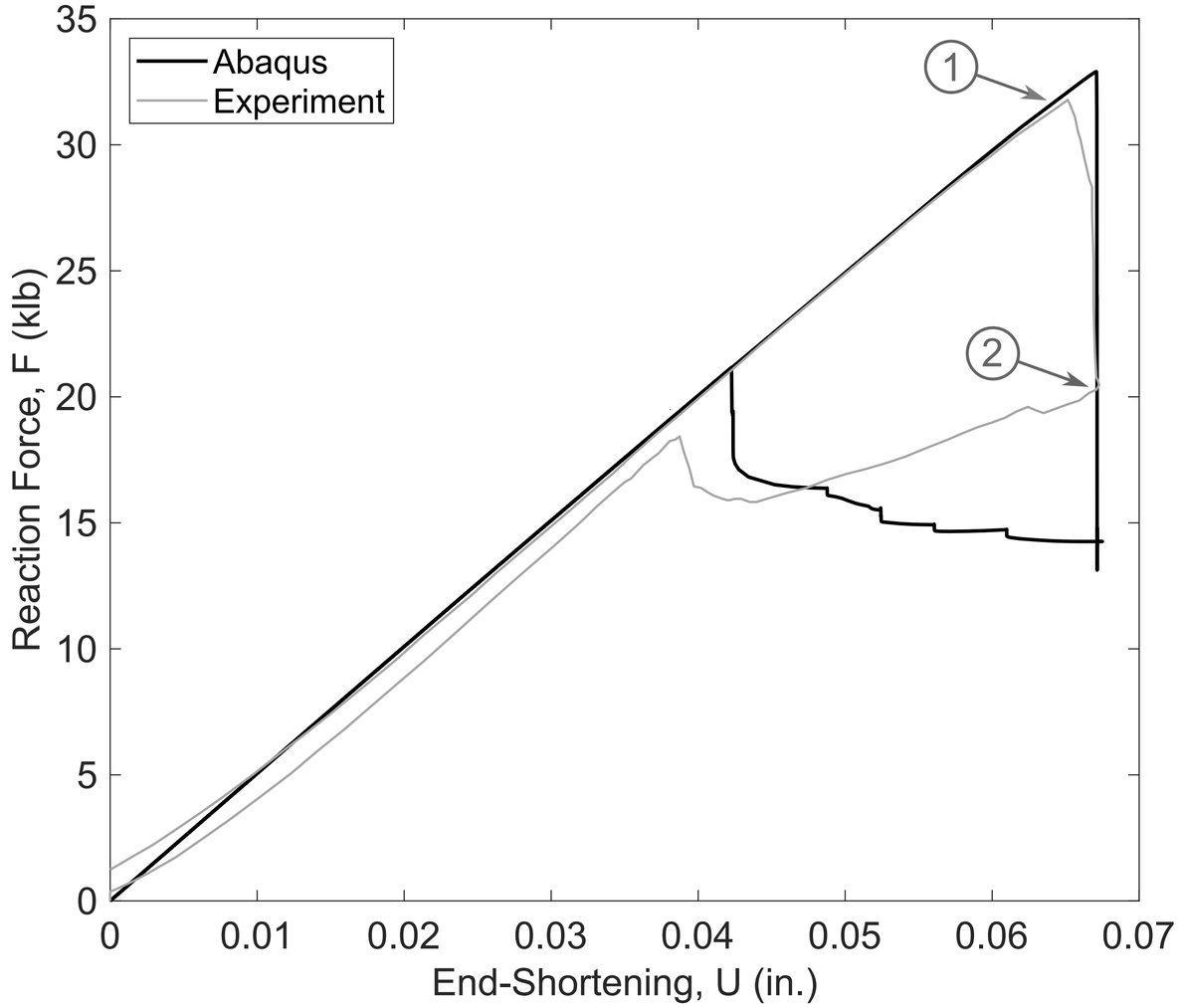
- First eigenmodes all local buckling
- Global buckling in stiffest and unsupported region, i.e. the crown/keel
- Akin to beam on foundation

Buckling Load	Shell A		Shell B	
	Small	Large	Small	Large
Local Buckling (klb)	18.6	14.0	10.1	7.85
Global Buckling (klb)	37.6 (18%)	37.2 (12.7%)	15.7 (-1.3%)	15.5 (6.2%)

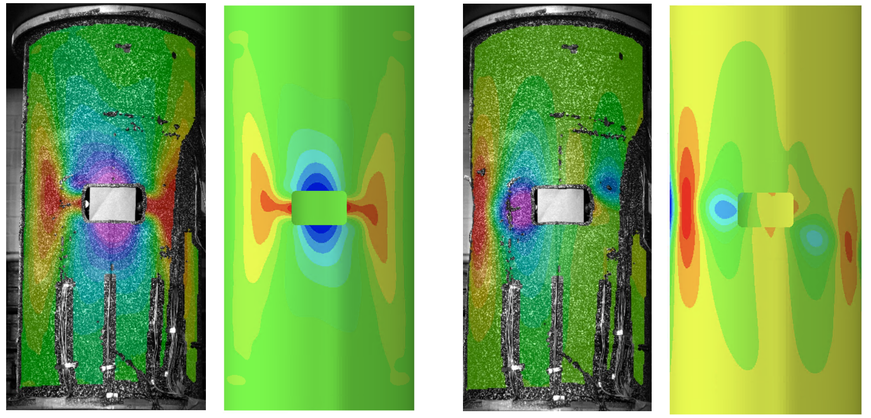
Overprediction of global buckling load due to linearization around the unloaded state



Shell A (Overlaps) - Small Cutout

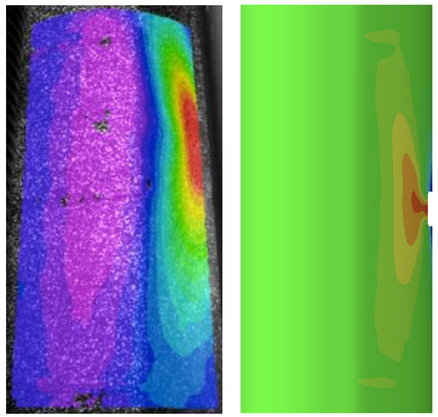


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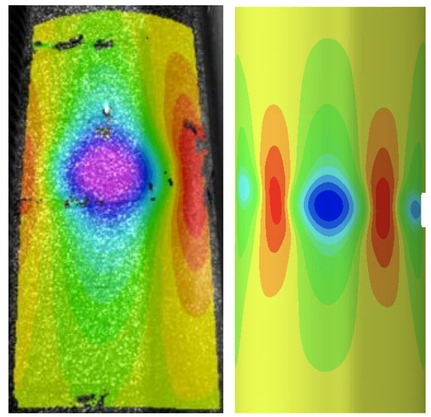


1 - Side View

2 - Side View

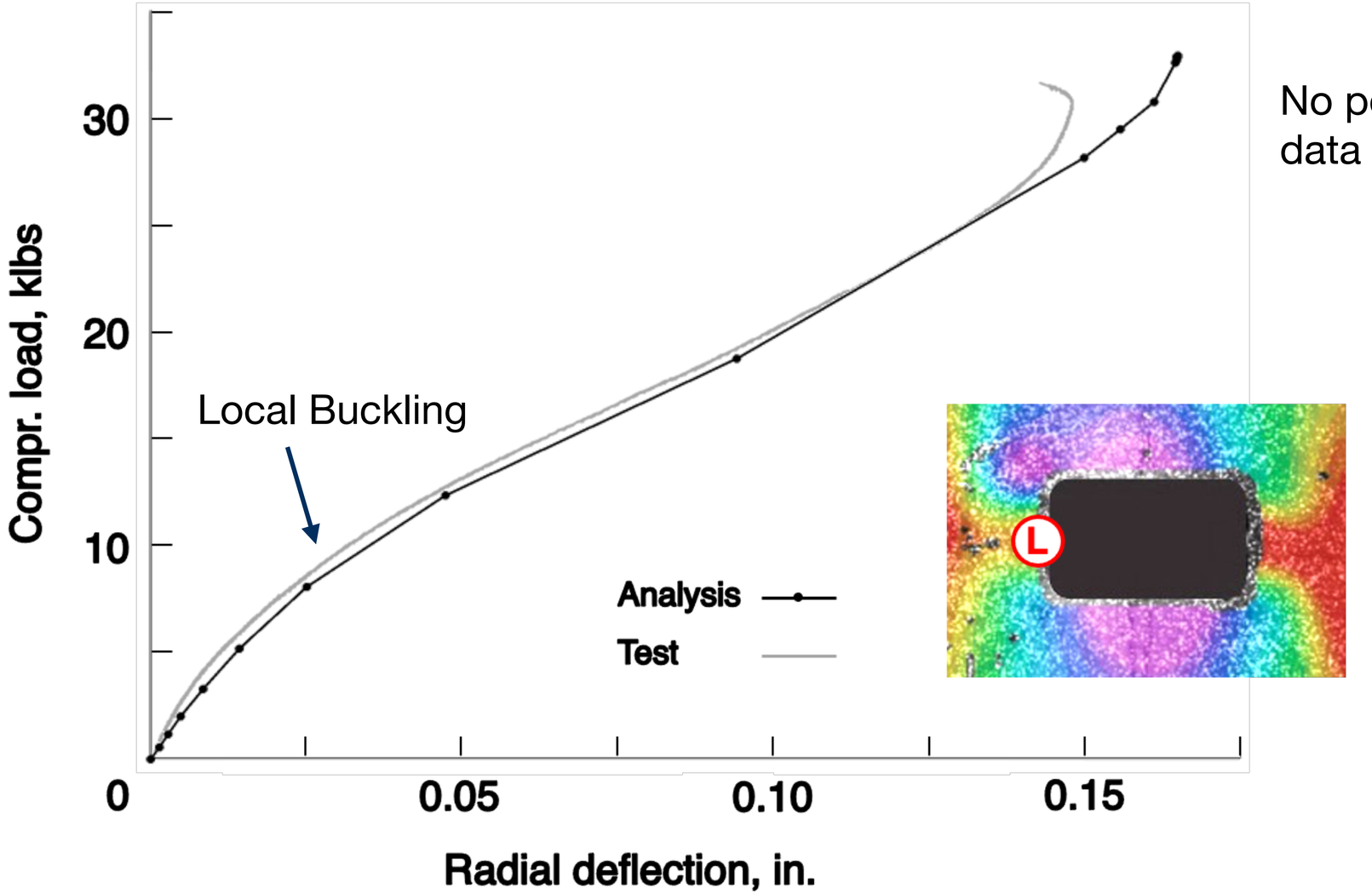


1 - Crown View



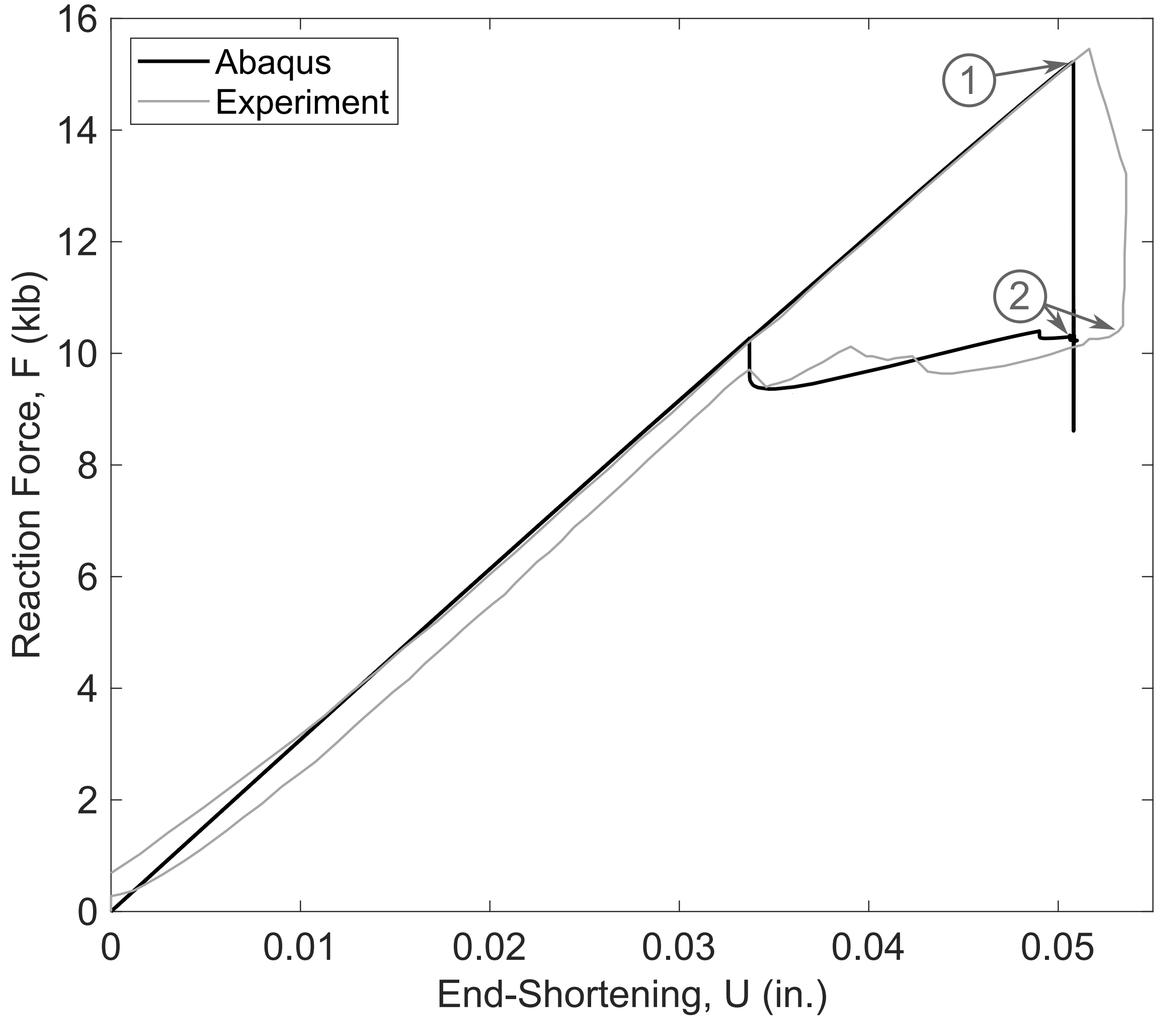
2 - Crown View

Shell A - Small - Radial Deflection

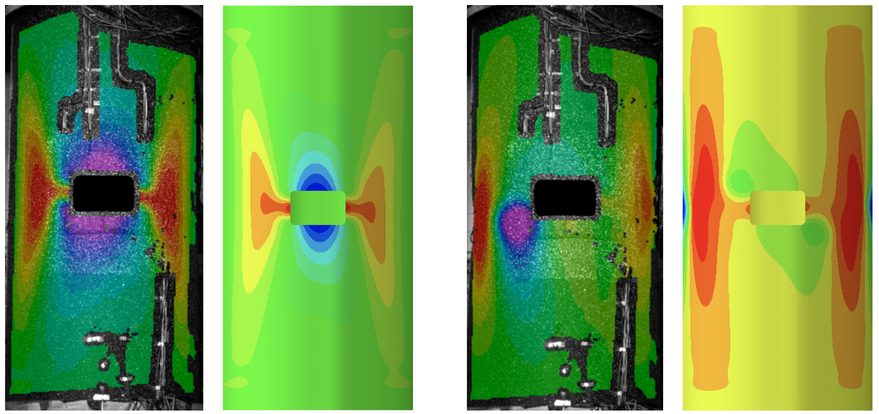


No postbuckling data shown

Shell B (No Overlaps) - Small Cutout

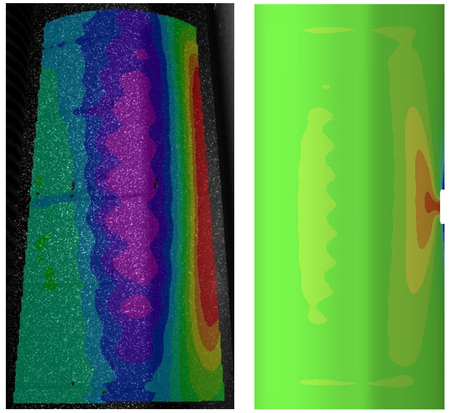


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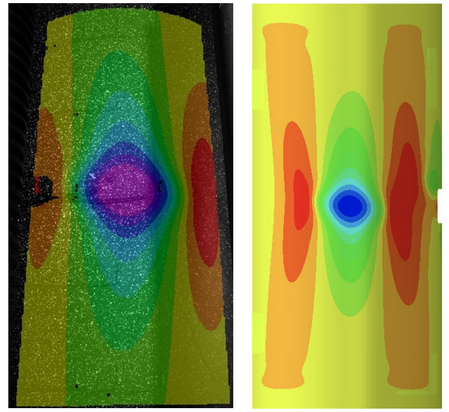


1 - Side View

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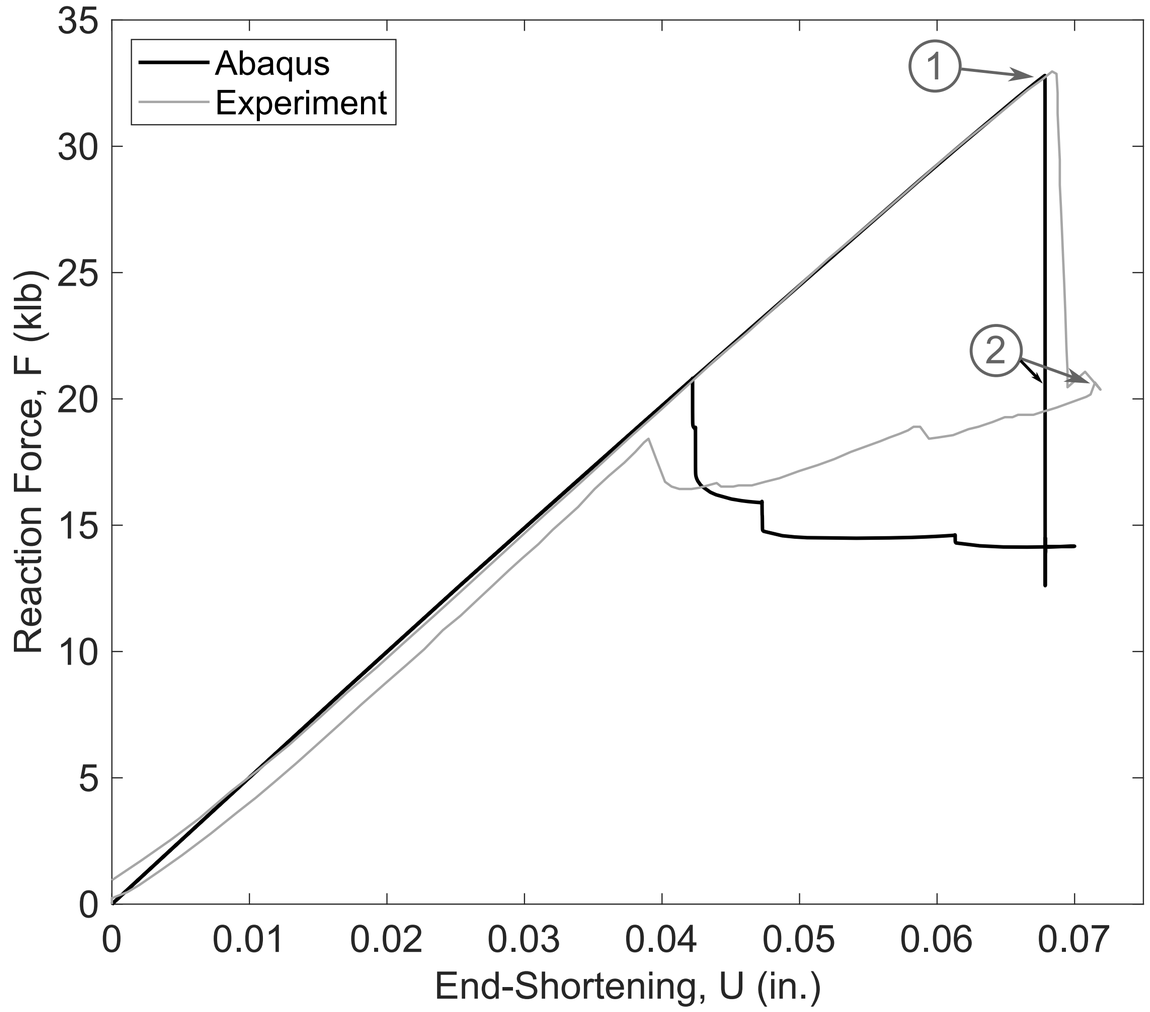


1 - Crown View

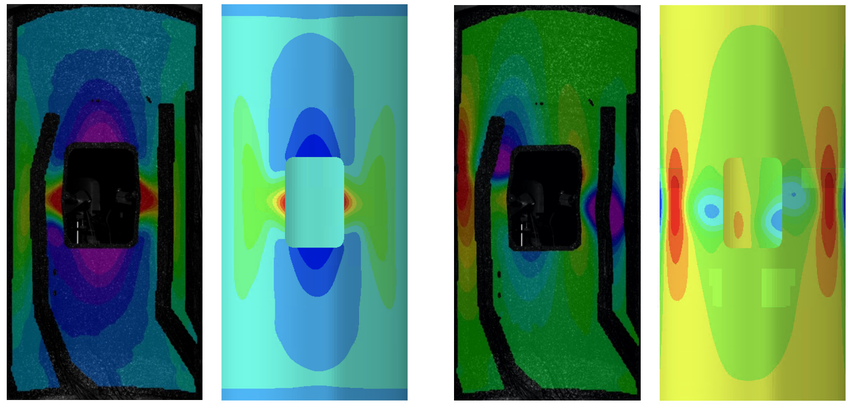


2 - Crown View

Shell A (Overlaps) - Large Cutout

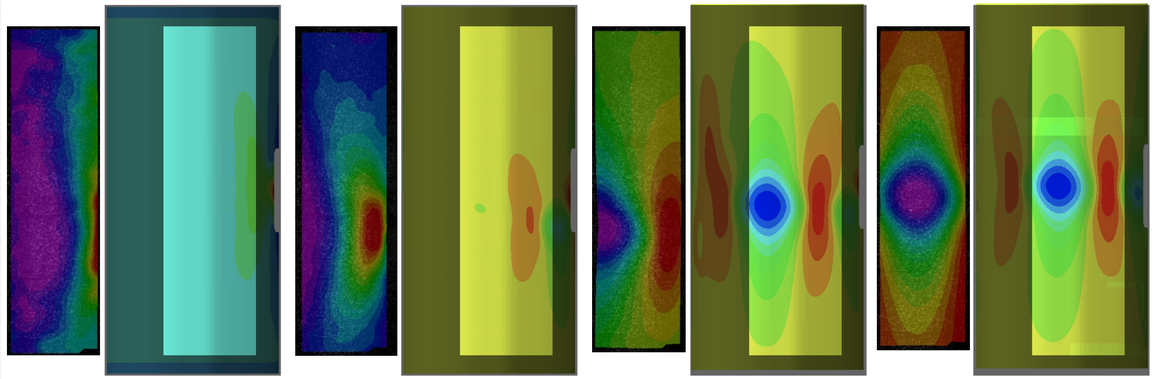


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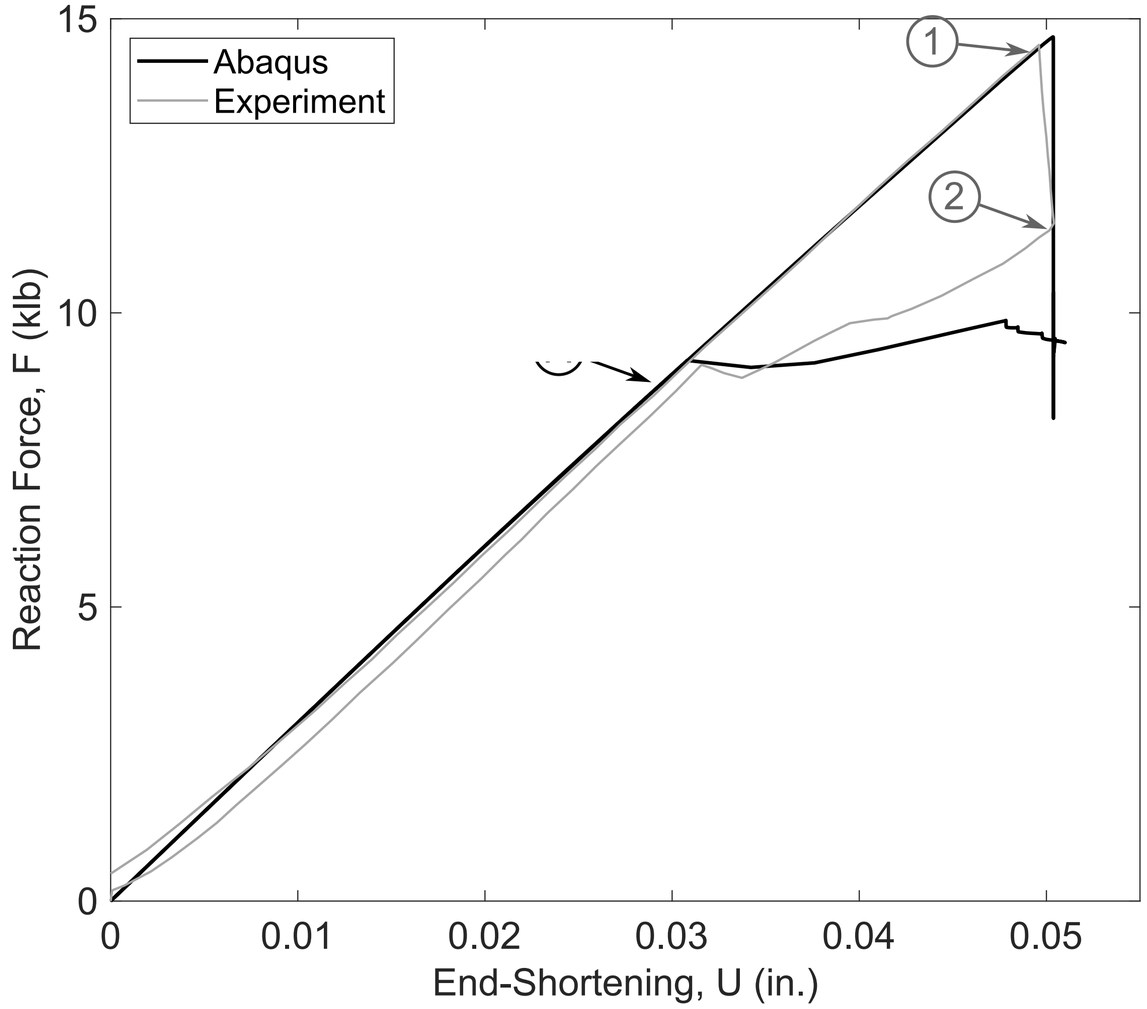
1 - Side View

2 - Side View

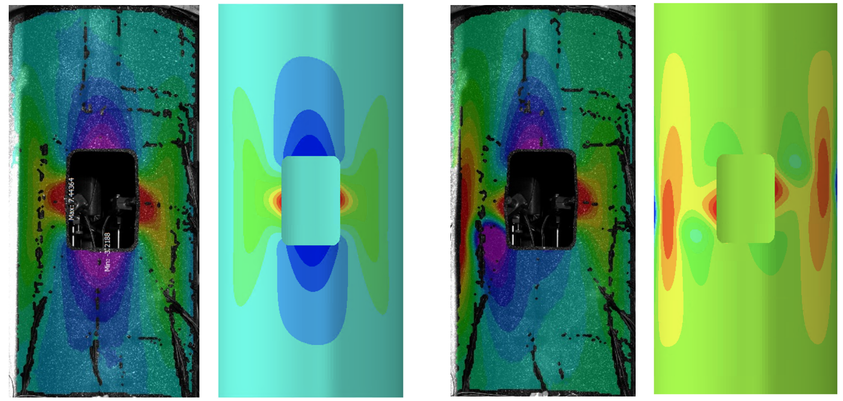


Crown view through time from 1 → 2
Gray matte around approx. DIC FoV

Shell B (No Overlaps) - Large Cutout

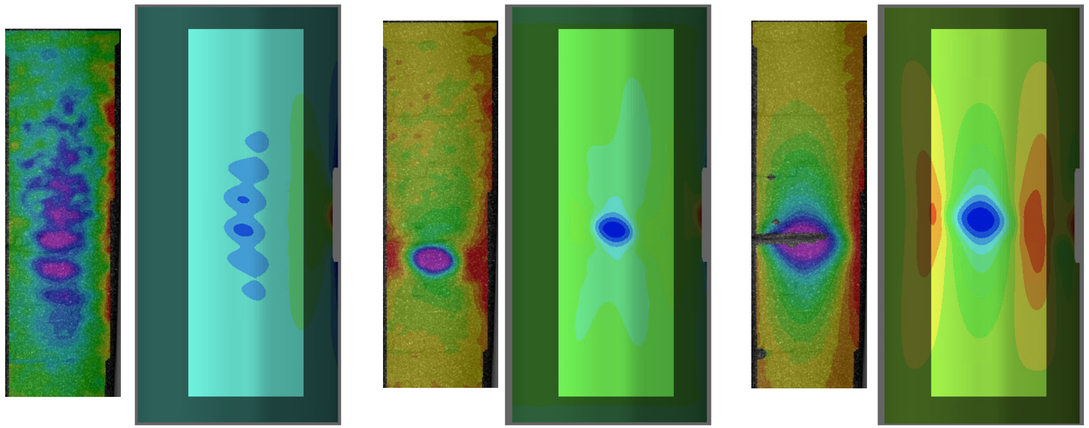


Left = Exp.; Right = FEA. + out / 0 / in -



1 - Side View

2 - Side View



Crown view through time from 1 → 2

Gray matte around approx. DIC FoV

Results Summary

Load	Shell A		Shell B	
	Small	Large	Small	Large
Global Buckling (klb)	32.9 (3.5%)	32.8 (-0.61%)	15.2 (-1.9%)	14.7 (0.68%)
Restabilized Postbuckling (klb)	14.3 (-30%)	14.5 (-29%)	10.2 (-2.9%)	9.5 (-17%)

- Excellent correlation between nonlinear dynamic models and tests
  - Noteworthy, as no geometric or loading imperfections included in models
  - Cylinders are essentially imperfection insensitive
  - Non-uniform stiffness distribution breaks symmetry → imperfections are only important in highly stressed regions
- Restabilised post-buckling load conservatively predicted
  - Friction and slack dissipating kinetic energy
  - Post-buckling mode shape predicted well, and also re-connection to pre-buckling path

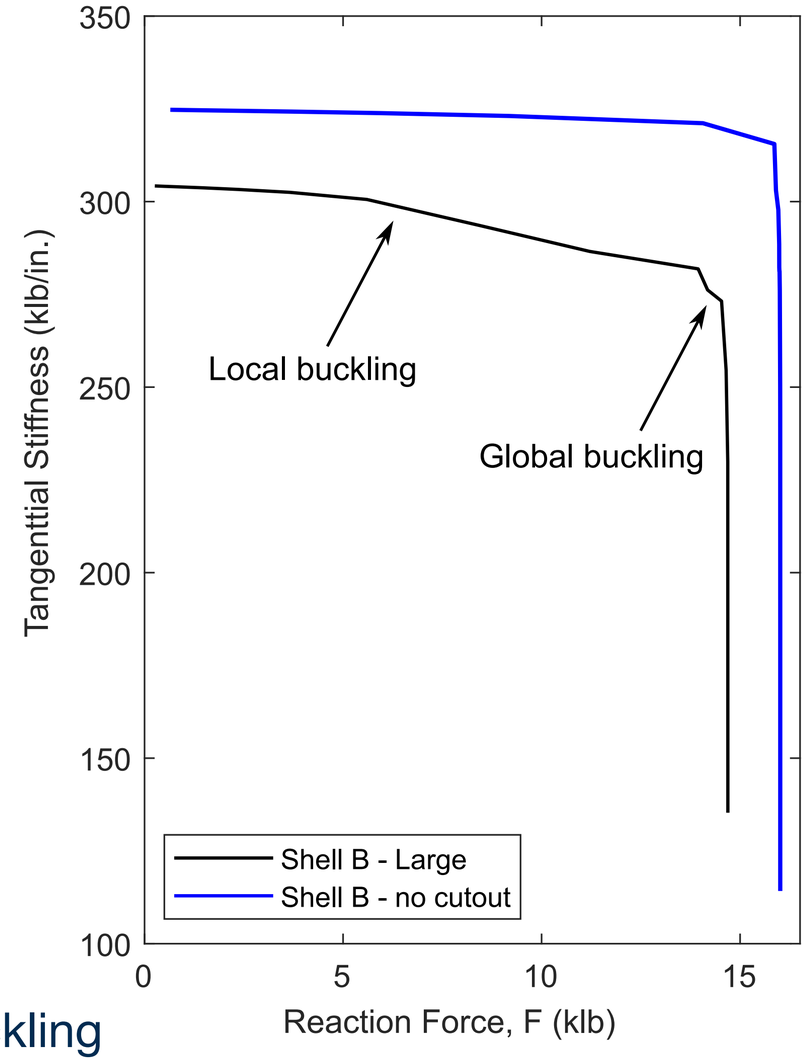
Load Redistribution

- Linear eigenvalue analysis accurately predicts local buckling load
- Reduction in axial tangential stiffness of 5–10% after local buckling (leads to linearized global buckling overprediction)
- Reduction in stiffness is low: redistribution of axial stress before local buckling
- Tow steering useful for reducing stress concentrations + minimizing effect of local buckling

Linearized Buckling Prediction

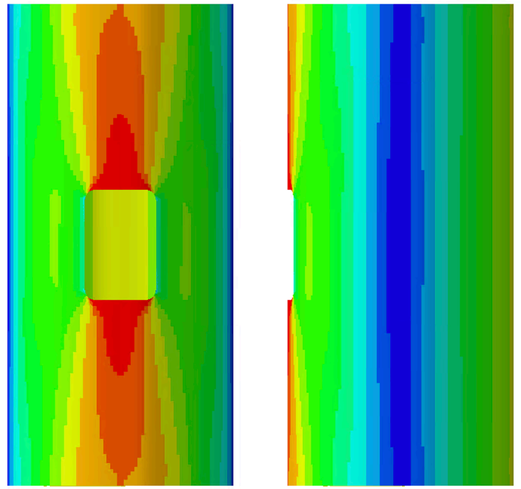
Buckling Load	Shell B Large
Local Buckling (klb)	7.85
Global Buckling (klb)	15.5 (6.2%)

Overprediction due to local buckling

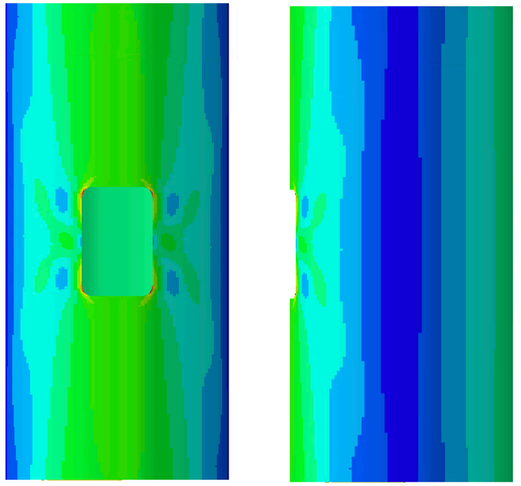


Axial Stress

Pre Local Buckling



Post Local Buckling



Conclusions

- Structural performance of four tow-steered composite shells with unreinforced cutouts modeled and compared with tests
- Shells first buckle locally around cutouts with a small effect on the global axial stiffness
- Stresses have already been reoriented away from cutouts to decrease effect of local buckling
- Nonlinear dynamic models without imperfections of any kind accurately predict global buckling loads
- Linear eigenvalue analyses accurately predict local buckling
- Future work:
  - Deep postbuckling
  - Material failure in post-buckling regime

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Questions?

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