Testing and Analyses of Advanced Composite Tow-Steered Shells with Cutouts

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Talk Outline

- Introduction
- Baseline shells w/o cutouts
  - Design and manufacturing
  - Testing and analyses
- Shells with small cutouts
  - Cutout description
  - Compression tests and finite element analyses
  - Correlation of results
    - Global, local
- Shells with large cutouts
  - Correlation of global results
- Summary and concluding remarks

Study Objectives

- Assess structural performance of tow-steered composite shells with small cutouts
  - Shells with and w/o tow overlaps
  - Same nominal layup

- Test shells in quasi-static end compression
  - Prebuckling deflections and strains
  - Postbuckling deflections and strains

- Compare nonlinear structural analysis results with corresponding test data
  - Discrete locations on shell planform
  - Measured analog (LVDT, strain gage) and digital image correlation (DIC) deflections and strains
  - Shell postbuckling behavior

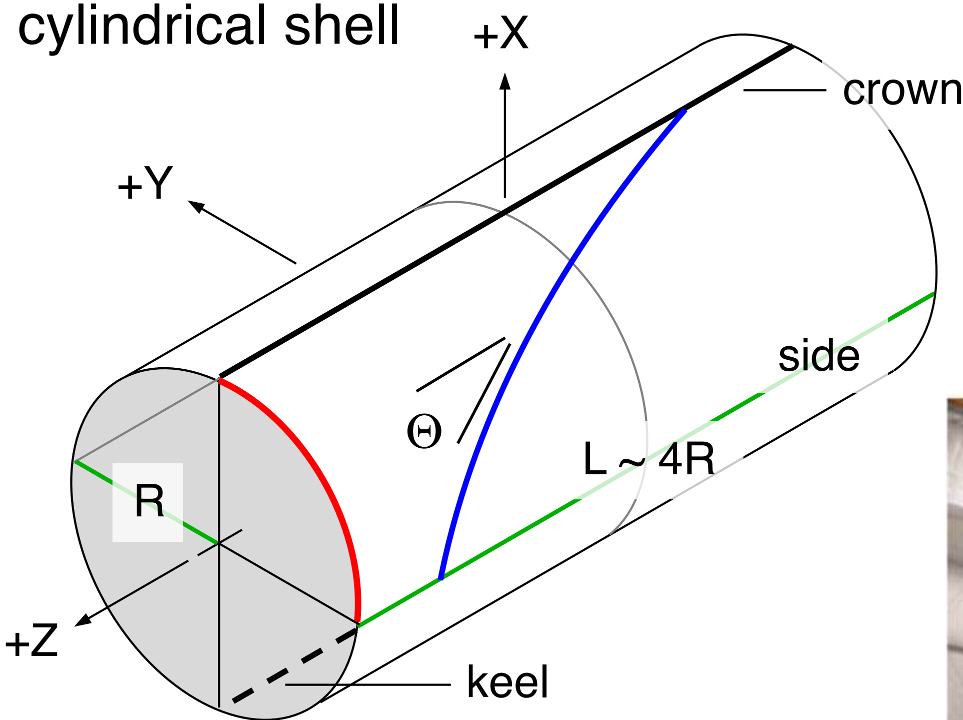
What Are Advanced Composites?

- In conventional composite laminates, all fibers in a ply are straight and parallel with a fixed orientation; structural tailoring is achieved by varying the numbers of plies and their relative orientations
- In advanced composites (a.k.a. *tow-steered* or *variable stiffness*) the fiber orientation within each ply can vary continuously over the structure's planform
- These configurations provide new opportunities for optimized design by tailoring load paths, thermal and mechanical properties, and damage tolerance
- Fiber placement systems that can precisely and accurately steer composite tows during manufacture are enabling technology for cost-effective fabrication of highly tailored structures

Baseline Shells w/o Cutouts
Design, Manufacturing, Testing, and Analyses

Tow-Steered Shell Concept

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

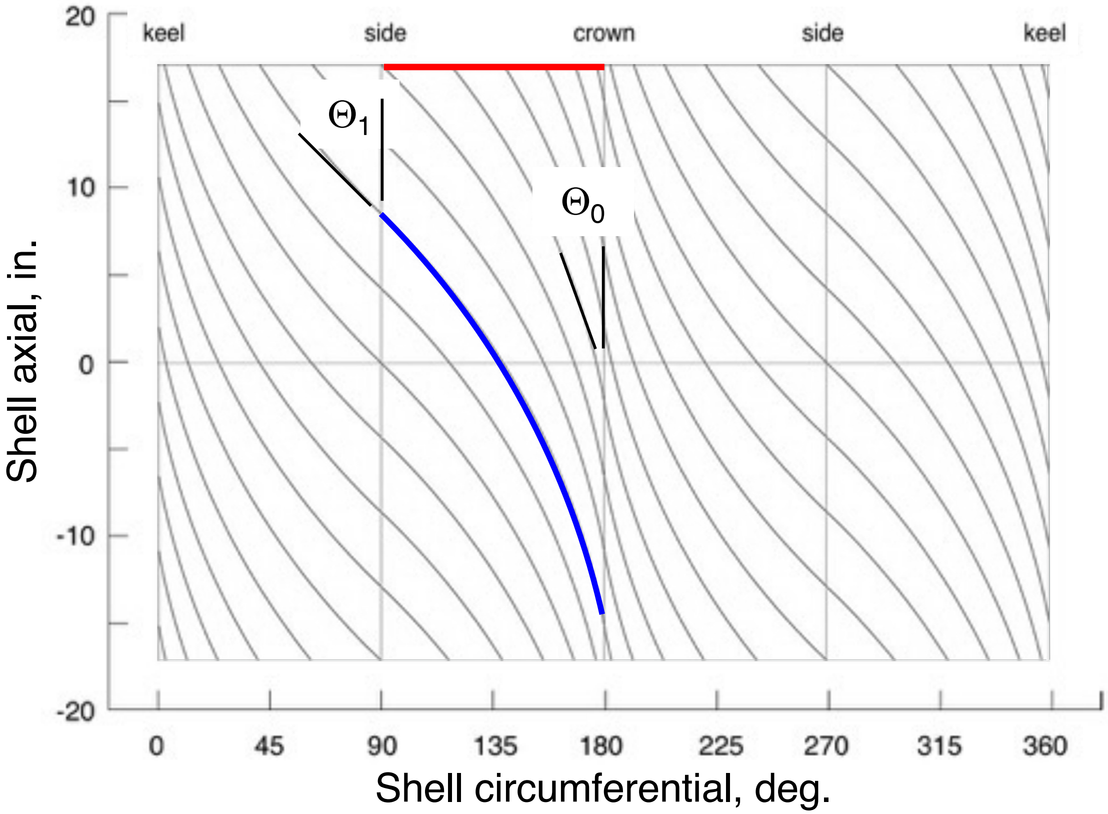
Arc width = mandrel circumf./4

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



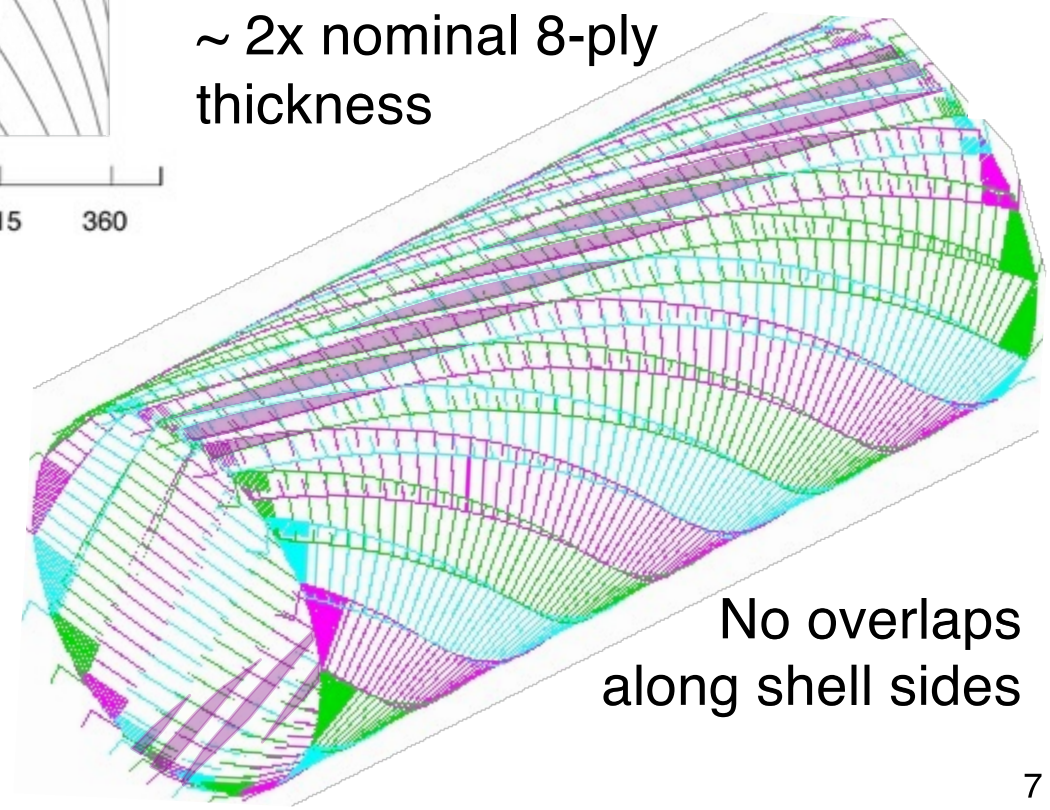
Continuous fiber angle variation from Θ_0 = 10 deg. on the shell crown/keel, to Θ_1 = 45 deg. on shell sides

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

22 steered courses req'd to fully cover 16.266 in.-OD mandrel

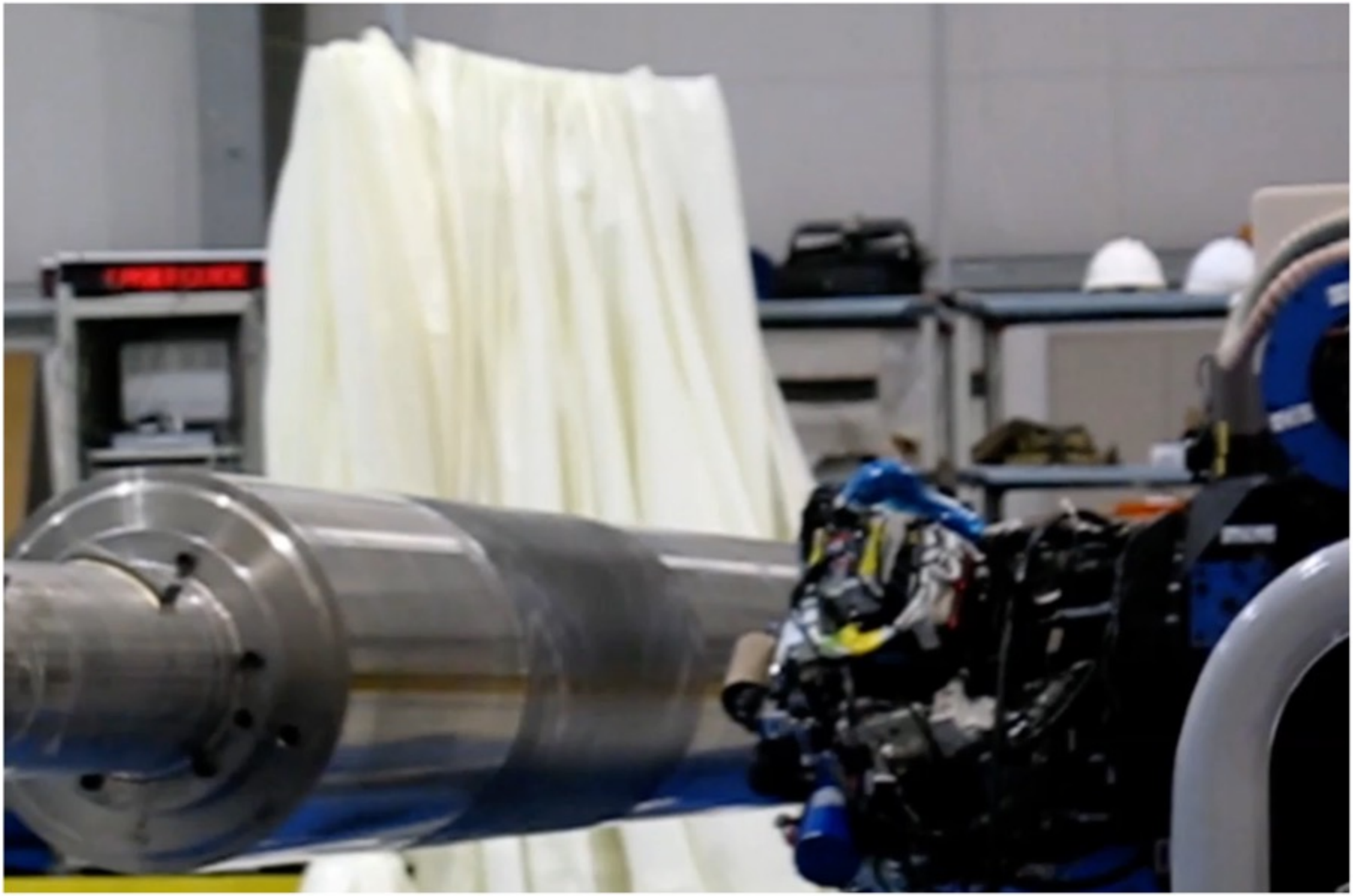
Nominal 8-ply $[\pm 45/\pm\Theta]_s$ layups

Shells both with and w/o tow overlaps fabricated



No overlaps along shell sides

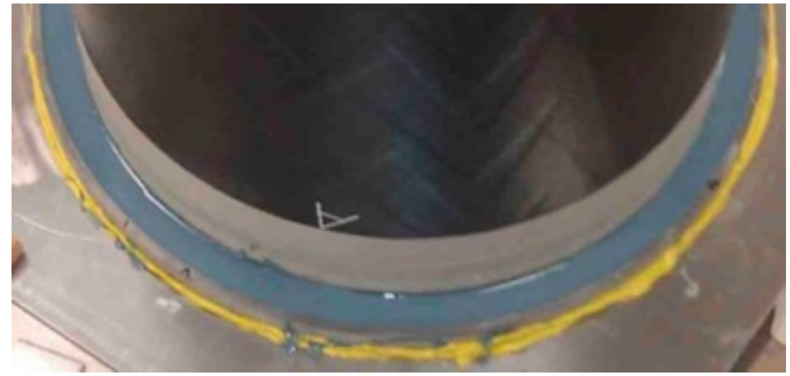
Tow-Steered Shell Fabrication



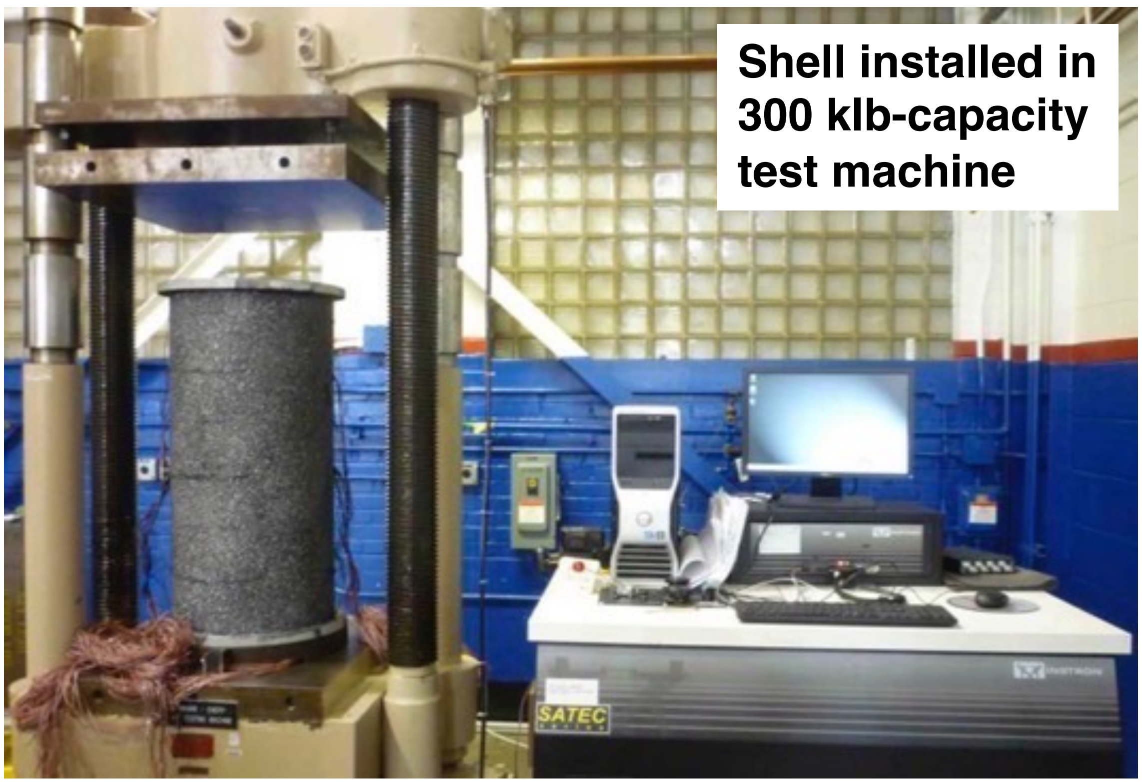
Shell Compression Test Set-up

Nominal shell dimensions
- Overall length = 35.00 inches
- Inner diameter = 16.290 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



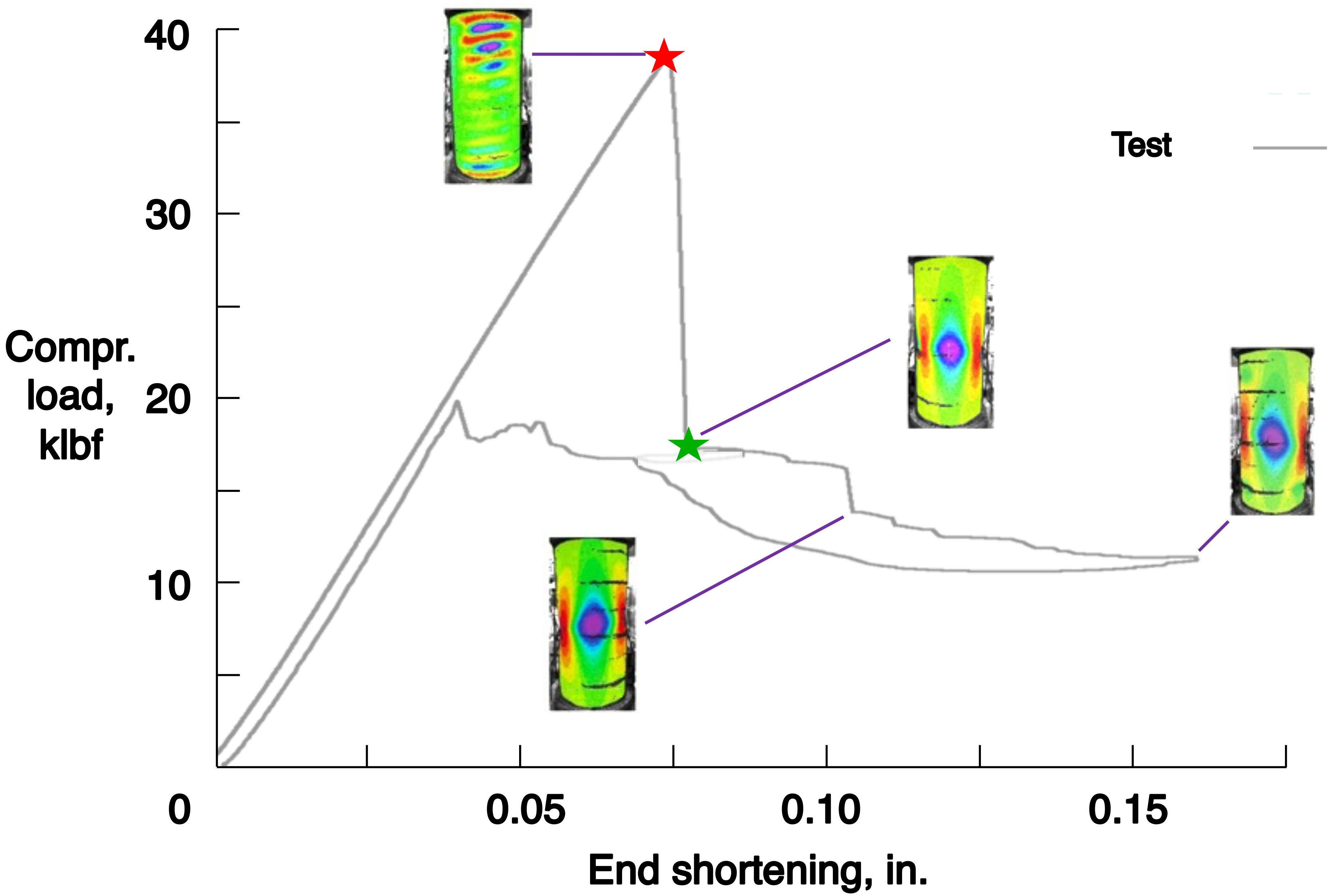
Shell installed in 300 klb-capacity test machine

4 displacement transducers measure relative platen motion
- Average = end shortening
- Diff’s = transv. bending

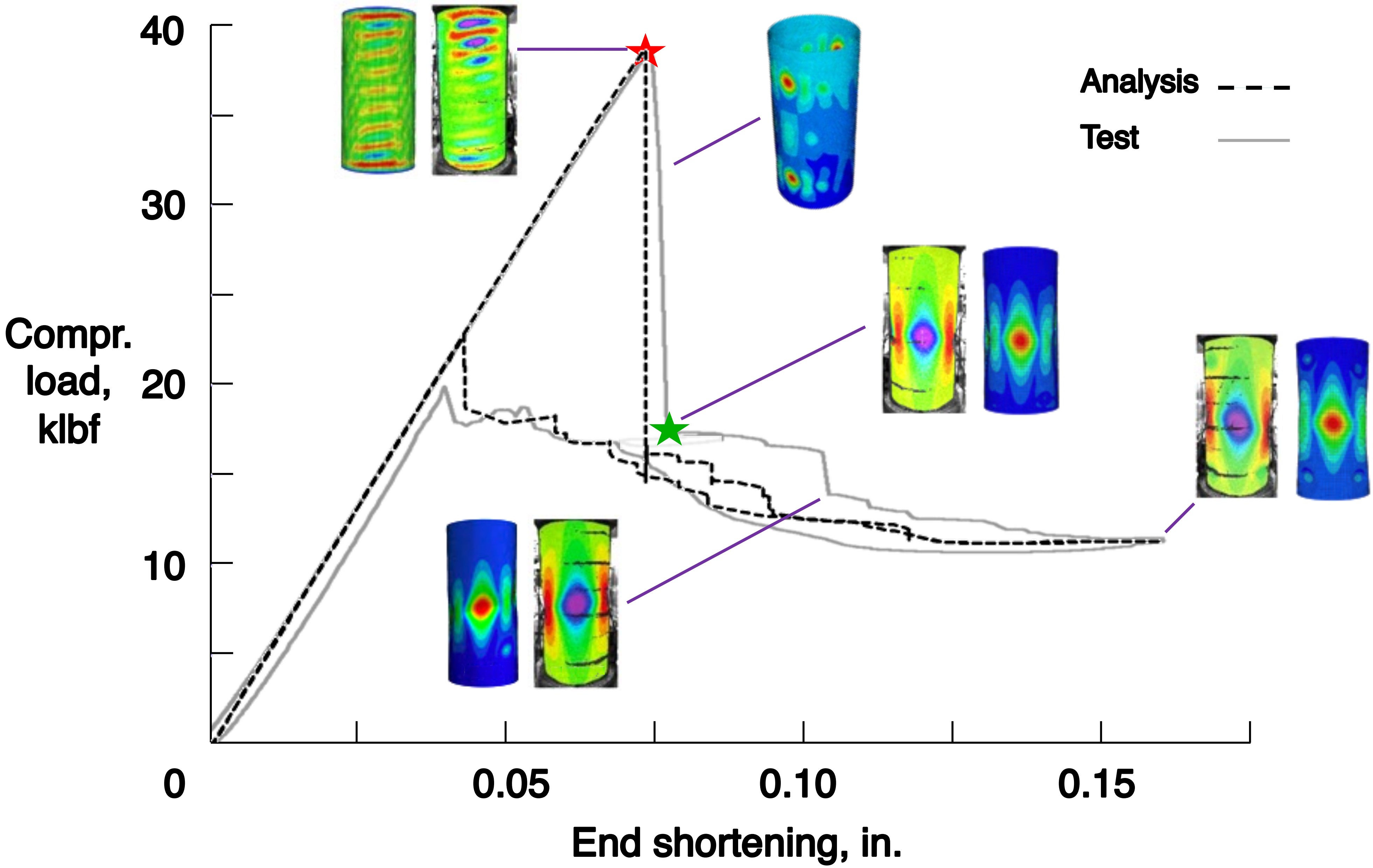
56 back-to-back strain gage pairs bonded to shell surfaces

Digital image correlation systems also used to image shells during tests

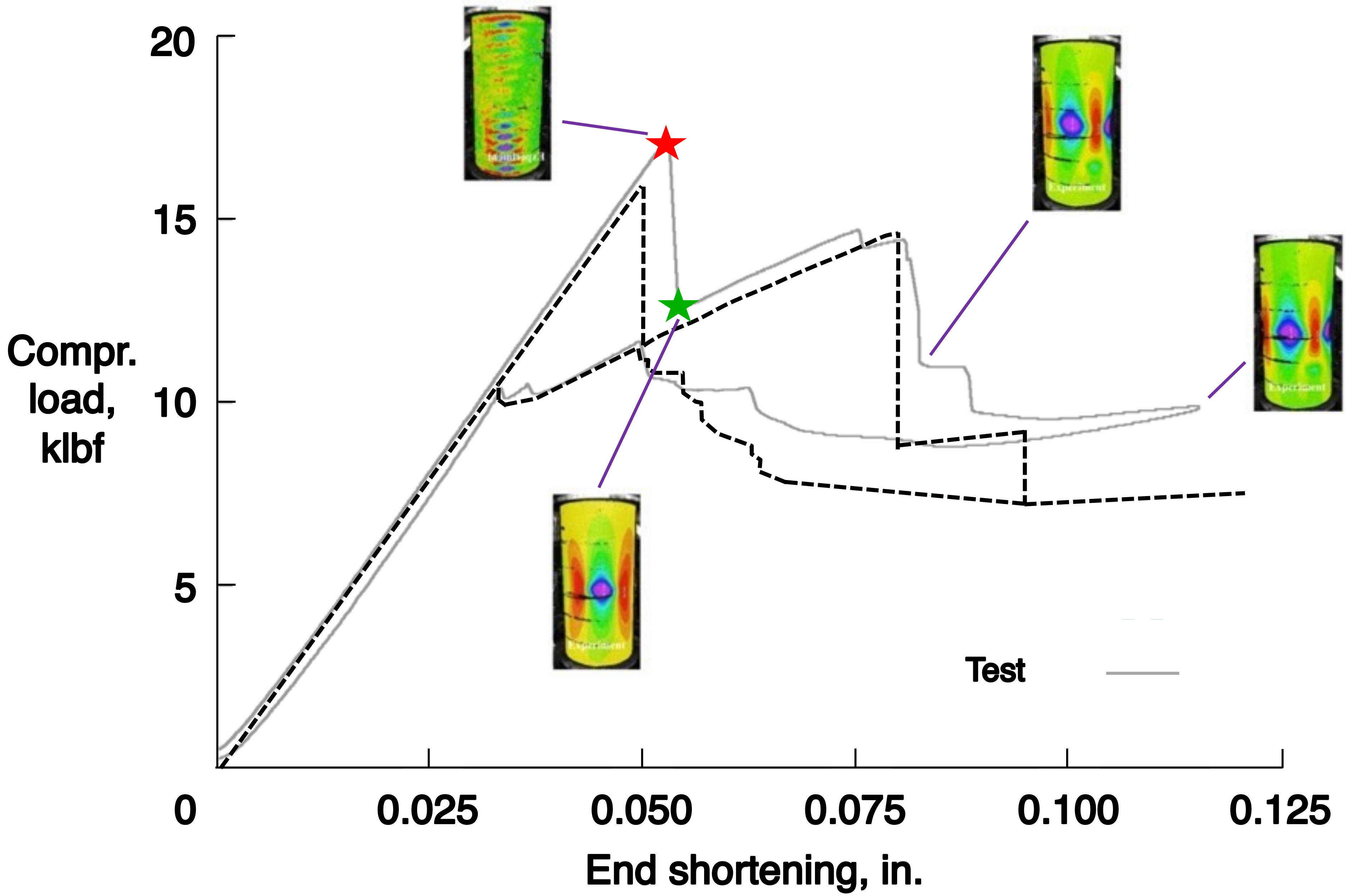
Shell with Overlaps Compression Test



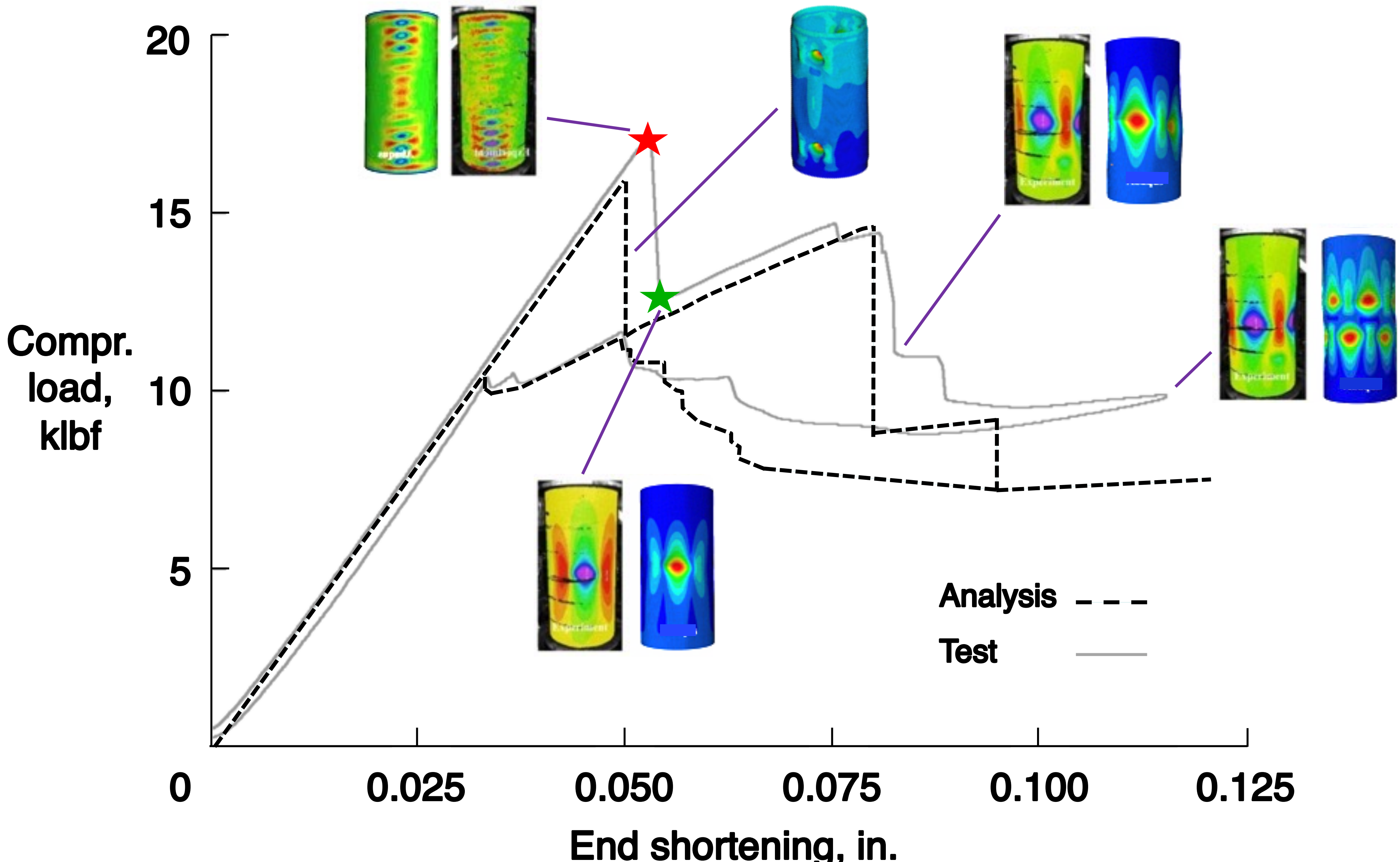
Shell with Overlaps Nonlinear FEA



Shell w/o Overlaps Compression Test



Shell w/o Overlaps Nonlinear FEA



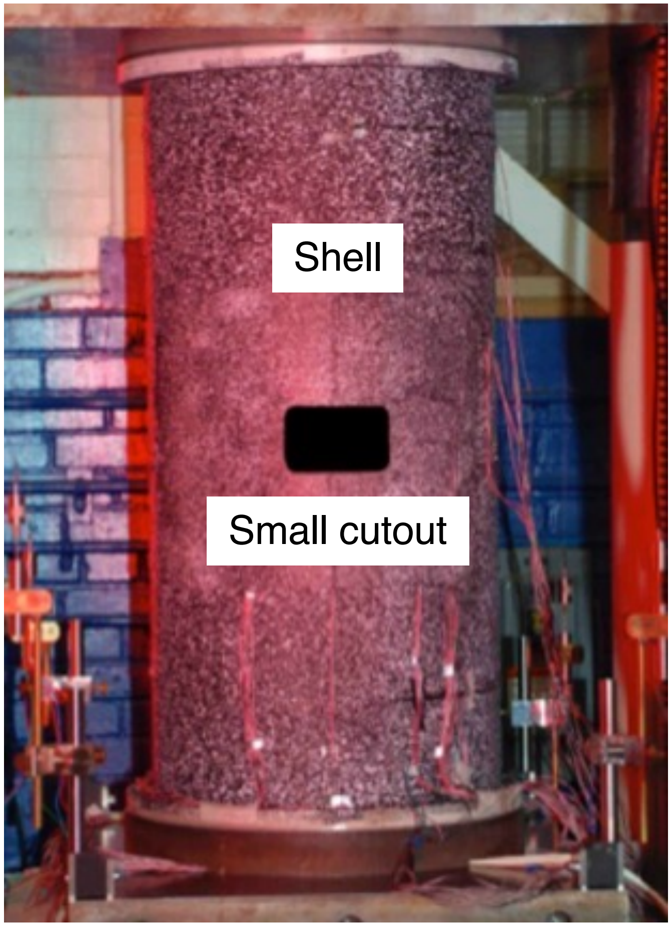
Six Shell Configurations Tested and Analyzed

	Includes Cutouts?		
Shell with Overlaps	***No***	***Small***	***Large***
Shell w/o Overlaps	***No***	***Small***	***Large***
	⇑ **Baseline**		

Shells with Small Cutouts
Testing and Analyses

Description of Small Cutouts

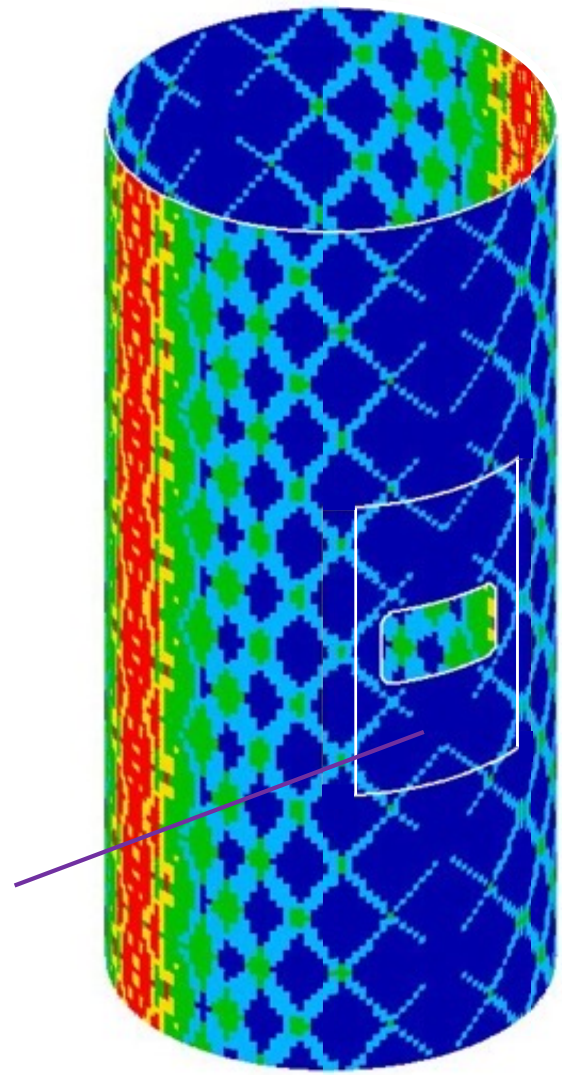
- Small cutouts scaled to represent passenger doors on commercial aircraft fuselage barrel
- Cutouts are 3 in. (axial) x 4.88 in. (circumferential), with 0.50-in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup ~ $[\pm 45]_{2s}$)
- 20 back-to-back strain gage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



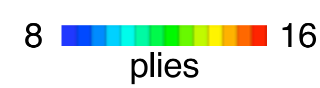
Shell with small cutout installed in test stand

Finite Element Models

- ABAQUS analyses performed
  - Geometrically nonlinear analyses
  - Axial end shortening applied / removed
- S4R shell elements used
  - Acreage elements ~ 0.25 in.-square
  - Each constant thickness and fiber angles
  - Measured IM7/8552 material properties and predicted ply thickness
- Refined FE mesh around small cutouts
  - Parametric mesh refinement studied
  - Refined elements surrounding cutout are ~ 0.083 in.-square (1/3 nominal)
  - Refinements have same thickness and layup as parent element



Shell with overlaps laminate thicknesses



Finite Element Models (2)

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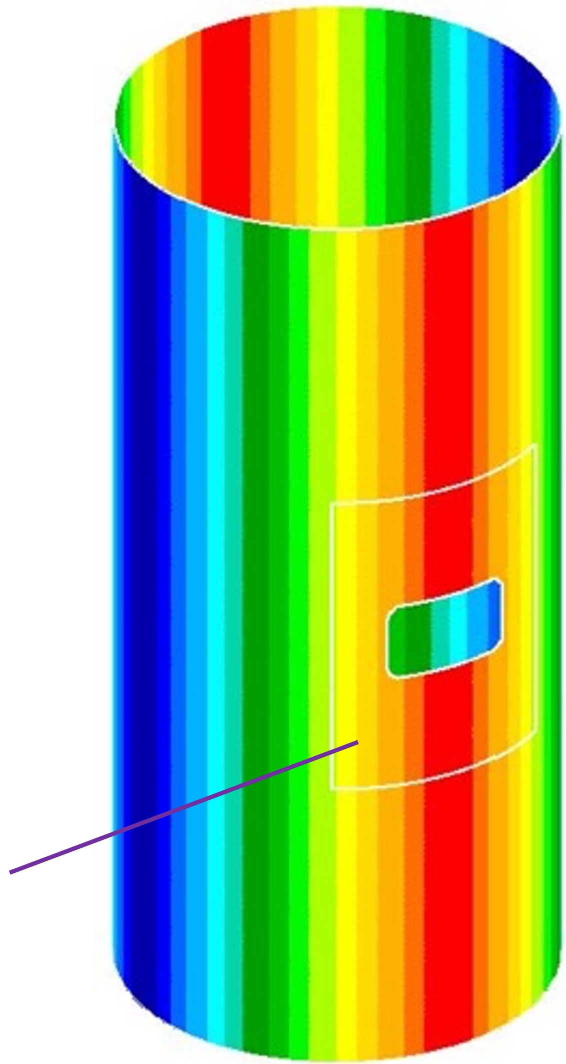


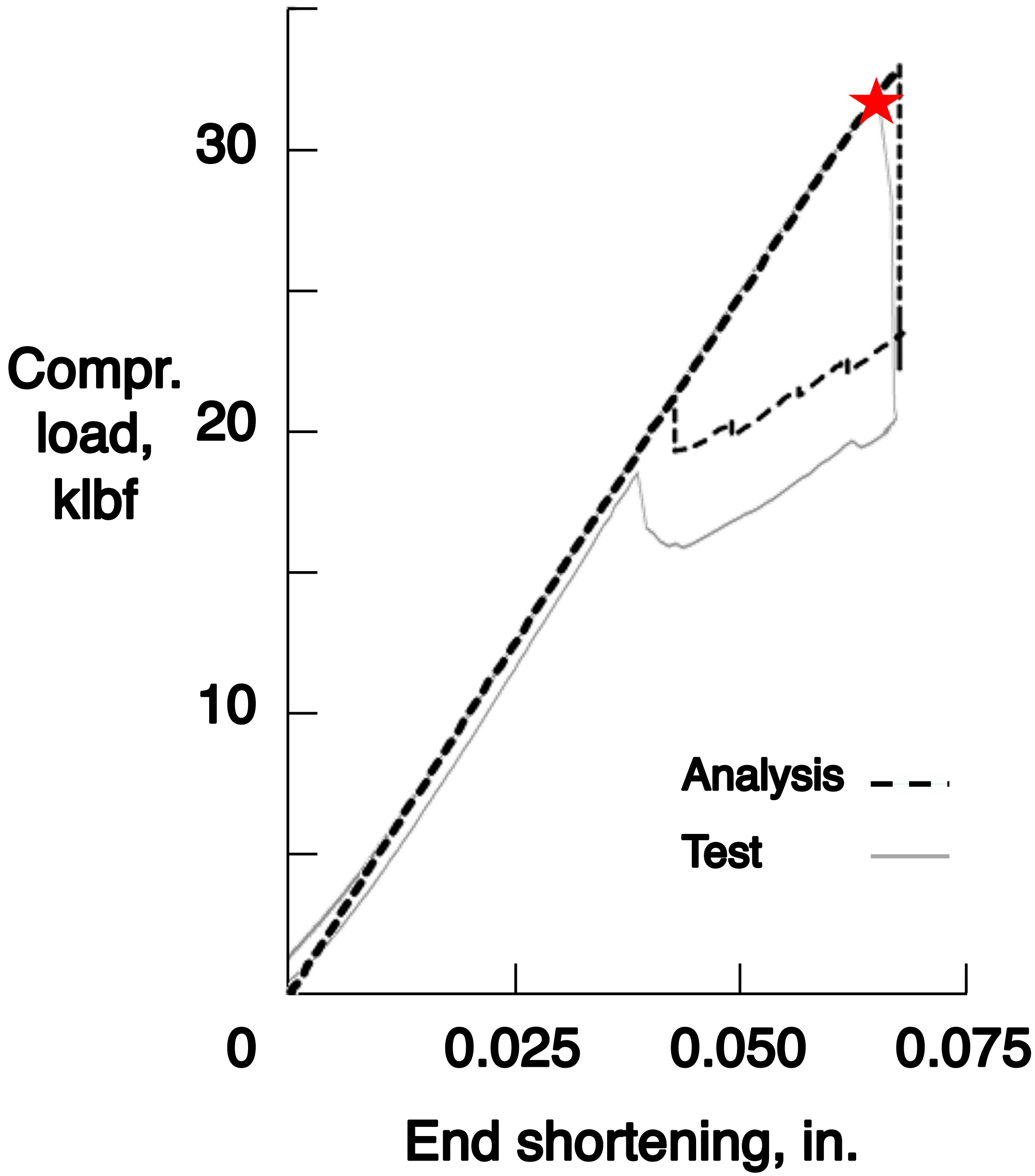
Steered ply 3 fiber orientation angles

Shells with Small Cutouts

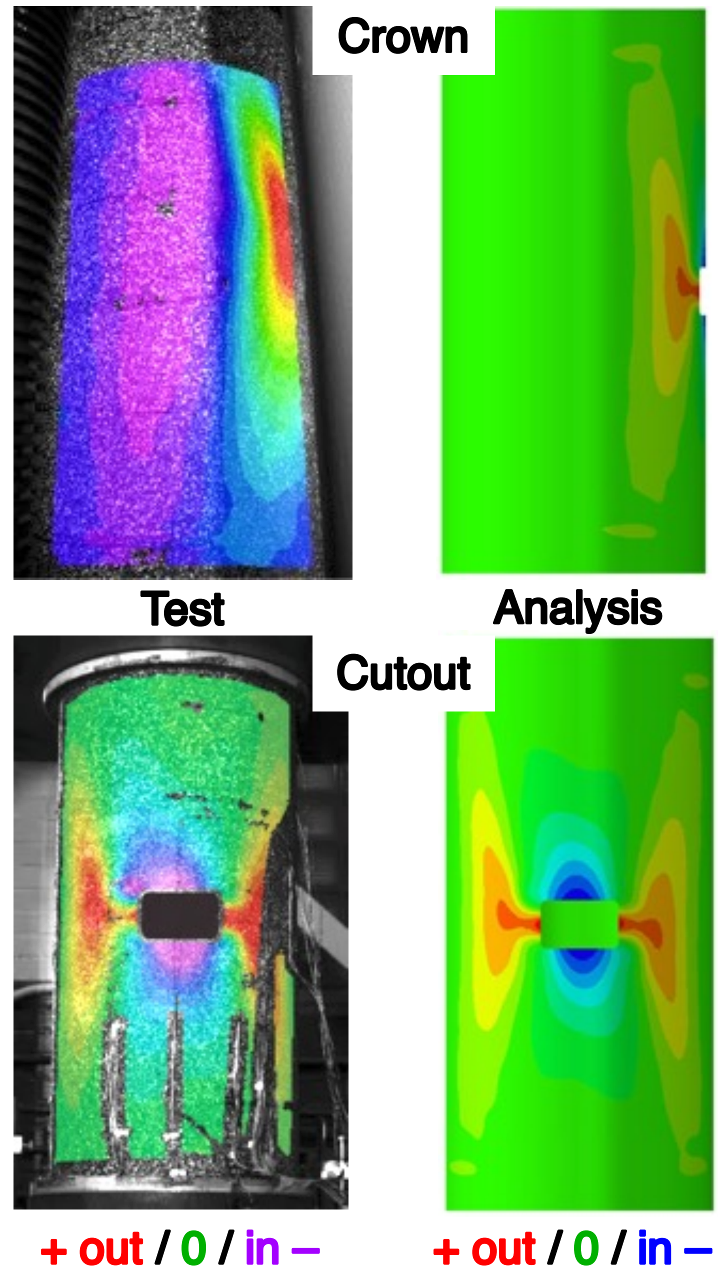
Shell with Overlaps

Shell with Overlaps Test and FEA

(Global buckling results shown)

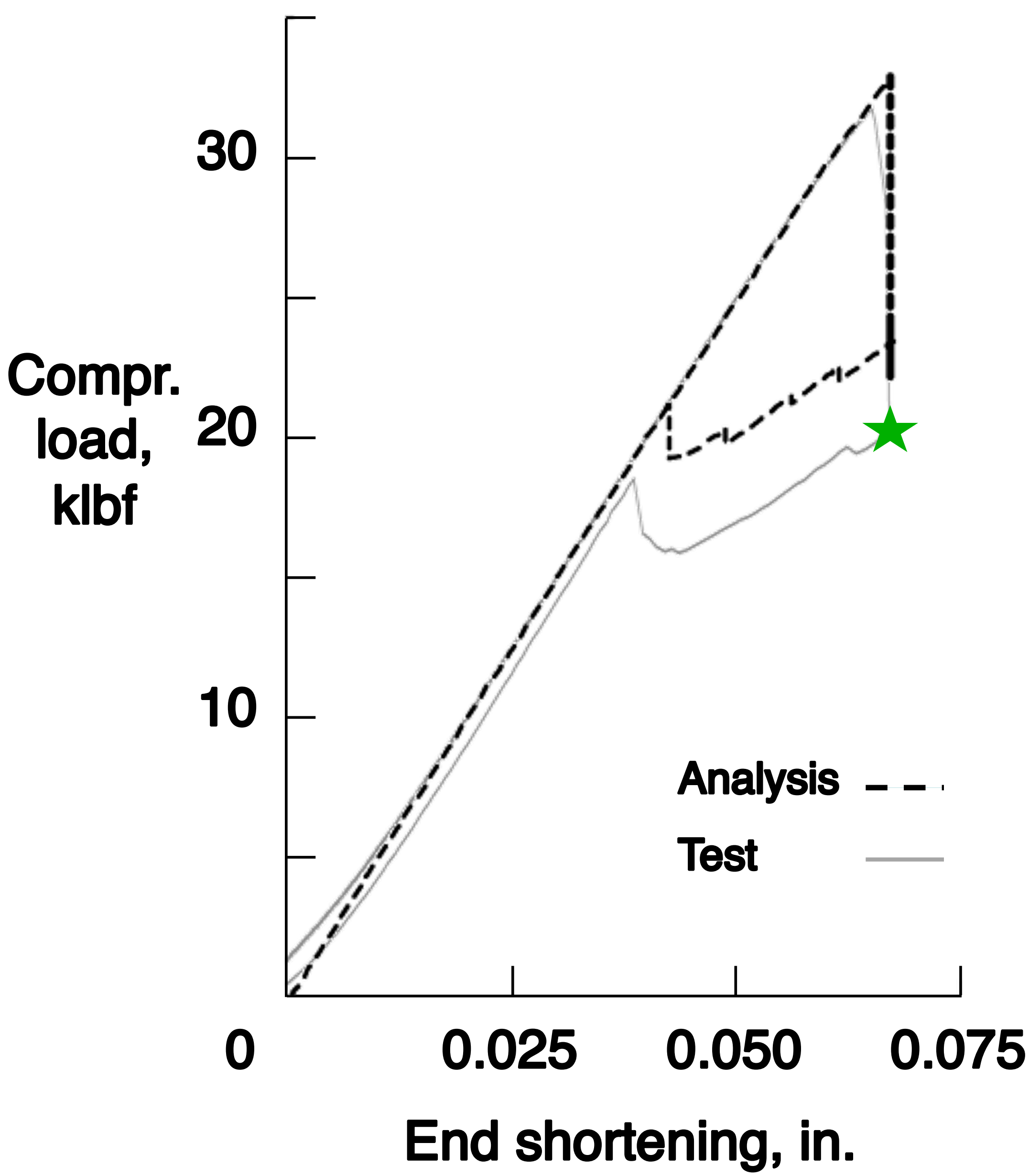


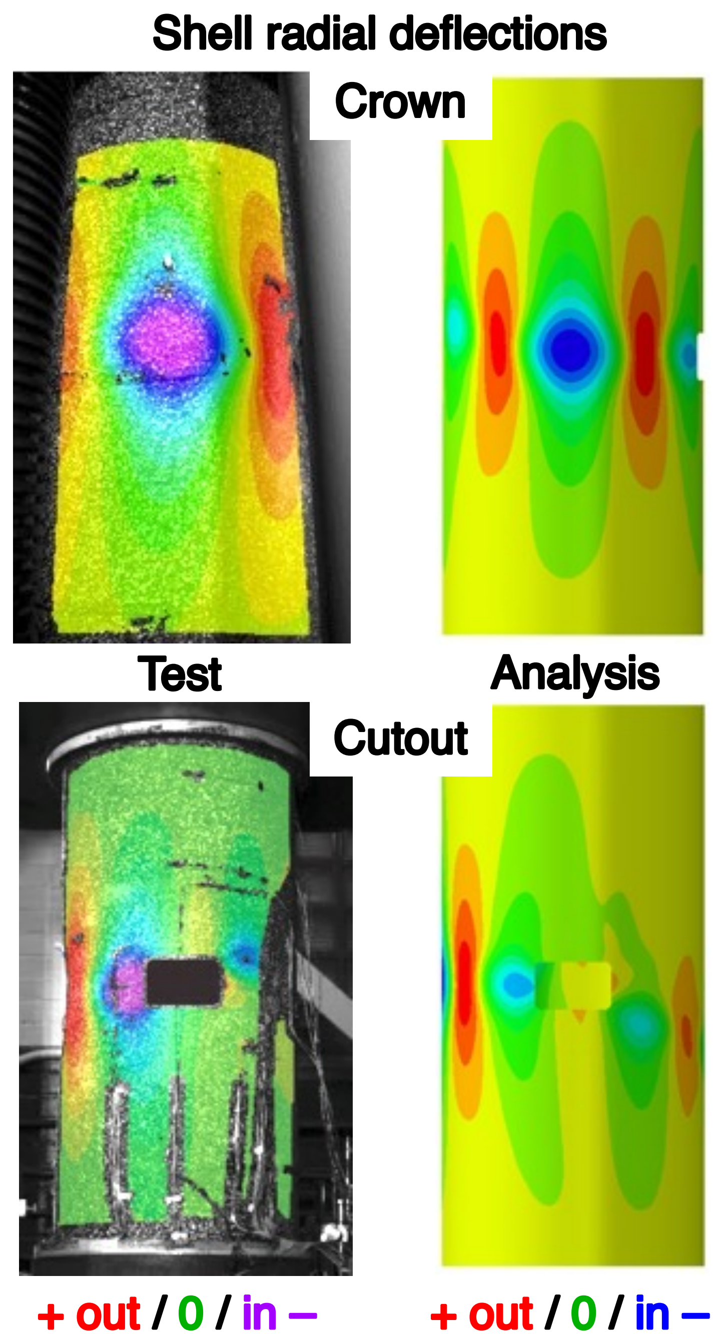
Shell radial deflections



Shell with Overlaps Test and FEA (2)

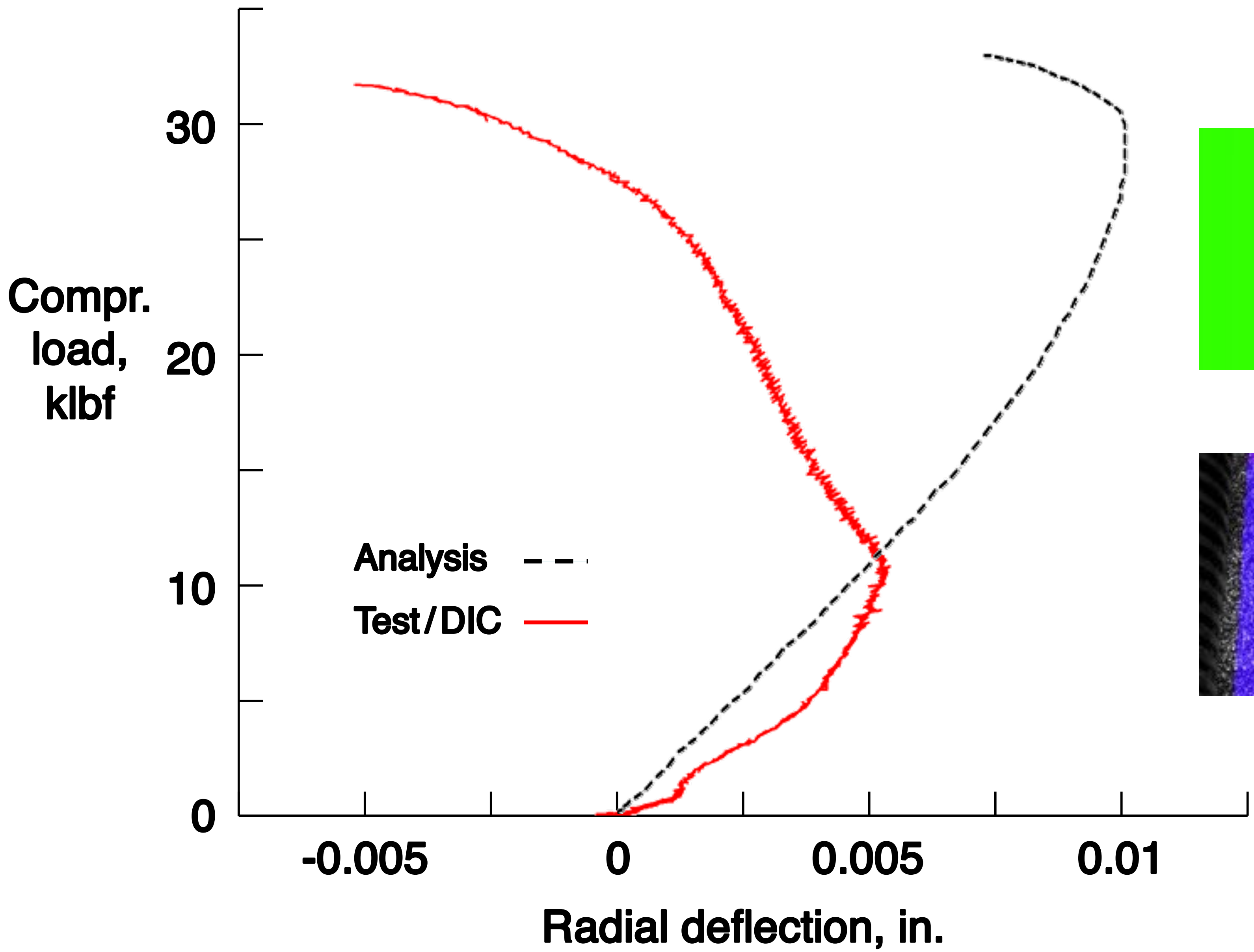
(Postbuckling results shown)

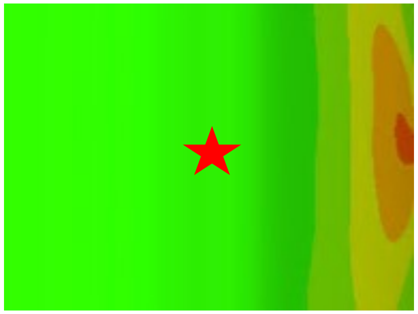




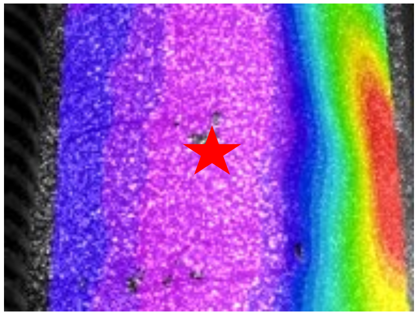
Shell with Overlaps Crown & Keel Deflections

(Prebuckling results shown)





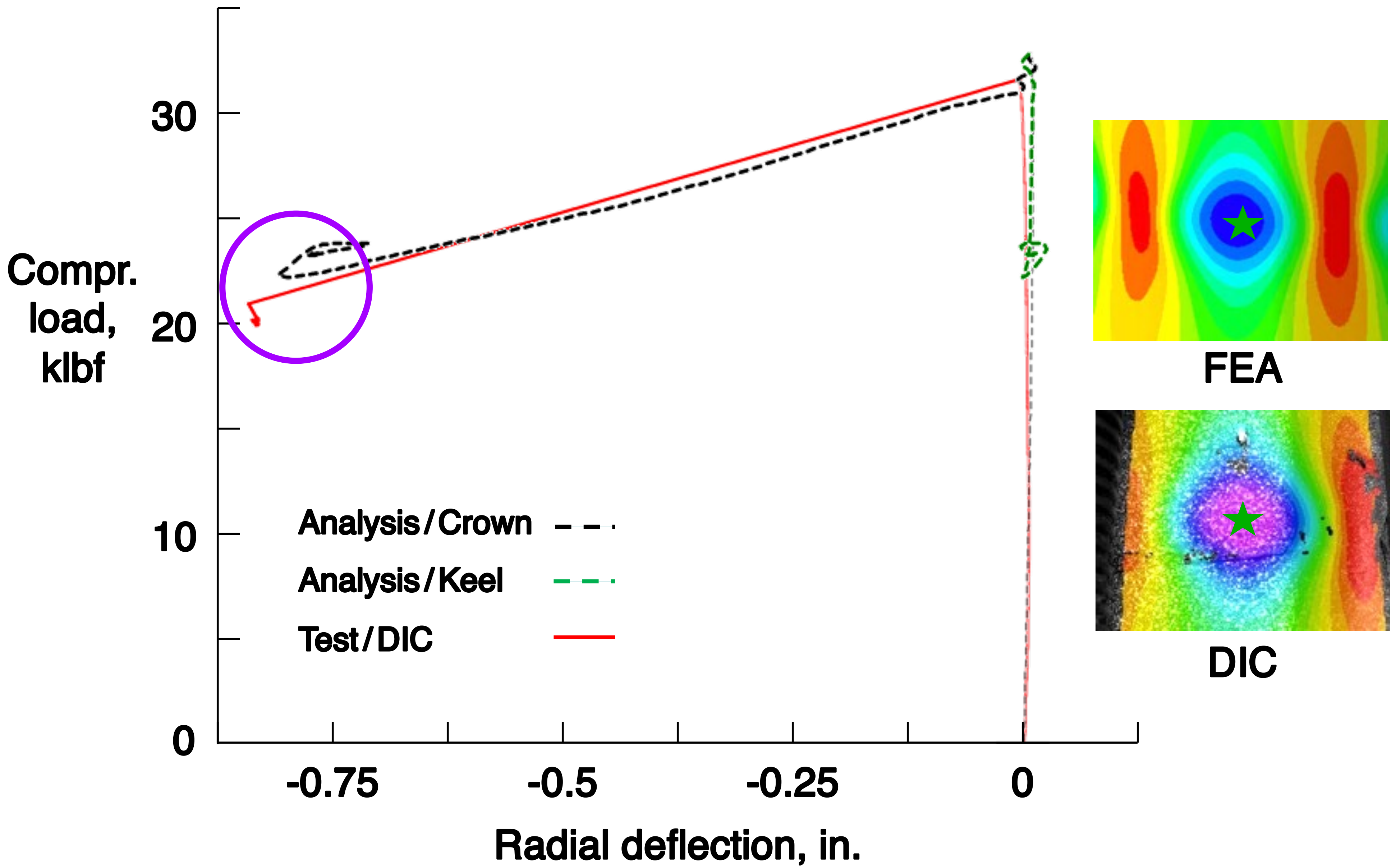
FEA



DIC

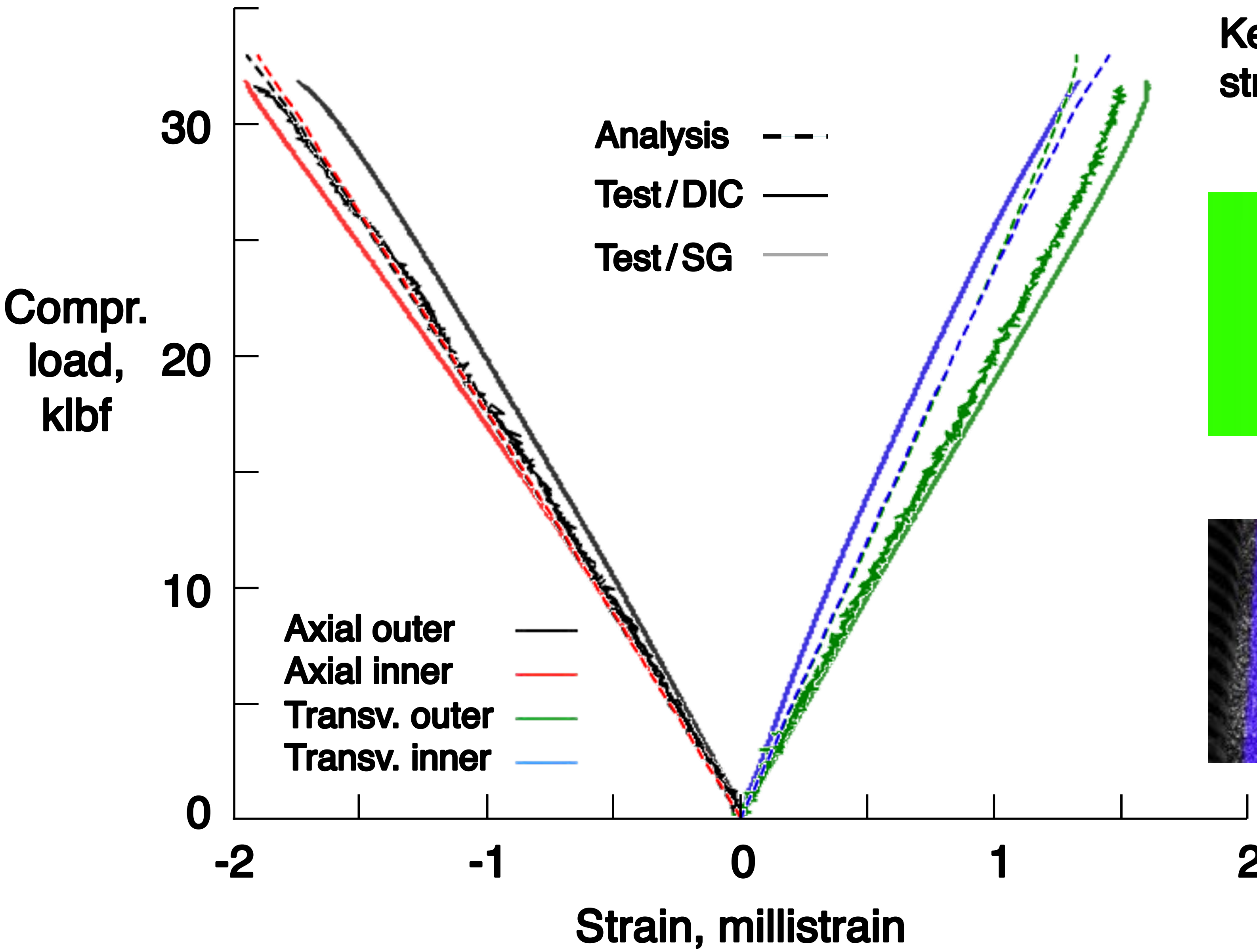
Shell with Overlaps Crown & Keel Defl's (2)

(Postbuckling results shown)

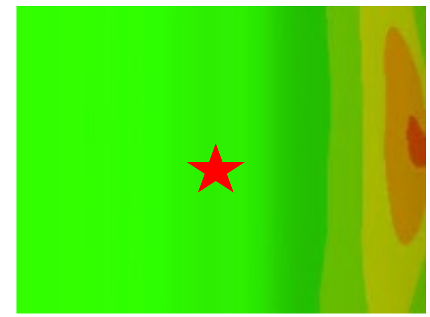


Shell with Overlaps Crown Strains

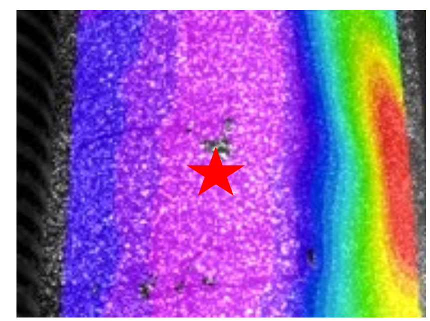
(Prebuckling results shown)



Keel prebuckling strains ~ equal



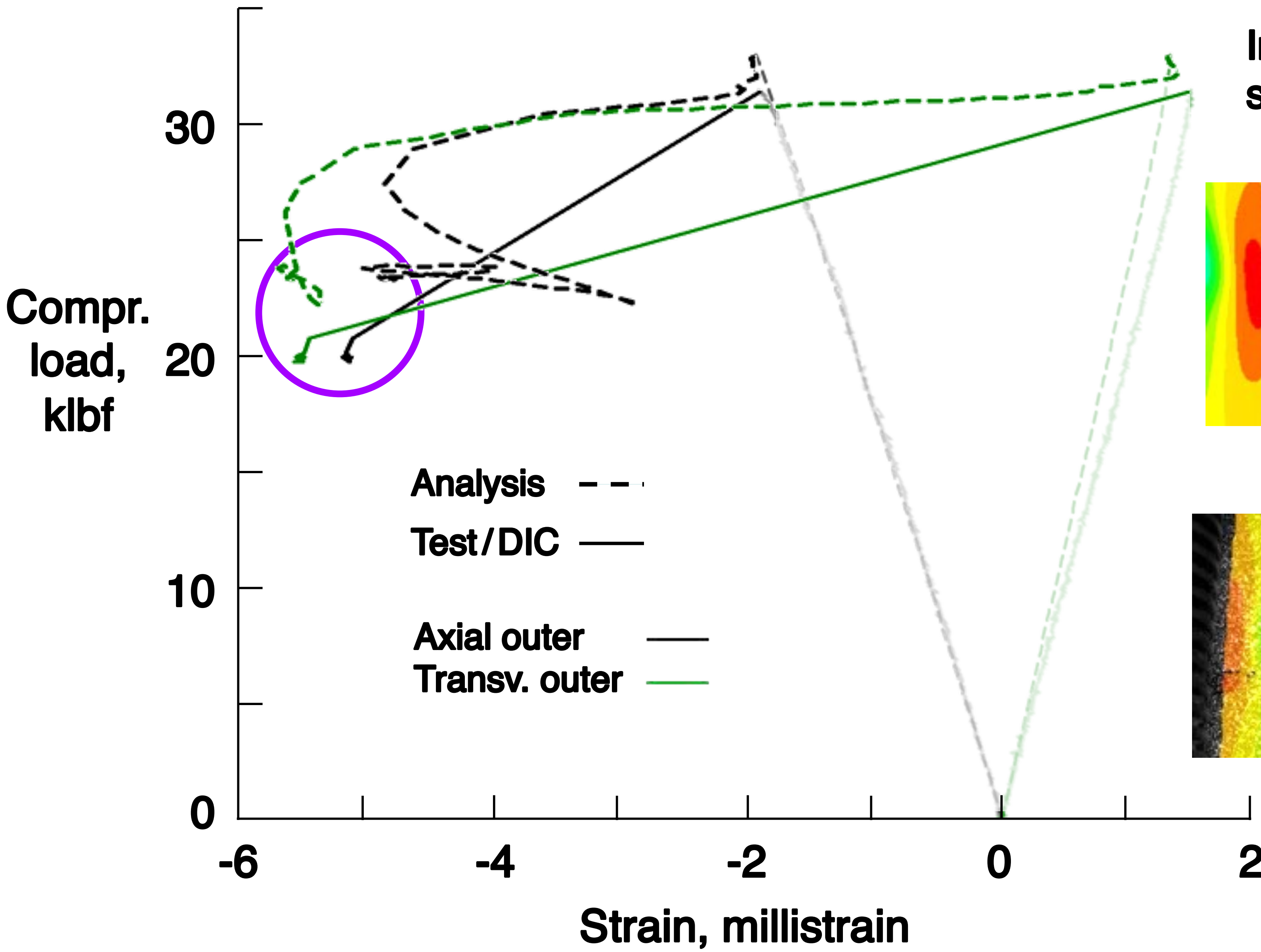
FEA



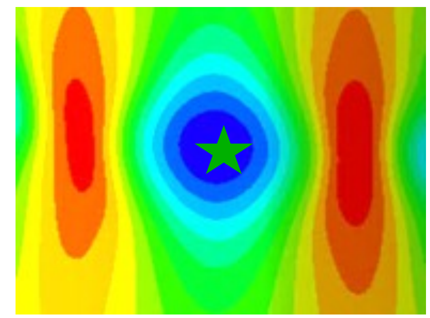
DIC

Shell with Overlaps Crown Strains (2)

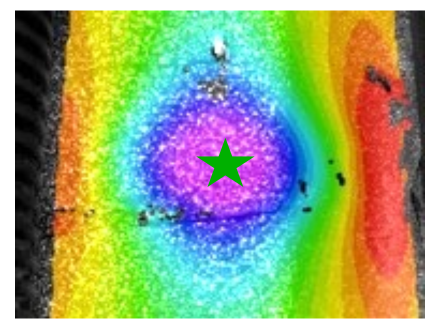
(Postbuckling results shown)



Inner surface strains not shown



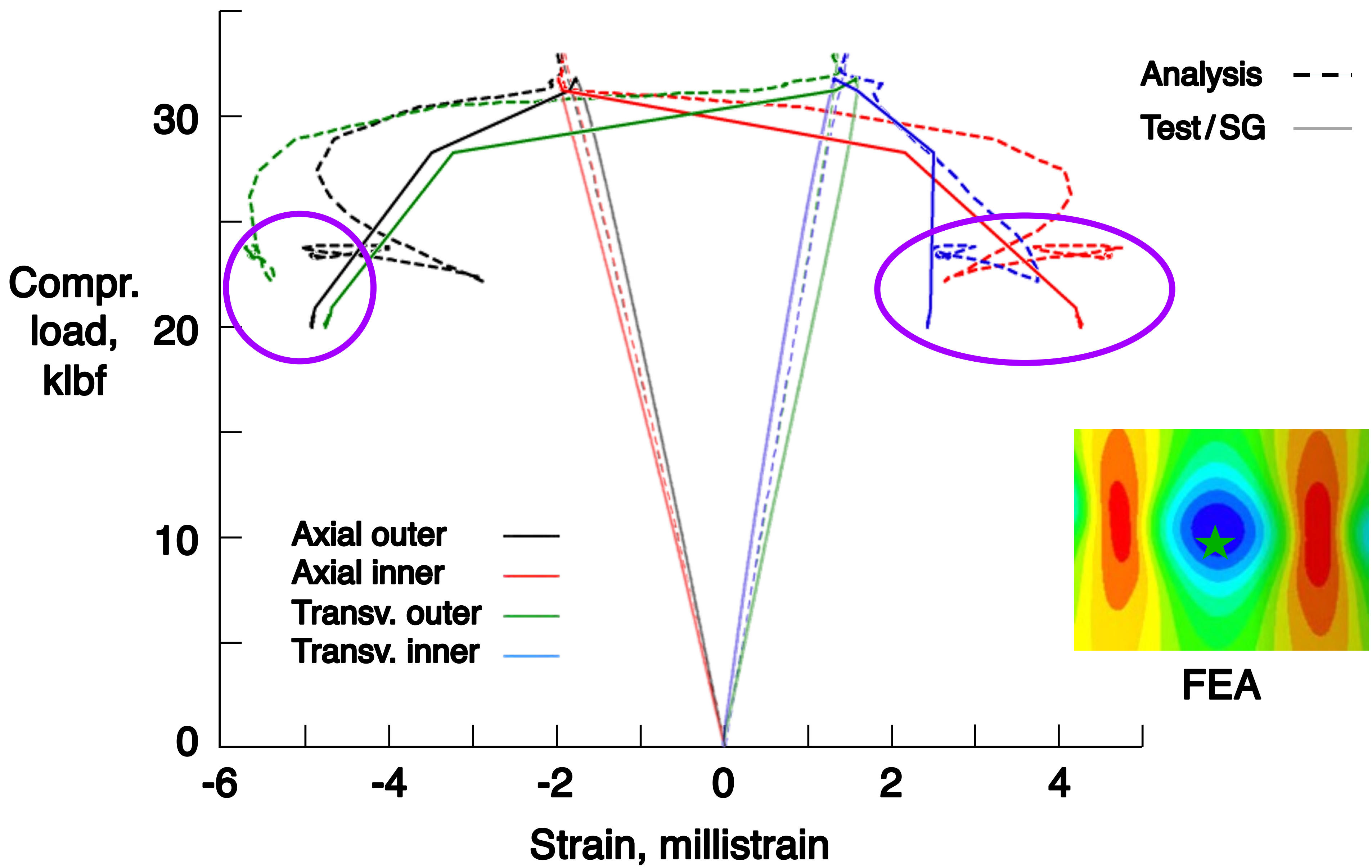
FEA



DIC

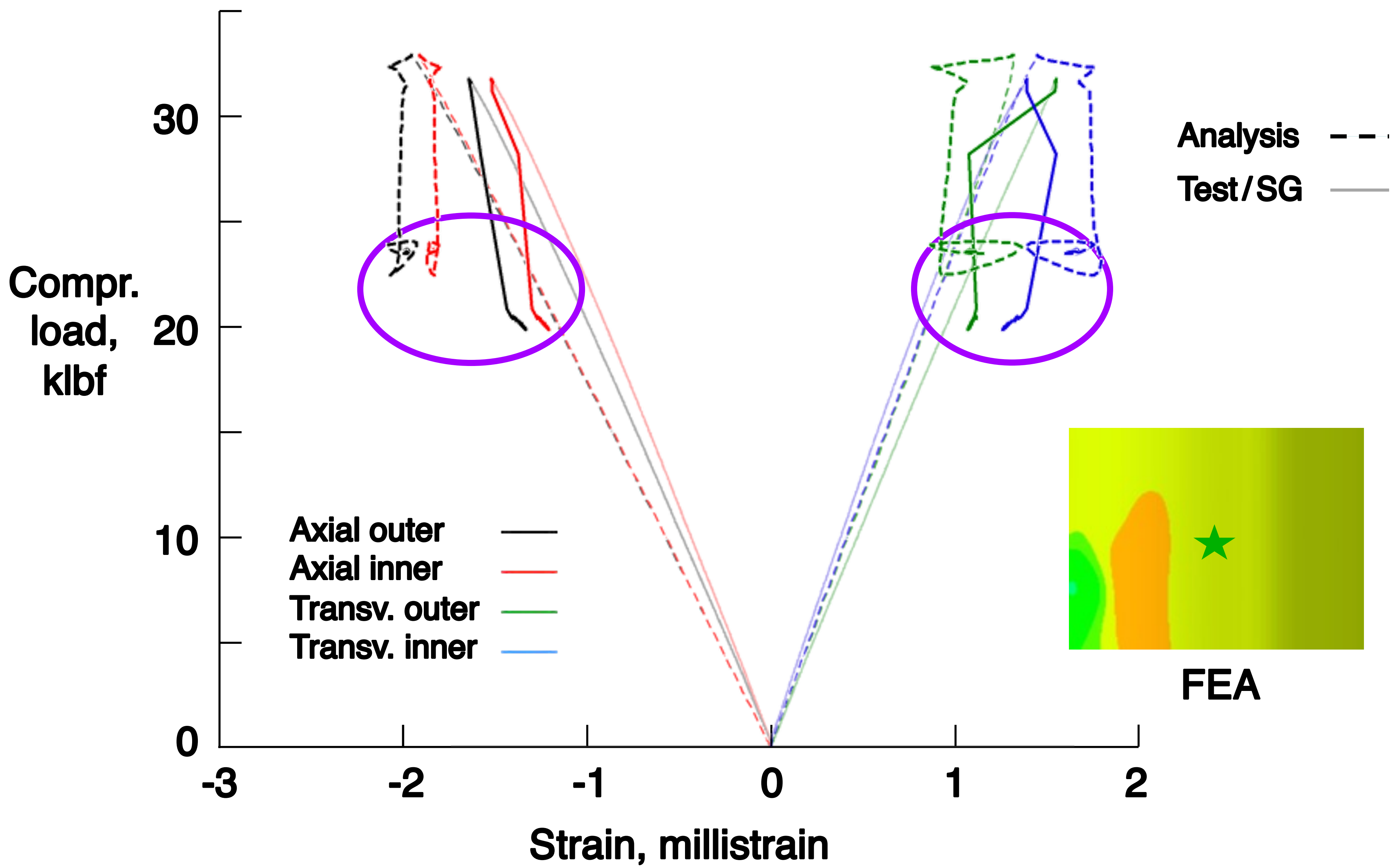
Shell with Overlaps Crown Strains (3)

(Postbuckling results shown)



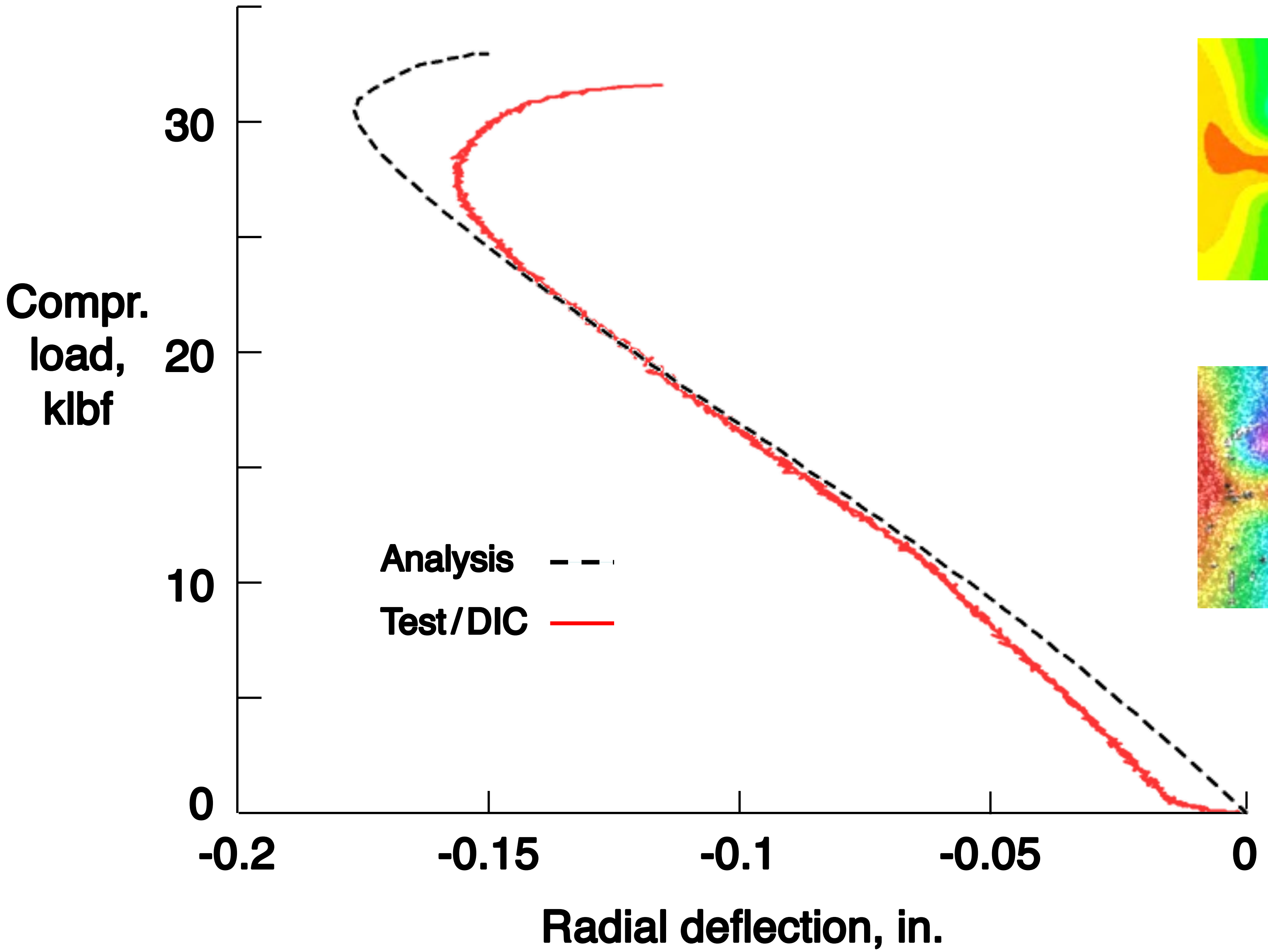
Shell with Overlaps Keel Strains

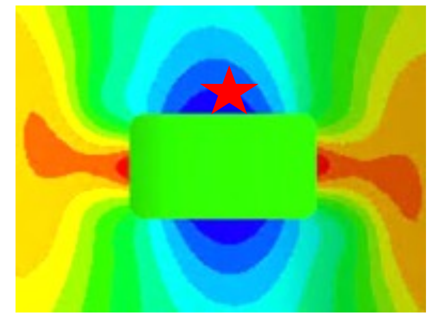
(Postbuckling results shown)



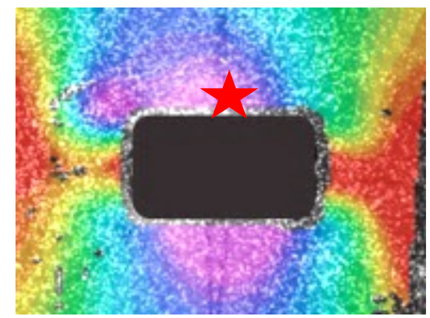
Shell with Overlaps Cutout Top

(Prebuckling results shown)





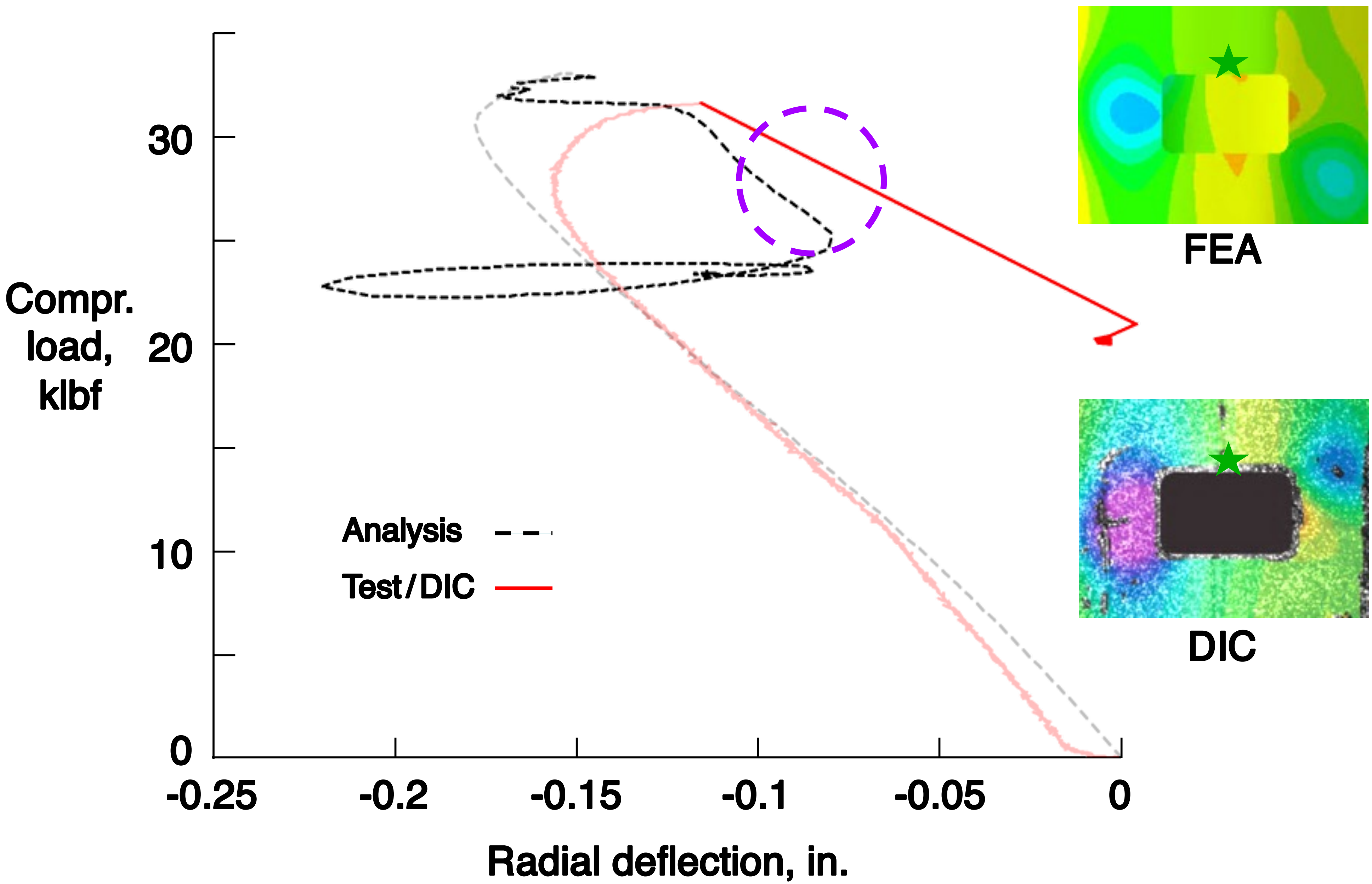
FEA



DIC

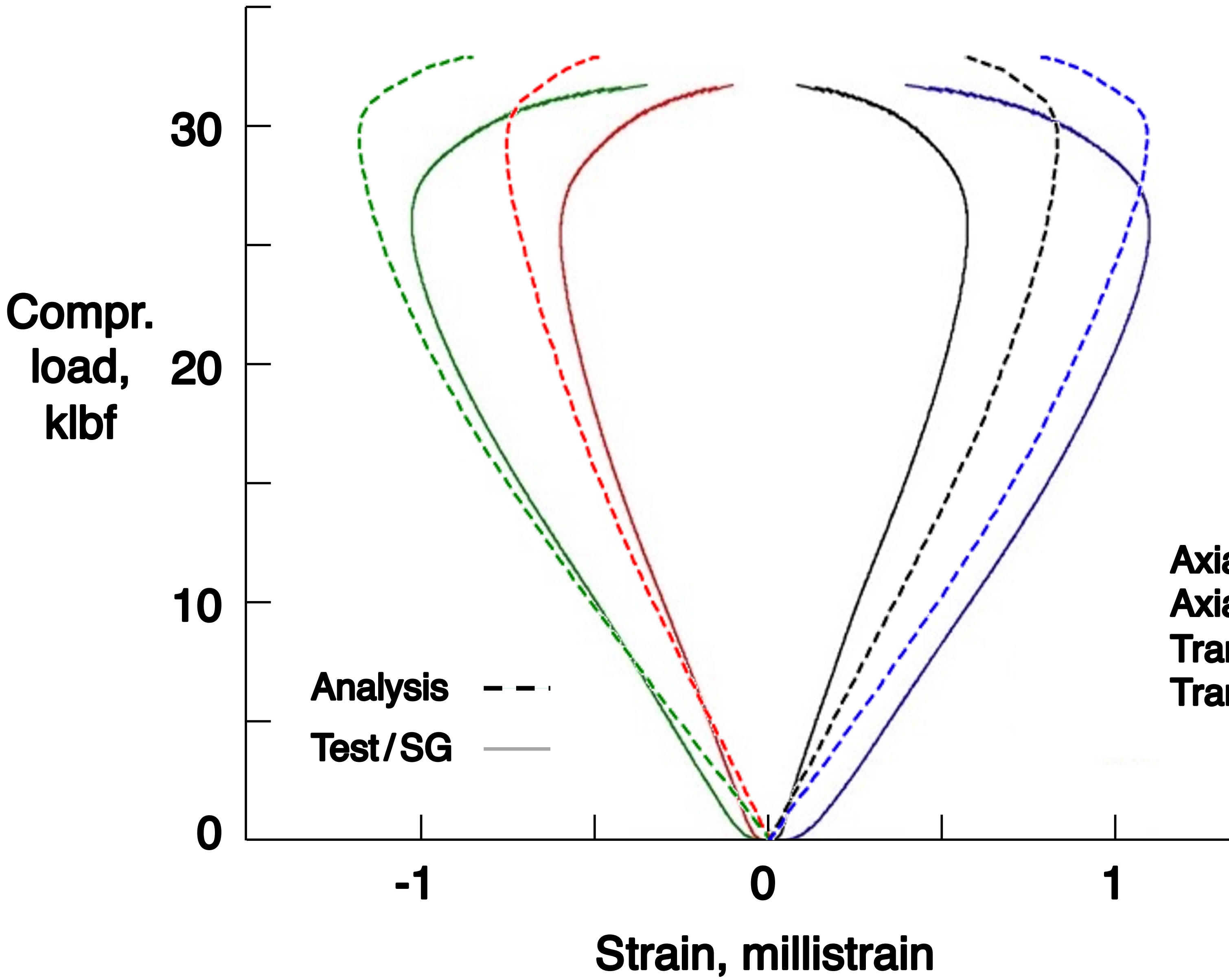
Shell with Overlaps Cutout Top (2)

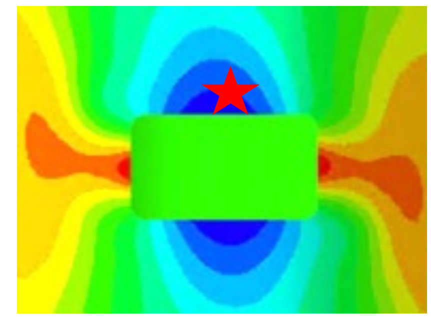
(Postbuckling results shown)



Shell with Overlaps Cutout Top

(Prebuckling results shown)

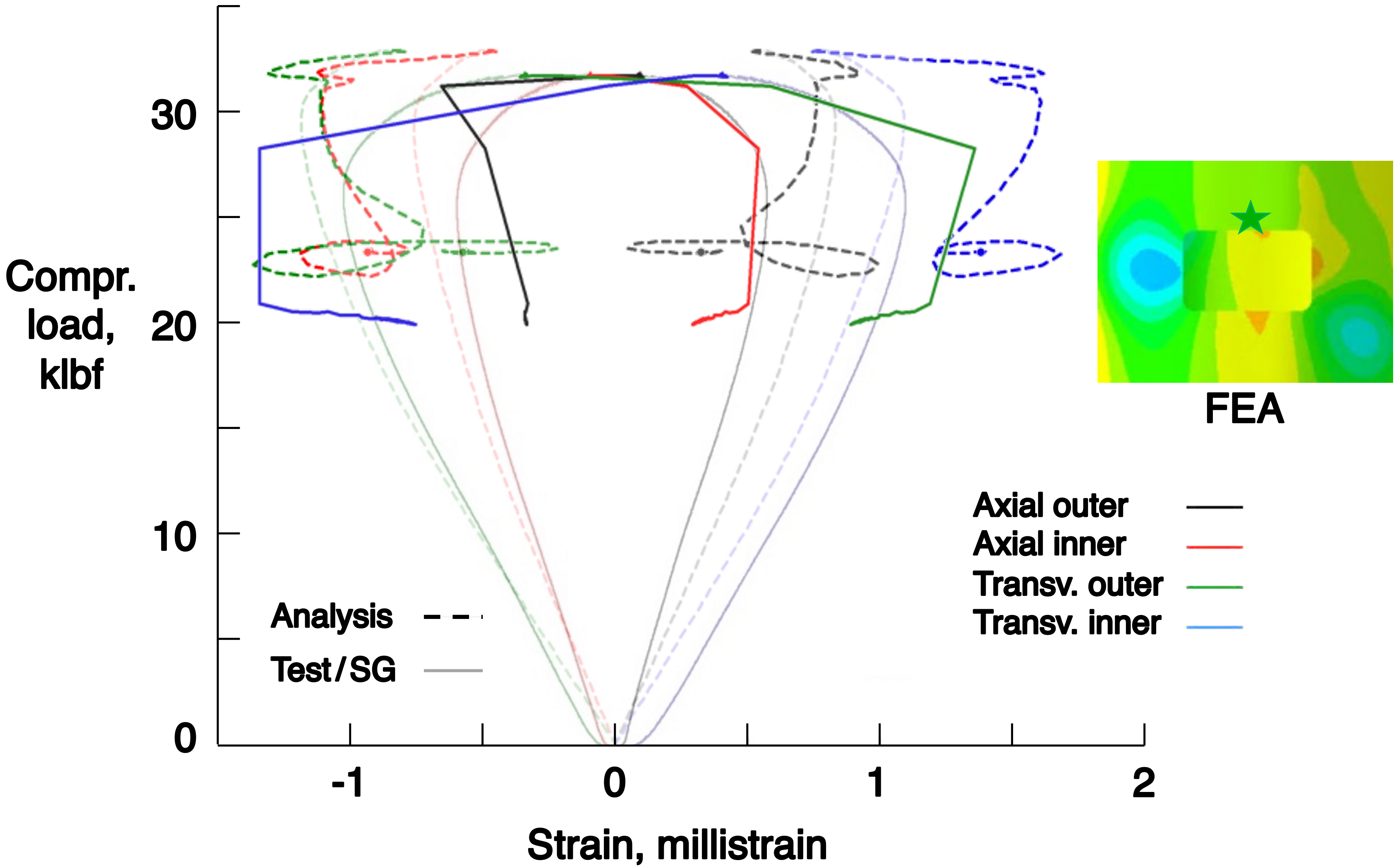




FEA

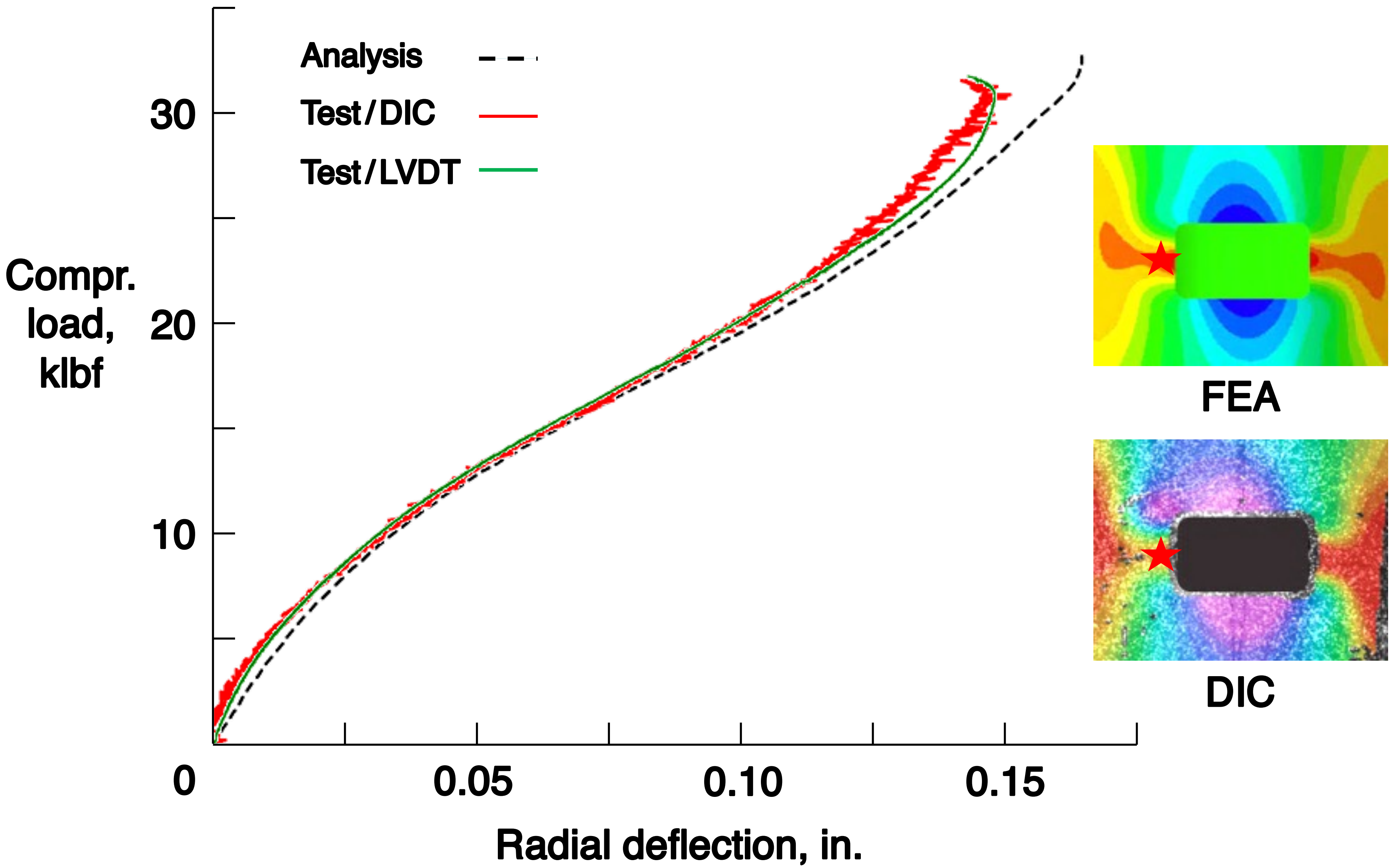
Shell with Overlaps Cutout Top (2)

(Postbuckling results shown)



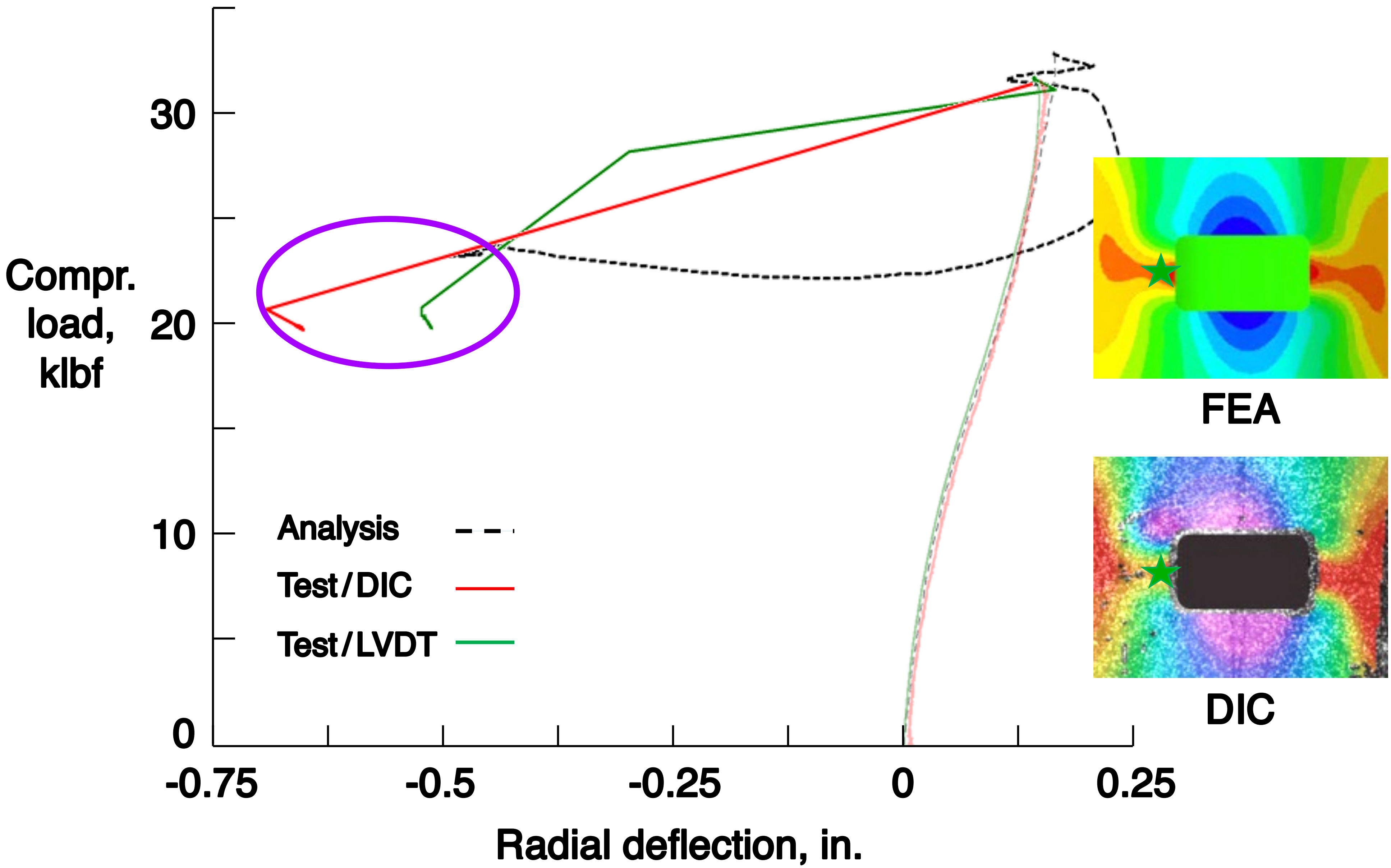
Shell with Overlaps Cutout LH Side

(Prebuckling results shown)



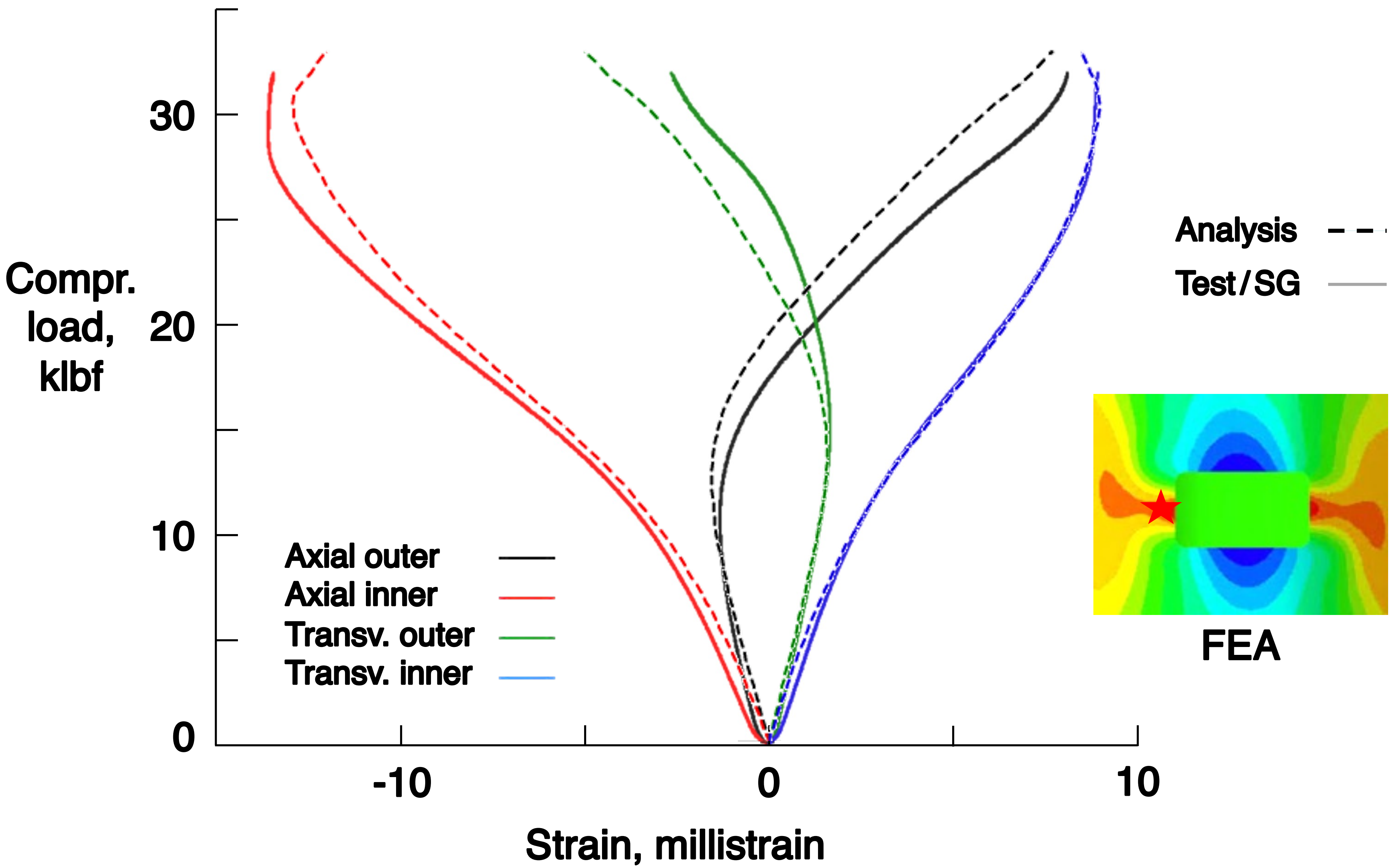
Shell with Overlaps Cutout LH Side (2)

(Postbuckling results shown)



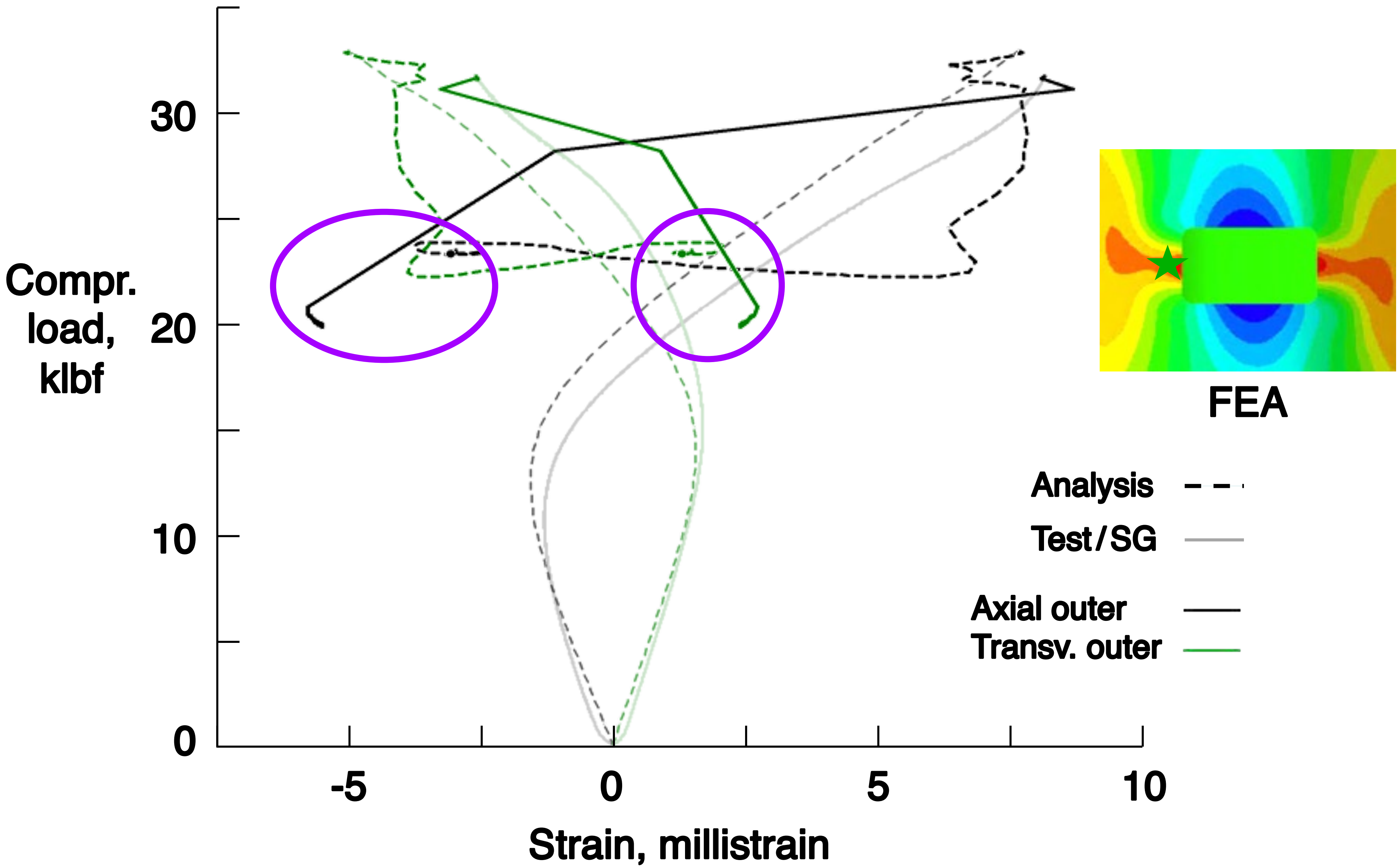
Shell with Overlaps Cutout LH Side

(Prebuckling results shown)



Shell with Overlaps Cutout LH Side (2)

(Postbuckling results shown)

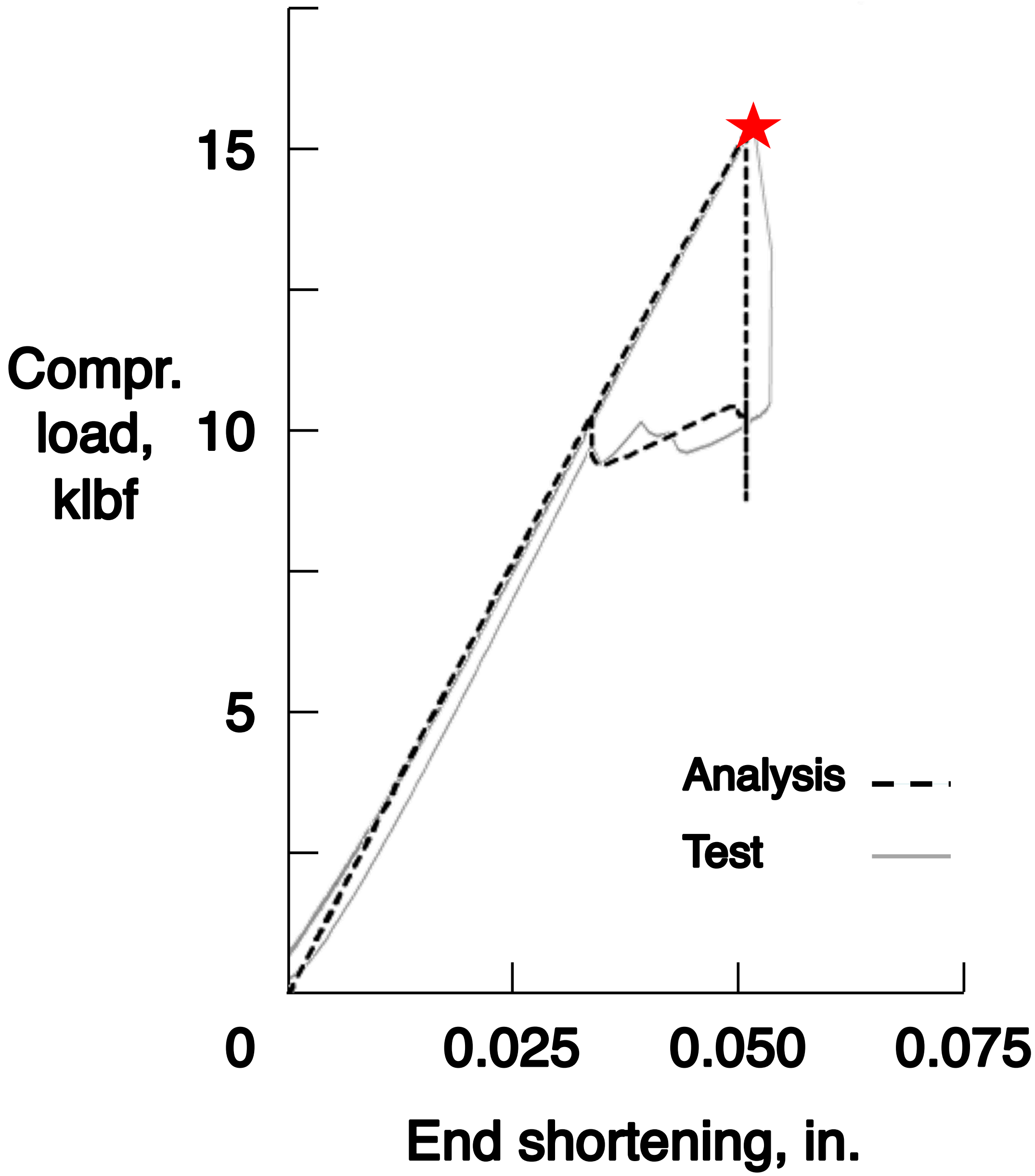


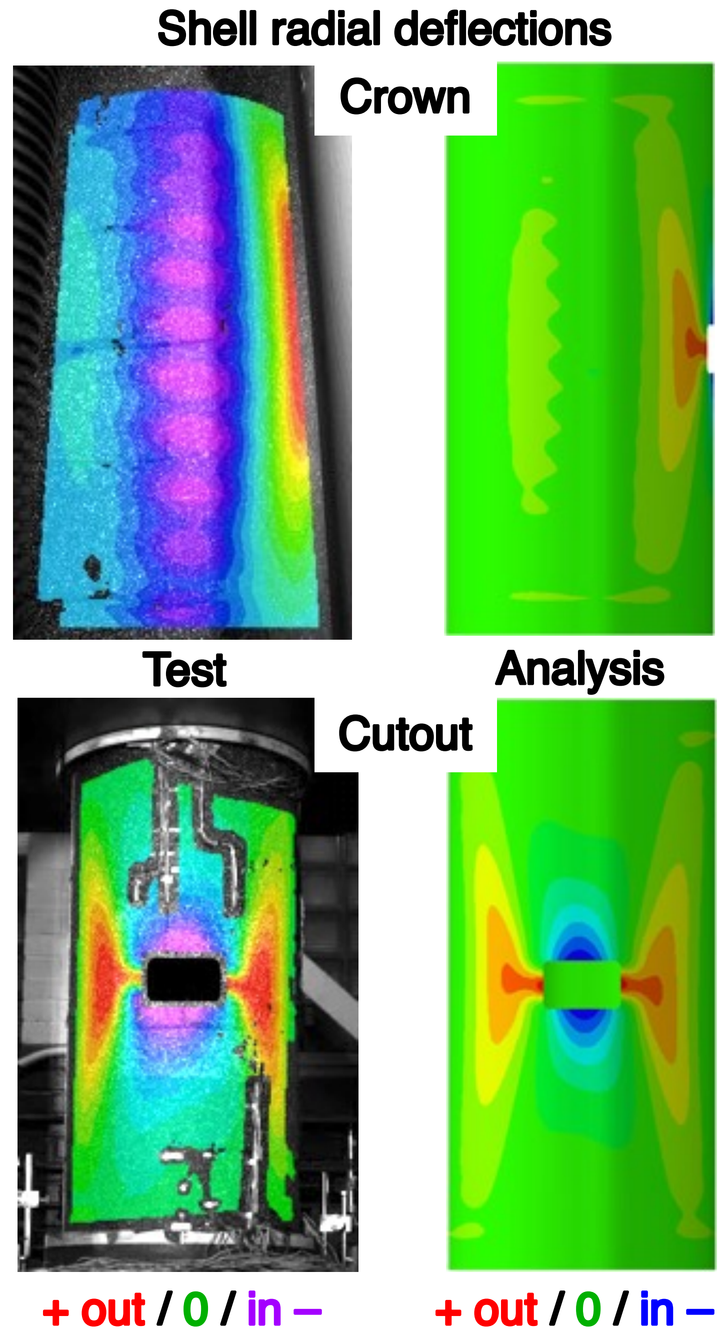
Shells with Small Cutouts

Shell w/o Overlaps

Shell w/o Overlaps Test and FEA

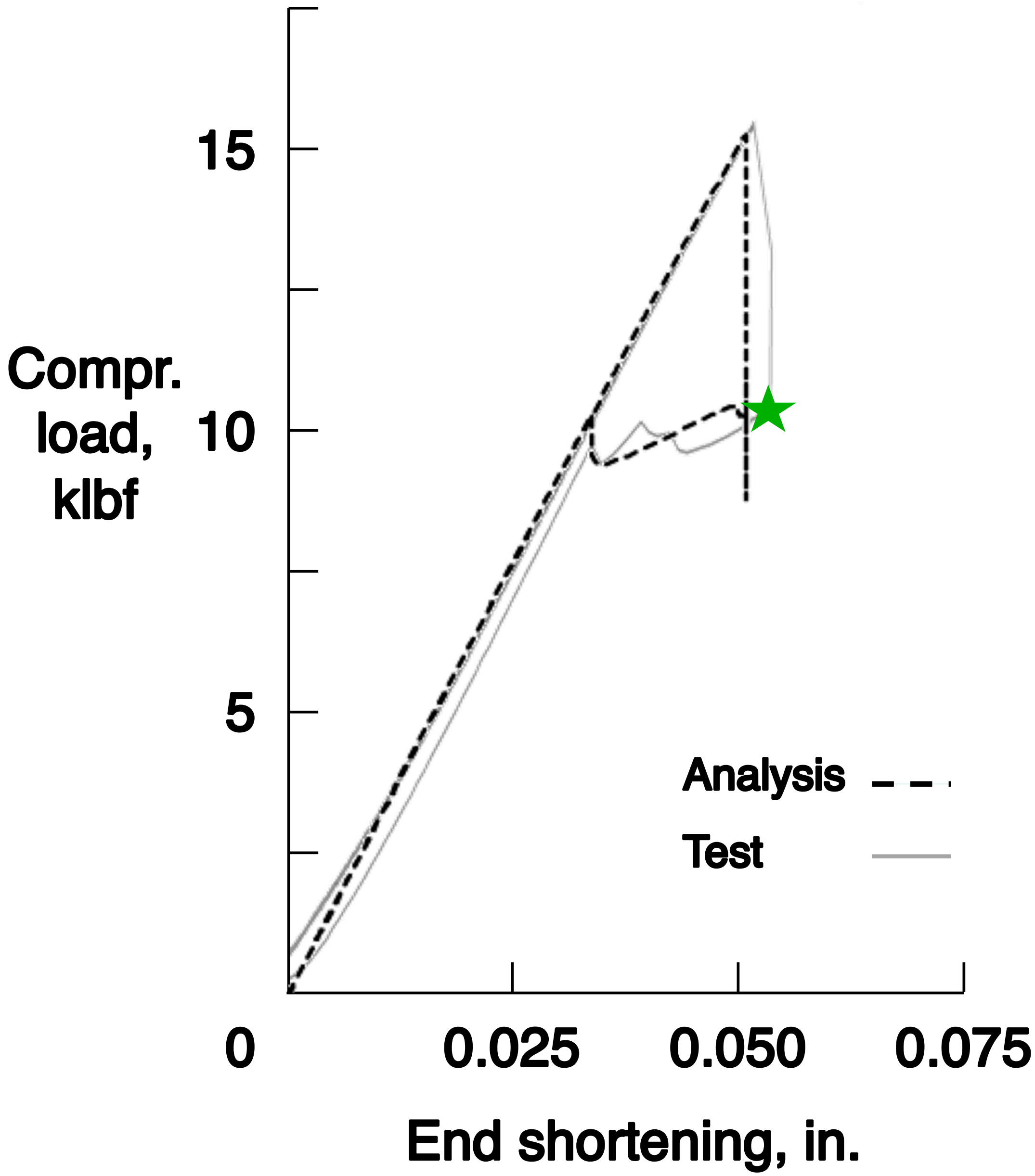
(Buckling results shown)

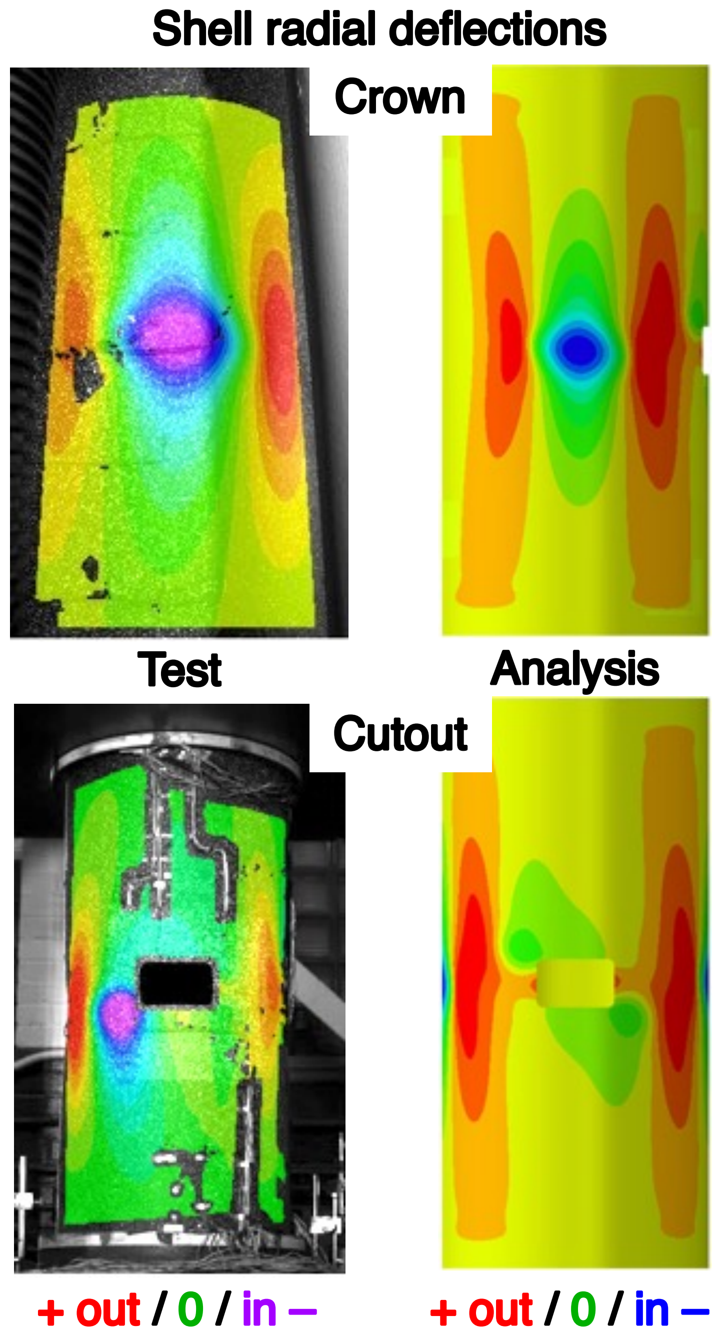




Shell w/o Overlaps Test and FEA (2)

(Postbuckling results shown)





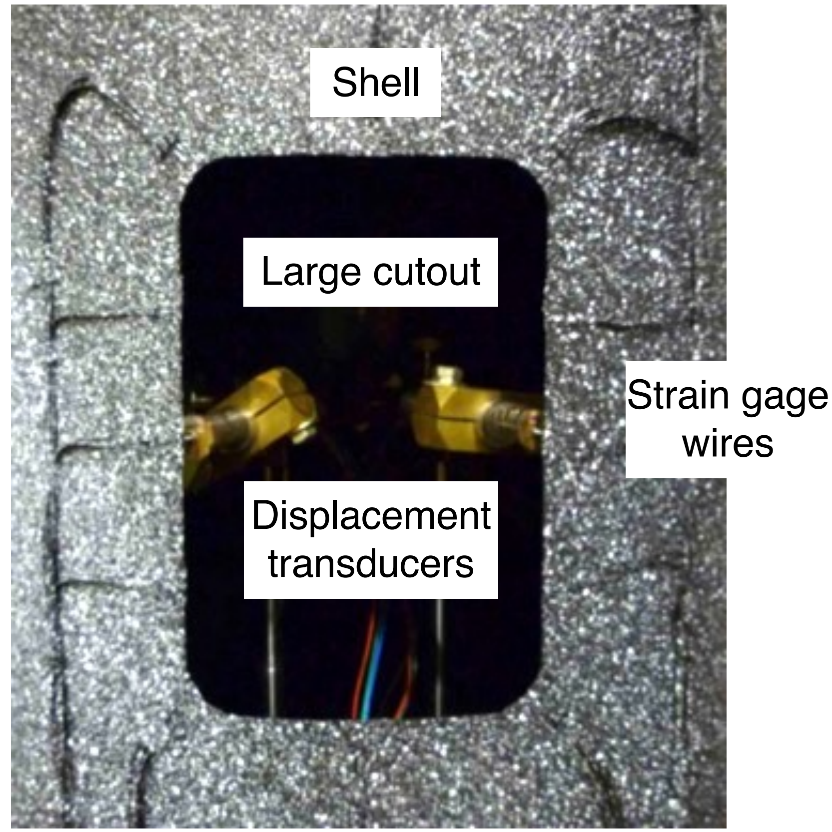
Results Summary

- Shells with small cutouts evaluated globally and at discrete locations
  - Crown/keel, cutout perimeter
- Loads, deflections and strains measured and computed using nonlinear finite element analyses
- Test-analysis correlation assessed during prebuckling, to global buckling, to stable postbuckling
  - Digital image correlation
  - Displacement transducer
  - Strain gage
- Excellent to very good correlation between FEA and test through buckling, and very good to good correlation at stable postbuckling

Shells with Large Cutouts Testing and Analyses

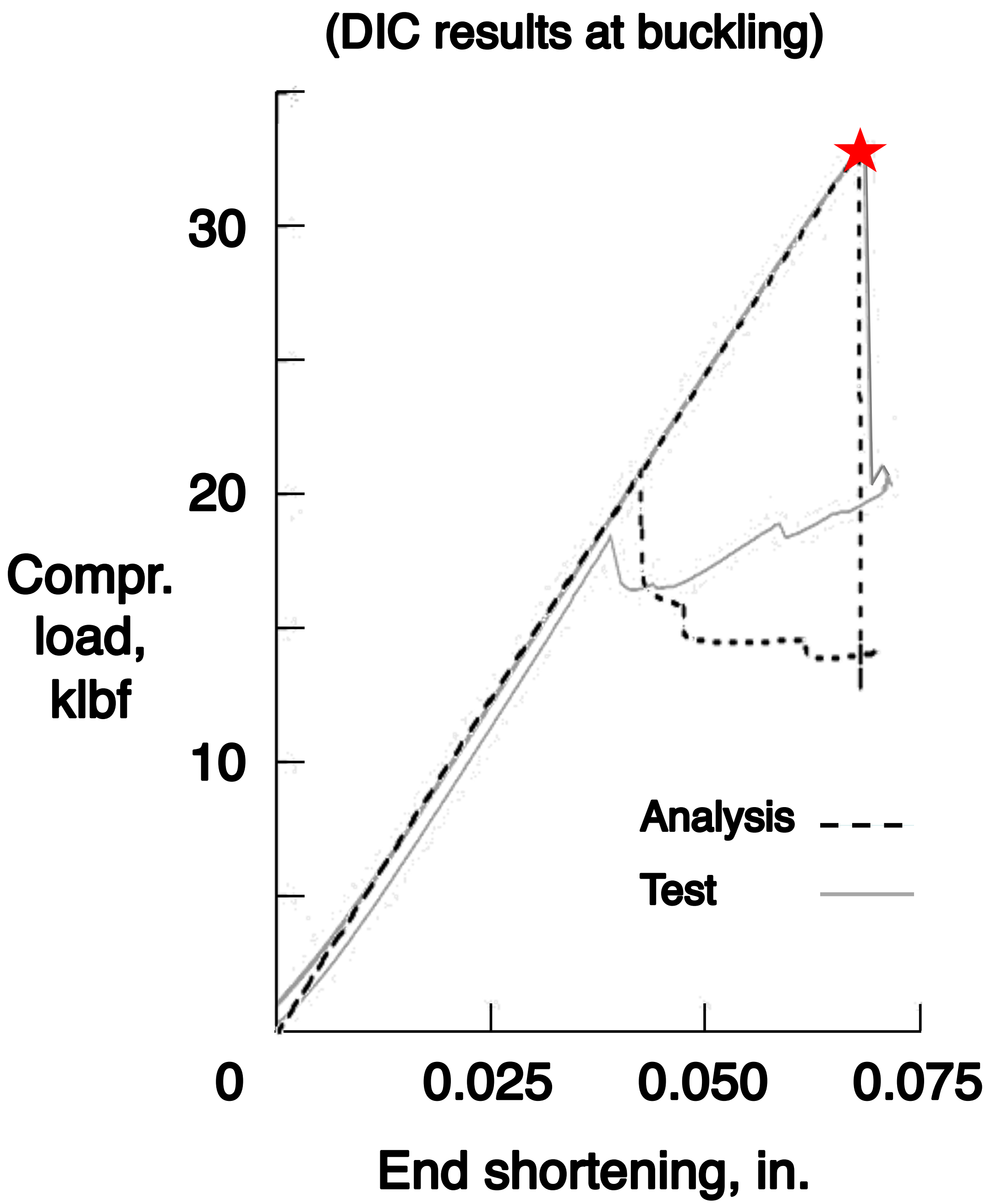
Description of Large Cutouts

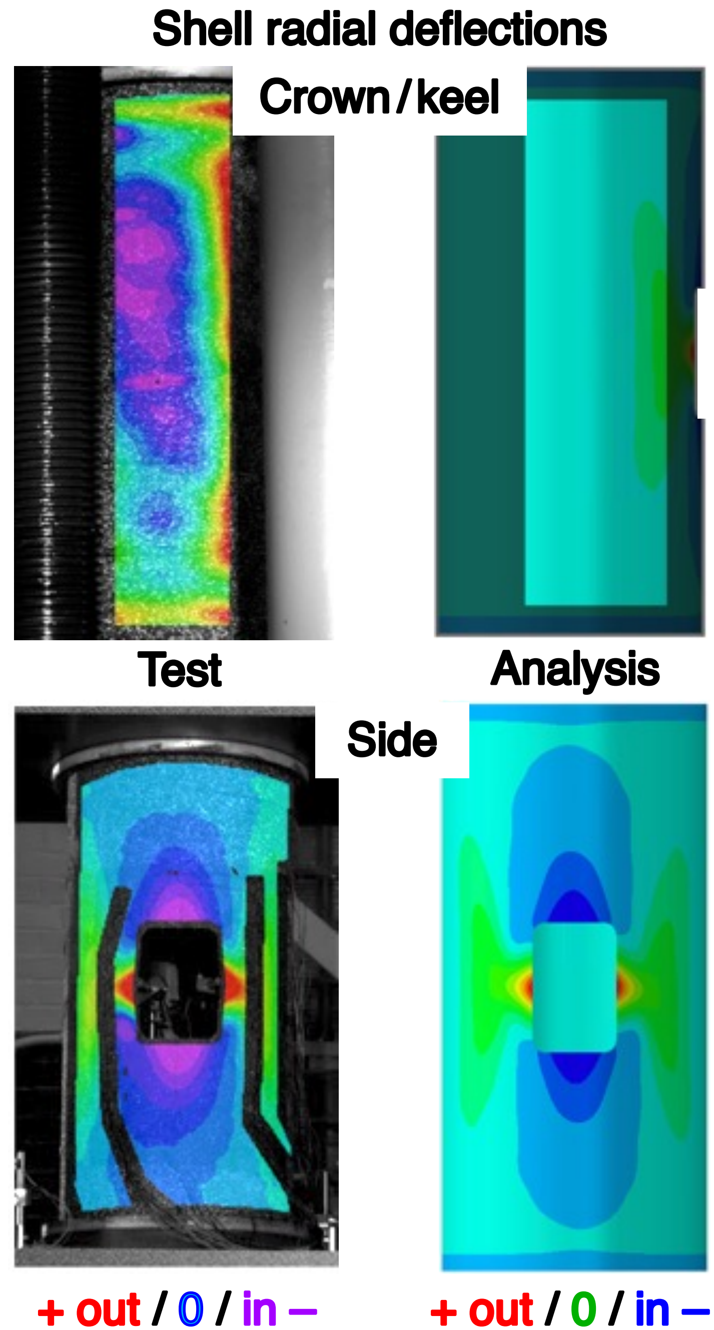
- Large cutouts scaled to represent cargo doors on commercial aircraft fuselage barrel
- Cutouts dimensions are 8 in. (axial) x 5.25 in. (circumferential), with 0.75-in. corner radii
- Unreinforced cutouts machined into center of one side of each shell (layup ~ $[\pm 45]_{2S}$)
- 24 back-to-back strain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



Detail of shell with large cutout

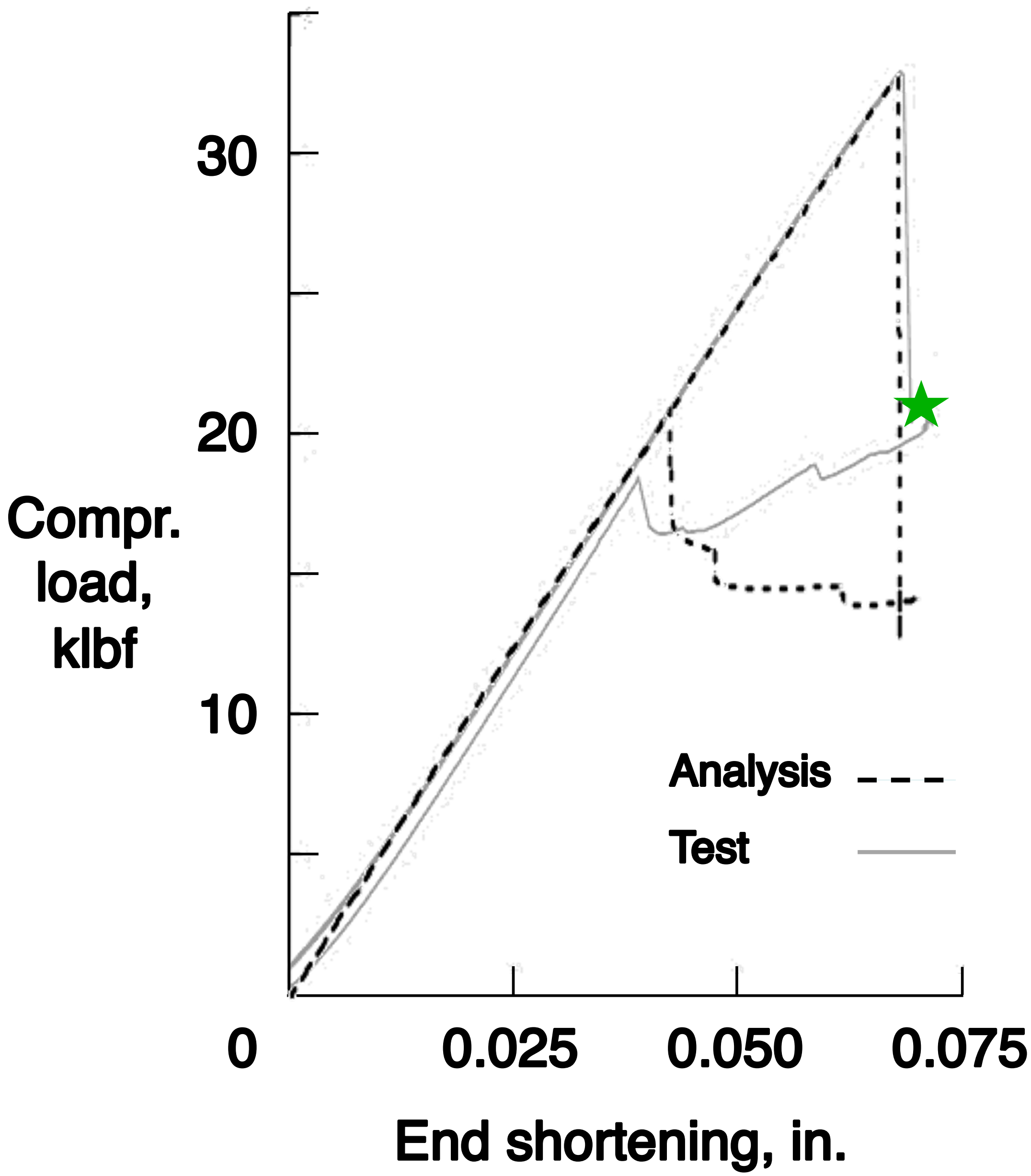
Shell with Overlaps Test and FEA

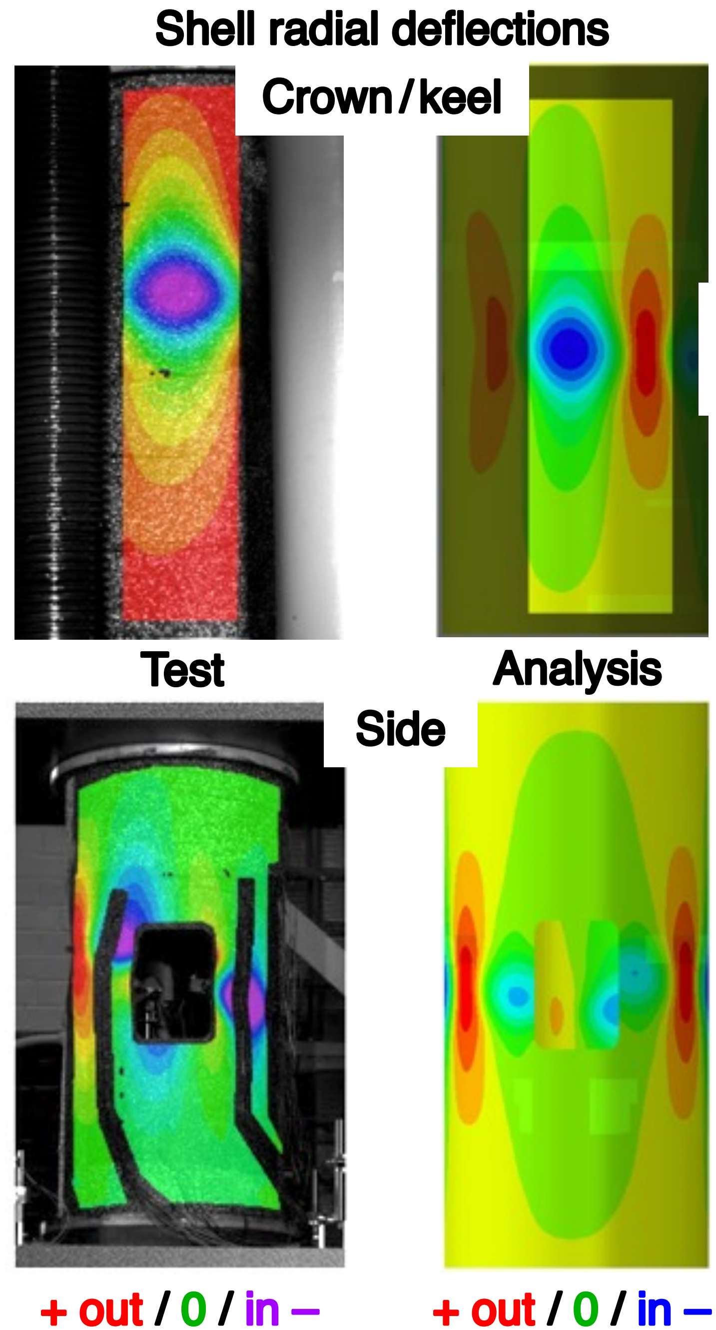




Shell with Overlaps Test and FEA (2)

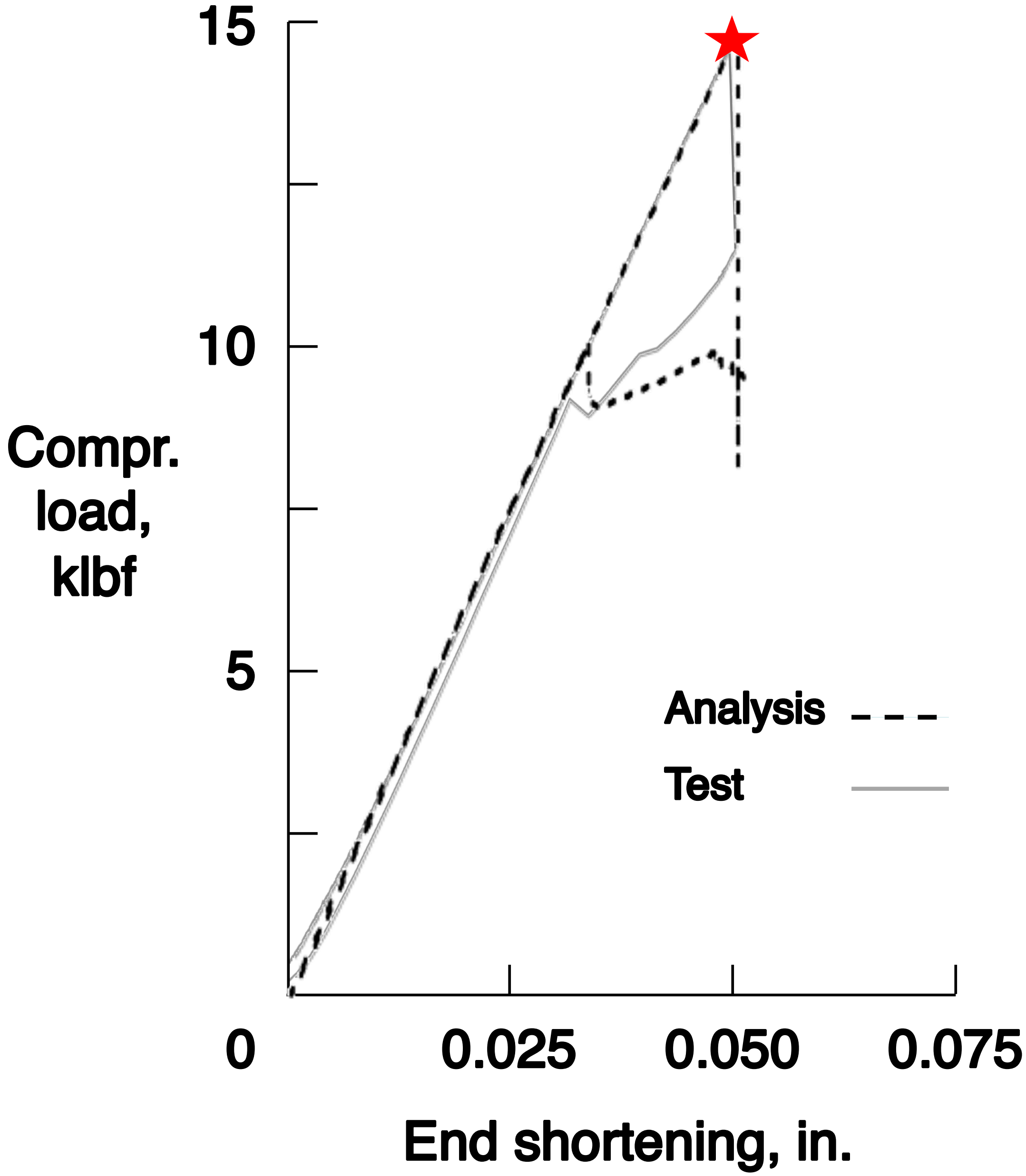
(DIC results at postbuckling)

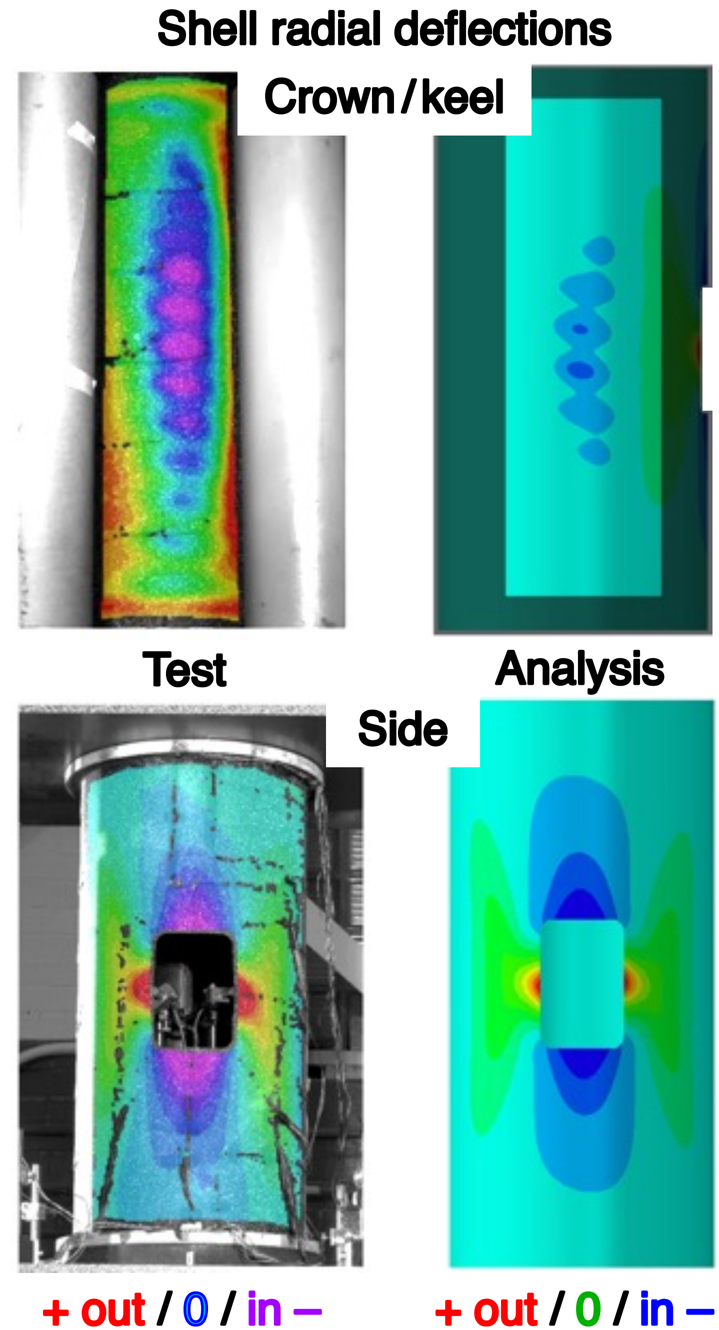




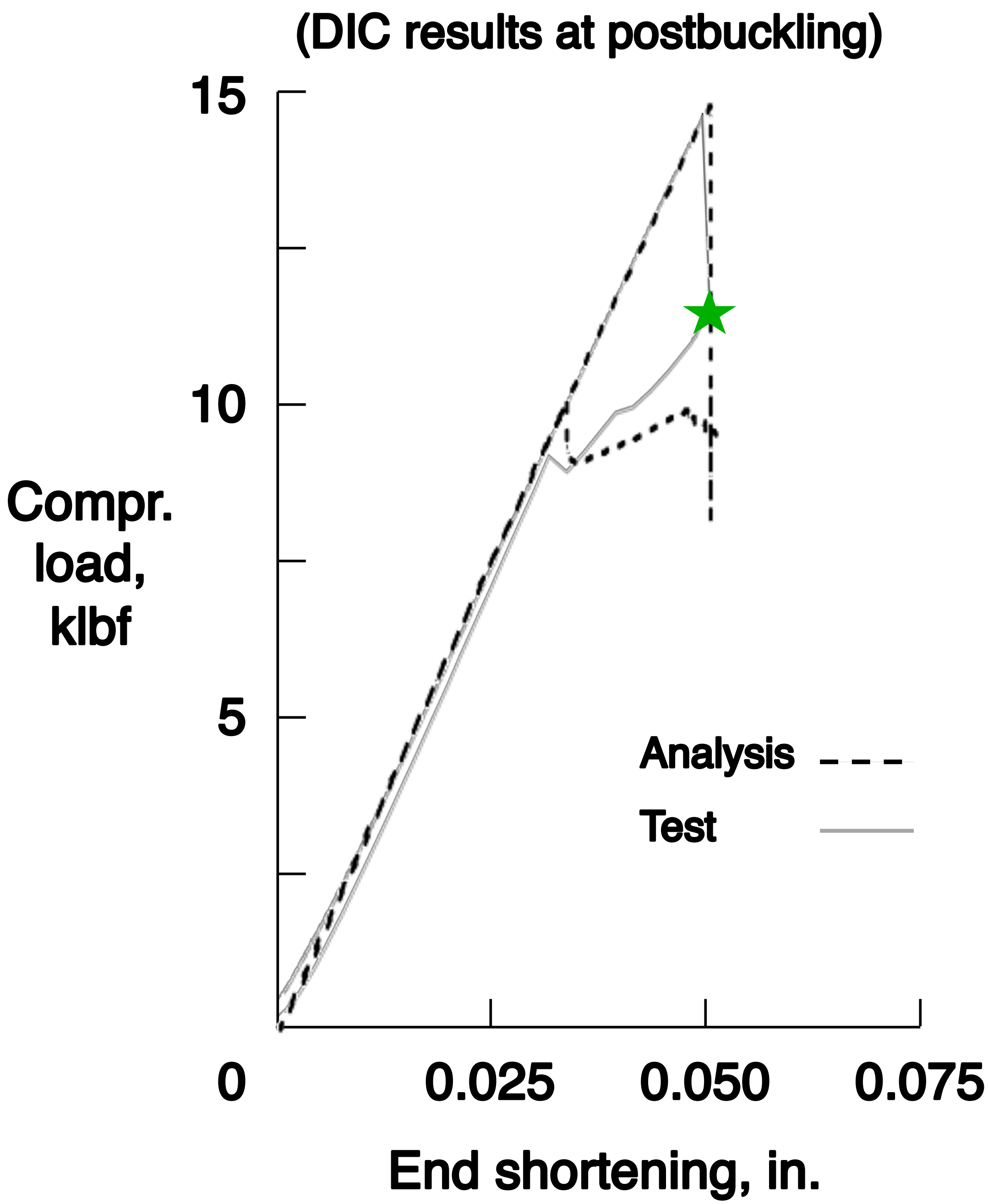
Shell w/o Overlaps Test and FEA

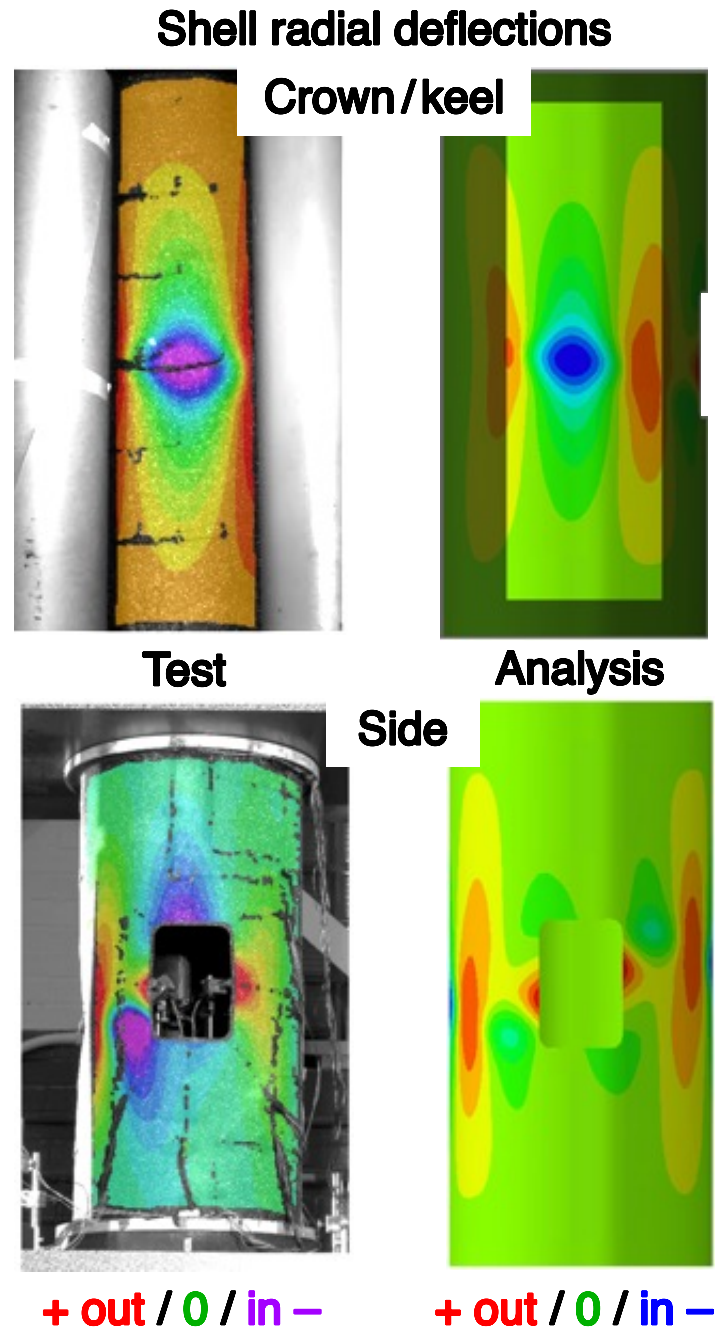
(DIC results at buckling)





Shell w/o Overlaps Test and FEA (2)





Concluding Remarks

- Structural performance of tow-steered composite shells with cutouts assessed using tests and analyses
- Shells tested in end compression through global buckling, into stable postbuckling, and elastic unloading
- Cutouts cause small reductions in axial stiffness (10%) and global buckling load (15%) vs. shells w/o cutouts
- Geometrically nonlinear finite element analyses performed for detailed comparisons with test results
- Detailed comparisons of local deflections and strains performed from prebuckling to stable postbuckling
- Planning for corresponding detailed comparisons of local behavior for shells with large cutouts

Acknowledgments

Thanks to Dr. Rainer Groh (University of Bristol, UK) and Dr. Nate Gardner (NASA Langley Research Center) and my many colleagues for their contributions to this research.

Thank you!
Questions?

References

Baseline shells design, manufacture, testing, and analyses

-- K. C. Wu: *Design and Analysis of Tow-Steered Composite Shells Using Fiber Placement*. Proceedings of the American Society for Composites 23rd Annual Technical Conference. Memphis, Tennessee, September 9-11, 2008. Paper no. 125.

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Baseline Shell Structural Performance

(1) 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

(2) 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

(3) Test / 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.*

Shells with Cutouts Linear FEA

(1) Baseline 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.

Normalized Shells with Cutouts Linear FEA

Performance metric: **Cutout / Baseline**

(1) Baseline 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	0.98	0.97
1st local buckling load*	0.52	0.67
1st global buckling load	0.98	0.97

(3) Shells with Large Cutouts

	Shell with Overlaps	**Shell w/o Overlaps**
Prebuckling axial stiffness	0.98	0.96
1st local buckling load*	0.39	0.51
1st global buckling load	0.97	0.96

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

** Divided by baseline 1st global buckling load*

Shells with Cutouts Test Results

(1) Baseline 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 local buckling load, klbs	19.9	10.5
1st global buckling load, klbs	31.8	15.5
Postbuckling load, klbs	20.2	10.5

(3) Shells with Large Cutouts

	Shell with Overlaps	Shell w/o Overlaps
Prebuckling axial stiffness, klb/in.	488.6	295.6
1st local buckling load, klbs	12.5	7.6
1st global buckling load, klbs	33.0	14.6
Postbuckling load, klbs	20.4	11.5

Normalized Shells with Cutouts Test Results

Performance metric: **Cutout / Baseline**

(1) Baseline 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

Normalized Test and Linear FEA Results

Performance metric: **Test / Linear FEA**

(1) Baseline Shells

	Shell with Overlaps	Shell w/o Overlaps
Prebuckling axial stiffness, klb/in.	1.06	1.07
1st global buckling load, klbs	1.04	1.10

(2) Shells with Small Cutouts

	Shell with Overlaps	Shell w/o Overlaps
Prebuckling axial stiffness	1.00	1.00
1st local buckling load	1.03	1.01
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 local buckling load	0.87	0.95
1st global buckling load	0.91	0.98