

Thermal And Structural Performance Of Tow-Steered, Variable Stiffness Panels

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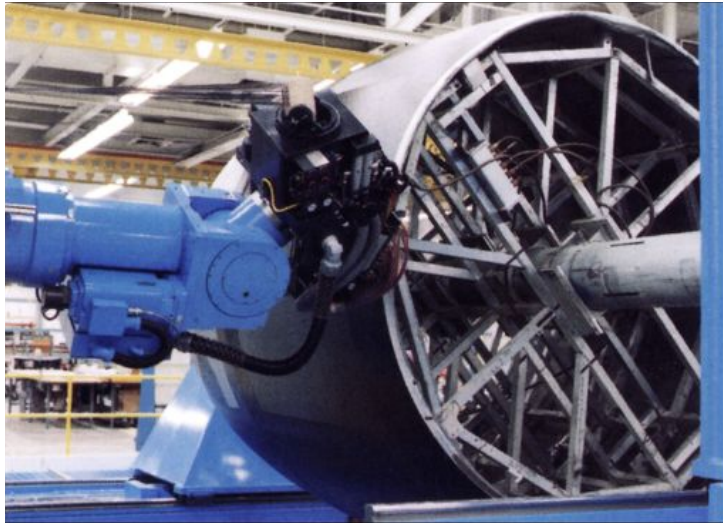
Thermal And Structural Performance Of Variable Stiffness Panels

- Variable stiffness concept
- Study objectives
- Variable stiffness panels
- Thermal tests and analyses
- Structural test preparation
- Structural tests and analyses
- Conclusions

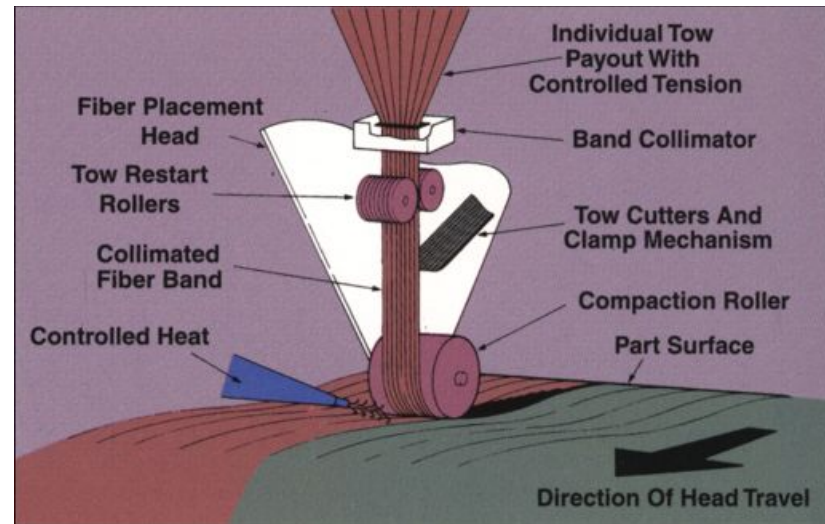
What Are Variable Stiffness Composites?

- In conventional laminates, all fibers in a given ply are straight and parallel with the same orientation.
- In advanced, tow-steered structures, the fiber orientation within each ply varies as a continuous function of location on the 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.

Advanced Fiber Placement System



Courtesy of Cincinnati Machine



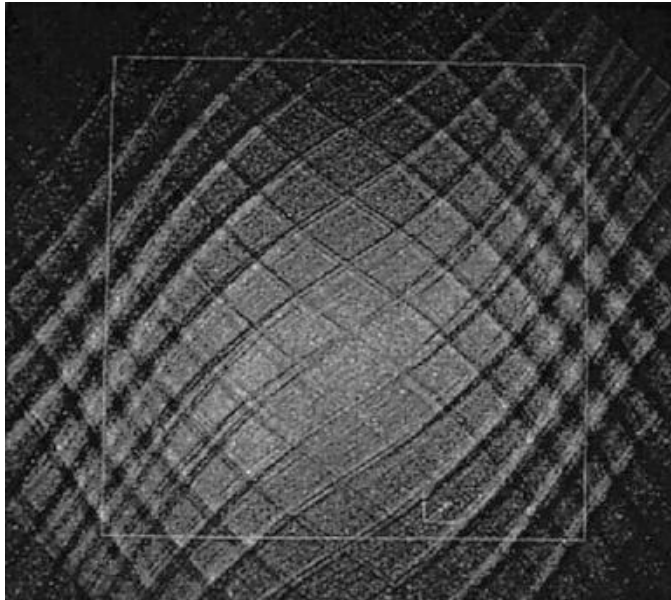
Courtesy of Cincinnati Machine

- Panels built on Cincinnati Machine's Viper FPS-3000.
- FPS has seven degrees of freedom in workspace.
- 24 x 1/8 inch-wide prepreg tows, with individual feed reels and cut/restart capability for tow overlap control.
- Minimum tow path radius of curvature of 25 inches.
- Precise, accurate, repeatable tow placement and steering using ACRAPLACE software.

Study Objectives

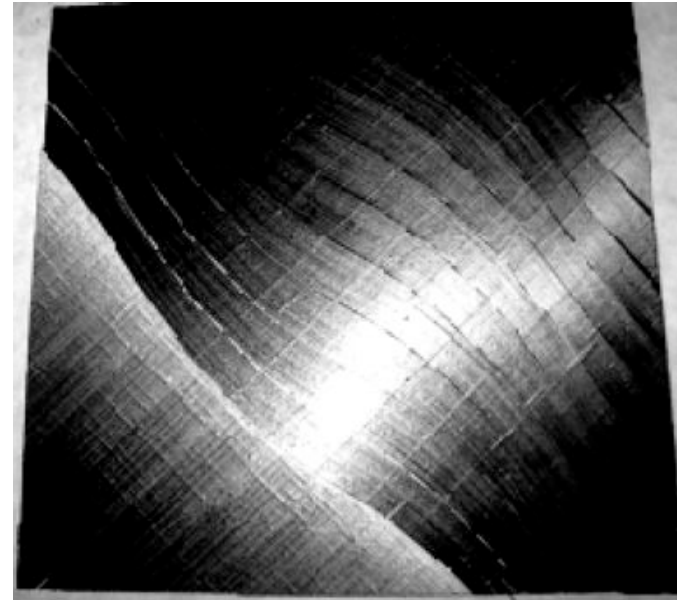
- Determine the structural response of two variable stiffness composite panels at sequential stages: 1) cure and post-cure, 2) thermal tests, 3) structural test preparation, and 4) compression to failure.
- Perform finite element analyses of these panels, including both geometric and material nonlinearities, at each stage to model structural performance.
- Where possible, compare these predictions with available experimental results.
- Estimate the level of analytical fidelity required to accurately model the response of these complex structures.

Two Variable Stiffness Panels Fabricated



Panel with overlaps

All 24 tows placed during each pass of the FPS for 100% overlaps.

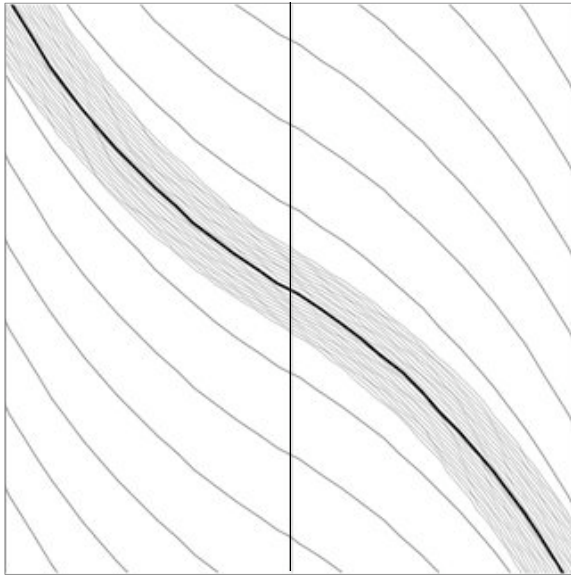


Panel without overlaps

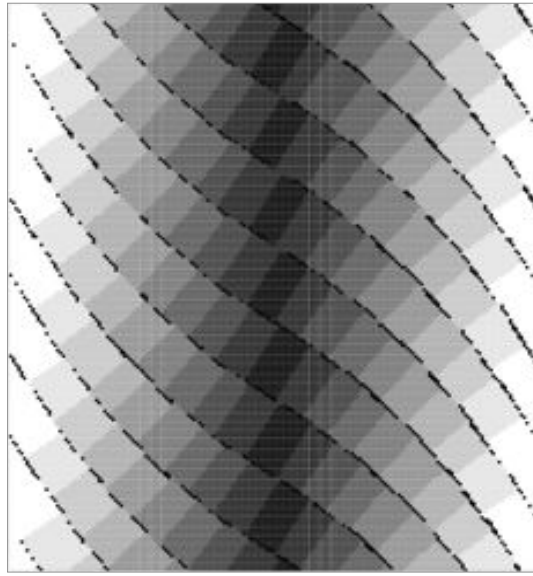
Cut/restart capability of FPS used to eliminate tow overlaps during fabrication.

- Both $[\pm 45/(\pm \Theta)_4]_S$ layups, with 16 variable stiffness plies.
- Conventional $[\pm 45]_{5S}$ panel also fabricated as a baseline.
- 0.00765 in.-thick AS4/977-3 graphite-epoxy prepreg tows.

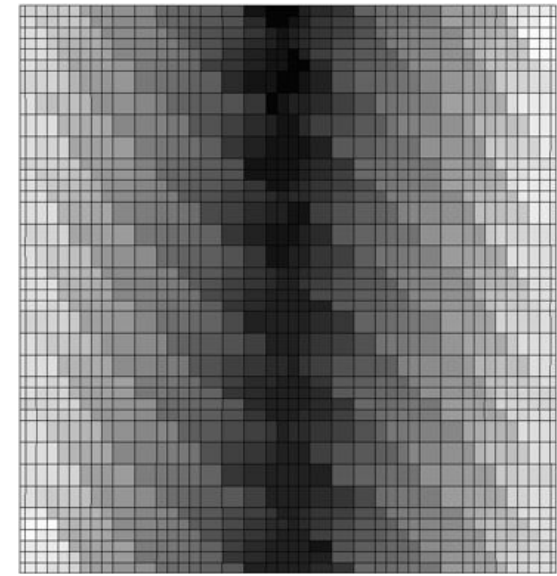
Tow Paths And Fiber Orientation Angles For Panel Without Overlaps



Tow paths and central tow band



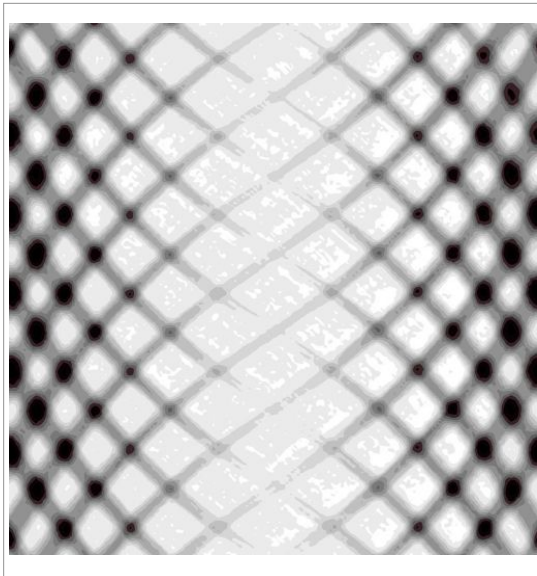
Predicted angles
and tow drops



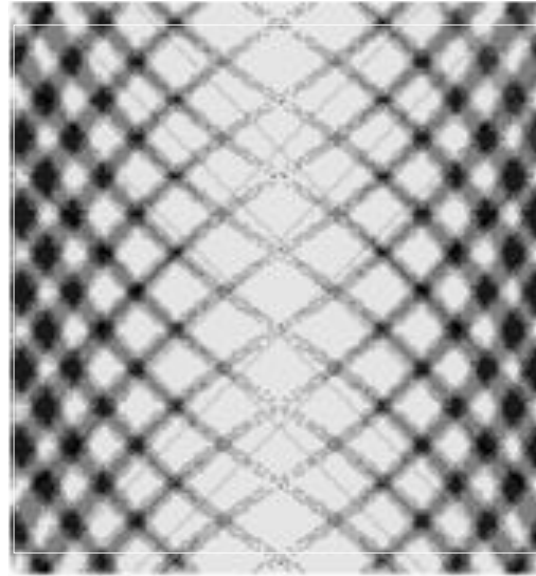
Discretized angles
(coarse FEM)

- Tow paths shown for $\langle 60|30 \rangle$ variable stiffness ply.
- Predicted and discretized fiber angles computed using ACRAPLACE data from panel manufacturer.
- Fiber angles constant within each ply of each element.
- Tow drops not included in discretized panel models.

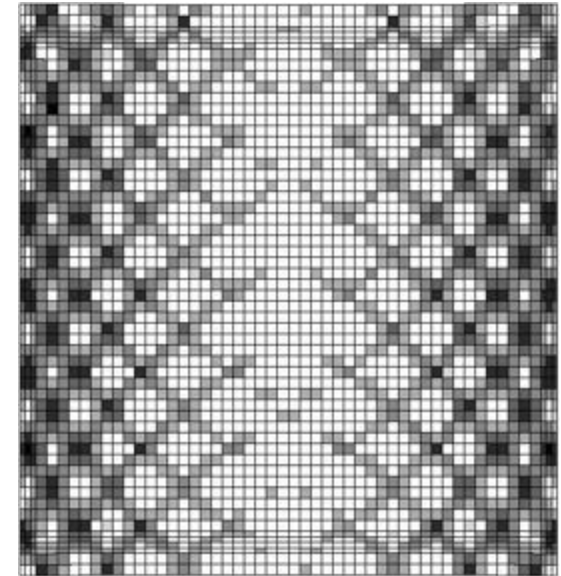
Laminate Thicknesses For Panel With Overlaps



Measured



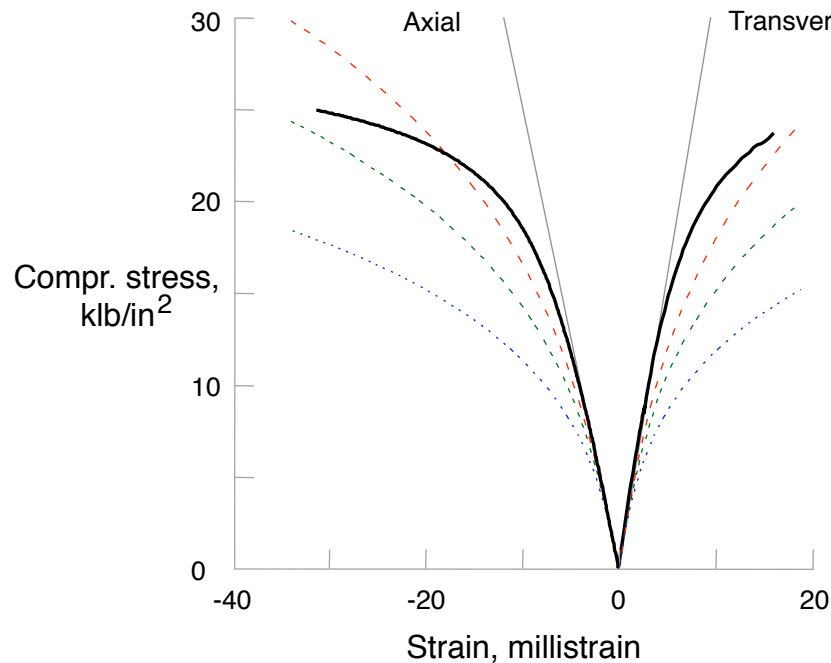
Predicted



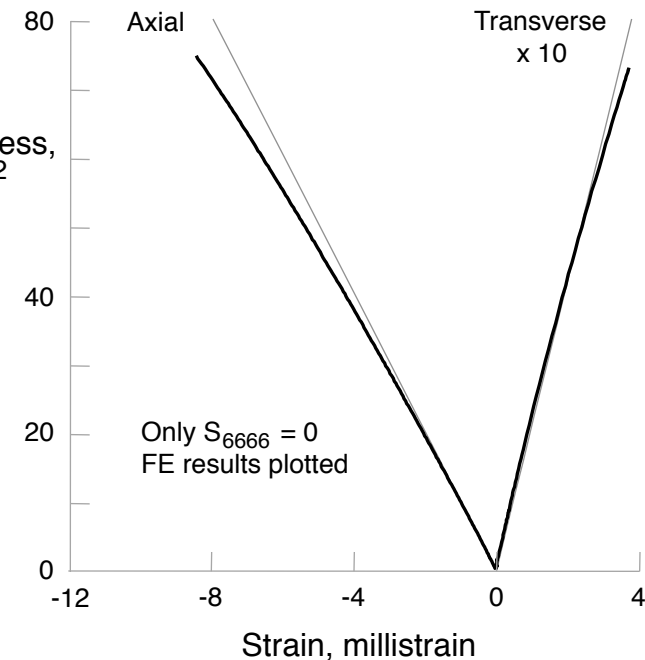
Discretized (ref. FEM)

- Measured panel thickness determined from surface surveys of cured panel using precision CMM.
- Predicted and discretized panel thicknesses computed using ACRAPLACE data from panel manufacturer.
- Each finite element has a uniform laminate thickness (integer number of plies) with a unique layup.

AS4/977-3 Coupon Tests And Analyses



$[\pm 45]_{5s}$ laminate

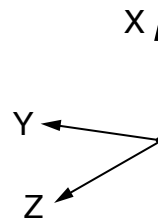
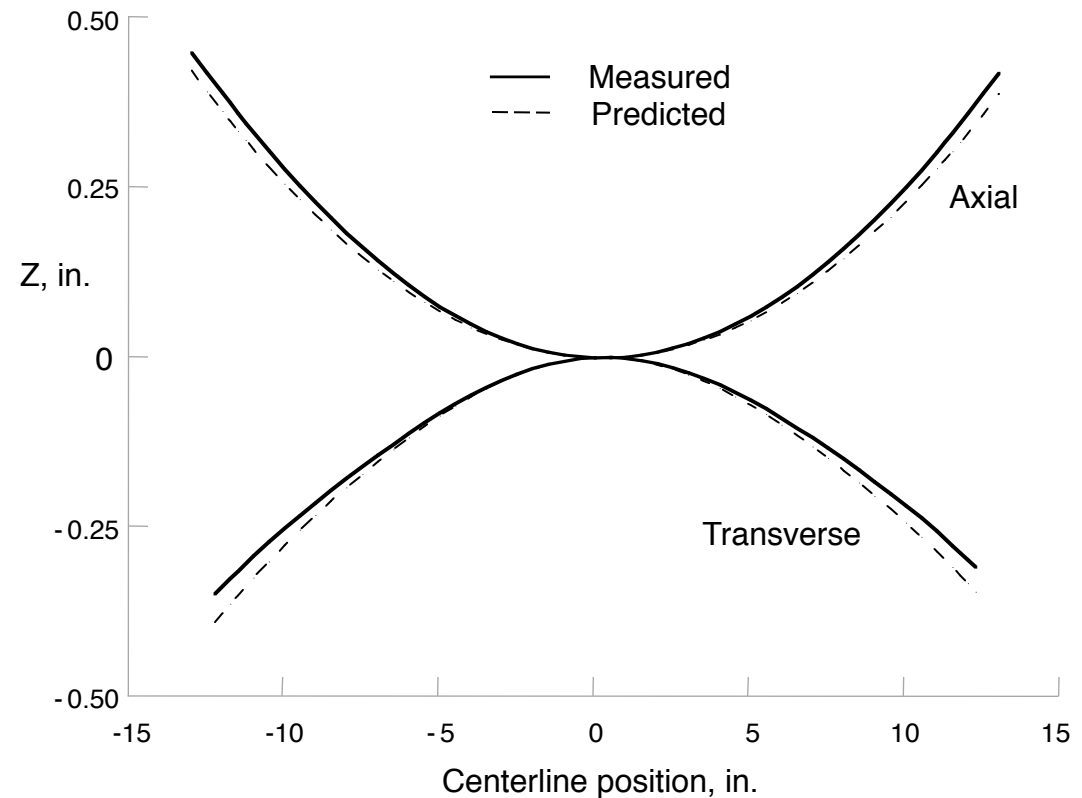
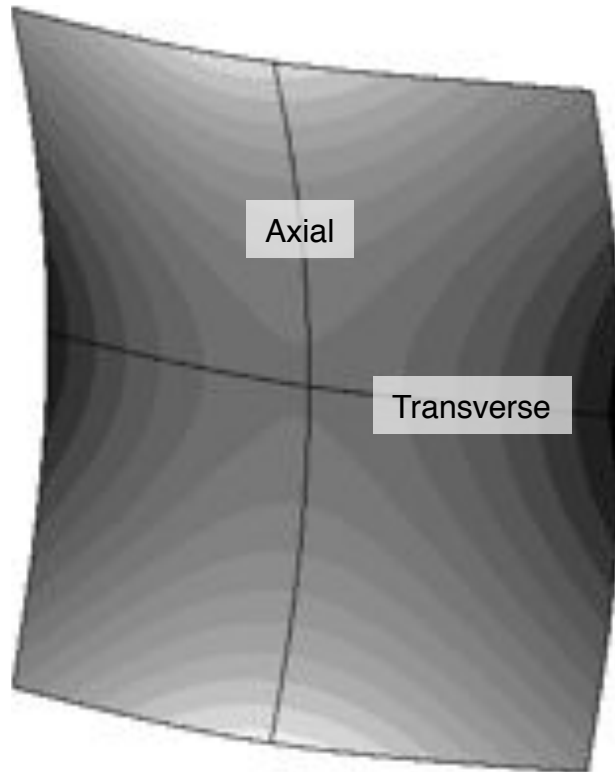


$[0/90]_{5s}$ laminate

- No uniaxial laminates available for ply property estimation.
- Classical lamination theory is used with orthotropic laminate test results to estimate ply properties E_1 , E_2 , ν_{12} and G_{12} .
- Good initial correlation between linear analyses and tests.
- Nonlinear shear strain model applied over range of S_{6666} .

Measured and Predicted Imperfections For Cured Panel With Overlaps

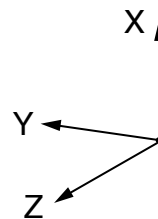
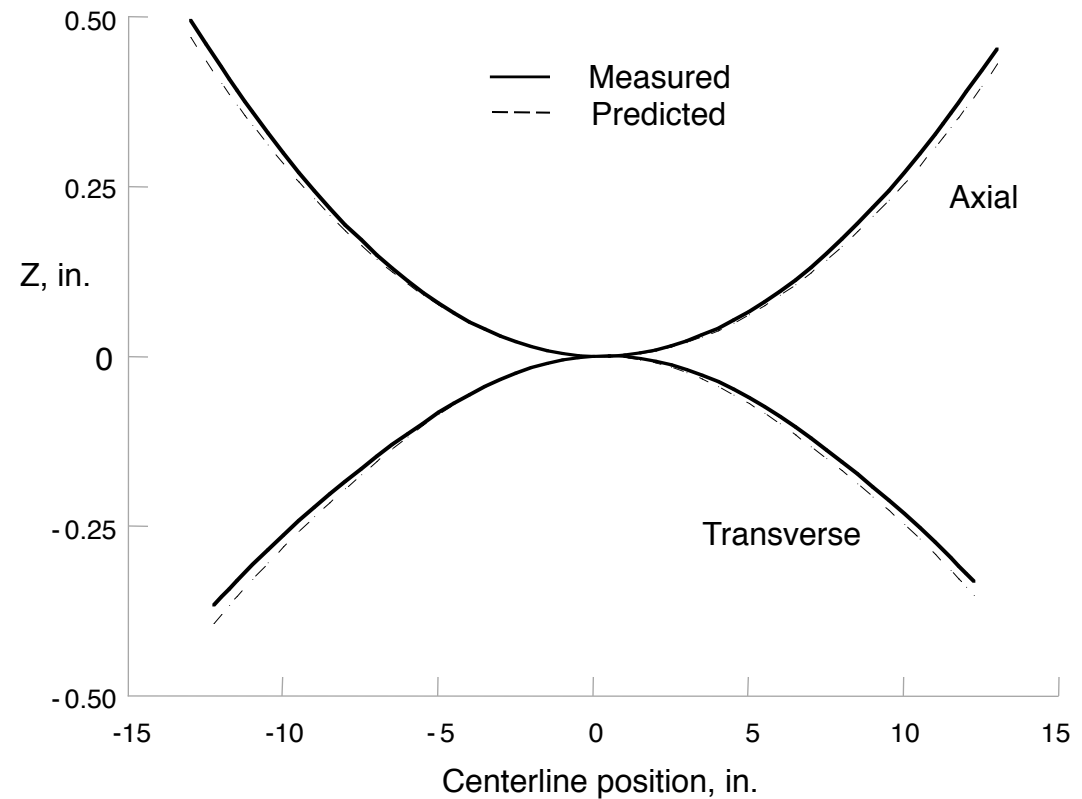
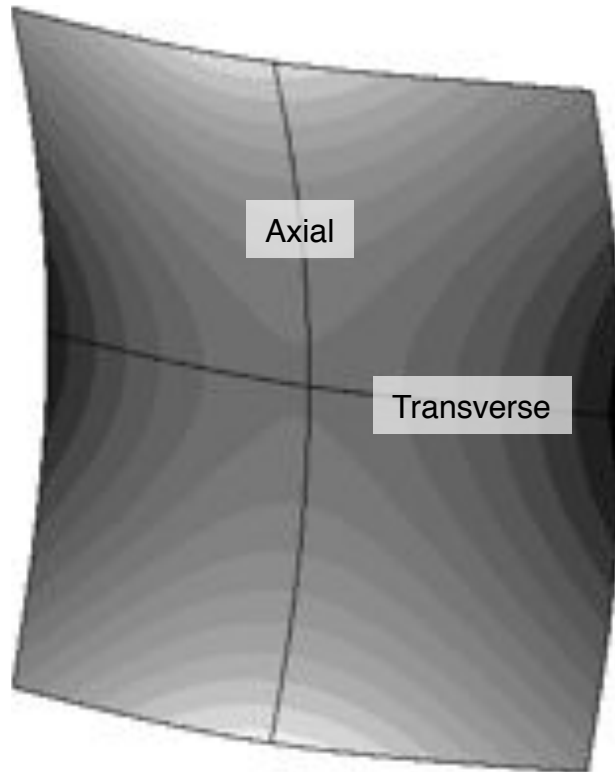
Panel imperfections measured on tool surface at RT. Max. $Z = 0.450$ in., min. $Z = -0.347$ in.



Predicted shape from geom. nonlinear analysis with $\Delta T = -280$ deg. F to RT. Max. $Z = 0.422$ in., min. $Z = -0.389$ in.

Measured and Predicted Imperfections For Cured Panel Without Overlaps

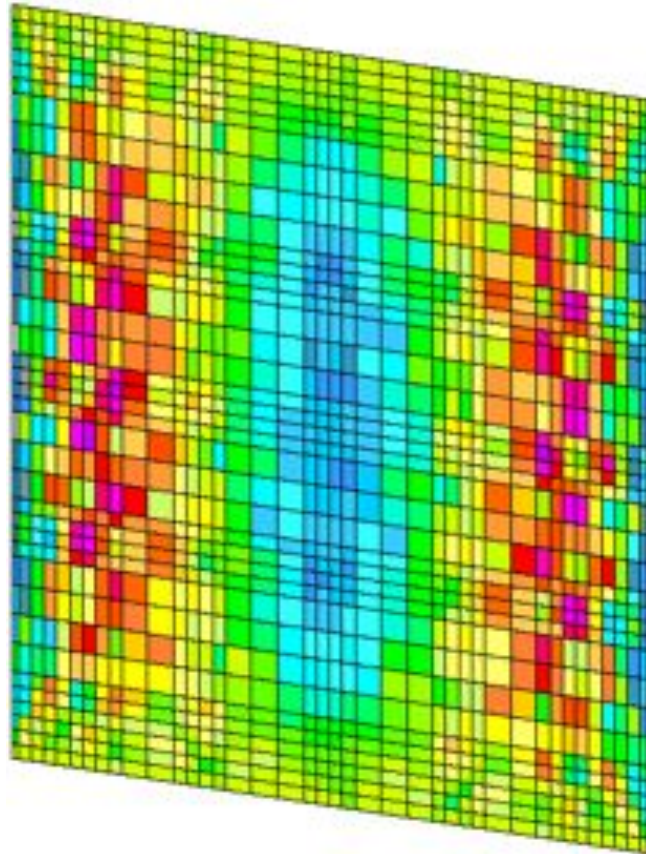
Panel imperfections measured on tool surface at RT. Max. $Z = 0.497$ in., min. $Z = -0.369$ in.



Predicted shape from geom. nonlinear analysis with $\Delta T = -280$ deg. F to RT. Max. $Z = 0.472$ in., min. $Z = -0.396$ in.

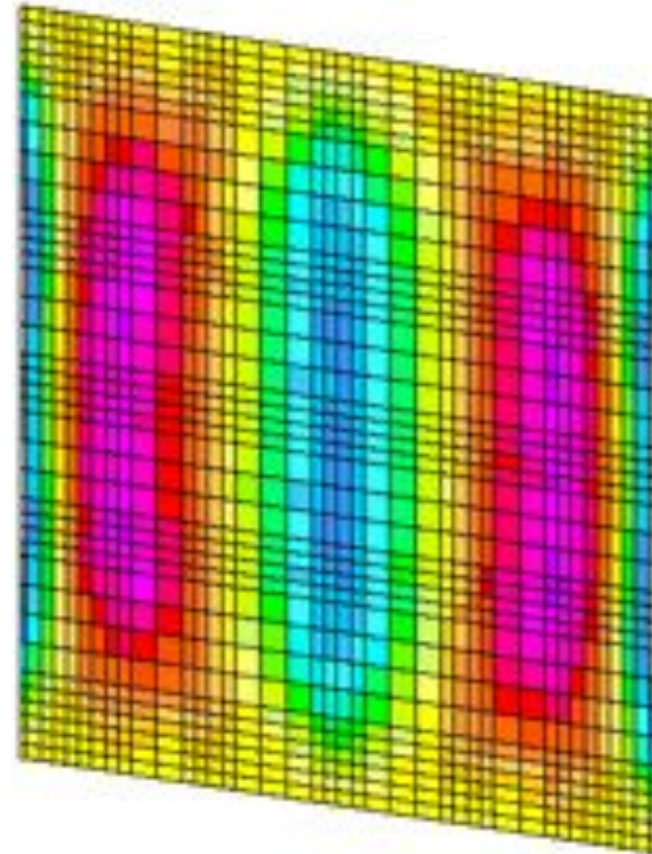
Predicted Thermal Prestress Resultants

Panel With Overlaps

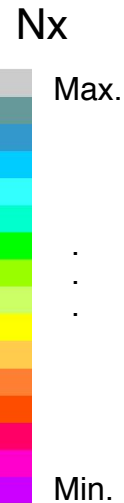


No axial load.
Max. $N_x = 446$ lb/in.,
min. $N_x = -447$ lb/in.

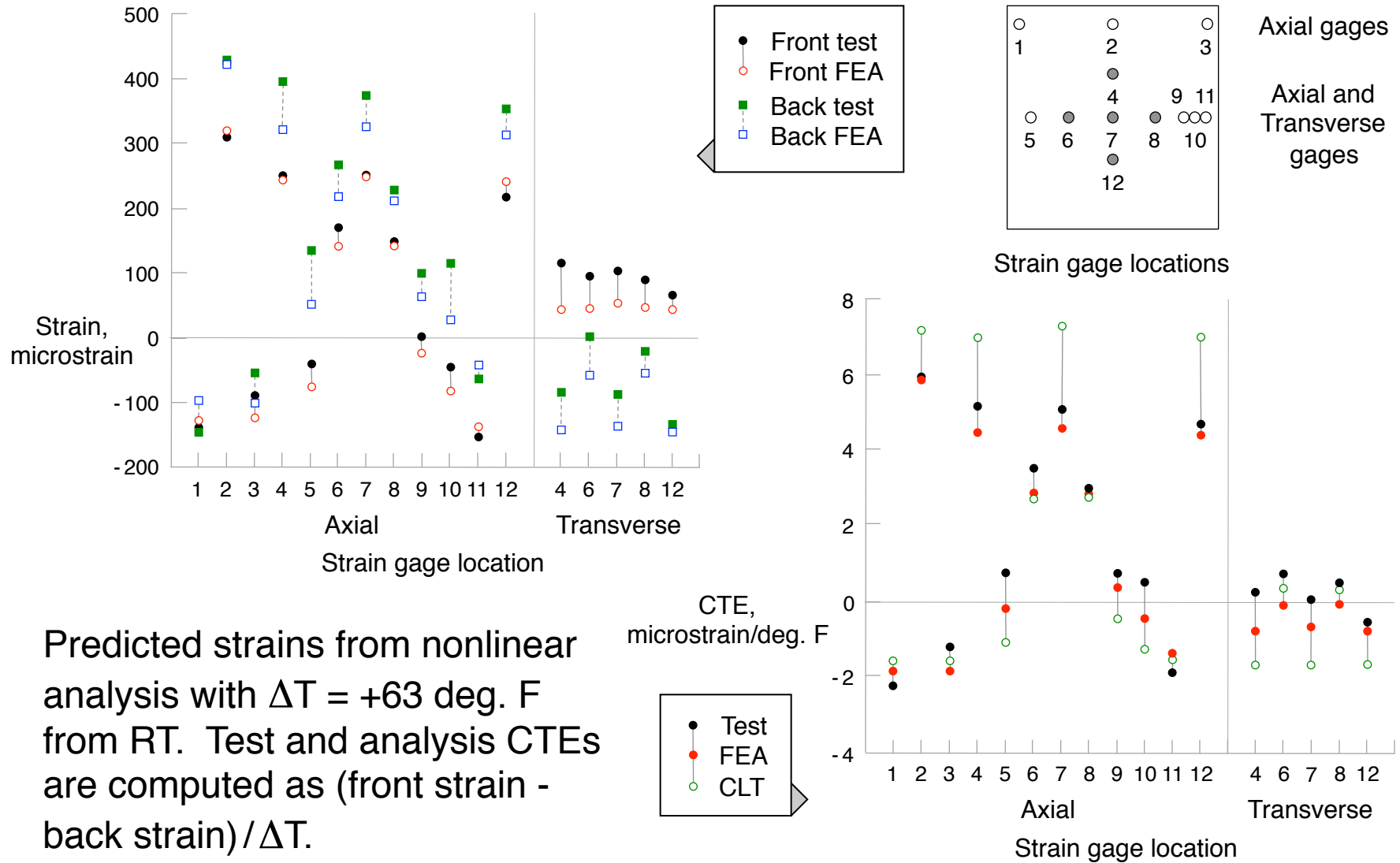
Panel Without Overlaps



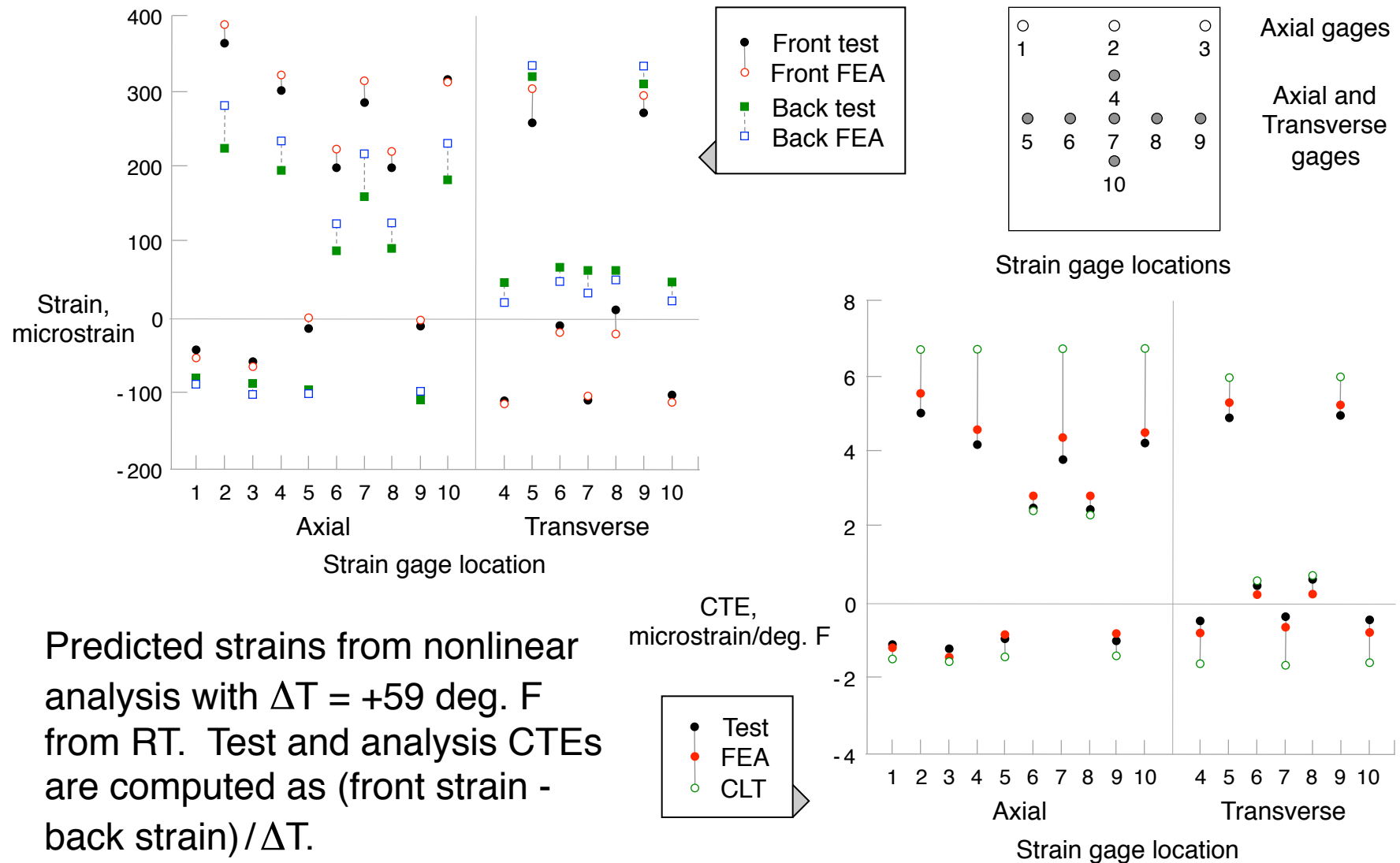
No axial load.
Max. $N_x = 311$ lb/in.,
min. $N_x = -197$ lb/in.



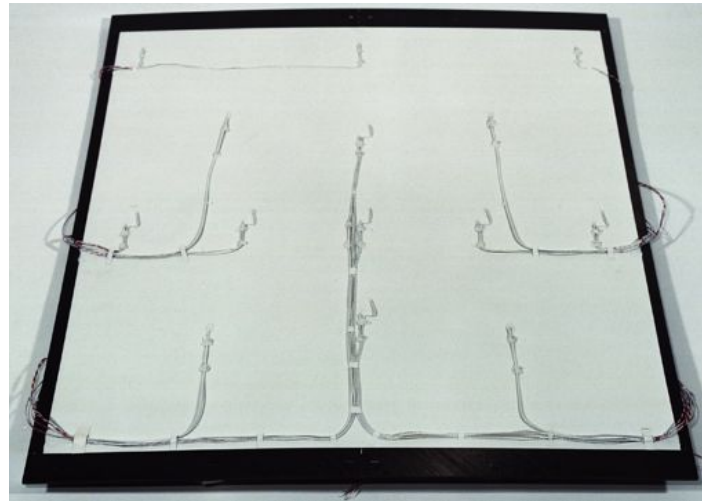
Measured and Predicted Strains And CTEs For Panel With Overlaps Thermal Loading



Measured and Predicted Strains And CTEs For Panel Without Overlaps Thermal Loading



Unique Structural Test Fixtures Developed



Front of cured panel shown.



Vertical edge test fixture

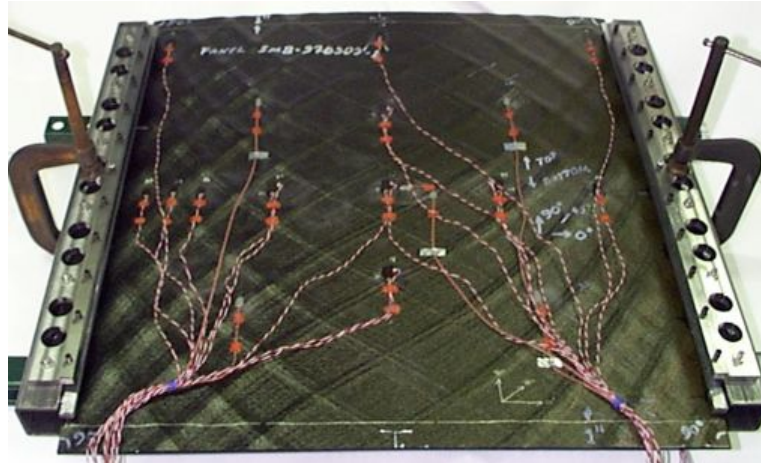


Horizontal edge test fixture

- Panels have internal thermal stress state from cure.

Unique Structural Test Fixtures Installed

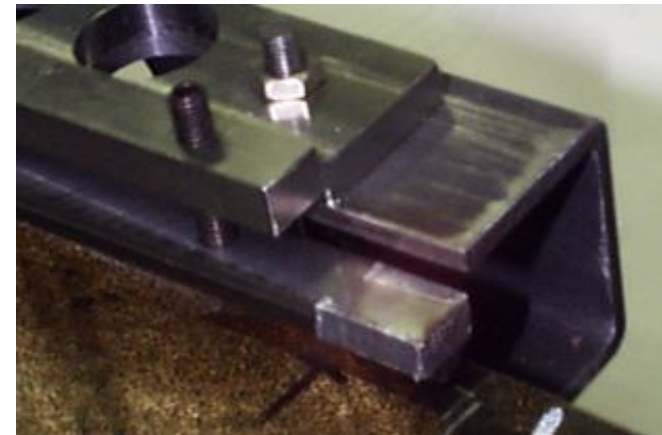
Panel with vertical edge test fixtures attached.



Back of cured panel shown.



Vertical edge test fixture

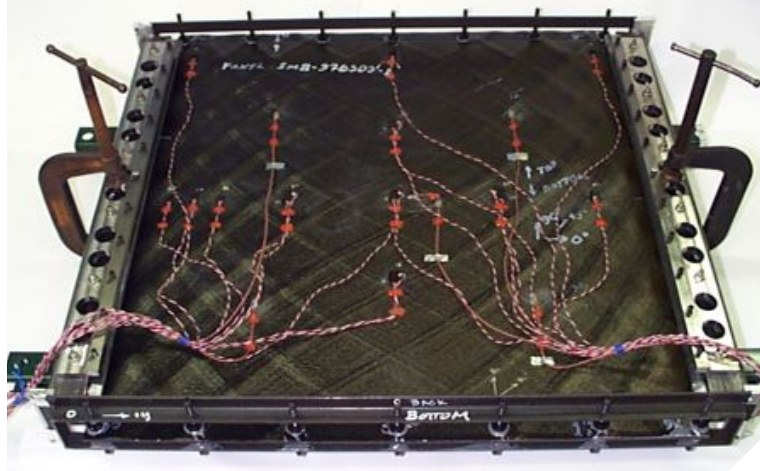


Test fixture detail

- Quasi-static deformations applied to straighten panel edges.

Unique Structural Test Fixtures Installed

Panel with all test fixtures attached.



C-clamps used to prevent test fixture motion.



Test fixture detail



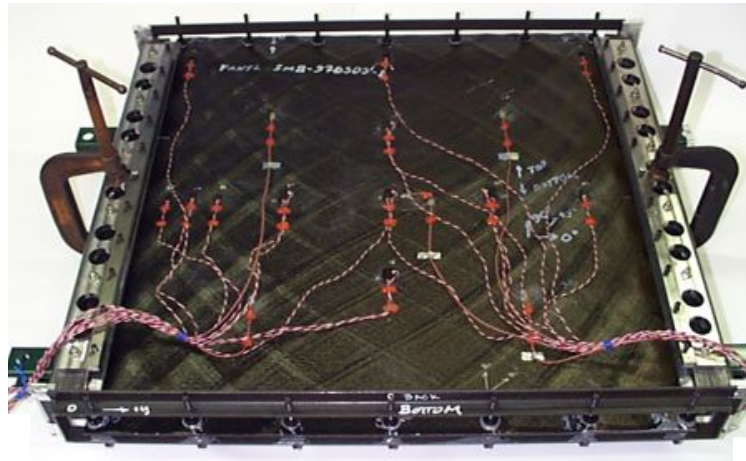
Horizontal edge test fixture

- Test fixtures superimpose mechanical prestress on panels.

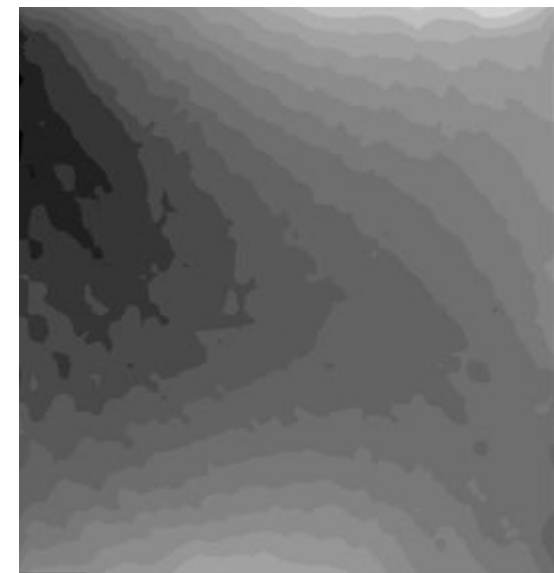
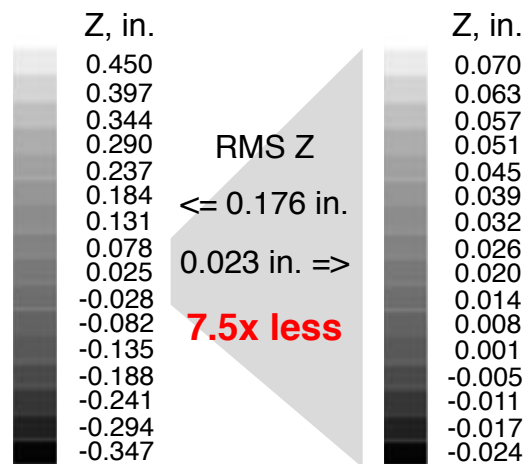
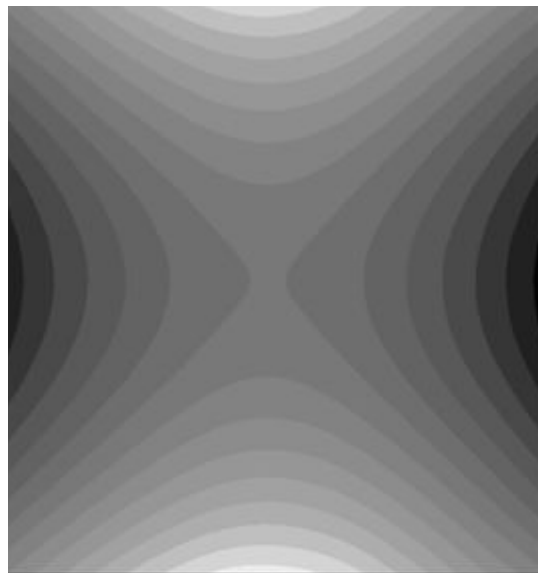
Panel Manufacturing Imperfections Reduced

Panel with test fixtures.

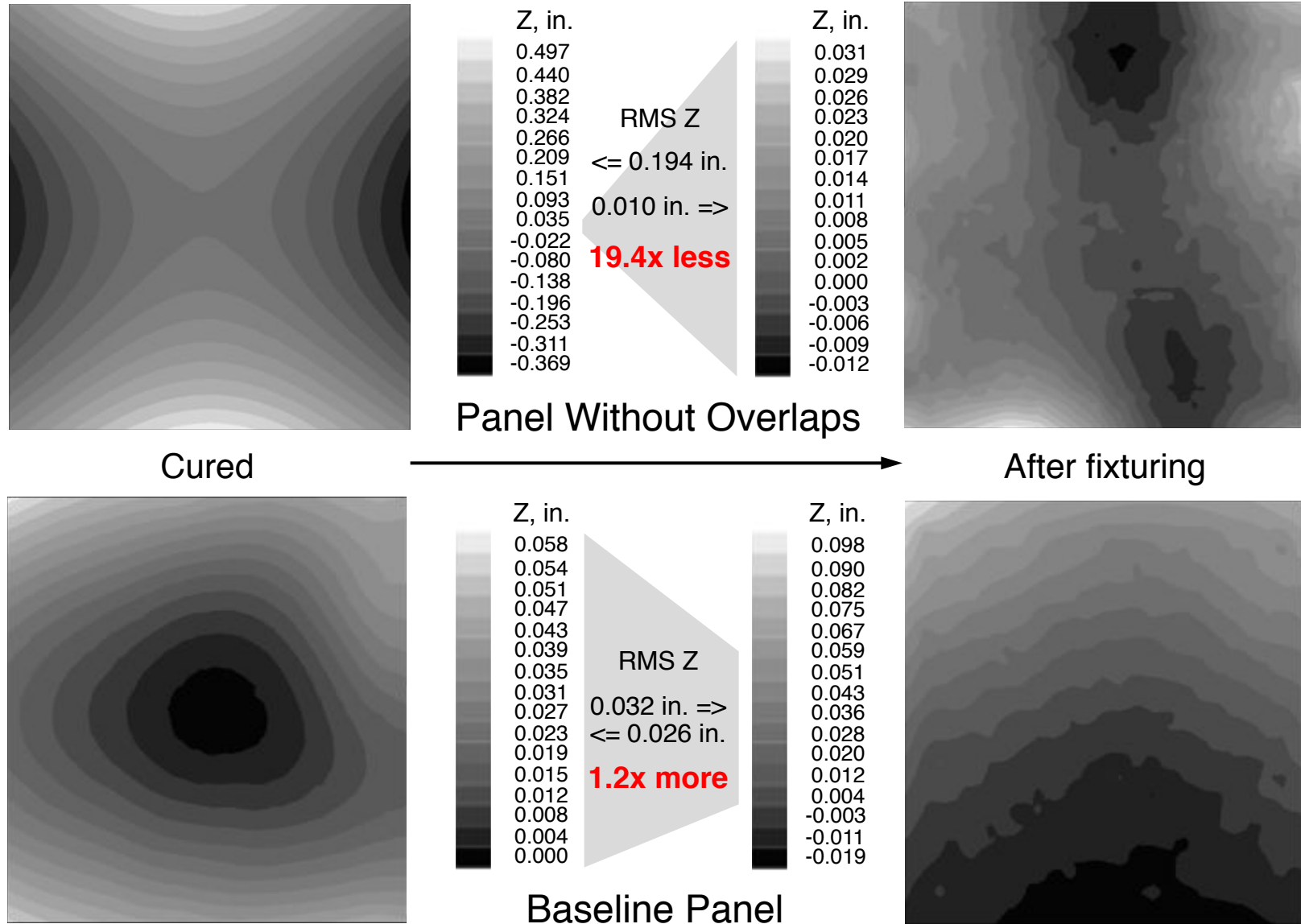
Large imperfections for cured, unfixtured panel with overlaps.



Much smaller imperfections for panel with test fixtures installed.

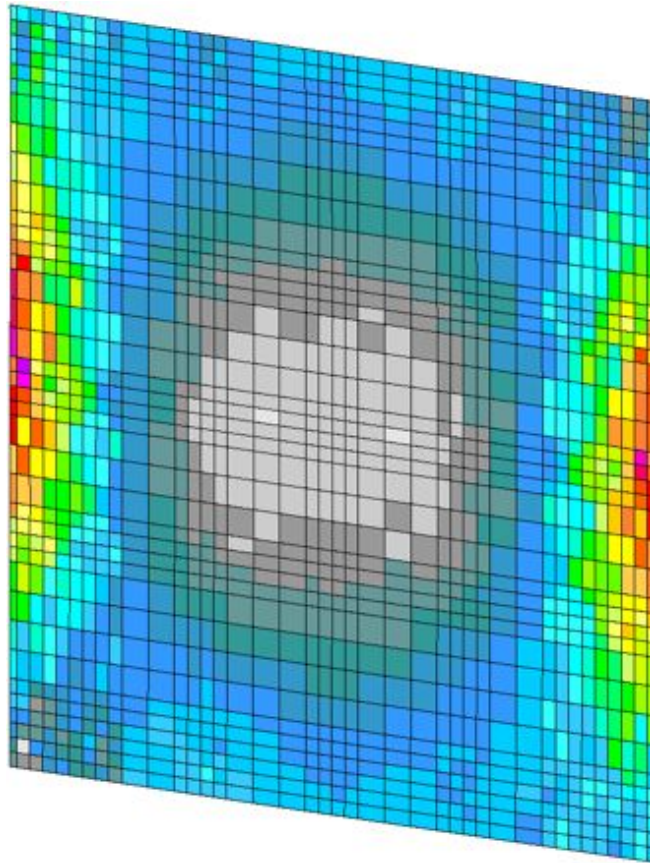


Panel Imperfections With Test Fixtures



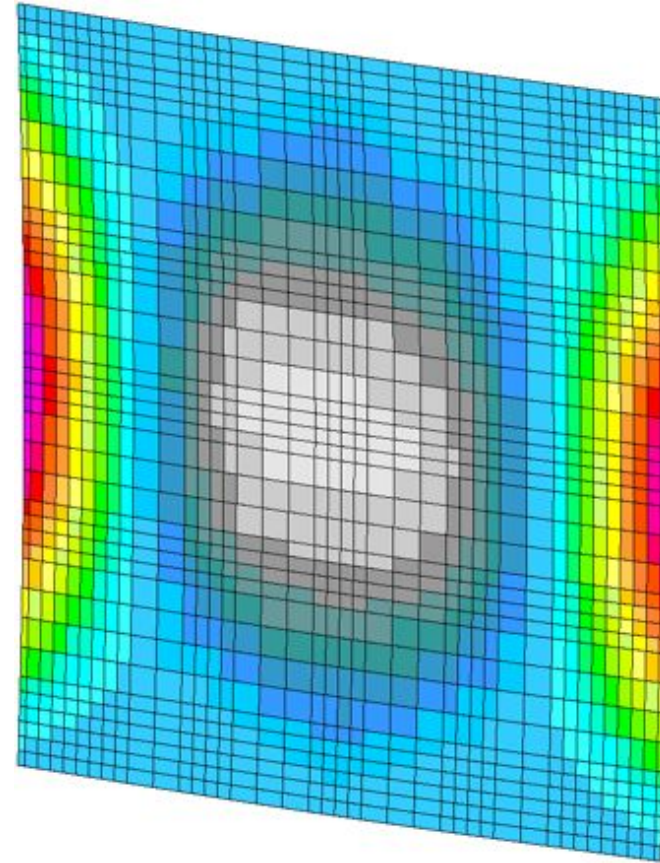
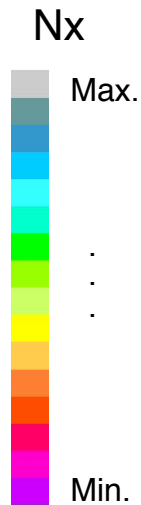
Predicted Mechanical Prestress Resultants

Panel With Overlaps



No axial load.
Max. $N_x = 285$ lb/in.,
min. $N_x = -1005$ lb/in.

Panel Without Overlaps



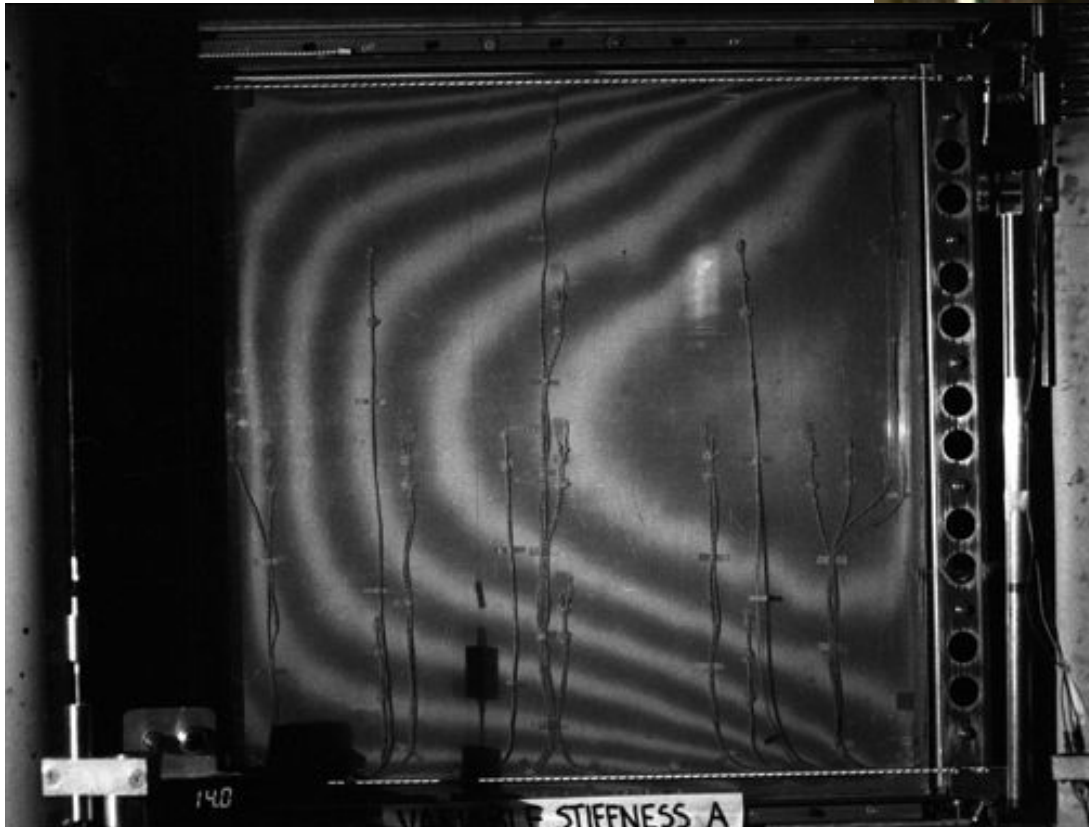
No axial load.
Max. $N_x = 236$ lb/in.,
min. $N_x = -668$ lb/in.

Composite Panel Installed In Test Stand

7 LVDTs used to measure panel/test stand deflections, and up to 34 strain gages used to measure panel surface strains.



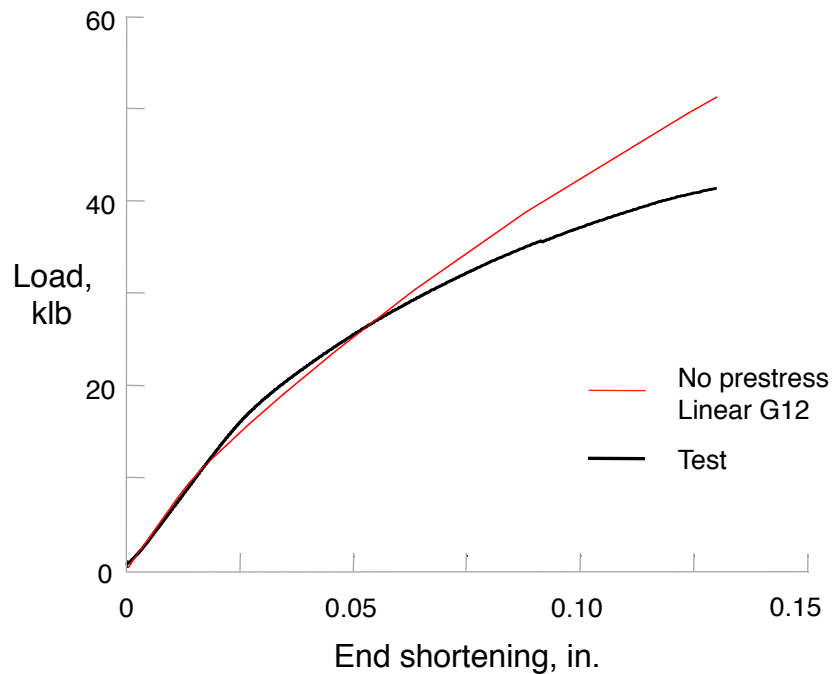
Back of panel



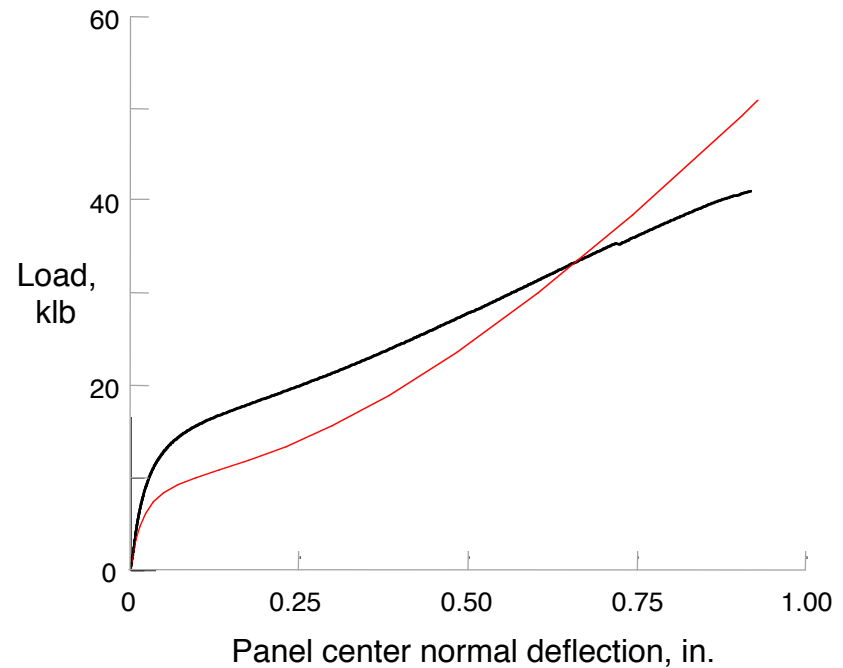
Uniform end shortening applied to panel, and axial force measured with integral load cell.

Front of panel

Measured and Predicted Deflections For Panel With Overlaps



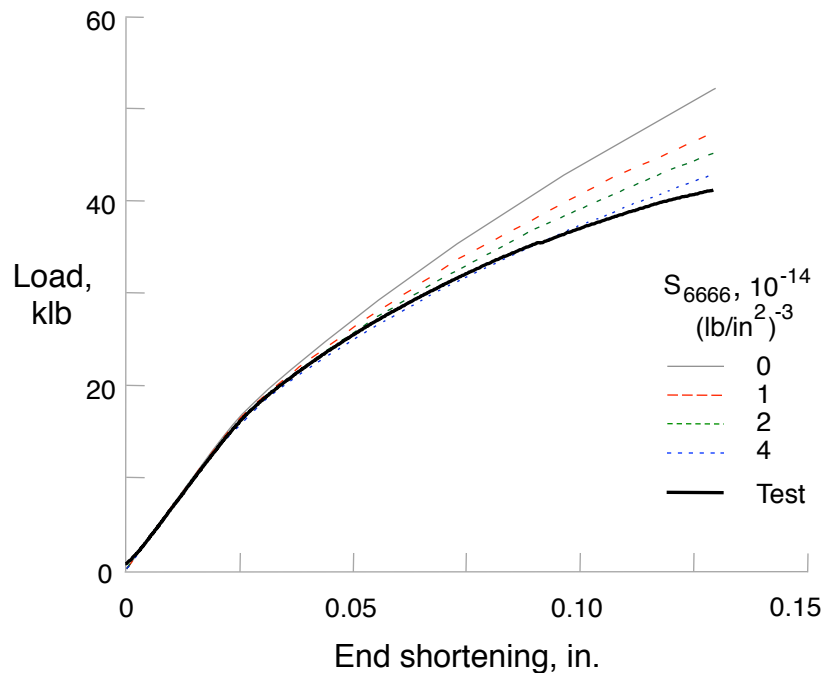
Load vs. end shortening



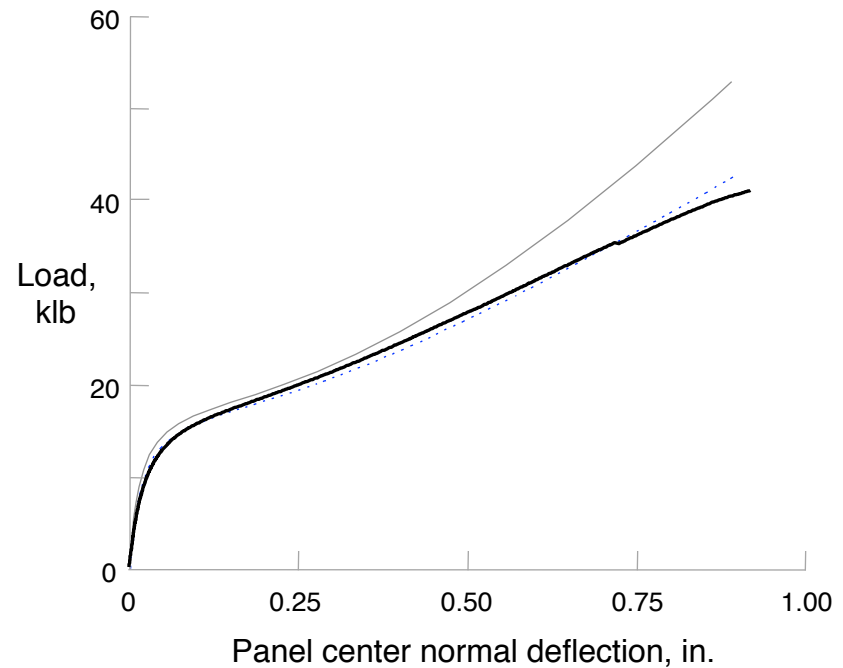
Load vs. normal deflection

- Linear prebuckling followed by nonlinear postbuckling.
- Analyses without mechanical prestresses from edge fixtures show poor overall correlation with test results.
- Fair prebuckling correlation between analyses and test.
- Poor buckling/postbuckling correlation up to global failure.

Measured and Predicted Deflections For Panel With Overlaps



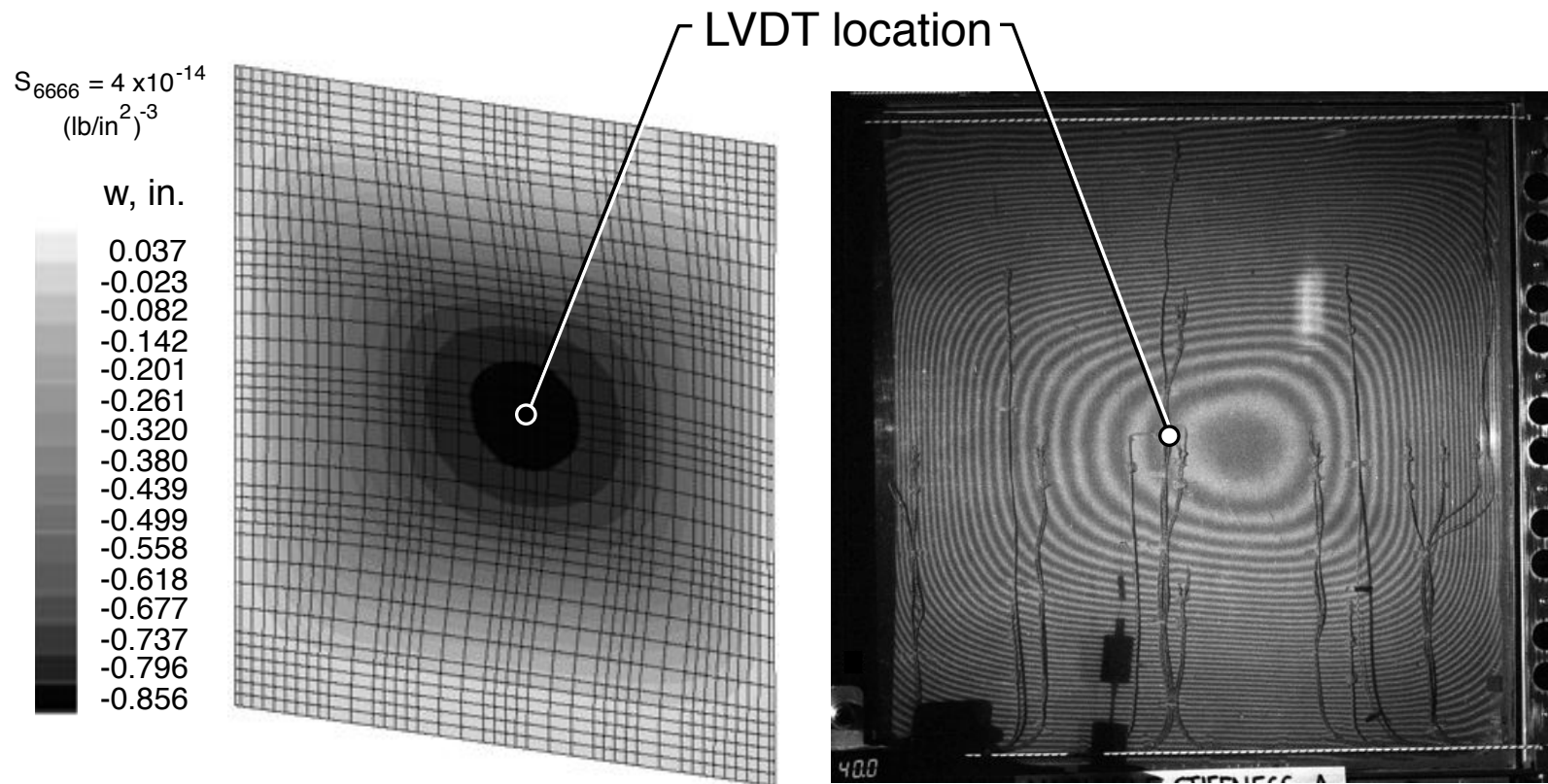
Load vs. end shortening



Load vs. normal deflection

- Analyses with both geometric and material nonlinearities include mechanical prestresses from edge fixtures.
- Very good prebuckling correlation between analyses and test.
- Good postbuckling correlation for $S_{6666} = 4 \times 10^{-14} \text{ (lb/in}^2\text{)}^{-3}$ up to panel global failure at $u = 0.130$ in.

Panel With Overlaps Normal Deflections

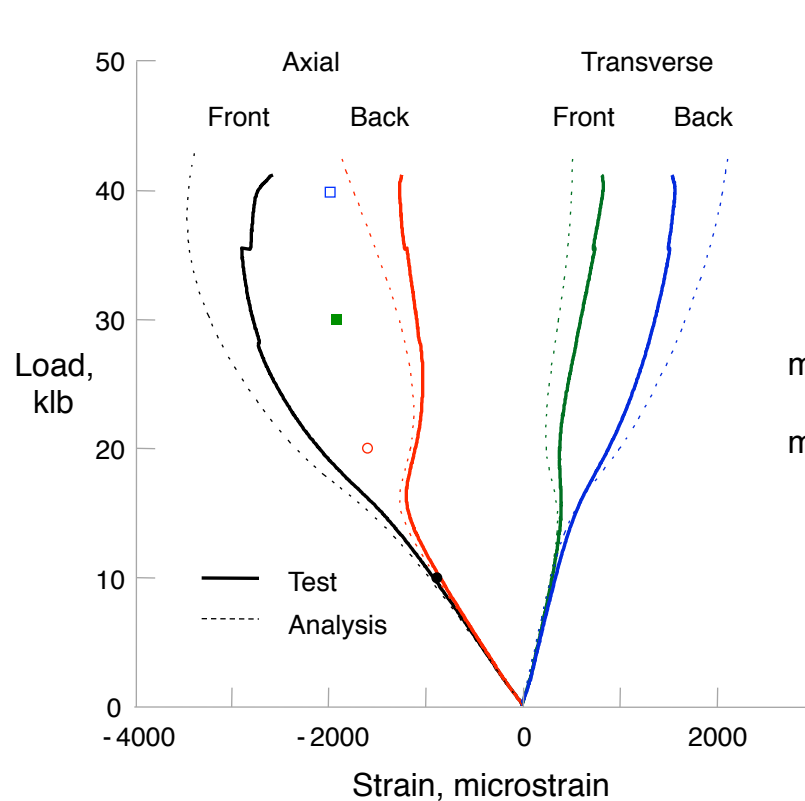


Predicted deflection contours

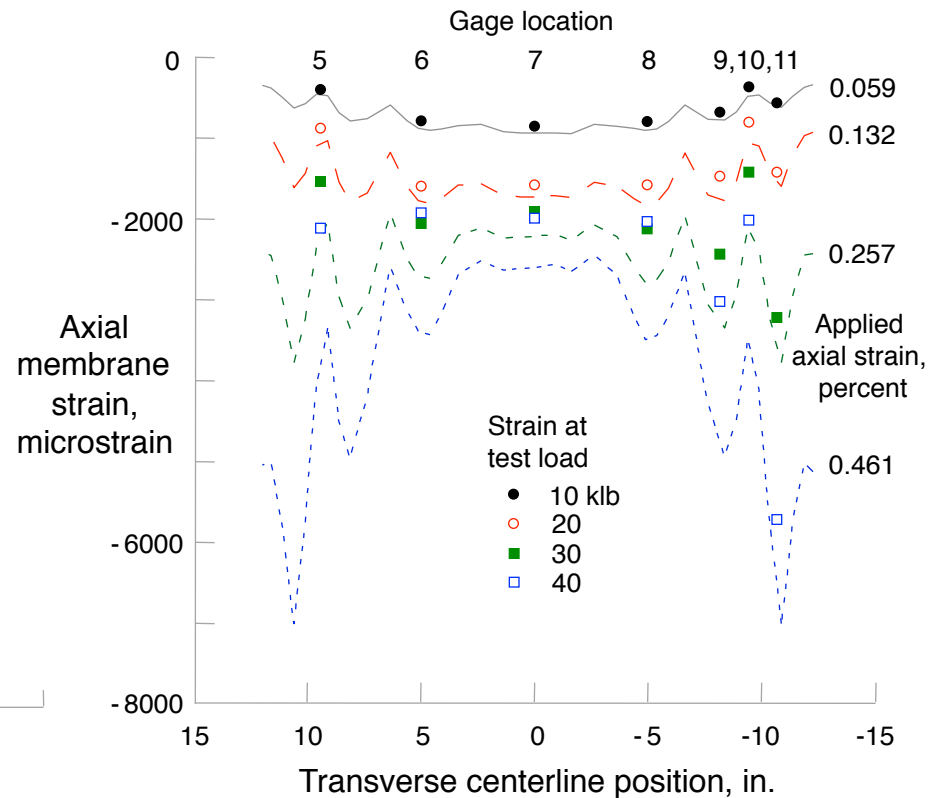
Photo of test shadow moiré

- End shortening = 0.120 in., or 0.461 percent applied strain.
- Compressive load = 41.1 klb analysis, 40.0 klb test.
- Panel center deflection = -0.856 in. analysis, -0.869 in. test.

Panel With Overlaps Strains



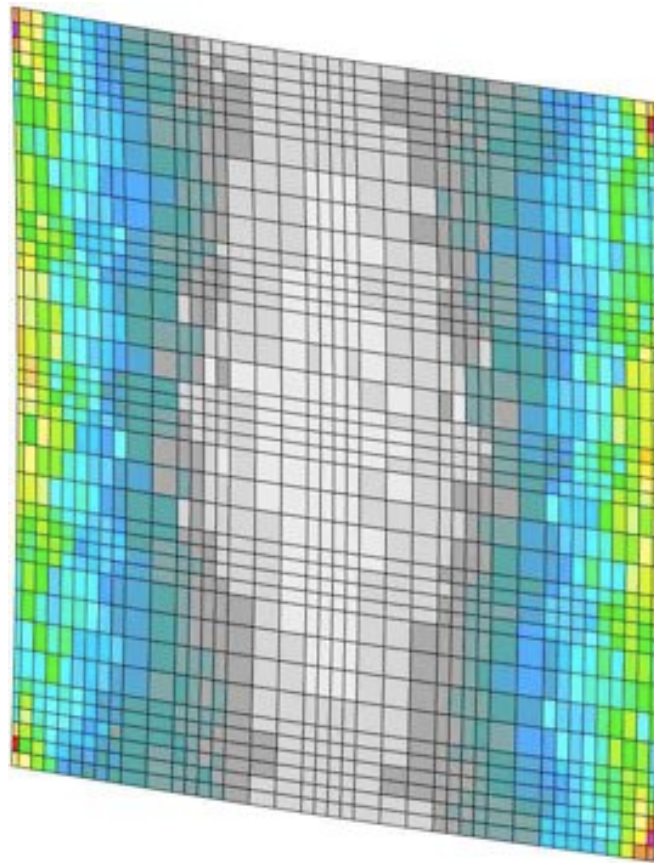
Load vs. panel center strain



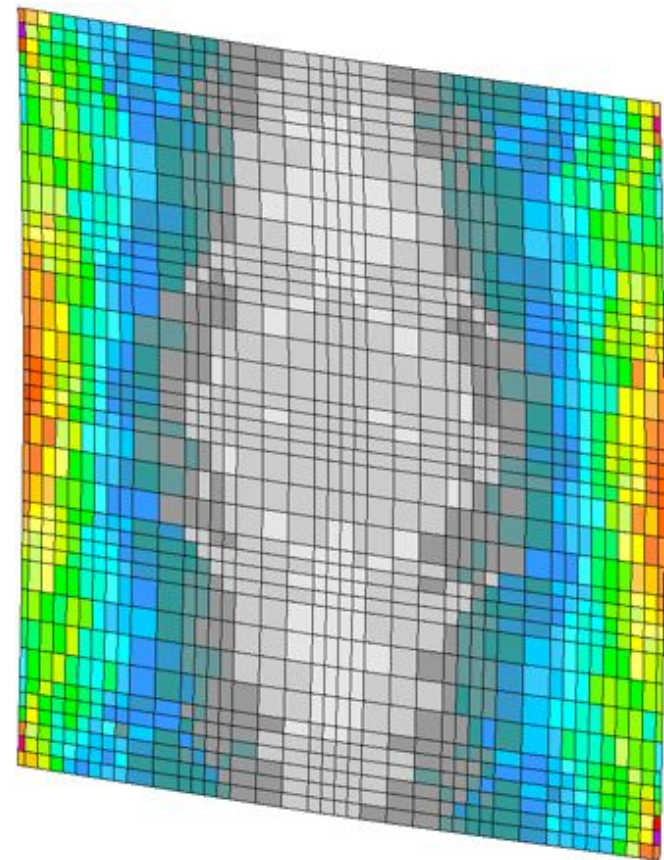
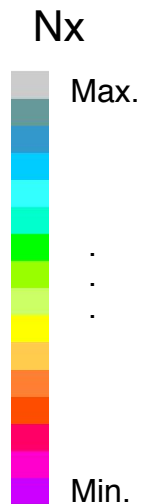
Membrane strain vs. position

- Results shown for $S_{6666} = 4 \times 10^{-14} (\text{lb/in}^2)^{-3}$.
- Fair to very good correlation between analysis and test.
- Large local variations in axial membrane strain.

Predicted Axial Stress Resultants For Panel With Overlaps

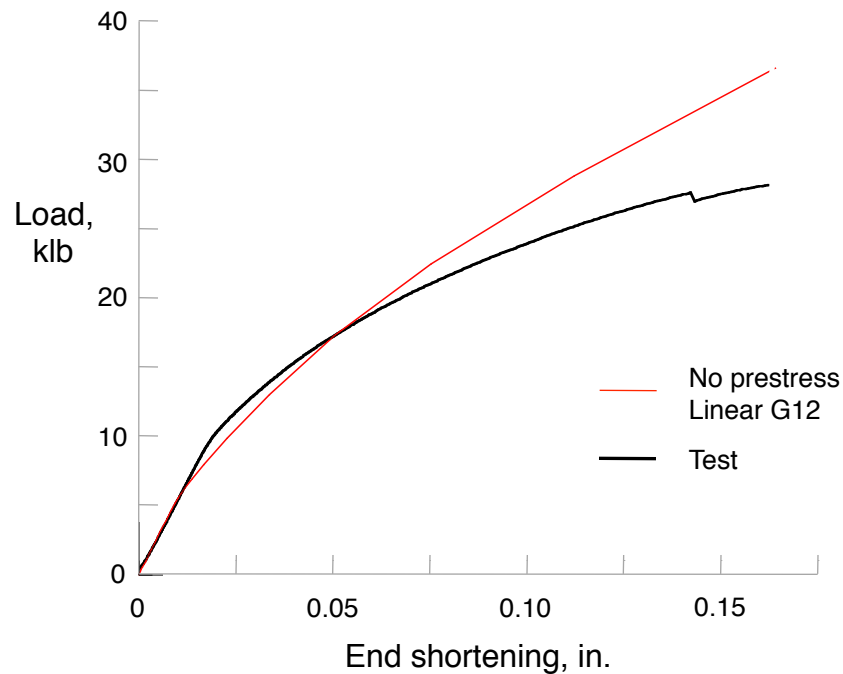


10 klb axial load
and mechanical prestress.
Max. $N_x = -59$ lb/in,
min. $N_x = -2289$ lb/in.

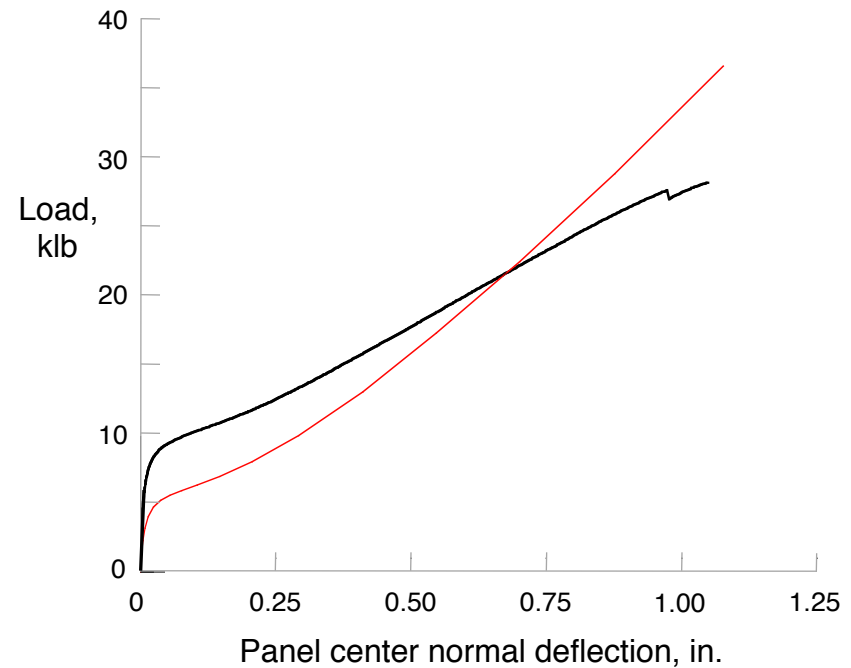


40 klb axial load
and mechanical prestress.
Max. $N_x = -140$ lb/in,
min. $N_x = -8301$ lb/in.

Measured and Predicted Deflections For Panel Without Overlaps



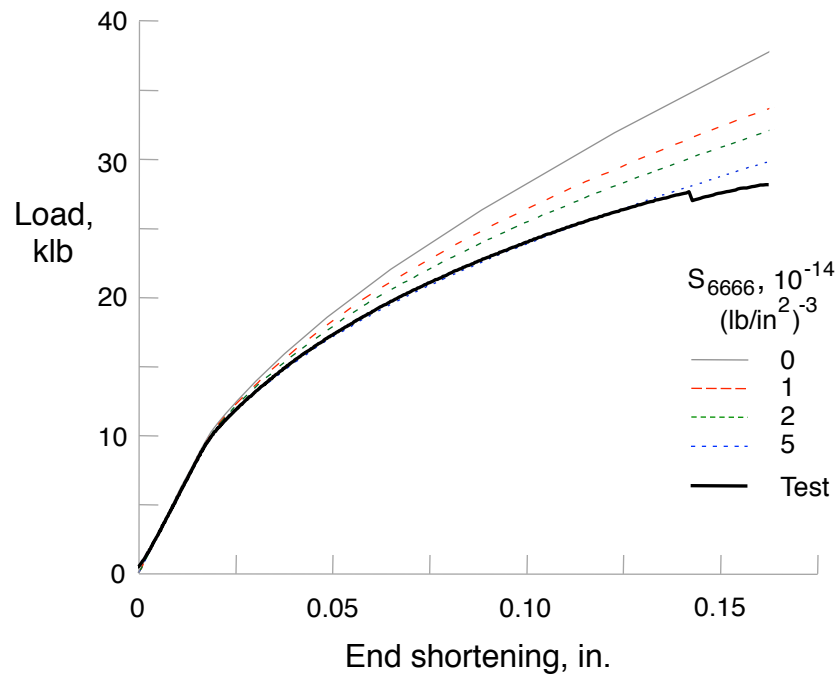
Load vs. end shortening



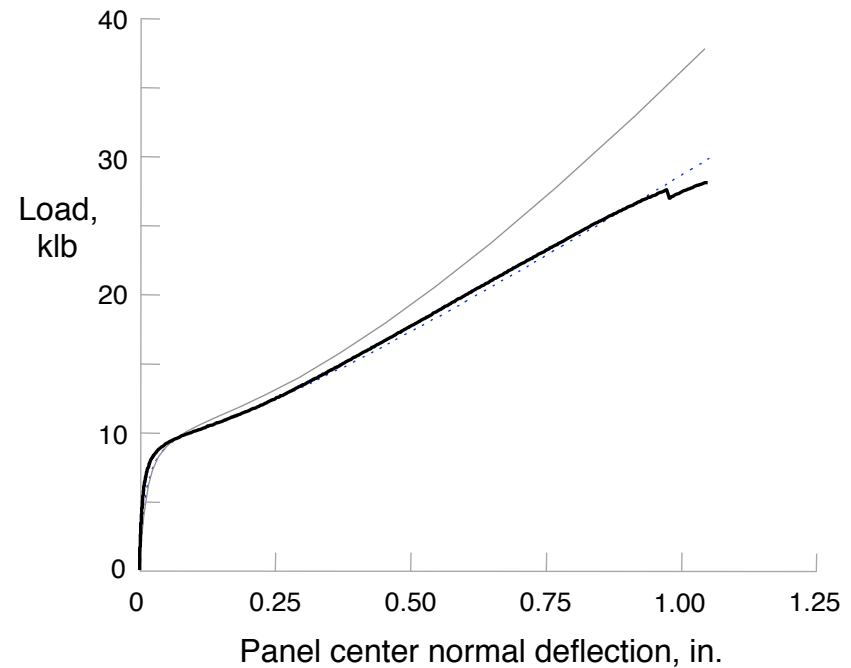
Load vs. normal deflection

- Linear prebuckling followed by nonlinear postbuckling.
- Very good prebuckling correlation between analyses and test.
- Good postbuckling correlation for $S_{6666} = 5 \times 10^{-14} (\text{lb/in}^2)^{-3}$ up to panel global failure at $u = 0.163$ in.

Measured and Predicted Deflections For Panel Without Overlaps



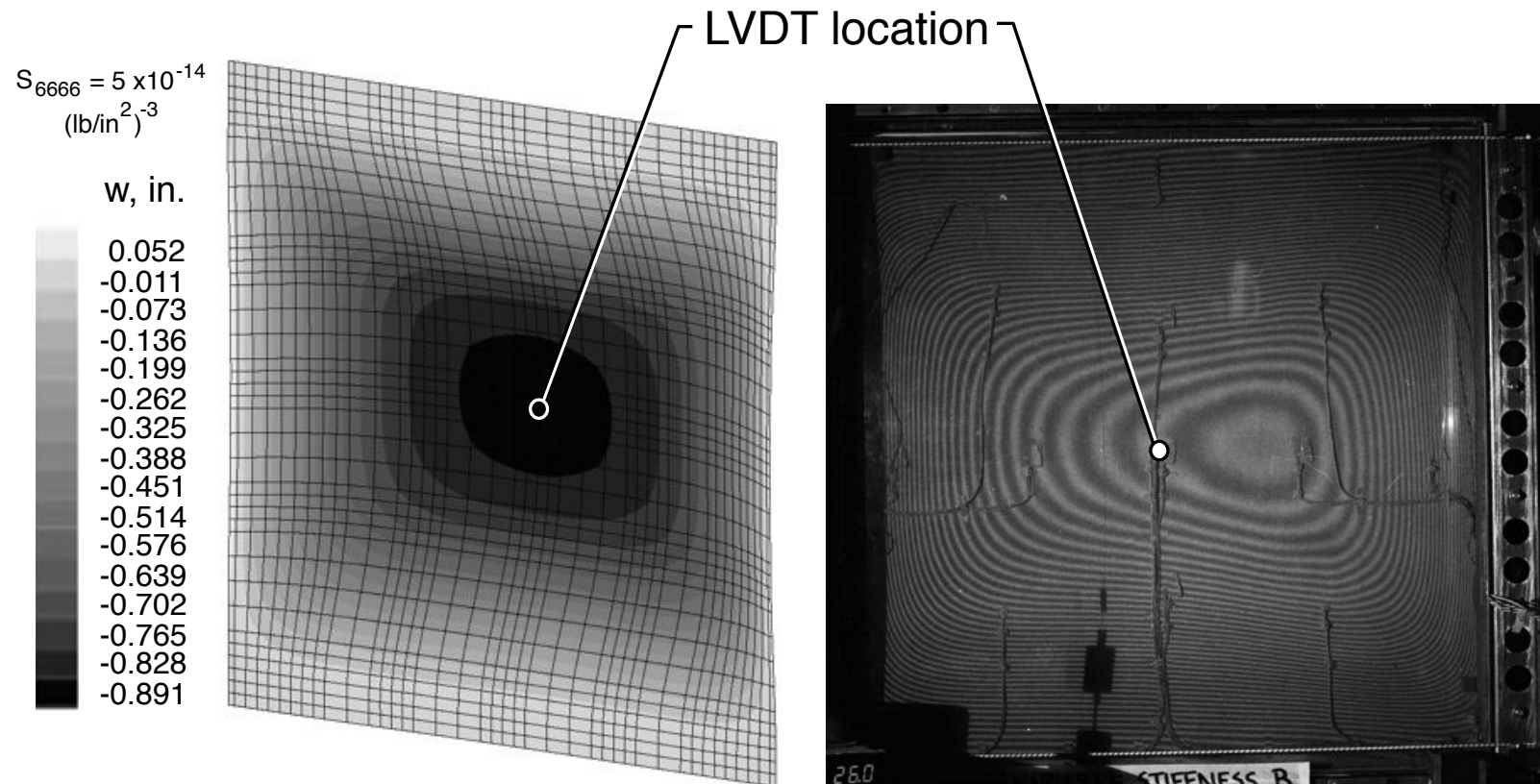
Load vs. end shortening



Load vs. normal deflection

- Linear prebuckling followed by nonlinear postbuckling.
- Very good prebuckling correlation between analyses and test.
- Good postbuckling correlation for $S_{6666} = 5 \times 10^{-14} \text{ (lb/in}^2\text{)}^{-3}$ up to panel global failure at $u = 0.163$ in.

Panel Without Overlaps Normal Deflections

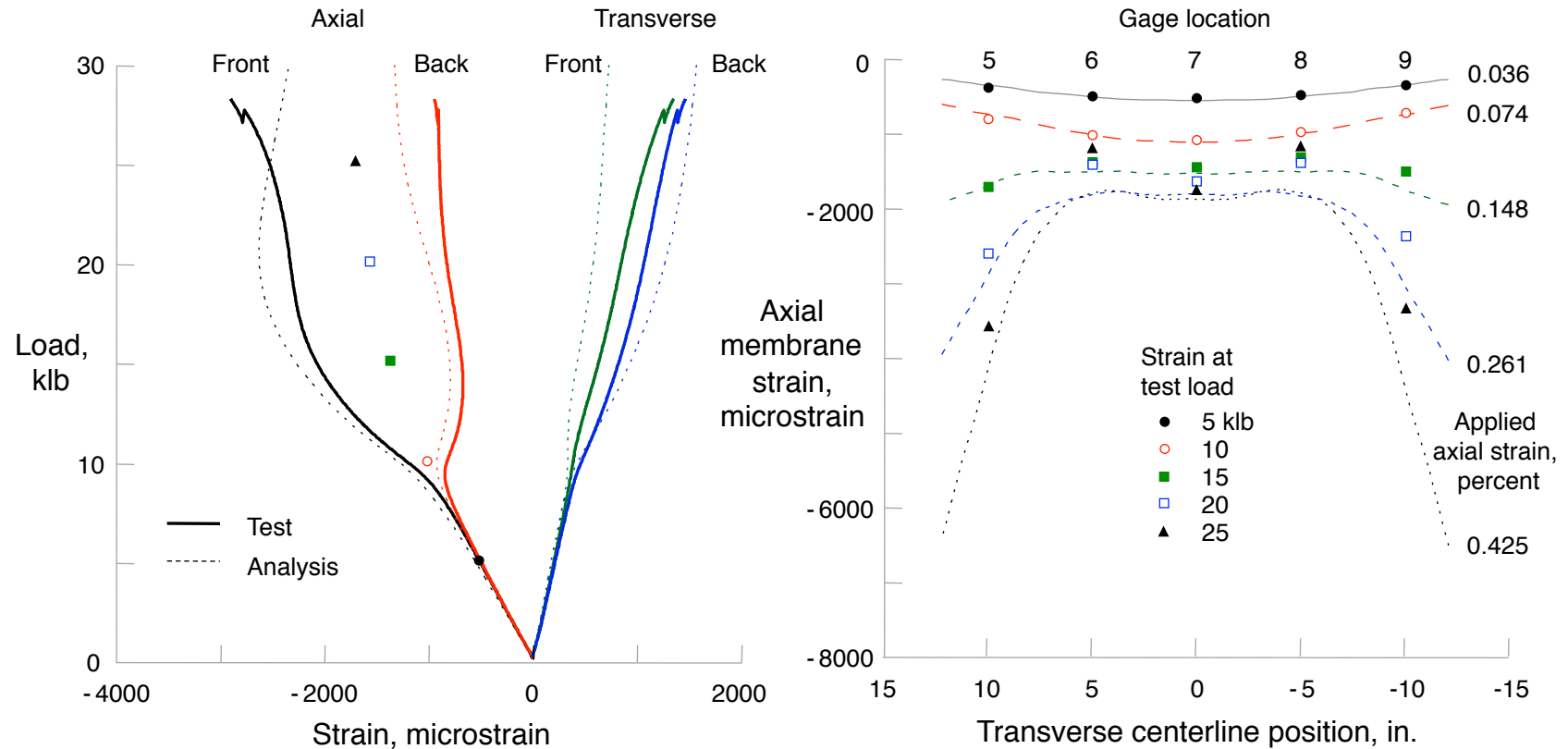


Predicted deflection contours

Photo of test shadow moiré

- End shortening = 0.122 in., or 0.467 percent applied strain.
- Compressive load = 26.1 klb analysis, 26.0 klb test.
- Panel center deflection = -0.891 in. analysis, -0.884 in. test.

Panel Without Overlaps Strains

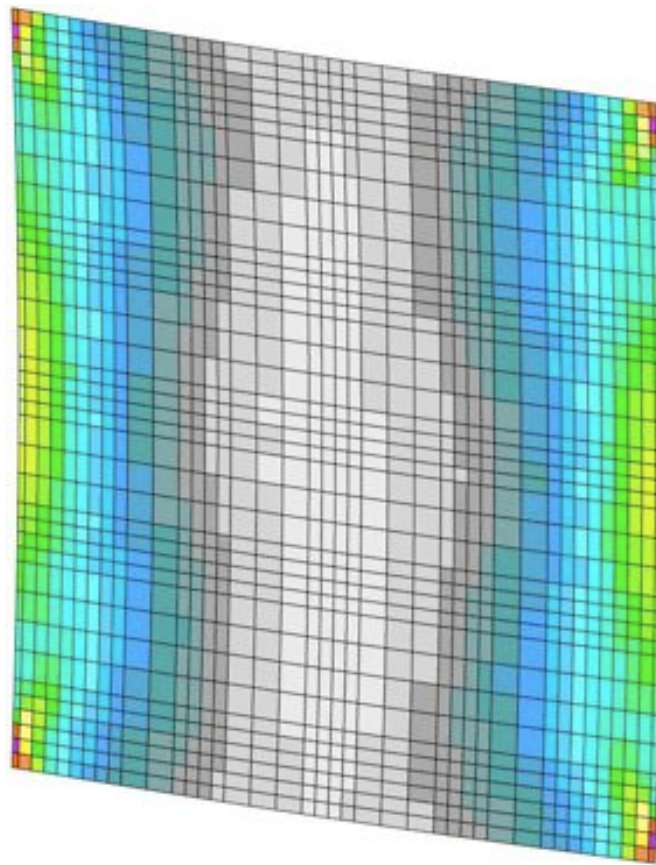


Load vs. panel center strain

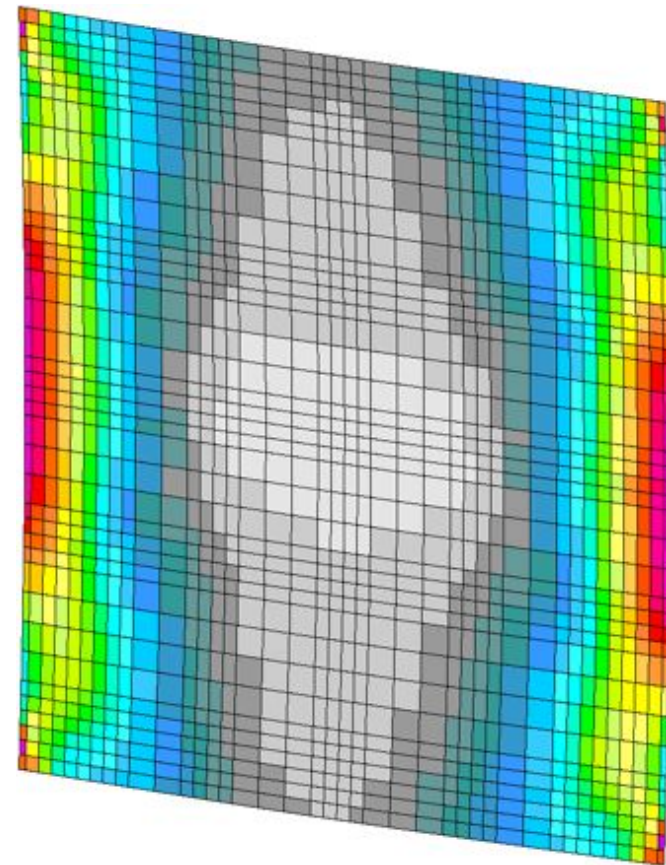
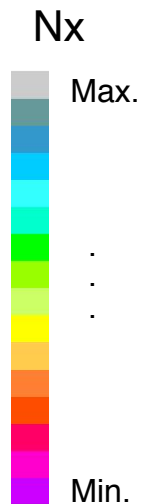
Membrane strain vs. position

- Results shown for $S_{6666} = 5 \times 10^{-14} (\text{lb/in}^2)^{-3}$.
- Good to very good correlation between analysis and test.

Predicted Axial Stress Resultants For Panel Without Overlaps

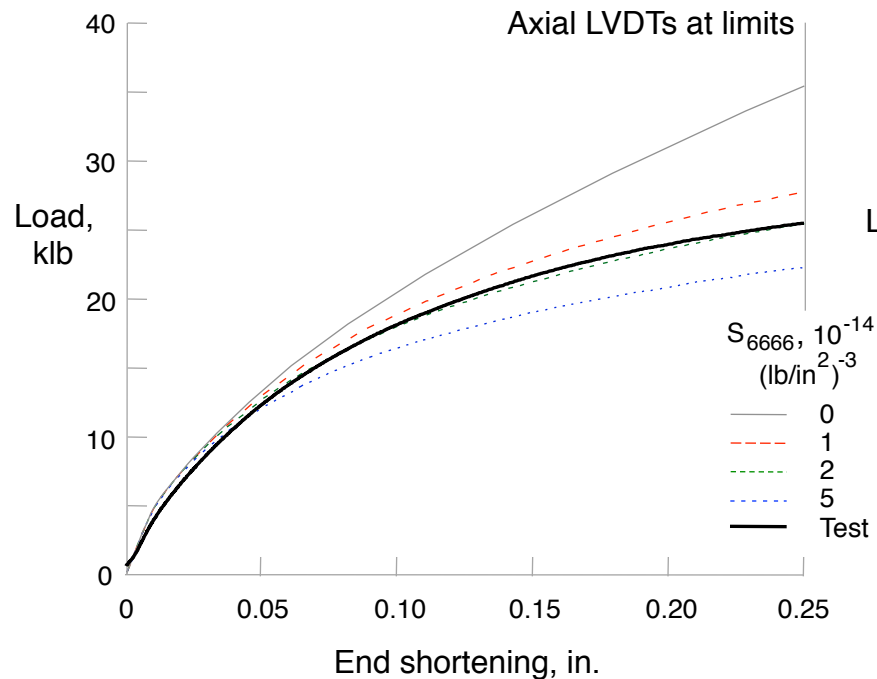


10 klb axial load
and mechanical prestress.
Max. $N_x = -117$ lb/in,
min. $N_x = -1938$ lb/in.

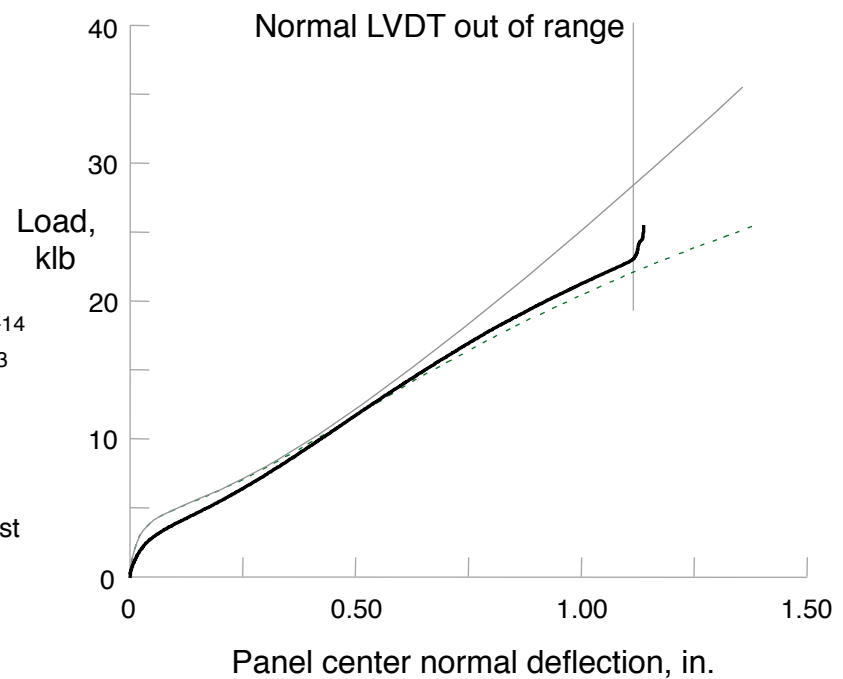


25 klb axial load
and mechanical prestress.
Max. $N_x = -108$ lb/in,
min. $N_x = -4294$ lb/in.

Measured and Predicted Deflections For $[\pm 45]_{5s}$ Baseline Panel



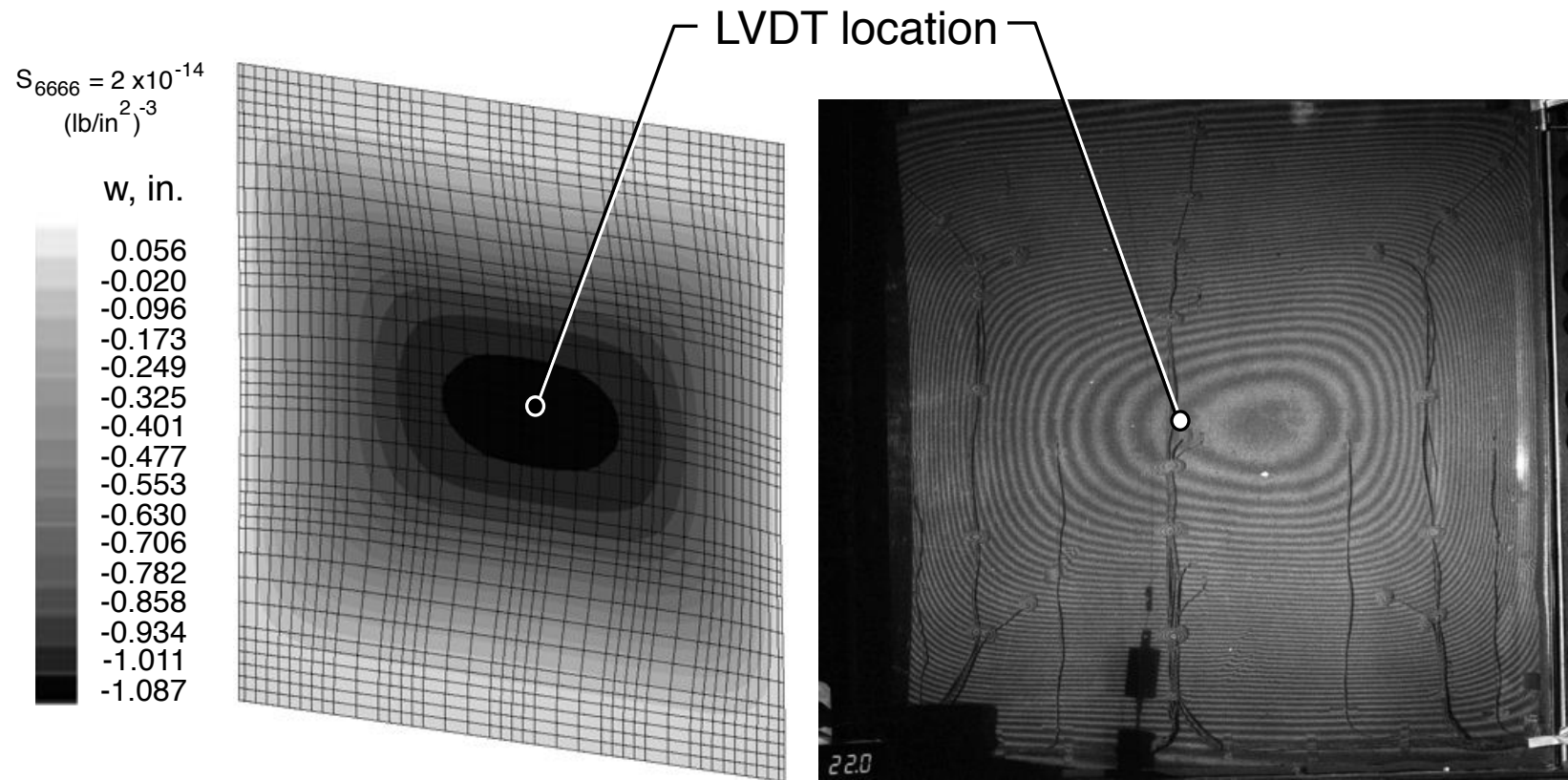
Load vs. end shortening



Load vs. normal deflection

- Fair correlation for prebuckling in this high-load test.
- Very good correlation for previous low-load test to 8 klb.
- Good postbuckling correlation for $S_{6666} = 2 \times 10^{-14} \text{ (lb/in}^2\text{)}^{-3}$ up to end of test at $u = 0.252$ in.

Baseline Panel Normal Deflections

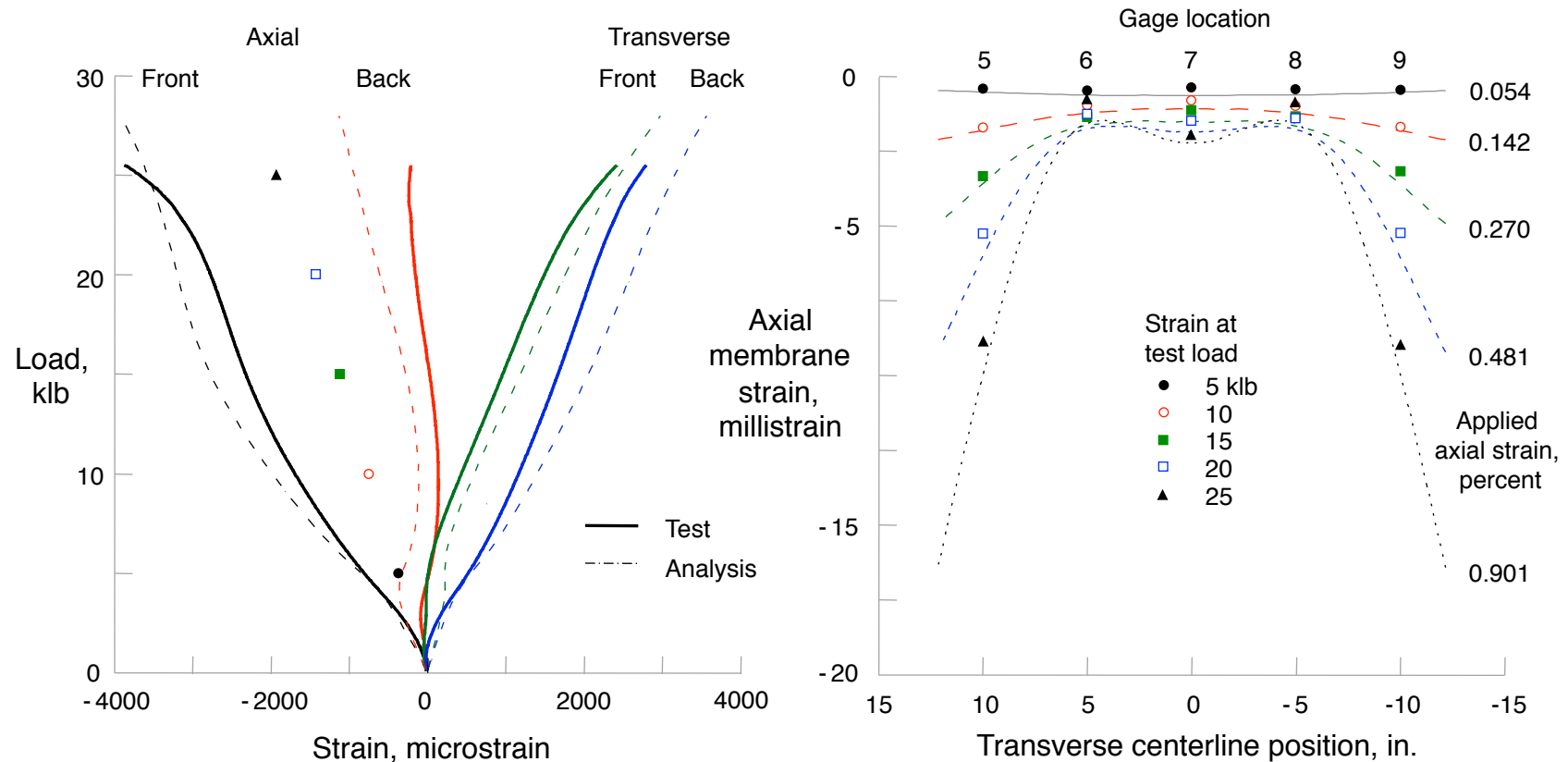


Predicted deflection contours

Photo of test shadow moiré

- End shortening = 0.157 in., or 0.604 percent applied strain.
- Compressive load = 21.7 klb analysis, 22.0 klb test.
- Panel center deflection = -1.087 in. analysis, -1.055 in. test.

Baseline Panel Strains

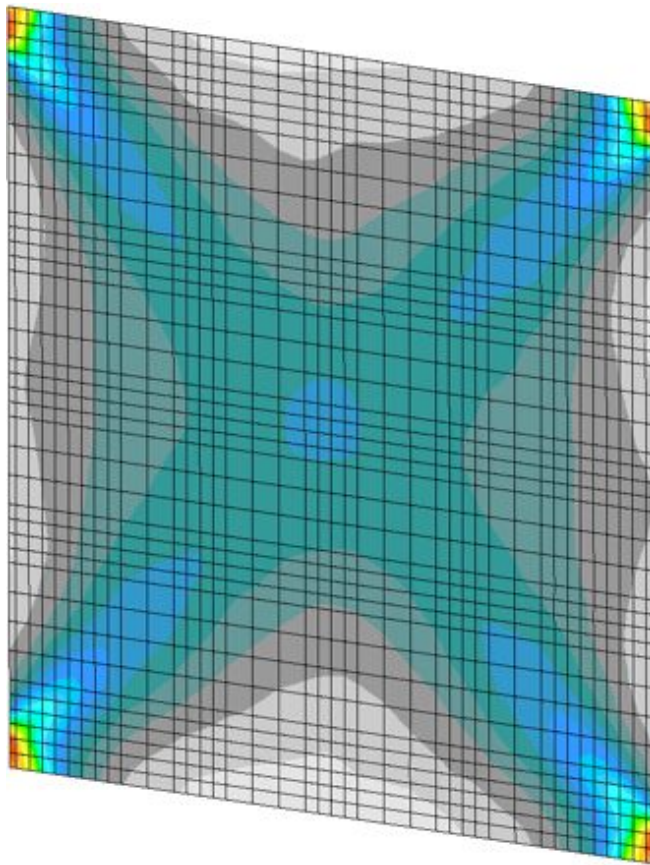


Load vs. panel center strain

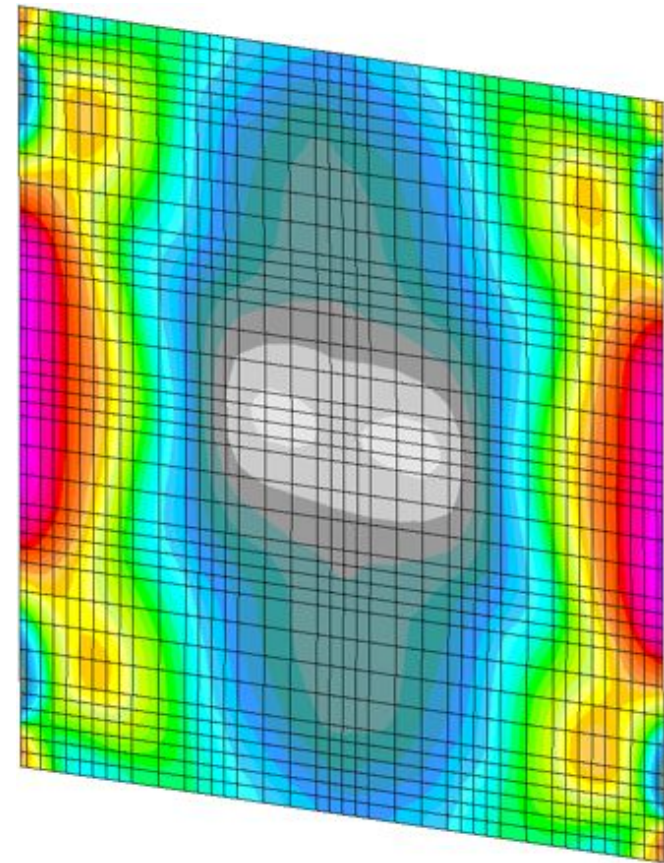
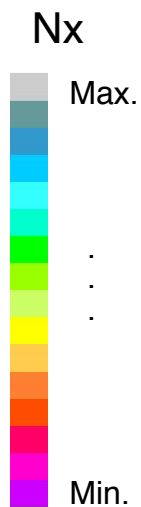
Membrane strain vs. position

- Results shown for $S_{6666} = 2 \times 10^{-14} (\text{lb/in}^2)^{-3}$.
- Fair to very good correlation between analysis and test.
- Peak membrane strains $\sim 2x >$ variable stiffness panels.

Predicted Axial Stress Resultants For Baseline Panel



5 klb axial load.
Max. $N_x = -171$ lb/in.,
min. $N_x = -837$ lb/in.



25 klb axial load.
Max. $N_x = 14$ lb/in.,
min. $N_x = -3006$ lb/in.

Conclusions

- Ply-level material properties computed from laminate-level coupon tests, but no *a priori* value of S_{6666} found.
- Measured shapes of cured panels correlate well with nonlinear structural analyses of post-cure cooldown.
- Good correlation observed between measured and predicted thermal strains and CTEs from thermal tests.
- Prestresses from test fixtures (applied to reduce large geometric imperfections) modeled in structural analyses.
- Large geometric and material nonlinearities present in postbuckling, requiring advanced structural analyses.
- Values of S_{6666} between 2 and $5 \times 10^{-14} (\text{lb/in}^2)^{-3}$ give best correlation with measured panel displacements.

Thank You!
Questions?