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A Simplified Method for Simulating Residual Stresses in Asymmetric Textile Composites

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THE COMPOSITES AND ADVANCED MATERIALS EXPO

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Outline of Presentation

- Introduction and Motivation for Work
- Objectives of the Study
- Validation Experiment
- Finite Element Methods
  – Solid element methods development
  – Shell element implementation and validation
- Discussion of Results
- Summary and Conclusions

Introduction

- Residual stresses should be considered when designing composite parts
- Verified and validated FE methods are alternatives to the experimental measurement of residual stresses
  - Experimental approaches become impractical with increasing part complexity
- Textile composites complicate residual stress considerations
  - Symmetric lay-ups are necessary to eliminate unbalanced thermal strains during elevated temperature curing cycles
- Low-cost/simple modeling methods are desirable
  - Residual stress prediction
    - High and low fidelity methods are found in literature
  - Predictions of stresses in unbalanced textile composites
    - Micromechanical methods dominate literature
      - Expensive and non-trivial implementation

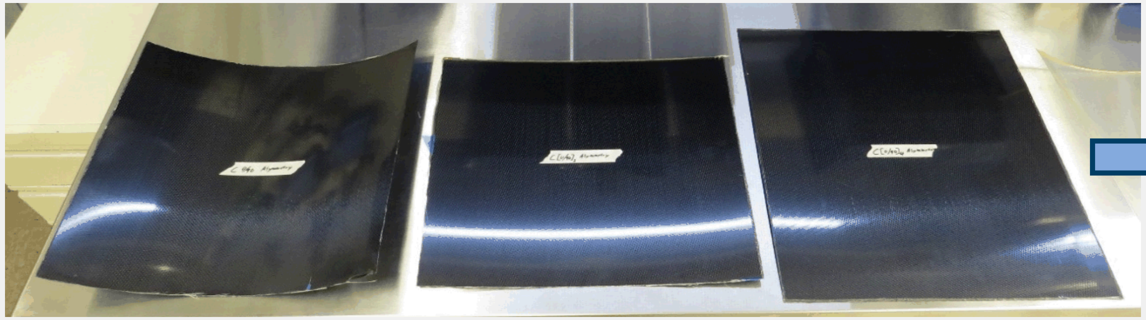
Objectives

- What level of model fidelity is necessary for realistic predictions of a textile composite's residual stress state?
  - Implement simplified residual stress modeling method in Sandia's SIERRA/SolidMechanics code
    - CTE mismatch during cooling from stress free temperature
  - Determine validity of a simplified representation of a woven composite ply
    - Textile fabrics are approximated as laminates of [0/90] unidirectional plies
  - Complete residual stress experiments for model validation
    - Measure displacements in asymmetric, woven composite plates

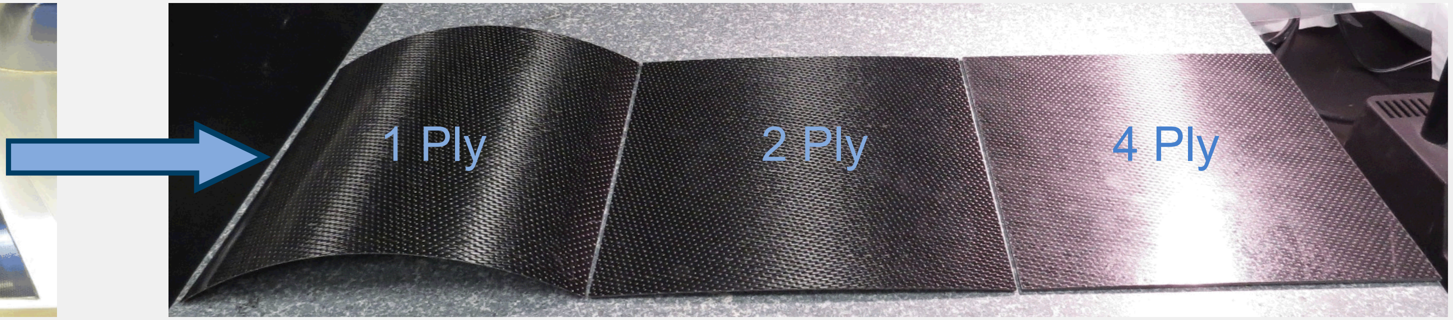
Validation Experiments

Materials and Manufacturing Process

- 3 asymmetric plates were manufactured
  - 8-harness satin weave, carbon/epoxy (CFRP) prepreg
    - Standard vacuum bag/autoclave cure
  - 1, 2, and 4 ply laminate thicknesses
    - Adjacent plies laid front-to-back
  - Bulk laminates measured 16”x16”-20” and were trimmed to 8”x8” prior to residual stress measurement
  - Plates warped due to unbalanced thermal strains



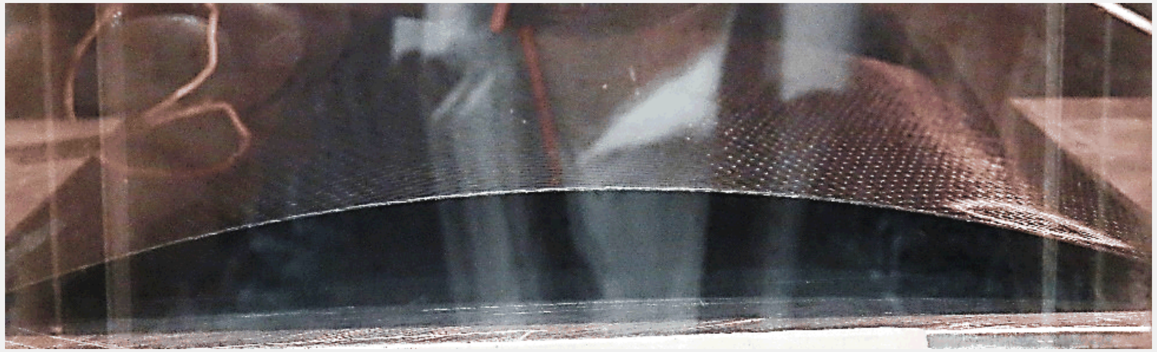
Bulk panels immediately after manufacturing



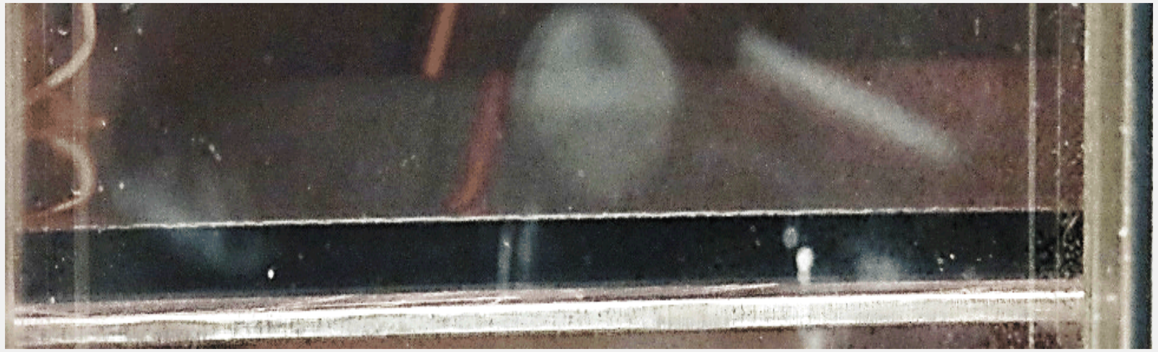
Trimmed panels prepared for residual stress measurement

Stress-Free Temperature Determination

- Residual stress modeling method depends on stress-free temperature
  - Accounts for polymer shrinkage
  - Development of thermal strains/CTE mismatch
- 1-ply laminate's "flatness" was observed during thermal cycle from ambient to 140°C
  - T_{sf} is between 100°C and 140°C



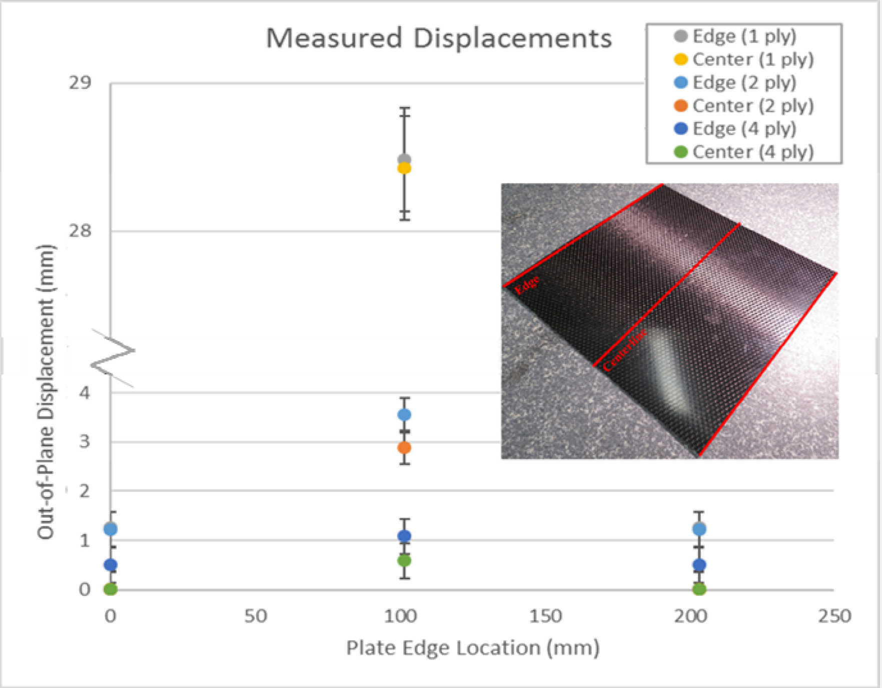
Curvature of 1 ply laminate at ambient conditions

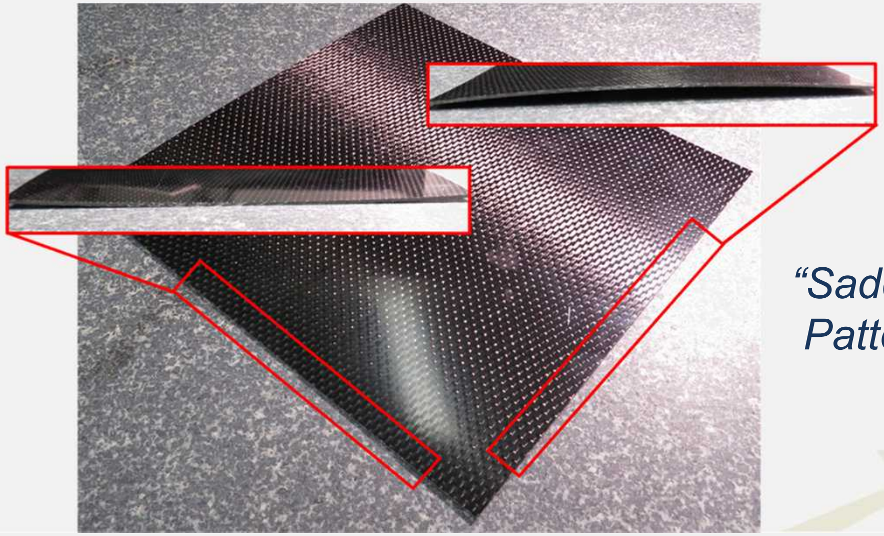


Curvature of 1 ply laminate at 120°C

Residual Stress Measurement

- Surface contours of trimmed panels were measured on a granite table with a digital height gage
  - Maximum/minimum out-of-plane displacements were determined at plate centerlines and edges
  - Measurement error of ±0.35 mm inherent to system
- Displacements decrease with increasing plate thickness
- Centerline displacements are slightly less than edgeline displacements
- Each plate exhibited a "saddle" displacement pattern
  - Maximum and minimum displacements were measured at the center points of the plates' orthogonal edges





"Saddle" Pattern

Computational Methods

Solid Elements

Analysis Software and Element Formulation

- All simulations were processed with Sandia's SIERRA SolidMechanics/Implicit ("Adagio")
  - Lagrangian, three dimensional code for FEA of solid structures
  - Suitable for implicit, quasi-static analyses

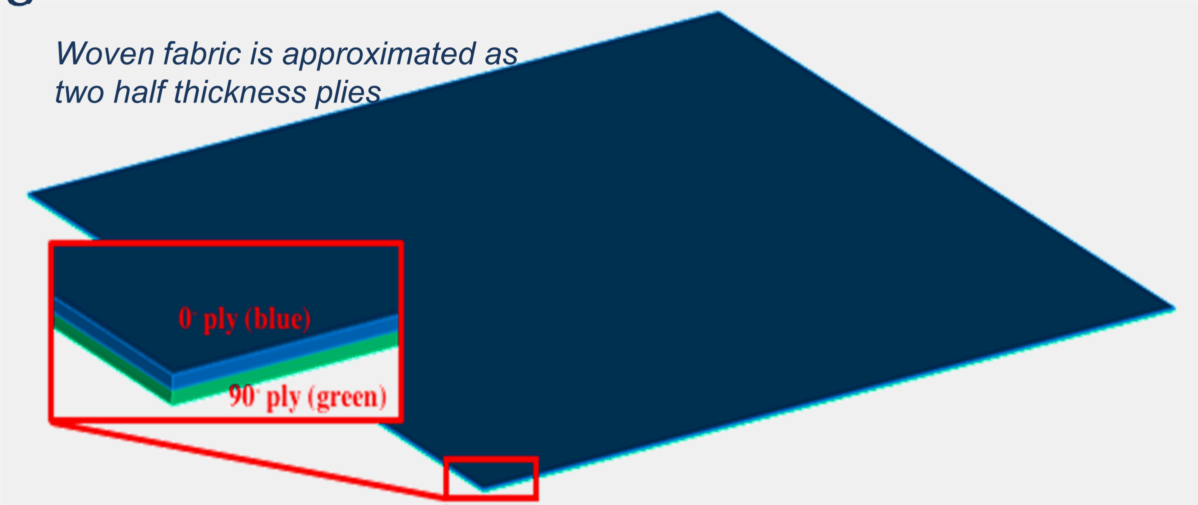
- 8-noded hexahedral elements were used exclusively
- A fully-integrated element formulation was used to avoid hourglass modes and shear locking
  - Bending response and plate stiffness is important
  - Selective deviatoric formulation
    - Deviatoric stress response is fully-integrated, hydrostatic pressure response in under-integrated

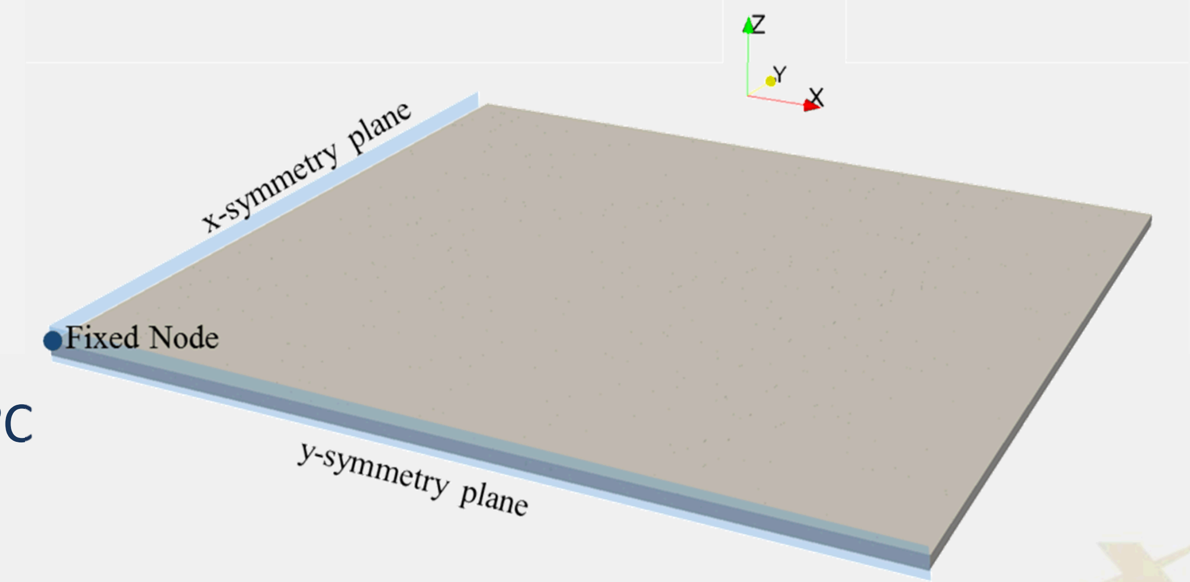
Material Models

- CFRP material was modeled with Adagio's Elastic-Orthotropic material model
  - No intralaminar failure was expected or observed
  - Applies Hooke's Law for orthotropic materials
  - Requires definition of 9 elastic constants and 3 thermal strain functions
    - Orthotropic CTE's allow for development of residual stresses in the asymmetric laminates
- Material properties taken from literature for a unidirectional carbon/epoxy material system
- Stress-free temperature was defined as a uniform distribution from 100°C to 140°C
  - The distribution was propagated through the finite element simulations to determine the corresponding distribution of residual stress predictions

Geometry and Boundary Conditions

- Each woven fabric layer was approximated as two homogenous, unidirectional layers
  - 1-ply model ≈ [0/90]
  - 2-ply model ≈ $[(0/90)_2]$
  - 4-ply model ≈ $[(0/90)_4]$
- Plates' planar dimensions = 203.2 mm
- Measured woven ply thickness = 0.39 mm
  - Half-thickness = 0.195 mm
- Quarter model symmetry conditions
- Central node fixed to eliminate RBM's
- Isothermal temperature ramp from T_{sf} to ambient
  - T_{sf} defined as uniform distribution, 100°C to 140°C
  - Simulations processed at T_{sf} bounds to define potential range of predictions

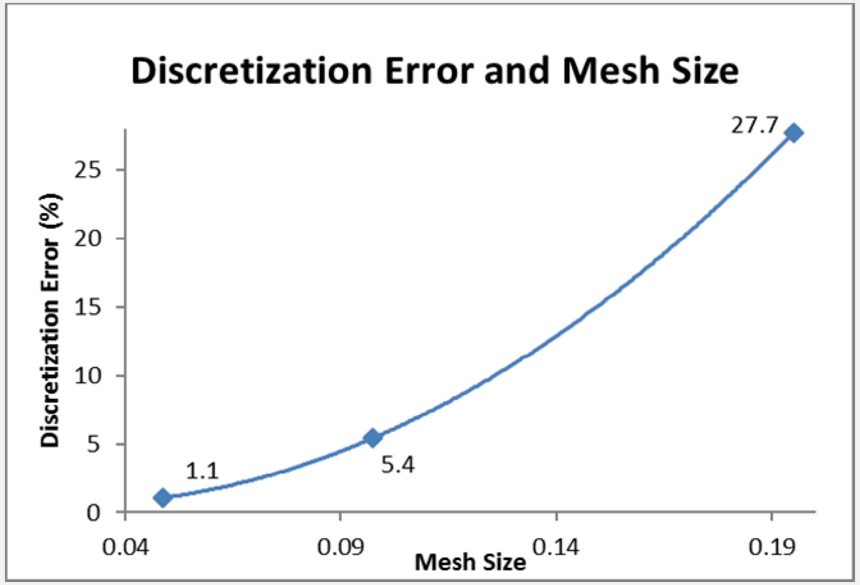


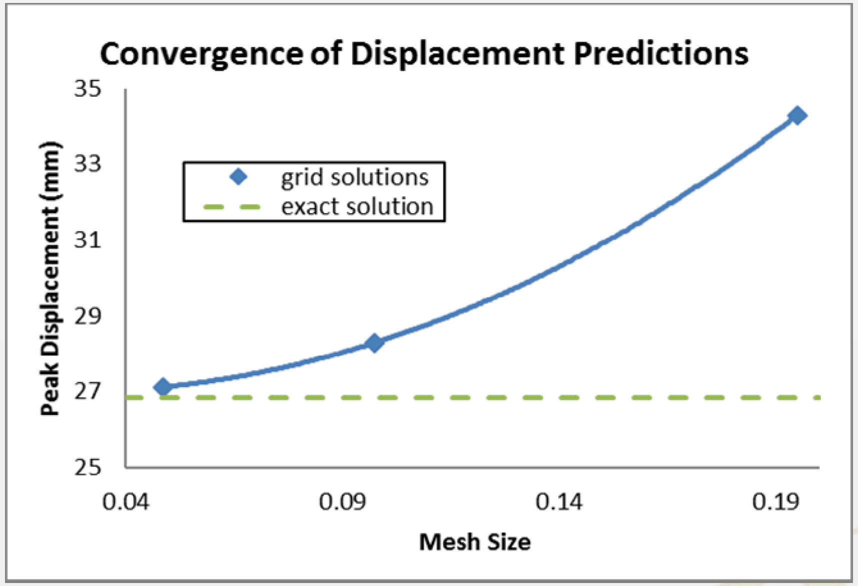


Mesh Convergence Study

- Verification of analysis methods
  - Quantify and show that the discretization errors are small
  - Determine the best mesh size
- 1-ply model was discretized 3 times and processed through Adagio with described methods
- Richardson's extrapolation estimated the peak out-of-plane displacement
  - Approximates a higher order estimate of a continuum value given discrete solutions
- Medium mesh size presents an error ≤ 10%

$$discretization\ error = \frac{f_{exact} - f_k}{f_{exact}} \cdot 100$$

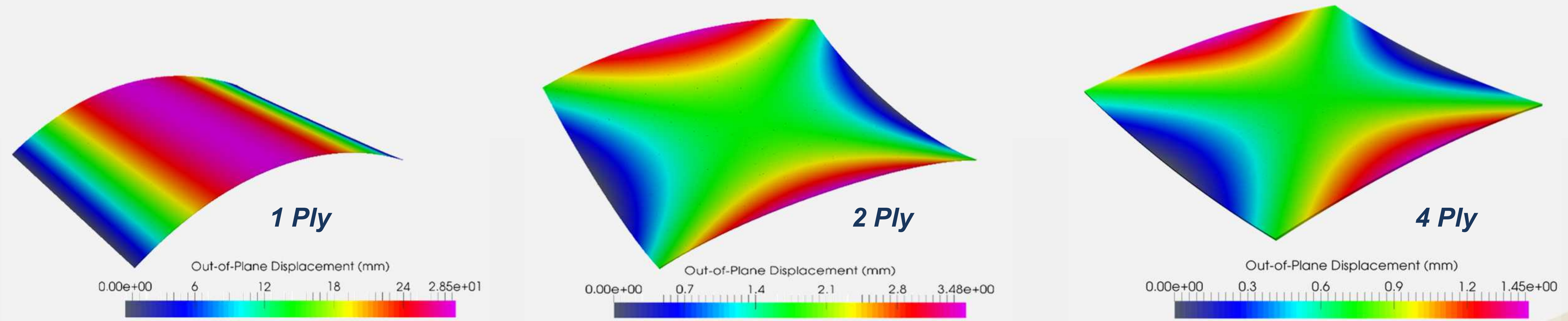




Model Results (Solid Elements)

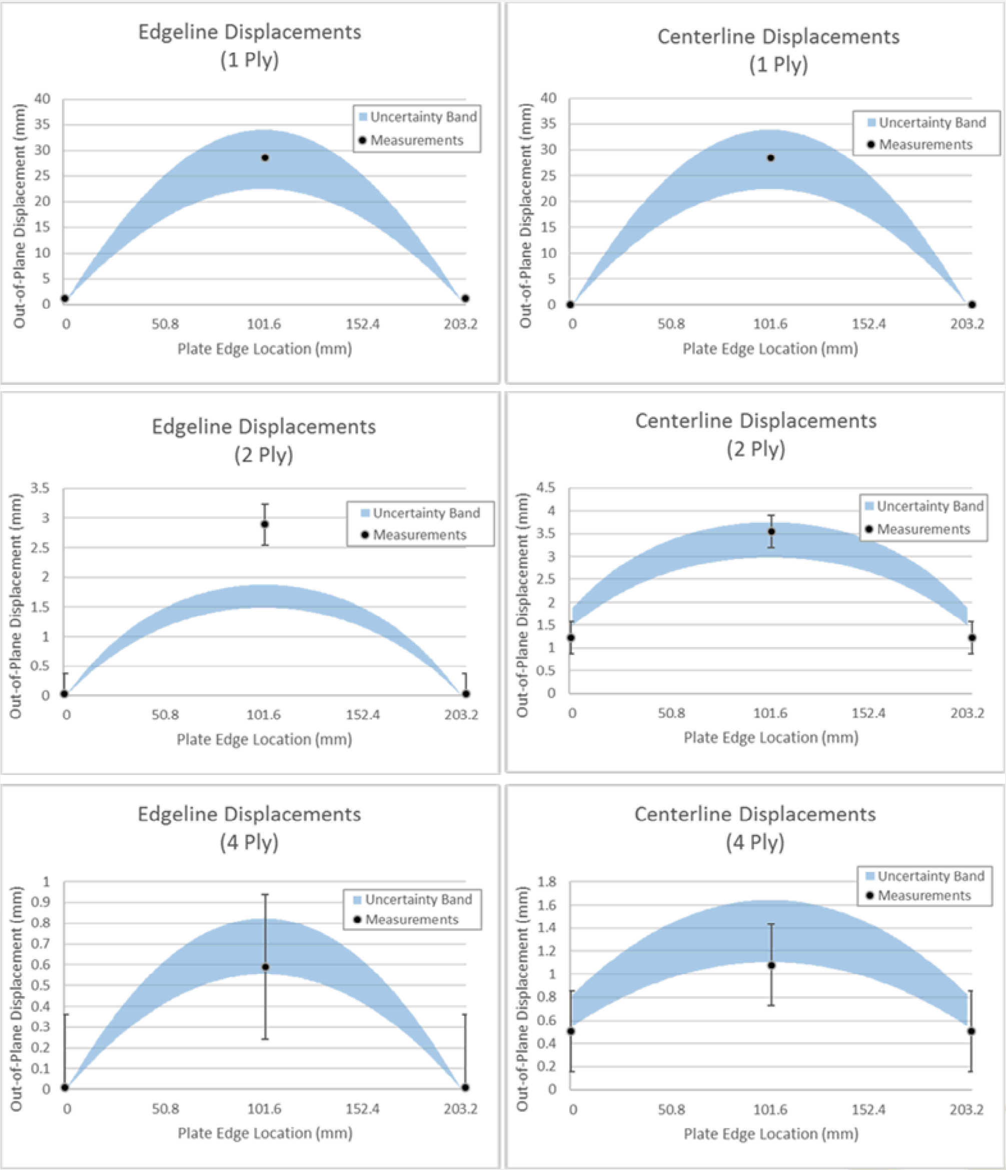
- Each laminate model was discretized with the medium mesh size and processed with described FE methods
  - Each model was solved at the limits of the T_{sf} range to bound displacement predictions
- Modeled displacement patterns agree with experimental observations
  - Simulated displacements decrease with increasing plate thickness
  - "Saddle" displacement pattern is captured
  - Centerline displacements are slightly less than edgeline displacements

Representative Contours of displacement:



Model Results (Solid Elements)

- Modeled displacement magnitudes agree reasonably with experimental observations
  - Possible error in experimental measurement, small sample size
- <u>Proposed modeling methodology shows promise</u>
  - Model error sources should be accounted for before final conclusions can be made
    - Uncertainty in material properties should be examined
      - Unidirectional properties are not conservative
    - Rigorous verification and validation could be completed
      - Studies of parameter sensivity and uncertainty quantification



Computational Methods

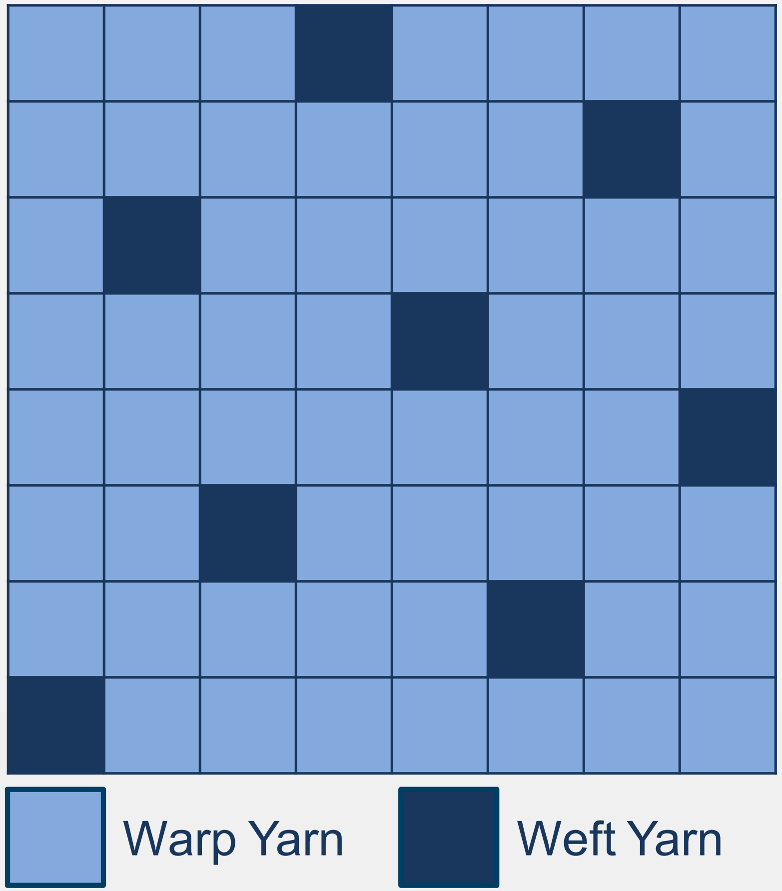
Shell Elements

Shell Element Investigation

- Use of unidirectional properties for half thickness plies may not be accurate
  - Warp face is “interrupted” by weft sinkers
  - Weft face is “interrupted” by warp raisers
  - Material properties should be degraded
- Uncertainty quantification can model the effect of material property downgrading
  - Define percent reductions for each material property of interest and systematically process simulations over the resulting distributions
  - Does not necessarily require rigorous material characterization

Sample 8-Harness Weave Pattern

Warp Face



Analysis Methods

- Analysis software, material properties, and boundary conditions are unchanged
- Belytschko-Tsay (BT) shell formulation
  - Computationally inexpensive
  - Reissner-Mindlin Type
    - Cross-section straight/unstretched, but transverse shear deformation are permitted
- Layered shell specification within SIERRA/SolidMechanics
  - Single shell element that is a composite of layers with different properties
- Same geometry for the 1, 2, and 4 ply models
  - Different layered shell specifications

Layered Shell Specification for 4 Ply Model

0° half thickness unidirectional ply

90° half thickness unidirectional ply

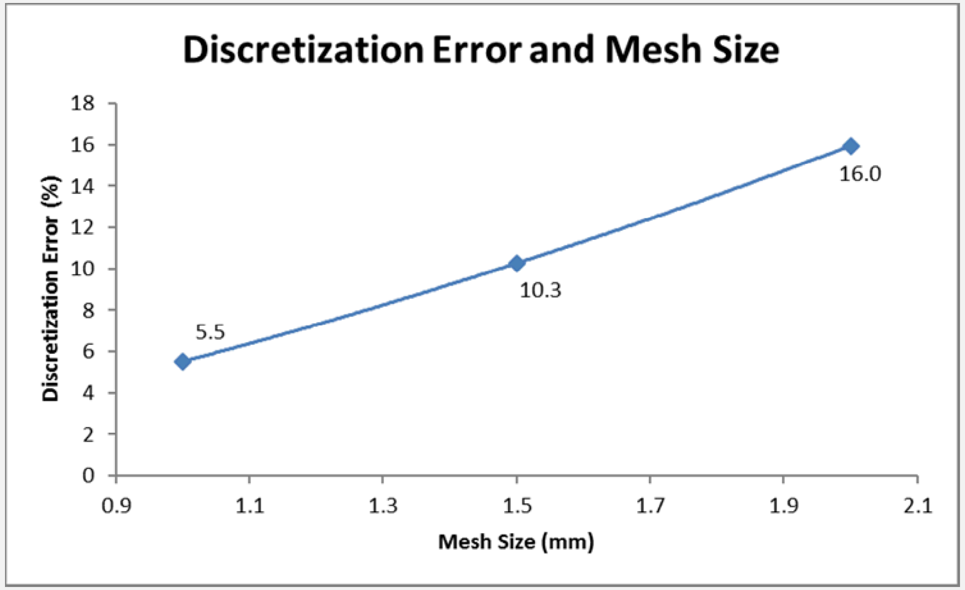
Ply 1, *Ply 2*, *Ply 3*, *Ply 4*

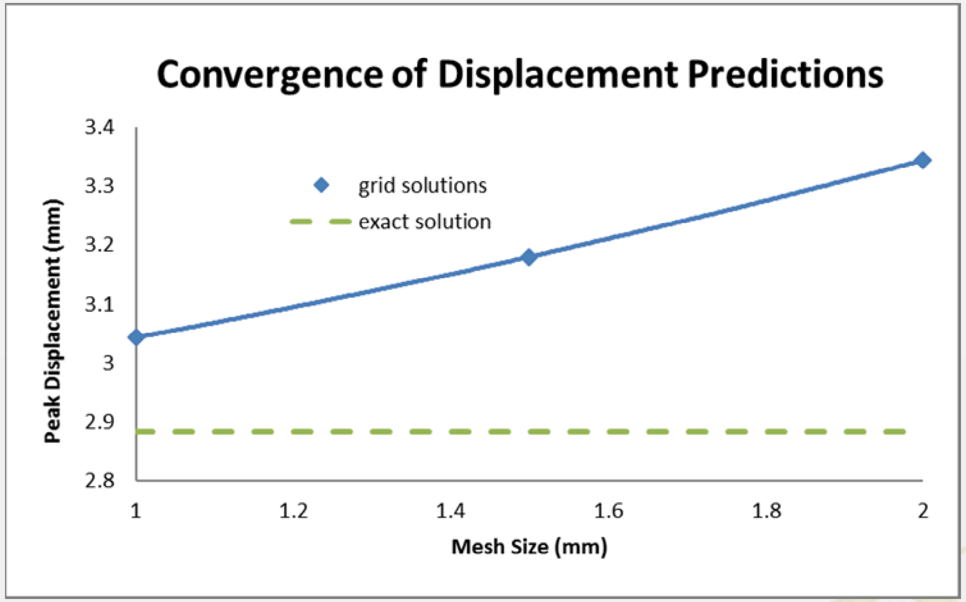
```
begin shell section fiber0
  thickness = 0.195
  fiber orientation = 0
  r vector read variable = r
  t vector read variable = t
end

begin shell section fiber90
  thickness = 0.195
  fiber orientation = 90
  r vector read variable = r
  t vector read variable = t
end

begin layered shell section layup
  layer 1 = fiber0 CFRP
  layer 2 = fiber90 CFRP
  layer 3 = fiber0 CFRP
  layer 4 = fiber90 CFRP
  layer 5 = fiber0 CFRP
  layer 6 = fiber90 CFRP
  layer 7 = fiber0 CFRP
  layer 8 = fiber90 CFRP
end
```

Mesh Convergence Study

- Verification of analysis methods
  - Quantify and show that the discretization errors are small
  - Determine the best mesh size
- 2-ply model was discretized 3 times and processed through Adagio with described methods
  - 2-ply model is less expensive than 1-ply model and was used for sensitivity and UQ studies
- Richardson's extrapolation estimated the peak out-of-plane displacement
  - Approximates a higher order estimate of a continuum value given discrete solutions
- Medium mesh size presents an error ≤ 10%

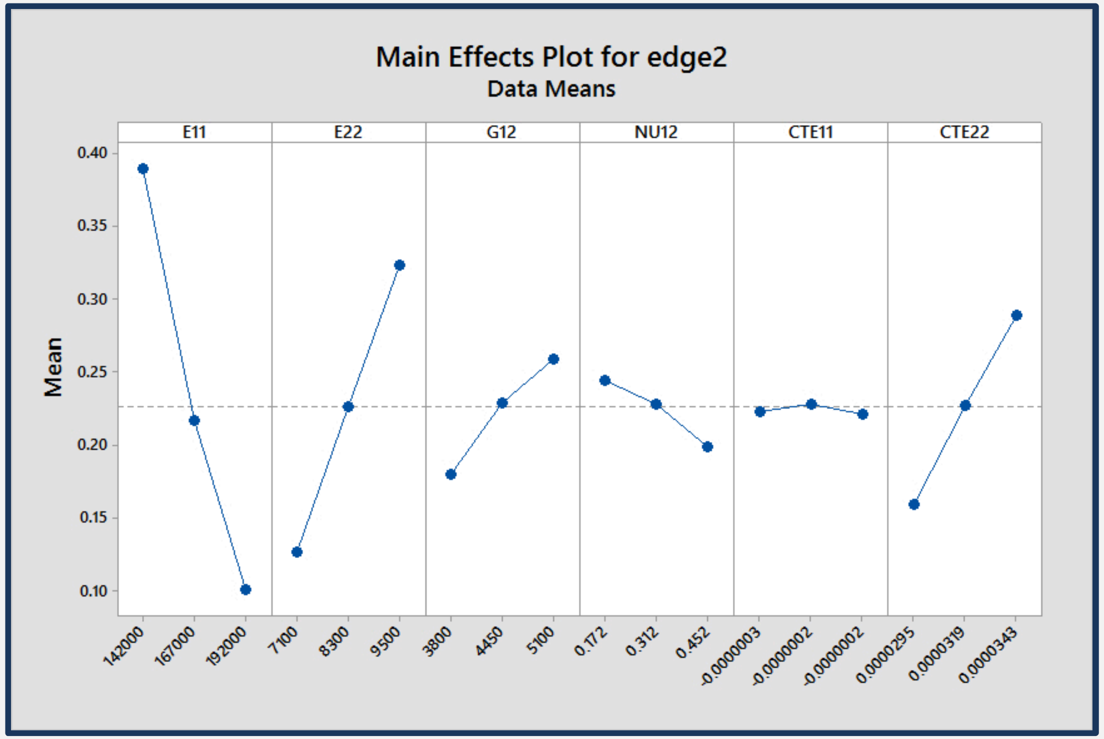
$$discretization\ error = \frac{f_{exact} - f_k}{f_{exact}} \cdot 100$$





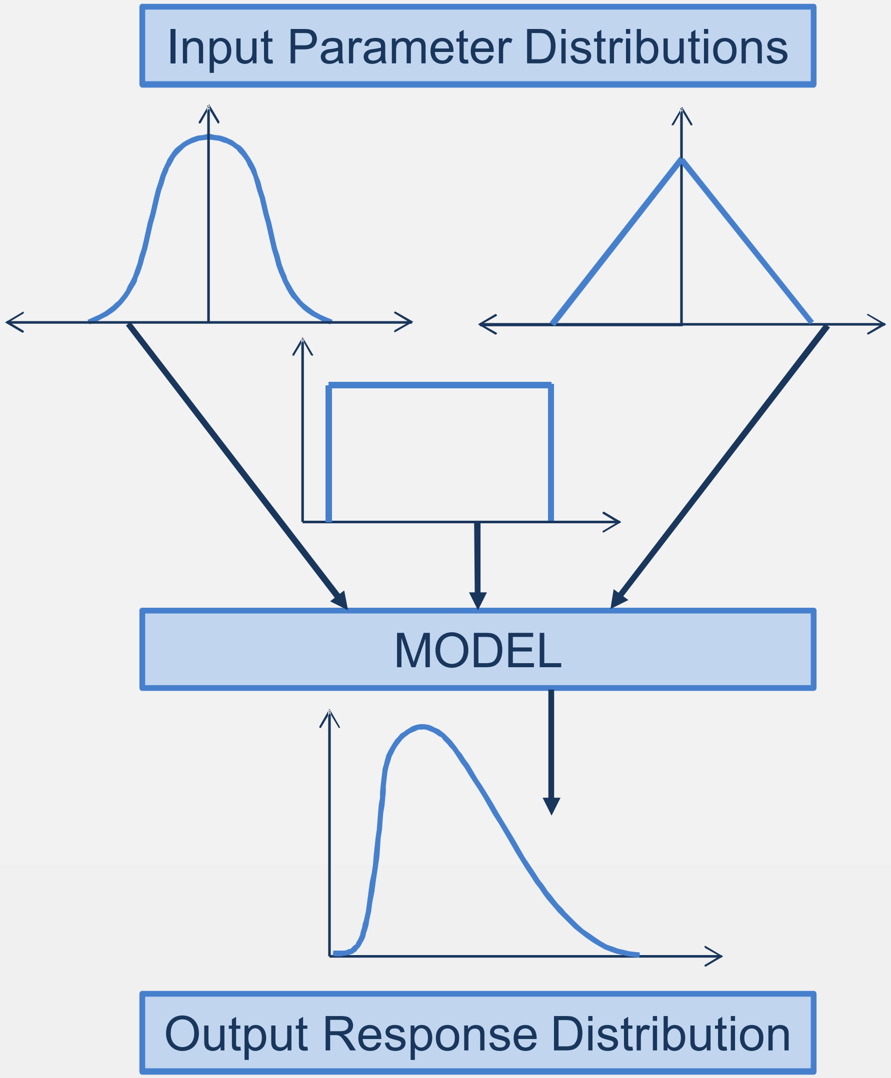
Sensitivity Analysis

- UQ should only be completed for critical model parameters determined from a sensitivity analysis
  - Define parameter space
    - Minimum and maximum values defined for in-plane properties (out-of-plane properties excluded)
  - Sample parameter space systematically
    - Box-Behnken sampling methodology
      - N = 2k(k-1)+1
  - Apply ANOVA to N predictions
    - Analytical method to develop statistical associations between the simulation output and one or more input parameter
- Sensitivity analysis completed for residual stress predictions in asymmetric plates
  - 2 ply model only
  - Sensitivity measured on peak out-of-plane displacement
  - All in-plane properties, except CTE11, are critical



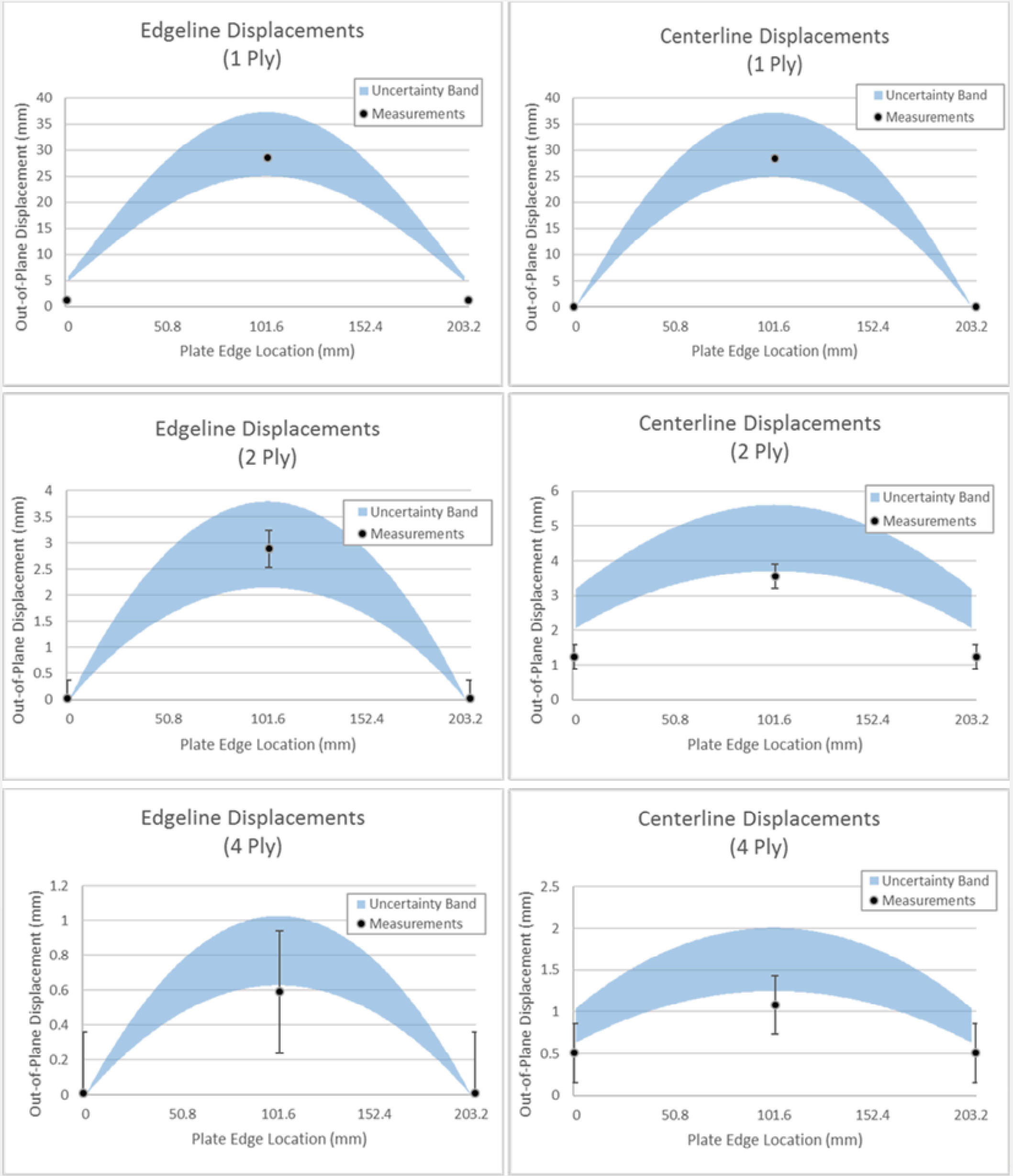
Uncertainty Quantification Overview

- Uncertainty quantification can estimate effect of weave pattern on unidirectional material properties without testing
  - A distribution is defined for each critical parameter
    - Uniform distributions from the “Pristine” material property value to X% of “pristine”
  - The parameter distributions are sampled N times, creating N parameter sets and N simulated predictions
    - LHS sampling is used to ensure complete coverage of the distributions
  - A uniform distribution of N responses is the final result



Uncertainty Quantification Results

- UQ completed for residual stress predictions in asymmetric plates
  - 1, 2, and 4 ply plates
  - Uniform distributions defined for critical model parameters
    - E11, E22, G12, Nu12, CTE22
    - 10% reduction in "pristine" material properties models effect of weave pattern
      - 10% arbitrarily chosen→Micromechanical model could improve reduction factor
    - 200 LHS samples of distributions
- Simulated uncertainty bands agree with experimental measurements
  - Measurement error lies within uncertainty band in all cases



Summary and Conclusion

- Process induced deformations can be predicted with a simplified modeling approach
  - Residual stress formation based on stress-free temperature
  - Textile fabrics approximated as laminates of [0/90] unidirectional plies
  - Statistical methods account for material property reduction due to weave pattern
- Both solid and shell element approaches are valid
  - Solid element methods might be non-conservative
    - "Pristine" material property values
    - Stiffer response is inherent
  - Shell element methods allow for rigorous V&V
- Simplified modeling approach should be used for deformation predictions only
  - Composite failure predictions are not possible with this method
- Additional modeling of more complex geometries is necessary

Questions?

Thank you!