

Design, Analysis And Manufacturing Of Tow-Steered Composite Shells Using Fiber Placement

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What Are Tow-Steered Composites?

In conventional laminates, all fibers in a given ply are straight and parallel with the same orientation.

In **advanced, tow-steered** (a.k.a. variable stiffness) structures, the fiber orientation within each ply varies continuously over the structure's planform.

Tow-steered laminates 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 are **enabling technology** for cost-effective fabrication of highly tailored structures.

Study Overview

Want structure that better resists bending from flight loads.

Desire high axial stiffness on shell crown and keel (replicate I-beam flanges), with high shear stiffness on the shell sides (I-beam shear web).

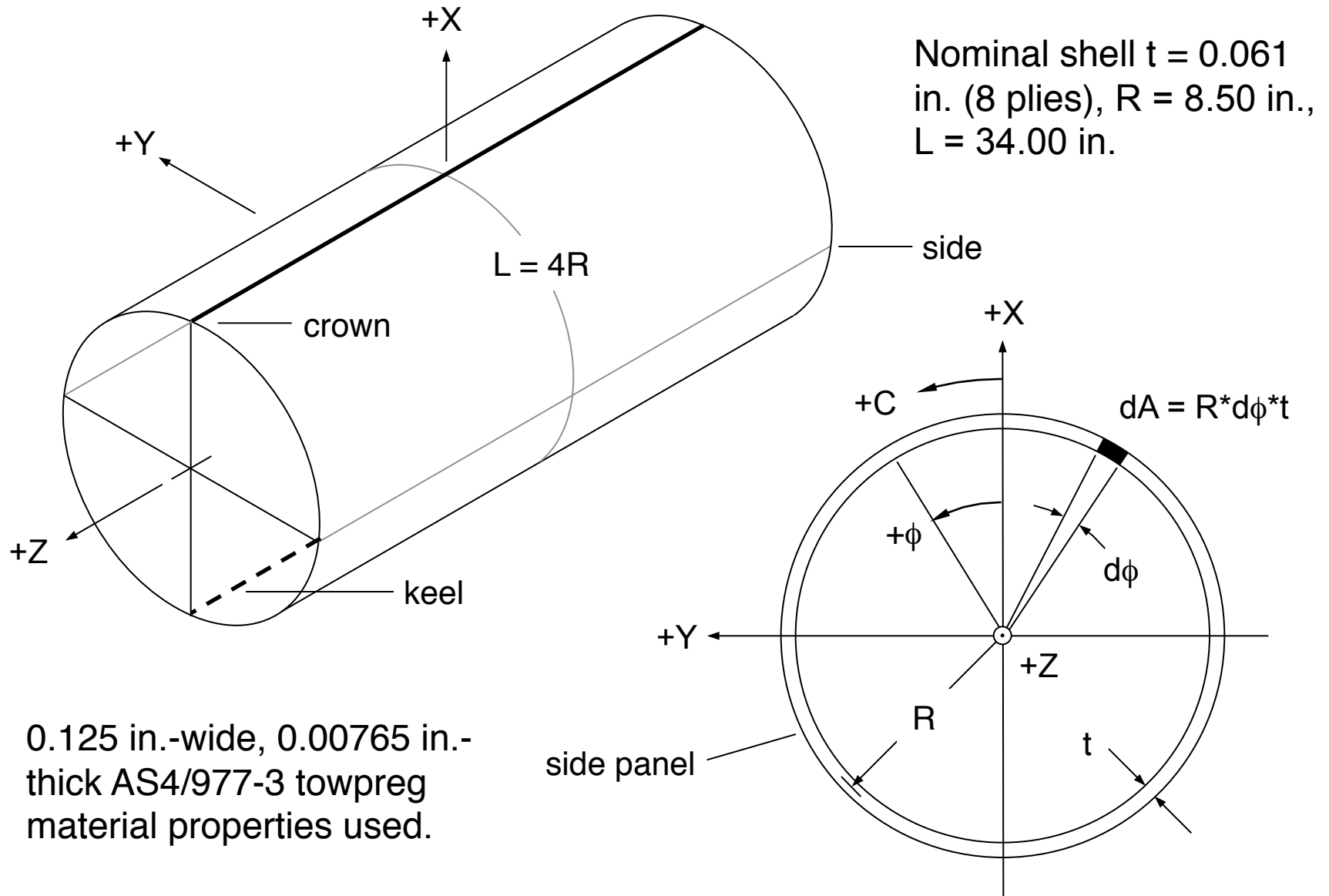
Use tow steering capabilities of fiber placement machines to align fibers to vehicle loads.

Predict structural performance of cylindrical shells without cutouts, rings or stiffeners.

Determine steps required for detailed design and manufacture.

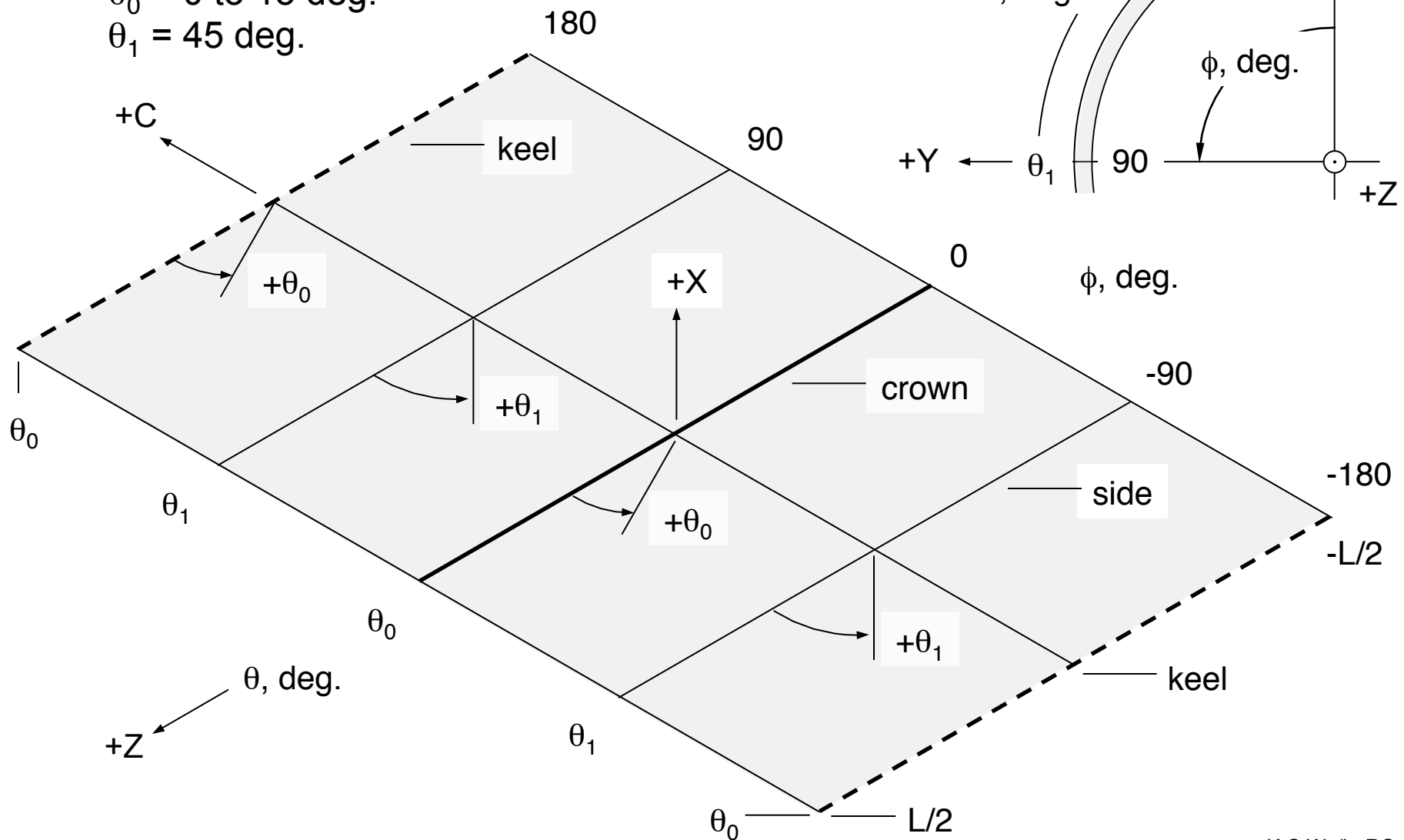
Evaluate geometric imperfections and laminate thicknesses of cured shells.

Tow-Steered Shell Configuration



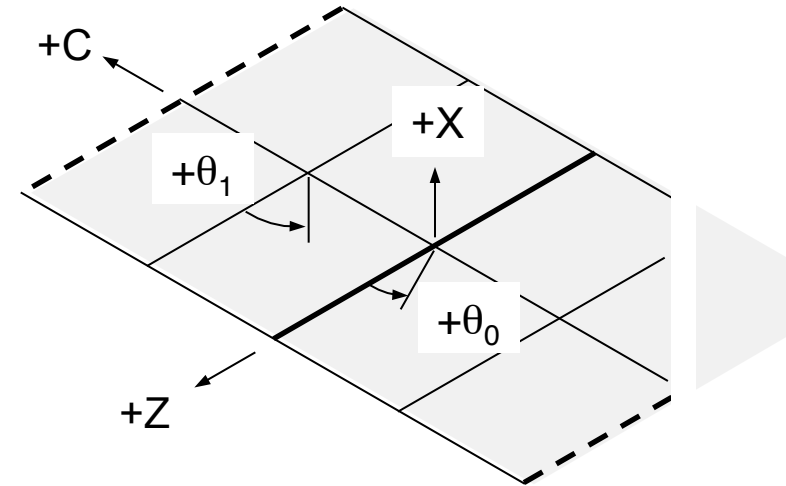
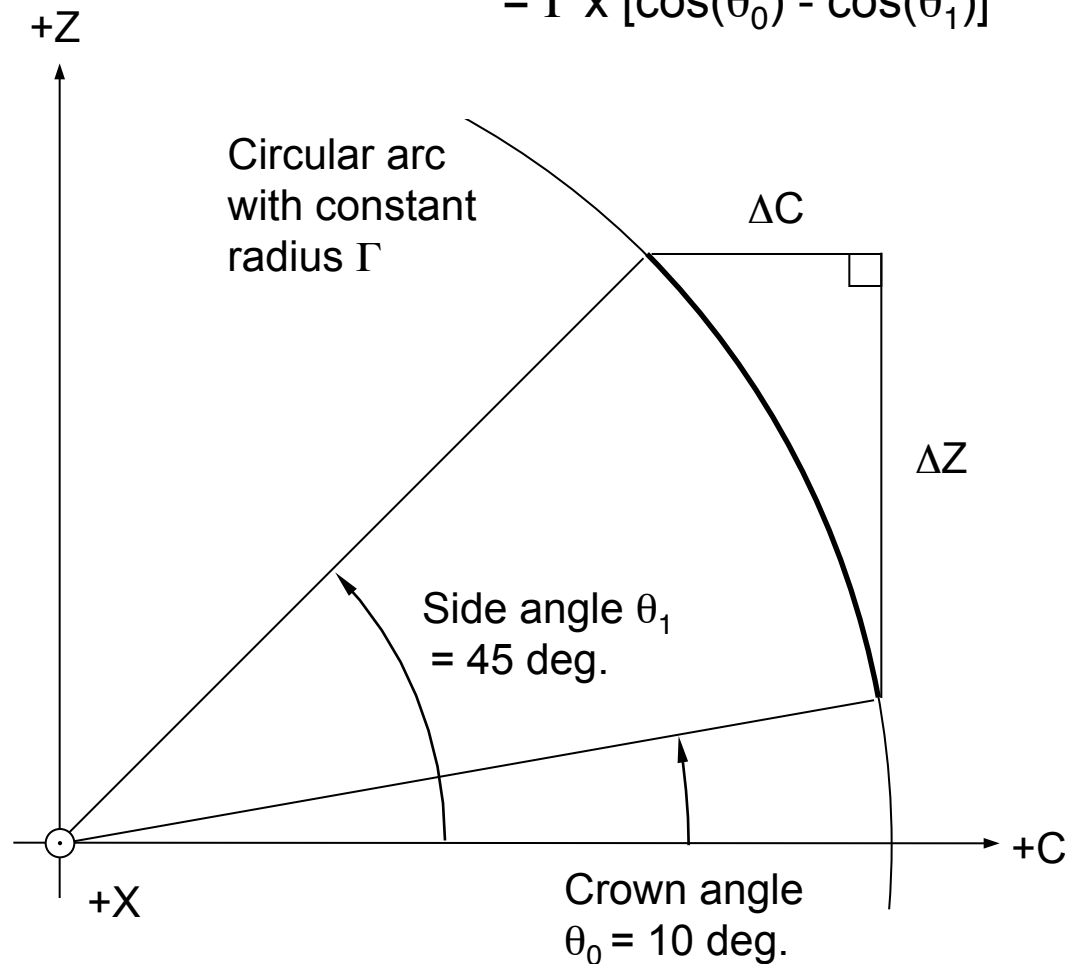
Tow-Steered Shell Platform

Nominal $[\pm 45/\pm \Theta]_s$ layup.

 $\theta_0 = 0 \text{ to } 15 \text{ deg.}$
$$\theta_1 = 45 \text{ deg.}$$


Reference Tow Path Definition

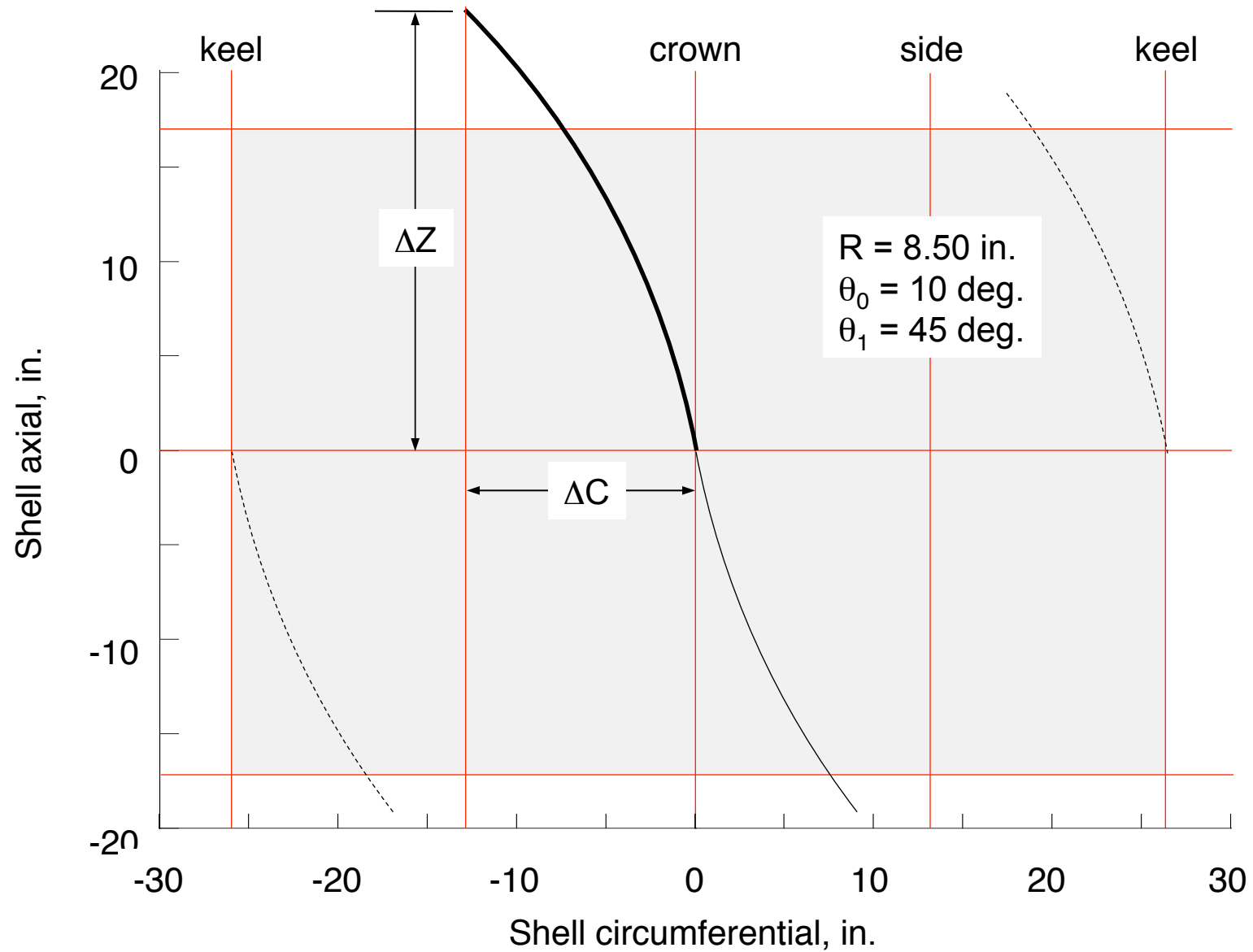
$$\begin{aligned}\Delta C &= \text{circumference}/4 \\ &= \pi R/2 \\ &= \Gamma \times [\cos(\theta_0) - \cos(\theta_1)]\end{aligned}$$



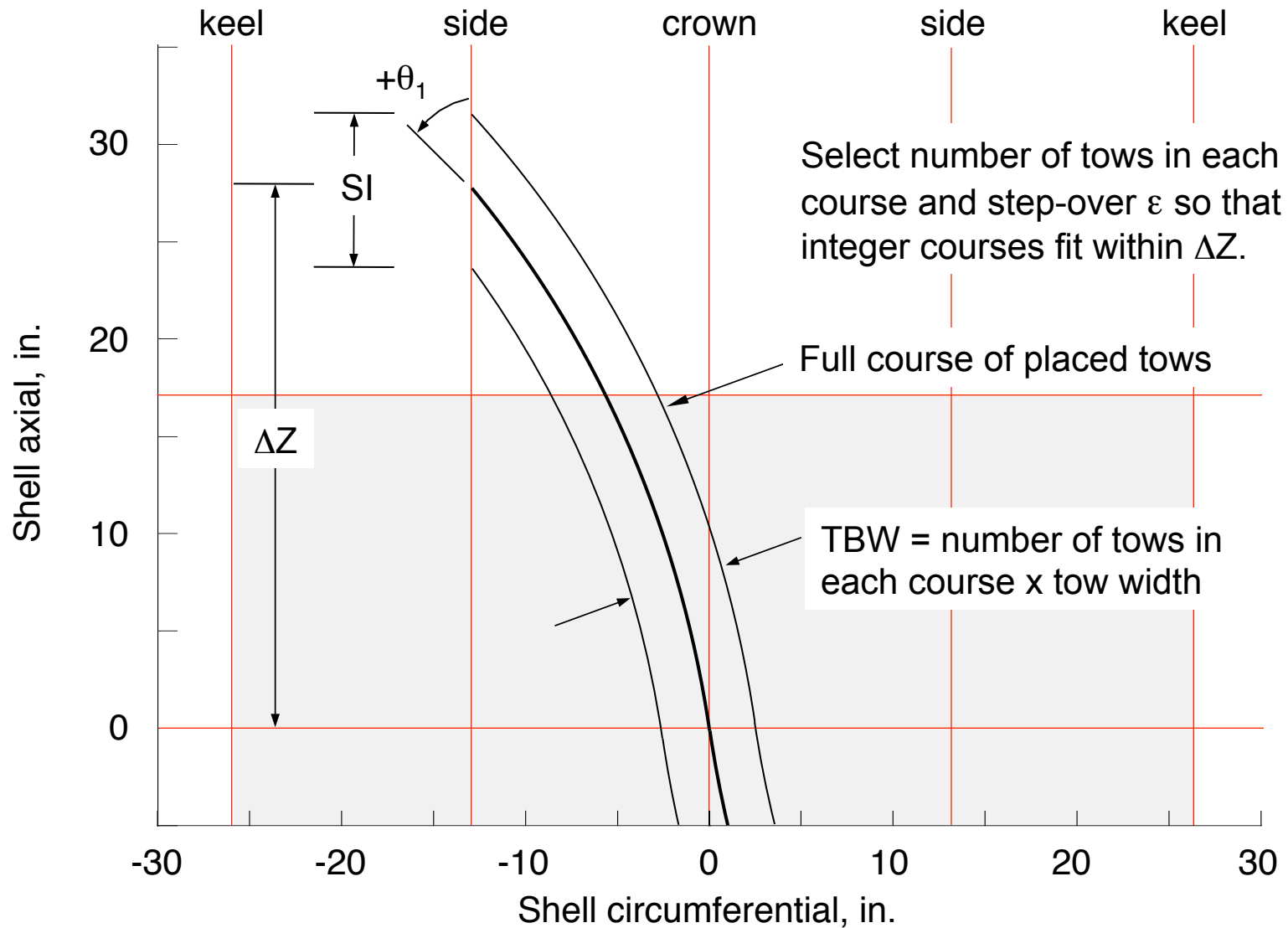
Given R , θ_i , compute $\Gamma = 48.080 \text{ in.}$ using equations for ΔC above.

$$\begin{aligned}\Delta Z &= \Gamma \times [\sin(\theta_1) - \sin(\theta_0)] \\ &= 25.649 \text{ in.}\end{aligned}$$

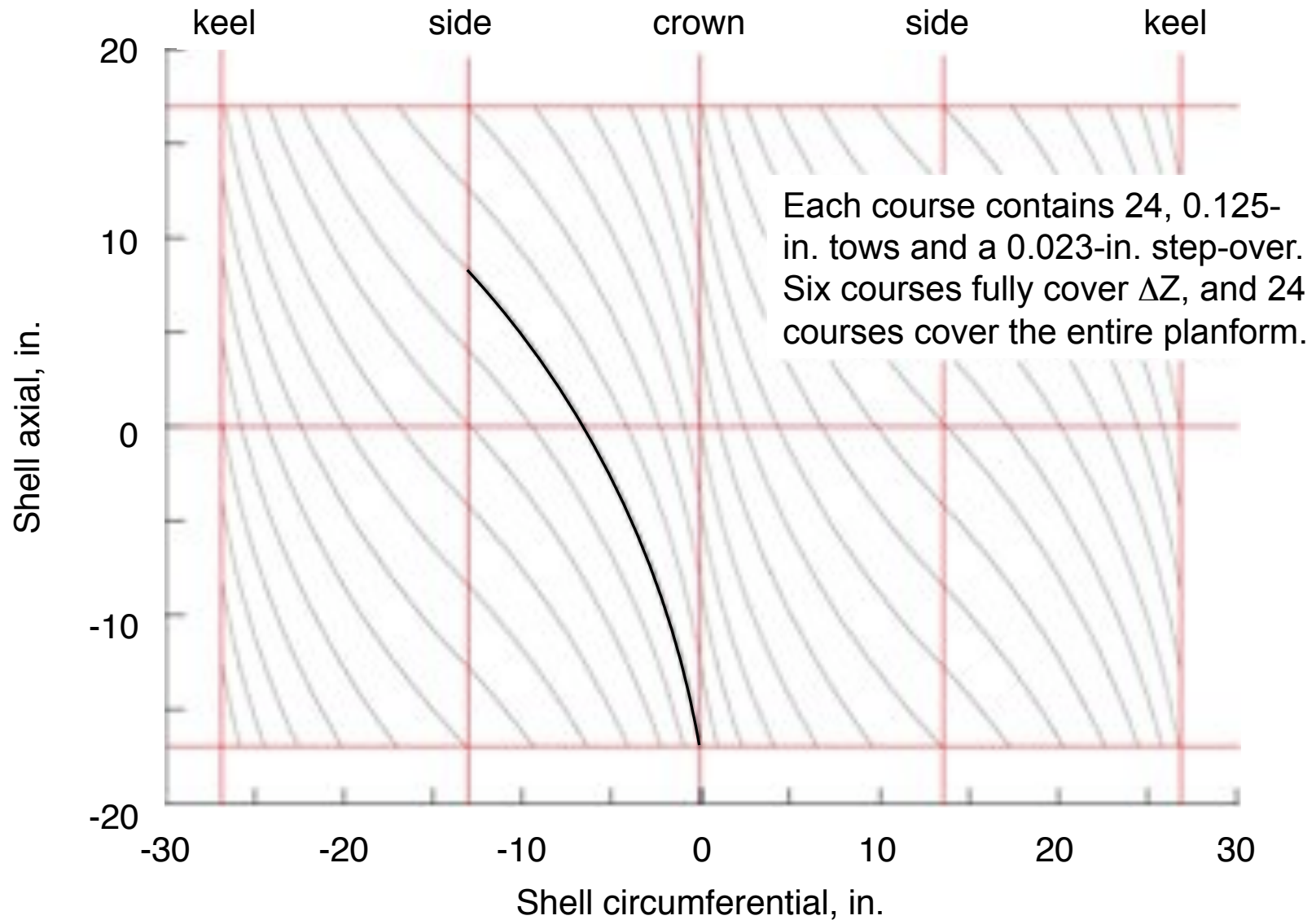
Reference Course On Shell Planform



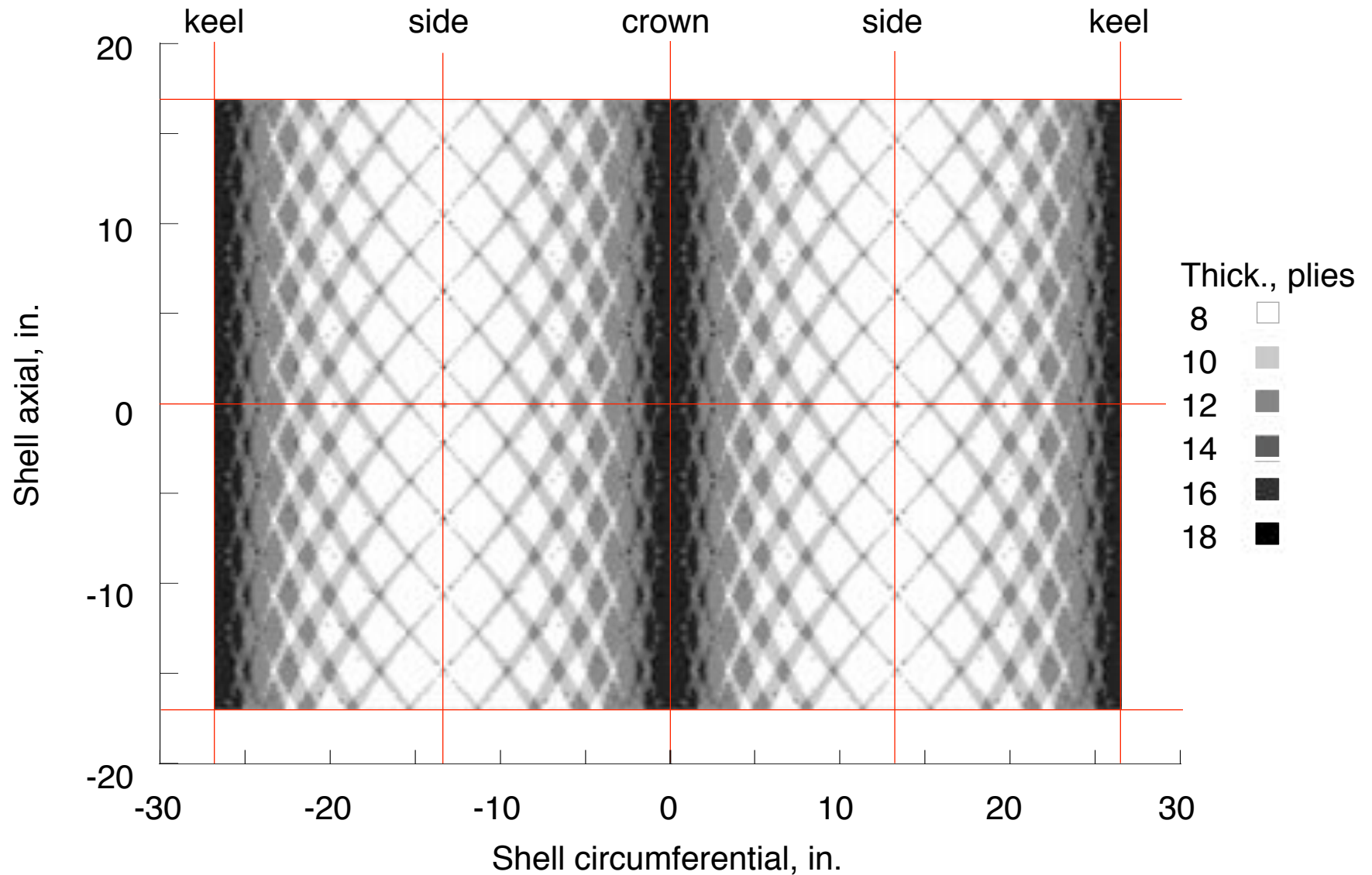
Computation Of Course Shift Increment



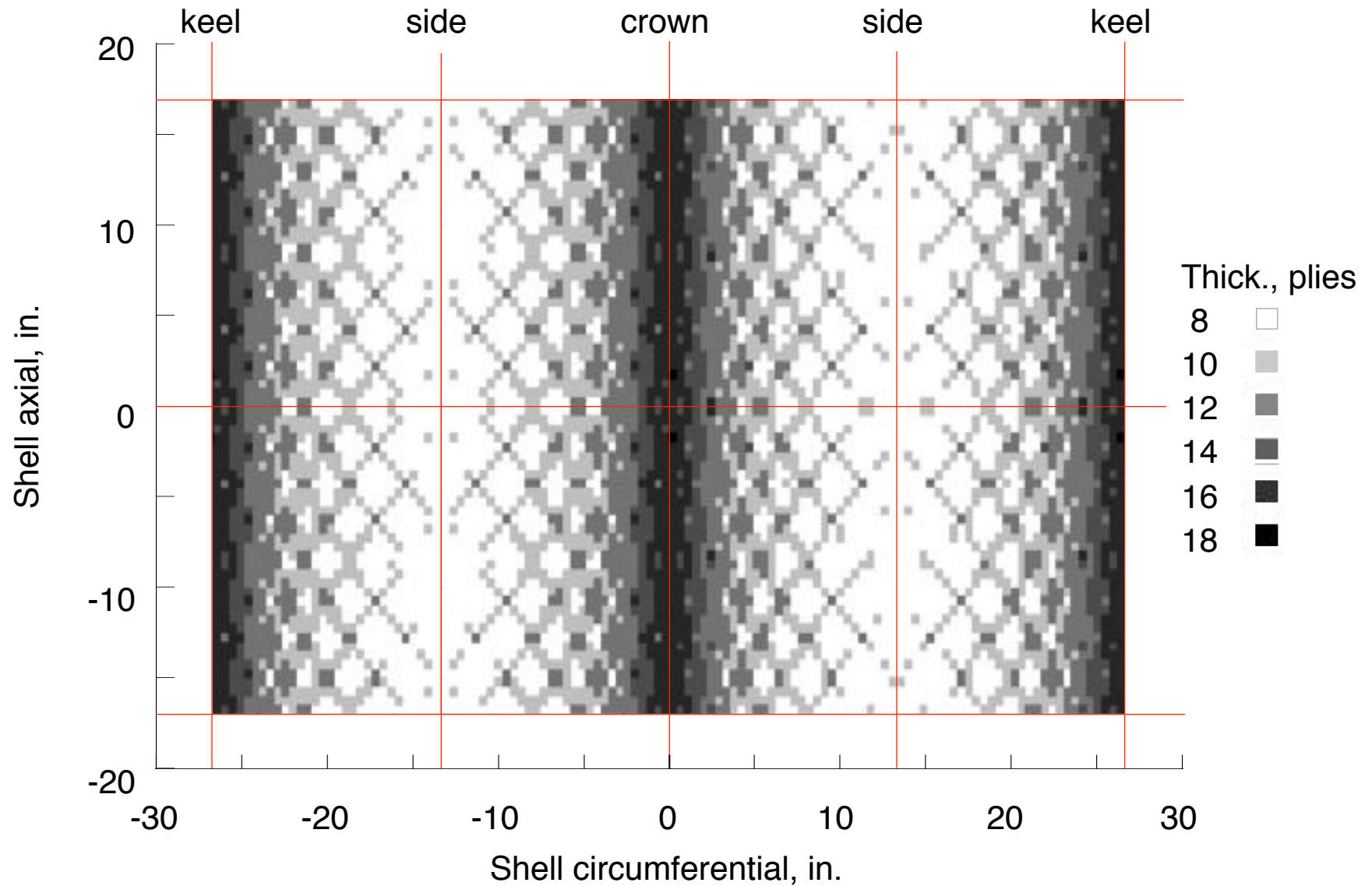
Shell Planform With All Course Centerlines Shown



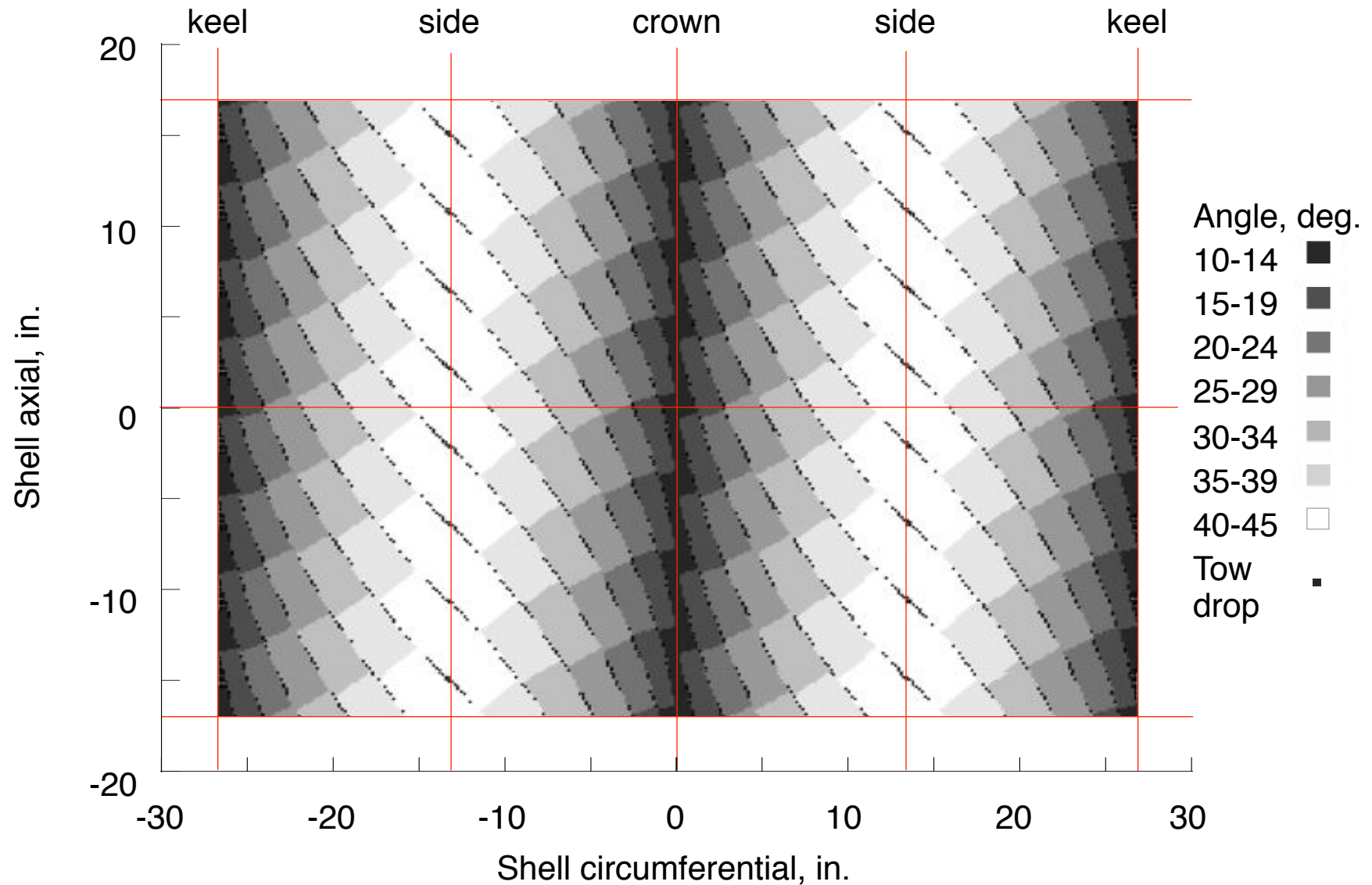
Shell With Overlaps Predicted Laminate Thicknesses



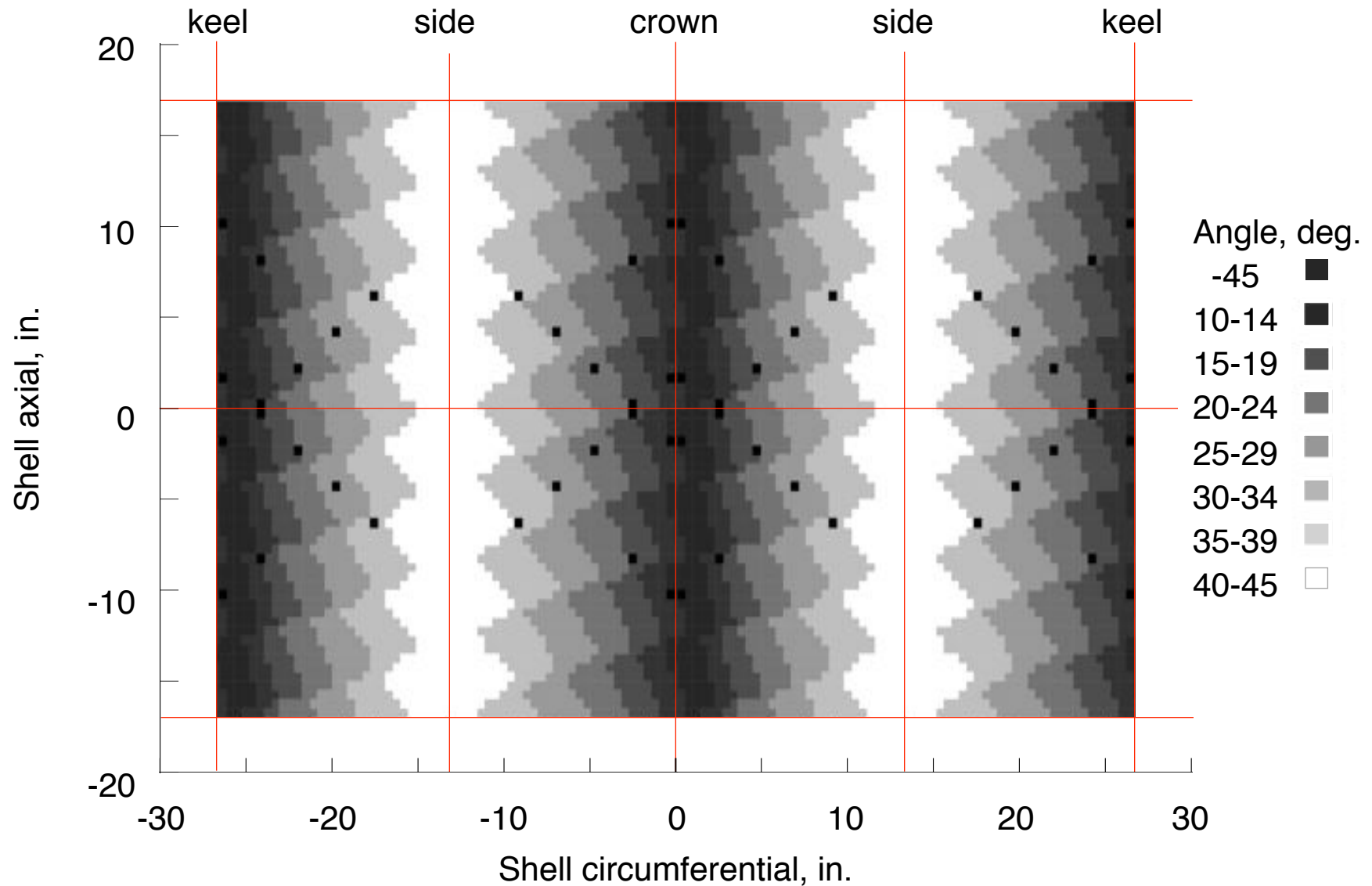
Shell With Overlaps FE Model Laminate Thicknesses



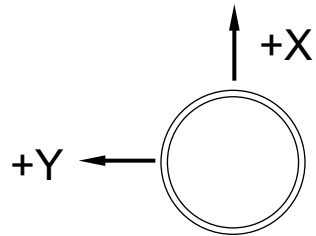
Shell Without Overlaps Predicted Ply 3 Fiber Angles



Shell Without Overlaps FE Model Ply 3 Fiber Angles

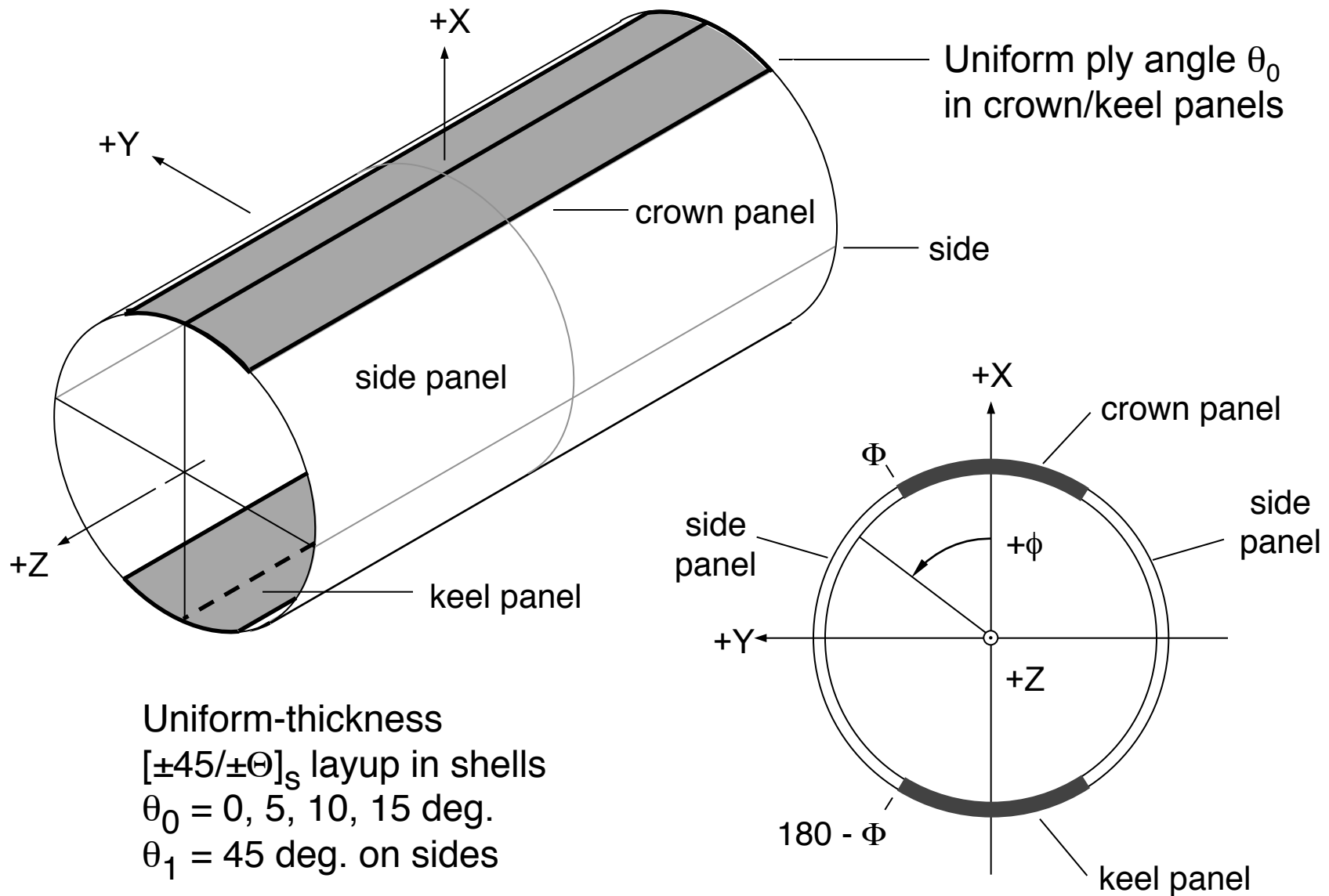


Predicted Shell Structural Performance



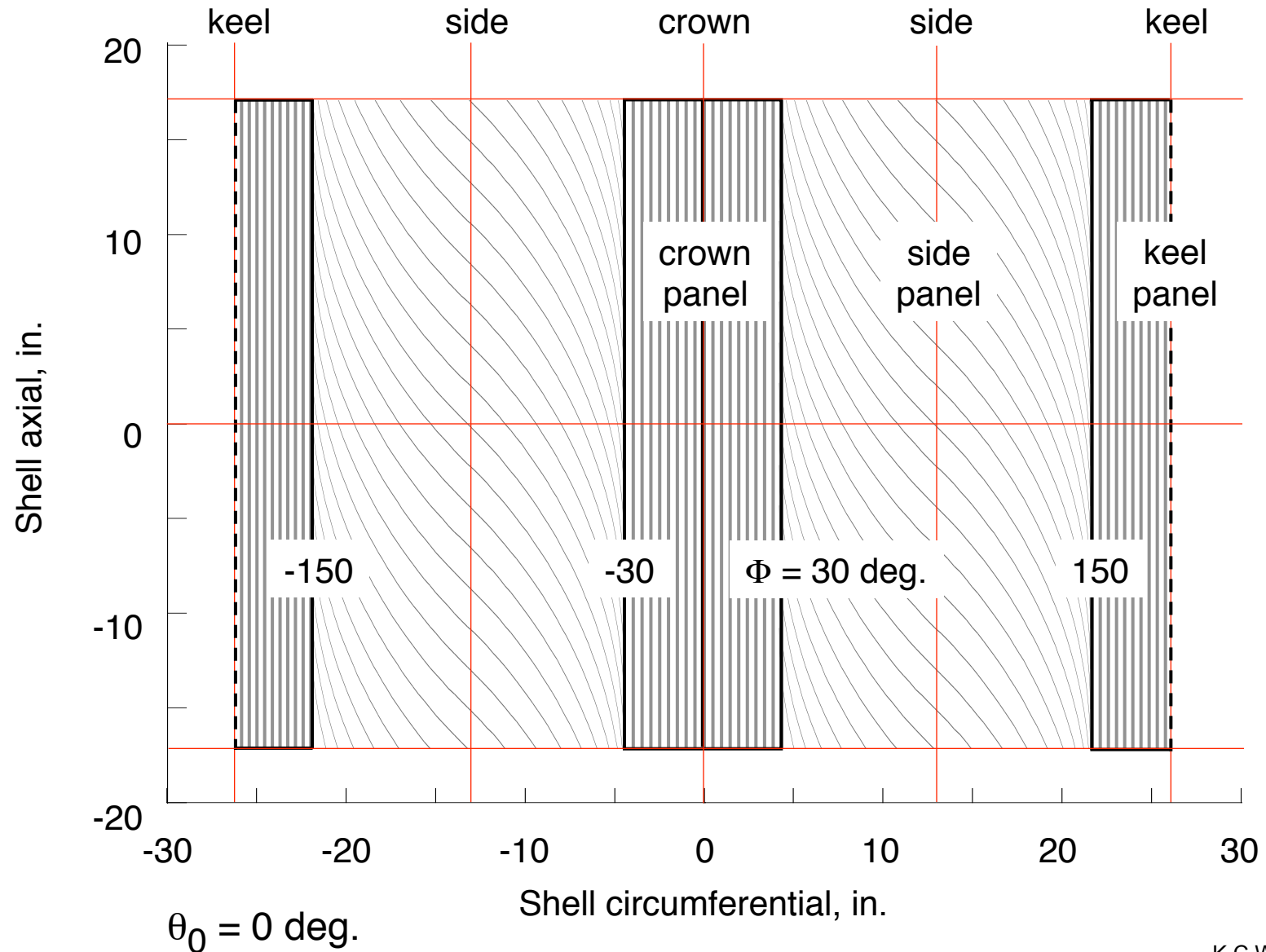
	Shell With Overlaps	Shell Without Overlaps	Quasi-Isotropic Shell
	X-axis bending stiffness, Mlb-in ²		
Closed-form	--	429.4	871.4
FE analysis	522.3	438.8	868.1
	X-axis buckling moment, klb-in.		
FE analysis	367.2	287.2	428.3
	Y-axis bending stiffness, Mlb-in ²		
Closed-form	--	771.2	871.4
FE analysis	1465.8	780.9	868.1
	Y-axis buckling moment, klb-in.		
FE analysis	589.3	210.2	428.3

Tow-Steered Shell With Discrete Crown/Keel Panels

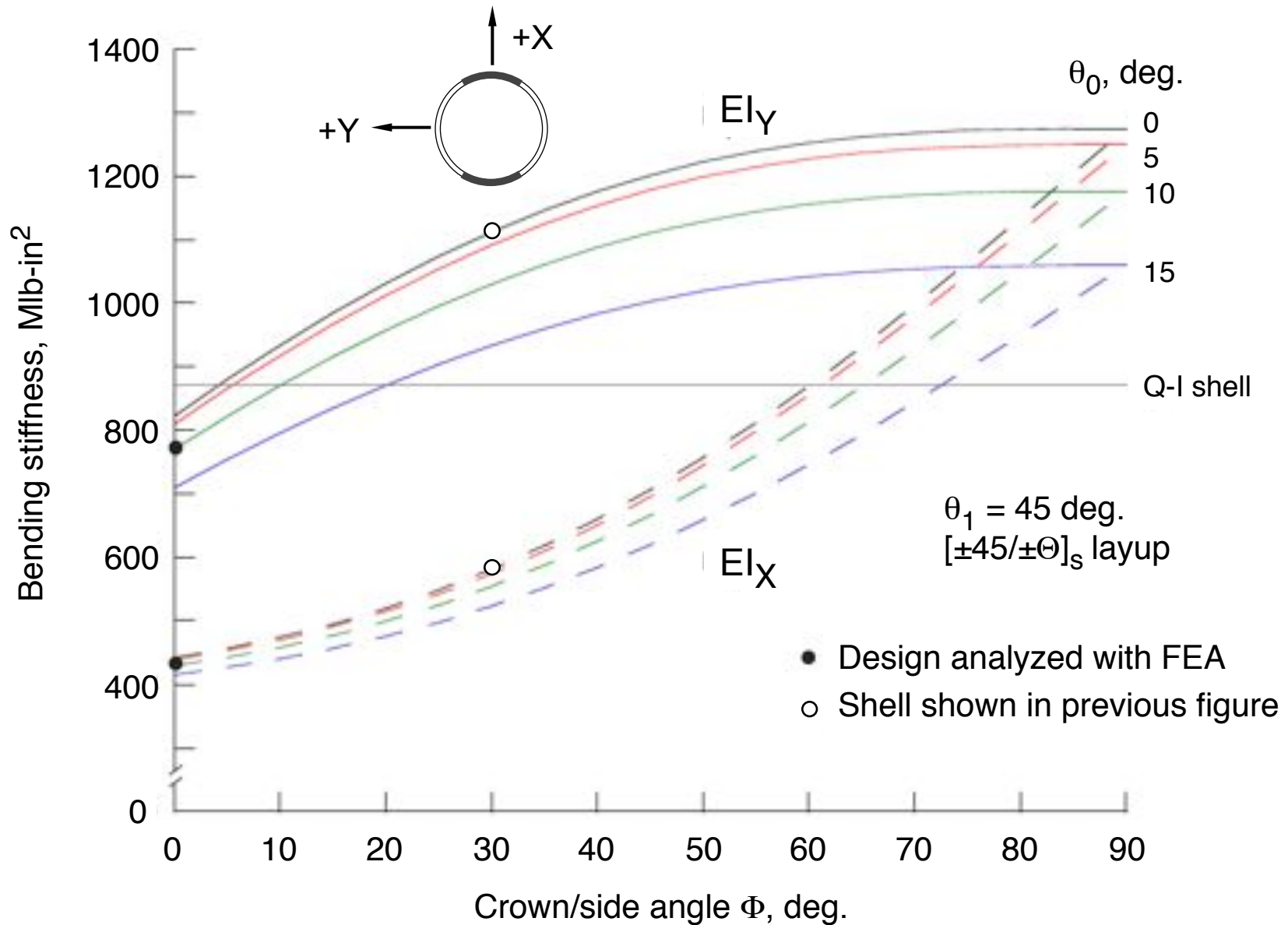


Planform Of Shell With Discrete Crown/Keel Panels

(notional tow paths shown)



Bending Stiffnesses For Shells Without Overlaps



Fiber Placement System Used To Manufacture Shells



Ingersoll Machine Tool FPS used to build shells at NCAM/MAF.

FPS has seven DOF in workspace.

Up to 24 x 1/8 inch-wide tows can be placed, with individual tow feed and cut/restart for overlap control.

Provides precise, accurate control of tow placement and steering.

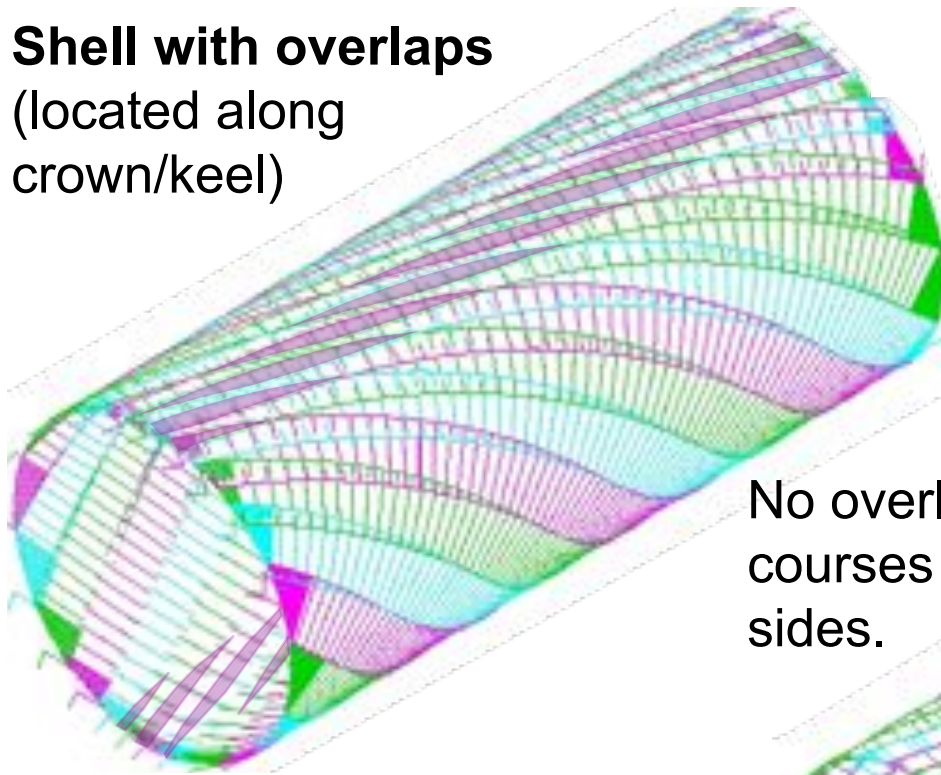
Shells were built on a constant-diameter hollow steel mandrel (16.266-in. OD at RT).



Steered Courses Defined For Shell Manufacturing

Shell with overlaps

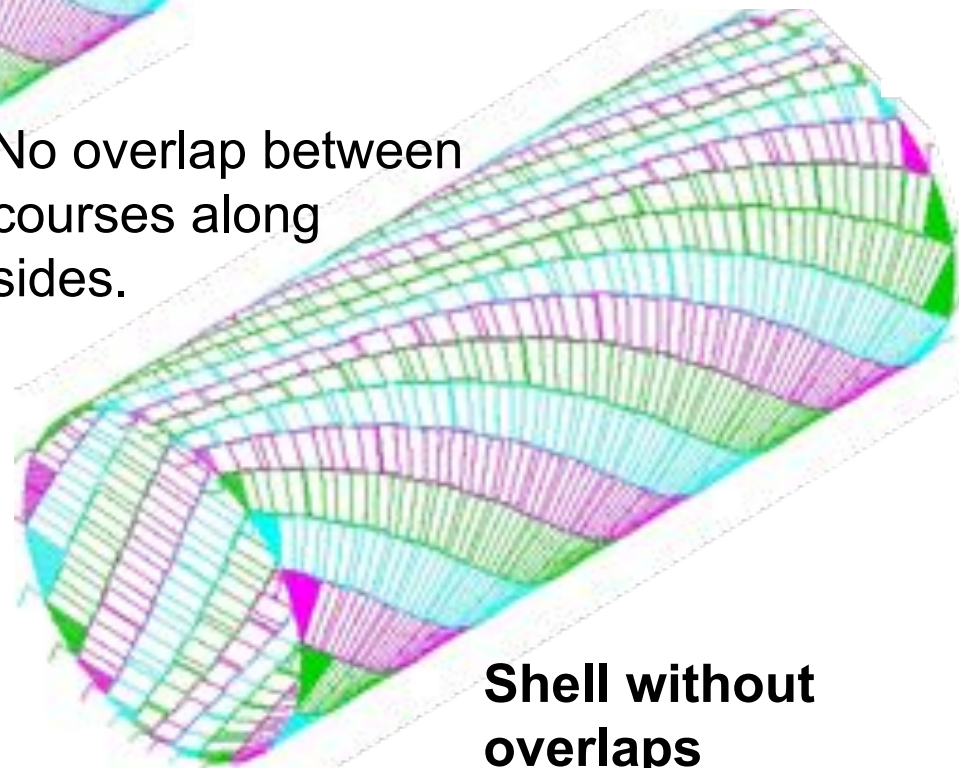
(located along crown/keel)



12 straight-fiber ($\pm 45^\circ$) or 22 tow-steered ($\pm \theta$) courses needed to fully cover mandrel used.

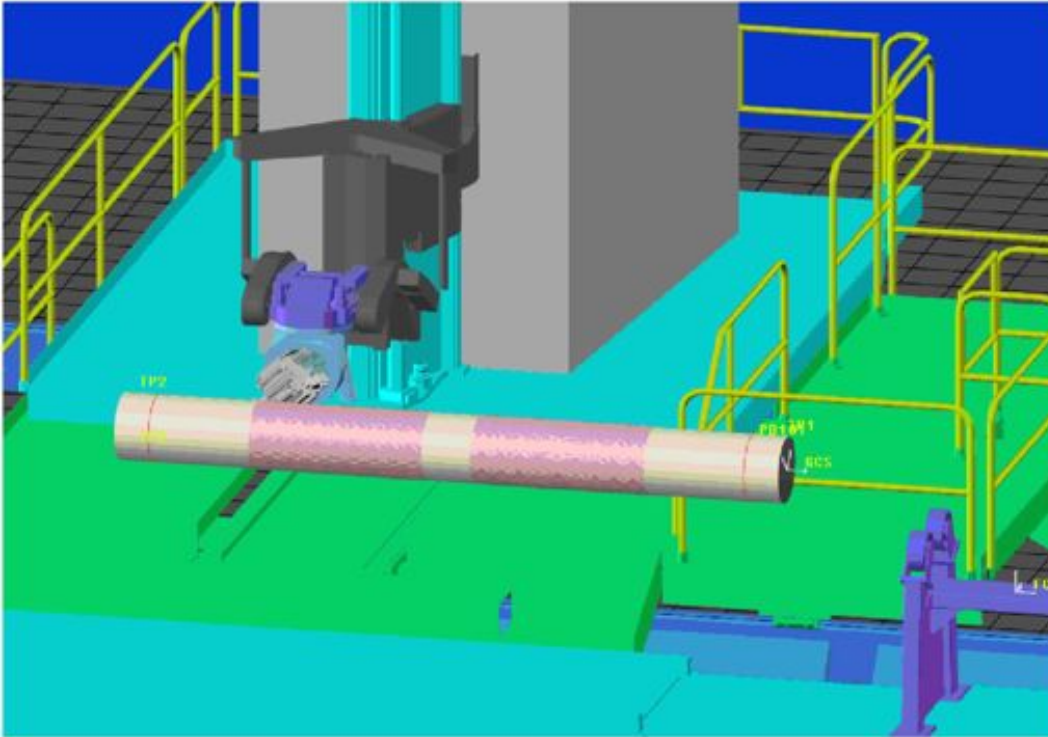
No overlap between courses along sides.

Gap between adjacent courses adjusted based on diameter of mandrel and previous plies.



Shell without overlaps

Extensive Manufacturing Simulations Performed

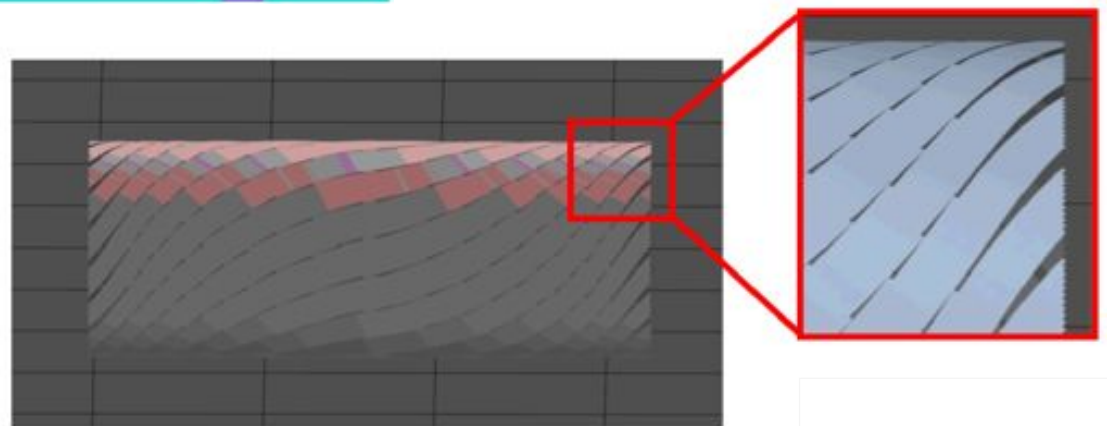


ADOPTTECH generated straight and steered course data, with head position, orientation and number of tows placed along courses.

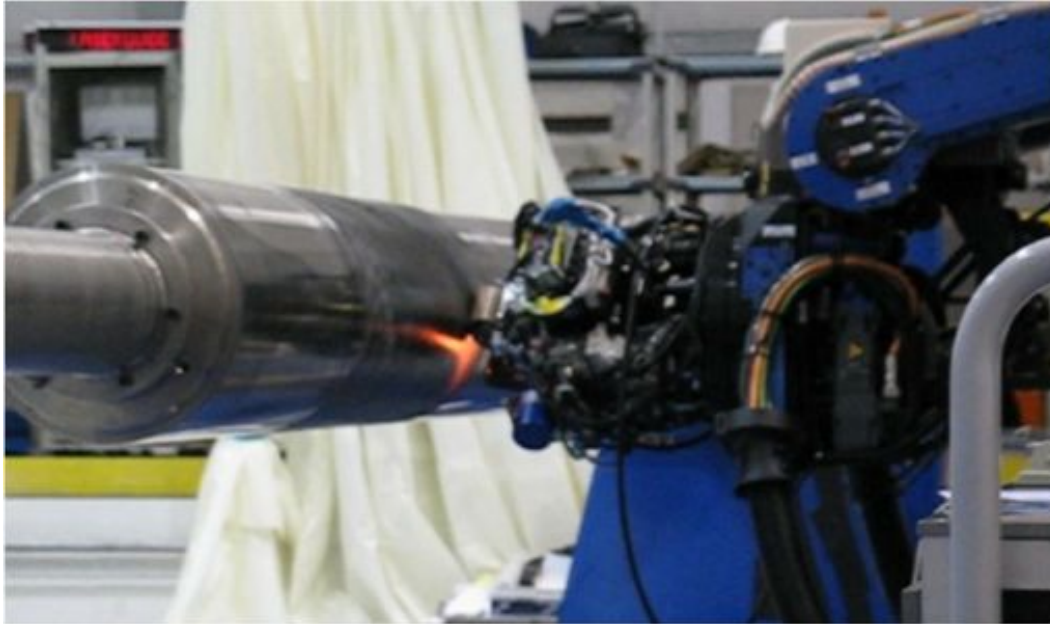
Ingersoll Machine Tools translated course data into project data format compatible with FPS.

Lockheed Martin simulated entire process to identify potential issues prior to start of fiber placement.

A ply book was developed to verify fiber orientations.



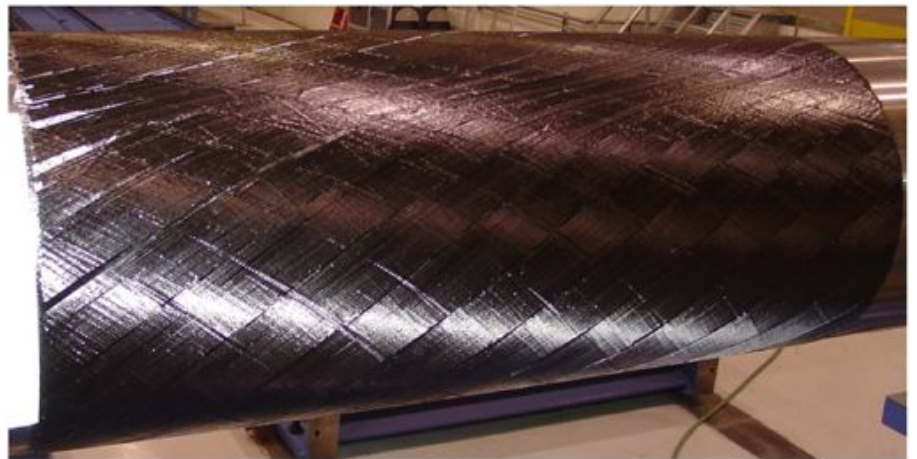
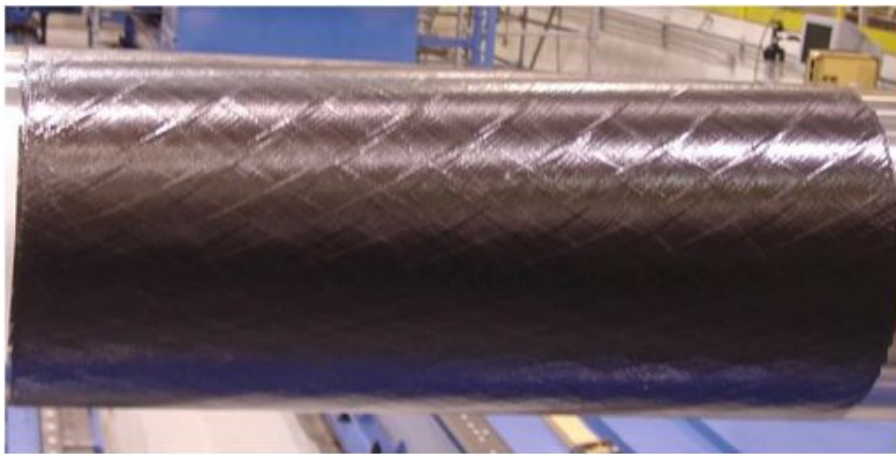
Fiber Placement Of Shells



IM7/8552 graphite-epoxy slit tape (1/8-in. width) used.

Shell with overlaps (below left) was built in 6.7 hours.

Shell without overlaps (below) was completed in 9.5 hours (additional time required to hand rework cut tows).



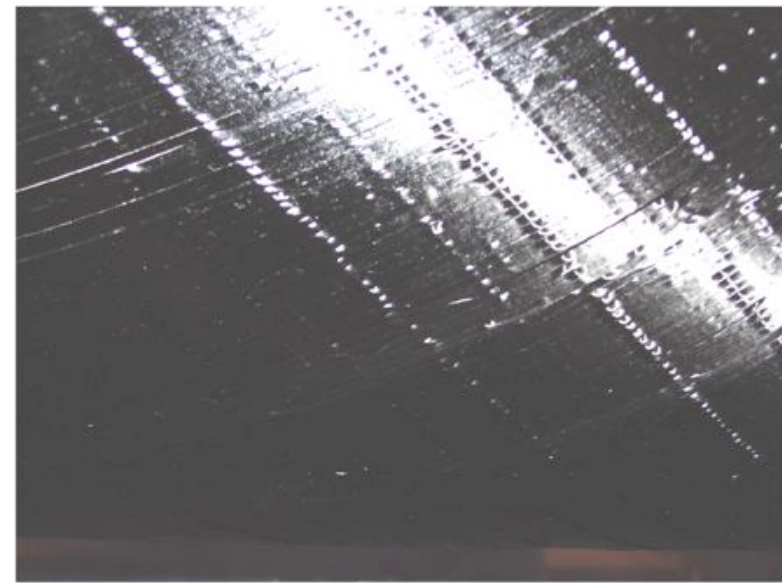
Manufacturing Issues And Lessons Learned



Shell without overlaps required additional hand rework of:

- unsteered cut tows.
- tows that did not adhere to laminate.

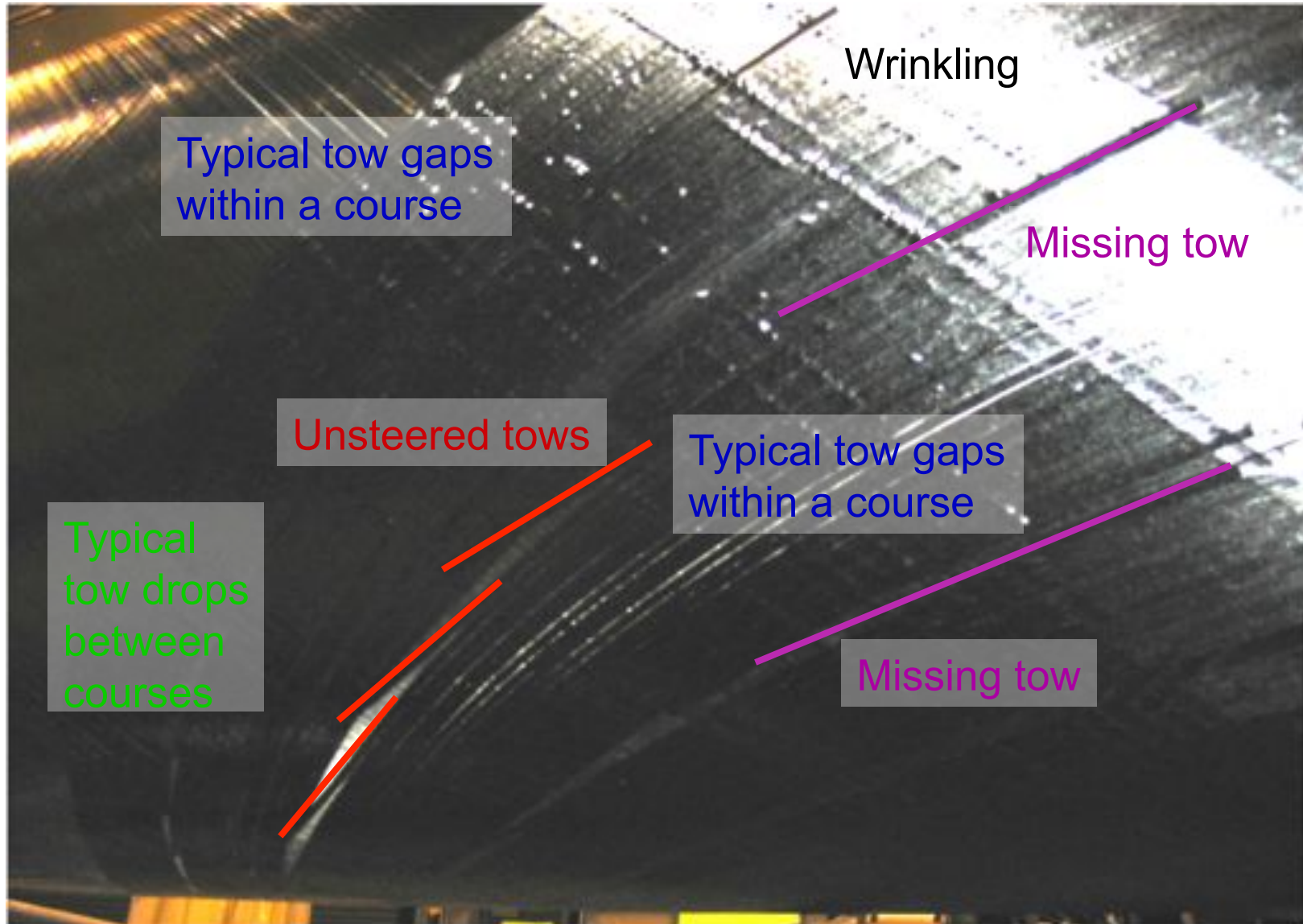
wrinkling before mitigation

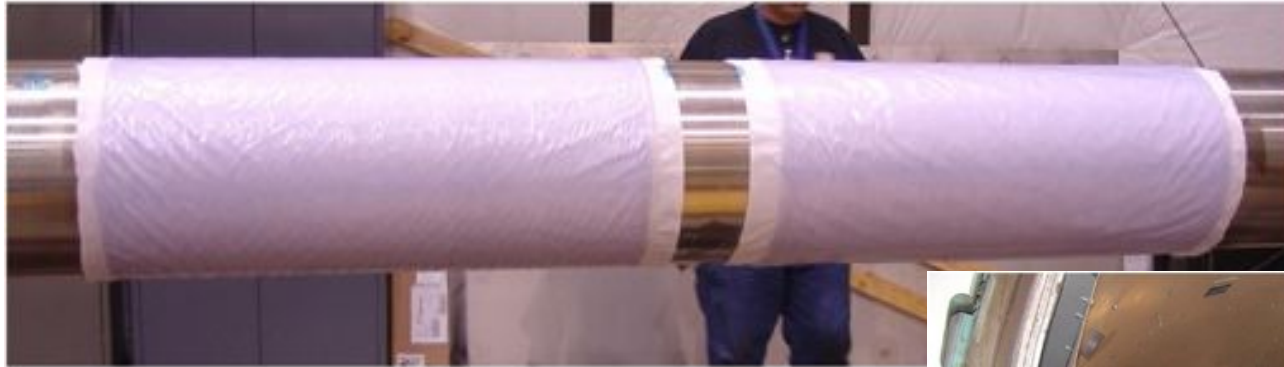


Steered tow wrinkling mitigation:

- debulk laminate between plies.
- increase head compaction force.
- reduce fiber placement speed.

Manufacturing Anomalies





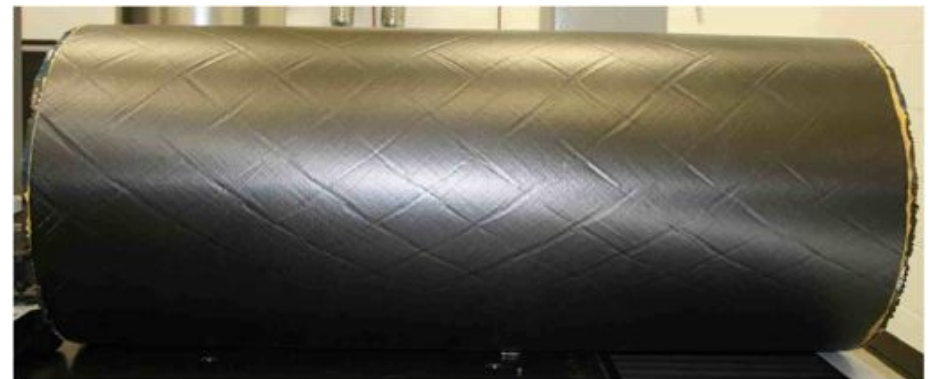
Cure Of Shells



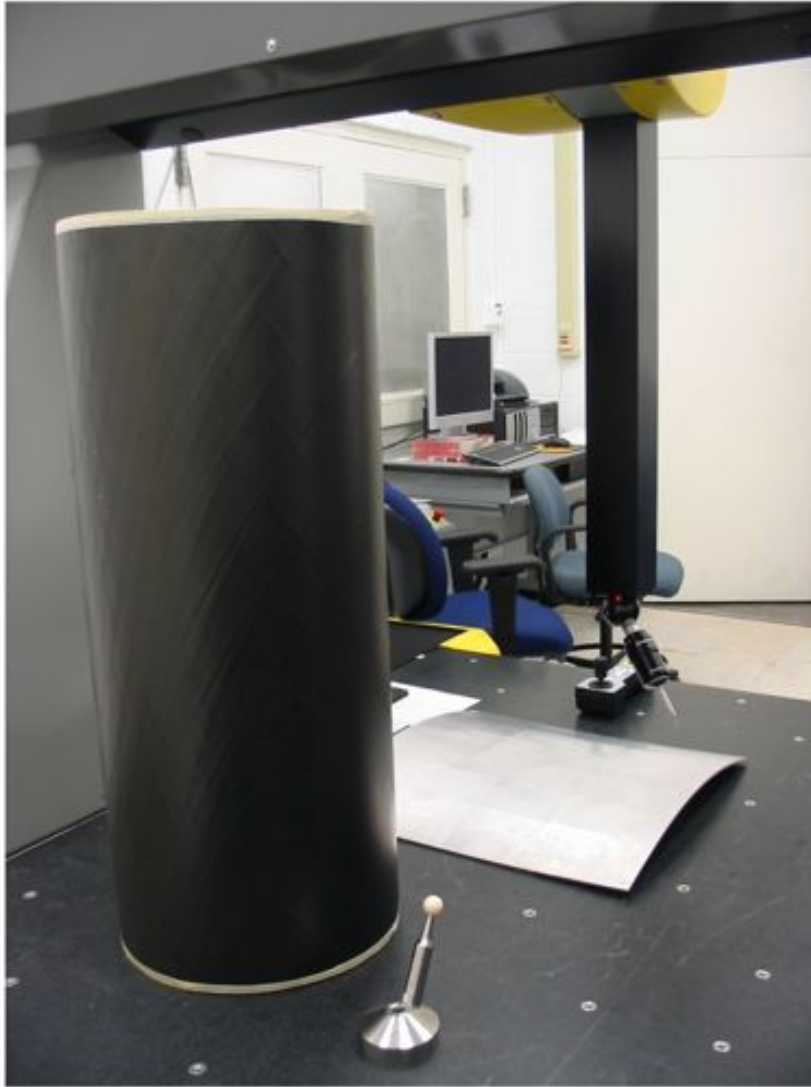
Conventional composite M&P techniques used to autoclave-cure shells.



Cured shells with (left) and without (right) tow overlaps.



Shell Surface Measurements Performed Using Coordinate Measuring Machine



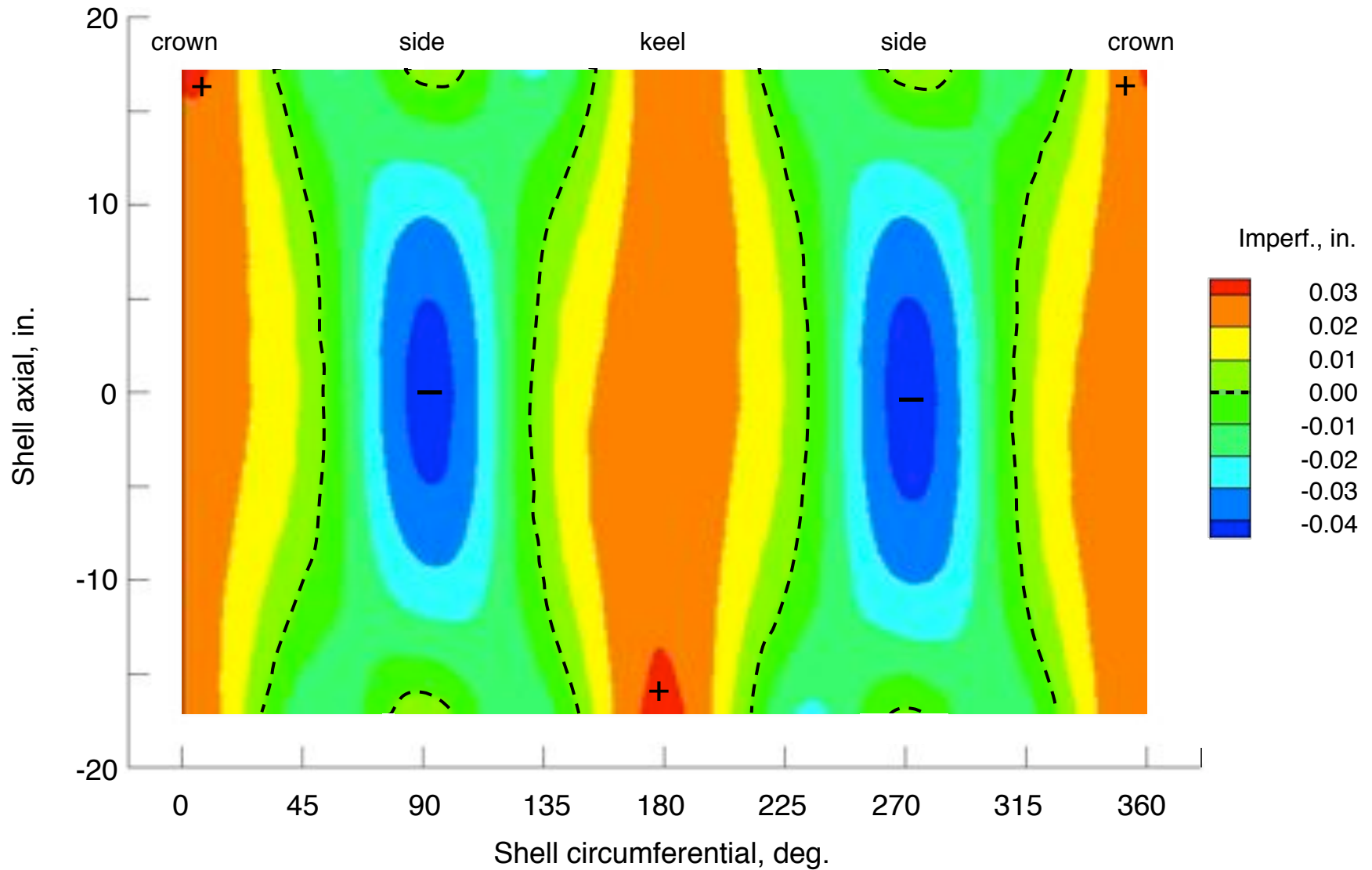
Spatial geometry data collected on both interior and exterior surfaces of cured shells.

0.75 degree ($\times R \sim 0.107$ in.)
circumferential $\times 0.100$ in. axial
data intervals $\Rightarrow \sim 164k$ points
per surface.

Deviation of the smooth interior
surface from right circular cylinder
with average measured radius
 $\Rightarrow$ geometric imperfection.

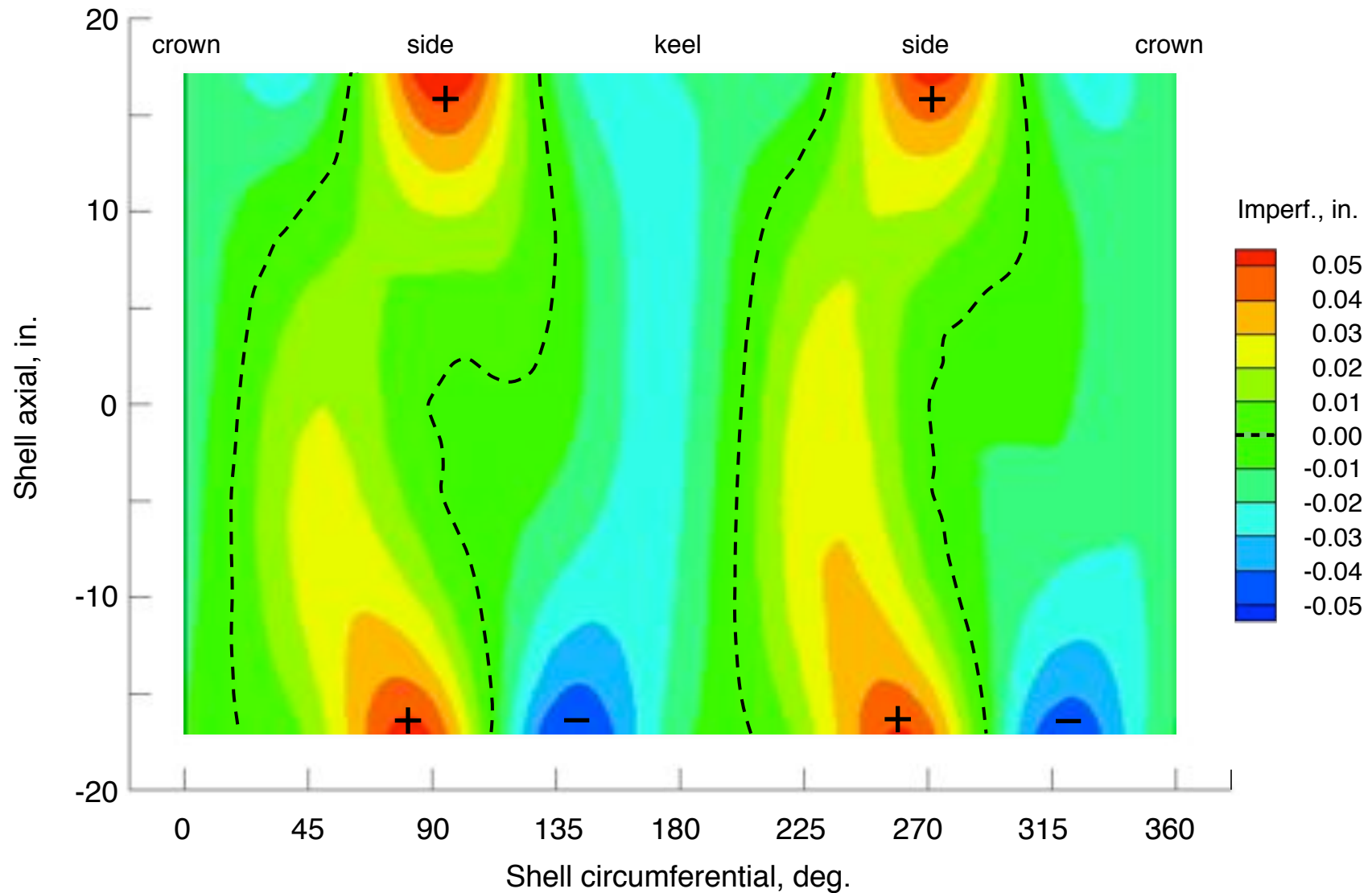
Difference between each interior
and exterior surface measurement
 $\Rightarrow$ laminate thickness.

Geometric Imperfections For Shell With Overlaps



+/- located at max/min amplitudes

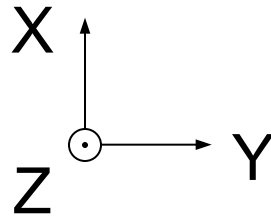
Geometric Imperfections For Shell Without Overlaps



+/- located at max/min amplitudes

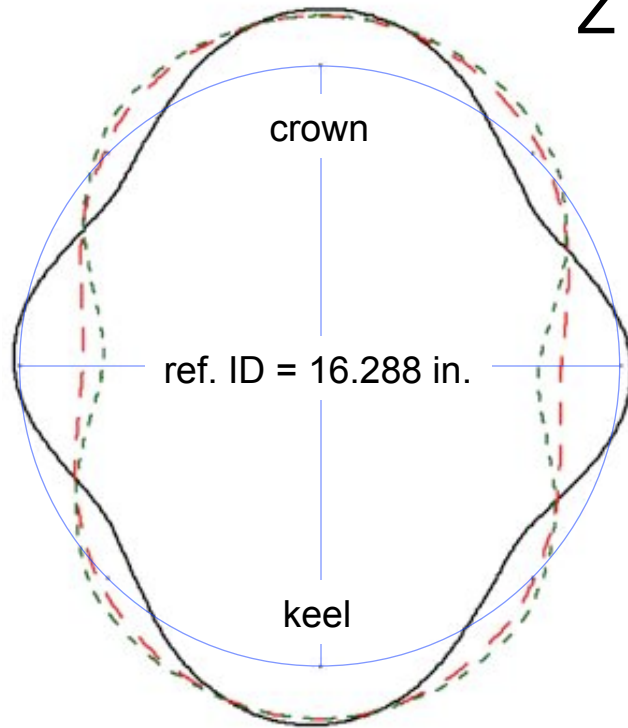
Averaged Geometric Imperfections

$Z = \pm 17$ in. ———
 $Z = \pm 8.5$ in. - - -
 $Z = 0$ in. - - -
 Ref. ID ———



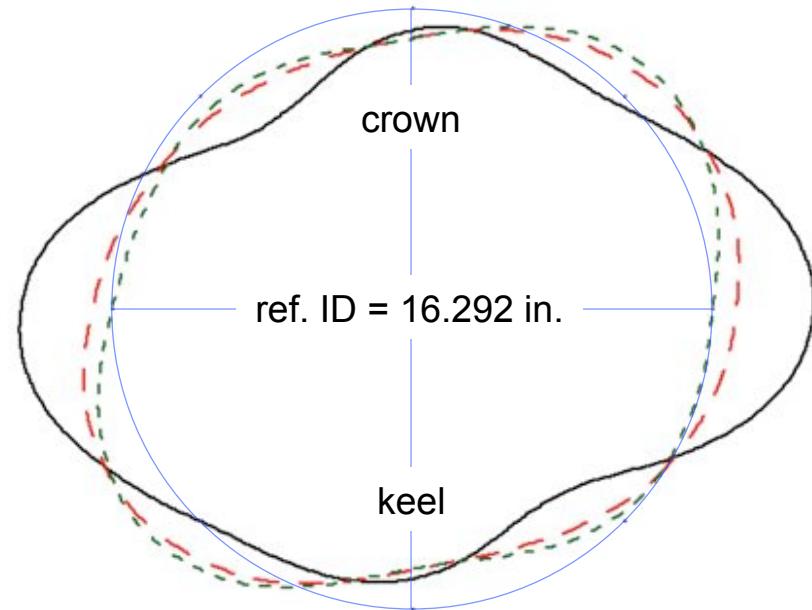
Imperfections plotted at
50x actual amplitude.

Mandrel OD = 16.266 in.



Shell with overlaps

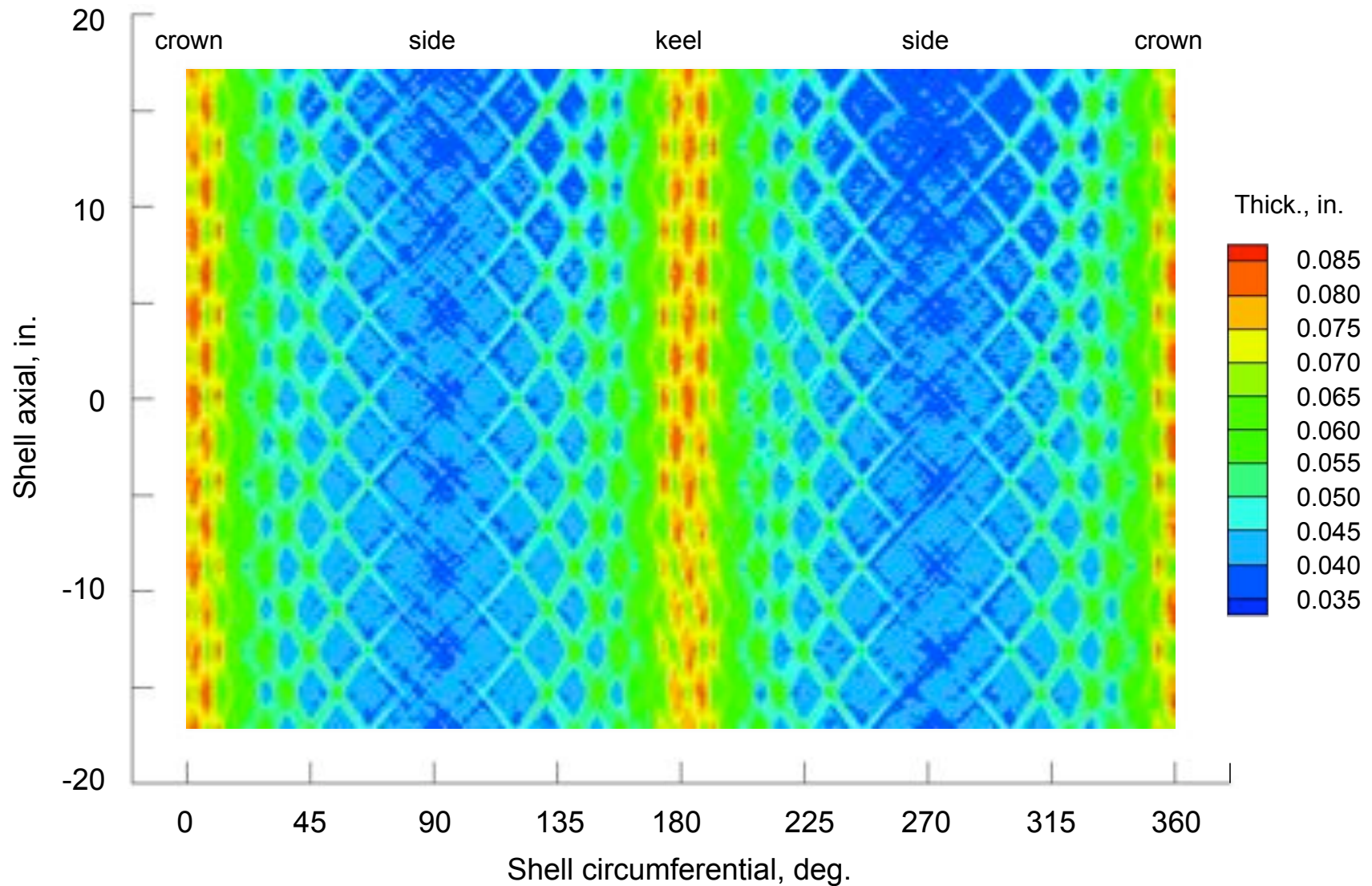
Imperf. = -0.045/+0.033 in.
 Imperf./R = -0.55/+0.41 pct.



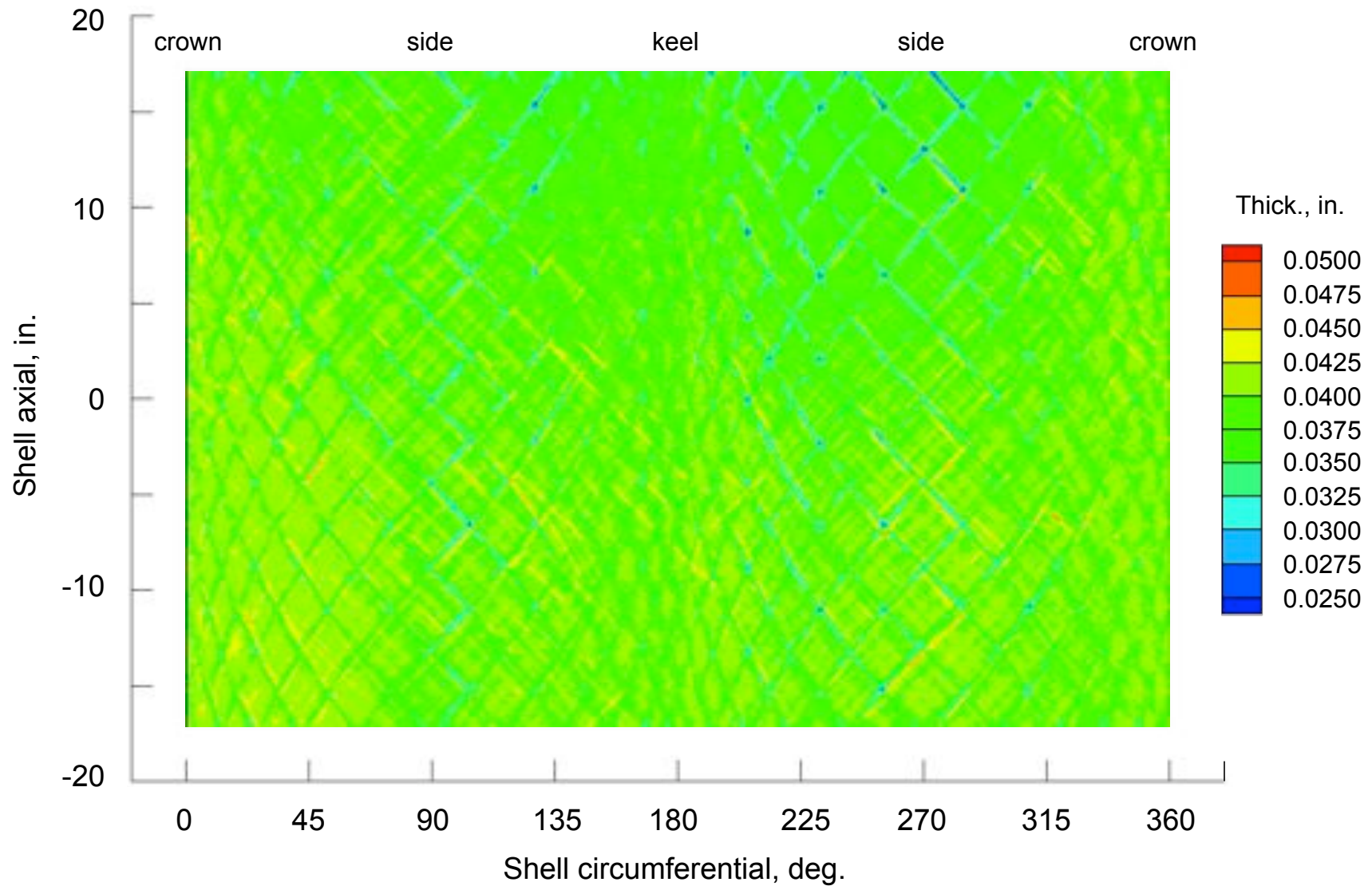
Shell without overlaps

Imperf. = -0.049/+0.059 in.
 Imperf./R = -0.60/+0.72 pct.

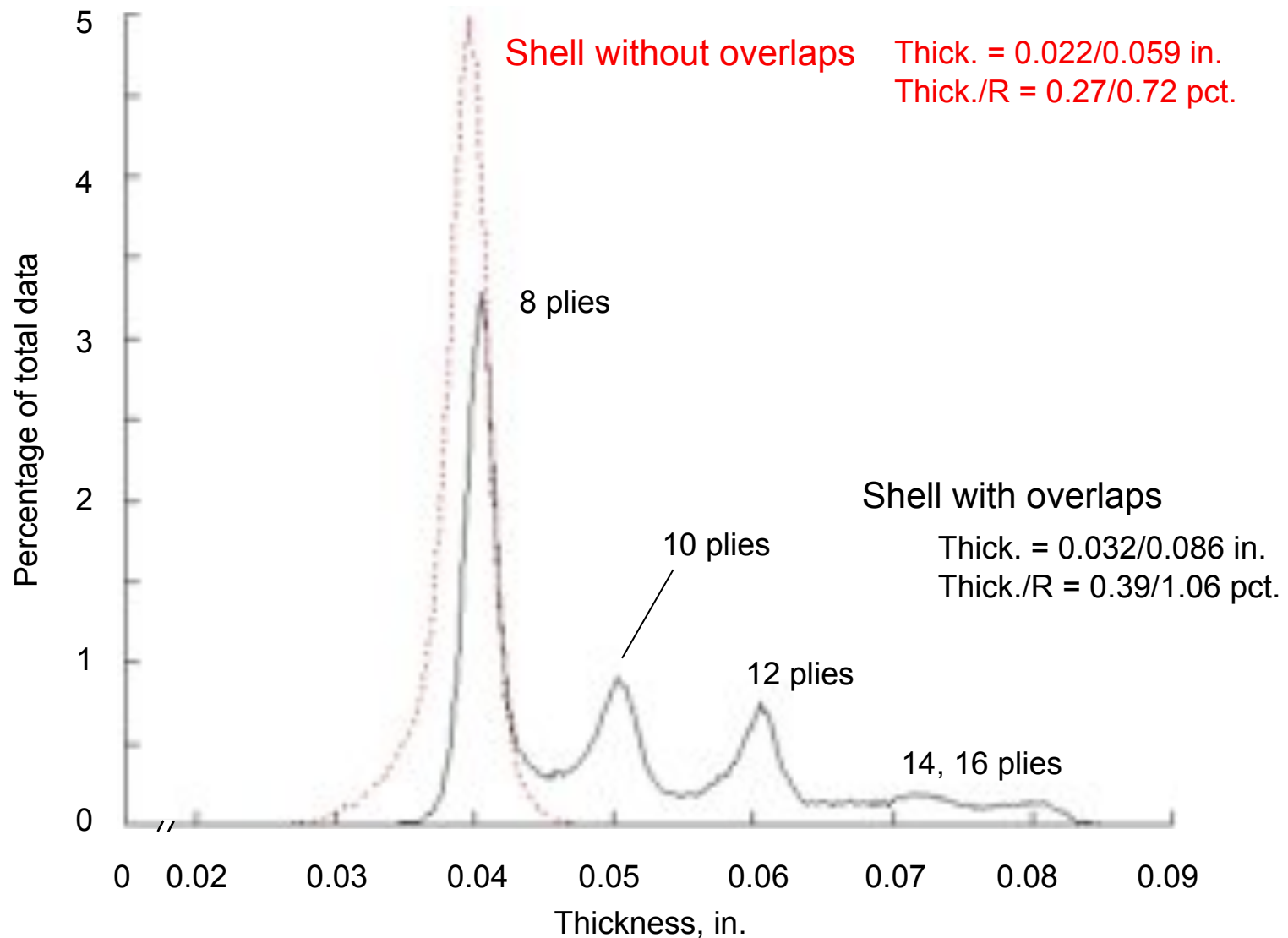
Laminate Thicknesses For Shell With Overlaps



Laminate Thicknesses For Shell Without Overlaps



Distribution Of Laminate Thicknesses



Concluding Remarks

A tow-steered shell configuration has been developed with ± 10 -deg. fiber angles along the crown and keel, and ± 45 -deg. fiber angles on the sides.

The structural performance of this design has been predicted using closed-form and finite element analyses for shells both with and without tow overlaps.

Mixed results are observed, with most performance measures lower than comparable results for a quasi-isotropic shell.

Bending stiffnesses for a larger family of tow-steered shells without overlaps and with discrete crown/keel panels are predicted using closed-form analyses.

Shell bending stiffnesses can be much improved over the quasi-isotropic shell bending stiffness.

Concluding Remarks

Processes were defined for the detailed design and manufacturing of two tow-steered shells.

Shell manufacturing issues were identified and mitigated (e.g., wrinkling and unsteered tows).

Good qualitative agreement noted between cured shapes of the two shells due to tow steered layup. Amplitude varies because of tow drops/overlaps.

Future plans call for testing of the shells under quasi-static applied loads, including associated linear and nonlinear structural analyses.

Proposed Future Work

Perform linear and nonlinear FEA of shells under shear, bending and/or torsion.

Design, manufacture and install end fittings for shell structural tests.

Instrument shells with strain gages and VIC-3D speckle photogrammetry.

Test shells under shear, bending and/or torsion, and perform test-analysis correlation.

Design tow paths for shells with large cutouts, then build and test hardware.

References

Wu, K.C., “Design and Analysis of Tow-Steered Composite Shells Using Fiber Placement,” Proceedings of the ASC 23rd Annual Technical Conference. Memphis, Tennessee, September 9-11, 2008. Paper number 125.

Wu, K.C, Tatting, B.F., Smith, B.H., Stevens, R.S., Occhipinti, G.P., Swift, J.B., Achary, D.C. and Thornburgh, R.P., “Design and Manufacturing of Tow-Steered Composite Shells Using Fiber Placement,” Proceedings of the 50th AIAA/ASME/ASCE/AHS/ASC SDM Conference. Palm Springs, California, May 4-7, 2009. AIAA paper no. 2009-2700.

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