



Large-Scale Sandwich Cylinder Test-Article Design and Analysis

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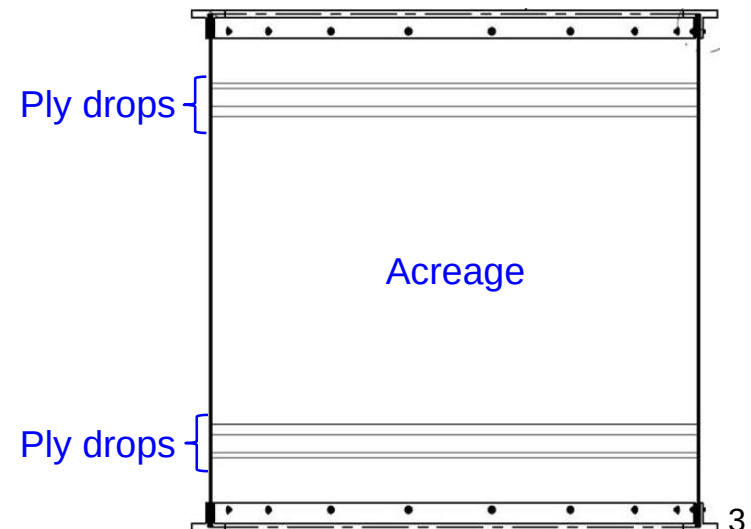
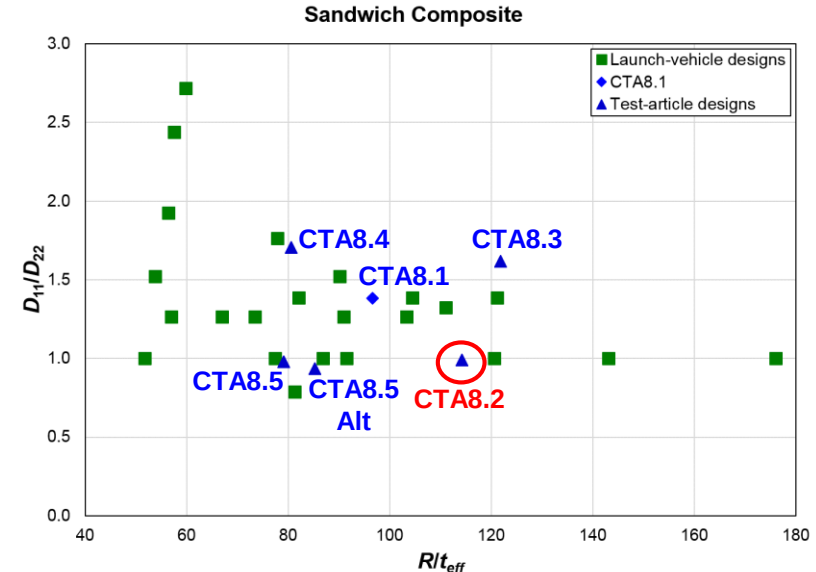


Outline

- **CTA8.2**
 - Design and as-built geometry
 - Pretest analysis approach
 - Test and posttest investigation
 - Enhanced analysis approach
- **Future Test Articles**
 - Remaining designs
 - Detailed CTA8.3 analysis results
 - Brief summary of CTA8.4, CTA8.5/8.5 Alt, and CTA8.2B analysis results
- **Conclusions**

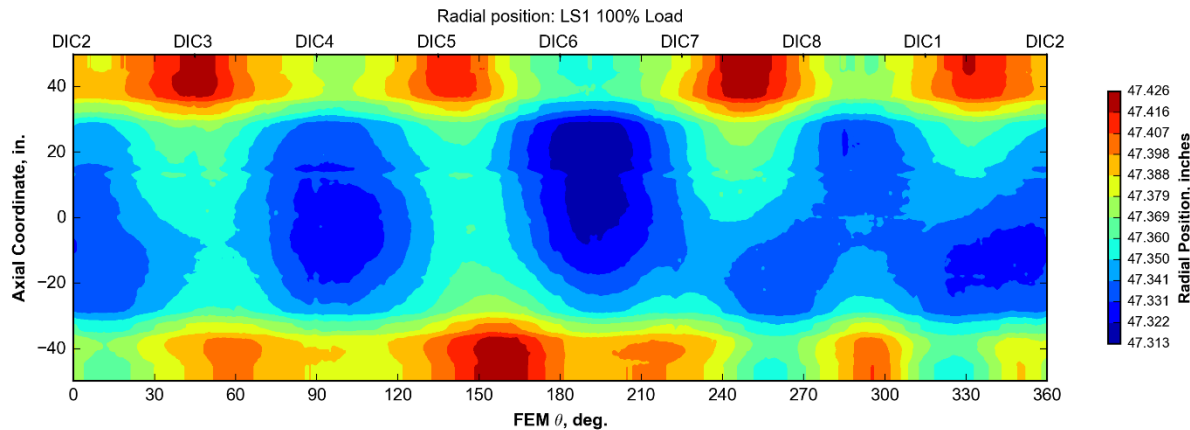
CTA8.2 Design

- **Faces**
 - 6-ply quasi-isotropic facesheets: $[\pm 60/0]_s$
 - 190 gsm IM7/8552
 - Padups: four interleaved ± 45 plies per face dropped at 13.5, 14.5, 18, and 20 in. from barrel ends (IML constant diameter)
- **Core**
 - 3.1 pcf aluminum honeycomb
 - Thickness: 0.20 in.
- **Adhesives**
 - Core splice: Hysol EA9396 paste
 - Film adhesive: Cytec FM209
- **Potted ends**
 - Mold release to allow sliding between test article/end rings and epoxy grout
- **Test**
 - Axial compression to failure



CTA8.2 Measured Geometry

- Midsurface radial position**

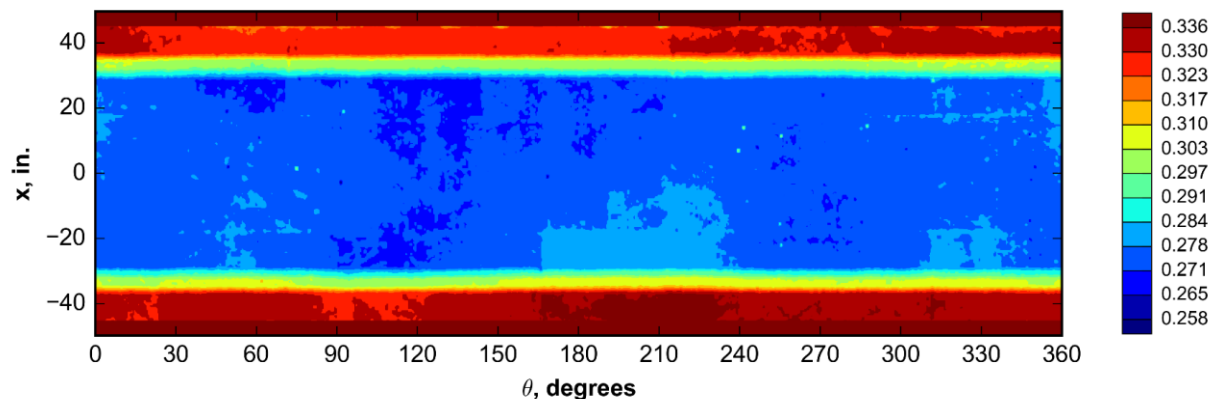


$$R = \frac{R_{OML} + R_{IML}}{2}$$

- Thickness**

CTA8.2 Shell Thickness Contours

Max. $t = 1.698$, Min. $t = 0.257$



$$t = R_{OML} - R_{IML}$$

CTA8.2 Pretest Analysis Approach

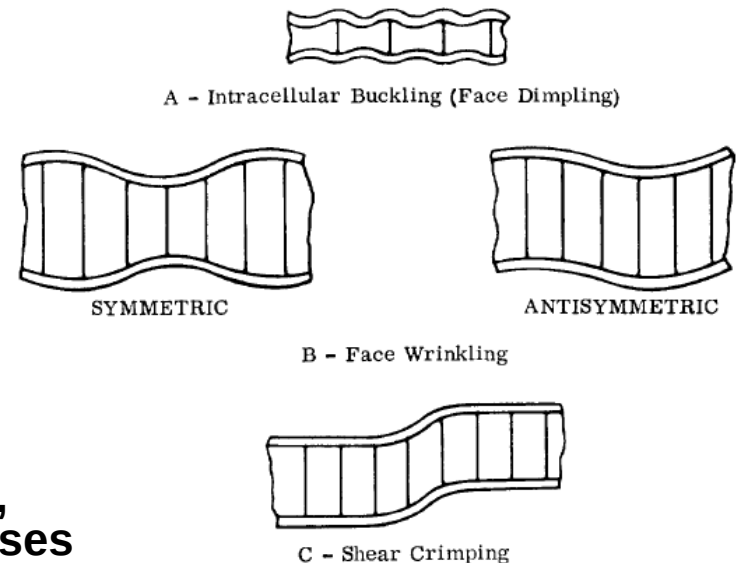


- **Closed-form analysis**

- For initial design down select
- To predict sandwich failure modes for final design
 - Facesheet wrinkling
 - Facesheet dimpling
 - Core shear crimping

- **Finite-element shell analysis**

- Test article modeled as layered composite shell
- Model fidelity
 - Padups/ply drops, metallic load introduction ring, potting compound, including entire test rig in final analyses
- Buckling
 - Linear and nonlinear predictions
- Facesheet strength failures
 - Minimum compressive strain



CTA8.2 Pretest Analysis Predictions



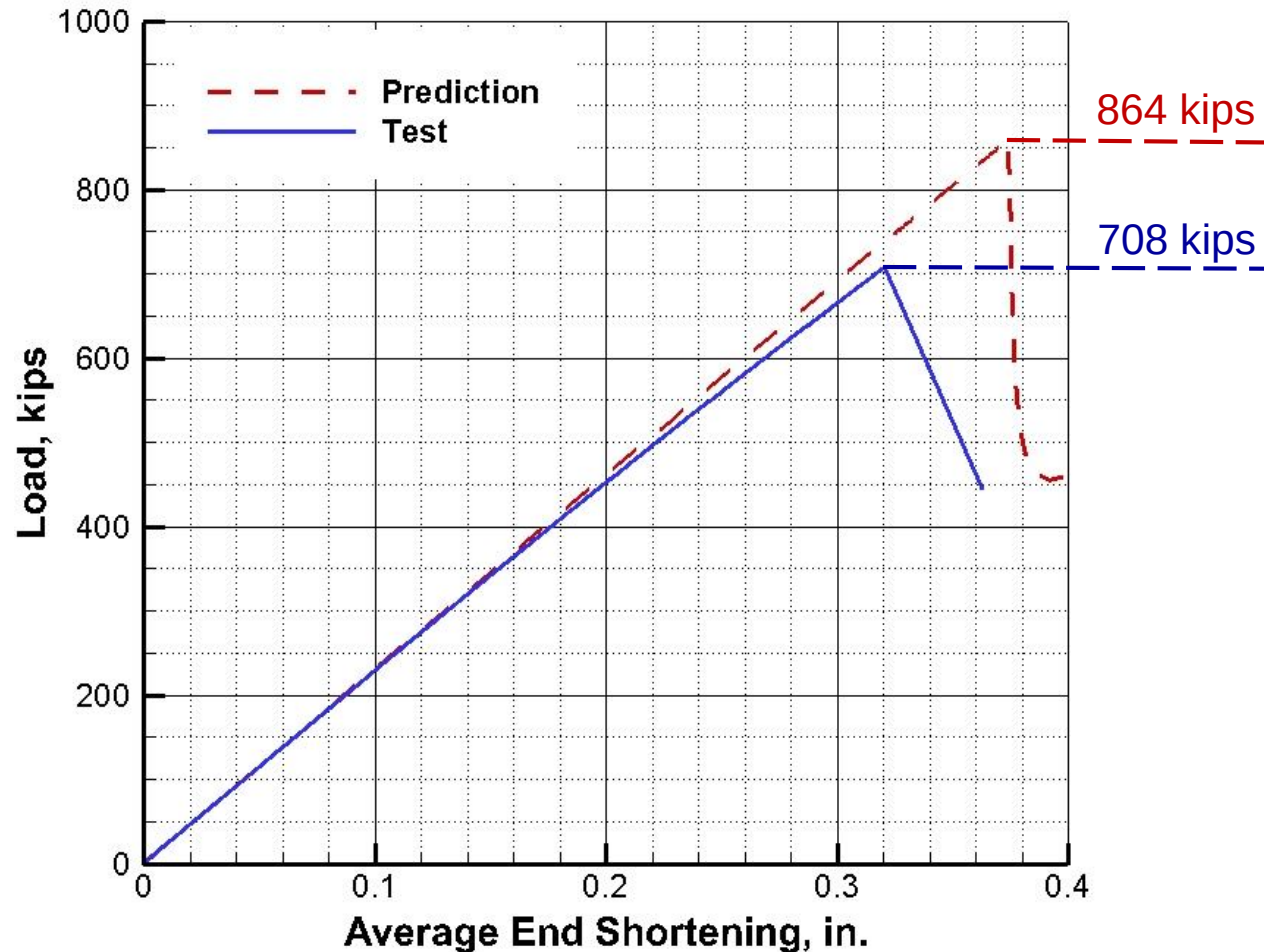
- **Closed-form analysis***
 - Vinson facesheet wrinkling: 9,200 kips ($10.6 P_{cr}$)
 - Vinson facesheet dimpling: 55,000 kips ($63.6 P_{cr}$)
 - Core shear crimping
 - Reese & Bert: 4,000 kips ($4.6 P_{cr}$)
 - Vinson: 2,700 kips ($3.1 P_{cr}$)
- **Finite-element analysis**
 - Global buckling
 - Linear, P_{bif} : 979.6 kips
 - Perfect geometry: 984.0 kips
 - Measured imperfection, P_{cr} : 864.2 kips ($0.88 P_{bif}$)
 - Facesheet peak axial strain at buckling
 - Perfect geometry: $-5,457 \mu\epsilon$
 - Measured imperfection: $-5,314 \mu\epsilon$

*Calculated with in-plane extensional stiffnesses
Closed-form analyses details included in Appendix

CTA8.2 Test Response

Test failure load = 708 kips

- 18.1% below the predicted failure load
- 40% higher than SP-8007 design recommendation



CTA8.2 Failure Observations

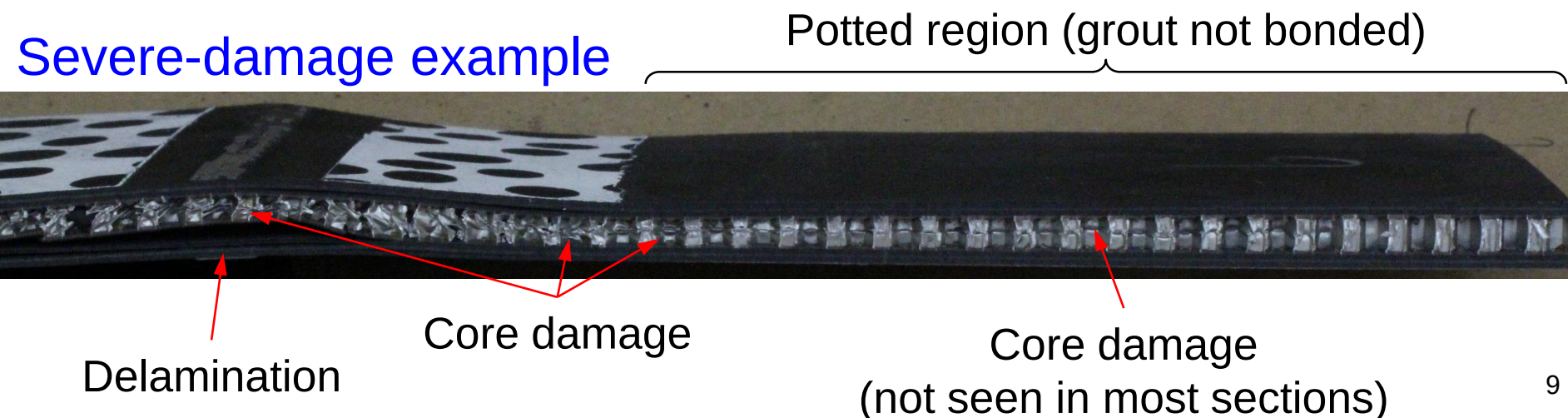


- Heard intermittent crackling over about the last minute before failure (starting at approx. 650 kips loading)
- Failure occurred close to top end ring
 - Near the edge of digital image correlation (DIC) coverage
 - IML and OML faces moved together (in phase)
 - Little fiber rupture



CTA8.2 Failure Observations

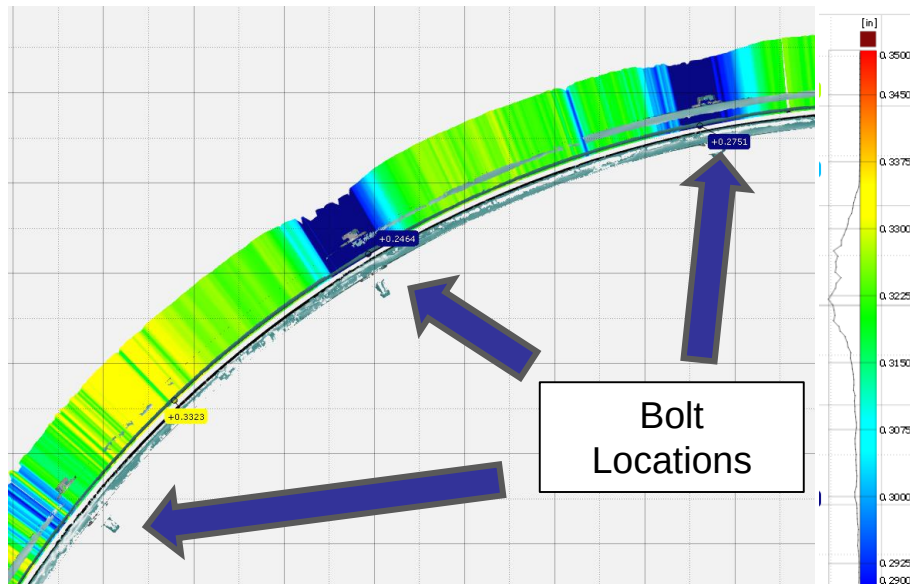
- **Thermography**
 - Damage indications appear limited to within 9 in. of end ring
- **Sectioning around failure initiation location (17 sections extracted)**
 - No core-to-facesheet separation seen
 - No damage observed at ply drops, tow splices, or core splices
 - Some delamination seen
 - Core **shear and crush** failures observed **outside potted region**
 - Limited core **crush failures (no shear)** observed **inside potted region**
 - Difficult to determine sequence of damage



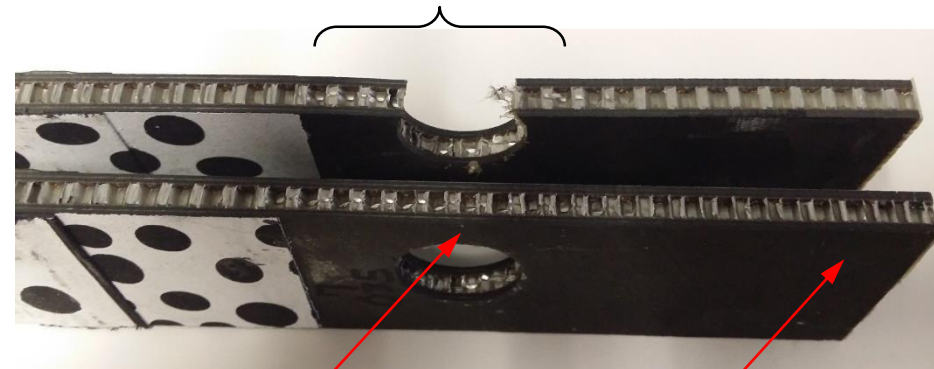
CTA8.2 Failure Observations

Sandwich thickness variations in the proximity of the load introduction rings

- Reduced sandwich thickness identified in the proximity of several load introduction ring bolts (torqued)
- Core crush identified near bolt holes in the section of the test article opposite to the failed end



Extent of core crush ~2.7 in.



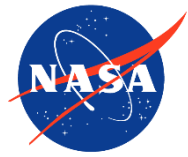
Thickness
0.328 in. 0.334 in.

CTA8.2 Pretest Analysis



Analysis type	Failures interrogated	Advantages	Limitations
Closed-form	• 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
FEA shell	• Global buckling • Facesheet strength failures	• Linear or nonlinear analyses • Can easily include measured radial and thickness imperfections • Used for pretest buckling predictions	• Cannot capture core crush or shear failures • Cannot capture end conditions in great detail

CTA8.2 Posttest Investigation: Additional Numerical Analyses

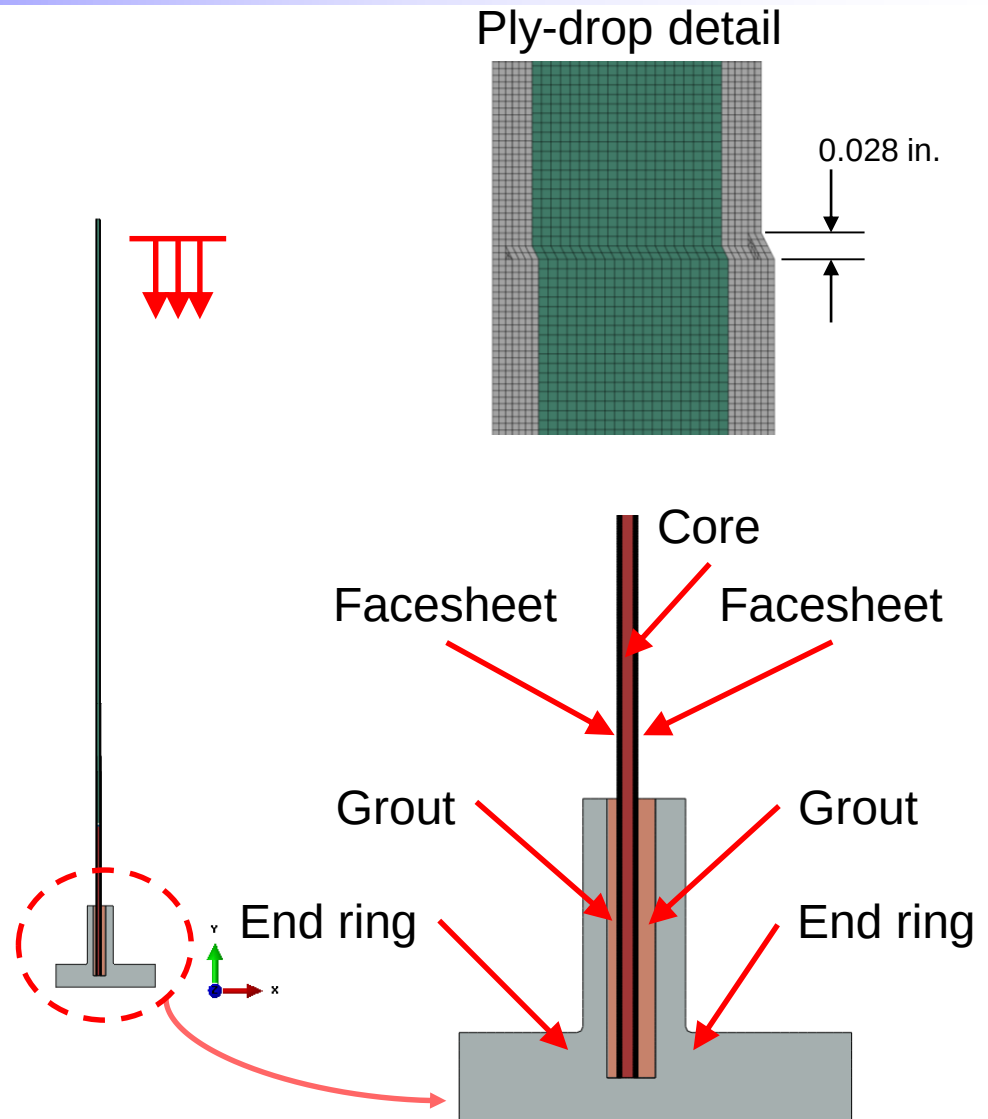


Analysis type	Failures interrogated	Advantages	Limitations
Closed-form	- Linear global buckling (for initial down select) - Facesheet wrinkling - Facesheet dimpling - Shear crimping	- Quickly assess many designs - Calculate otherwise difficult-to-predict failure loads	- Linear only - Perfect geometry only
FEA shell	- Global buckling - Facesheet strength failures	- Linear or nonlinear analyses - Can easily include measured radial and thickness imperfections - Used for 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 - 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 - Reasonably 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

CTA8.2 Axisymmetric 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

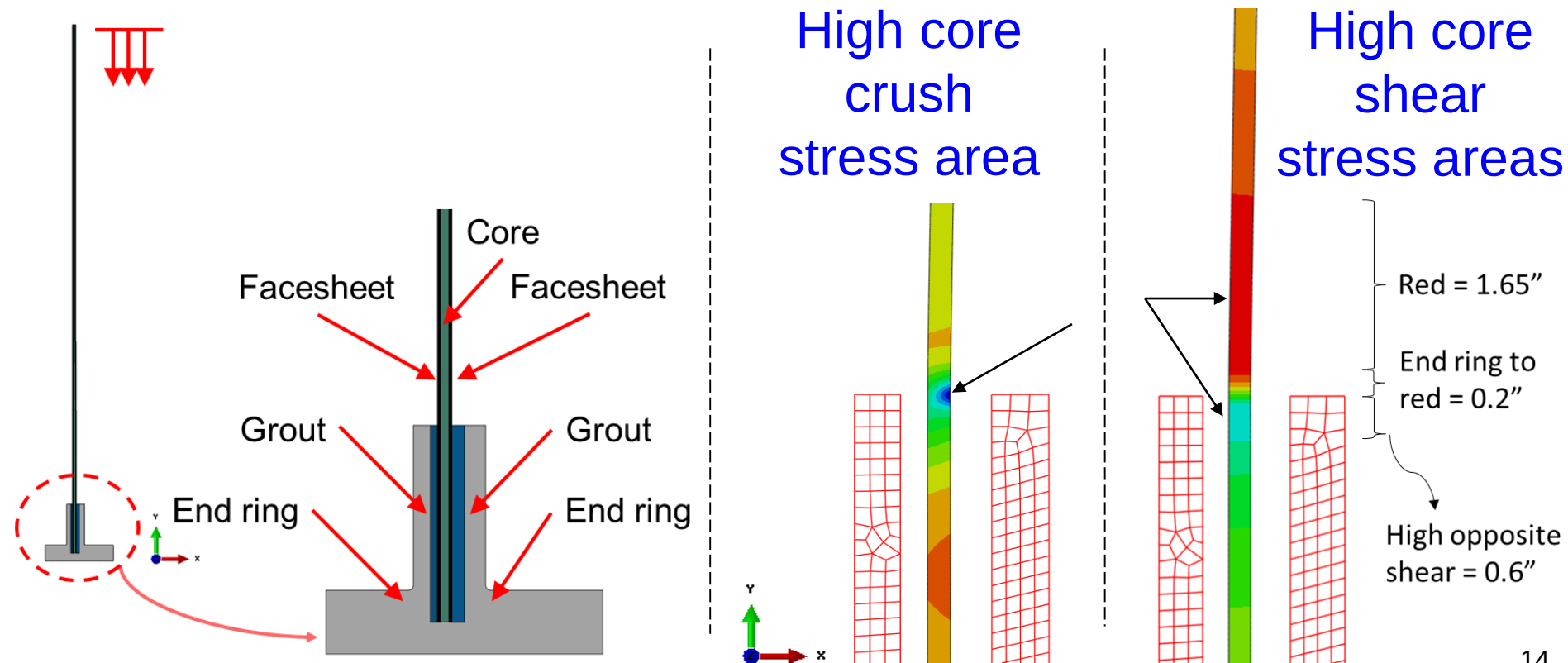


CTA8.2 Axisymmetric Analysis Results in Proximity of the Load Introduction Ring



Observations at/near the load introduction ring termination

- Predicted core crushing stresses were high
- Predicted core shear stresses were high



CTA8.2 Axisymmetric Analysis

Core Crush and Shear Stresses



		At Failure Load of 708 kips							
BCs Metric				Outside Ring			Within Ring		
	σ_{11} (psi)	Failure Index		σ_{13} (psi)	Failure Index		σ_{13} (psi)	Failure Index	
Sliding	-258	0.74 [†]	0.99 [*]	181	0.72 [†]	0.91 [*]	-138	0.55 [†]	0.69 [*]

[†]Core failure index = $\sigma_{FEA} / \sigma_{\text{Hexcel typical strength}}$

^{*}Core failure index = $\sigma_{FEA} / \sigma_{\text{Hexcel minimum strength}}$

CTA8.2 Posttest Failure Investigation and Additional Analysis Summary



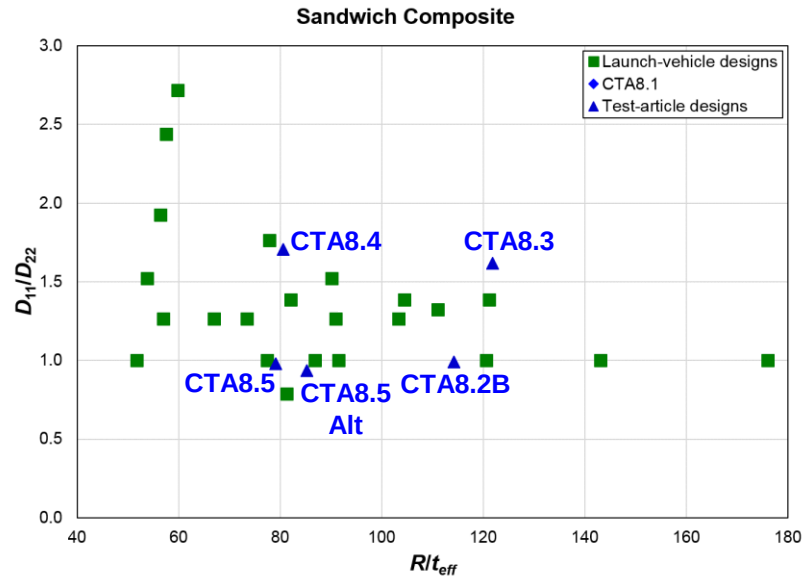
- **Test article inspection results**
 - Significant core failure just outside top load introduction ring
 - Localized evidence of core crush failure within top load introduction ring
 - No evidence of
 - Shear failure within ring
 - Core-to-facesheet disbonds
 - Failure at core splices
 - Failure at or near ply drops
 - Failure at facesheet tow splices
- **Axisymmetric model results**
 - Predicted high core stresses, core strength failure appears to be likely cause for test-article failure
 - Crush failure at end-ring termination and/or shear failure outside ring
 - Core-to-facesheet predicted interface stresses generally low away from rings, but large spikes at ply drops
- **Global-local model results**
 - Core performance not significantly affected by the global geometric imperfections
- **Overall Conclusions**
 - Posttest observations in agreement with axisymmetric and global-local analyses indicating a core shear strength and/or crush failure



Path Forward

- **Design changes**
 - Increase core density in end sections of test articles
 - Do not torque safety bolts in the load introduction metallic rings
- **Additional analysis to interrogate core and core-to-facesheet response**
 - Axisymmetric (must have)
 - Global-local (nice to have)

Future Test Articles



Design	Acreage Facesheet Layup	Core Thickness, in.	Ply Fiber Aerial Weight, gsm	Comments
CTA8.3	$[\pm 30/90]_s$	0.20	145	Fabricated, to be tested in September
CTA8.4	$[\pm 30/90/0]_s$	0.30	145	Material characterization testing underway
CTA8.5	$[90/0/90/0/\mp 30/90/90/0]_T$	0.30	145	Almost crossply facesheet lamination
CTA8.5Alt	$[\pm 60/0/90/0]_T$	0.30	145	Alternative CTA8.5 design
CTA8.2B	$[\pm 60/0]_s$	0.20	190	CTA8.2 with denser core at the ends



CTA8.3 Design Requirements

- Test article design should be in desired design space (“thin,” axially stiff, etc.)
- Test-article first failure mode in 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 ($\sim 1.5 \times 10^6$ lbf)
- Design should generally follow recommended best practices for composite design and fabrication
- Test article fabricated using automated fiber placement
- Risk reduction
 - Because layup is different from CTA8.2, there is the inclusion of a denser core at the ends, and there is a change in core-to-facesheet film adhesive, relevant material characterization testing was completed before fabrication
 - Half-length manufacturing demonstration units were fabricated before CTA8.3 test article

CTA8.3 Design

• Faces

- 5-ply axially stiff facesheets: $[\pm 30/\overline{90}]_s$
 - 90° ply effectively slightly off-90° to avoid excessive splicing
- 145 gsm IM7/8552
- Padups: four interleaved ± 45 plies per face dropped at 14, 16, 18, and 20 in.

• Core

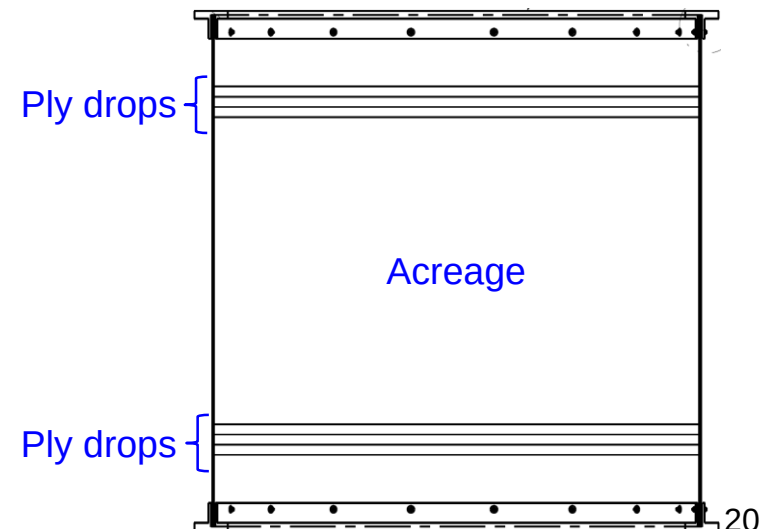
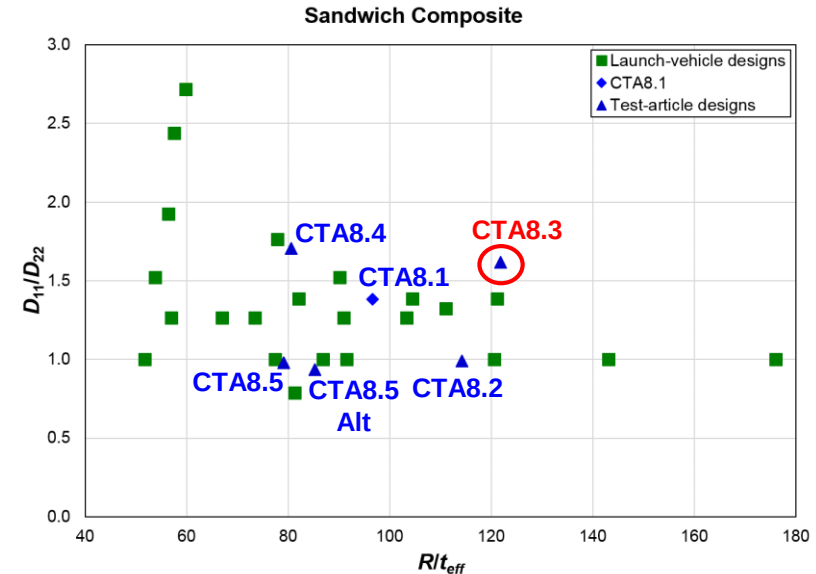
- Axial stations 10 to 90 in.: 3.1 pcf aluminum honeycomb
- Axial stations 0 in. to 10 in. and 90 in. to 100 in.: 8.1 pcf aluminum honeycomb
- Thickness: 0.20 in.

• Adhesives

- Core splice: Hysol EA9396 paste
- Film adhesive: Cytec FM300-2M

• Potted ends

- Mold release to allow sliding between test article/end rings and epoxy grout



CTA 8.3 Closed-Form Failure Predictions*



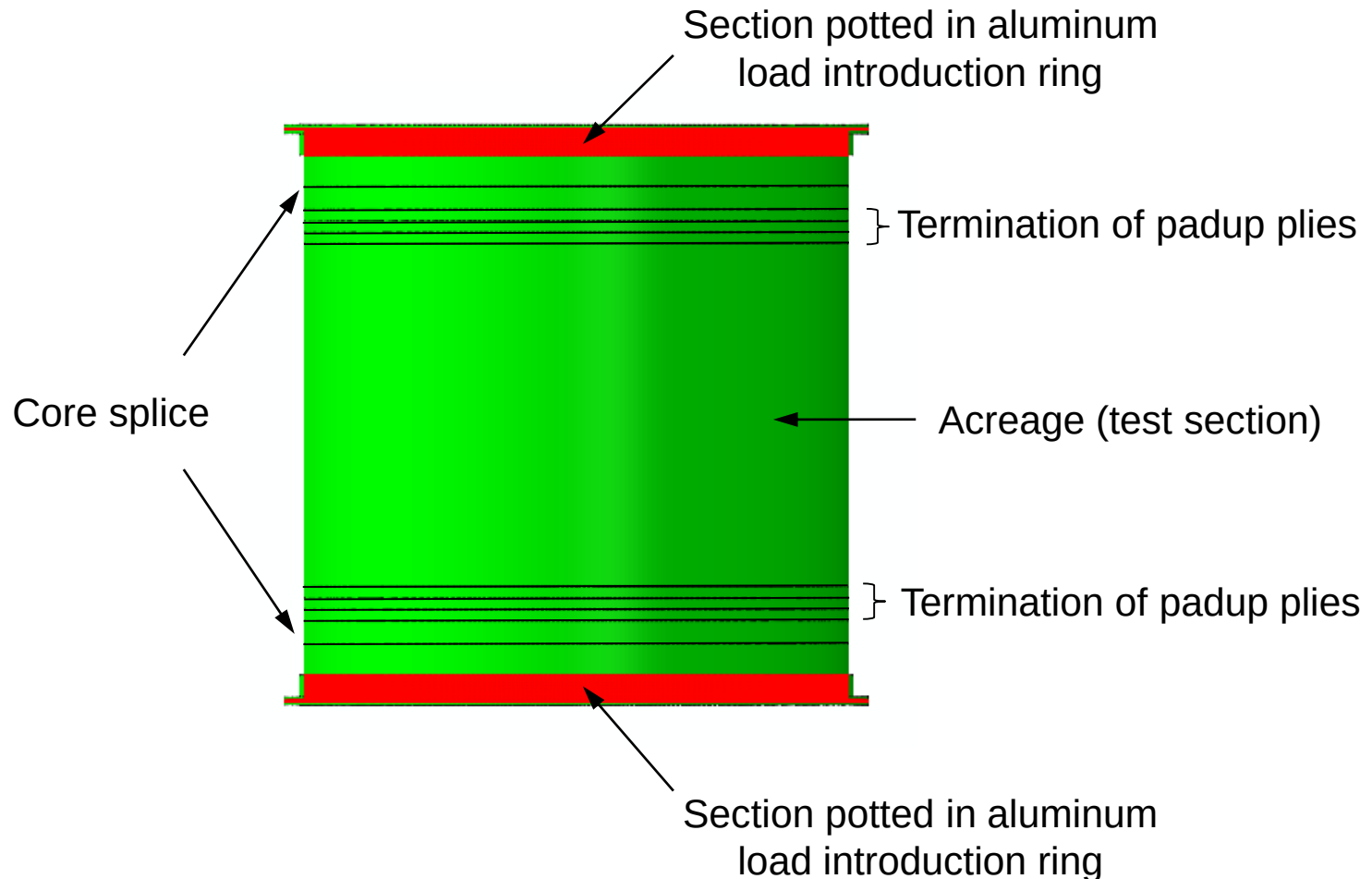
Critical closed-form calculated loads

	Facesheet Wrinkling	Facesheet Dimpling	Shear Crimping
Load (lb)	1.09E+06	4.81E+06	2.71E+06
Failure Index	0.51	0.12	0.20

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

*See Appendix for equations and complete set of calculated loads

CTA8.3 Finite-Element Shell Model



CTA8.3 Finite-Element Shell Model and Analyses



- **Model**

- Approximately 154,000 layered shell elements (S4R)
- Element size: 0.5 in. in the axial direction by 0.5 degree (approximately 0.4 in.) in the circumferential direction
- Problem size: approximately 932,000 degrees-of-freedom
- Top/bottom load introduction ring flanges attached via kinematic constraints to a single top/bottom node located on the cylinder axis
 - Bottom node fixed
 - Force applied to the top node in the linear buckling analysis
 - Displacement applied to the top node in the nonlinear analyses

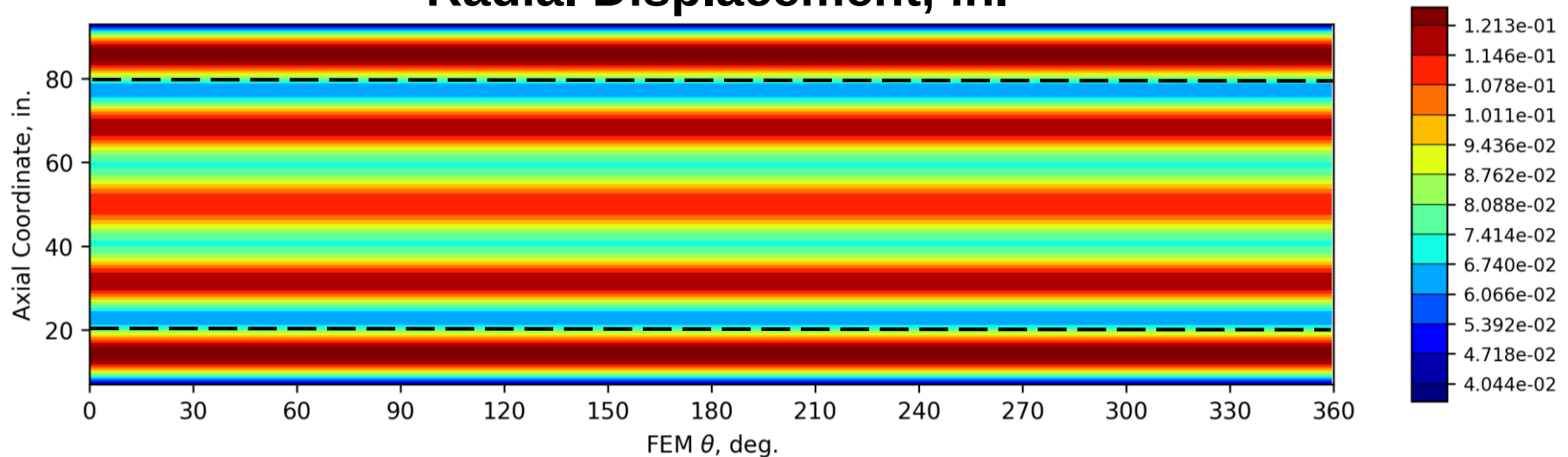
- **Analyses**

- Linear buckling using the subspace solver (perfect geometry)
- Nonlinear buckling using a general static solver preload step followed by a dynamic standard/implicit step to capture buckling and post-buckled response (perfect and imperfect geometries)
 - Imperfect geometry measured from [CTA8.2 applied as radial imperfection only](#)

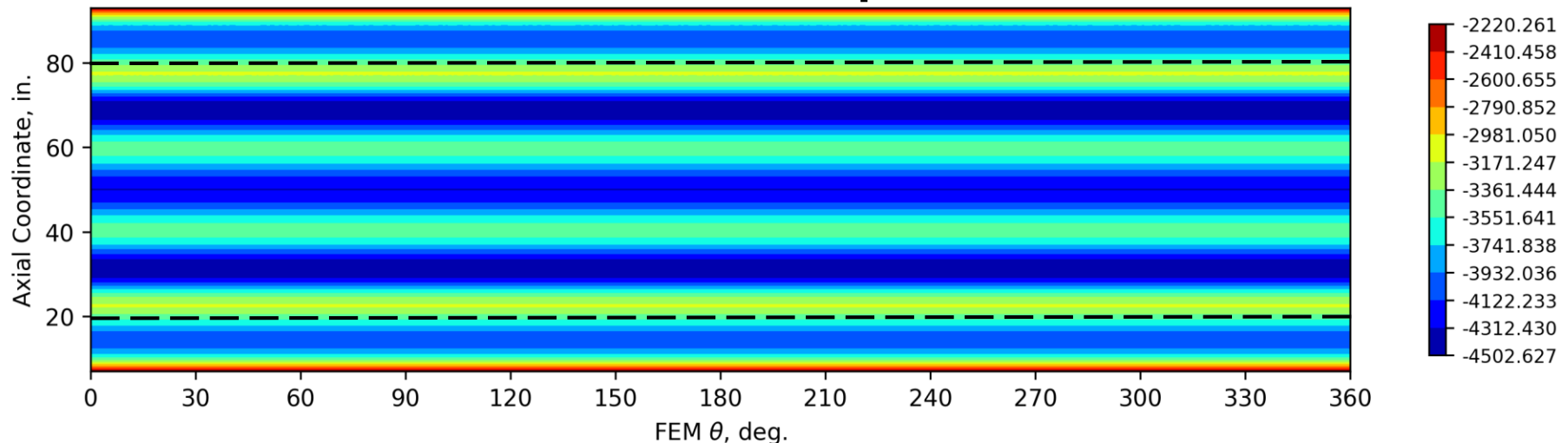
CTA8.3 Nonlinear Analysis at Buckling Load of 538.9 kips, Perfect Geometry



Radial Displacement, in.



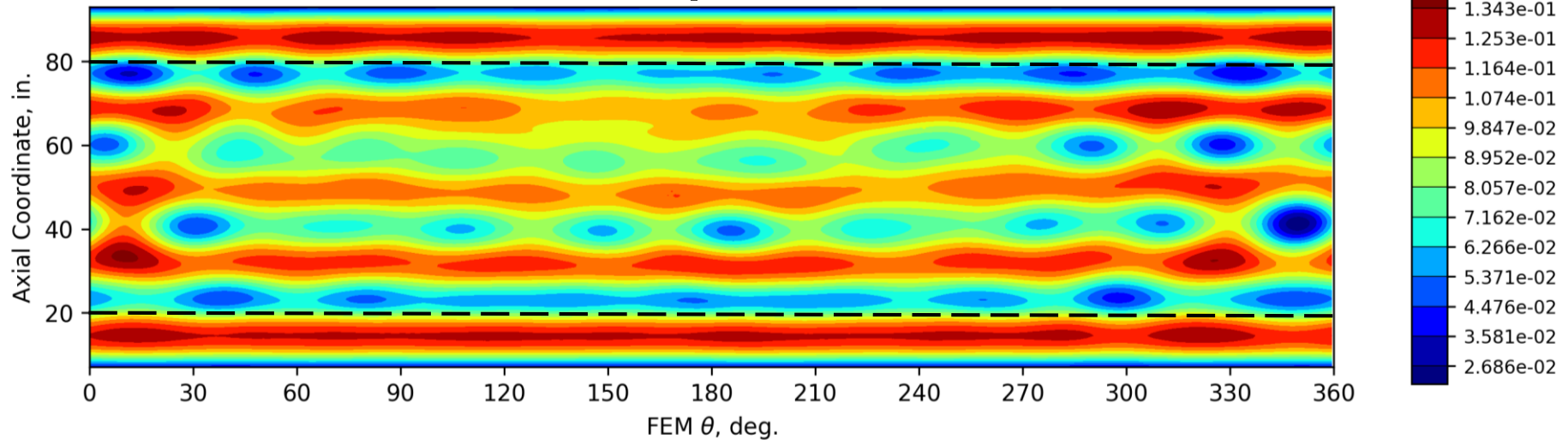
Axial Strain, $\mu\epsilon$



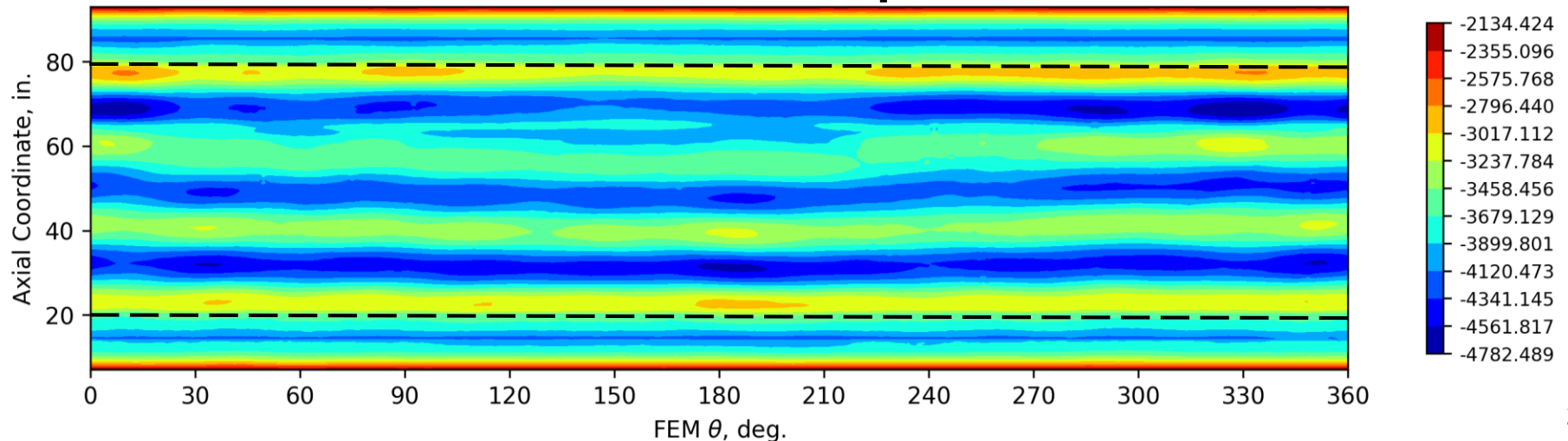
CTA8.3 Nonlinear Analysis at Buckling Load of 529.6 kips, CTA8.2 Radial Imperfections



Radial Displacement, in.



Axial Strain, $\mu\epsilon$



CTA8.3 Shell Analysis Facesheet Results



Reasonable axial strains and Tsai-Hill indices that satisfy design requirements

	Perfect, 538.9 kips			Radial Imperfection from CTA8.2, 529.6 kips		
Measure	Axial Strain ($\mu\epsilon$)	Hoop Strain ($\mu\epsilon$)	Tsai- Hill Index	Axial Strain ($\mu\epsilon$)	Hoop Strain ($\mu\epsilon$)	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 ^{**}

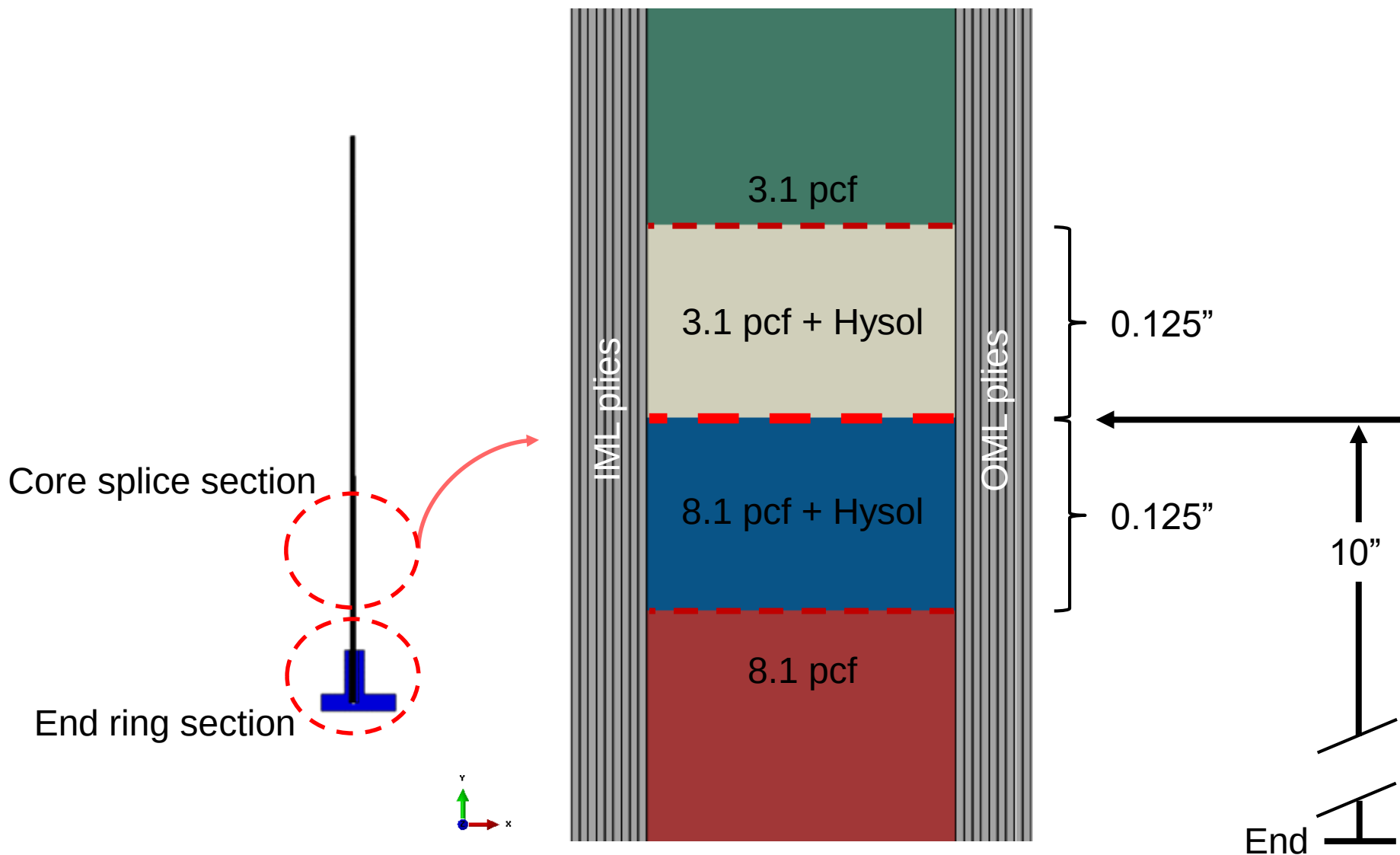
[‡]Axial-strain failure index = $\epsilon_{\text{FEA axial}} / -7926 \mu\epsilon$

[^]Hoop-strain failure index = $\epsilon_{\text{FEA hoop}} / 17,400 \mu\epsilon$

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

CTA8.3 Axisymmetric Model

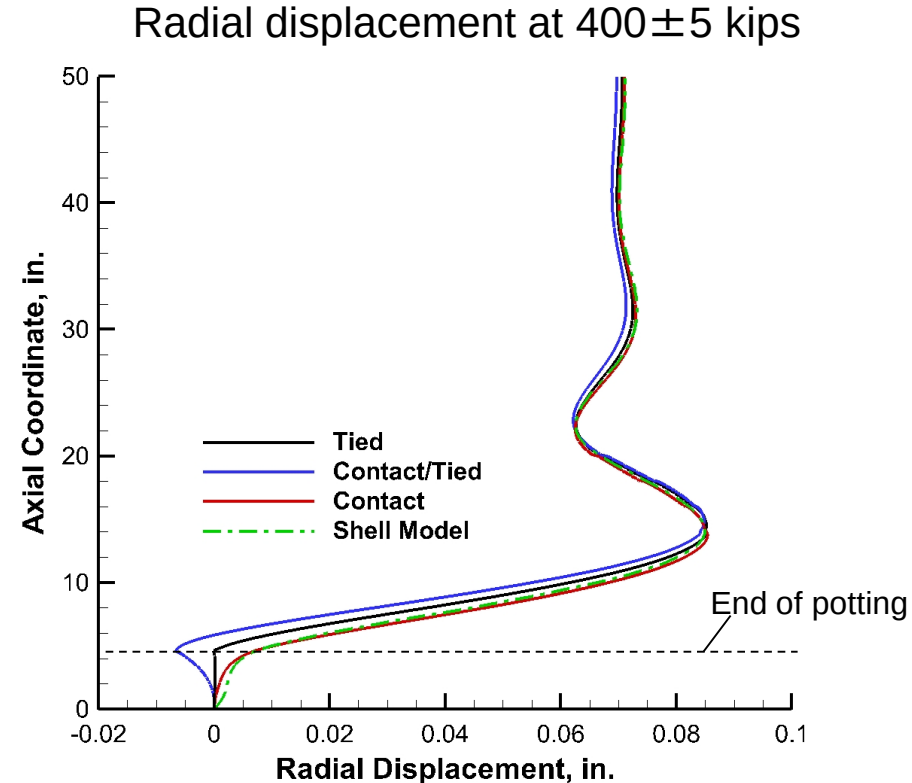
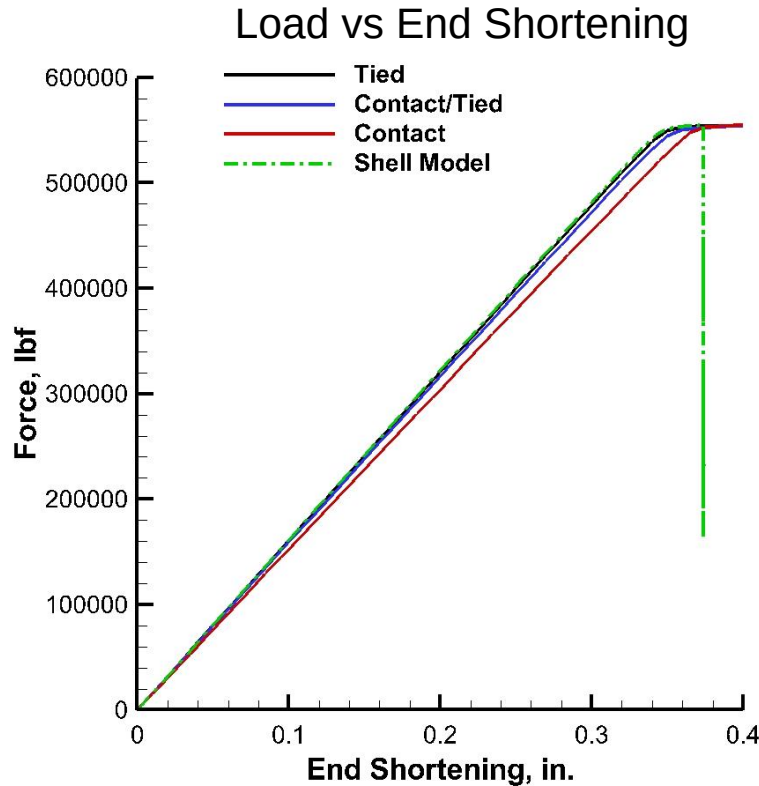
Core-Splice Detail



End

CTA8.3 Axisymmetric Analysis Validation

Comparison with perfect-geometry shell model



CTA8.3 Axisymmetric Analysis

Core Crush and Shear Stresses



		At Buckling Load								
BCs \ Metric				Outside Ring			Within Ring			
	σ_{11} (psi)	Failure Index		σ_{13} (psi)	Failure Index		σ_{13} (psi)	Failure Index		
Sliding	-566	0.30 [†]	0.44 [*]	162	0.17 [†]	0.22 [*]	-167	0.18 [†]	0.23 [*]	

[†]Core failure index = $\sigma_{FEA} / \sigma_{\text{Hexcel typical strength}}$

^{*}Core failure index = $\sigma_{FEA} / \sigma_{\text{Hexcel minimum strength}}$

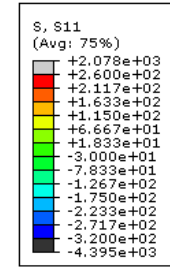
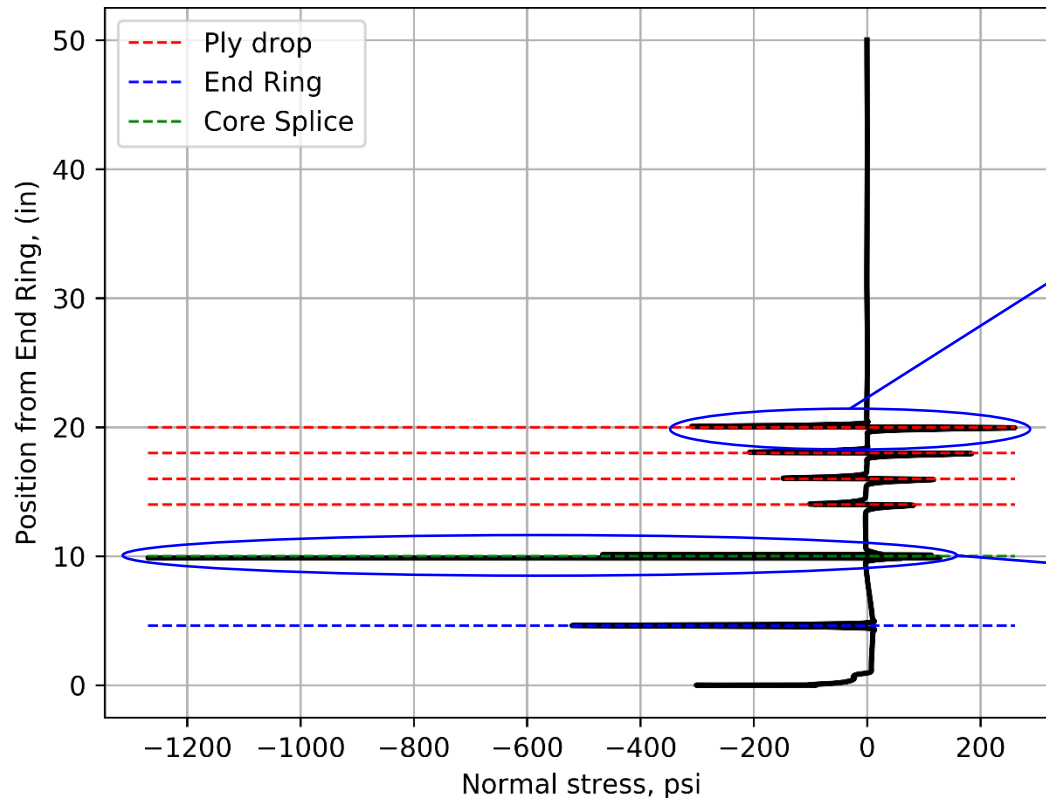
CTA8.3 Axisymmetric Analysis

Core-to-Facesheet Interface Stresses



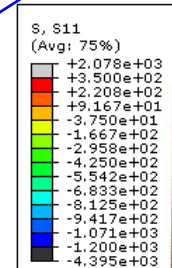
Normal Stress

OML Interface



Core to
scale

0.125 in.



Core to
scale

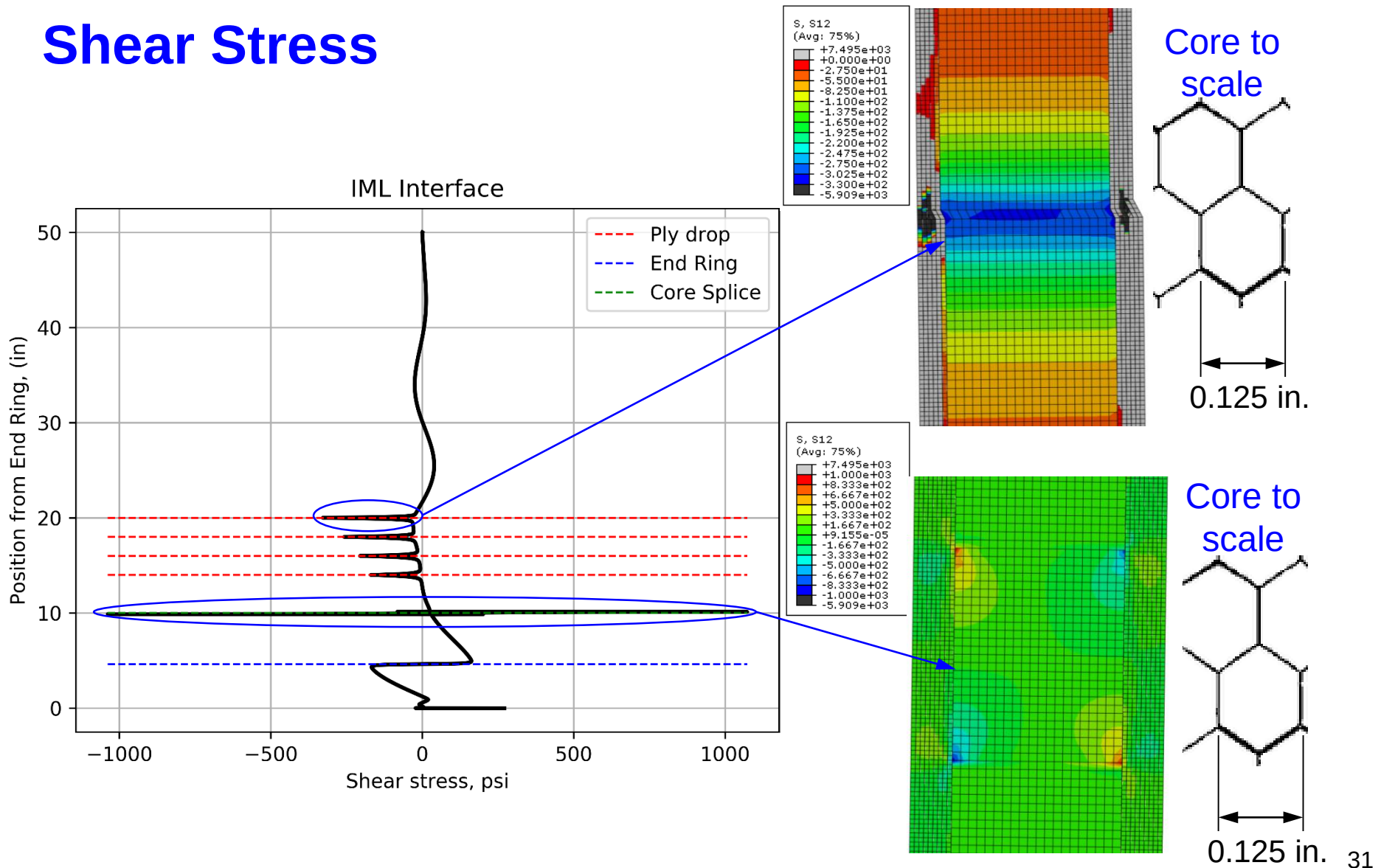
0.125 in. 30

CTA8.3 Axisymmetric Analysis

Core-to-Facesheet Interface Stresses



Shear Stress



Conclusions Based on CTA8.3

Axisymmetric Finite Element Analysis

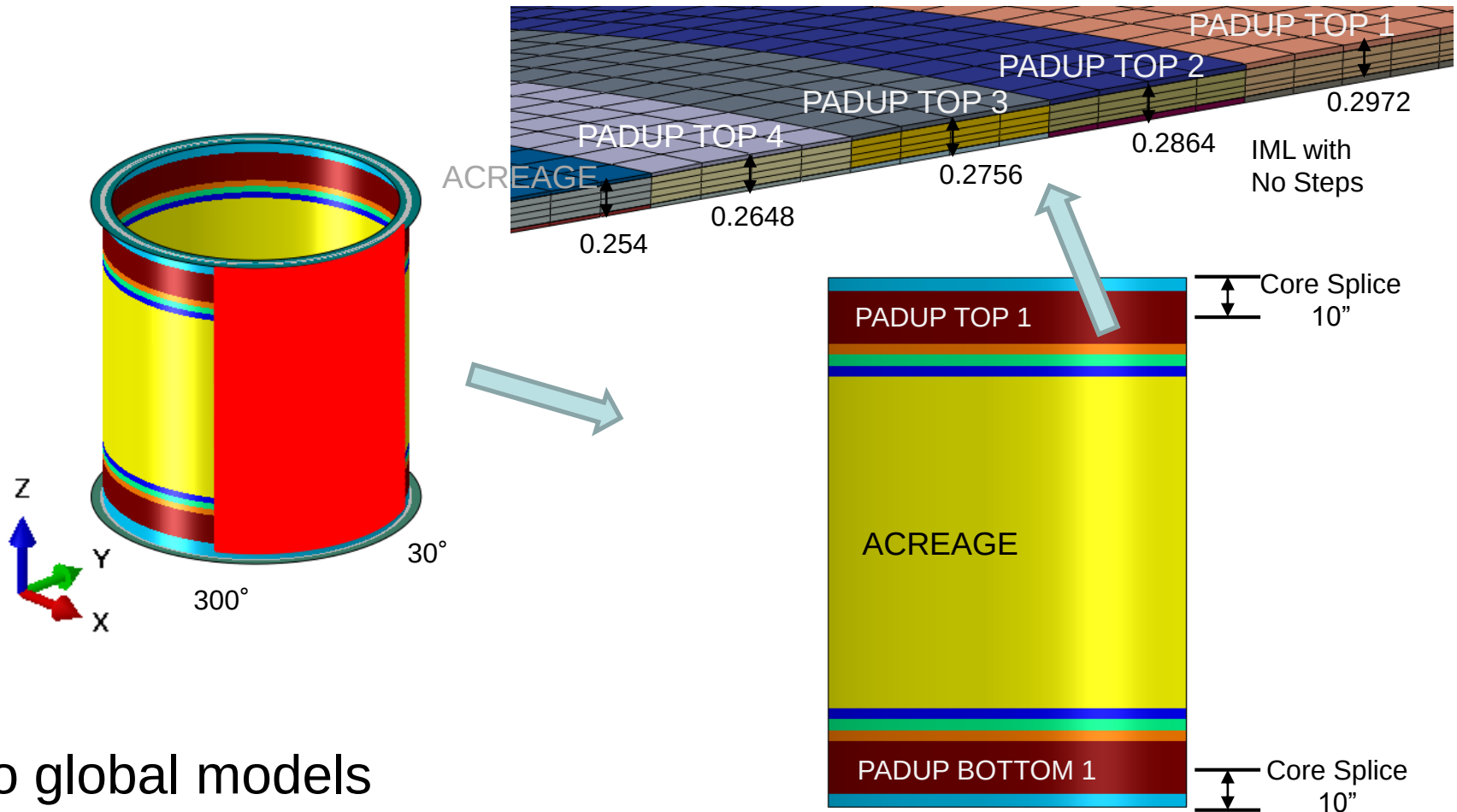


- **Core stresses**
 - Well below crush and shear allowables
- **Interface stresses**
 - Generally low predicted **normal stresses** (well below min. core strength), but **sharp spikes** predicted at core splice and last ply drop that **exceed minimum core and interface strengths**
 - Generally low predicted **shear stresses** (well below min. core strength), but **sharp spikes** predicted at core splice and last ply drop that **exceed core and interface strengths**
 - Though high, these normal and shear spikes are isolated to extremely small regions (on the order of the core cell size or less) and the model is not adequate to predict these stresses and they are believed to be artificial
 - Nonuniform mesh tied together can cause artificial stress concentrations
 - CTA8.2 **did not fail in or near ply drops**, even under large dynamic forces during failure
 - CTA8.2 **did not fail in or near core splices**, even under large dynamic forces during failure
 - Ply drop microscopy and measured geometry showed significantly longer ply-drop ramp length than models (0.5 in. vs. 0.028 in.)

Based on this evidence and general composite design guidelines regarding ply drops* (>20:1 taper here) and extremely isolated stress spikes, it is believed that these stress spikes are an artifact of the modeling approach

*See for example the Notes on Ply Drops in the Appendix

Global-Local CTA8.3 Finite Element Models



Two global models

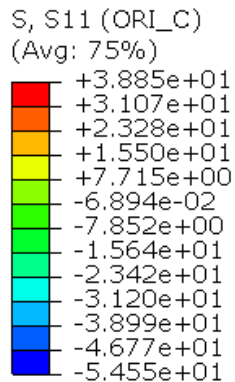
- Perfect mesh model
- Radial imperfection mesh model

Global-Local CTA8.3 Finite Element Analysis – Core Stresses

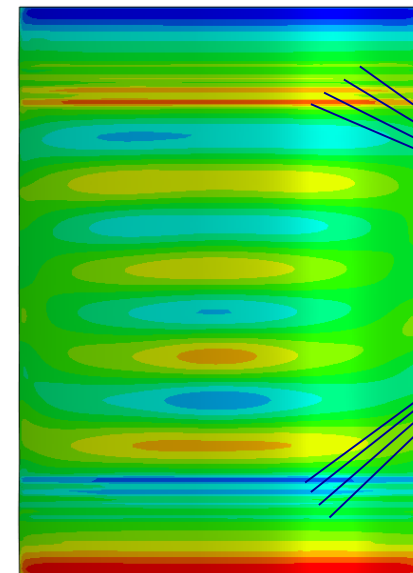
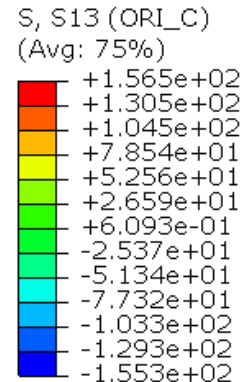


With radial imperfection, 530 kips*

Normal stress



L-direction
shear stress



Ply drops

*the peak load

CTA8.3 Global-Local Analysis

Perfect Geometry Summary



	Buckling Load (538 kips) Stresses, Strains, and Failure Indices						
	Facesheets			3.1 pcf Core		8.1 pcf Core	
Measure	Axial Strain ($\mu\epsilon$)	Hoop Strain ($\mu\epsilon$)	Tsai-Hill Index	σ_{11} (psi)	σ_{13} (psi)	σ_{11} (psi)	σ_{13} (psi)
Value	-5054	2945	0.429	45	-120	-16	157
Failure Index	0.64 [‡]	0.17 [^]	0.60 ^{**}	0.13 [†]	0.48 [†]	0.01 [†]	0.17 [†]
				0.17 [*]	0.60 [*]	0.01 [*]	0.21 [*]

[†]Core failure index = $\sigma_{FEA} / \sigma_{Hexcel \text{ typical strength}}$

^{*}Core failure index = $\sigma_{FEA} / \sigma_{Hexcel \text{ minimum strength}}$

[‡]Axial-strain failure index = $\epsilon_{FEA \text{ axial}} / -7926 \mu\epsilon$

[^]Hoop-strain failure index = $\epsilon_{FEA \text{ hoop}} / 17,400 \mu\epsilon$

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

CTA8.3 Global-Local Analysis with CTA8.2 Radial Imperfection Summary



	Buckling Load (530 kips) Stresses, Strains, and Failure Indices						
	Facesheets			3.1 pcf Core		8.1 pcf Core	
Measure	Axial Strain ($\mu\epsilon$)	Hoop Strain ($\mu\epsilon$)	Tsai-Hill Index	σ_{11} (psi)	σ_{13} (psi)	σ_{11} (psi)	σ_{13} (psi)
Value	-4922	2879	0.420	-55	-118	-33	155
Failure Index	0.62 [‡]	0.17 [^]	0.59 ^{**}	0.16 [†]	0.47 [†]	0.02 [†]	0.16 [†]
				0.21 [*]	0.59 [*]	0.03 [*]	0.21 [*]

[†]Core failure index = $\sigma_{FEA} / \sigma_{Hexcel \text{ typical strength}}$

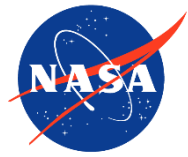
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[‡]Axial-strain failure index = $\epsilon_{FEA \text{ axial}} / -7926 \mu\epsilon$

[^]Hoop-strain failure index = $\epsilon_{FEA \text{ hoop}} / 17,400 \mu\epsilon$

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

Conclusions Based on CTA8.3 Finite Element Global-Local Analysis



- **Acceptable axial strains and Tsai-Hill index that compare well with shell model**
- **Low normal (radial) and reasonable shear stresses in the 8.1 pcf core**
- **Acceptable normal (radial) stress in the 3.1 pcf core**
- **Highest shear stress in the 3.1 pcf core predicted at the ply drops, but still within design requirements**



CTA8.3 Summary

- The closed-form loads for shear crimping, facesheet wrinkling, and facesheet dimpling are predicted to be within design requirements
- The predicted facesheet strains and Tsai-Hill failure indices are all predicted to be within design requirements
- The high core stresses predicted at core splice appear to be an artifact of the axisymmetric modeling approach
- The high core normal stresses at the ply drops were predicted to be very localized with axisymmetric model, but were not indicated with local solid model
 - It is believed that these stresses are and artifact of the axisymmetric modeling approach and not a concern
- The high core shear stresses were predicted to be very localized with the axisymmetric models but were not indicated with local solid model
 - Ply drops satisfy typical design guidelines for laminate
 - It is believed that these stresses are an artifact of the axisymmetric modeling approach and not a concern
- Risk reduction
 - Selective material characterization testing was completed
 - A half-length manufacturing demonstration barrels were fabricated before CTA8.3 test article

Analysis Summary for CTA8.4, 8.5, 8.5Alt, and 8.2B



Lowest failure indices obtained consistently using axial strains

- Meet design requirements

CTA	Analysis Type/Model	Axial Strain	Failure Index
8.4	Shell FEM/Perfect	-5085 $\mu\epsilon$	0.64
8.5		-4484 $\mu\epsilon$	0.57
8.5Alt		-5509 $\mu\epsilon$	0.70
8.2B		-5566 $\mu\epsilon$	0.70



Conclusions

- **CTA8.2**
 - Test-article failed prematurely due to core strength failure
 - Good evidence that mold release allowed slipping in the end rings, as intended
 - Ply drops did not appear to be a concern
 - Evaluation of core performance was enabled by axisymmetric and solid/continuum shell global-local finite element analysis
- **Future test articles**
 - When analyzed according to the new/enhanced analysis procedure, satisfy all design requirements



Appendices

- Summary of Results for CTA8.4, 8.5, 8.5Alt, and 8.2B
- Material Properties
- Approach for Calculating Co-Cured Knockdown (KD) Factor
- Closed-Form Sandwich Failure Calculations
- CTA8.2B Refined Global-Local Analysis
- CTA8.3 Material Characterization Testing Plan
- Notes on Ply Drops



Summary of Results for CTA8.4, 8.5, 8.5Alt, and 8.2B



CTA8.4 Summary

Analysis Type	Model	Metric	Value Unit	Failure Index
Closed Form	Perfect	Facesheet Wrinkling	2.37×10^6 lbf	0.55
		Facesheet Dimpling	3.38×10^7 lbf	0.04
		Shear Crimping	4.07×10^6 lbf	0.32
Shell FEA	Perfect	Axial Strain	-5085 $\mu\epsilon$	0.64
		Hoop Strain	2442 $\mu\epsilon$	0.14
		Tsai-Hill Index	0.449	0.63
	With Radial & Thickness Imperfections	Axial Strain	-5021 $\mu\epsilon$	0.63
		Hoop Strain	2509 $\mu\epsilon$	0.14
		Tsai-Hill Index	0.442	0.62
Axially Symmetric FEA	Perfect	Crush Stress	-612 psi	0.47
		Shear Stress	232 psi	0.31



CTA8.5 Summary

Analysis Type	Model	Metric	Value Unit	Failure Index
Closed Form	Perfect	Facesheet Wrinkling	3.80×10^6 lbf	0.32
		Facesheet Dimpling	7.72×10^7 lbf	0.02
		Shear Crimping	4.07×10^6 lbf	0.30
Shell FEA	Perfect	Axial Strain	-4484 $\mu\epsilon$	0.57
		Hoop Strain	1209 $\mu\epsilon$	0.07
		Tsai-Hill Index	0.400	0.56
	With Radial & Thickness Imperfections	Axial Strain	-4470 $\mu\epsilon$	0.56
		Hoop Strain	1265 $\mu\epsilon$	0.07
		Tsai-Hill Index	0.398	0.56
Axially Symmetric FEA	Perfect	Crush Stress	-342 psi	0.26
		Shear Stress	148 psi	0.20



CTA8.5 Alt Summary

Analysis Type	Model	Metric	Value Unit	Failure Index
Closed Form	Perfect	Facesheet Wrinkling	1.43×10^6 lbf	0.53
		Facesheet Dimpling	1.23×10^7 lbf	0.06
		Shear Crimping	4.07×10^6 lbf	0.19
Shell FEA	Perfect	Axial Strain	$-5509 \mu\epsilon$	0.70
		Hoop Strain	$1854 \mu\epsilon$	0.11
		Tsai-Hill Index	0.489	0.69
	With Radial & Thickness Imperfections	Axial Strain	$-5327 \mu\epsilon$	0.67
		Hoop Strain	$1840 \mu\epsilon$	0.11
		Tsai-Hill Index	0.472	0.66
Axially Symmetric FEA	Perfect	Crush Stress	-545 psi	0.42
		Shear Stress	143 psi	0.19



CTA8.2B Summary

Analysis Type	Model	Metric	Value Unit	Failure Index
Closed Form	Perfect	Facesheet Wrinkling	1.75×10^6 lbf	0.56
		Facesheet Dimpling	1.22×10^7 lbf	0.08
		Shear Crimping	2.71×10^6 lbf	0.36
Shell FEA	Perfect	Axial Strain	$-5566 \mu\epsilon$	0.70
		Hoop Strain	$2384 \mu\epsilon$	0.14
		Tsai-Hill Index	0.491	0.69
	With Radial & Thickness Imperfections	Axial Strain	$-2319 \mu\epsilon$	0.67
		Hoop Strain	$2289 \mu\epsilon$	0.13
		Tsai-Hill Index	0.464	0.65
Axially Symmetric FEA	Perfect	Crush Stress	-625 psi	0.48
		Shear Stress	231 psi	0.31



Material Properties

IM7/8552 Properties

• Stiffness

$E_1^{(4)}$ Msi	$E_2^{(4)}$ Msi	$\nu_{12}^{(4)}$	$G_{12}^{(4)}$ Msi	$G_{13}^{(1)}$ Msi	$G_{23}^{(2)}$ Msi
20.4	1.33	0.345	0.68	0.68	0.33

• Failure

$F_{1t}^{(2)}$ ksi	$F_{1c}^{(2),(3)}$ ksi	$F_{2t}^{(2)}$ ksi	$F_{2c}^{(2)}$ ksi	$F_{12}^{(2)}$ ksi	$\epsilon_c^{(4)}$ $\mu\epsilon$	$\epsilon_t^{(5)}$ $\mu\epsilon$
354.6	229.2	15.5	34.3	14.2	7,926	17,400

(1) Assumed $G_{13} = G_{12}$

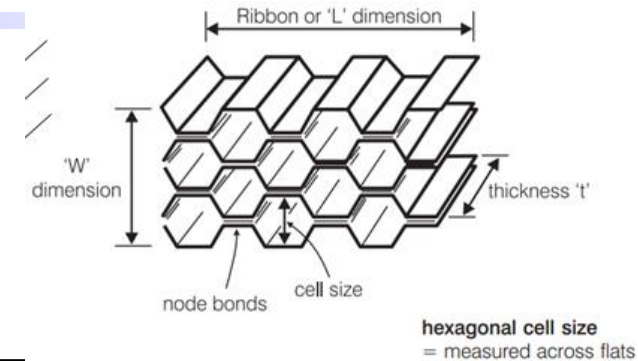
(2) Reeder, J. R., "Property Values for Preliminary Design of the Ares I Composite Interstage," Memo, 14 March 2007

(3) Before applying co-cure knockdown, see charts "Approach for Calculating Co-Cured Knockdown (KD) Factor" slides for knockdown calculations

(4) From SBKF coupon testing performed at NIAR

(5) Estimated from Clarkson, E., "Hexcel 8552 IM7 Unidirectional Prepreg 190 gsm & 35%RC Statistical Analysis Report for Combined NASA Samples (Glenn, Langley & Marshall) Test," NIAR Report #: NCP-RP-2016-001 NC, 2016.

Hexcel 1/8" AL 5056 Honeycomb Properties*



• Stiffness

Density	Through-thickness modulus, psi	L-direction shear modulus, psi	W-direction shear modulus, psi
3.1 pcf	97,000	45,000	20,000
8.1 pcf	435,000	143,000	51,000

• Strength

Density	Normal-dir., σ_{11} , typ. (psi)	Normal-dir., σ_{11} , min. (psi)	L-direction, σ_{13} , typ. (psi)	L-direction, σ_{13} , min. (psi)
3.1 pcf	350	260	250	200
8.1 pcf	1900	1300	945	740

*Anonymous, "HexWeb™ Honeycomb Attributes and Properties," Hexcel, TSB 120 (11/99), 1999.

Hysol EA 9396.6MD

Core Splice Properties



- Stiffnesses**

Tensile modulus, psi*	Poisson's ratio (assumed)	Shear modulus, psi (calculated)
290,000	0.2	120,833

- Stiffnesses in core splice region**

- Assumed to be larger of honeycomb or splice stiffness

	E_1 psi	E_2 psi	E_3 psi	$\nu_{12}, \nu_{13},$ ν_{23}	G_{12} psi	G_{13} psi	G_{23} psi
Hysol + 3.1pcf	435,000	290,000	290,000	0.2	143,000	120,833	120,833
Hysol + 3.1pcf	290,000	290,000	290,000	0.2	143,000	120,833	120,833

*Anonymous, "LOCTITE EA 9396.6MD AERO Epoxy Paste Adhesive (KNOWN AS Hysol EA 9396.6MD)," LOCTITE Technical Process Bulletin, Rev. 7/13.



Core-to-Face Strengths

- **Tensile strength in literature**
 - 1518 psi* (FM 309-1M to T40/5320)
 - 1257 psi* (AF-555M to IM7/MTM45)
 - 1250 psi* (FM-300K to T40/5320)
 - 686 psi* (XMTA-241/PM15 to IM7/MTM45)
 - 1092 psi† (AF 555L)
- **Shear strength in literature**
 - 5224 psi† (AF 555L)
 - 2479 psi (FM 209 to CYCOM 5320-1 OOA Composite (Uni-Tape))‡
- **Available properties in literature are greater than core properties for 3.1 pcf core, so core should fail before bond**

*Hou, et al., "Evaluation of Sandwich Structure Bonding In Out-of Autoclave processing," SAMPE Technical Conference, Salt Lake City, UT, Oct. 2010.

†Collett, A., "Cylindrical Test Article Design for NESC Shell Buckling Knockdown Factors Assessment," ATK Doc. #TR023120, 2008.

‡FM 209-1 Film Adhesive Technical Data Sheet, Cytec Engineered Materials, AEAD-00086, 2012



Approach for Calculating Co-Cured Knockdown (KD) Factor

Co-Cured Knockdown Factor

$$\text{KD Factor} = \frac{\sigma_{cc}}{\sigma}$$

where

σ_{cc} – co-cured compressive strength of facesheet

σ – compressive strength without co-cured imperfections

Co-Cured Knockdown Factor Literature Review

- Ref. 1: T800/5320, 0.04 in.-thick quasi-isotropic facesheets, FM300 adhesive film, aluminum honeycomb core, 1/8 in. cells (40 psi cure)
 - 0.75 KD factor
- Ref. 2: Generic
 - Up to 30% KD (KD factor of 0.7)
- Ref. 3: AS4-8552 PW, 0.06 in.– 0.09 in.-thick facesheets, Scotch-Weld AF 555L adhesive film, Hexcel 1/8-5052-0.002 (8.1 pcf) aluminum honeycomb
 - 0.6 KD factor
- Ref. 4: Generic
 - 30%-50% KD (KD factor 0.5 – 0.7)
- **Summary: typically cited values are 25% – 50% KD
or 0.75 – 0.50 KD factor**

Co-Cured Knockdown Factor Calculations for CTA8.2/2B (1/3)

$$\mathbf{KD\ Factor} = \frac{\sigma_{cc}}{\sigma}$$

where

σ_{cc} – co-cured compressive strength of facesheet

σ – compressive strength without co-cured imperfections

Available information

σ_x – angle-ply facesheet strength

$F1_c$ – compressive strength of lamina in fiber direction

→ Need to calculate compressive strength of facesheet in fiber direction, σ_u , based on available σ_x

Then,

$$\mathbf{KD\ Factor} = \frac{\sigma_u}{F1_c}$$

Co-Cured Knockdown Factor Calculations for CTA8.2/2B (2/3)

Mechanics of materials/rule-of-mixtures approach (Ref. 5)

$$\sigma_U = \frac{\sigma_x - E_0 \epsilon_x (1 - V)}{V}$$

where

σ_U – unidirectional lamina axial strength

σ_x – measured angle-ply laminate strength

E_0 – axial modulus of the ($\pm 60^\circ$) laminae material

ϵ_x – measured angle-ply laminate axial strain at failure

V – volume fraction of axial laminae (0°)

Co-Cured Knockdown Factor Calculations for CTA8.2/2B (3/3)

- Edgewise compressive strength of sandwich construction (ASTM D364, CTA8.2/2B acreage facesheet [$\pm 60/0$]_s)
 - Average compressive strength $\sigma_x = 61.779$ ksi
 - Average strain at failure $\epsilon_x = 7926 \mu\epsilon$
- $V = 0.333$ (two out of six facesheet plies are 0°)
- $E_0 = 1.497$ Msi (lamination-theory-based calculation)
- $F1_c = 229.2$ ksi (compressive axial strength, Mil 17 4.2.22)
 - Based on cross-ply (0/90) laminate compression test

$$\sigma_U = 161.75 \text{ ksi}$$

$$\text{KD factor} = 0.71$$

Co-Cure Knockdown References

1. Nettles, A., "Some Examples of the Relation Between Processing and Damage Tolerance," <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130000533.pdf>
2. Campbell, F. C., "Manufacturing Processes for Advanced Composites," Chapter 8, Elsevier Advanced Technology, Oxford, UK, 2004.
3. Collet, A., "Cylindrical Test Article Design for NESC Shell Buckling Knockdown Factors Assessment," Report TR023120, ATK Space Systems, Clearfield, UT, April 2008.
4. Zhou, X., "Characterization and Validation of Material Knockdown Factors for Sandwich Structures," White Paper, ATK Mission Systems, Clearfield, UT, February 2008.
5. Welsh, J. S., Adams, D. F., "Testing of Angle-Ply Laminates to Obtain Unidirectional Composite Compression Strength," *Composites Part A*, Vol. 28(A), 1997, pp. 387-396



Closed-Form Sandwich Failure Calculations



Introduction

- **Objective**

- Use closed-form equations for common “local” sandwich failure modes: **shear crimping, facesheet wrinkling, facesheet dimpling**

- **Background**

- Most such equations in the literature were developed for isotropic facesheets
- The equations developed for composite facesheets typically use the equivalent engineering extensional stiffnesses rather than the equivalent engineering flexural stiffnesses, which can be significantly lower

- **Method**

- In an effort to be conservative, equations from multiple sources were used and calculations were modified to use both extensional and bending stiffnesses

- **References**

- Reese, C. D., and Bert, C. W. “Buckling of orthotropic sandwich cylinders under axial compression and bending,” *Journal of Aircraft*, vol. 11, 1974, pp. 207-212.
- Anonymous, “Buckling of Thin-Walled Circular Cylinders,” NASA SP-8007, August 1968.
- Camarda, C.J., “Tests of Graphite/Polyimide Sandwich Panels in Uniaxial Edgewise Compression,” NASA TP 1785, December 1980.
- Anonymous, “HexWeb™ HONEYCOMB SANDWICH DESIGN TECHNOLOGY,” Hexcel Publication No. AGU 075b, 2000, pg. 27.
- Vinson, J.R., The Behavior of Sandwich Structures of Isotropic and Composite Materials, Technomic, Lancaster 1999.

Closed-Form Calculations: Nomenclature



E_x, E_y, G_{xy} = facesheet effective engineering in-plane
extensional stiffnesses

ν_{xy}, ν_{yx} = facesheet effective engineering in-plane
extensional Poisson's ratios

E_{xb}, E_{yb}, G_{xyb} = facesheet effective engineering in-plane
flexural stiffnesses

ν_{xyb}, ν_{yxb} = facesheet effective engineering in-plane
flexural Poisson's ratios

E_c = core thickness-direction stiffness

G_{xz} = core axial-transverse shear stiffness

h_f = distance between facesheet midsurfaces, $t_c + t_f$

t_f = facesheet thickness

t_c = core thickness

d = core cell diameter

Closed-Form Calculations: Modified Facesheet Dimpling Equations



$$\sigma_{crDimpVinson} = \frac{2 \sqrt{E_x E_y}}{1 - \nu_{xy} \nu_{yx}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpVinsonb} = \frac{2 \sqrt{E_{xb} E_{yb}}}{1 - \nu_{xyb} \nu_{yxb}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpCamarda} = 0.825 \frac{\pi^2}{3} \left(\frac{2 \sqrt{E_x E_y} + \nu_{yx} E_x + \nu_{xy} E_y}{4(1 - \nu_{xy} \nu_{yx})} + G_{xy} \right) \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpCamardab} = 0.825 \frac{\pi^2}{3} \left(\frac{2 \sqrt{E_{xb} E_{yb}} + \nu_{yxb} E_{xb} + \nu_{xyb} E_{yb}}{4(1 - \nu_{xyb} \nu_{yxb})} + G_{xyb} \right) \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpSullins} = \frac{2 \sqrt{E_x E_y}}{1 - \nu_{xy} \nu_{yx}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpSullins2} = \frac{2 E_x}{1 - \nu_{xy} \nu_{yx}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpSullinsb} = \frac{2 \sqrt{E_{xb} E_{yb}}}{1 - \nu_{xyb} \nu_{yxb}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpSullinsb2} = \frac{2 E_{xb}}{1 - \nu_{xyb} \nu_{yxb}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpHexWeb} = 2 \sqrt{E_x E_y} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpHexWeb2} = 2 E_x \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpHexWebb} = 2 \sqrt{E_{xb} E_{yb}} \left(\frac{t_f}{d} \right)^2$$

$$\sigma_{crDimpHexWebb2} = 2 E_{xb} \left(\frac{t_f}{d} \right)^2$$

Closed-Form Calculations: Modified Facesheet Wrinkling Equations



$$\sigma_{crFW} = \sqrt{\frac{2}{3} \frac{t_f}{t_c} \frac{E_c \sqrt{E_x E_y}}{1 - \nu_{xy} \nu_{yx}}}$$

$$\sigma_{crFWb} = \sqrt{\frac{2}{3} \frac{t_f}{t_c} \frac{E_c \sqrt{E_{xb} E_{yb}}}{1 - \nu_{xyb} \nu_{yxb}}}$$

$$\sigma_{crFWCamarda} = 0.33 \sqrt{\frac{E_c t_f}{\sqrt{E_x E_y} t_c}} \sqrt{E_x E_y}$$

$$\sigma_{crFWCamarda2} = 0.33 \sqrt{\frac{E_c t_f}{E_x t_c}} E_x$$

$$\sigma_{crFWCamardab} = 0.33 \sqrt{\frac{E_c t_f}{\sqrt{E_{xb} E_{yb}} t_c}} \sqrt{E_{xb} E_{yb}}$$

$$\sigma_{crFWCamardab2} = 0.33 \sqrt{\frac{E_c t_f}{E_{xb} t_c}} E_{xb}$$

$$\sigma_{crFWSullins} = 0.5 \left(\frac{G_{xz} E_c \sqrt{E_x E_y}}{1 - \nu_{xy} \nu_{yx}} \right)^{0.33}$$

$$\sigma_{crFWSullins2} = 0.5 \left(\frac{G_{xz} E_c E_x}{1 - \nu_{xy} \nu_{yx}} \right)^{0.33}$$

$$\sigma_{crFWSullinsb} = 0.5 \left(\frac{G_{xz} E_c \sqrt{E_{xb} E_{yb}}}{1 - \nu_{xy} \nu_{yx}} \right)^{0.33}$$

$$\sigma_{crFWSullinsb2} = 0.5 \left(\frac{G_{xz} E_c E_{xb}}{1 - \nu_{xy} \nu_{yx}} \right)^{0.33}$$

$$\sigma_{crFWHexWeb} = 0.5 (G_{xz} E_c \sqrt{E_x E_y})^{0.33}$$

$$\sigma_{crFWHexWeb2} = 0.5 (G_{xz} E_c E_x)^{0.33}$$

$$\sigma_{crFWHexWebb} = 0.5 (G_{xz} E_c \sqrt{E_{xb} E_{yb}})^{0.33}$$

$$\sigma_{crFWHexWebb2} = 0.5 (G_{xz} E_c E_{xb})^{0.33}$$

Closed-Form Calculations: Modified Shear Crimping Equations



$$\sigma_{crRBcoreshear} = \frac{G_{xz} h f^2}{2 t f t c}$$

$$\sigma_{crCSVinson} = \frac{G_{xz} t c}{2 t f}$$

$$\sigma_{crCSSullins} = \frac{h f^2 G_{xz}}{2 t f t c}$$

CTA 8.3 Closed-Form Failure Predictions*



Facesheet Wrinkling

	PcrFWVinson	PcrFWVinsonb	PcrFWCamarda	PcrFWCamarda2	PcrFWCamardab	PcrFWCamardab2	PcrFWSullins
Load (lb)	4.30E+06	3.32E+06	1.59E+06	1.79E+06	1.09E+06	1.52E+06	2.34E+06
Margin of Safety	4.54	3.28	1.05	1.31	0.41	0.96	2.02
Failure Index	0.13	0.17	0.35	0.31	0.51	0.37	0.24

	PcrFWSullins2	PcrFWSullinsb	PcrFWSullinsb2	PcrFWHexWeb	PcrFWHexWeb2	PcrFWHexWebb	PcrFWHexWebb2	PcrFW8007
Load (lb)	2.54E+06	1.83E+06	2.27E+06	2.21E+06	2.39E+06	1.73E+06	2.14E+06	2.72E+06
Margin of Safety	2.27	1.36	1.92	1.85	2.08	1.22	1.76	2.50
Failure Index	0.22	0.30	0.24	0.25	0.23	0.32	0.26	0.20

Facesheet Dimpling

	PcrDimpVinson	PcrDimpVinsonb	PcrDimpCamarda	PcrDimpCamardab	PcrDimpSullins	PcrDimpSullins2	PcrDimpSullinsb
Load (lb)	1.21E+07	7.25E+06	1.86E+07	1.41E+07	1.21E+07	1.54E+07	7.25E+06
Margin of Safety	14.65	8.34	22.97	17.11	14.65	18.87	8.34
Failure Index	0.05	0.08	0.03	0.04	0.05	0.04	0.08

	PcrDimpSullinsb2	PcrDimpHexWeb	PcrDimpHexWeb2	PcrDimpHexWebb	PcrDimpHexWebb2	PcrDimp8007
Load (lb)	1.40E+07	1.02E+07	1.29E+07	4.81E+06	9.26E+06	1.42E+07
Margin of Safety	16.99	12.13	15.67	5.19	10.93	17.34
Failure Index	0.04	0.05	0.04	0.12	0.06	0.04

Shear Crimping

	PcrCSVinson	PcrCSSullins
Load (lb)	2.71E+06	3.50E+06
Margin of Safety	2.50	3.50
Failure Index	0.20	0.16

$$\text{Margin of Safety} = \frac{P_{fail}}{1.4 P_{cr}^{FEA Perfect}} - 1$$

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

*See Appendix for equations

Reese, C. D., and Bert, C. W. “Buckling of orthotropic sandwich cylinders under axial compression and bending,” *Journal of Aircraft*, vol. 11, 1974, pp. 207-212.



Shear Crimping (Eq. 9): $\sigma_{cr} = \frac{G_{xz} h^2}{2 c t}$

Anonymous, “Buckling of Thin-Walled Circular Cylinders,” NASA SP-8007, August 1968.



Facesheet Wrinkling (Eq. 95): $\sigma_X = 0.5(E_{sec}E_ZG_{xz})^{\frac{1}{3}}$

Facesheet Dimpling (Eq. 94): $\sigma_X = 2.2 \frac{4EE_{tan}}{(\sqrt{E} + \sqrt{E_{tan}})^2} \left(\frac{t}{S}\right)^2$

Camarda, C.J., “Tests of Graphite/Polyimide Sandwich Panels in Uniaxial Edgewise Compression,” NASA TP 1785, December 1980.

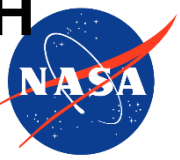


Shear Crimping (Eq. B9):
$$\sigma_{\text{crim}} = \frac{(t_c + t_f)^2}{2t_f t_c} G_{c_{xz}}$$

Skin Wrinkling (Eq. B4):
$$\sigma_{\text{wr}} = 0.33 E_f \left(\frac{E_{c_z} t_f}{E_f t_c} \right)^{\frac{1}{2}}$$

Dimpling (Eq. B3):

$$\sigma_{\text{dim}} = 0.825 \frac{\pi^2}{3} \left[\frac{2 \sqrt{E_{f_x} E_{f_y}} + \bar{\mu}_{yx} E_{f_x} + \bar{\mu}_{xy} E_{f_y}}{4(1 - \bar{\mu}_{xy} \bar{\mu}_{yx})} + G_{f_{xy}} \right] \left(\frac{t_f}{s} \right)^2$$



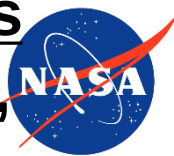
Last three equations, Appendix III, pg. 27:

Shear Crimping: $P_b = t_c G_c b$

Skin Wrinkling: $\sigma_{CR} = 0.5 [G_c E_c E_f]^{\frac{1}{3}}$

Intra Cell Buckling: $\sigma_{CR} = 2E_f \left(\frac{t_f}{s} \right)^2$

Vinson, J.R., The Behavior of Sandwich Structures of Isotropic and Composite Materials, Technomic, Lancaster 1999.



Shear Crimping (Eq. 9.36): $\sigma_{CR} = \frac{G'_{cx} h_c}{2t_f}$

Facesheet Wrinkling (Eq. 9.40): $\sigma_{CR} = \left[\frac{2 t_f}{3 h_c} \frac{E'_c \sqrt{E_{fx} E_{fy}}}{(1 - \nu_{xy} \nu_{yx})} \right]^{\frac{1}{2}}$

Facesheet Dimpling (Eq. 9.42): $\sigma_{CR} = \frac{2(E_{fxT} E_{fy})^{\frac{1}{2}}}{(1 - \nu_{xy} \nu_{yx})} \left(\frac{t_f}{d} \right)^2$



CTA8.3 Material Characterization Testing Plan



Planned CTA8.3 Coupon Testing

Test Type	ASTM Standard	Drawing Number	Comments ¹⁻³	Number of Specimens
Sandwich Flexural Properties	D7249	1284802-1	Core transition, padup	6
		1284802-2	8.1 pcf core, padup	6
		1284802-3	3.1 pcf core, padup	6
		1284802-4	3.1 pcf core	6
Core Shear Strength	C393	1284803-1	Core transition type 1, padup	6
		1284803-2	Core transition type 2, padup	6
		1284803-3	8.1 pcf core, padup	6
		1284803-4	3.1 pcf core, padup	6
		1284803-5	3.1 pcf core	6
Sandwich Edgewise Compressive Strength	C364	1284804-1	Core transition, padup	6
		1284804-2	8.1 pcf core, padup	6
		1284804-3	3.1 pcf core, padup	6
		1284804-4	3.1 pcf core	6
Sandwich Flatwise Tensile Strength	C297	1284806-3	8.1 pcf core, FM 300-2M film	6
		1284806-4	3.1 pcf core, FM 300-2M film	6
		1284806-5	8.1 pcf core, FM 209-1M film	6
		1284806-6	3.1 pcf core, FM 209-1M film	6
Core Compressive Strength and Modulus (Stabilized)	C365	1284806-1	8.1 pcf core, FM 300-2M film	6
		1284806-2	3.1 pcf core, FM 300-2M film	6

¹ Acreage layup, [+30/-30/90/-30/+30/core/+30/-30/90/-30/+30], unless otherwise stated

² Padup layup [+30/-45/-30/45/90/45/-30/-45/+30/core/+30/-45/-30/45/90/45/-30/-45/+30]

³ Laminate 4 x acreage facesheet layup [$\pm 30/90/\mp 30$]_{4s}



Planned CTA8.3 Coupon Testing

Test Type	ASTM Standard	Drawing Number	Comments ¹⁻³	Number of Specimens
Sandwich Climbing Drum Peel	D1781	1284807-1	8.1 pcf core, FM 300-2M film	6
		1284807-2	3.1 pcf core, FM 300-2M film	6
		1284807-3	8.1 pcf core, FM 209-1M film	6
		1284807-4	3.1 pcf core, FM 209-1M film	6
Core (Plate) Shear Strength and Modulus	C273 (Tension)	1284808-1	Core transition, FM 300-2M film	6
		1284808-2	Core transition, FM 209-1M film	6
		1284808-3	8.1 pcf core, FM 300-2M film	6
		1284808-4	3.1 pcf core, FM 300-2M film	6
		1284808-5	8.1 pcf core, FM 209-1M film	6
		1284808-6	3.1 pcf core, FM 209-1M film	6
Tensile Strength, Modulus, and Poisson Ratio	D3039	1284805-2	Laminate tension (4 x acreage facesheet layup)	6
Compressive Strength, Modulus, and Poisson Ratio	D6641	1284805-1	Laminate compression (4 x acreage facesheet layup)	6
Fiber, Resin, and Void Content	D792/ D3171 (Method I) /D2734	N/A	Extracted from different panels	6

¹ Acreage layup, [+30/-30/90/-30/+30/core/+30/-30/90/-30/+30], unless otherwise stated

² Padup layup [+30/-45/-30/45/90/45/-30/-45/+30/core/+30/-45/-30/45/90/45/-30/-45/+30]

³ Laminate 4 x acreage facesheet layup [$\pm 30/90/\mp 30$]_{4s}



Notes on Ply Drops



Notes on Ply Drops

- **CMH17-3G, 2012: Section 8.7.2.2 Internal ply drop-offs, pg. 8-53.**
 - “Internal ply drop-offs are common features of laminated structural components. In-plane membrane and bending loads lead to interlaminar shear and normal stresses at such features. **A common aerospace industry design rule is to ignore such interlaminar stresses if the ply drop-off ratio (distance between successive ply drops to ply thickness) is greater than 10:1.** If the taper in the laminate due to ply drops is steeper than 10:1, the interlaminar shear and normal stresses are determined via either strength of materials or fine grid finite element analysis methods, and strength margins calculated using those stresses and appropriate allowable strength values.”
- **Kirsch, M., “Composite Crew Module: Design,” NESC-RP- 06-019, 2011 pg. 76.**
 - “Laminate transition taper rates are dependent on the load condition of the part. **Primary load directions should have a minimum taper rate of 20 to 1** and secondary load directions should have a minimum taper rate of 10 to 1. These taper rates should minimize, but not eliminate, the secondary effects on the laminate due to the change in load line, kicks in plies, etc. **When applying these guidelines, the resulting laminates will have the equivalent strength of the nominally tested laminate.**”