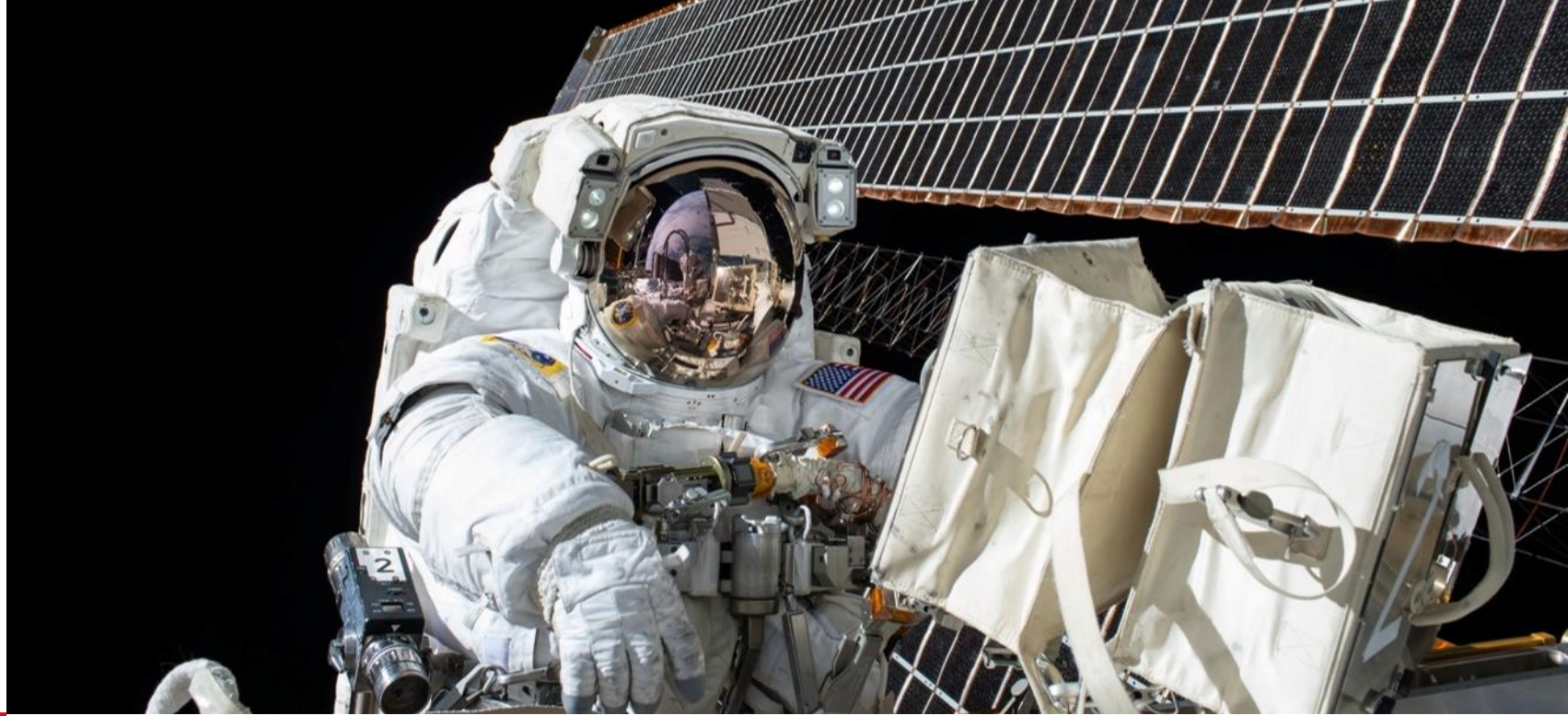




Progressive Damage Mechanisms in Thick 3D Composite Structures under Static and Fatigue Loading

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Motivation

Enable reduced testing and accelerated certification of composite structures



Examples of rotating composite structures

Structural and Performance Characteristics

- Complex geometries, spatially varying thickness and ply layups
- Subjected to combined tension-torsion-bending static and fatigue loading
- Interacting damage modes involving matrix cracking and delaminations from ply-drops

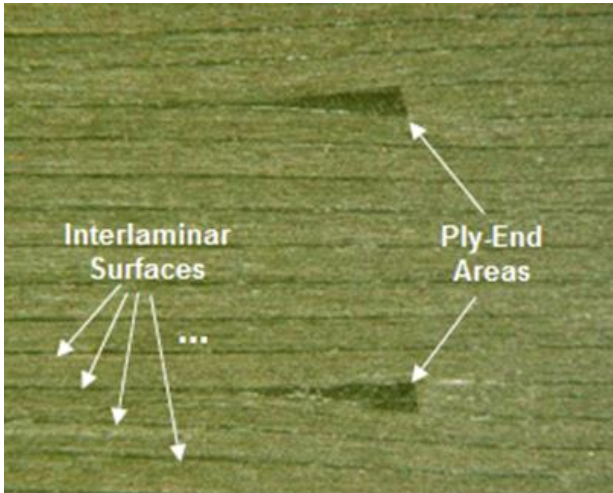
SoA Composite Structural Characterization

- Mostly driven by extensive testing resulting in high costs for development, design allowable and certification
- Validated performance prediction tools can help reduce required testing leading to cost savings and efficiencies

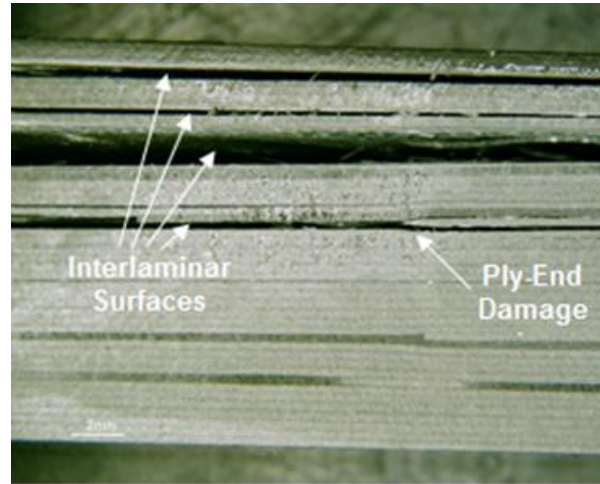
Need advanced validated tools to enable reduced testing and accelerated certification

Overall Objectives

Develop and validate advanced PDA tools for composite structures

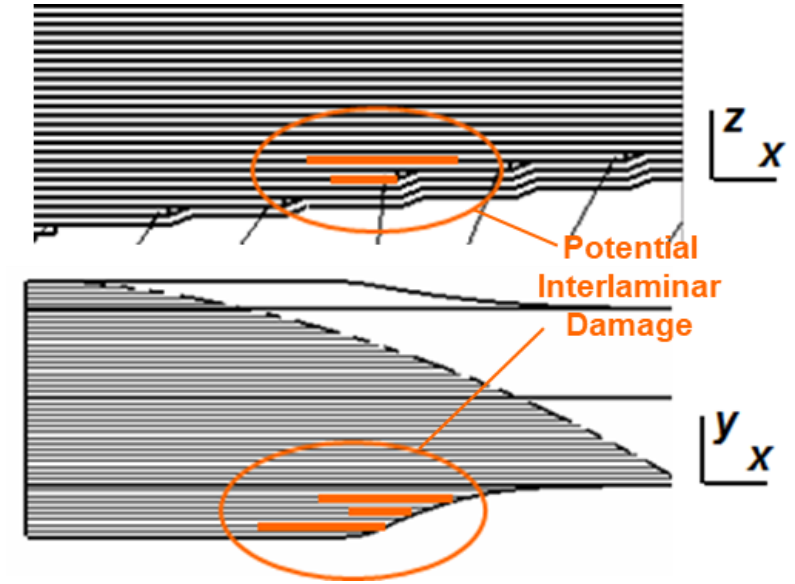


Thick tapered lay-up



Interlaminar damage

Amis, E.J., Gurdich, M.R., *Fall 2011 National ACS Meeting*, Denver, CO, 2011.



Schaff, J.R., Gurdich, M.R., et al., *AHS Specialists' Meeting on Rotorcraft Structures and Survivability*, Williamsburg, VA, 2009.

- Predict damage onset and growth from the vicinity of design and manufacturing artifacts such as ply-drops & ply-ends
- Validate predictions against experimental data
- Enable reduced testing to develop design allowable, development and certification time & cost

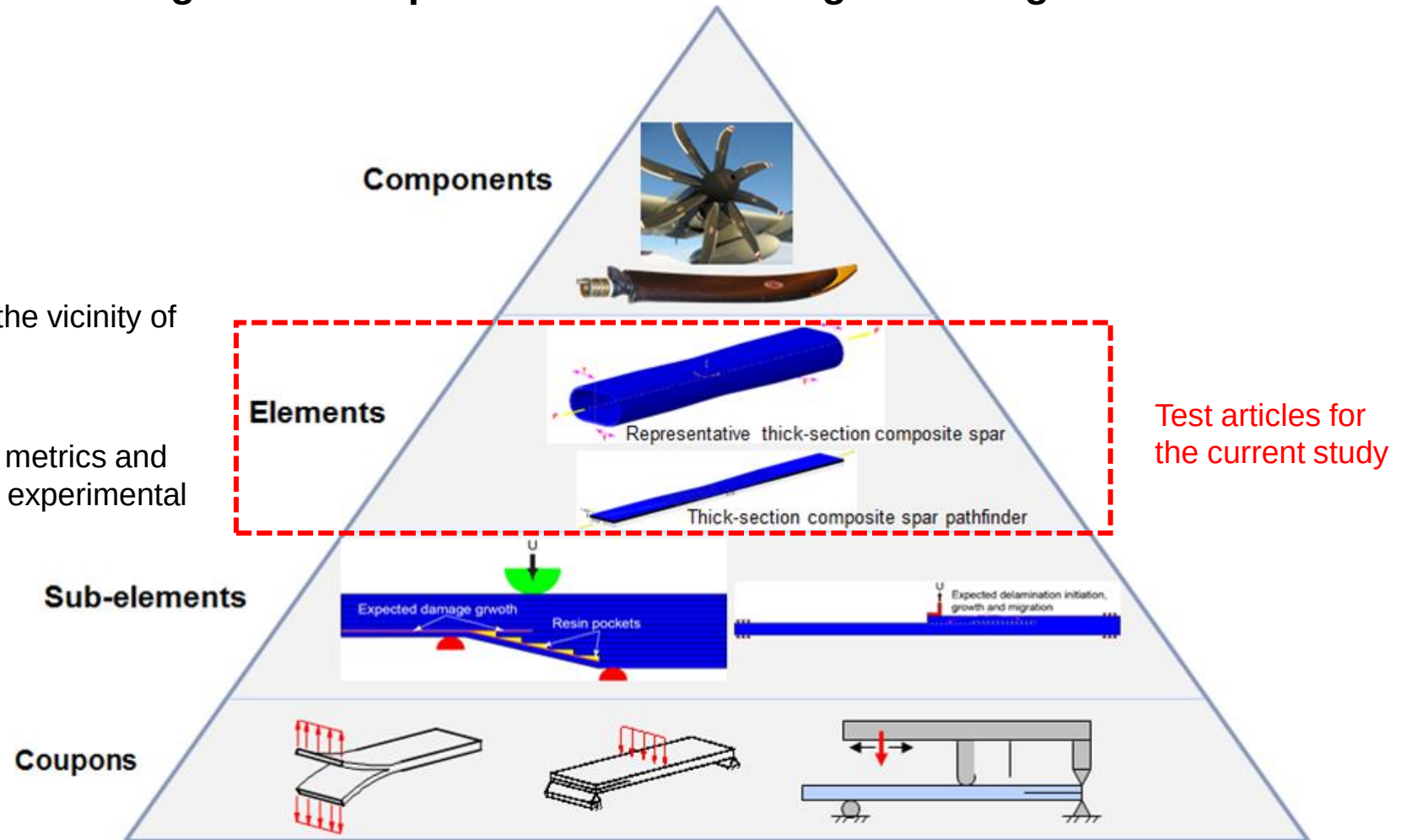
Develop protocols enabling characterization of damage morphologies and quantitative metrics

Specific Objectives

Systematic approach to validating PDA code predictions under fatigue loading



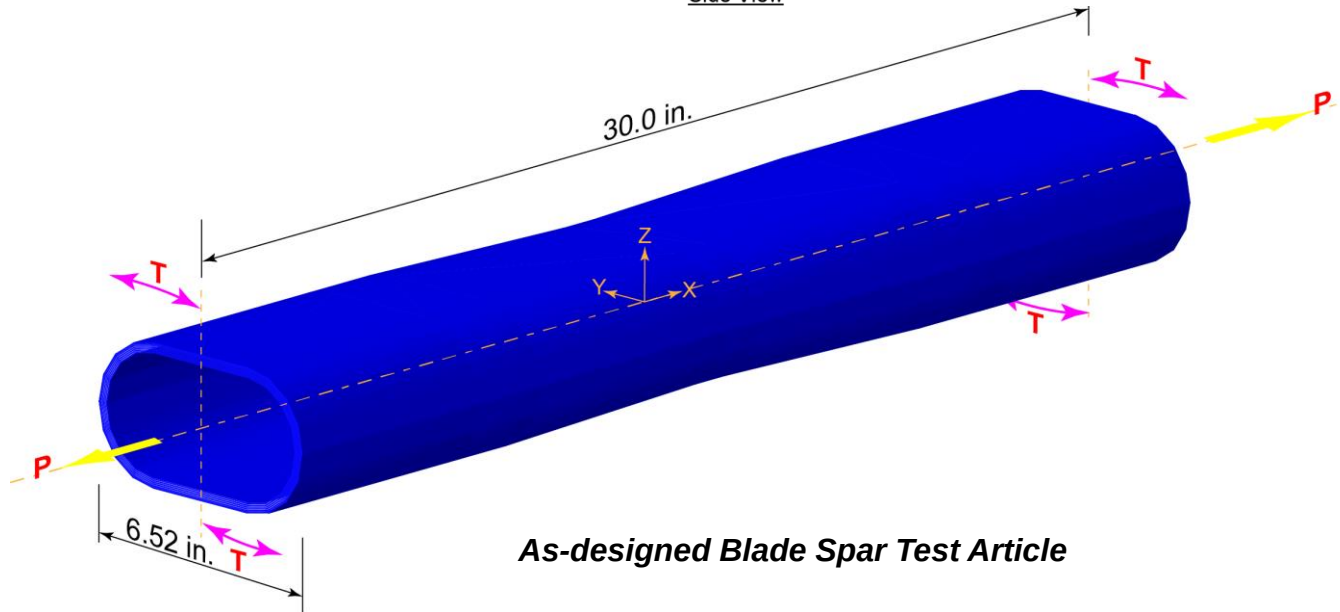
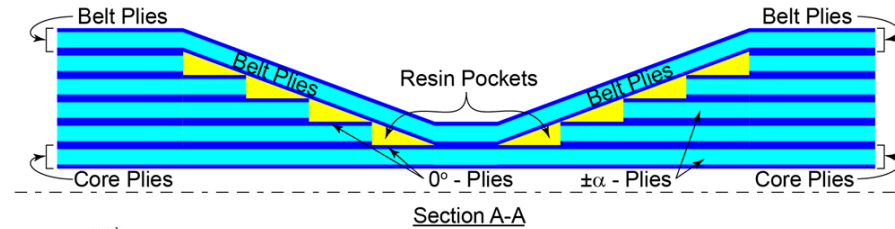
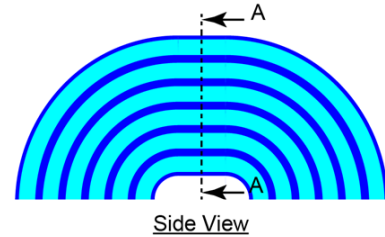
- Capture damage growth from the vicinity of ply-drops
- Validate predicted quantitative metrics and damage morphologies against experimental data



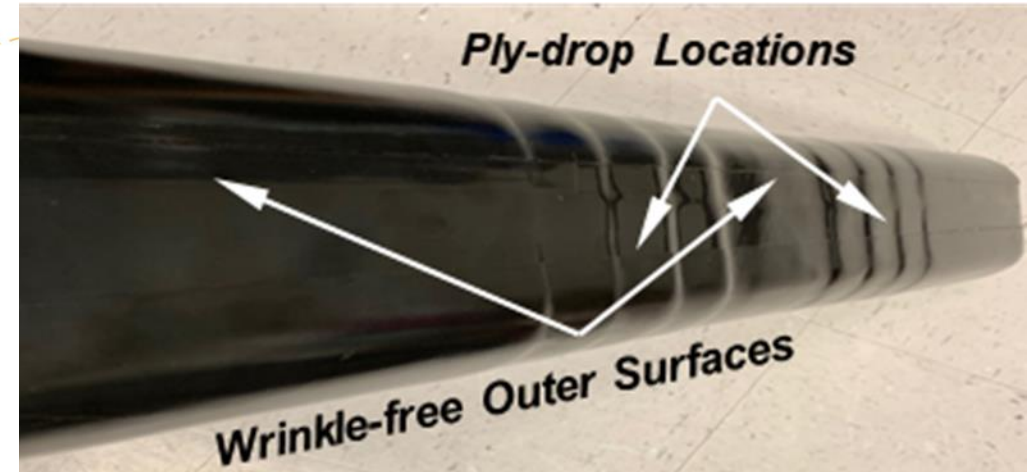
Building-block approach for validating PDA code predictions

Blade Spar Element Test Article

Composite structures incorporating structural features of blade spars



Variable race track cross-section geometry reminiscent of blade spars

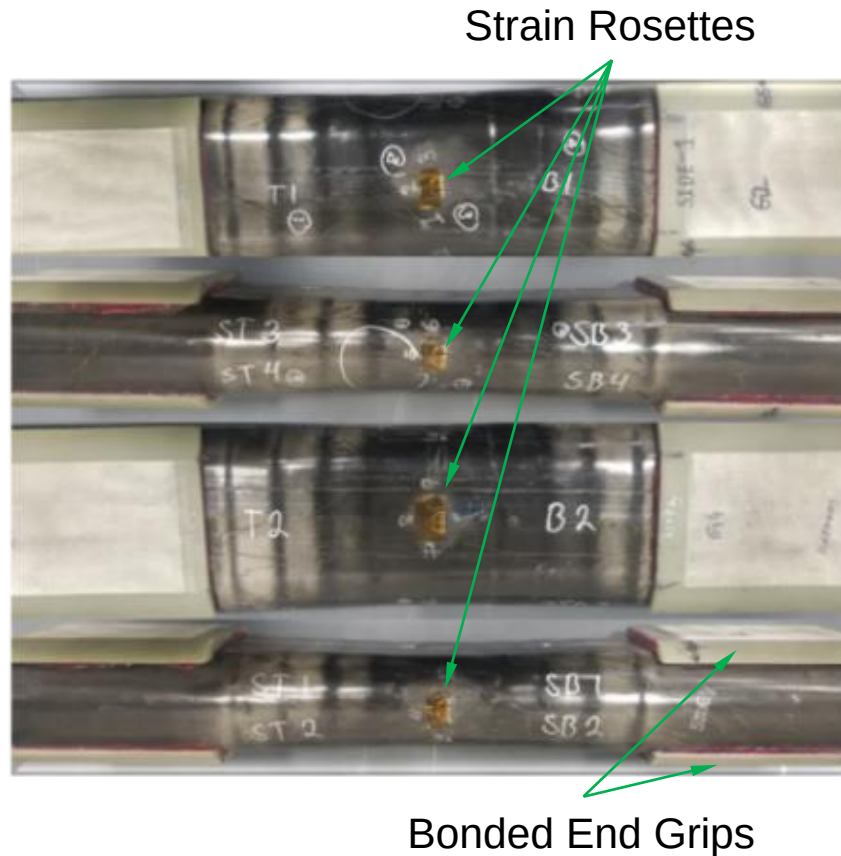
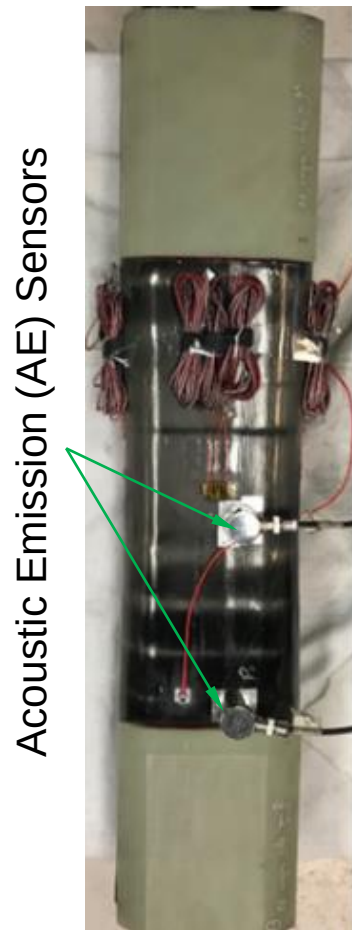


- 3D geometry with curved off-axis plies and resin pockets
- Combined axial tension and torsional loading may lead to interacting damage modes

Representative composite structure for capturing damage onset and growth from ply-drop regions

Test Article Instrumentation

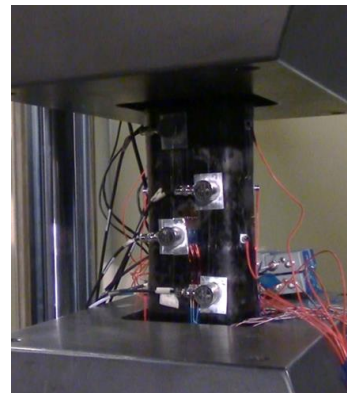
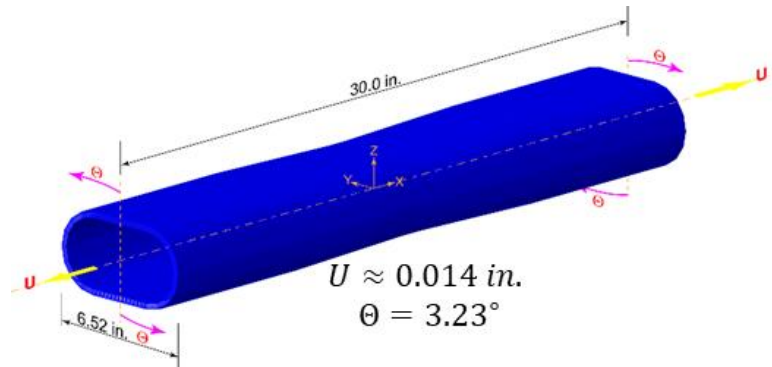
Data acquisition to capture the response of the blade spar



Capture quantitative metrics and guide damage morphologies characterization

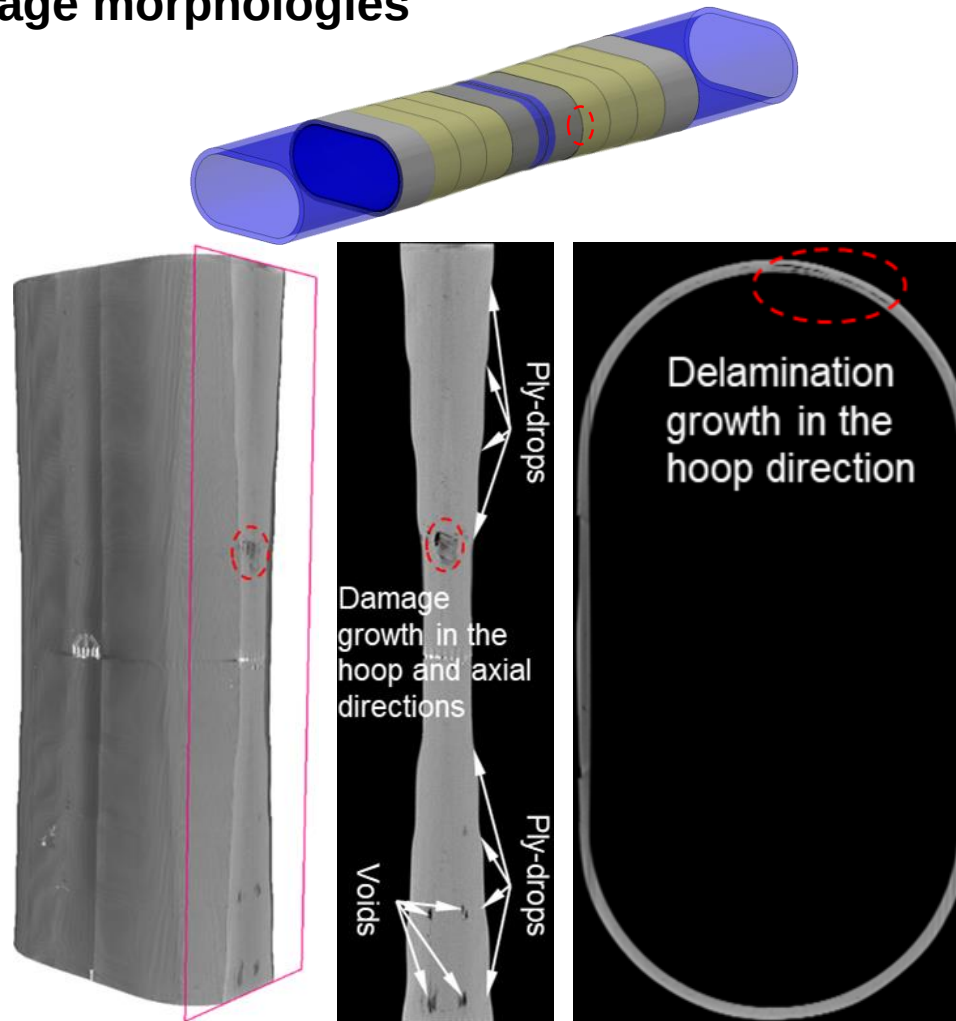
Blade Spar Static Testing

Successfully captured expected damage morphologies



Test setup and procedure

- **Step # 1:** Tension load under displacement control – no damage
- **Step # 2:** Held tension load fixed and applied torque under angle-of-twist control

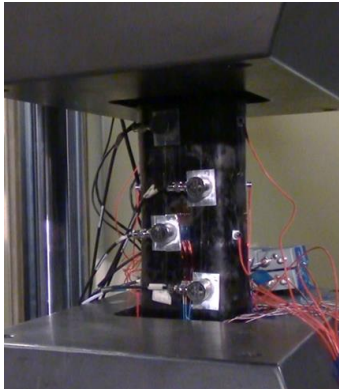
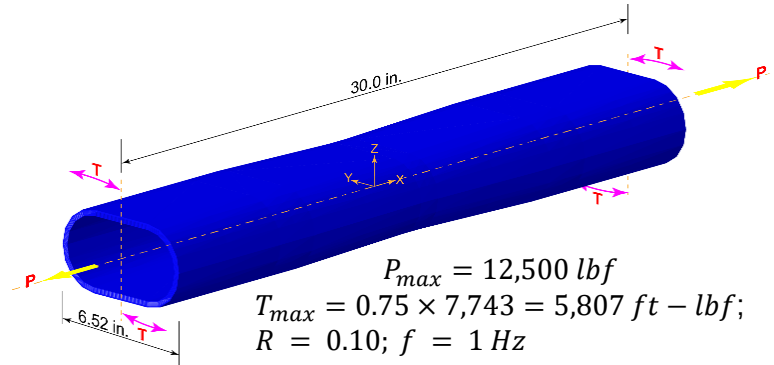


- Tests paused intermittently based on high energy AE events to capture damage morphology
- X-Ray CT imaging used to capture damage morphology composed of matrix cracking and delamination onset and growth from ply-drop regions
- Damage observed only during Step # 2, as designed

Tests captured expected damage morphologies – matrix cracking & delaminations from ply-drops

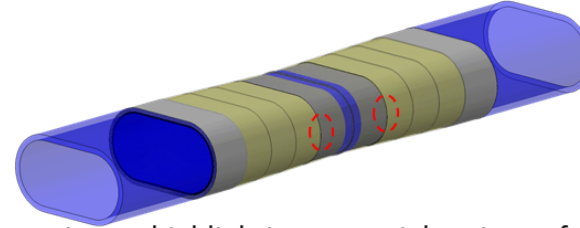
Blade Spar Fatigue Testing

Successfully captured expected damage morphologies

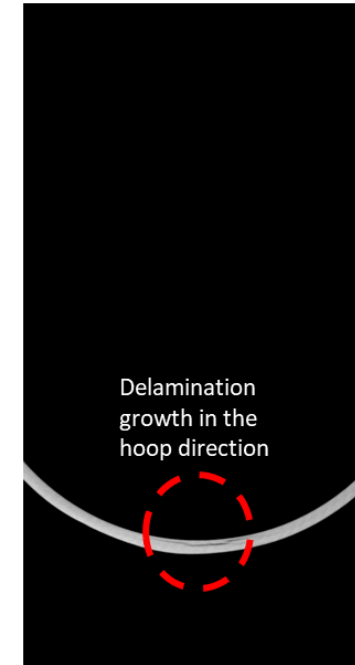
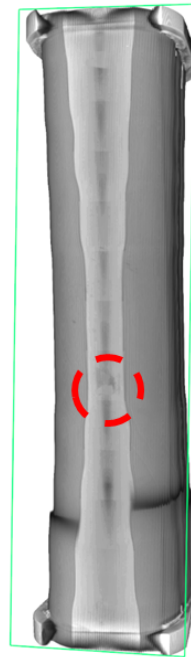


Test setup and procedure

- **Step # 1:** Axial tension load under displacement control – no damage
- **Step # 2:** Held tension load fixed and applied fatigue load under cyclic torquing



Blade spar image highlighting potential regions of damage



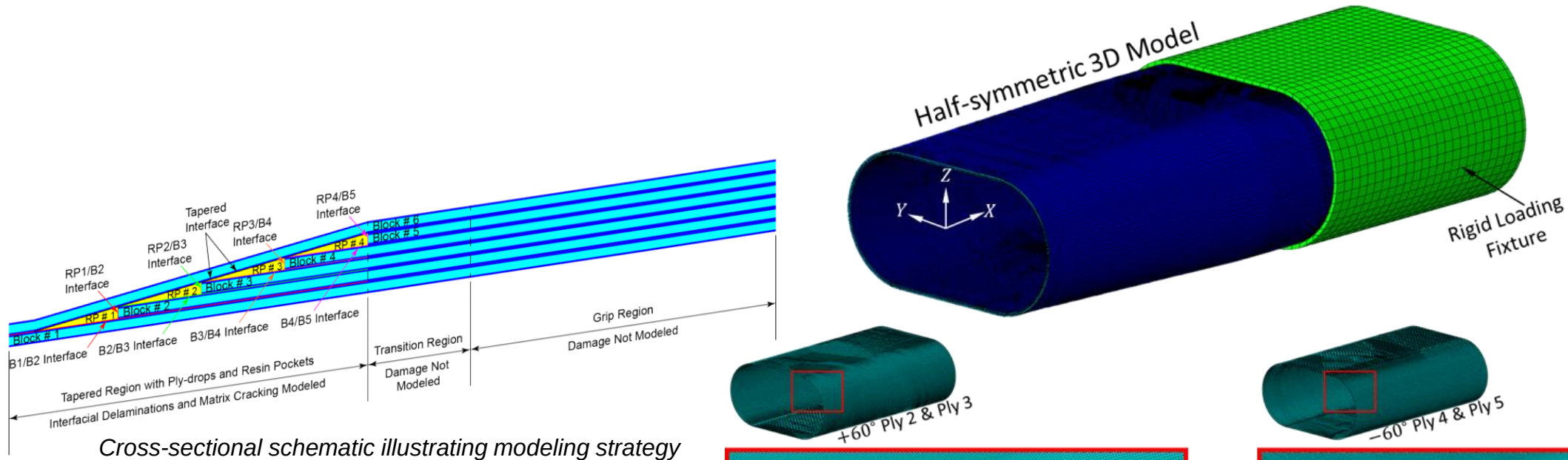
X-Ray CT images showing location, size and mode of damage

- Tests paused based on recording four (4) high energy AE events to capture X-Ray CT images
- After 10,000 torsional loading cycles, X-Ray CT images did not indicate any damage – baseline reference
- After ~40,000 torsional loading cycles, the observed damage appeared suddenly
- Damage observed to grow from the vicinity of the expected ply-drop regions

Tests captured expected damage morphologies – matrix cracking & delaminations from ply-drops

FE Modeling of the Blade Spar

Approach to predicting mechanical response and damage morphologies



PDA Codes:

- ABAQUS/STANDARD and ABAQUS/EXPLICIT – Pre-test simulations for guiding experiments
- COMPDAM – Post-test predictions with as-characterized properties



Detail showing +60° oriented elements



Detail showing -60° oriented elements

Detailed 3D FE model with selectively introduced damageable zones

COMP DAM Overview



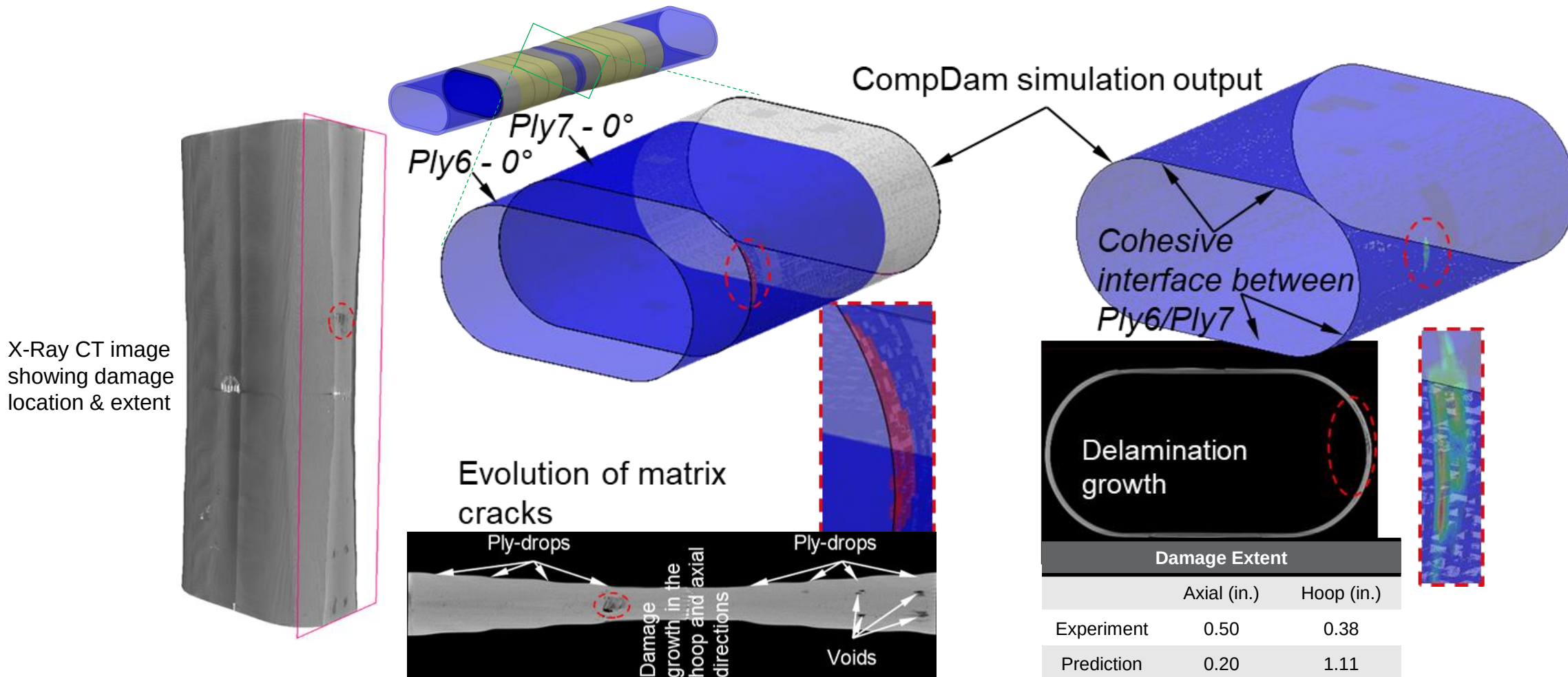
A State-of-the-art continuum damage mechanics (CDM) based code

- Deformation Gradient Decomposition (DGD) based Continuum Damage Mechanics (CDM) code
 - Uses LaRC04 failure criteria to predict matrix crack initiation
 - Matrix crack kinematics modeled by treating them as cohesive surfaces embedded in a deformable bulk material
 - Details: Frank A. Leone Jr. “*Deformation gradient tensor decomposition for representing matrix cracks in fiber-reinforced materials*” Composites Part A (2015) 76:334-341
- Implemented as a Vectorized User Material (VUMAT) FORTRAN subroutine in ABAQUS/Explicit
- **Requires** fiber aligned meshes to accurately capture orientation of matrix cracks
- Uses native ABAQUS cohesive elements to model inter-laminar delamination
 - Cohesive fatigue law for capturing onset and growth and delaminations under fatigue loading
- Download link: https://github.com/nasa/CompDam_DGD

NASA state-of-the-art PDA code for predicting damage morphologies in composite structures

Blade Spar Static Correlations

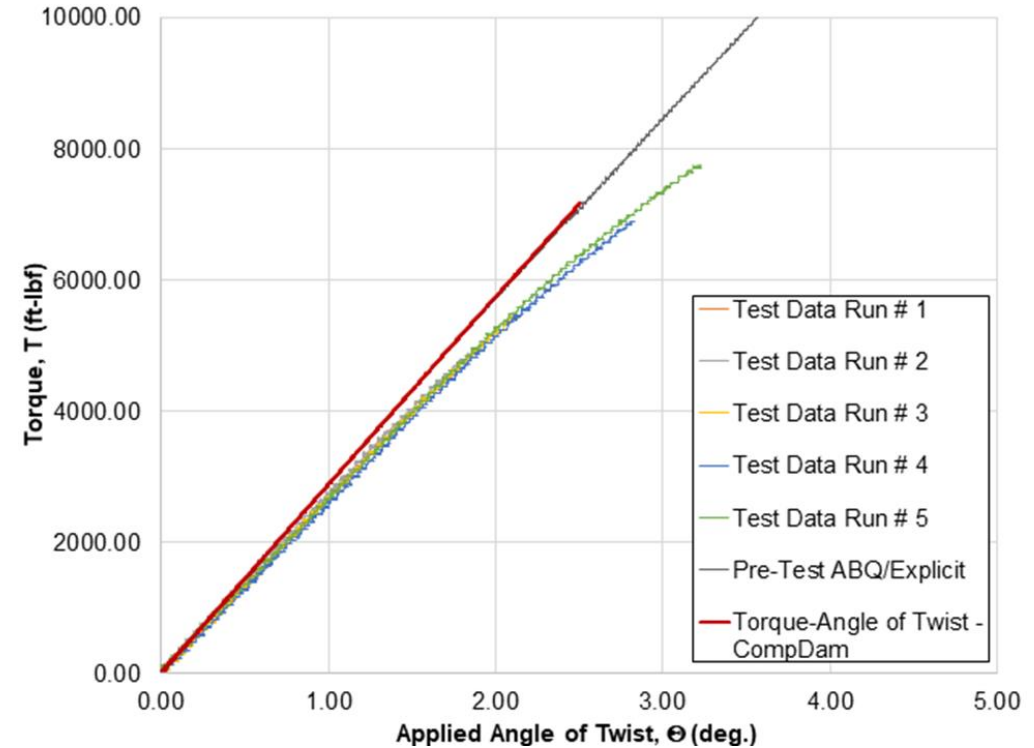
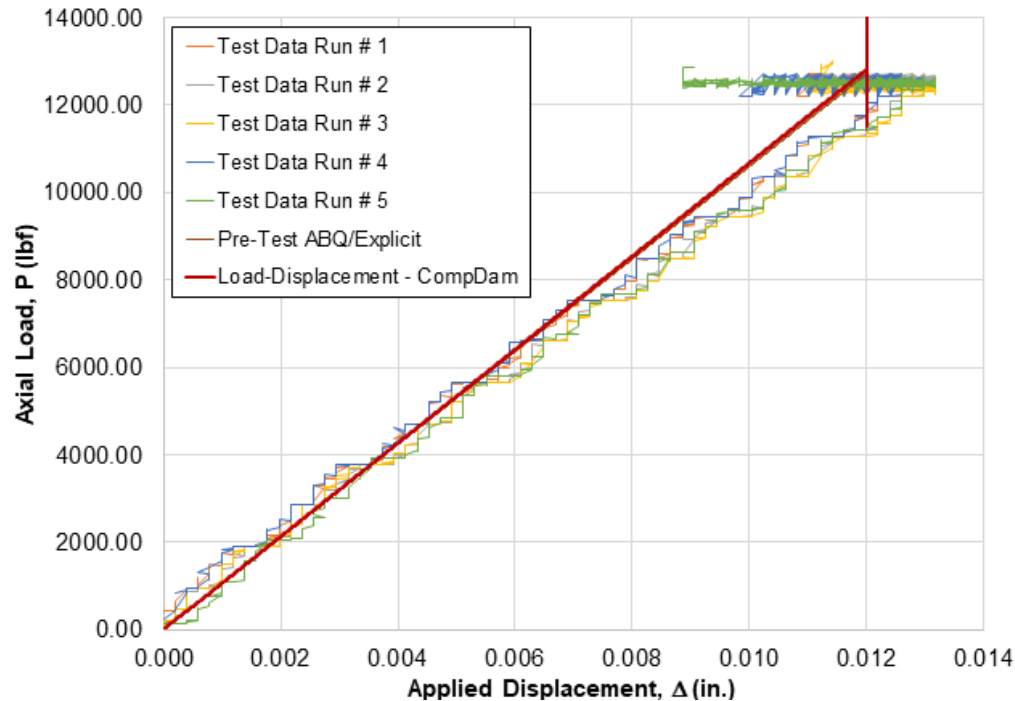
Successfully correlated damage morphologies



Damage modes and location of onset and growth successfully correlated

Blade Spar Static Correlations

Test-model comparisons of load-displacement and torque-angle metrics

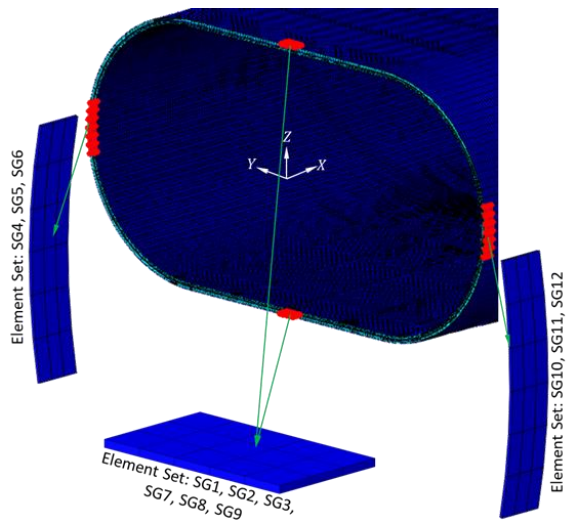


- Acceptable correlations of predicted and measured load-displacement response – observed non-linearity may be potentially attributed to the effects of defects which were not modeled in this study
- Non-linearity in torque-angle of twist response attributable to axial motion of actuator during Step # 2 (not modeled in simulations) and potentially to the effects of defects

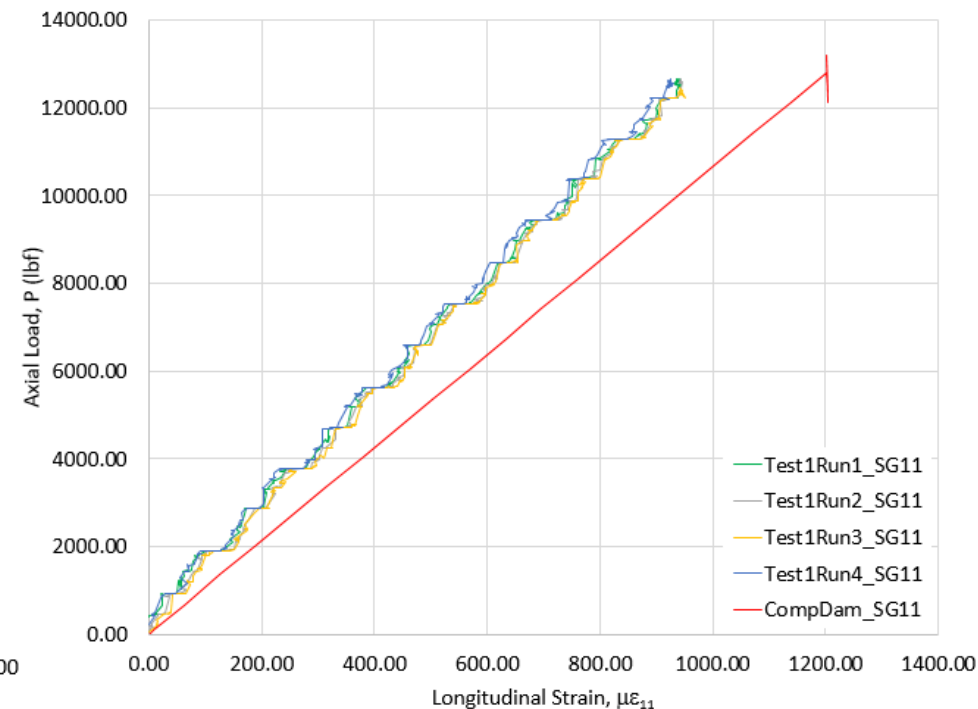
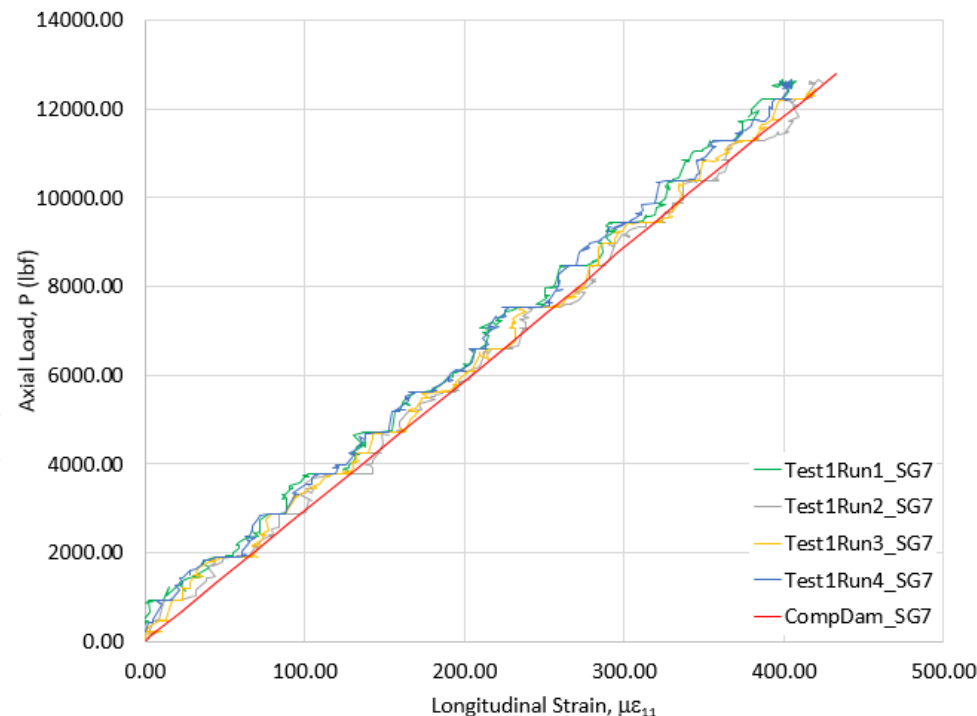
Overall reasonably acceptable correlations of quantitative metrics demonstrated

Blade Spar Static Correlations

Test-model comparisons of load-strain metrics



Locations and geometry of element sets representing corresponding strain gages

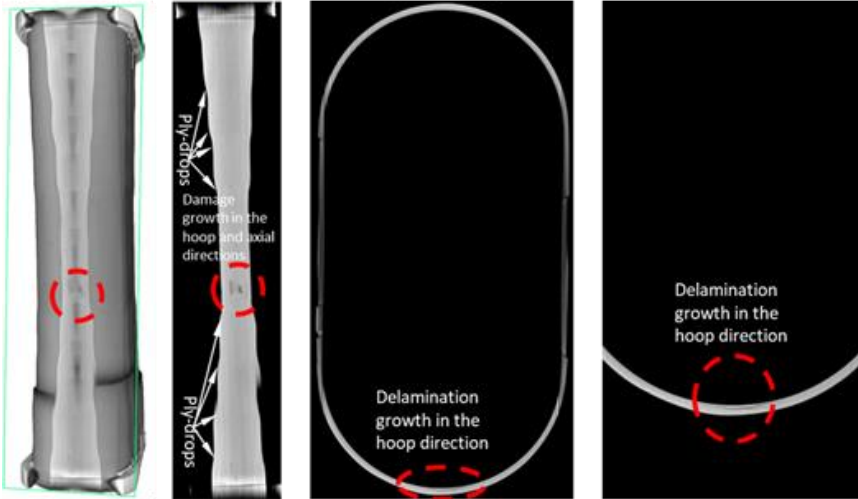
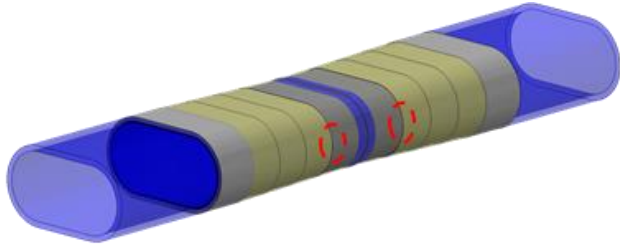


- Successful correlations of predicted and measured load-strain response based on measurements from strain gages located on the central flat regions of the blade spar
- Disagreement between predicted and measured load-strain response based on measurements from strain gages located on the central curved regions of the blade spar attributable to the underlying coarse FE mesh

Overall partially acceptable correlations of quantitative metrics demonstrated

Blade Spar Fatigue Correlations

Qualitative correlation of damage morphology



Observed Damage Morphology after 40,000 Torque Cycles



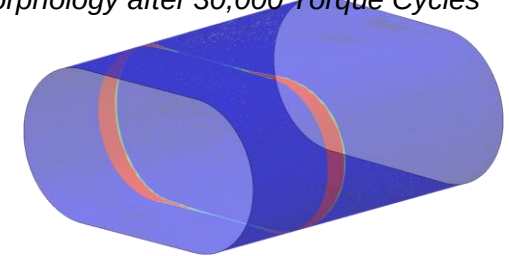
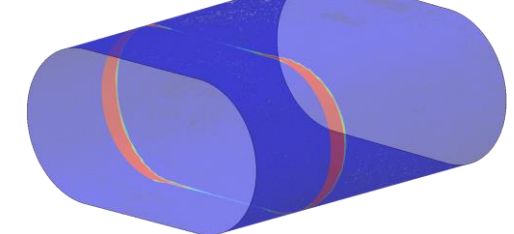
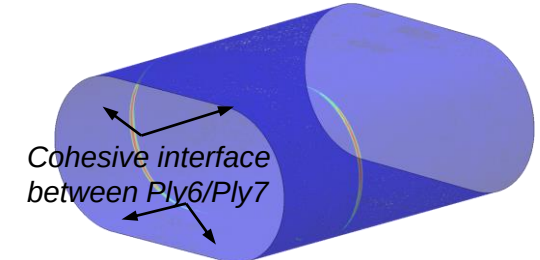
Observed and Predicted Damage Morphology after 10,000 Torque Cycles



Observed and Predicted Damage Morphology after 30,000 Torque Cycles



Observed and Predicted Damage Morphology after 40,000 Torque Cycles



- Captured expected delamination onset and growth from ply-drop regions
- Damage observed only during Step # 2, as designed

- Location and mode of damage onset and growth predicted consistent with experiments using CompDam
- Predicted damage extent is greater than that observed in experiments

Damage modes and location of onset and growth successfully correlated

Overall Summary



Developed and demonstrated a systematic approach to validating PDA code predictions

- Experimental procedures successfully captured expected interacting damage modes
 - Matrix cracking and delamination onset and growth from ply-drop regions were shown to be the dominant interacting damage modes
 - While not discussed herein, damage modes were captured in a repeatable manner at the structural length scale
- PDA codes have the ability to model interacting damage modes
 - Damage morphologies composed of matrix cracking and delamination onset and growth from the vicinities of ply-drops were successfully captured under the applied static and fatigue loads
- Overall, the program demonstrated reasonably successful validation of the state-of-the-art PDA codes at different structural length-scales
 - Validated PDA codes at the sub-element (Tapered Beam Sub-element – ASC2018, Tapered Tensile Sub-element – ASC2019) and element (Blade Spar – ASC2020) levels against experimental data acquired under static and fatigue loads

Need to apply PDA codes on structural components including effects of defects for practical uses

Acknowledgements



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Thank You