

# Testing And Analysis Of Advanced Composite Tow-Steered Shells

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NESC Structures TDT

NESC Academy Webcast

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# Talk Outline

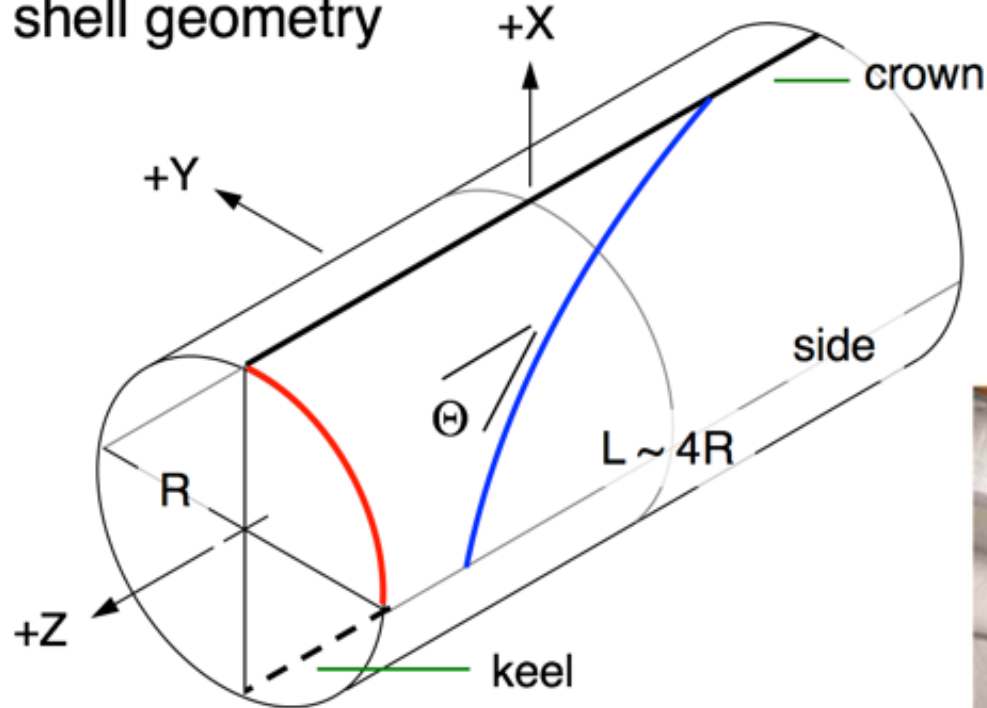
- Introduction
- Pristine shells
  - With and without tow overlaps
  - No cutouts
- Shells with cutouts
  - Both small and large cutouts
- Shell imperfection analyses
  - Measured data from pristine shells
- Concluding remarks

# Study Objectives

- Assess structural performance of two advanced composite tow-steered shells
  - Axial stiffness, buckling load
- Apply finite element methods
  - Linear static and bifurcation buckling analyses
  - Detailed nonlinear analyses
- Apply experimental methods
  - Quasi-static loading in axial compression
- Repeat tests and analyses for shells with small and large cutouts to assess effect on performance
- Assess effect of geometric imperfections on shell performance using linear FEA

# Tow-Steered Shell Conceptual Design

Right-circular cylindrical shell geometry



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

- start angle  $\Theta_0$  on crown/keel
- end angle  $\Theta_1$  on sides

**Arc width** = mandrel circumf./4

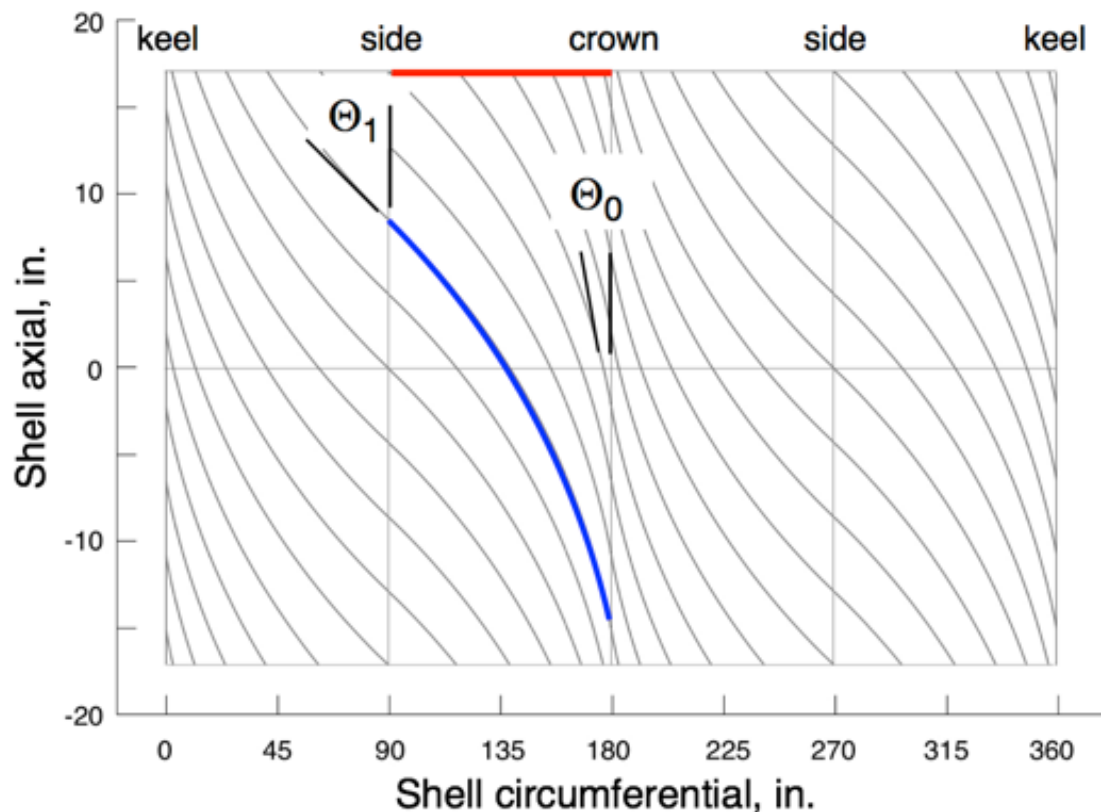
Design laminates to replicate I-beam bending response

- shell crown/keel carry axial compression/tension
  - sides carry shear loads
- => Circumf. angle variation



**Fiber placement system** has minimum steering radius => manufacturing constraint

# Design for Manufacturing



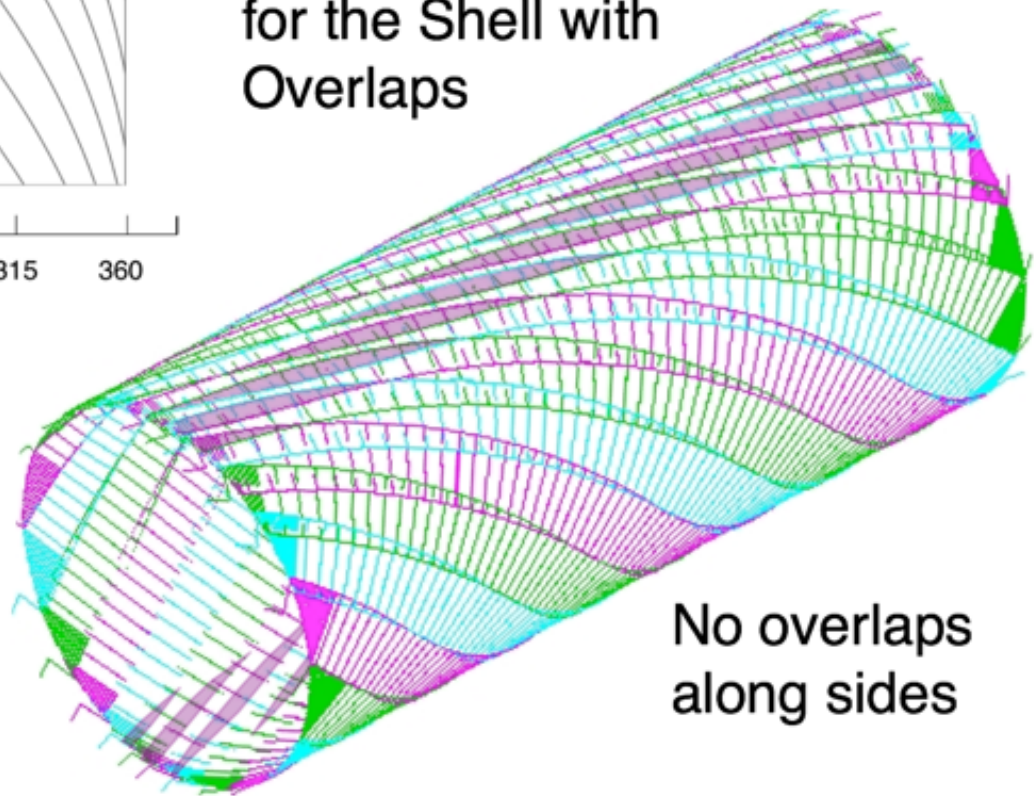
Continuous fiber angle variation from  $\Theta_0 = 10$  deg. on the shell crown/keel, to  $\Theta_1 = 45$  deg. on shell sides

Thicker crown/ keel layups for the Shell with Overlaps

22 steered courses required to cover 16.266 in.-OD mandrel

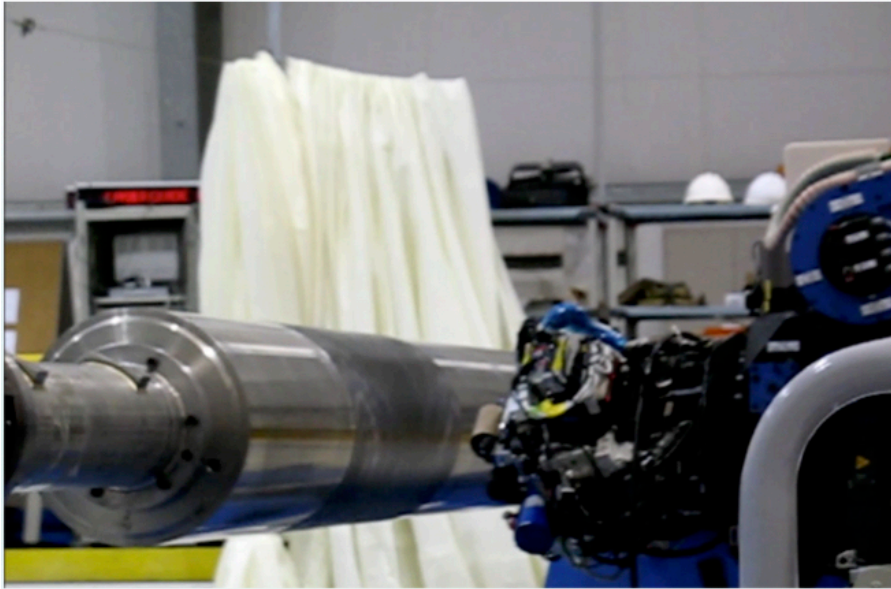
Nominal 8-ply  $[\pm 45/\pm \Theta]_s$  layups

Two shells, with and without tow overlaps, are fabricated



No overlaps along sides

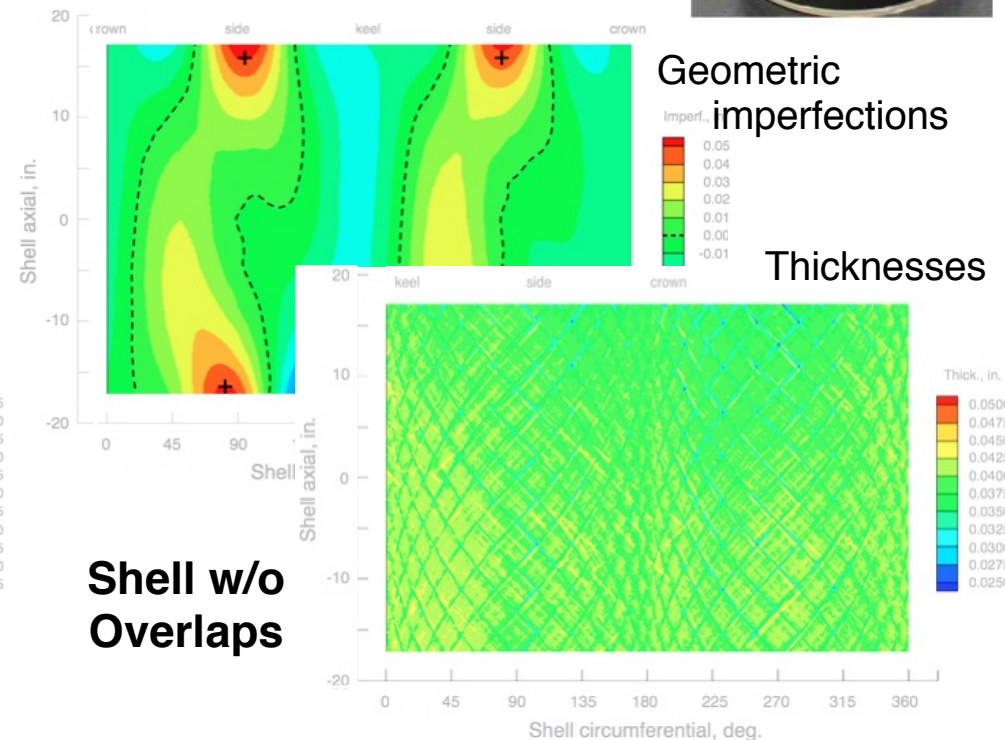
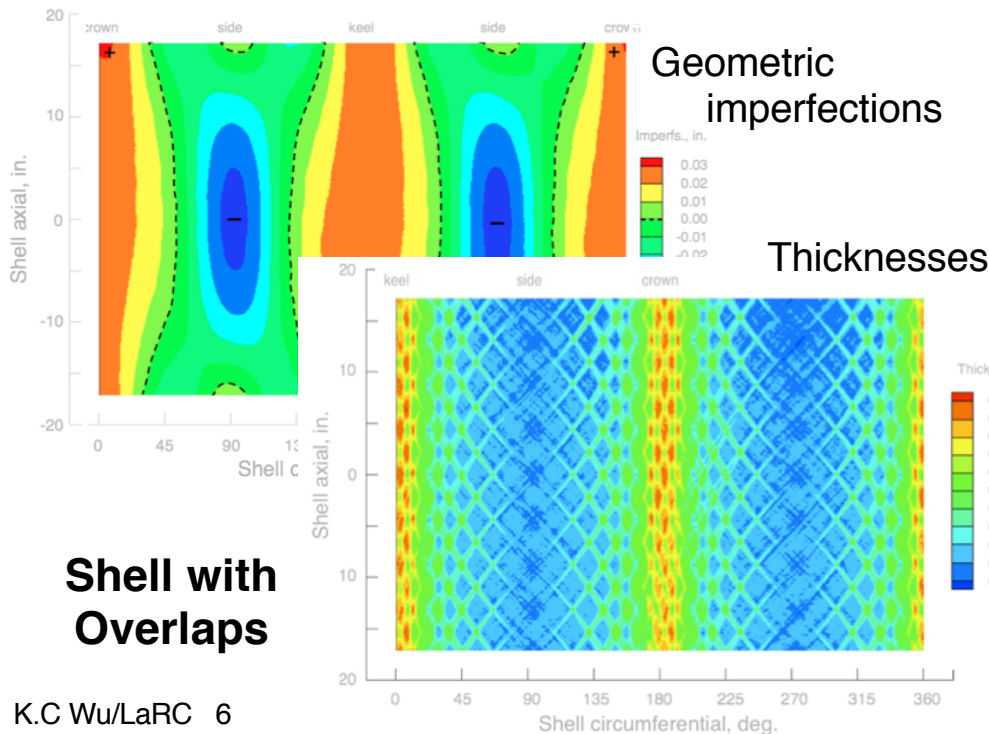
# Fabrication and QA Assessment



Shells built at NCAM/MAF  
on fiber placement system



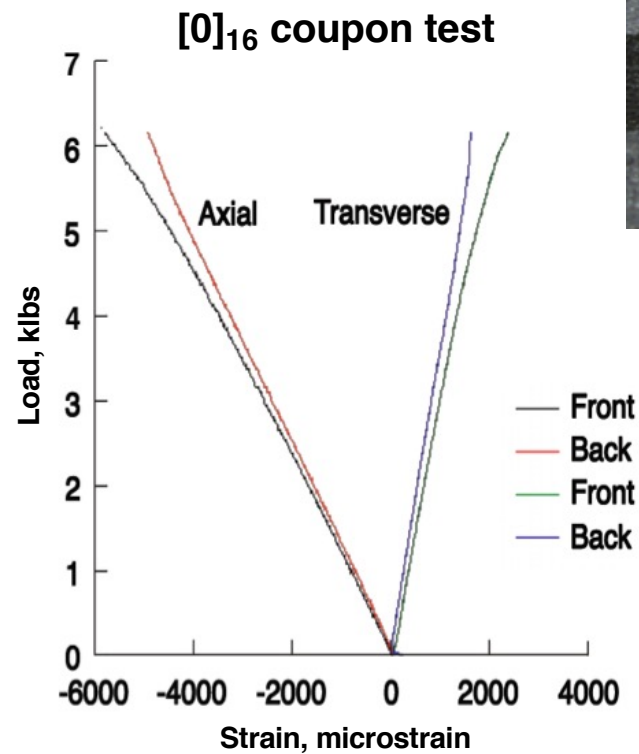
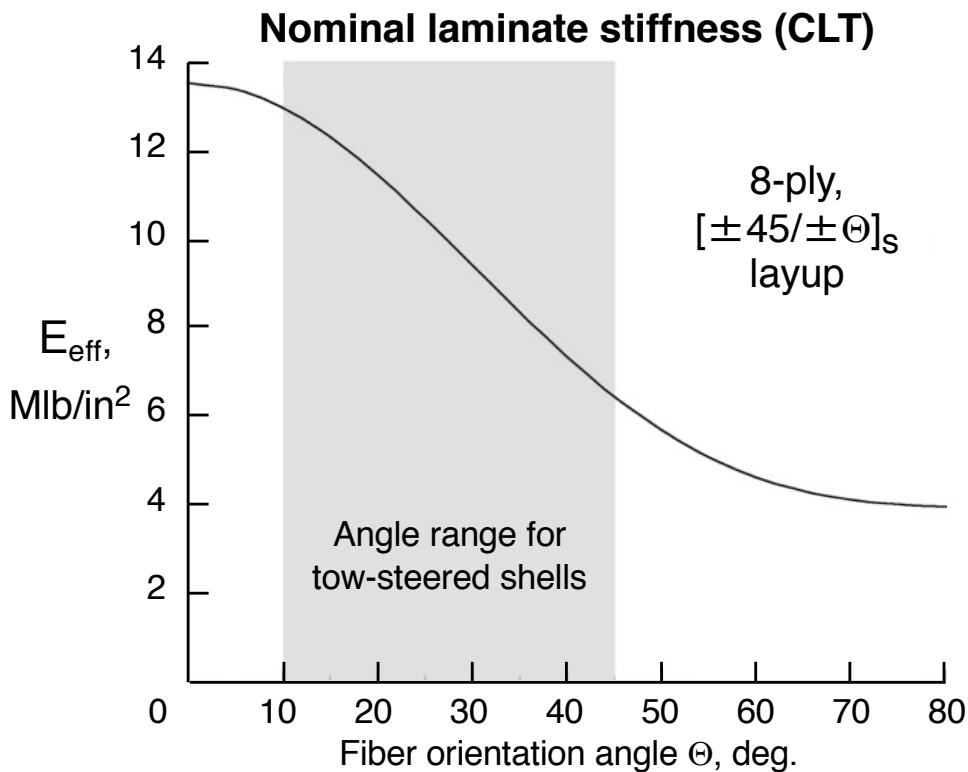
Cured shells surveyed  
at LaRC using CMM



# IM7/8552 Ply Stiffness Testing

|                           | $E_1$ , Mlb/in <sup>2</sup> | $E_2$ , Mlb/in <sup>2</sup> | $\nu_{12}$   | $G_{12}$ , Mlb/in <sup>2</sup> |
|---------------------------|-----------------------------|-----------------------------|--------------|--------------------------------|
| Nominal (NCAMP)           | 20.44                       | 1.41                        | 0.356        | 0.68                           |
| <b>Measured (D695)</b>    | <b>18.04</b>                | <b>1.26</b>                 | <b>0.347</b> | <b>0.70</b>                    |
| Coeff. of variation, pct. | 1.0                         | 1.7                         | 1.8          | 3.2                            |

Average cured ply thickness = **0.0054 in./ply (coupons)**, 0.0050 in./ply (shells)  
 1/8-in. slit tape nominal density = 0.058 lb/in<sup>3</sup>



**D695 compression test set-up**

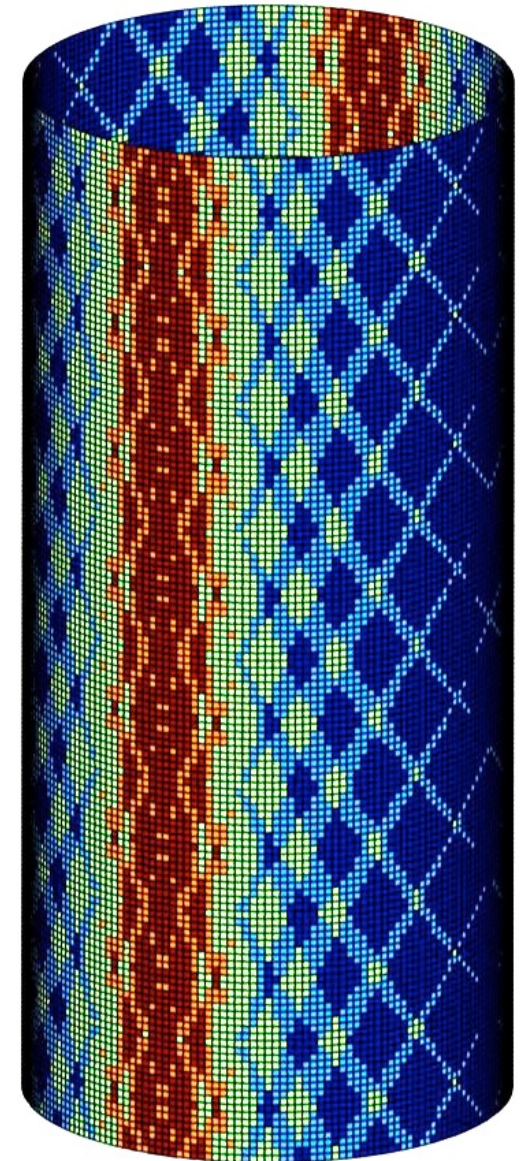
Coupons with  $[90]_{16}$ ,  $[\pm 45]_{4s}$  and  $[0/90]_{4s}$  layups were also tested



# Pristine Shells

# Shell Finite Element Models

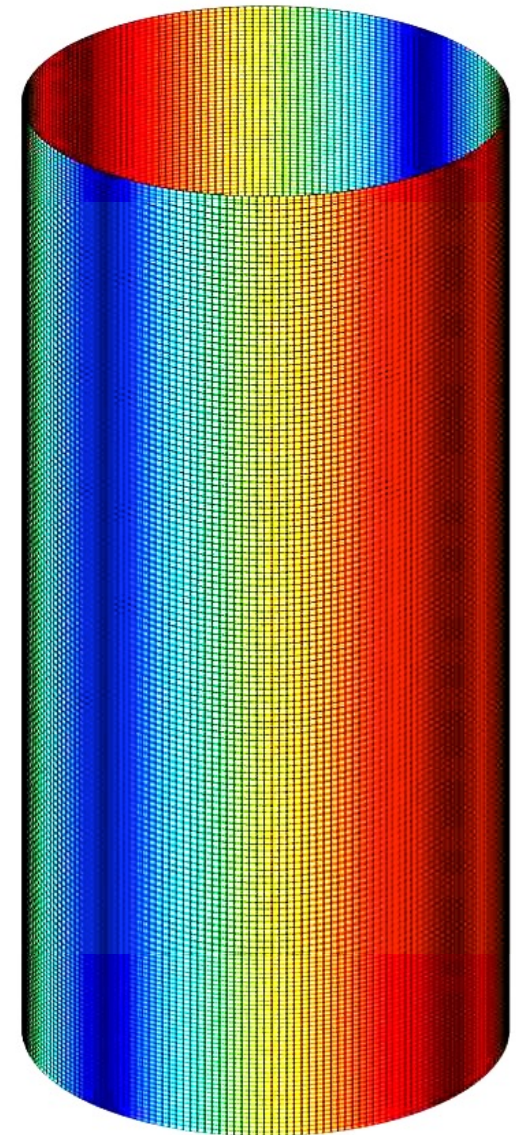
- NASTRAN analyses performed
  - Linear static analyses
  - Linear bifurcation buckling analyses
  - Without geometric imperfections
- 28,560 CQUAD4 shell elements
  - Each element  $\sim 0.25$  in.-square
  - Predicted thickness and fiber angles
  - Measured ply properties and thickness
  - Without and with laminate offsets
- Loads and boundary conditions
  - RBE2 “wagon wheel” for axial load intro.
  - All other DOF = 0 at shell ends
  - Transverse displacements = 0 in potting
- Circumferential fiber angles from design values using constant-radius circular arc



**Shell with Overlaps  
FE model thicknesses**

# Shell Finite Element Models (2)

- NASTRAN analyses performed
  - Linear static analyses
  - Linear bifurcation buckling analyses
  - Without geometric imperfections
- 28,560 CQUAD4 shell elements
  - Each element  $\sim 0.25$  in.-square
  - Predicted thickness and fiber angles
  - Measured ply properties and thickness
  - Without and with laminate offsets
- Loads and boundary conditions
  - RBE2 “wagon wheel” for axial load intro.
  - All other DOF = 0 at shell ends
  - Transverse displacements = 0 in potting
- Circumferential fiber angles from design values using constant-radius circular arc



**FE model ply 3 fiber orientation angles**

# Shell Compression Tests

Nominal shell dimensions

- Overall length = 35.00 inches
- Inner diameter = 16.266 inches

Measured shell weights

- Shell with overlaps = 5.23 lbs
- Shell without overlaps = 4.13 lbs



**Epoxy potting compound cast on shell ends to prevent brooming**

4 displacement transducers measure relative platen motion

- Average = end shortening
- Diff's = transv. bending

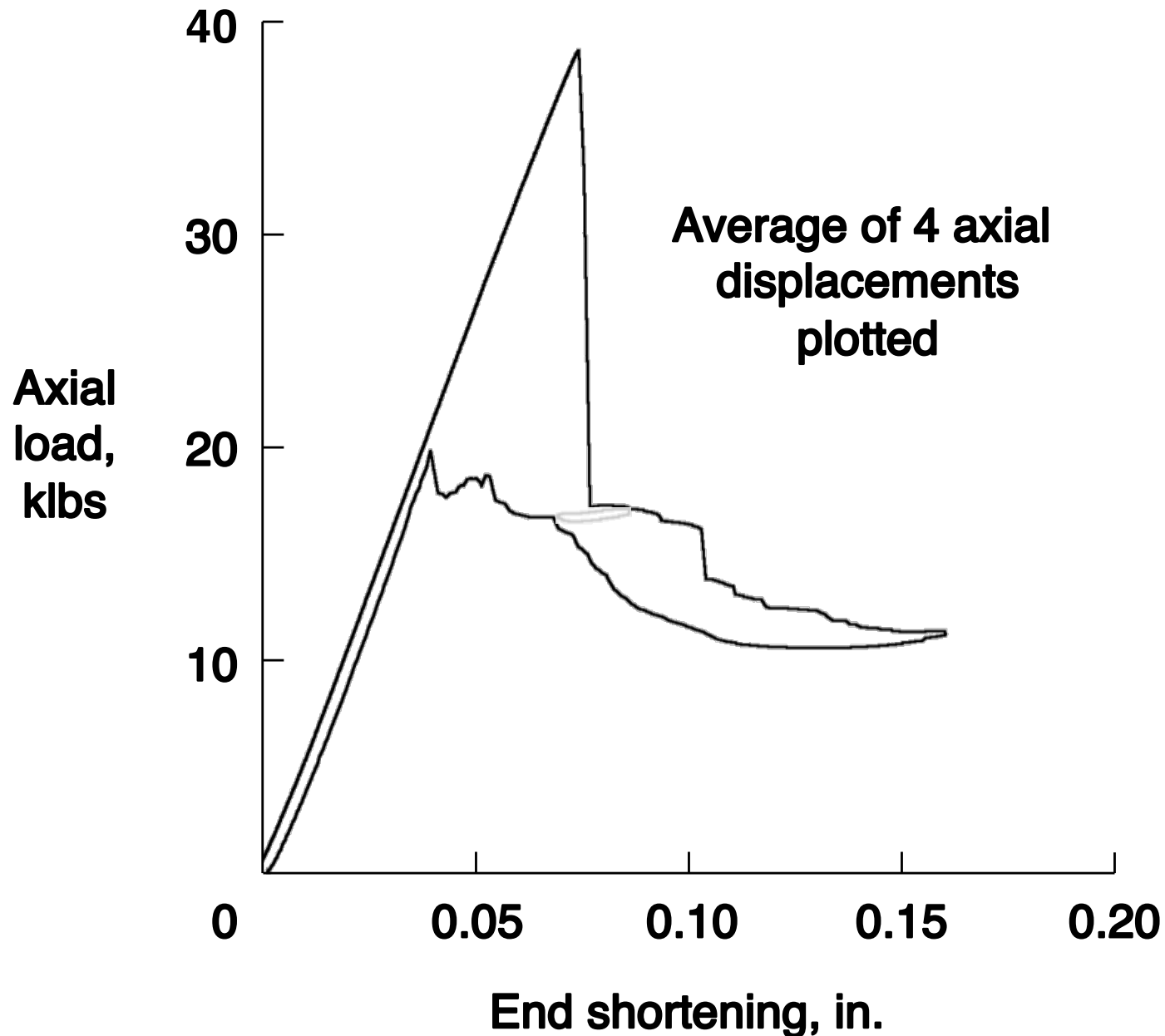
56 back-to-back strain gage pairs bonded to shell surfaces (no results presented here)

Digital image correlation systems also used to image shells during tests



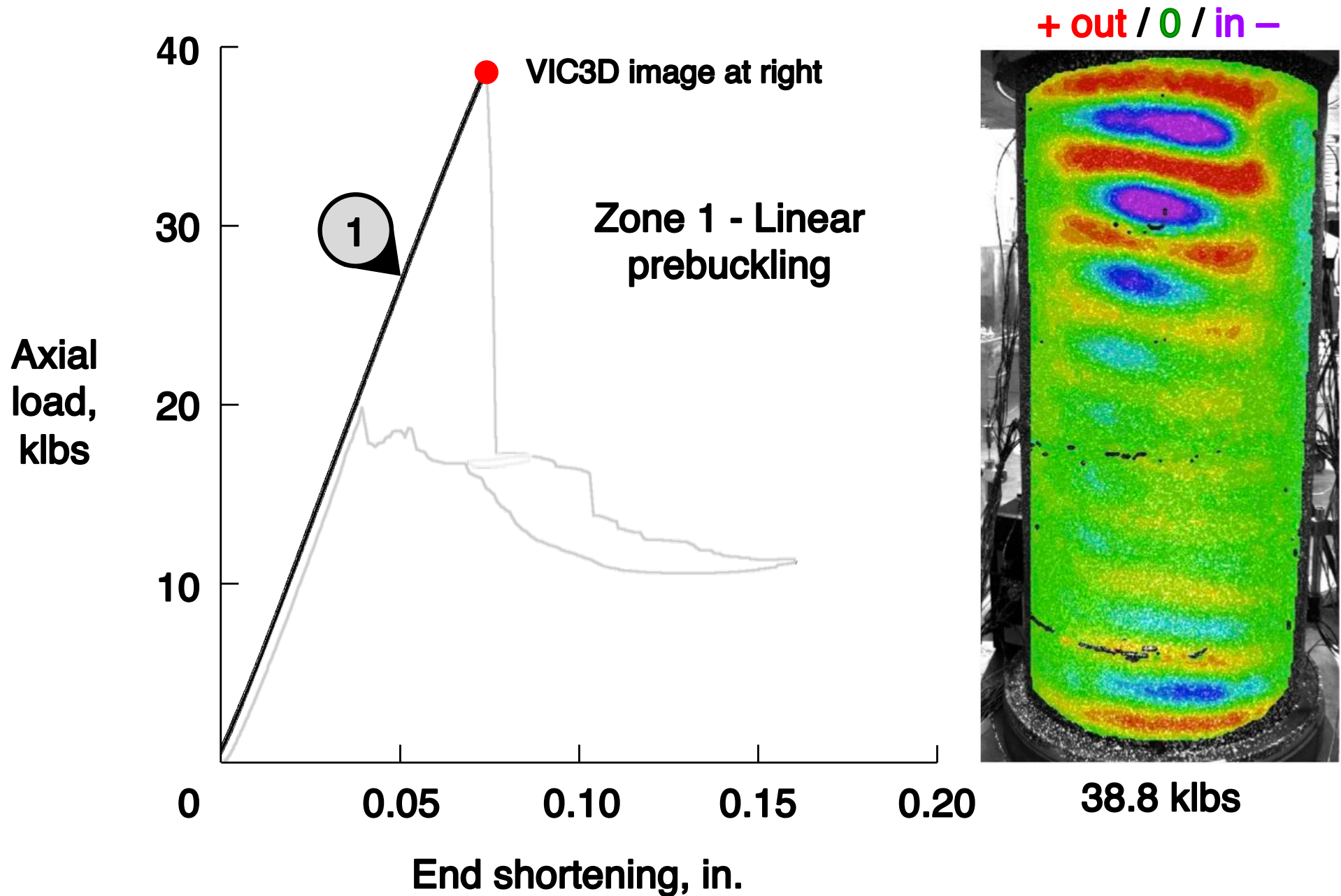
# Shell with Overlaps Results

# Shell with Overlaps Test

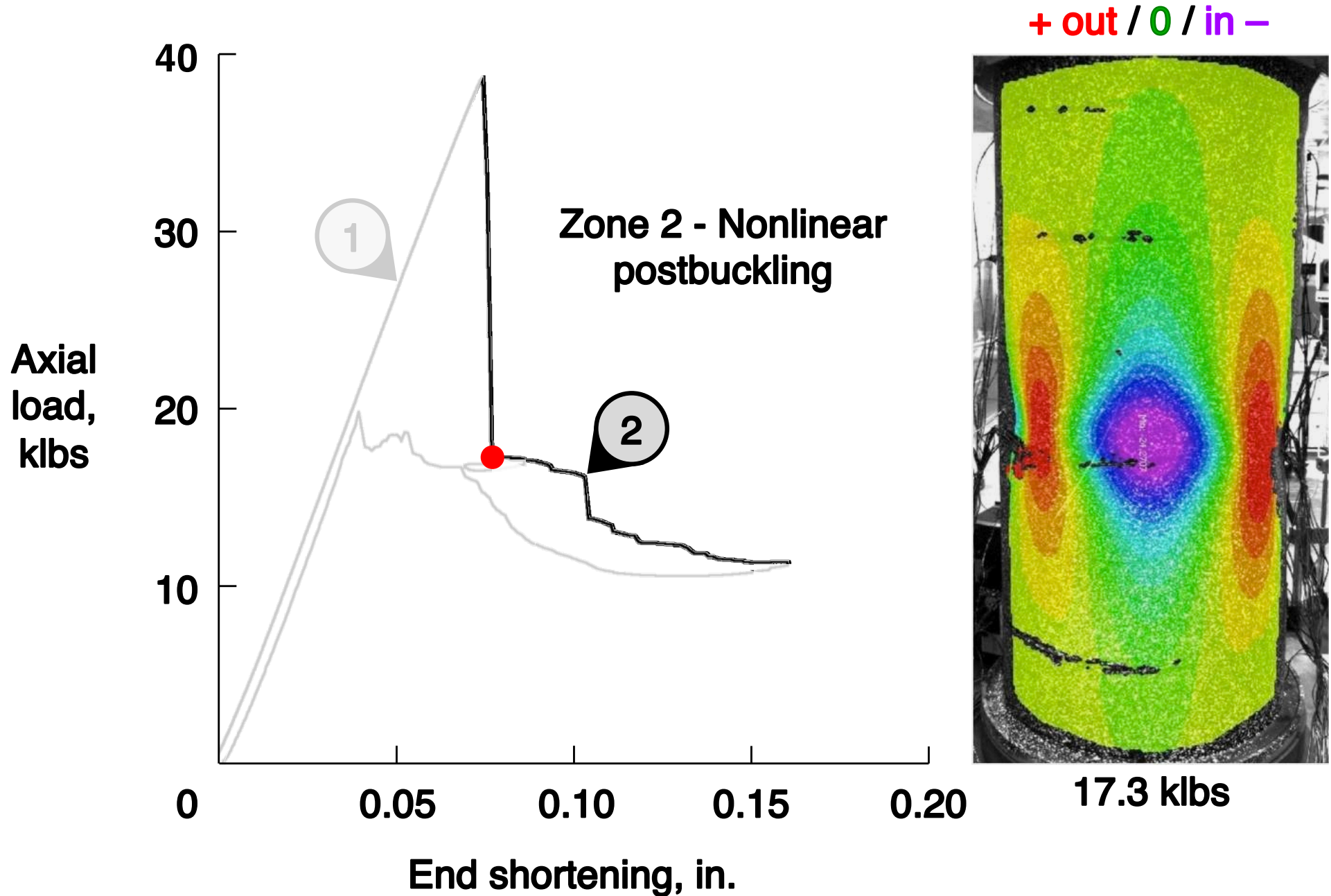


Crown / keel radial deflections measured with VIC3D

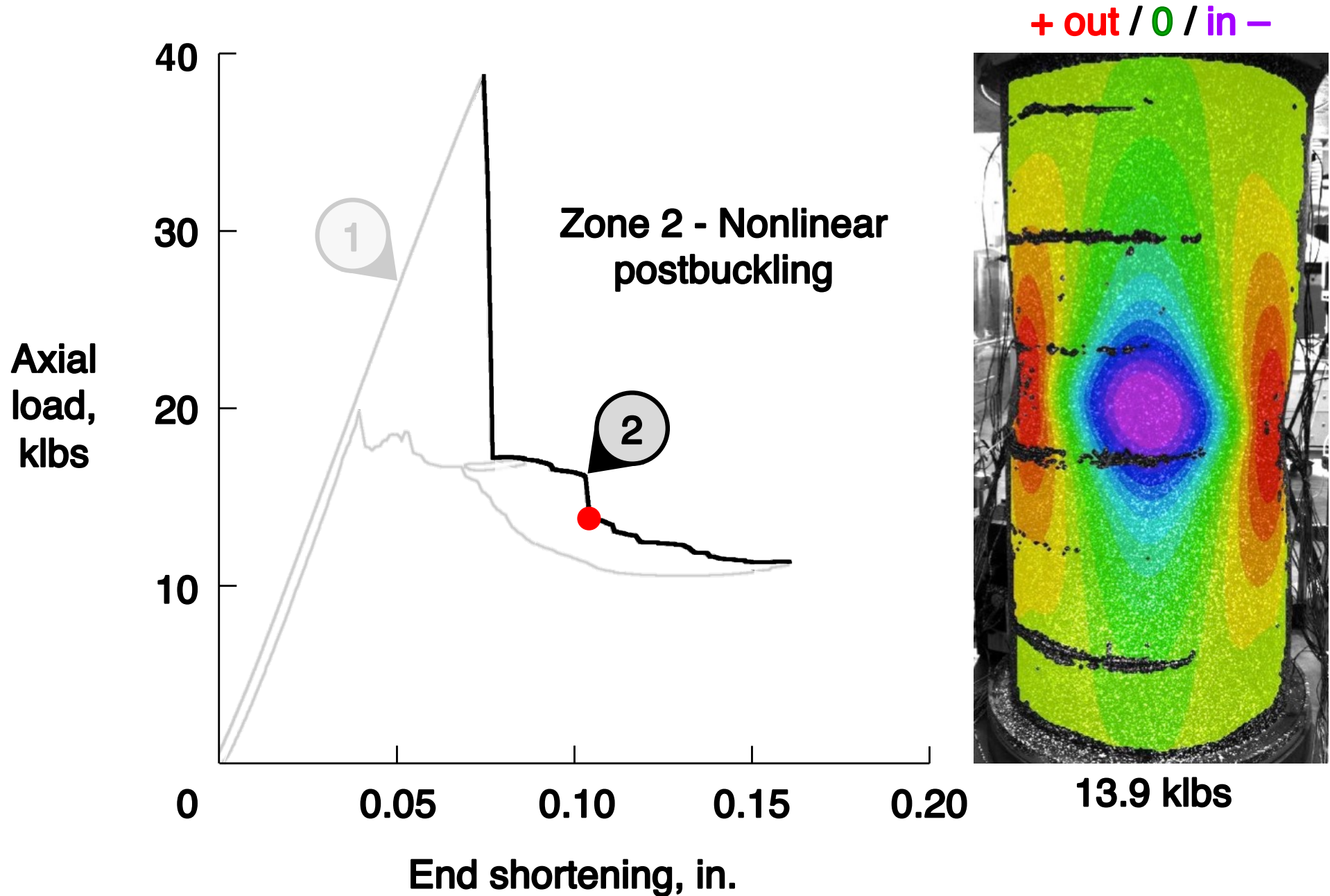
# Shell with Overlaps Test (2)



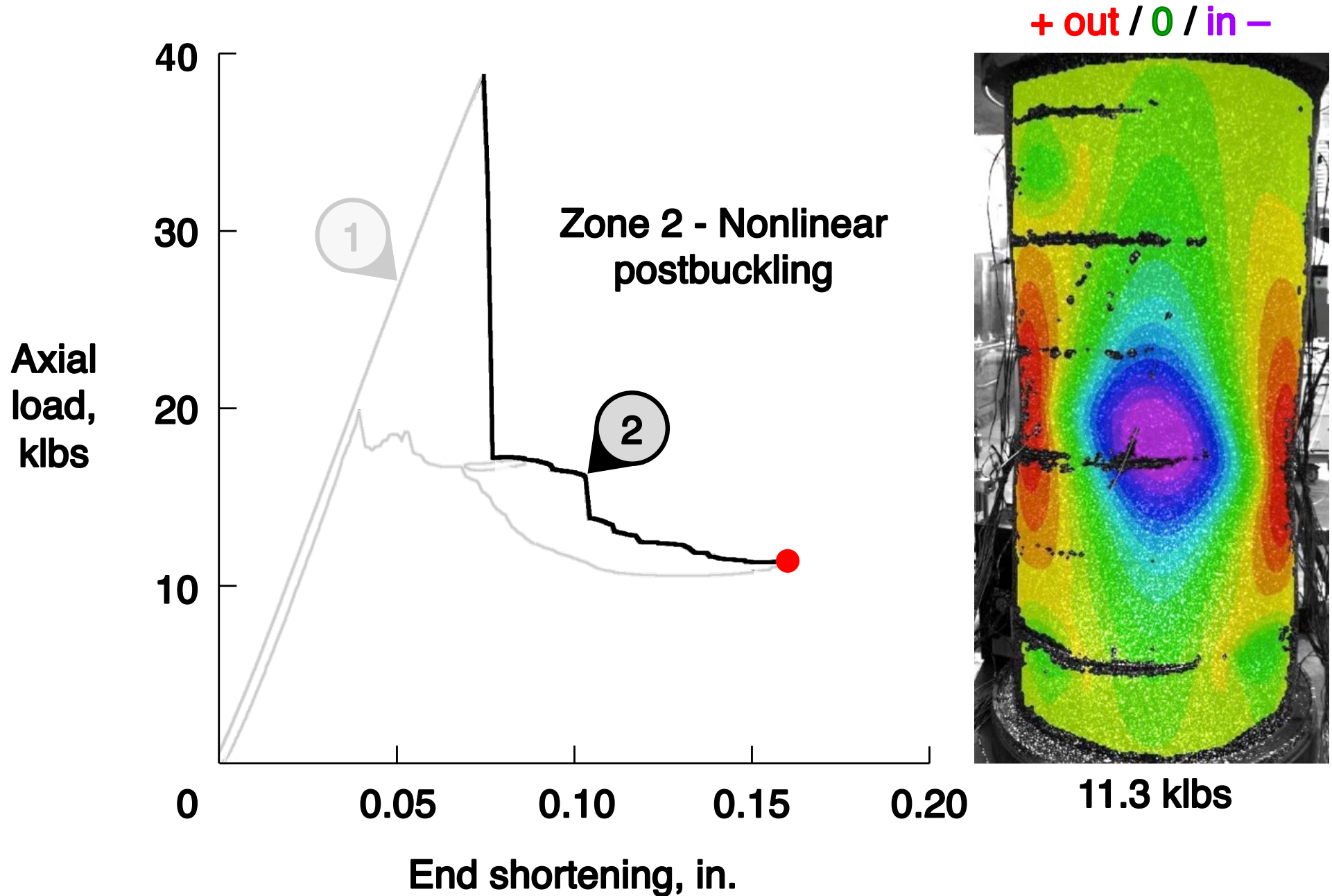
# Shell with Overlaps Test (2)



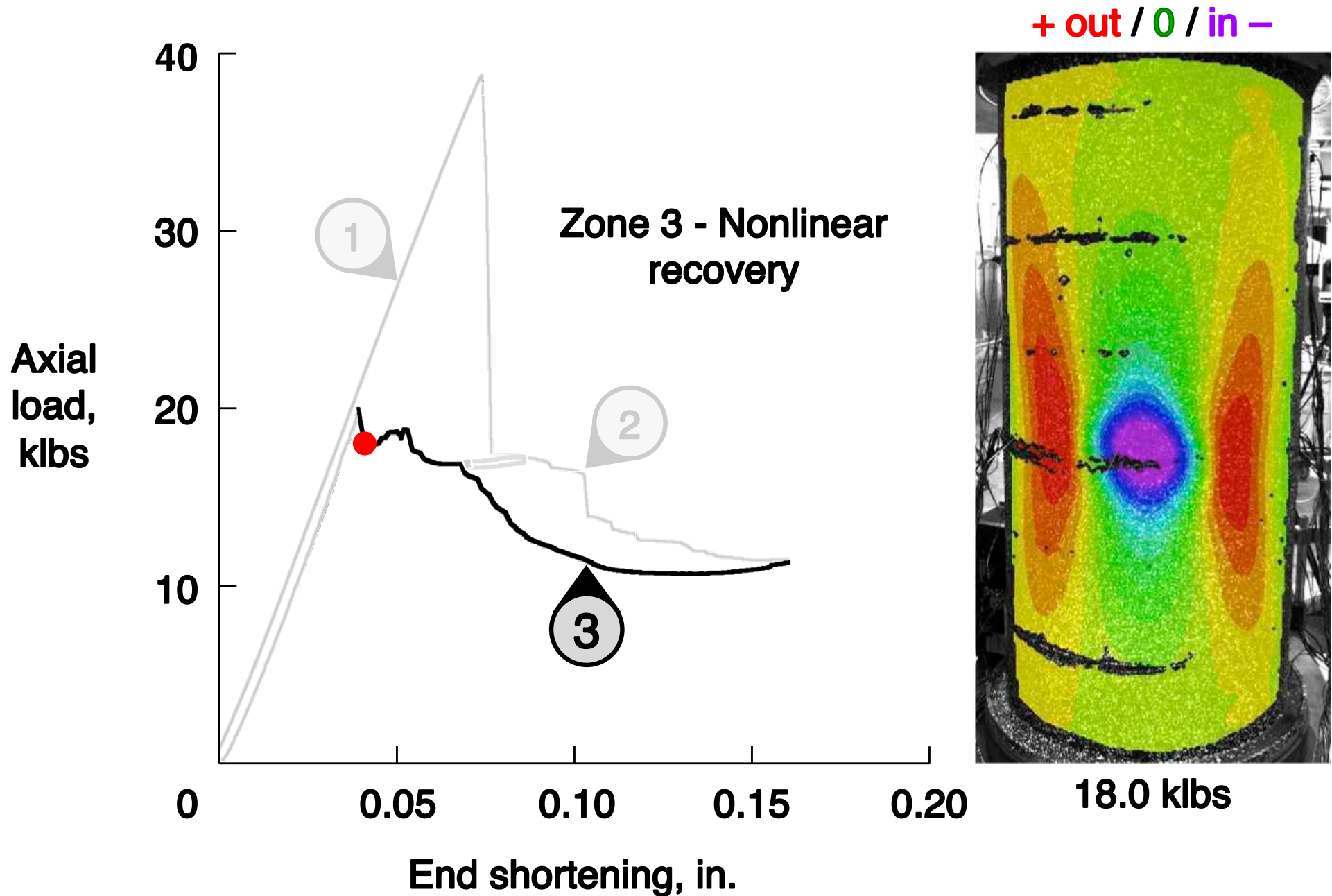
# Shell with Overlaps Test (2)



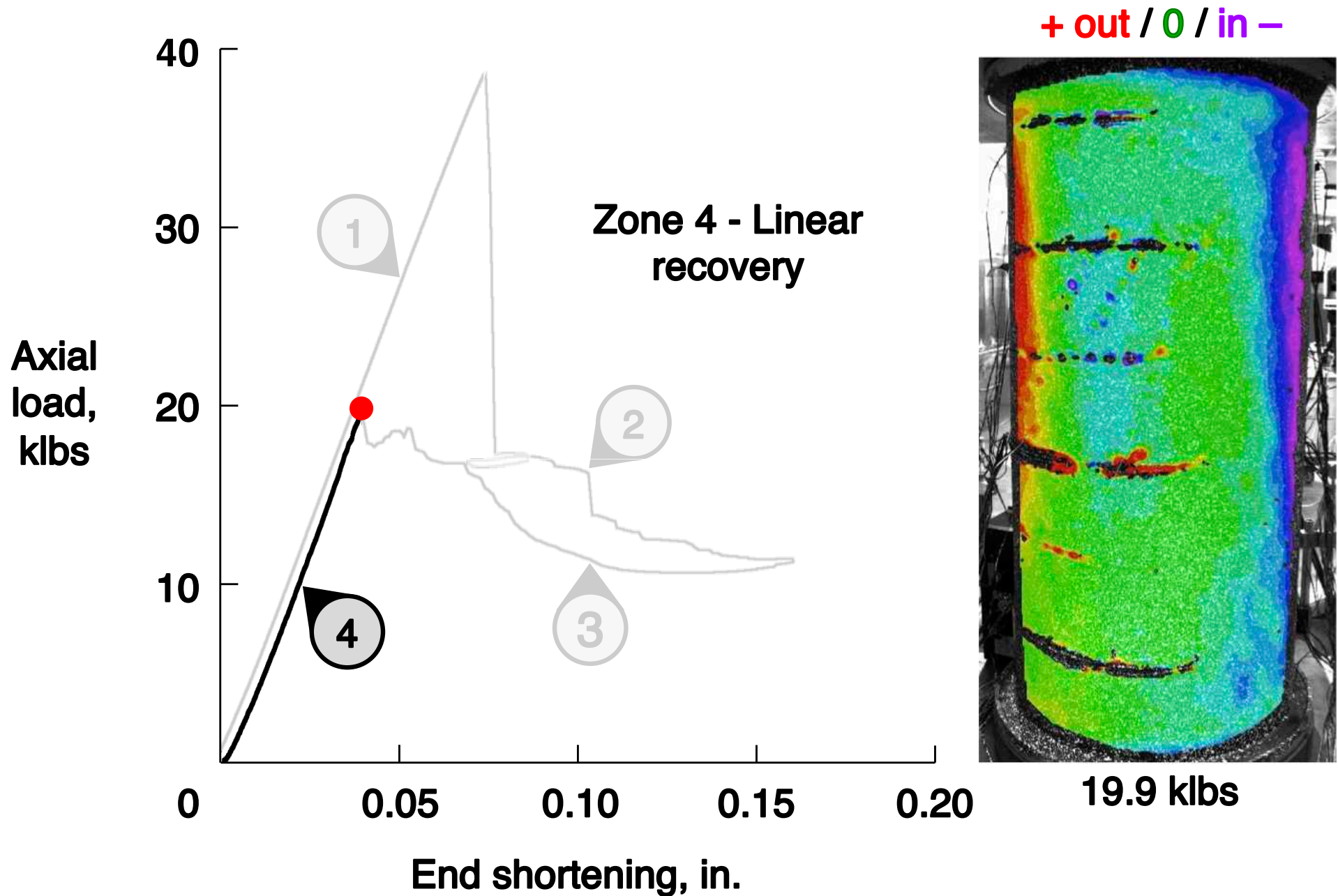
# Shell with Overlaps Test (2)



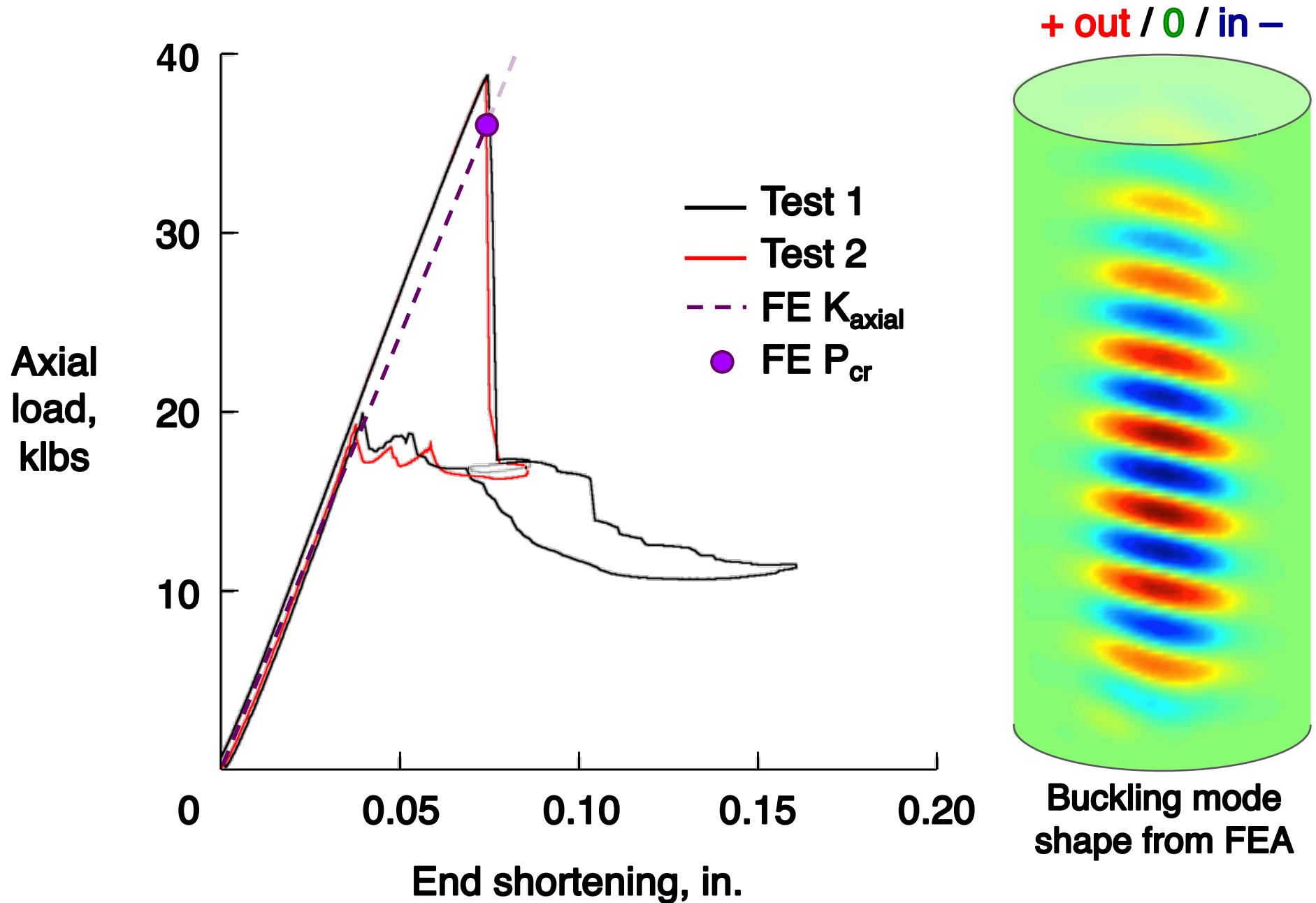
# Shell with Overlaps Test (2)



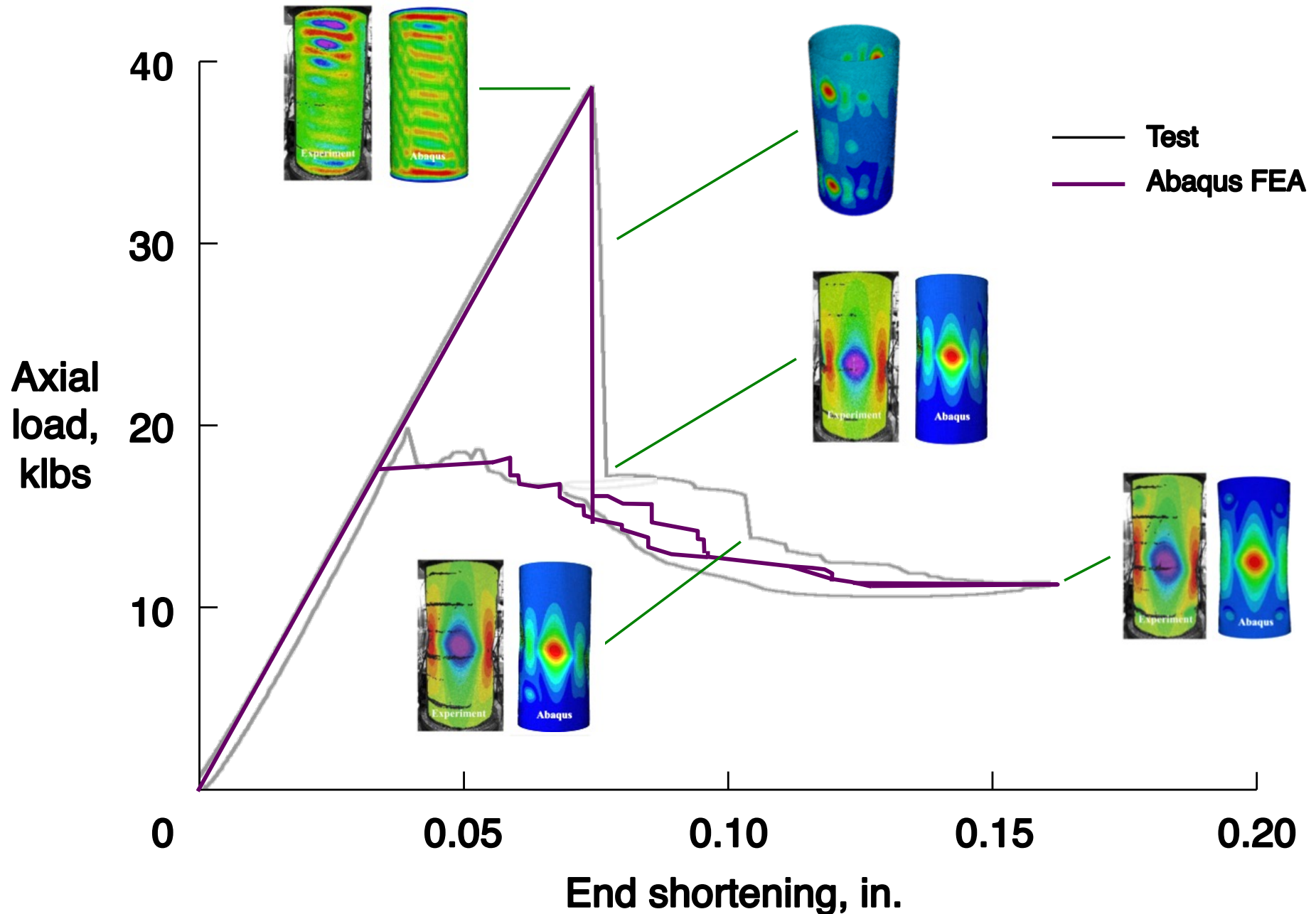
# Shell with Overlaps Test (2)



# Shell with Overlaps Linear FEA



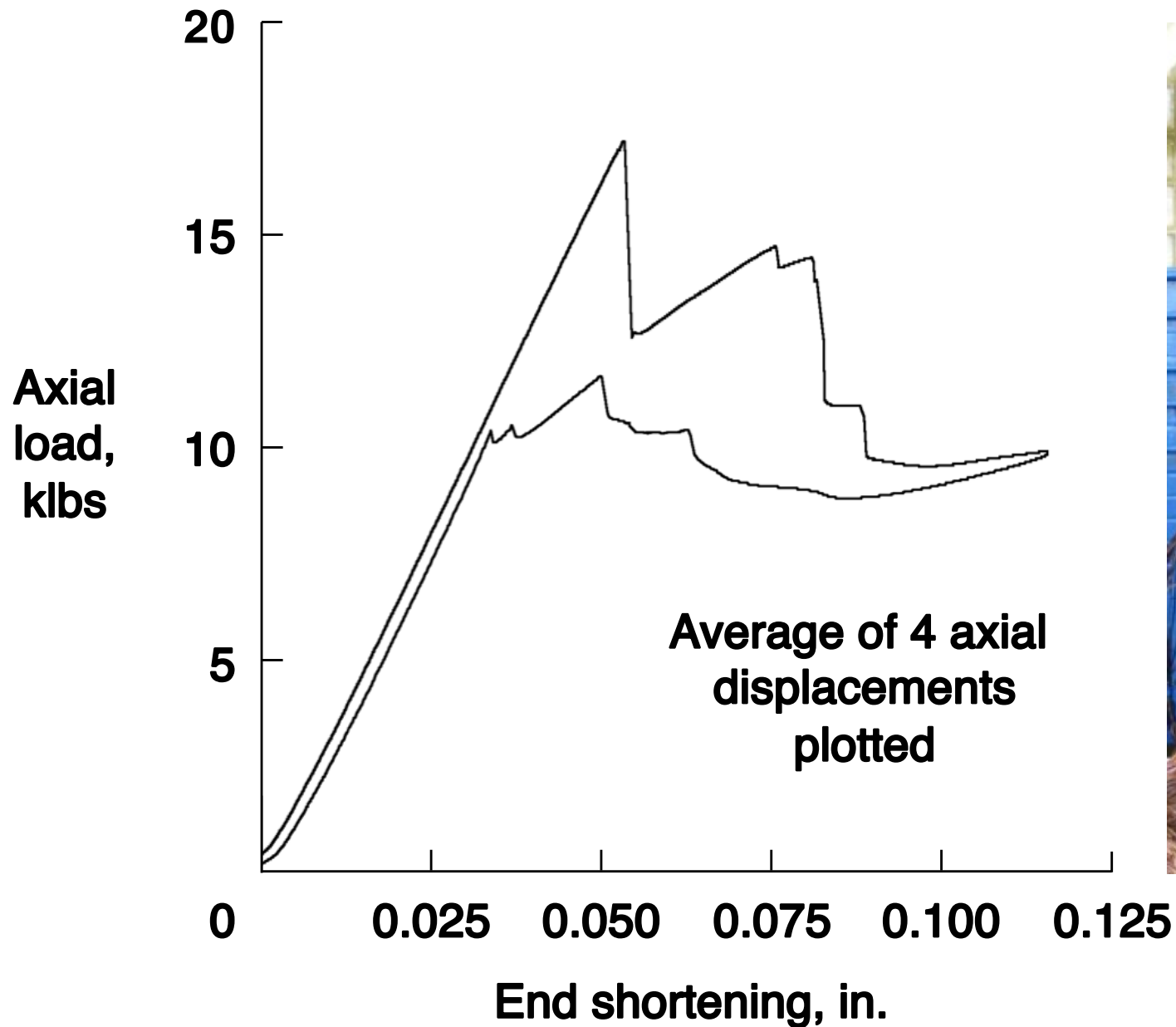
# Shell with Overlaps Nonlinear FEA





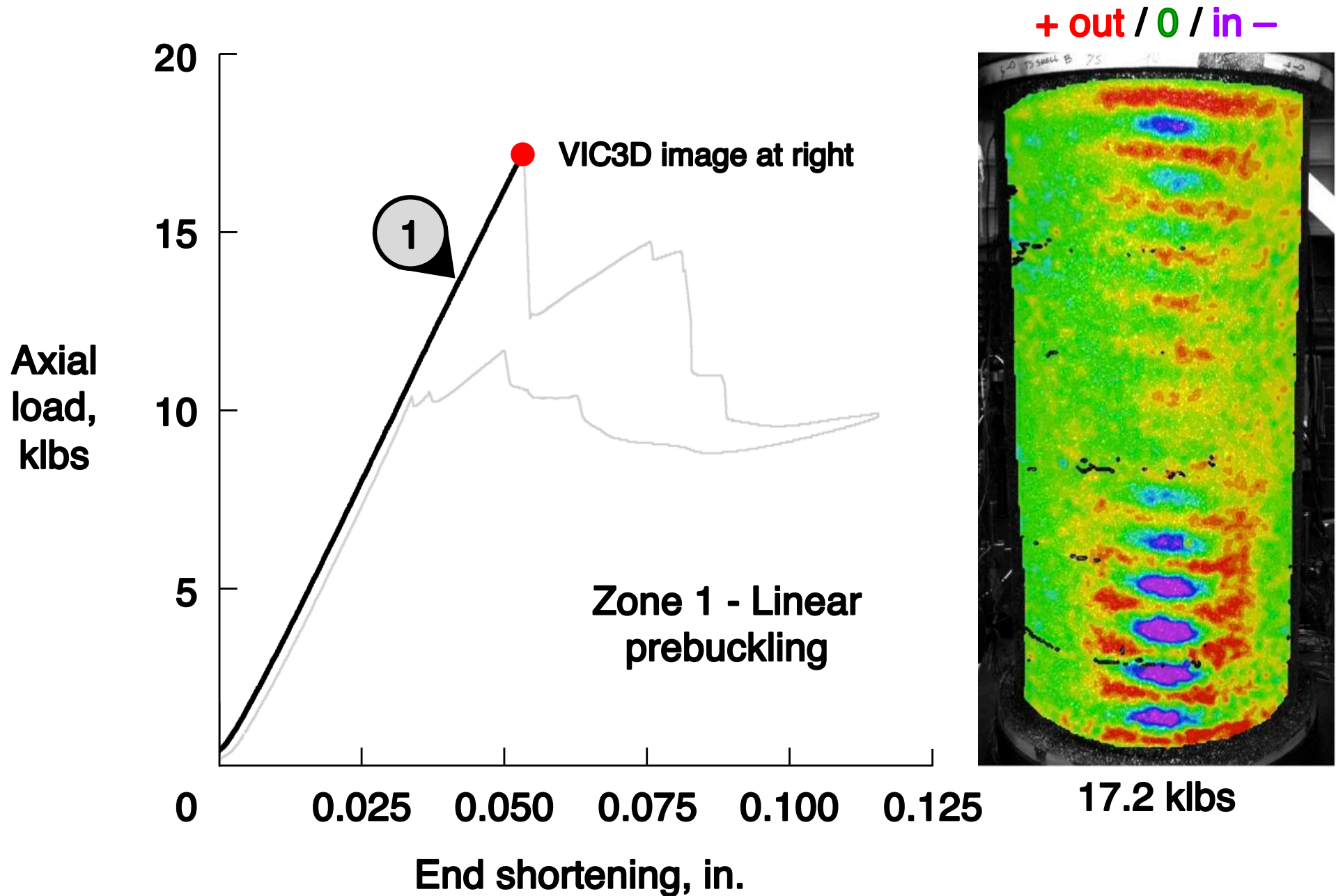
# Shell w/o Overlaps Results

# Shell w/o Overlaps Test

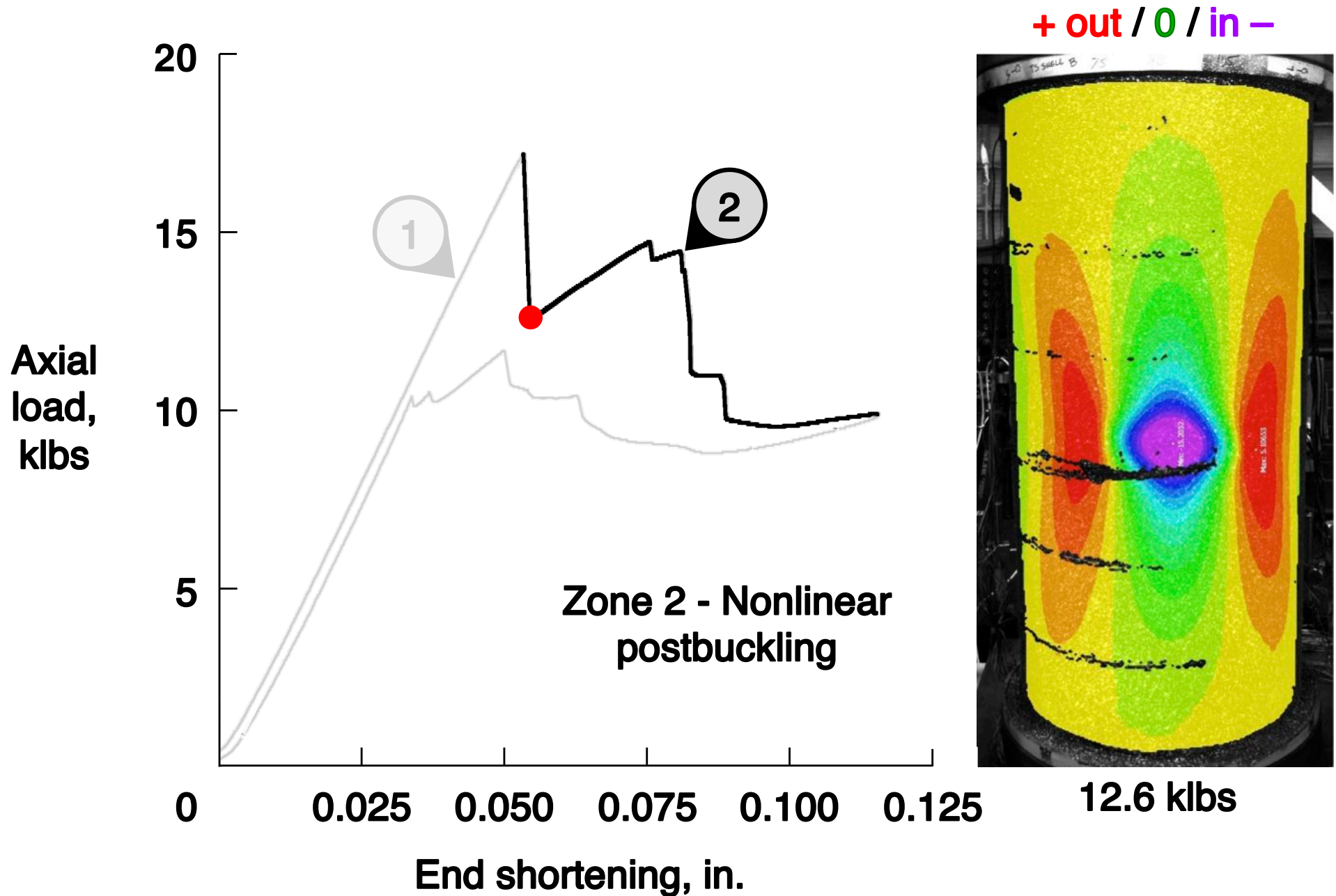


Crown / keel radial deflections measured with VIC3D

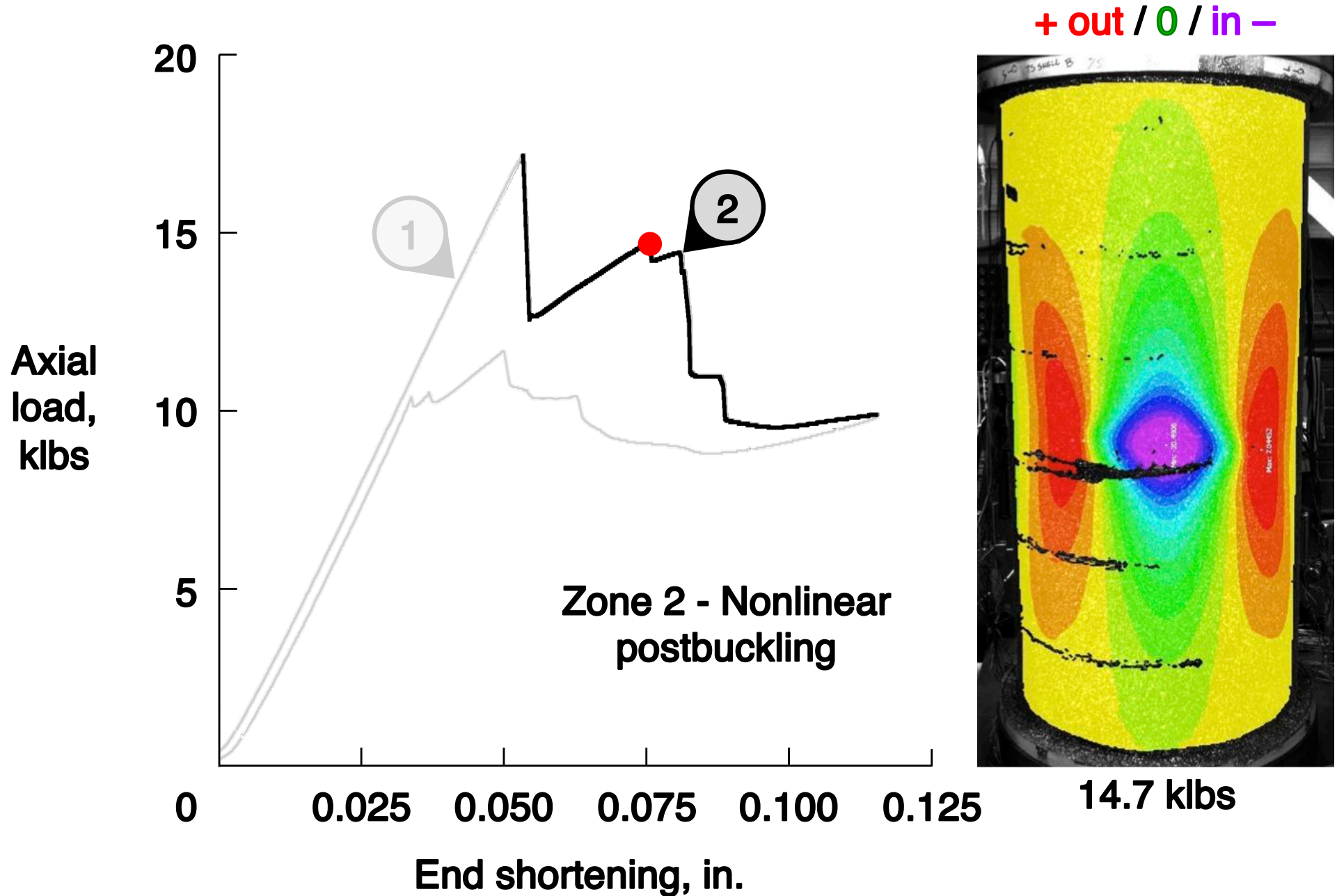
# Shell w/o Overlaps Test (2)



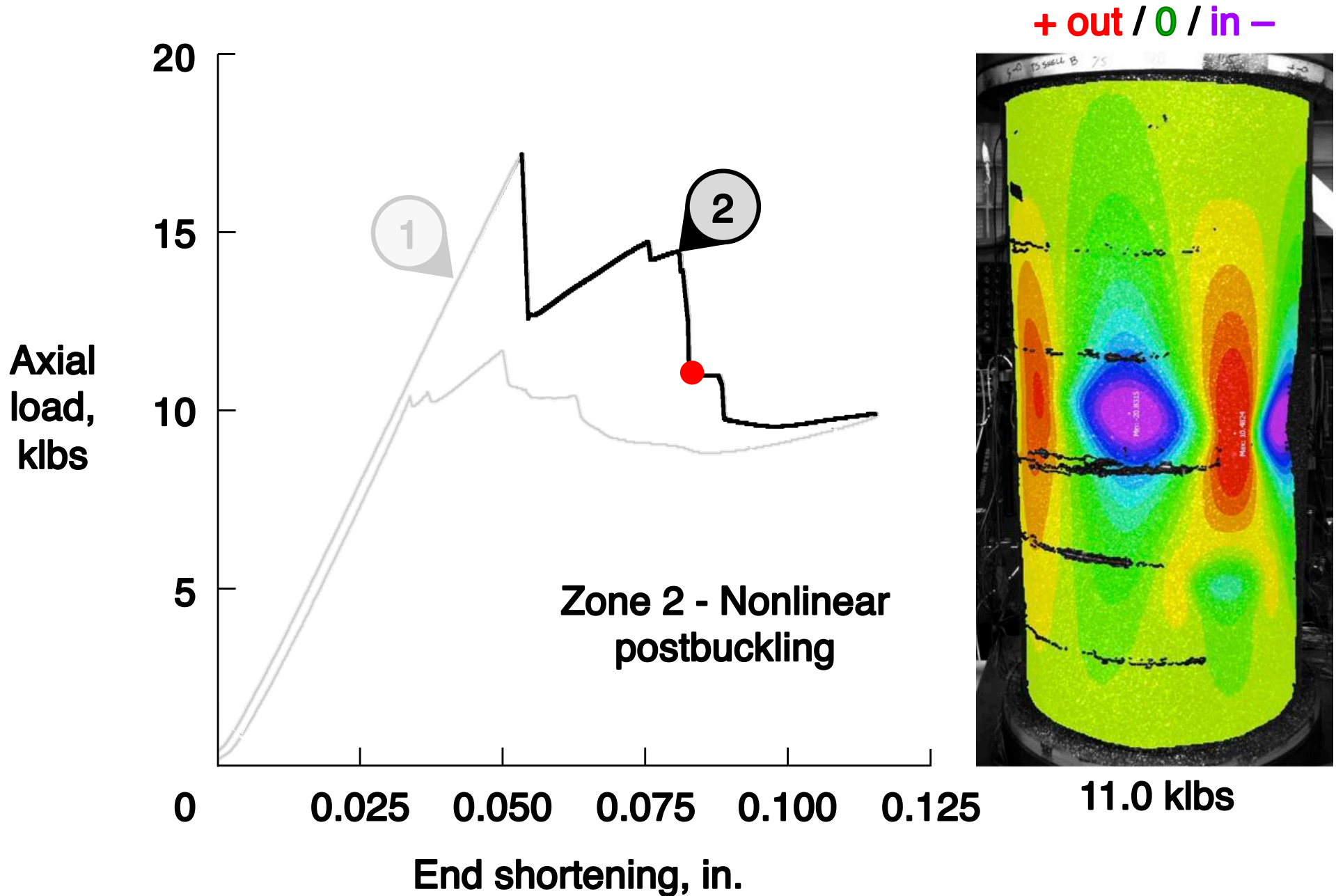
# Shell w/o Overlaps Test (2)



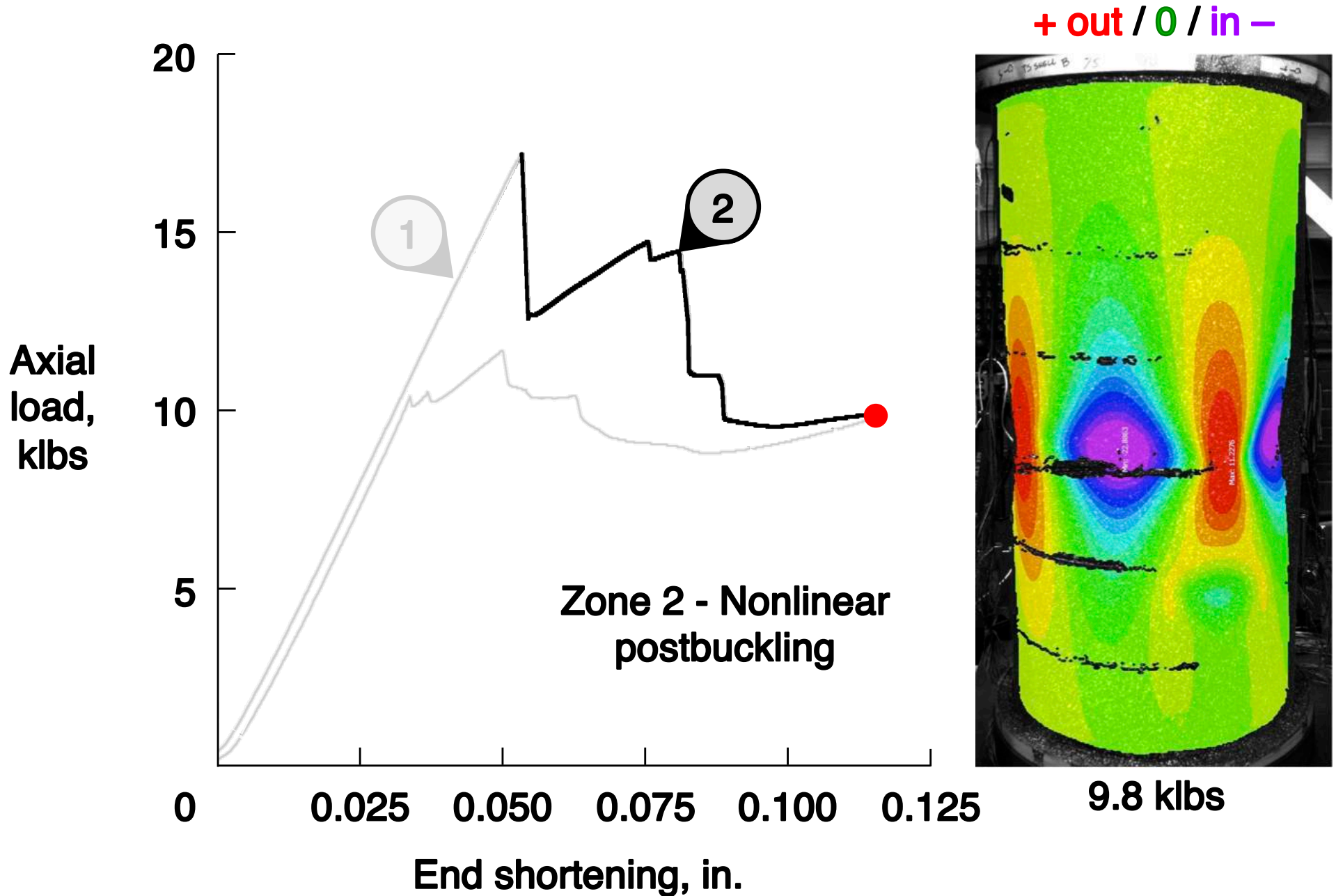
# Shell w/o Overlaps Test (2)



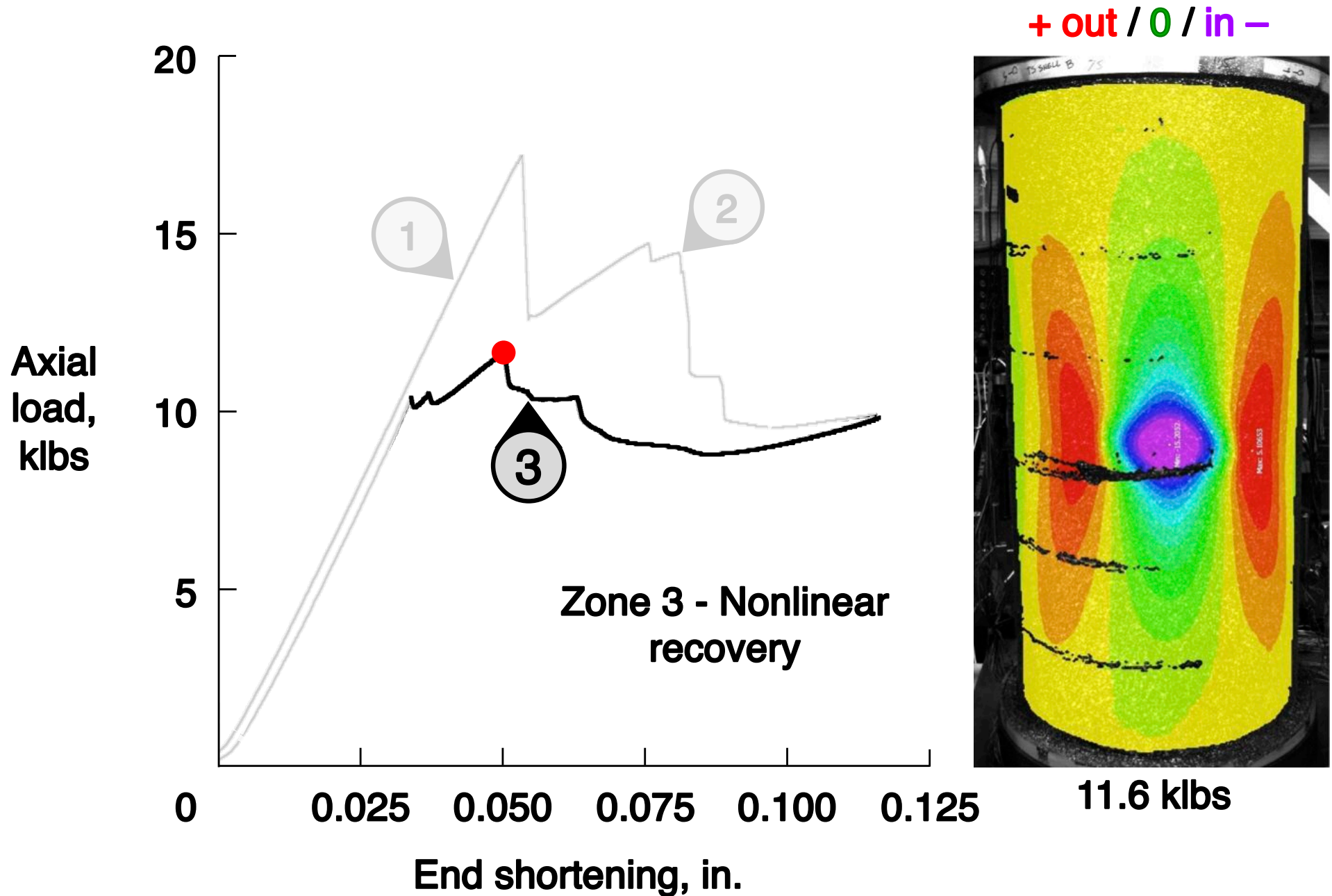
# Shell w/o Overlaps Test (2)



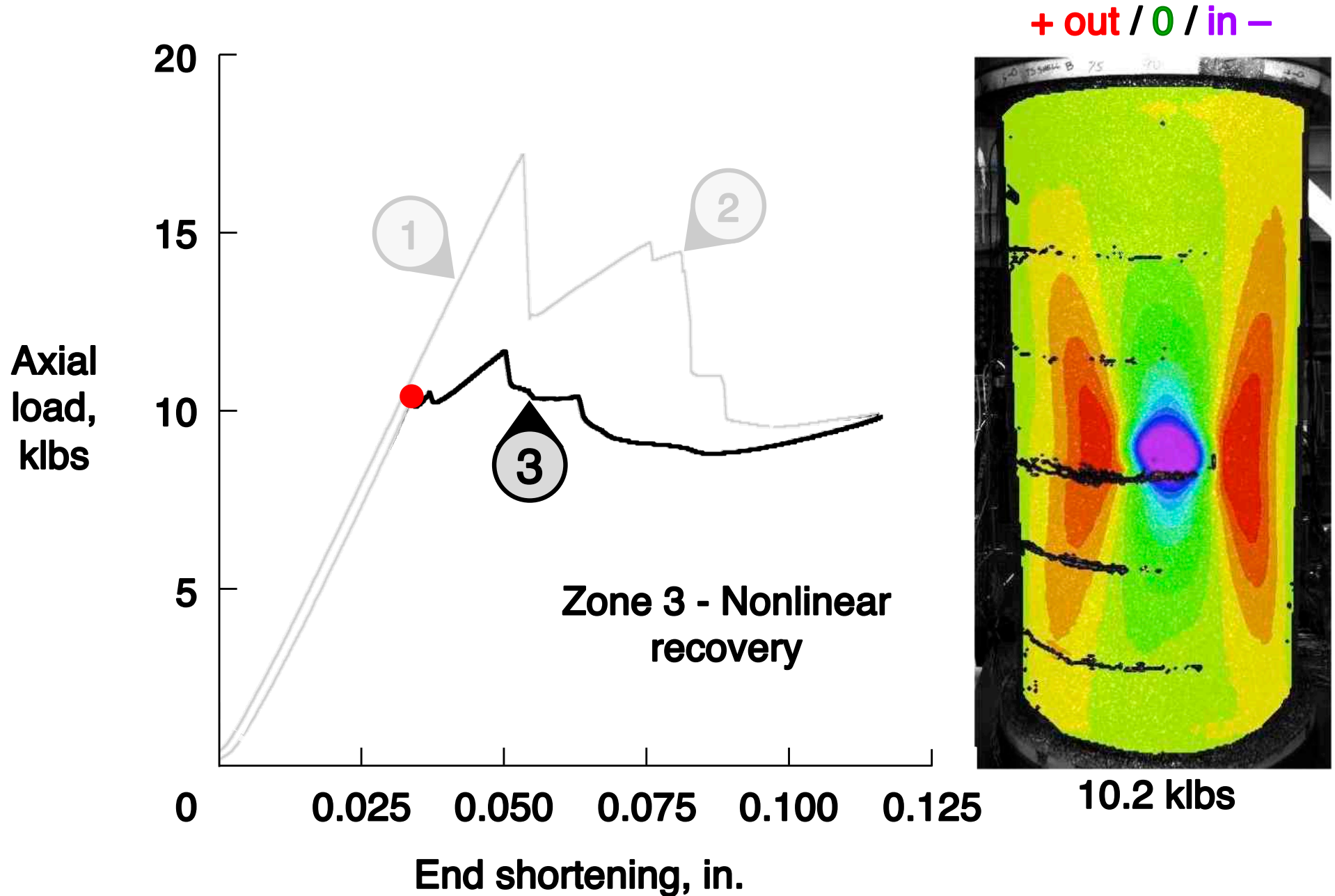
# Shell w/o Overlaps Test (2)



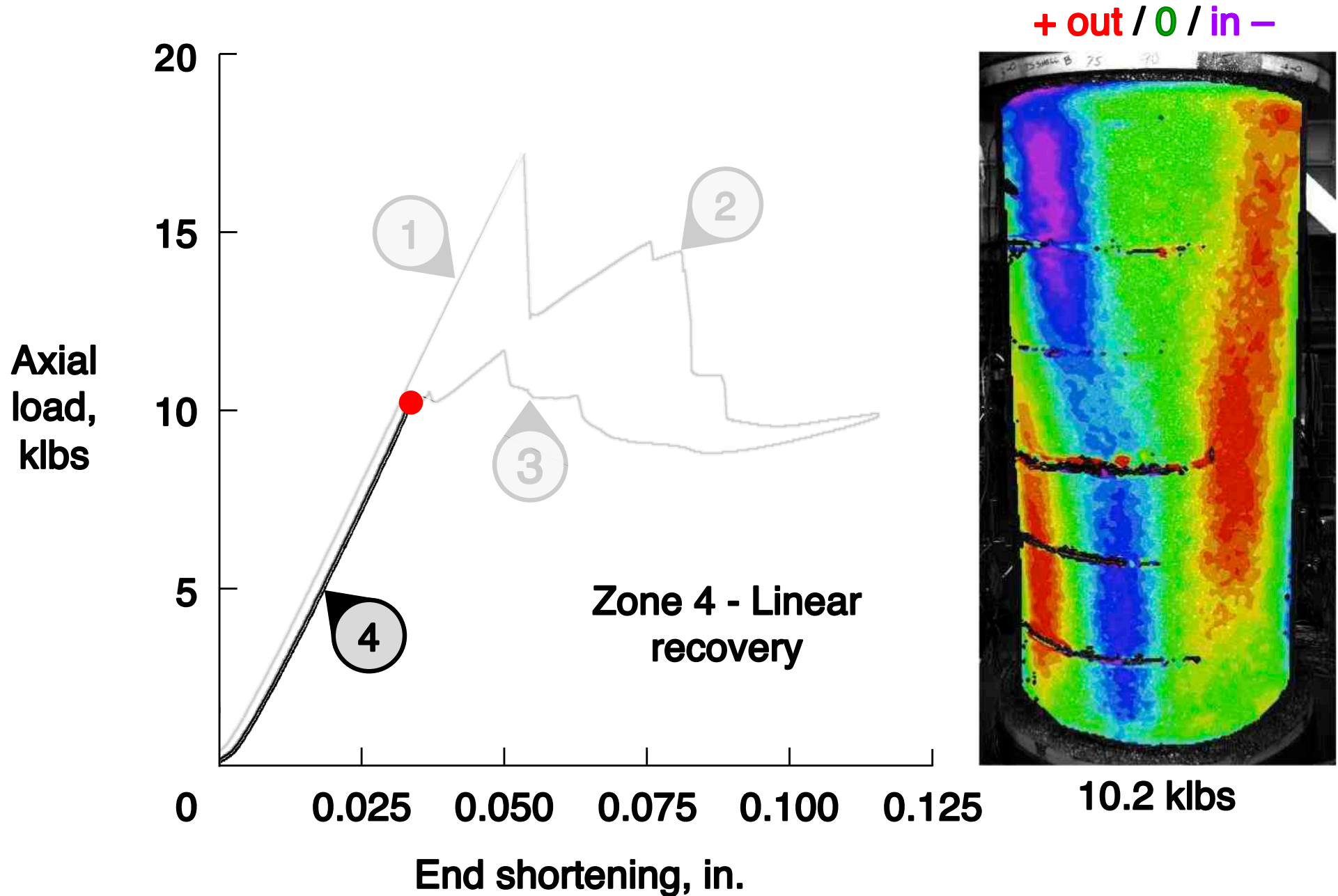
# Shell w/o Overlaps Test (2)



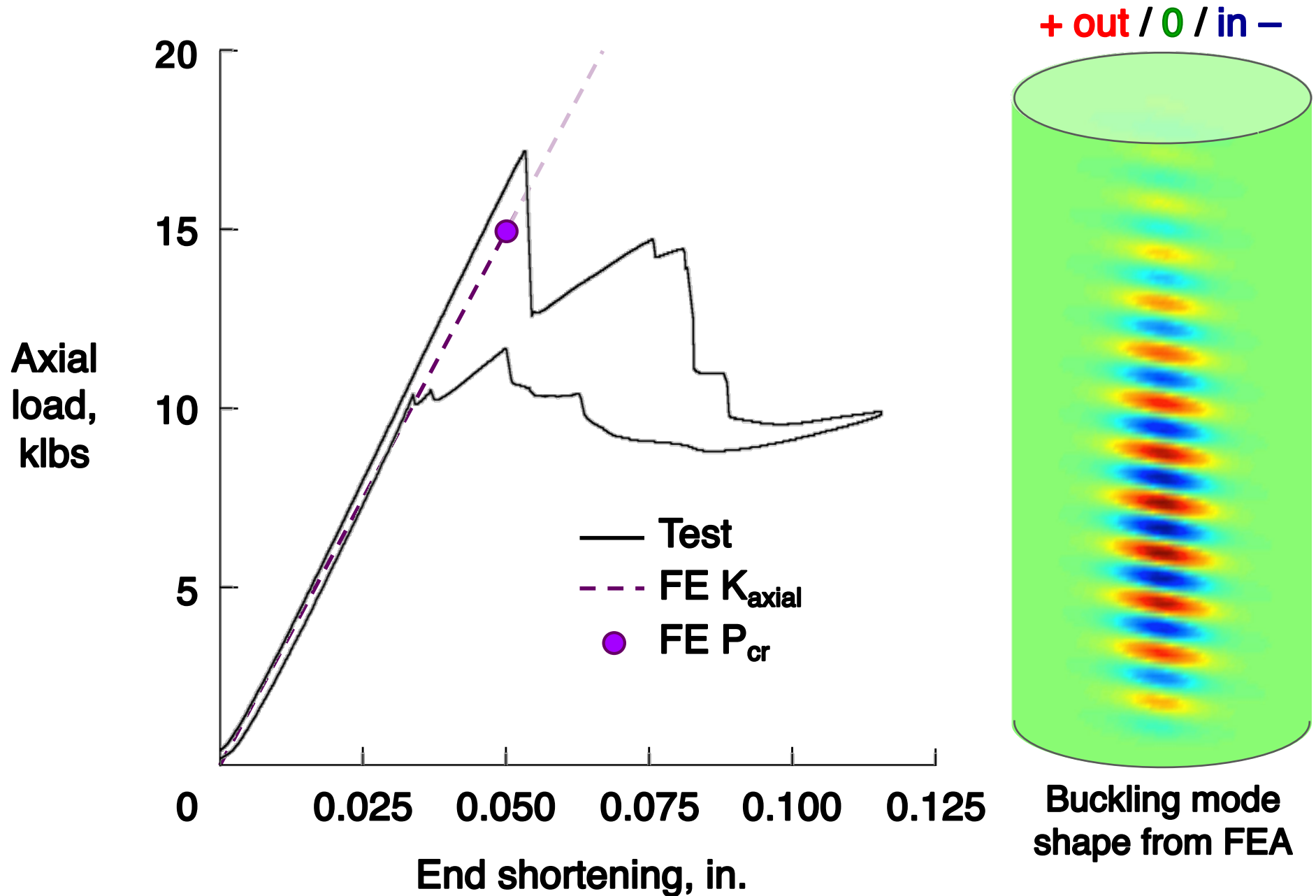
# Shell w/o Overlaps Test (2)



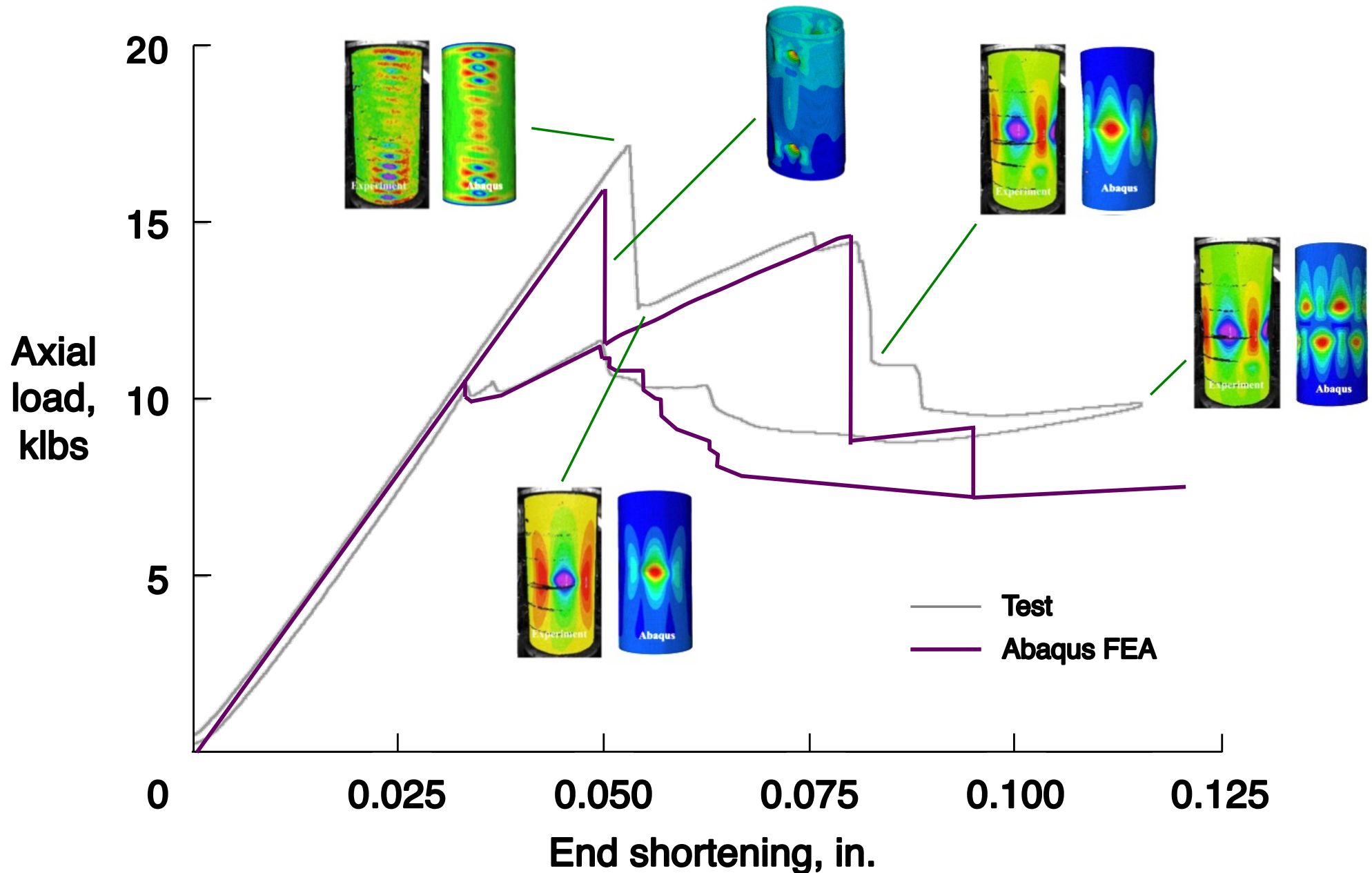
# Shell w/o Overlaps Test (2)



# Shell w/o Overlaps Linear FEA



# Shell w/o Overlaps Nonlinear FEA



# Pristine Shell Structural Performance

## (1) Baseline Linear FEA

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 503.2               | 306.7              |
| 1st global buckling load, klbs       | 37.3                | 15.6               |

## (2) Test Results

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 531.2               | 328.7              |
| 1st global buckling load, klbs       | 38.8                | 17.2               |
| Postbuckling load, klbs              | 17.3                | 12.6               |

## (3) Test / Baseline Linear FEA

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 1.06                | 1.07               |
| 1st global buckling load    | 1.04                | 1.10               |

*Avg. shell radius, ply thickness and adj.  $E_1$  used. No geometric imperfections.*

# Pristine Shells Summary

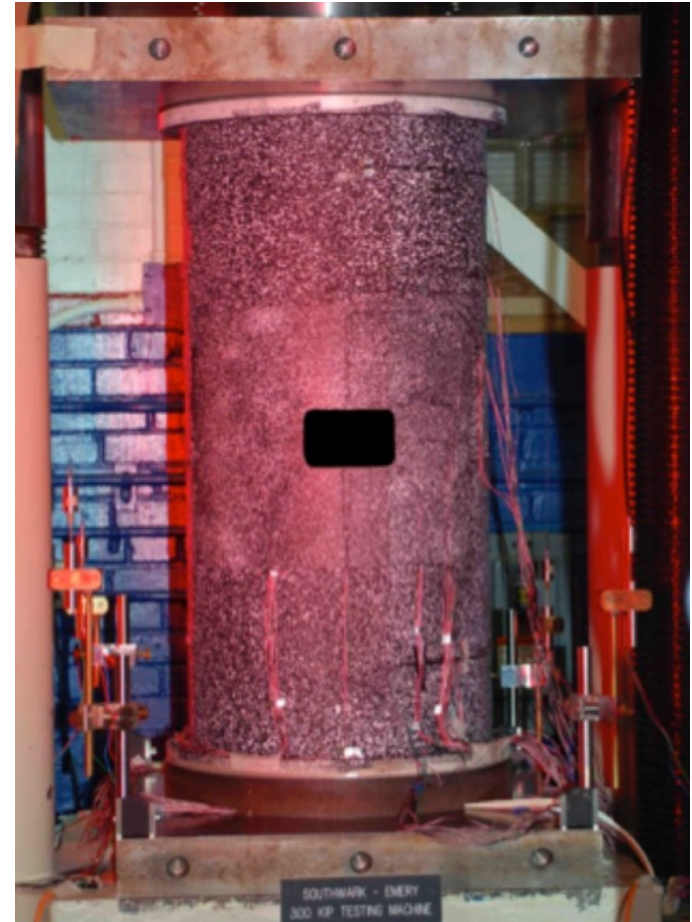
- Measured prebuckling stiffnesses and buckling loads average 7 percent higher than corresponding linear FEA
- Serial linear- and nonlinear-elastic responses observed into deep postbuckling, and upon unloading
- Normalized by weight, shell with overlaps has 30 percent higher axial stiffness, and 89 percent higher buckling load, than shell without overlaps
- Good agreement between test and linear analyses suggests insensitivity to measured geometric imperfections
- Geometrically nonlinear FEA closely replicates observed shell structural response, and provides additional insight into global buckling behavior



# Shells with Cutouts

# Description of Small Cutouts

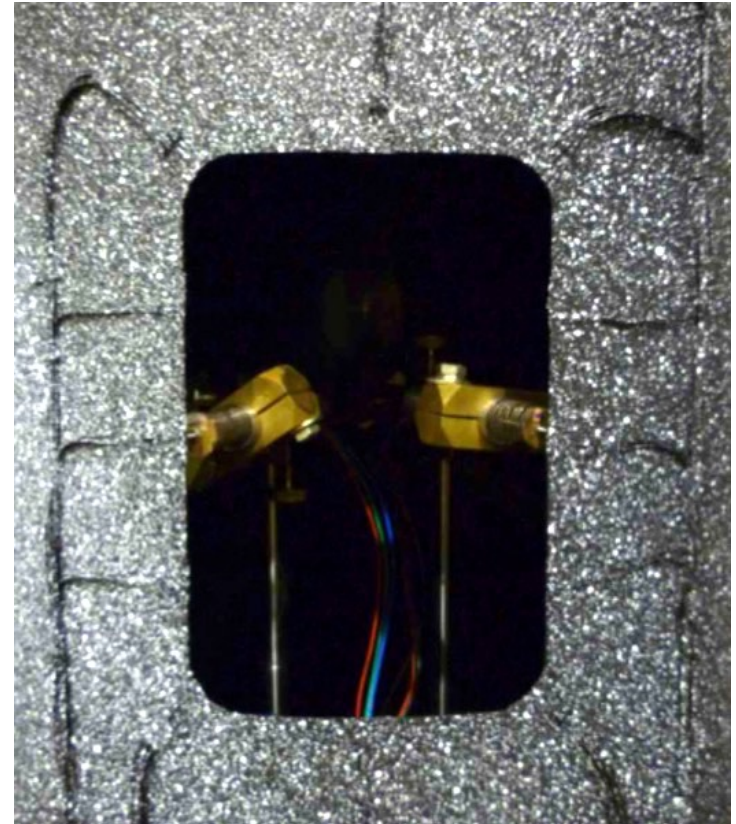
- Small cutouts are scaled to represent passenger doors on commercial aircraft fuselage
- Cutout dimensions are 3 in. (axial) x 4.88 in. (circumf.), with 0.50-in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup  $\sim [\pm 45]_{2s}$ )
- 20 back-to-back strain gage pairs installed around cutout perimeter



**Shell with small cutout in test stand**

# Description of Large Cutouts

- Large cutouts are scaled to represent cargo doors on commercial aircraft fuselage
- Cutout dimensions are 8 in. (axial) x 5.25 in. (circumf.), with 0.75-in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup  $\sim [\pm 45]_{2s}$ )
- 24 back-to-back strain gage pairs and 2 displacement transducers installed around cutout perimeter



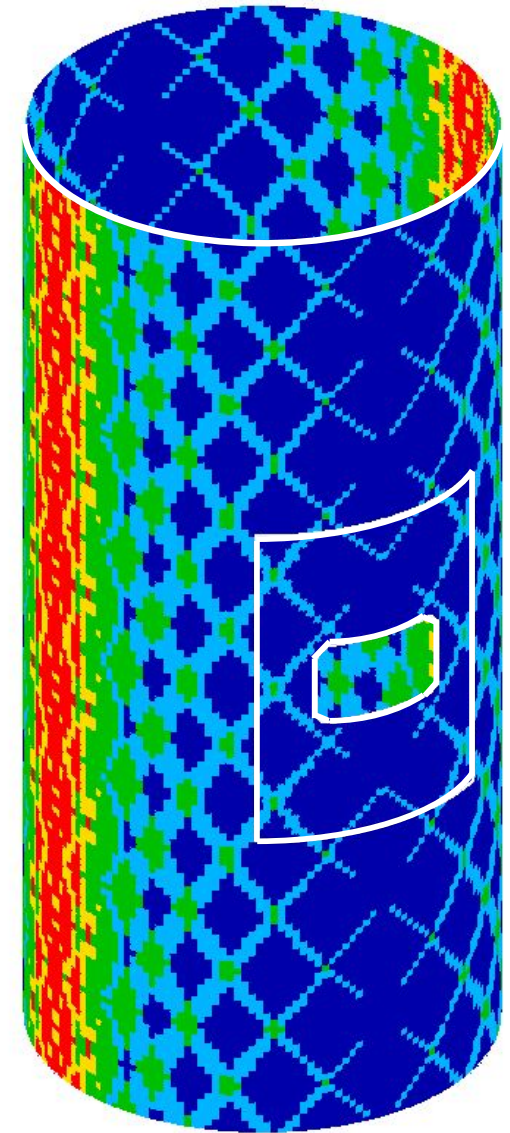
**Detail of shell with large cutout**



# **Finite Element Modeling and Analyses**

# Modified Finite Element Models

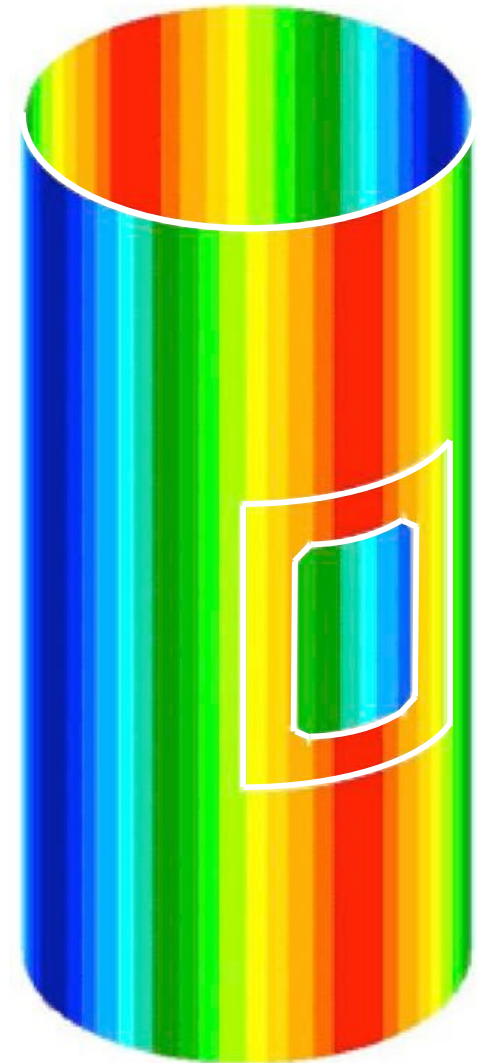
- NASTRAN analyses performed
  - Linear static analyses
  - Linear bifurcation buckling analyses
- CQUAD4 shell elements
  - Acreage elements  $\sim 0.25$  in.-square
  - Each constant thickness and fiber angles
  - Ply principal stiffness increased based on reduced ply thickness
- Refined FE mesh around cutouts
  - “Glued contact” into existing FE models
  - Parametric mesh refinement applied
  - Refined elements surrounding cutout are  $\sim 0.063$  in.-square (4x nominal)
  - Refinements have same thickness and layup as parent element



**Shell with Overlaps  
FE model thicknesses**

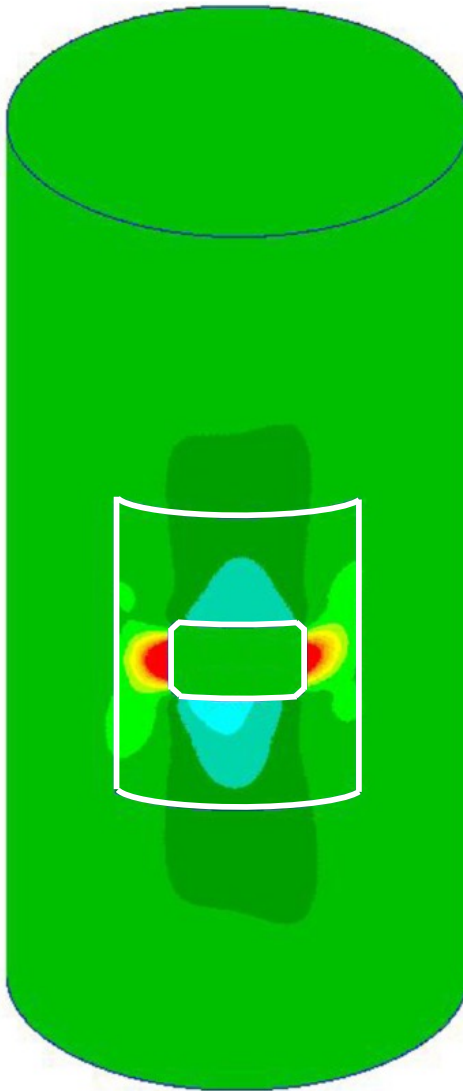
# Modified Finite Element Models (2)

- NASTRAN analyses performed
  - Linear static analyses
  - Linear bifurcation buckling analyses
- CQUAD4 shell elements
  - Acreage elements  $\sim 0.25$  in.-square
  - Each constant thickness and fiber angles
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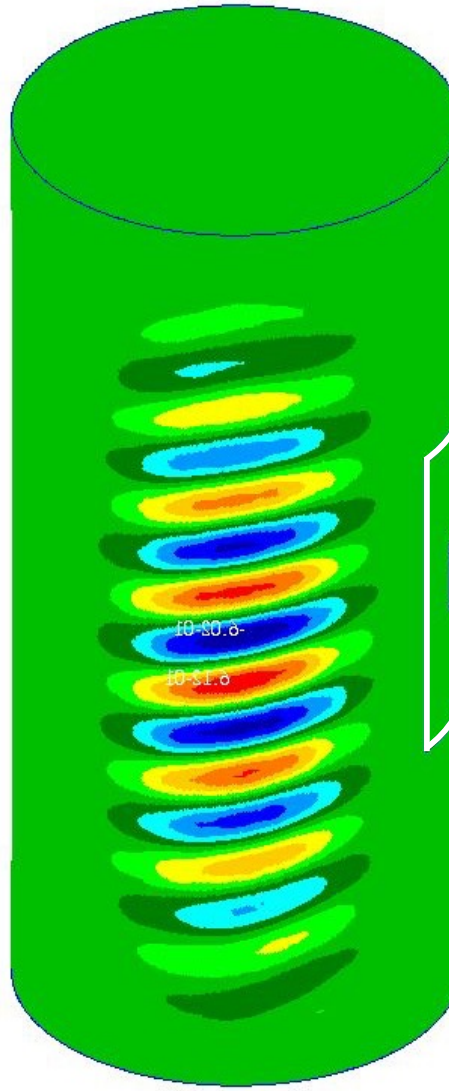


**FE model ply 3 fiber orientation angles**

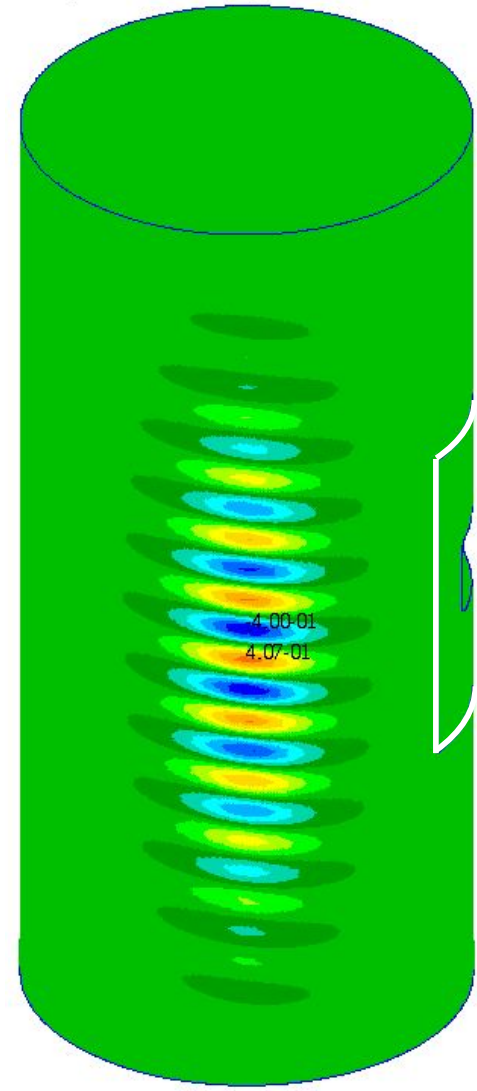
# Predicted Buckling Modes - Small Cutouts



**Local buckling - mode 1  
(both shells)**



**Global buckling - mode 7  
(Shell with Overlaps)**

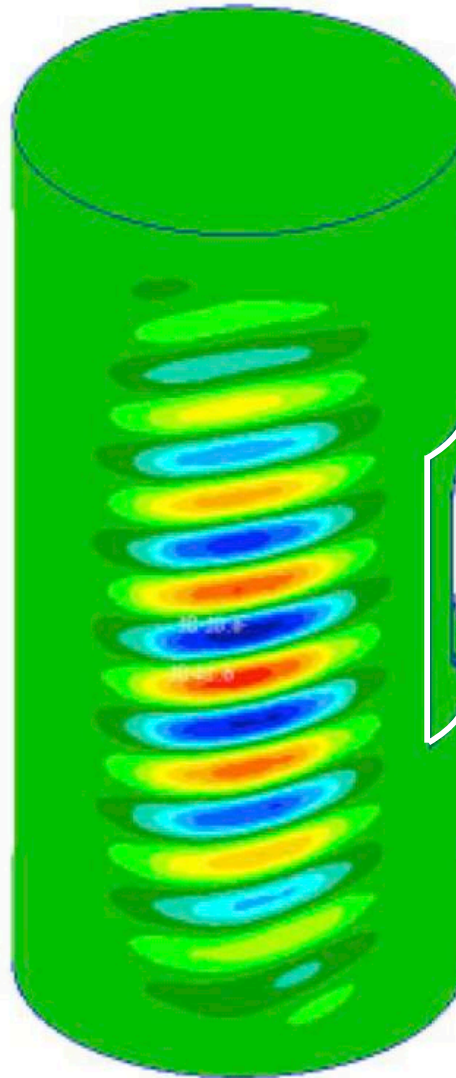


**Global buckling - mode 5  
(Shell w/o Overlaps)**

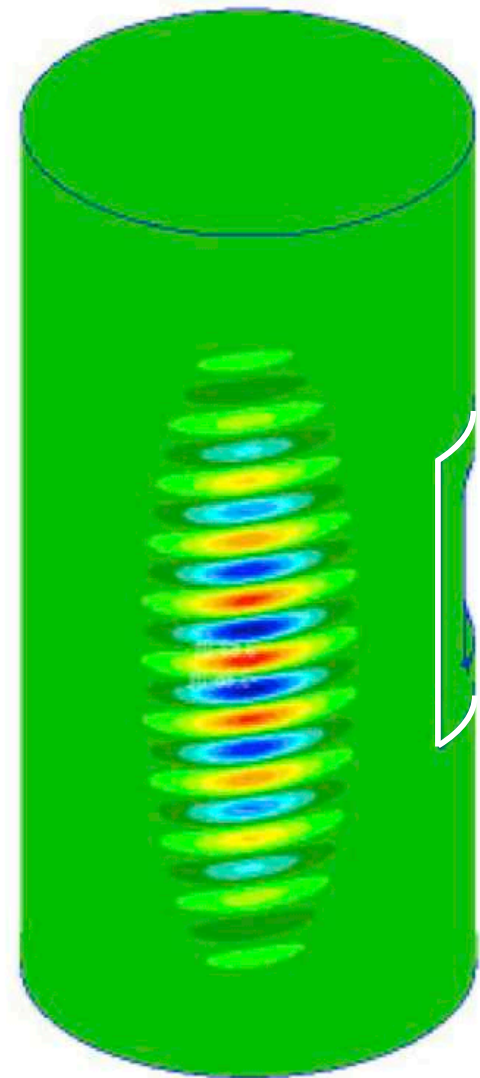
# Predicted Buckling Modes - Large Cutouts



**Local buckling - mode 1  
(both Shells)**



**Global buckling - mode 13  
(Shell with Overlaps)**



**Global buckling - mode 9  
(Shell w/o Overlaps)**

# Baseline Linear FEA Results

## (1) Pristine Shells

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 503.2               | 306.7              |
| 1st global buckling load, klbs       | 37.3                | 15.6               |

## (2) Shells with Small Cutouts

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 495.2               | 298.8              |
| 1st local buckling load, klbs        | 19.3                | 10.4               |
| 1st global buckling load, klbs       | 36.6                | 15.2               |

## (3) Shells with Large Cutouts

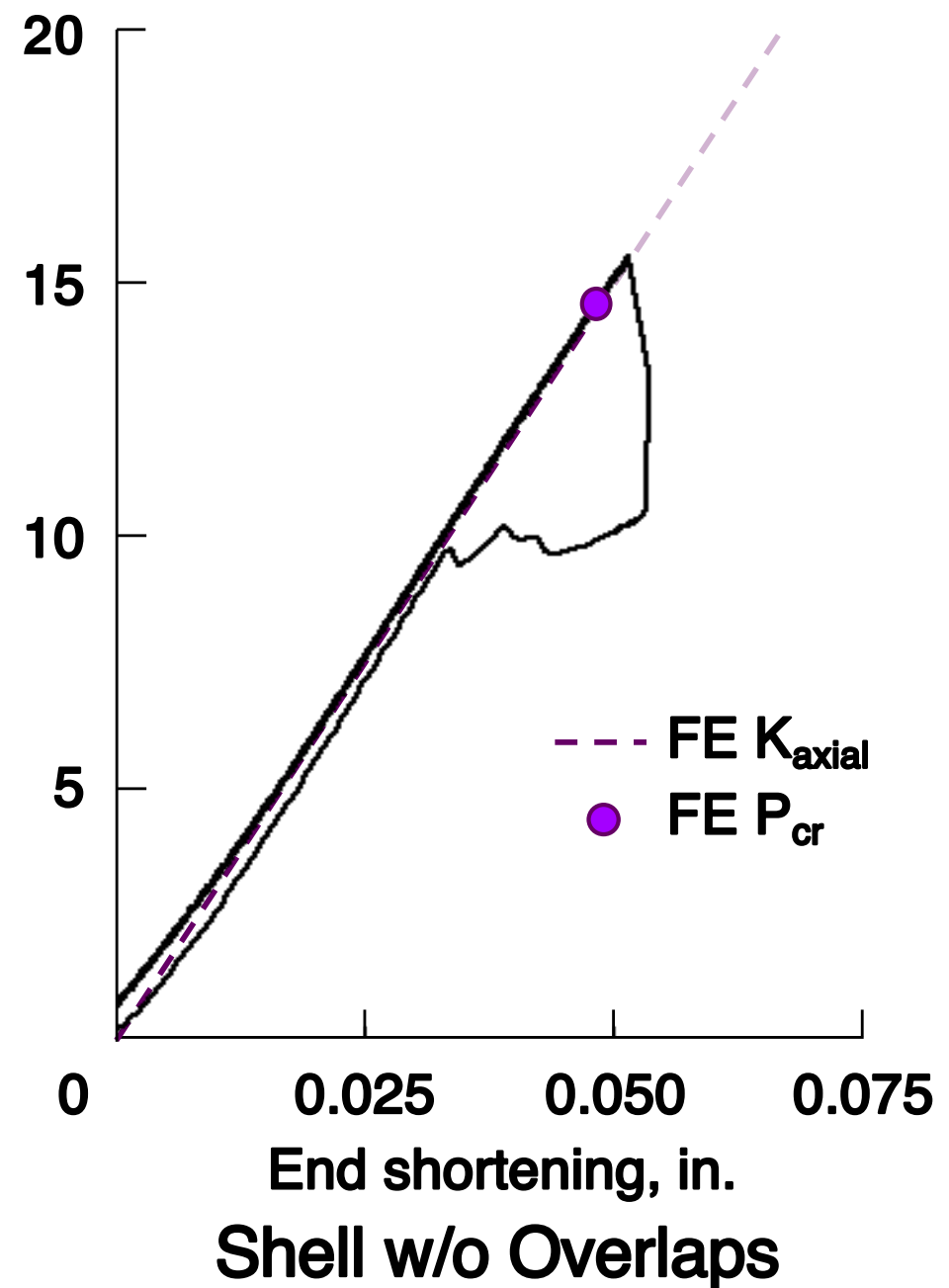
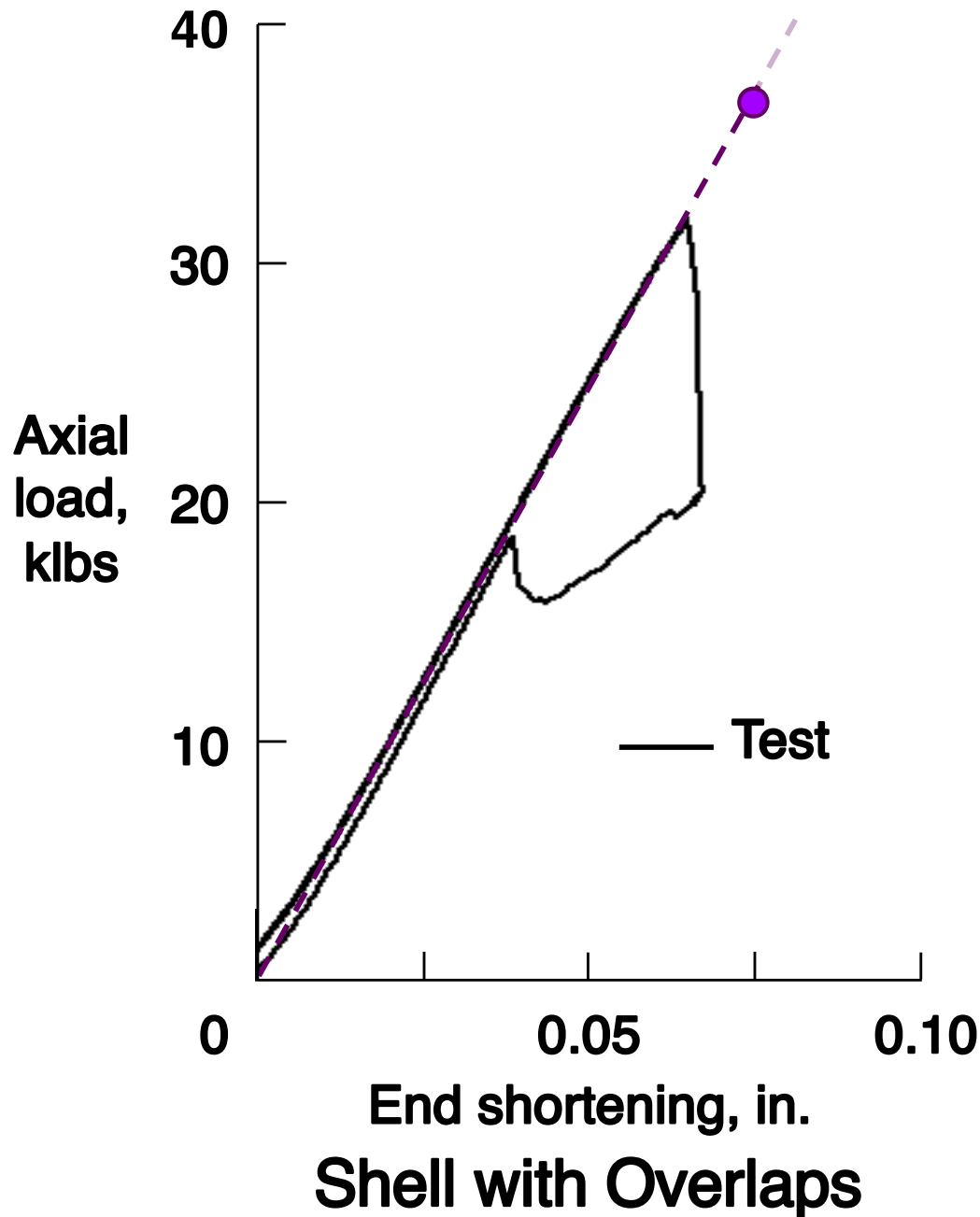
|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 491.0               | 294.7              |
| 1st local buckling load, klbs        | 14.4                | 8.0                |
| 1st global buckling load, klbs       | 36.3                | 14.9               |

*Avg. shell radius, ply thickness and adj.  $E_1$  used. No geometric imperfections.*

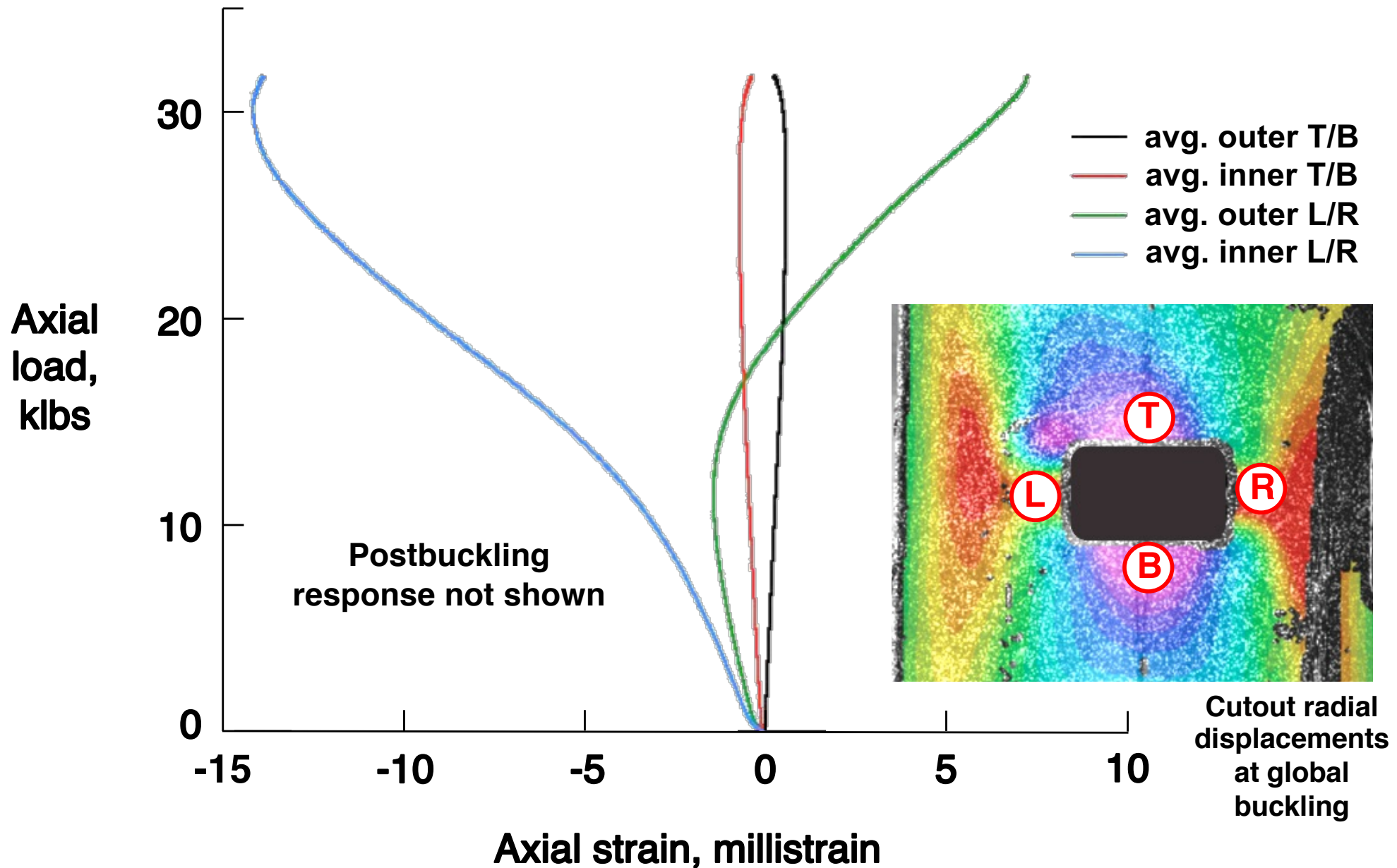


# Structural Test Results

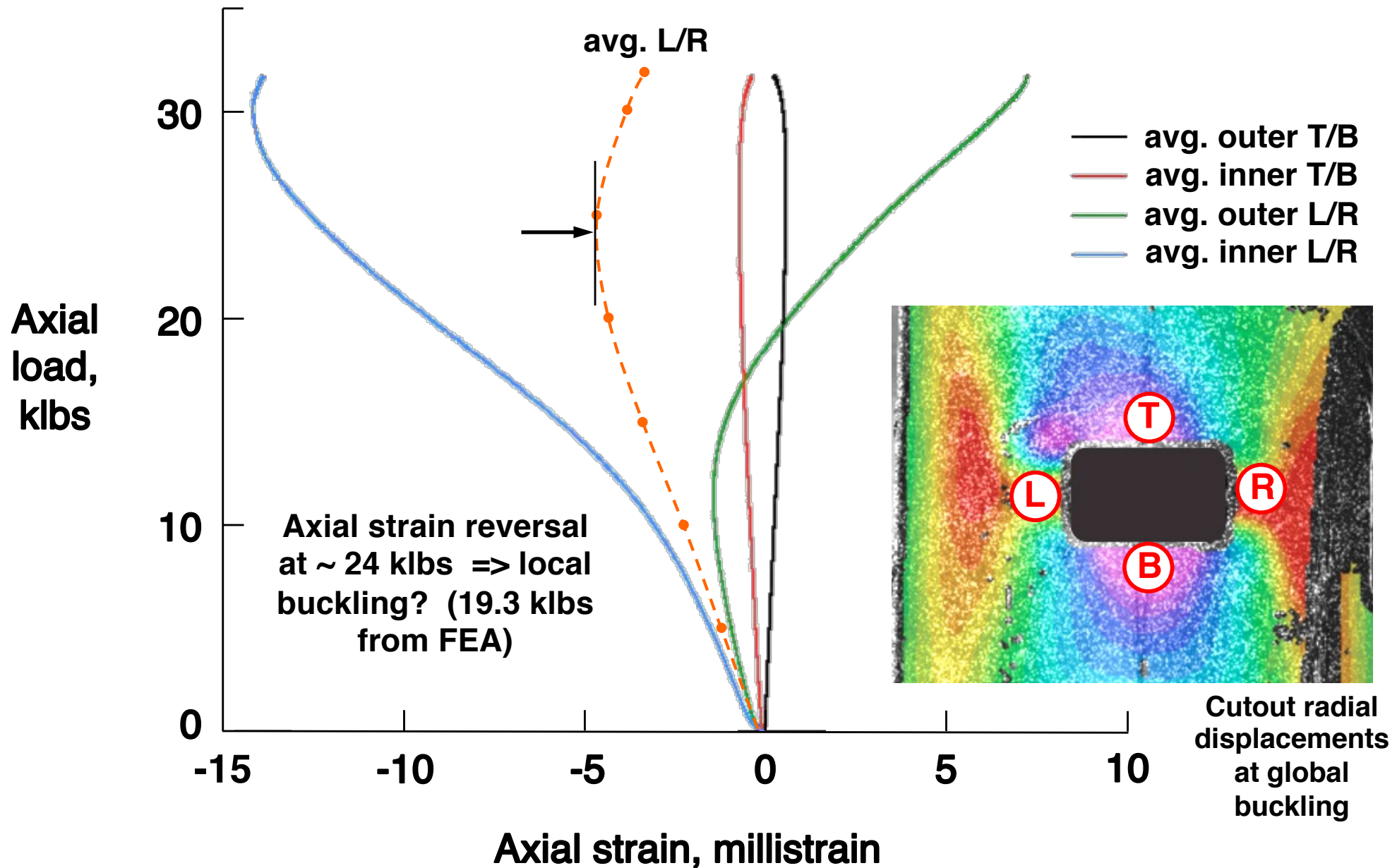
# Shells with Small Cutouts Tests and Analyses



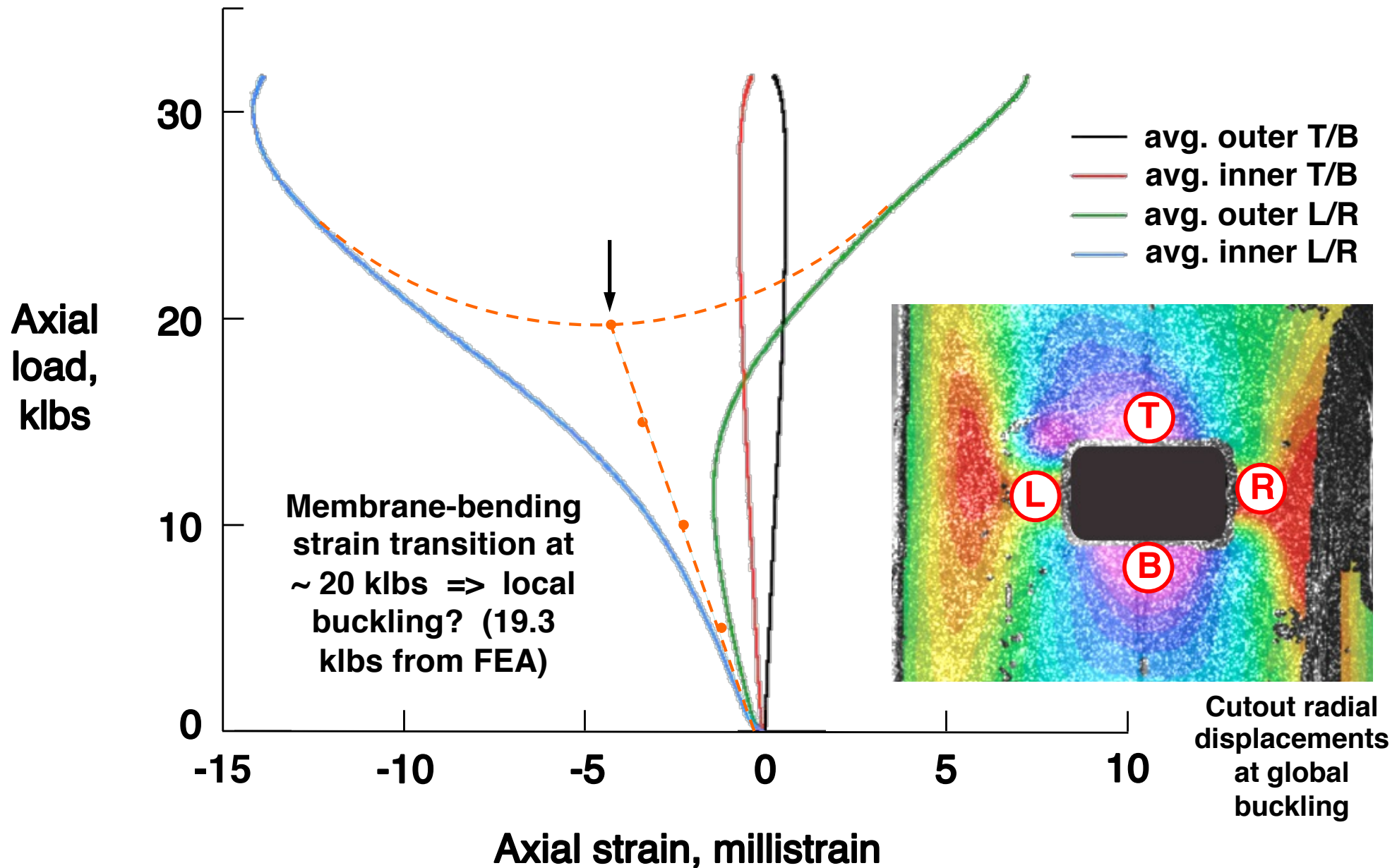
# Shell with Overlaps Test Results



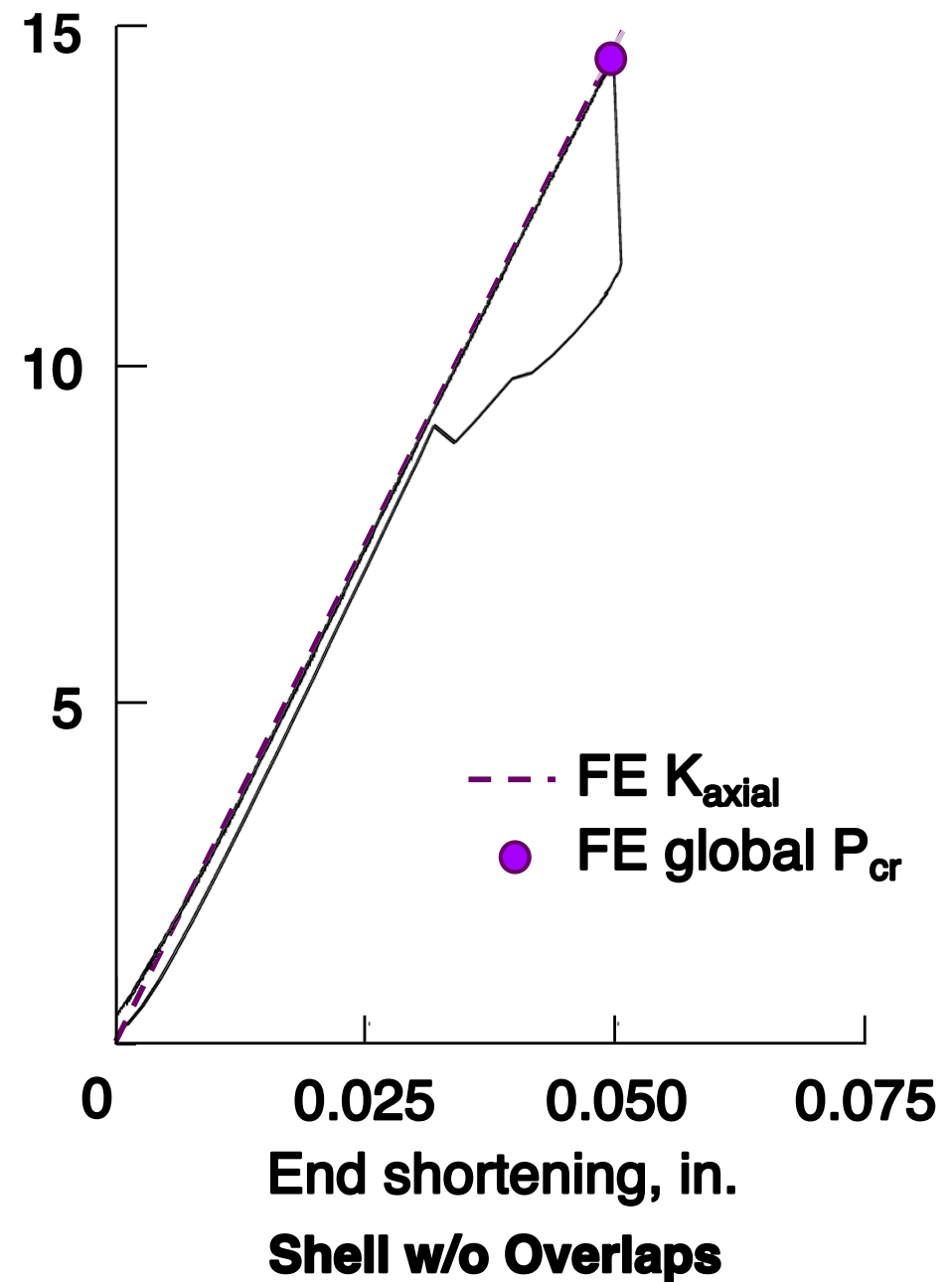
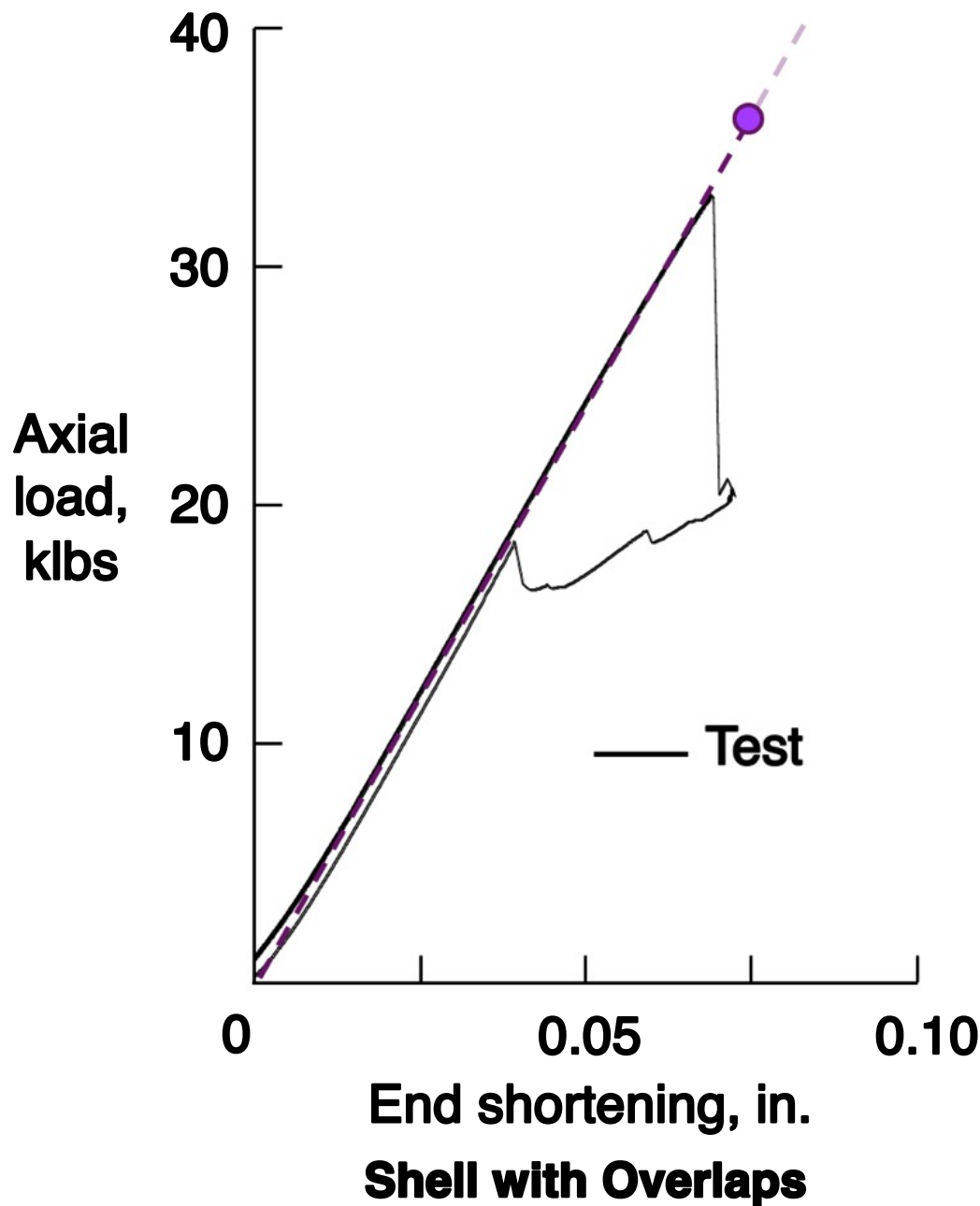
# Shell with Overlaps Test Results



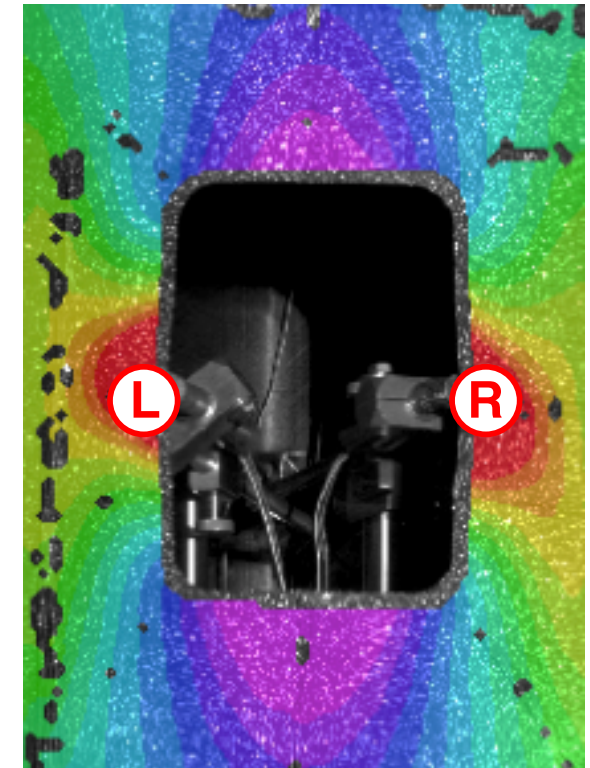
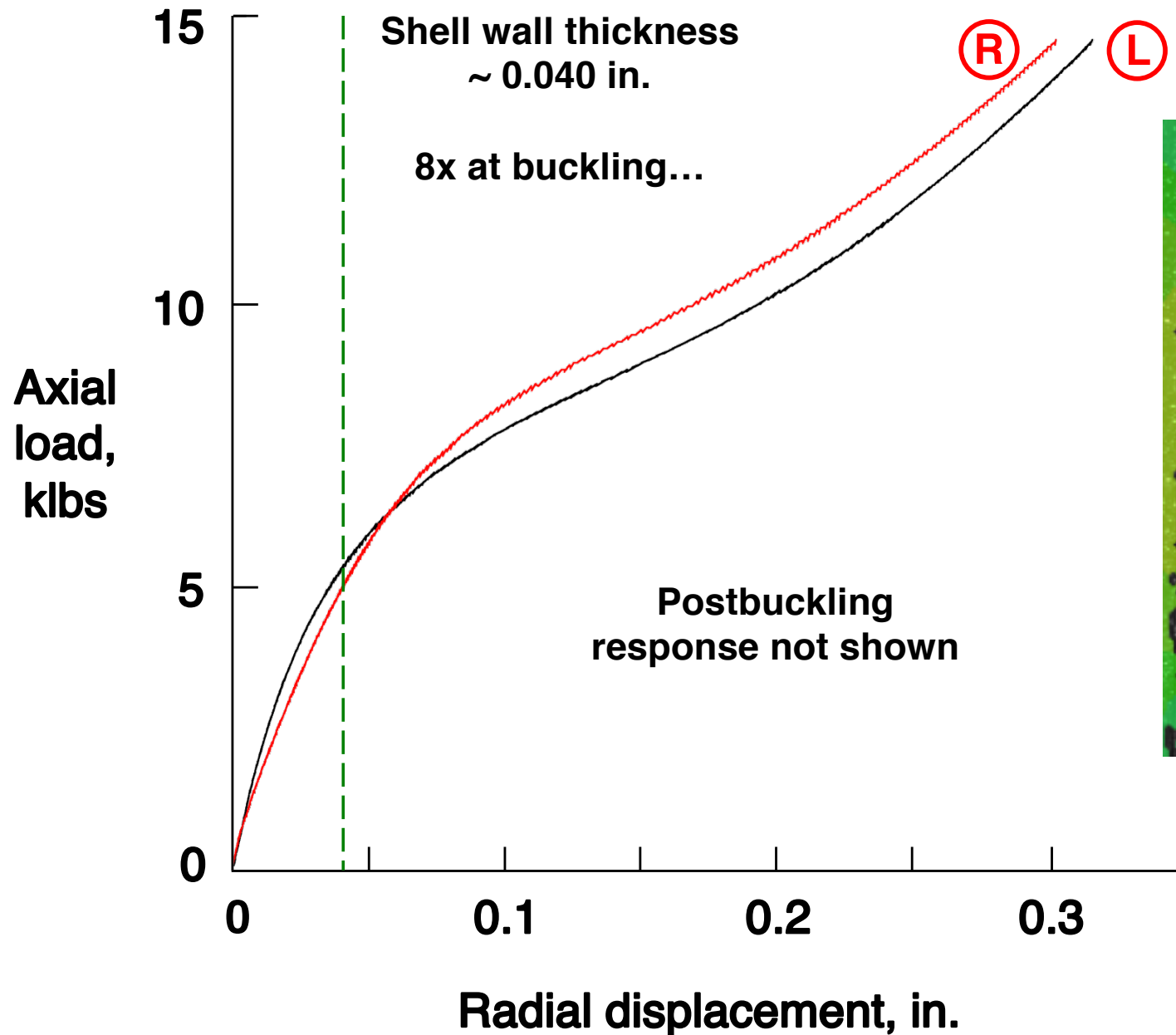
# Shell with Overlaps Test Results



# Shells with Large Cutouts Test and Analysis

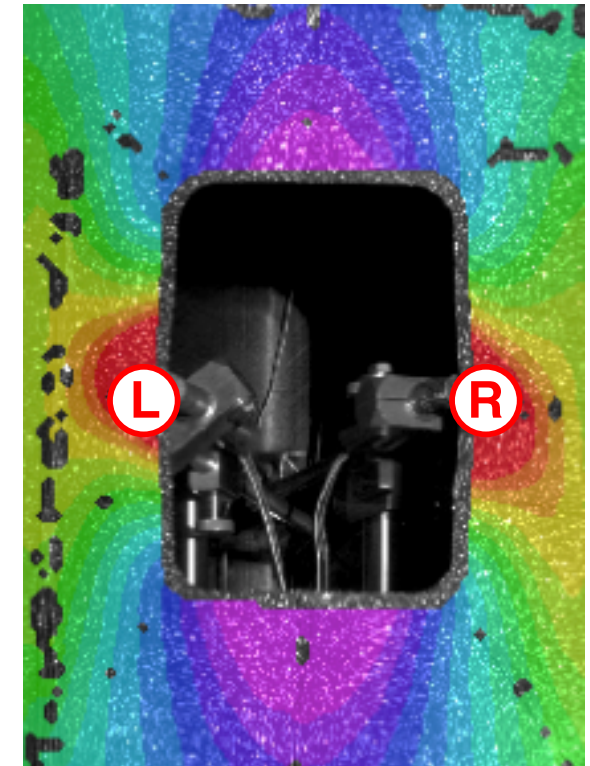
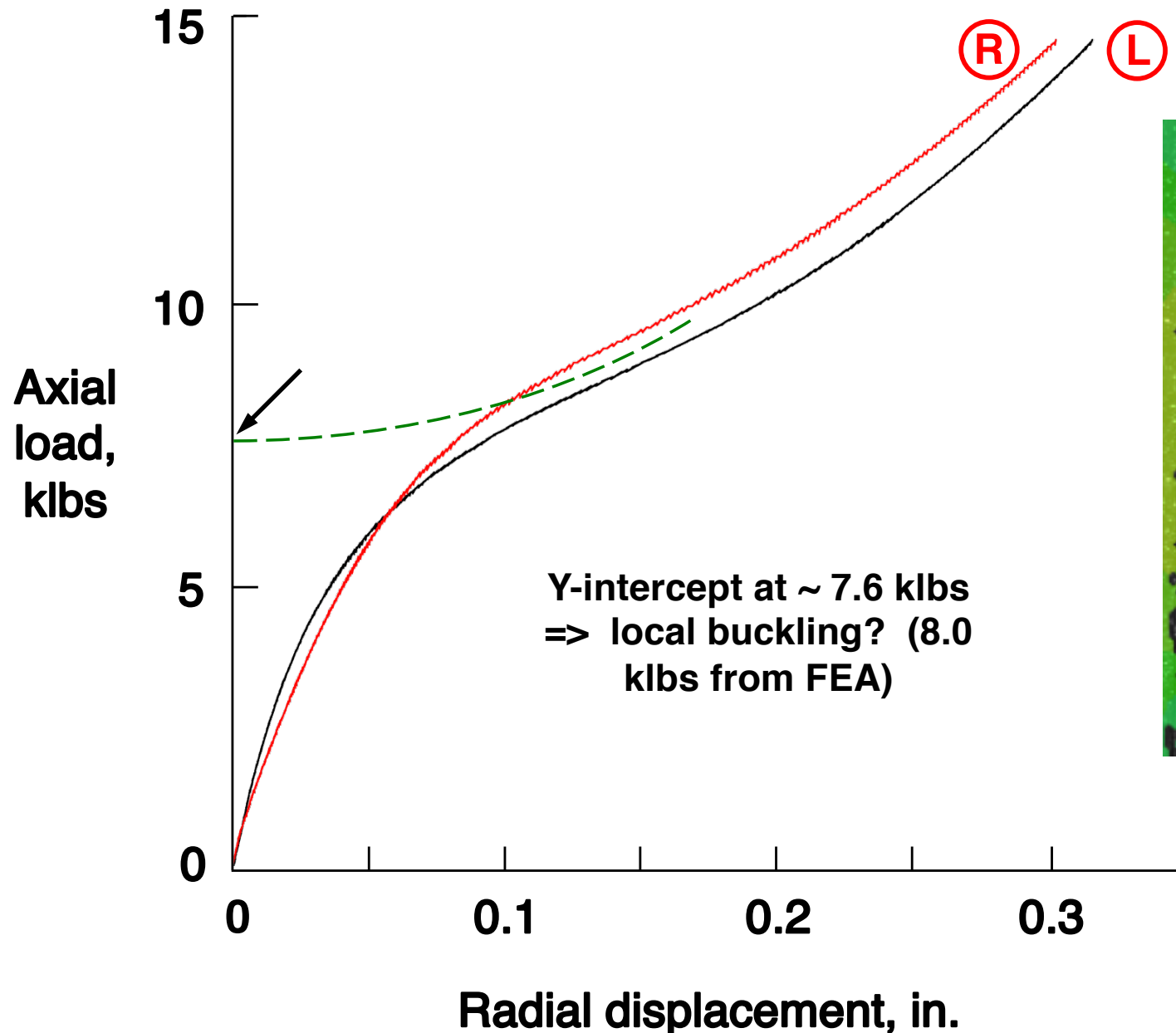


# Shell w/o Overlaps Test Results



Cutout radial displacements at global buckling

# Shell w/o Overlaps Test Results



Cutout radial displacements at global buckling

# Shell Test Results

## (1) Pristine Shells

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 531.2               | 328.7              |
| 1st global buckling load, klbs       | 38.8                | 17.2               |
| Postbuckling load, klbs              | 17.3                | 12.6               |

## (2) Shells with Small Cutouts

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 497.1               | 299.5              |
| 1st global buckling load, klbs       | 31.8                | 15.5               |
| Postbuckling load, klbs              | 20.3                | 10.5               |

## (3) Shells with Large Cutouts

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 488.6               | 295.6              |
| 1st global buckling load, klbs       | 33.0                | 14.6               |
| Postbuckling load, klbs              | 20.4                | 11.5               |

# Effect of Cutouts on Measured Performance

Performance metric: **Cutout / Pristine**

## (1) Pristine Shells

|                                      | Shell with Overlaps | Shell w/o Overlaps |
|--------------------------------------|---------------------|--------------------|
| Prebuckling axial stiffness, klb/in. | 531.2               | 328.7              |
| 1st global buckling load, klbs       | 38.8                | 17.2               |
| Postbuckling load, klbs              | 17.3                | 12.6               |

## (2) Shells with Small Cutouts

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 0.94                | 0.91               |
| 1st global buckling load    | 0.82                | 0.90               |
| Postbuckling load           | 1.17                | 0.83               |

## (3) Shells with Large Cutouts

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 0.92                | 0.90               |
| 1st global buckling load    | 0.85                | 0.85               |
| Postbuckling load           | 1.18                | 0.91               |

# Comparison of Shell Test and FEA Results

Performance metric: **Test / Baseline Linear FEA**

## (1) Pristine Shells

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 1.06                | 1.07               |
| 1st global buckling load    | 1.04                | 1.10               |

## (2) Shells with Small Cutouts

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 1.00                | 1.00               |
| 1st global buckling load    | 0.87                | 1.02               |

## (3) Shells with Large Cutouts

|                             | Shell with Overlaps | Shell w/o Overlaps |
|-----------------------------|---------------------|--------------------|
| Prebuckling axial stiffness | 1.00                | 1.00               |
| 1st global buckling load    | 0.91                | 0.98               |

*Avg. shell radius, ply thickness and adj.  $E_1$  in FEA. No geometric imperfections.*

# Shells with Cutouts Summary

- Predicted prebuckling axial stiffnesses match well with corresponding measured values
- Predicted global buckling load magnitudes within 6 percent of corresponding measured values
- Cutouts reduce measured axial prebuckling stiffnesses by an average 8 percent ( $5 \text{ in.}/2 \cdot \pi \cdot R \sim 10 \text{ percent}$ )
- Cutouts reduce measured global buckling loads by an average 14 percent
- Linear FEA predicted multiple local buckling modes around cutouts, which were not observed during tests
- Large nonlinear strains and deflections noted around cutouts (layup  $\sim [\pm 45]_{2s}$ )

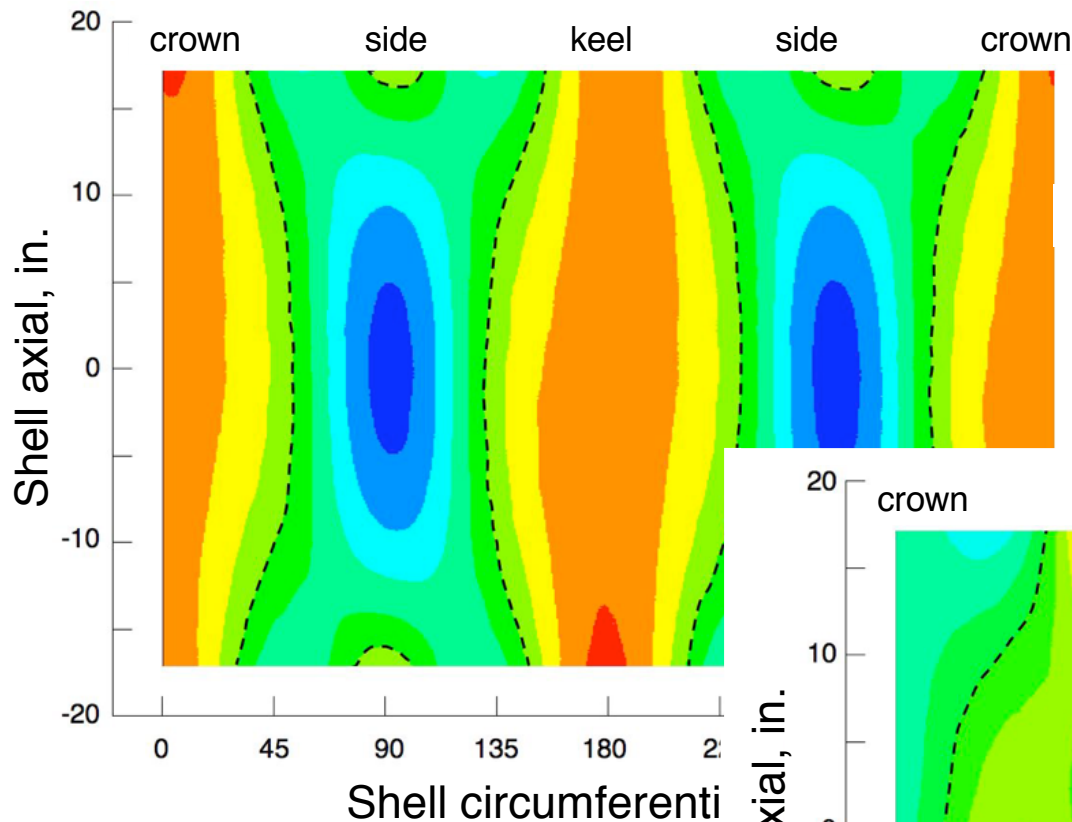


# Shell Imperfection Insensitivity

# Study Approach

- Assess structural performance variations for two advanced composite tow-steered shells
  - With and without tow overlaps
  - Without cutouts, and with small and large cutouts
- Perform linear FE analyses
  - Baseline shells without imperfections
  - Compare axial stiffness and buckling load
- Apply measured geometric imperfection data
  - Data from both pristine shells without cutouts
  - Imperfections rotated on structural models
- Assessment of trends and results
  - Compare test data with FEA results for shells with and without overlaps, cutouts and imperfections

# Shell Measured Geometric Imperfections

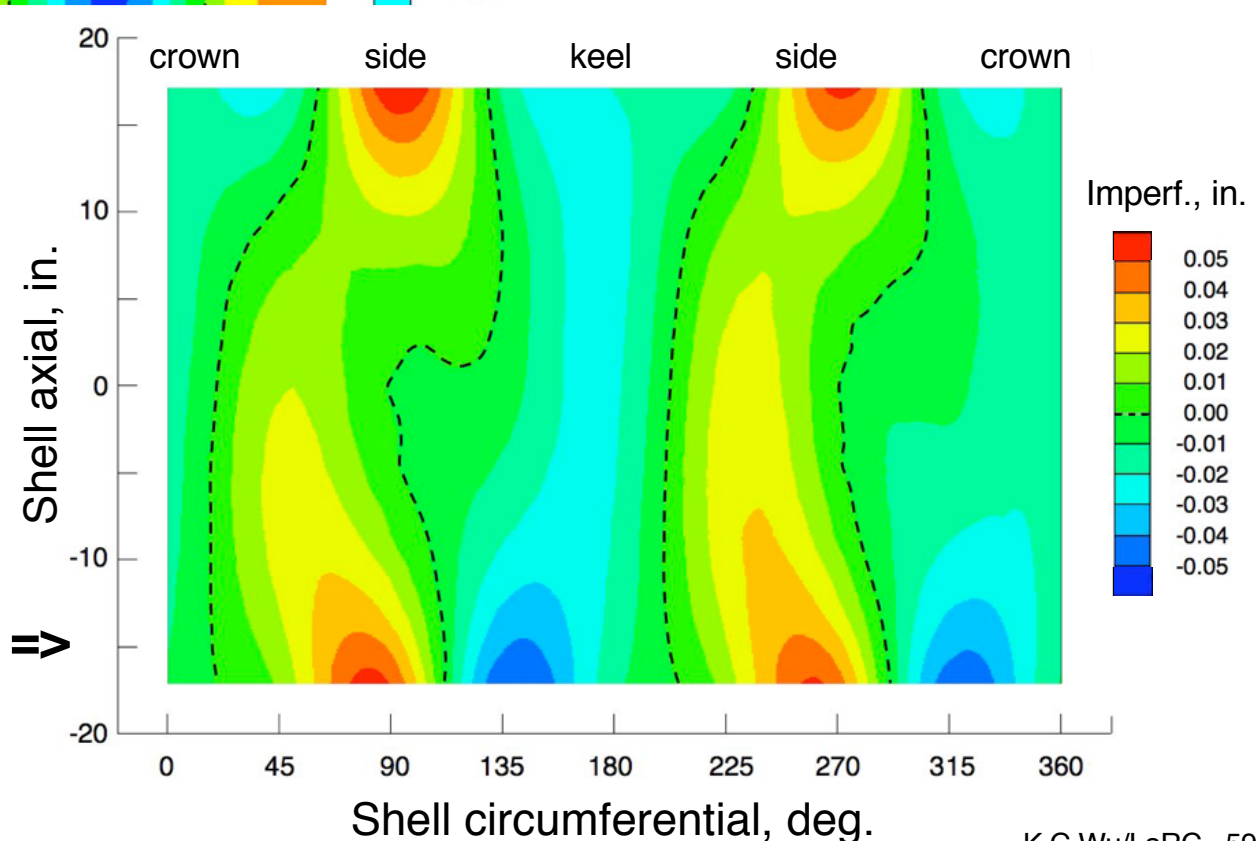


**Imperf. case A** - symmetric  
+0.825/−1.125 wall thickness  
Shell with overlaps

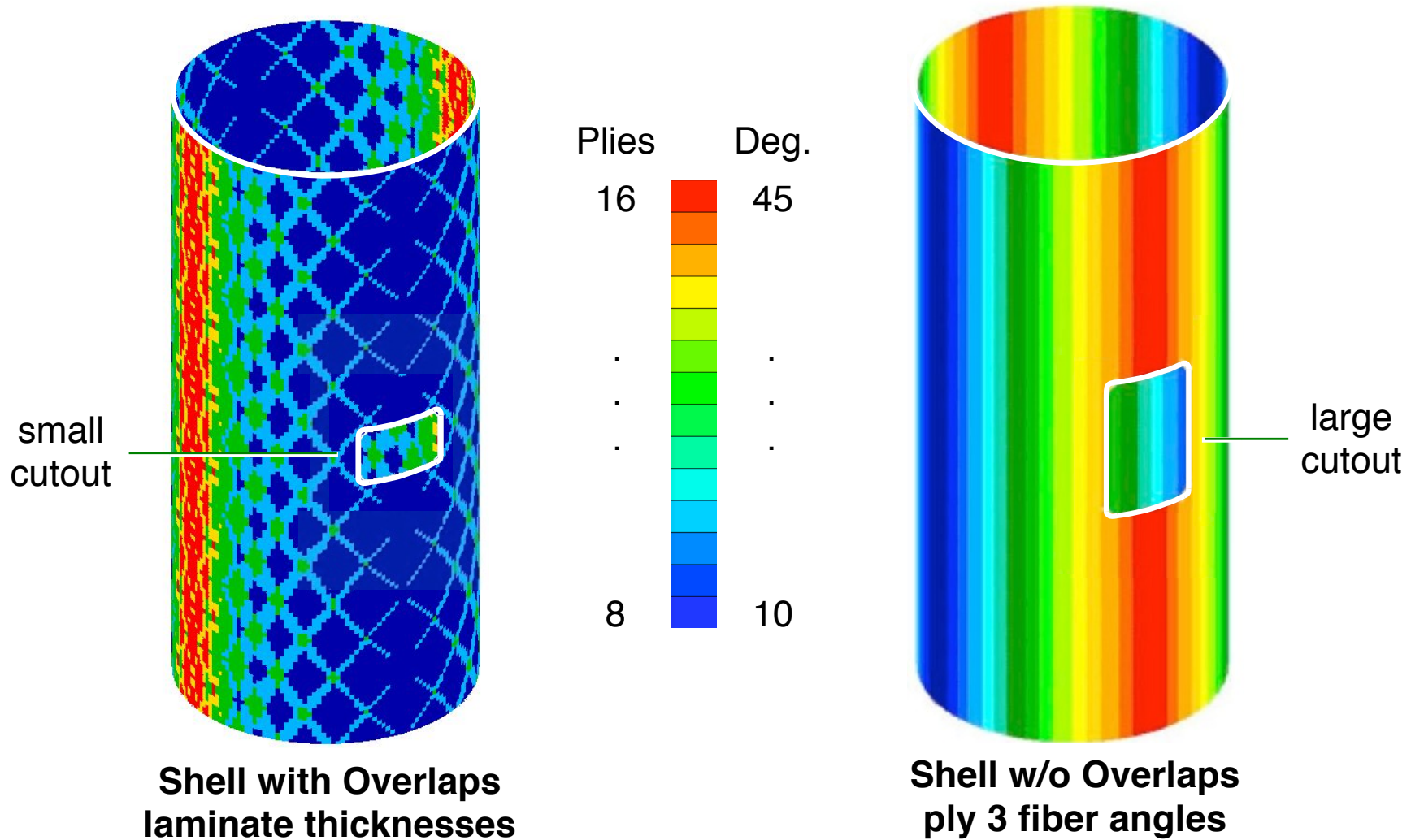
Imperfection data  
measured at  $\Phi = 0$  deg.

Nominal 8-ply shell wall  
thickness = 0.040 in.

**Imperf. case B** - asymmetric  
+1.475/−1.225 wall thickness  
Shell w/o overlaps

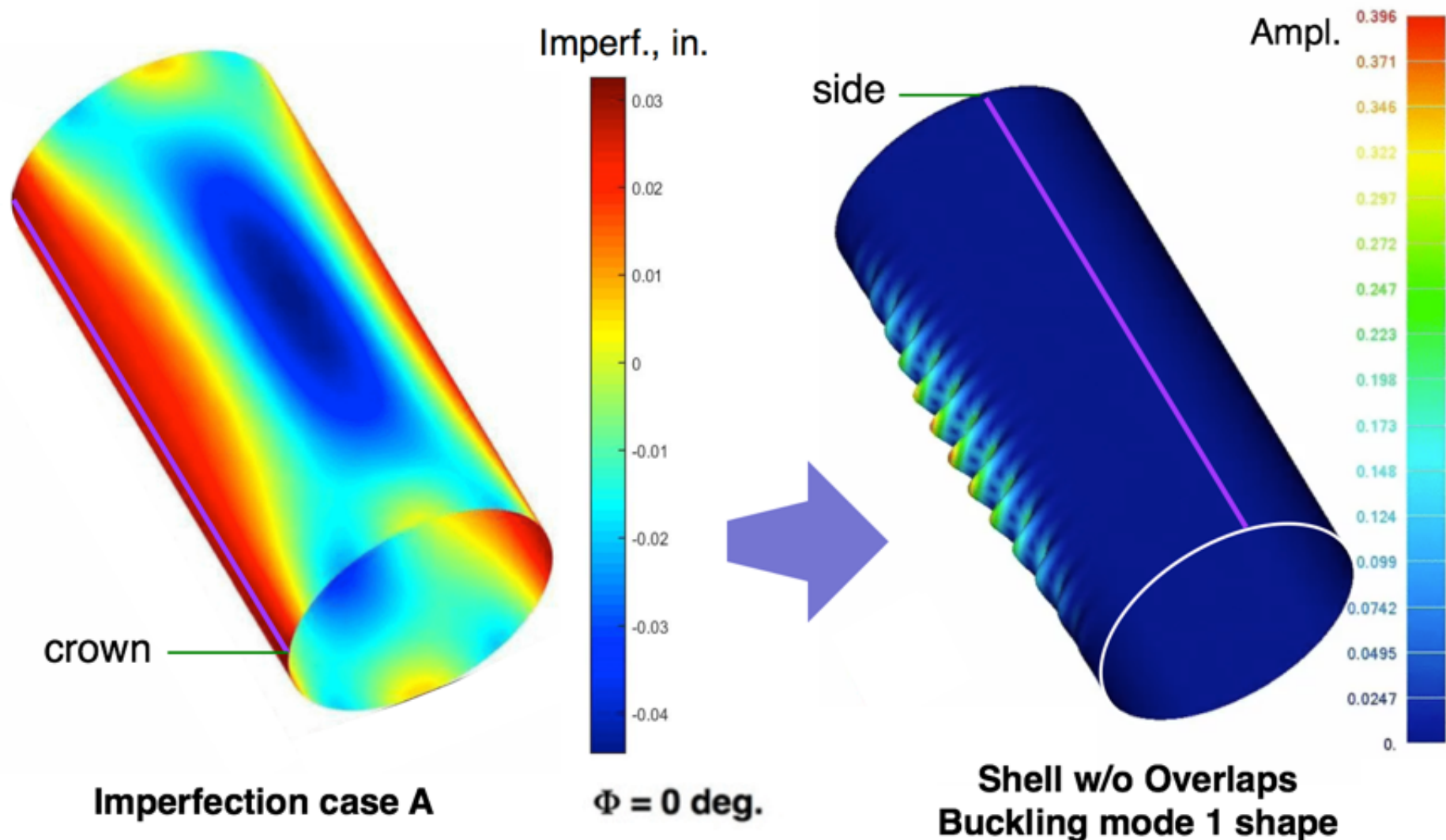


# Shell Finite Element Models



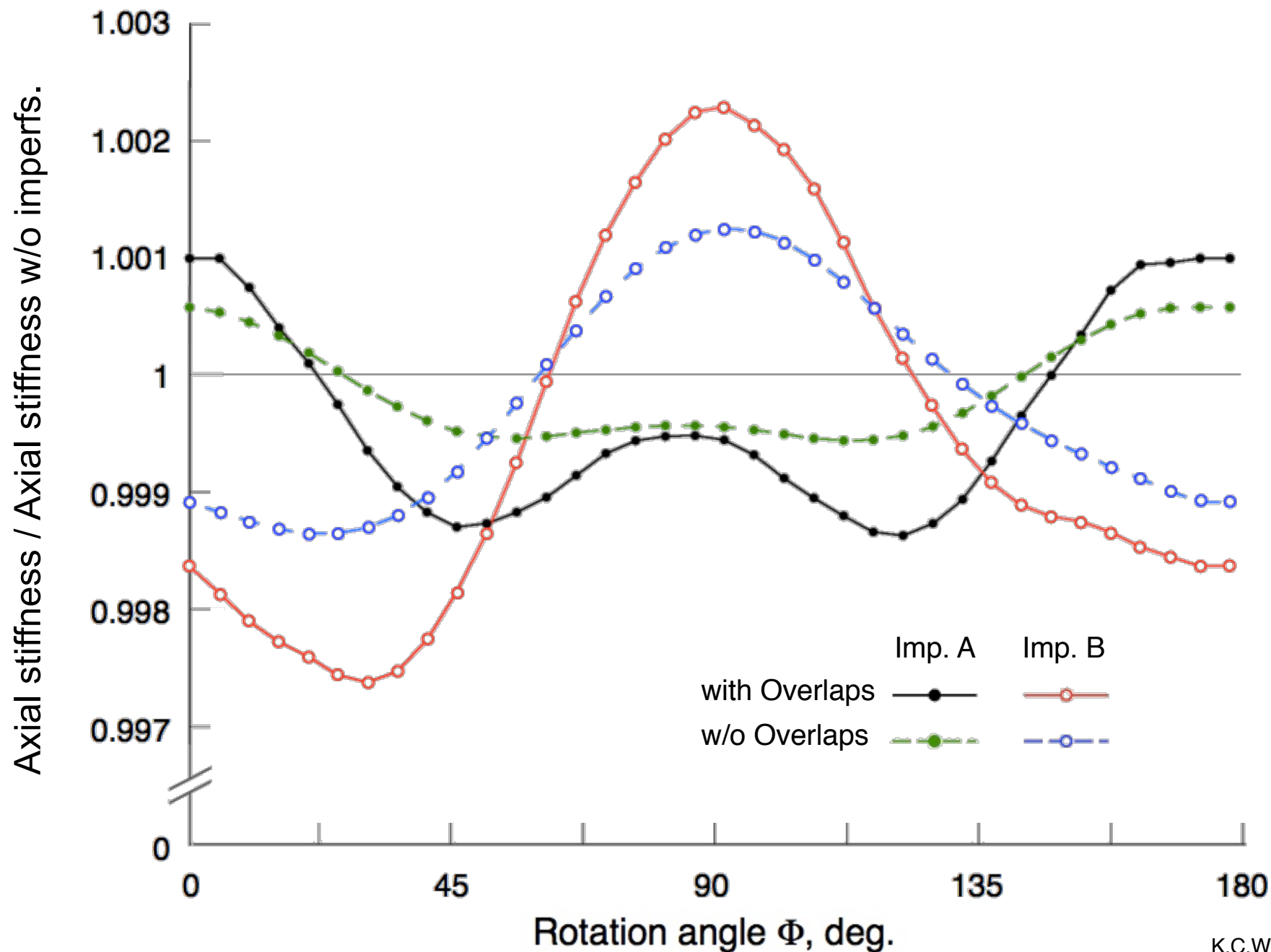
- => 18 combinations of overlaps, cutout sizes and imperfection cases
- => Subcases analyzed at rotation angles from  $\Phi = 0$  up to 360 deg.

# Pristine Shells with Imperfections FEA

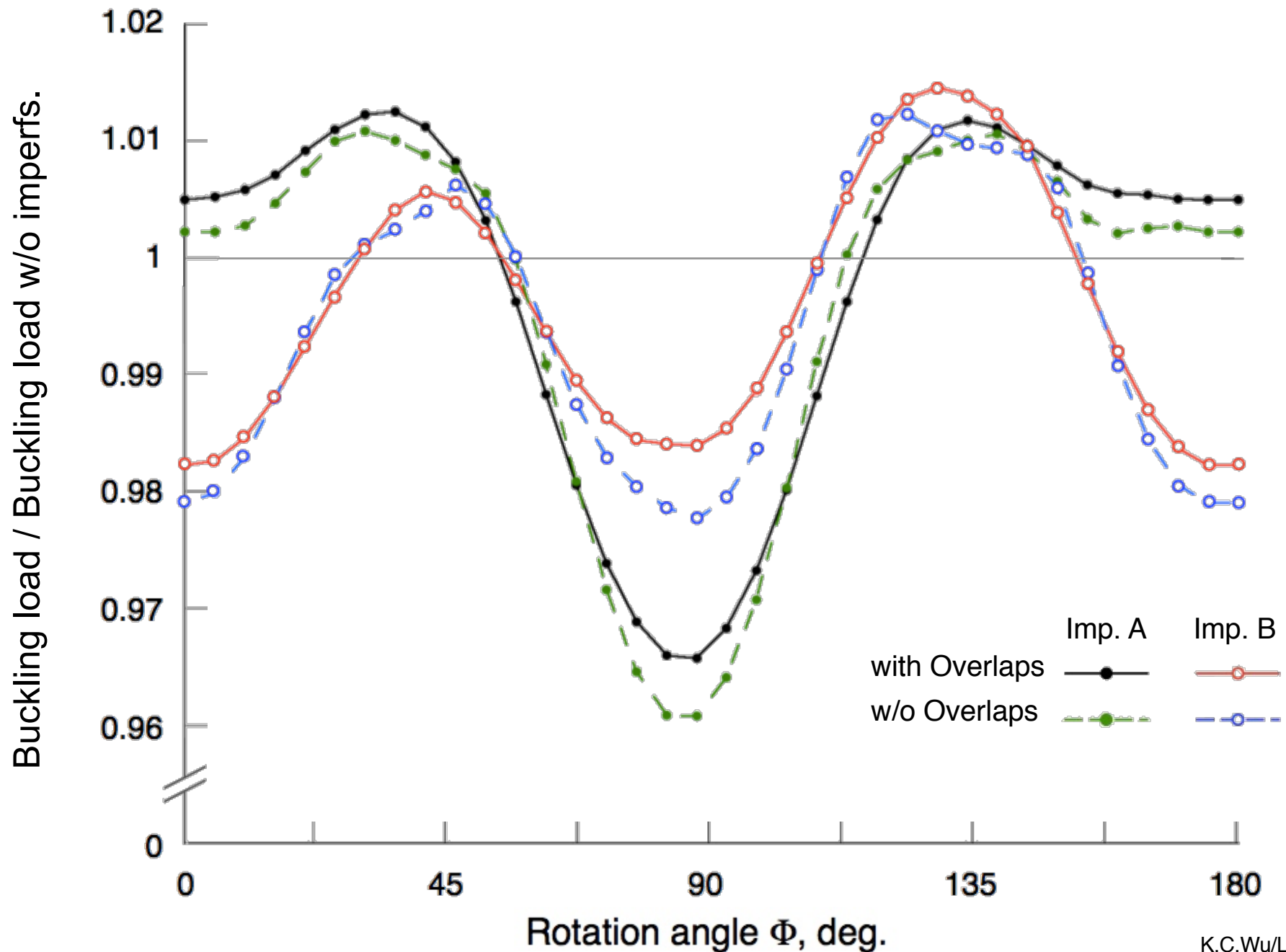


- $\Rightarrow$  Principal eigenvector varies over  $\Phi = 0$  to  $180$  deg.
- $\Rightarrow$  Buckling displacements localized to shell crown/keel

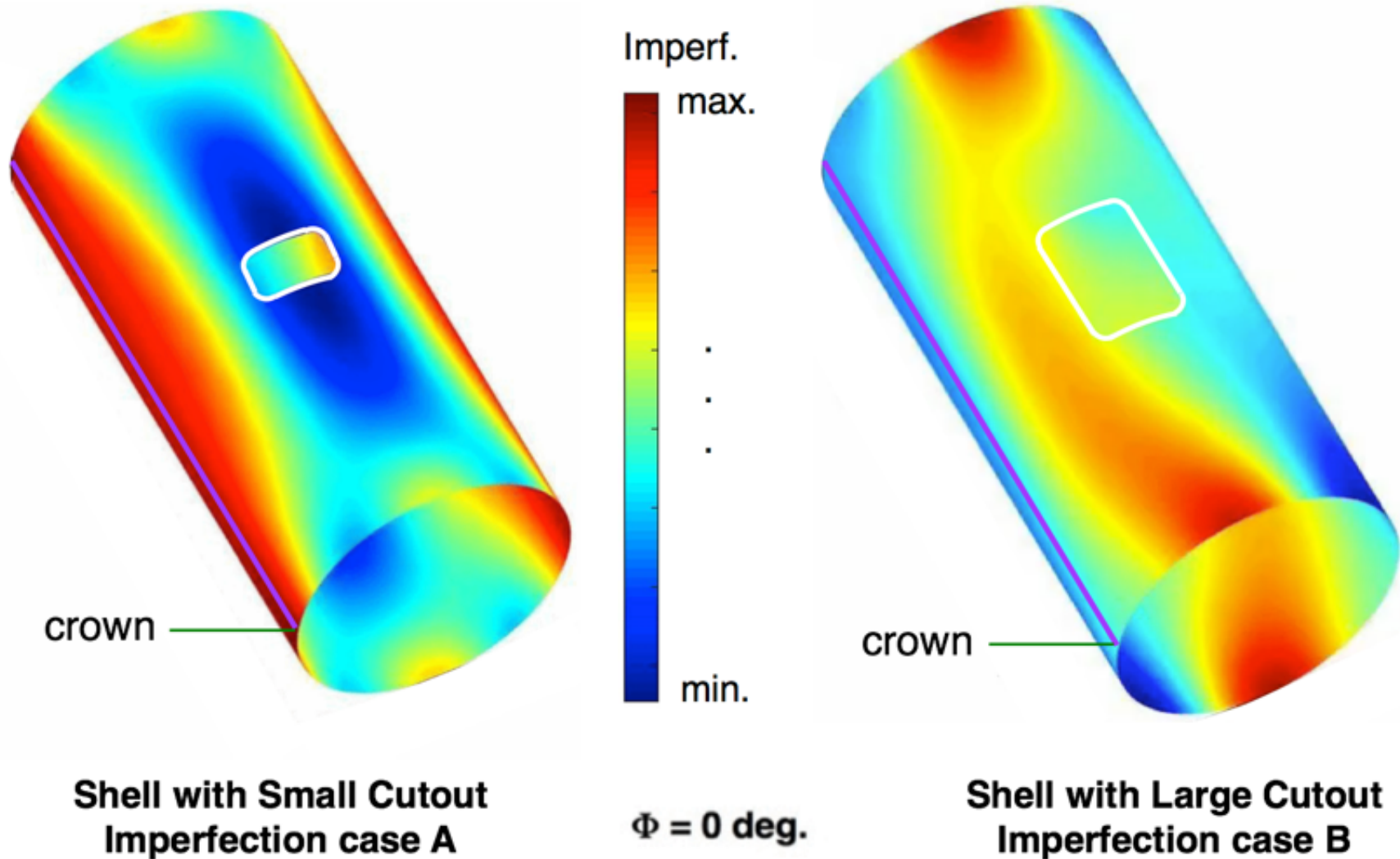
# Pristine Shell FEA - Norm. Stiffness



# Pristine Shell FEA - Norm. Buckling

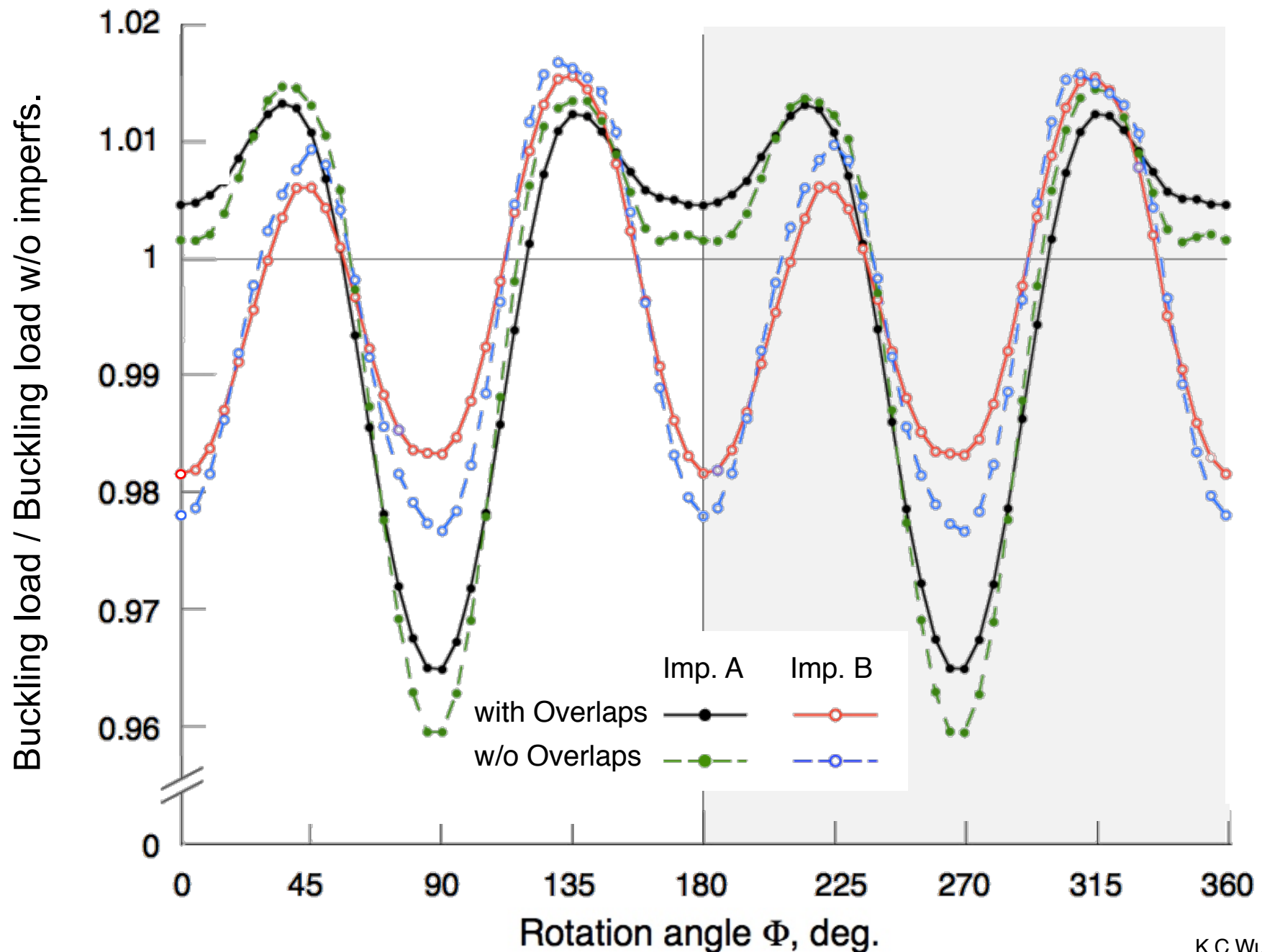


# Shells with Cutouts and Imperfections FEA

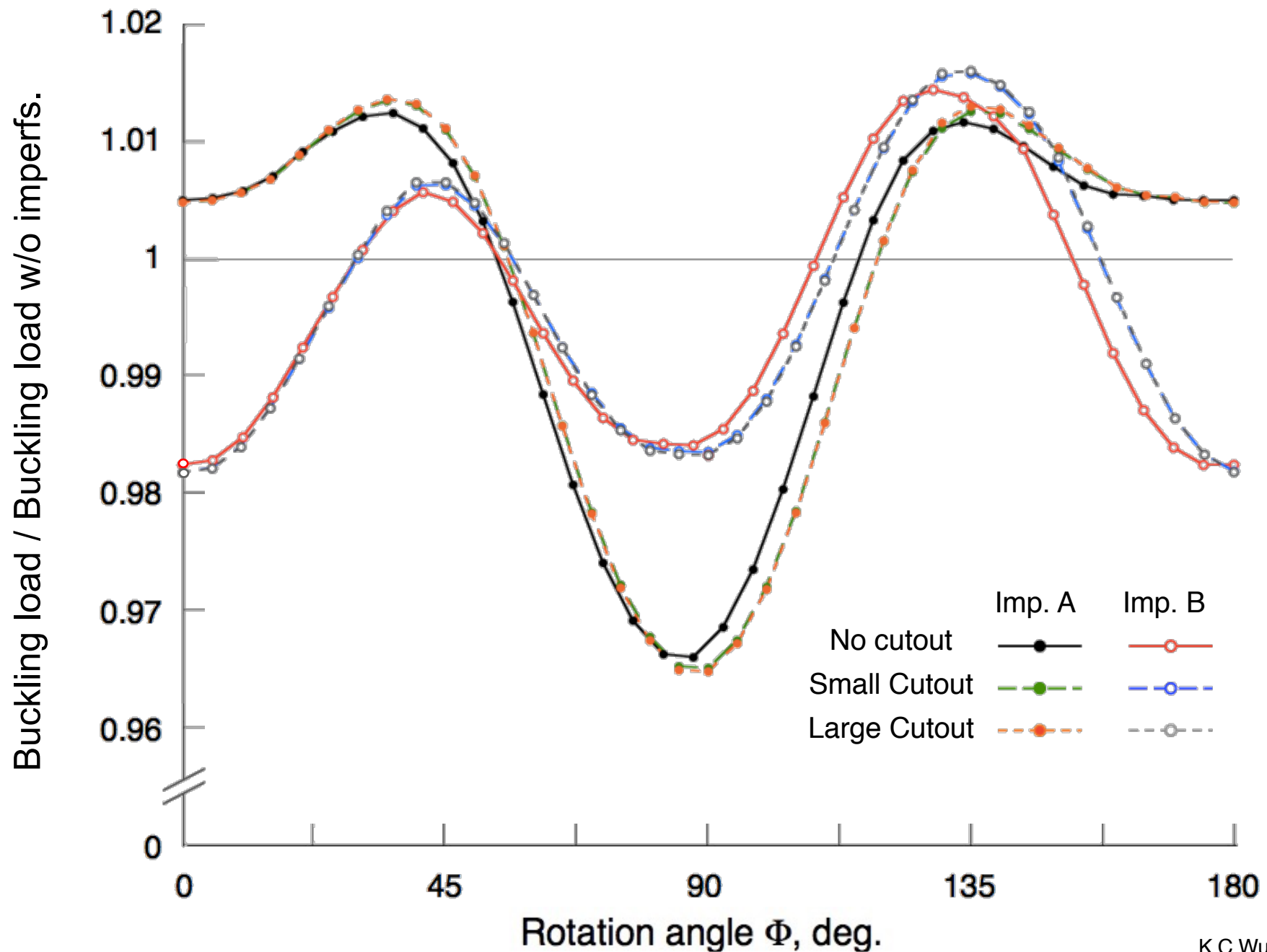


Rotation angles from  $\Phi = 0$  to 360 deg. due to cutout asymmetry  
 => Eigenvalue for lowest global buckling mode recorded

# Shells with Small Cutouts - Norm. Buckling



# Shell with Overlaps - Norm. Buckling



# Imperfection Study Summary

- Negligible variations ( $\pm 0.25$  percent) in normalized linear axial prebuckling stiffness with rotated imperfections
- Small variations (+1.5/–4 percent) in normalized bifurcation buckling loads with rotated imperfections
- Wide variety of global bifurcation buckling mode shapes observed with rotated imperfections
- Buckling mode shapes localized to shell crown/keel, regardless of imperfection amplitude and location
- Inclusion of cutout, and increasing its size, resulted in small variations in normalized performance metrics
- Test and baseline FEA shell prebuckling stiffness and bifurcation buckling loads compared very well



# Concluding Remarks

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- Structural performance of two advanced composite tow-steered shells assessed with tests and analyses
- Shells loaded in end compression through global buckling, into deep postbuckling, and elastic unloading
- Linear finite element analyses performed to guide testing, and for preliminary comparisons with test results
- Detailed analyses including geometric nonlinearities also performed for better comparison with tests
- Shell buckling deformations highly localized to stiffer crown and keel (Hooke's Law)
- Buckling results demonstrated insensitivity to geometric imperfections from manufacturing

## Concluding Remarks (2)

- Structural performance of two tow-steered shells with unreinforced cutouts evaluated using tests and analyses
- Shells loaded in end compression through global buckling into near postbuckling, and unloaded elastically
- Measured geometric imperfections applied to shell analysis models at different rotation angles to assess sensitivity of structural performance
- Small variations in axial stiffness and buckling loads demonstrate potential for tow steering to mitigate the effects of discontinuities on structural performance
- May perform similar analyses with scaled or normalized imperfection amplitudes to further assess shell imperfection (in)sensitivity