Verification and Validation of Progressive Damage Analysis Methods for Laminated Composite Structures

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Outline

- Progressive Damage Analysis (PDA) codes and their verification
- Approach for validating PDA codes
- Test articles for acquiring validation data
- Static and fatigue test data
- PDA models and correlations with test data
- Work-in-progress and next steps
- Summary

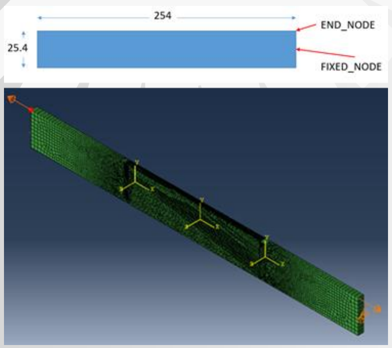
PDA CODES AND VERIFICATION

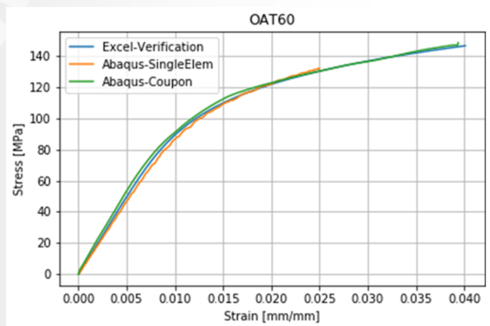
PDA Codes and Verification

Exemplar results showing verification of PDA codes against NASA benchmarks

CompDam

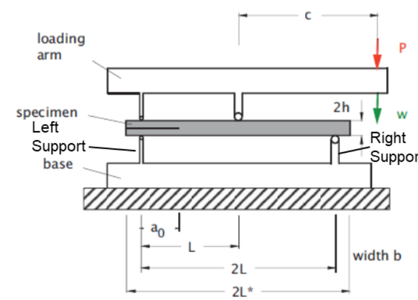
Deformation Gradient Decomposition (DGD) based Continuum Damage Mechanics (CDM) code

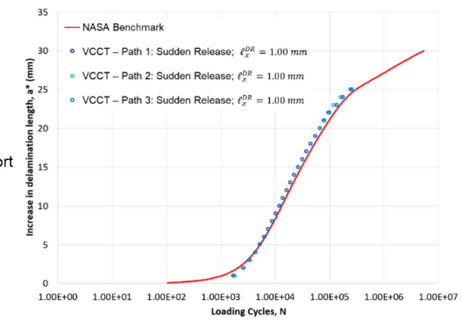




ABAQUS/VCCT

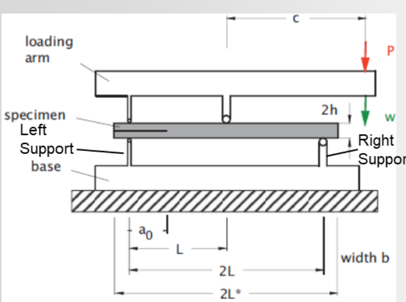
LEFM based Discrete Damage Mechanics (DDM) code

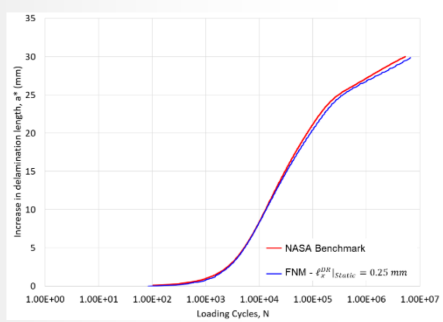




Floating Node Method (FNM)

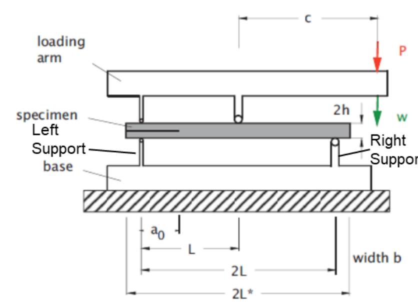
Fracture mechanics based Discrete Damage Mechanics (DDM) code

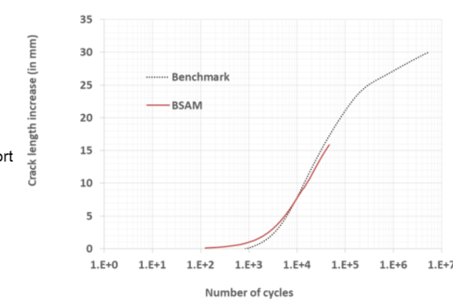




B-Spline Analysis Method (BSAM)

Regularized XFEM based Discrete Damage Mechanics (DDM) code





Successful code verification confirms correct implementation

VALIDATION APPROACH AND TEST ARTICLES

Validation Building Block

Approach for validating Progressive Damage Analysis (PDA) codes

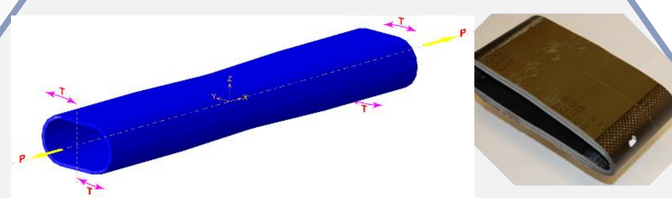
Blade spar component:

- Thick-section composite spar is the main load bearing member
- Ply drops to taper thickness along span

Increasing complexity :

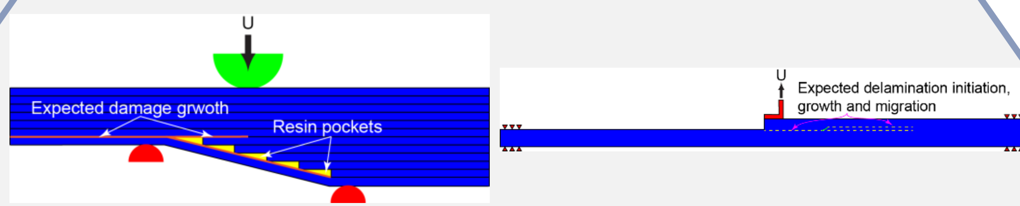
- Geometry and Loading
- Failure mode interaction

Phase II:
Elements

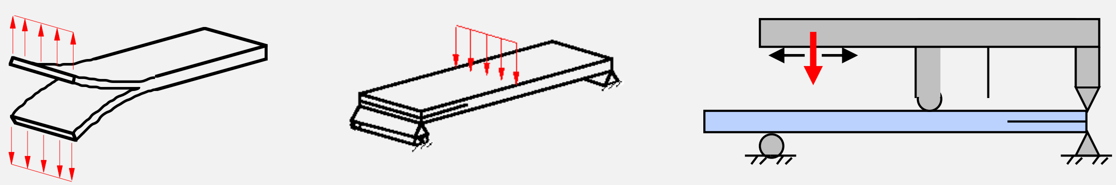


Thick-section composite spars

Phase I:
Sub-elements



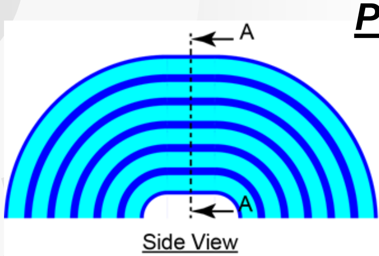
Coupons

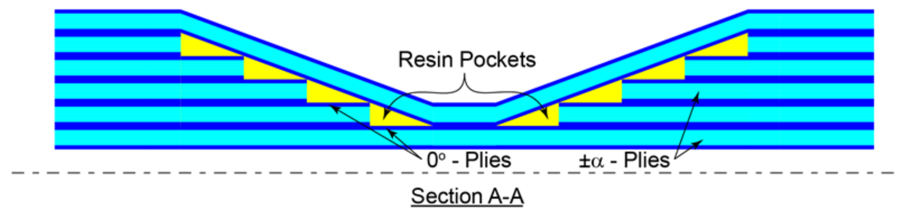


Blade Spar Validation Article Design

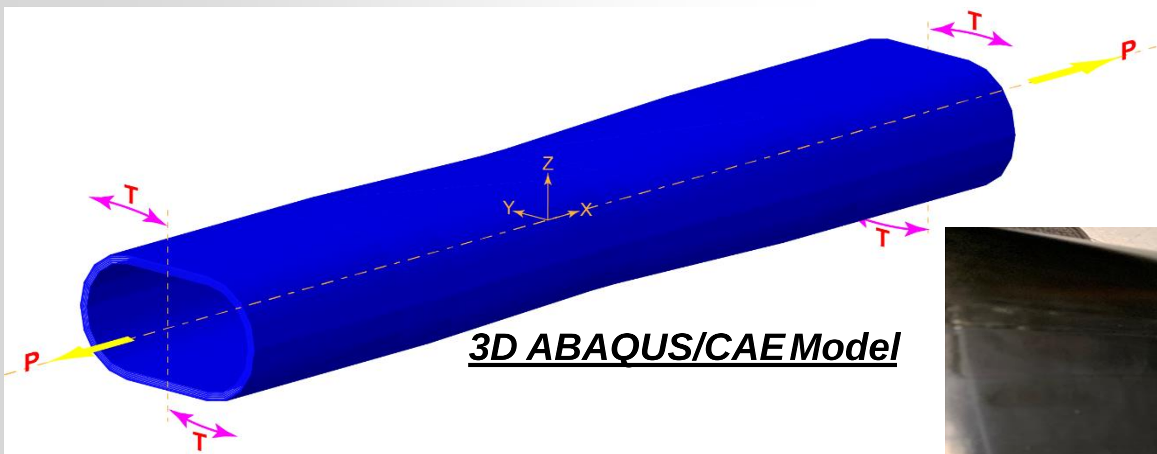
<u>Objective:</u> Capture delamination growth from the vicinity of ply-drops under tension-torsion fatigue loading

Ply thicknesses scaled up for clarity



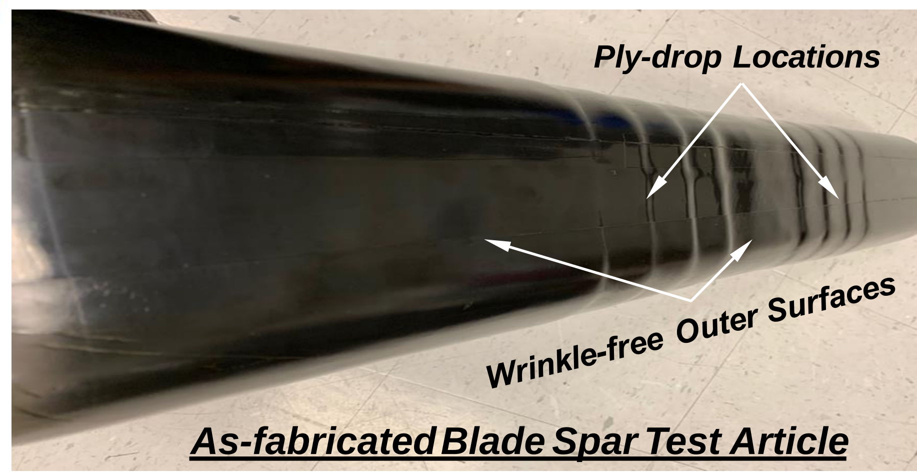


2D Cross-sectional Schematics



3D ABAQUS/CAE Model

- *Complex geometry*
- *Potentially interacting damage modes*
- *May be difficult to isolate inter-laminar delamination damage modes*



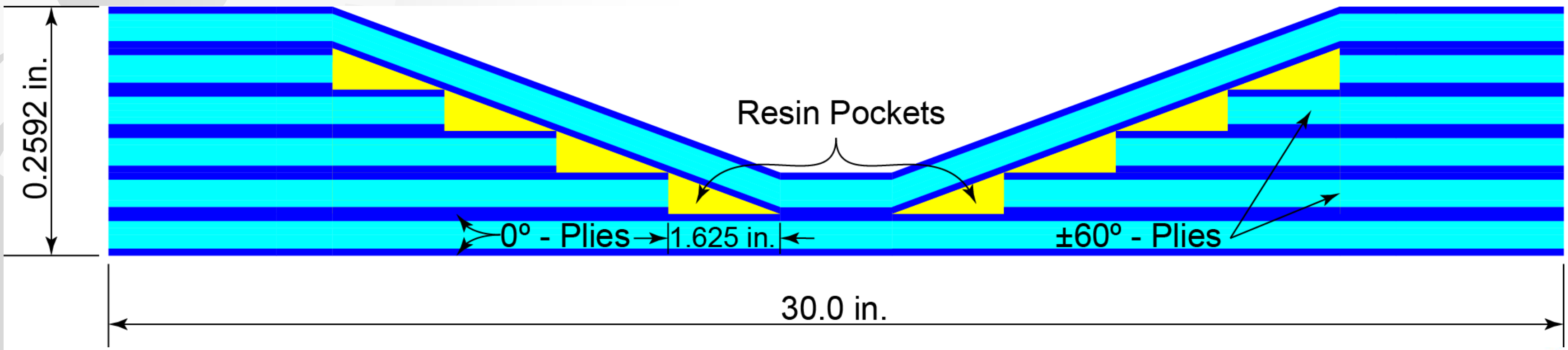
As-fabricated Blade Spar Test Article

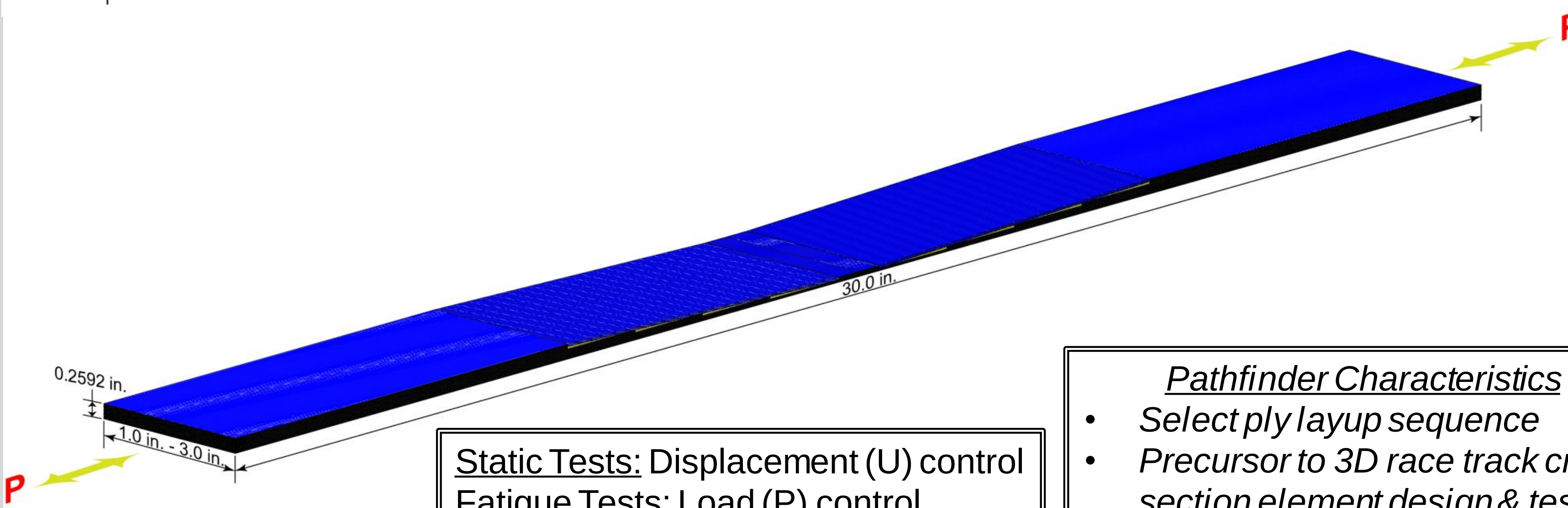
Variable race track cross-section geometry representative of blade spars

Blade Spar Pathfinder Article Design

Rationale: *Validate delamination growth from the ply-drops*

Ply thicknesses scaled up for clarity





Static Tests: Displacement (U) control
Fatigue Tests: Load (P) control

Pathfinder Characteristics

- *Select ply layup sequence*
- *Precursor to 3D race track cross-section element design & testing*

Quasi-2D control specimen for isolating delaminations from ply-drops

PATHFINDER TESTING

Pathfinder Article Test Setup and Data Acquisition

Test setup at National Institute for Aviation Research (NIAR) and NASA Langley Research Center (LaRC)

NIAR

Data Acquisition at NIAR

- Digital Image Correlation (DIC)
- Strain gages and Acoustic Emission (AE) sensors
- Through-thickness ultrasonic interval imaging

NASA LaRC

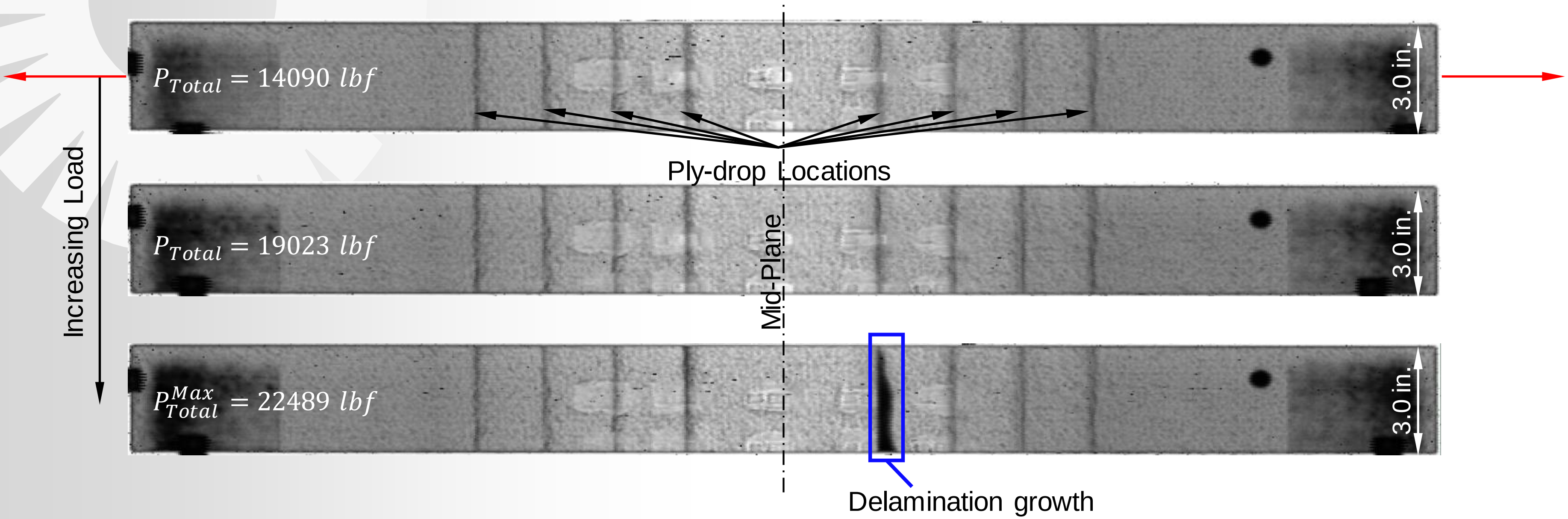
Data Acquisition at LaRC

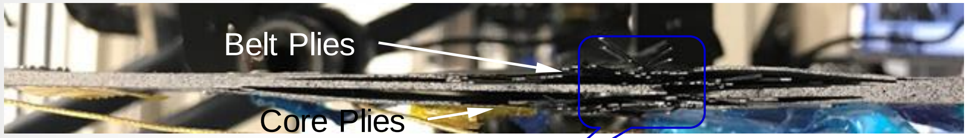
- Passive thermography on tapered side
- Infrared camera
- AE sensors on flat side
- Through-thickness ultrasonic interval imaging

United Technologies Research Center

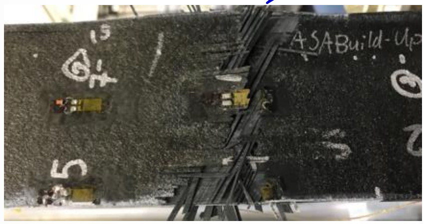
Pathfinder Damage Evolution under Static Loading

Delamination growth from the ply-drops; unstable fracture shortly thereafter





Belt and Core Pies delaminate from the dropped ply blocks

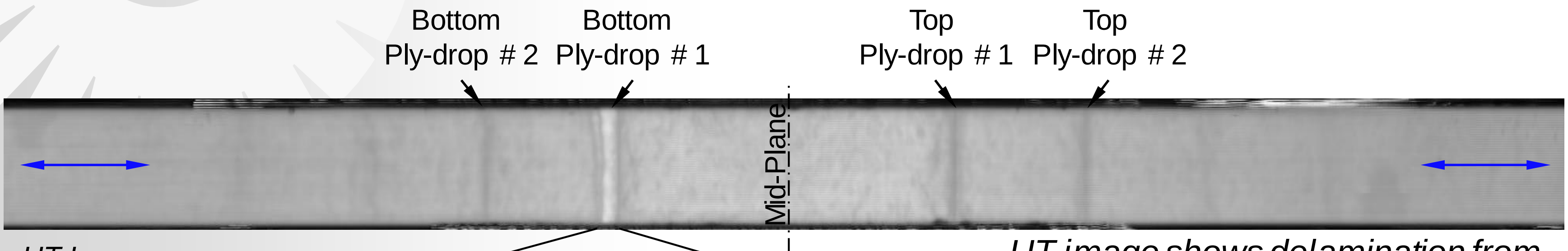


Matrix cracking and fiber breakage confined to the central region

Pathfinder Damage Initiation under Fatigue Loading

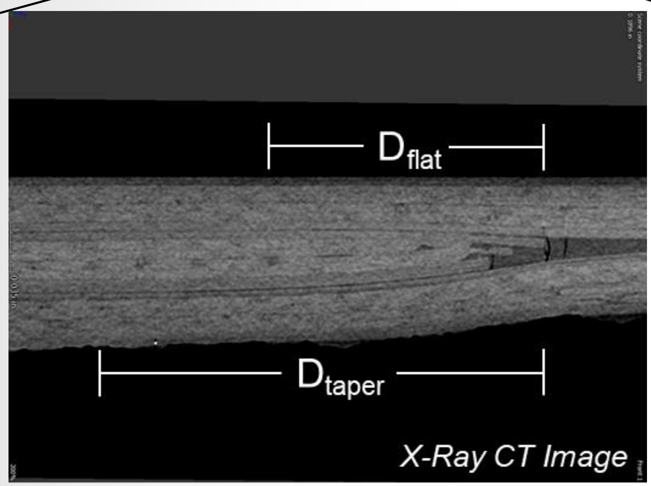
Cracking at the tips of dropped plies leads to delaminations at flat and tapered interfaces

P_{max} **= 5,000 lbf, R = 0.10, f = 2 Hz**



UT Image

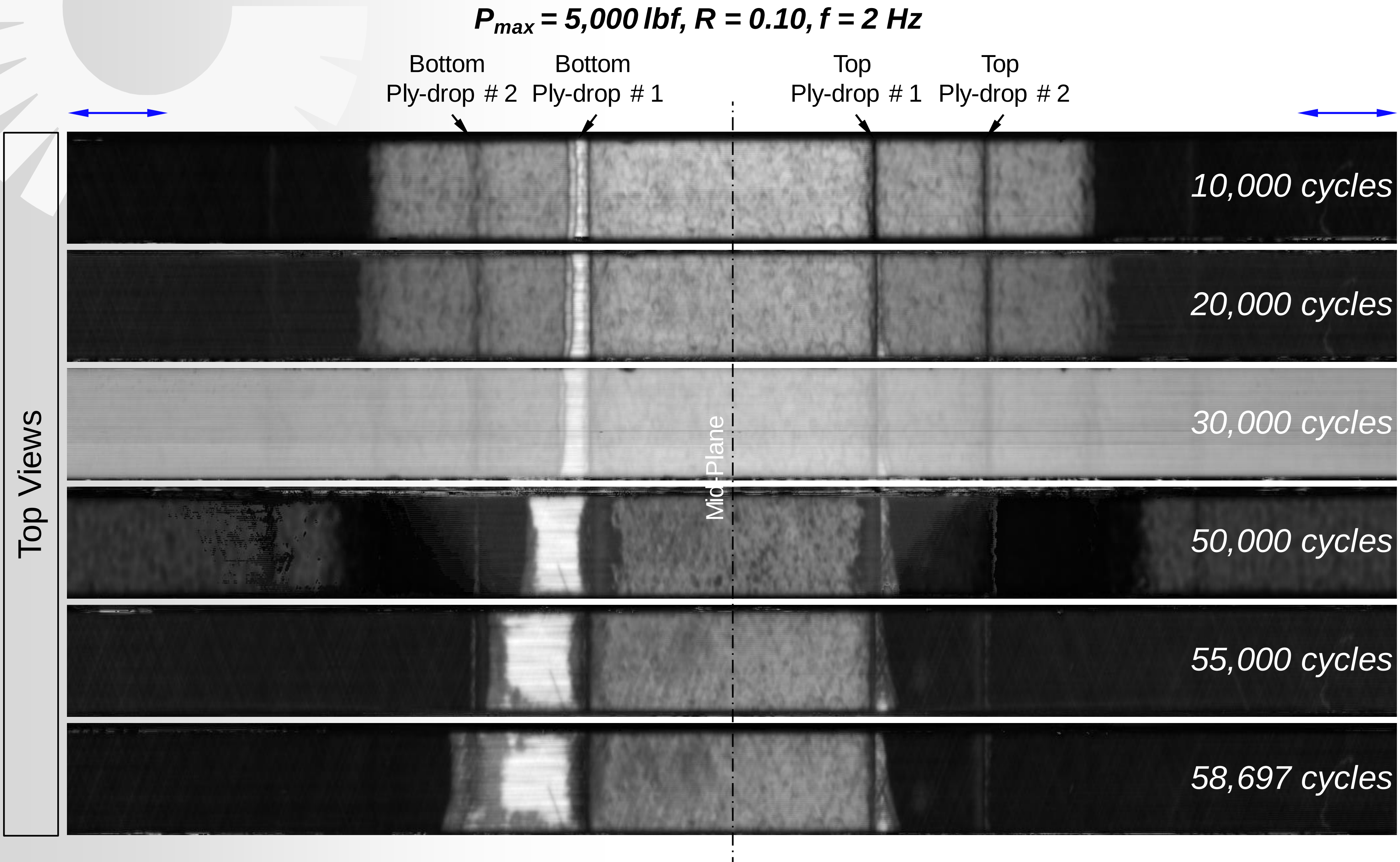
UT image shows delamination from first ply drop after 14,000 cycles



X-ray CT image shows multiple cracks between resin and tip of plies in dropped region

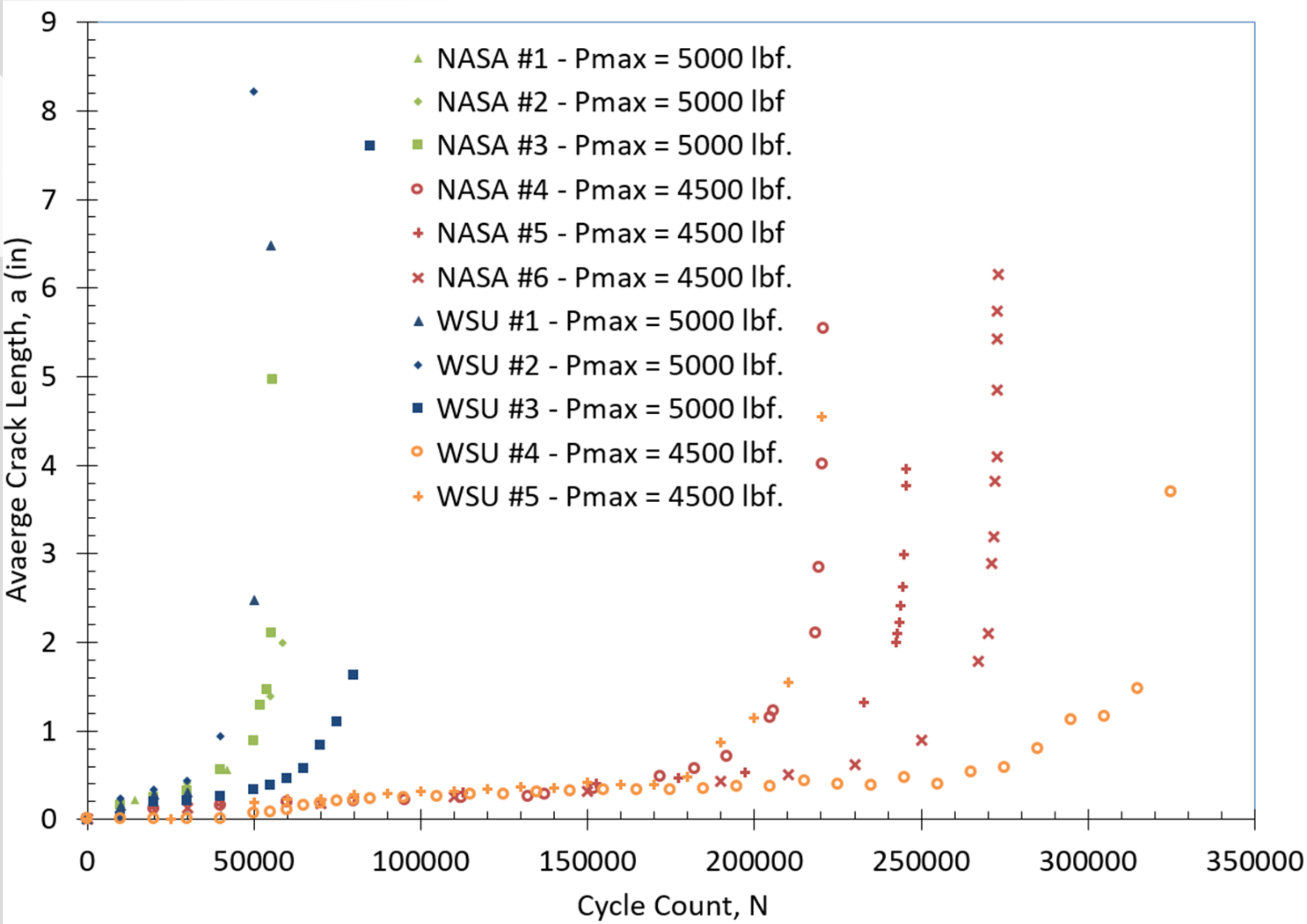
Pathfinder Damage Evolution under Fatigue Loading

Progressive delamination growth from the ply-drops captured via UT scans



Pathfinder Fatigue Data

At this time only test data is shown as fatigue simulations are work-in-progress



TEST-MODEL CORRELATIONS

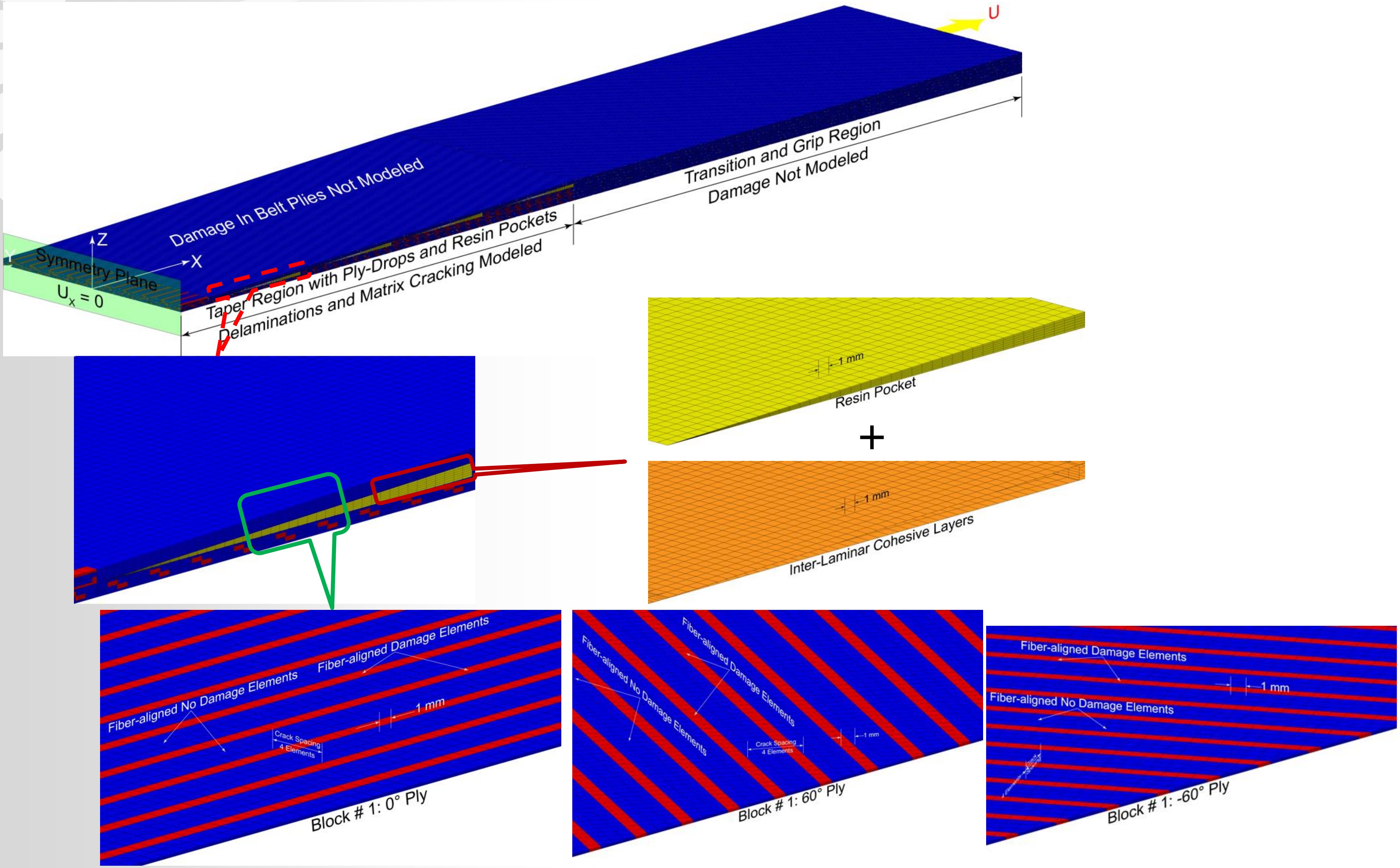
CompDam Overview

Features and characteristics

- 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
- Download link: https://github.com/nasa/CompDam_DGD

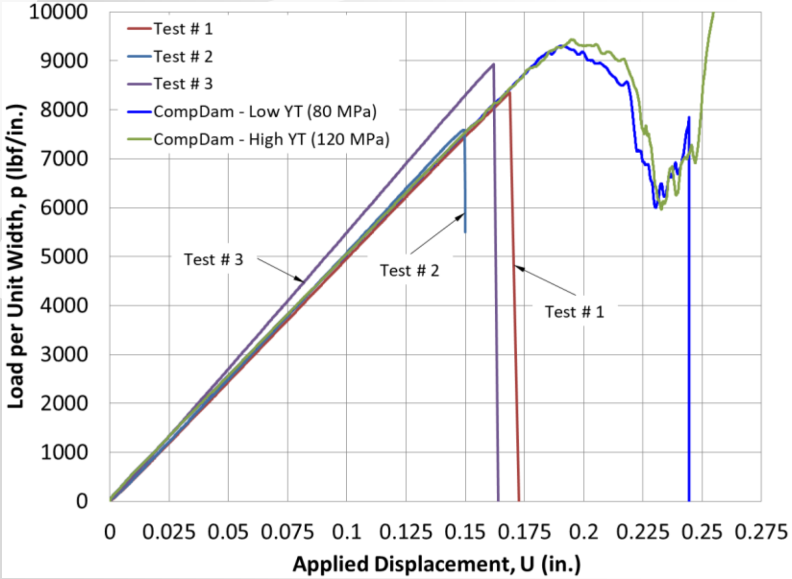
Pathfinder CompDam Model

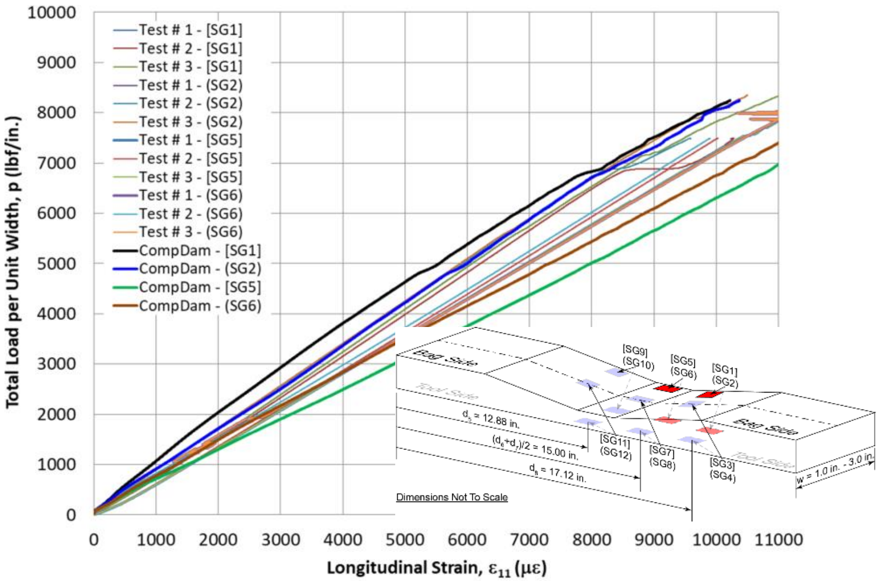
Symmetric model of pristine pathfinder specimen

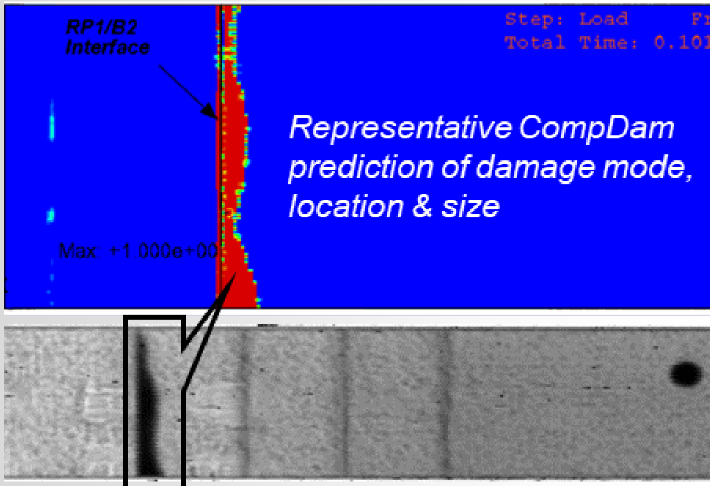


Pathfinder Static Correlations – CompDam

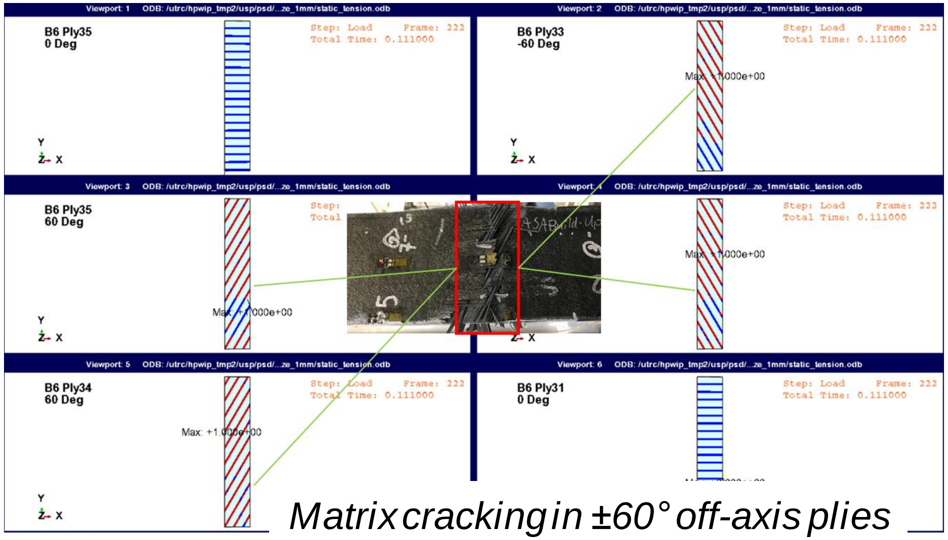
Successful correlations of stiffness, peak load, strains and damage modes







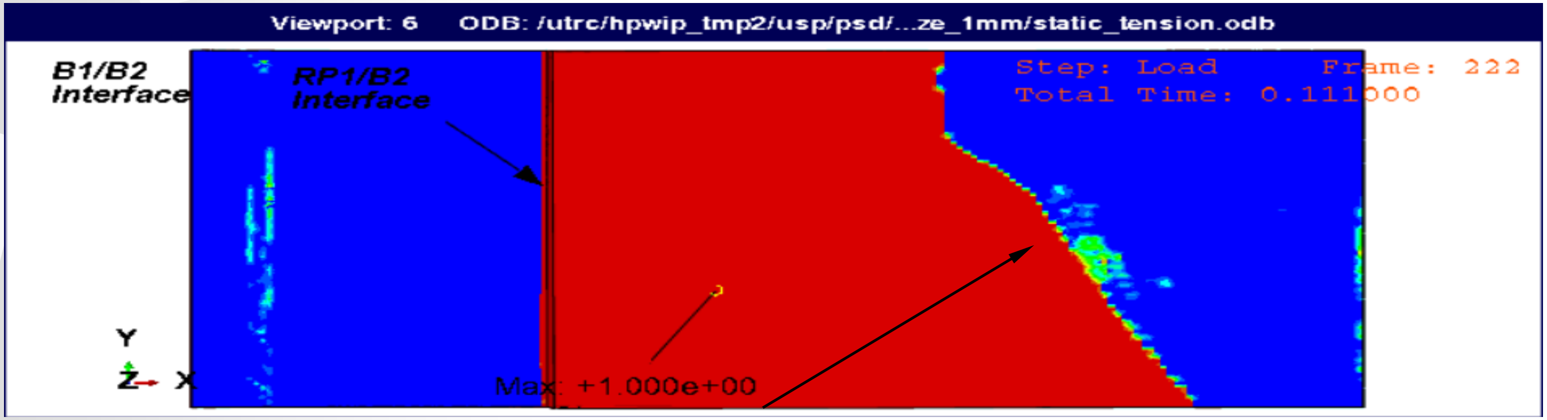
UT image showing delamination growth



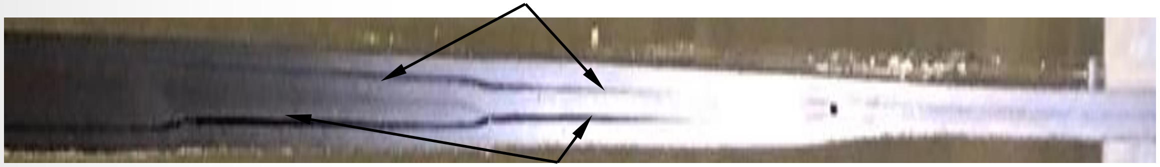
Matrix cracking in ±60° off-axis plies

Pathfinder Static Delamination Growth – CompDam

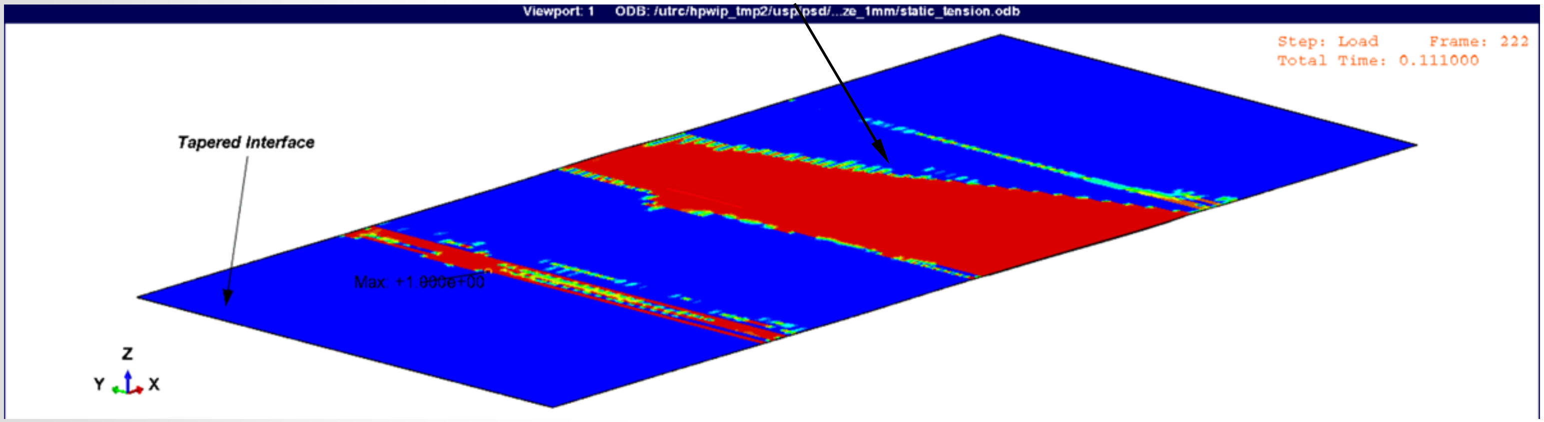
Successful correlations of delamination growth



Delamination along the B1/B2 Interface

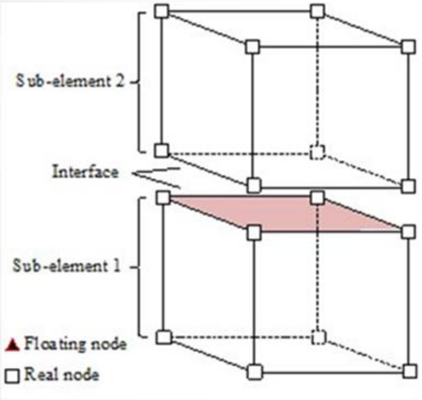


Delamination along the Tapered Interface

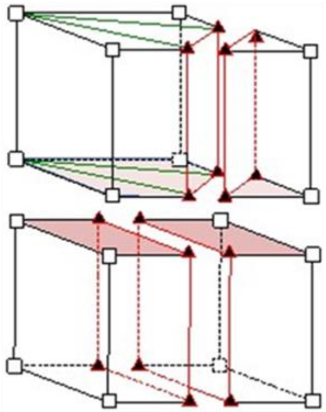


Floating Node Method Overview

Features and characteristics



Pristine extended interface element with finite sub-elements above and below the interface

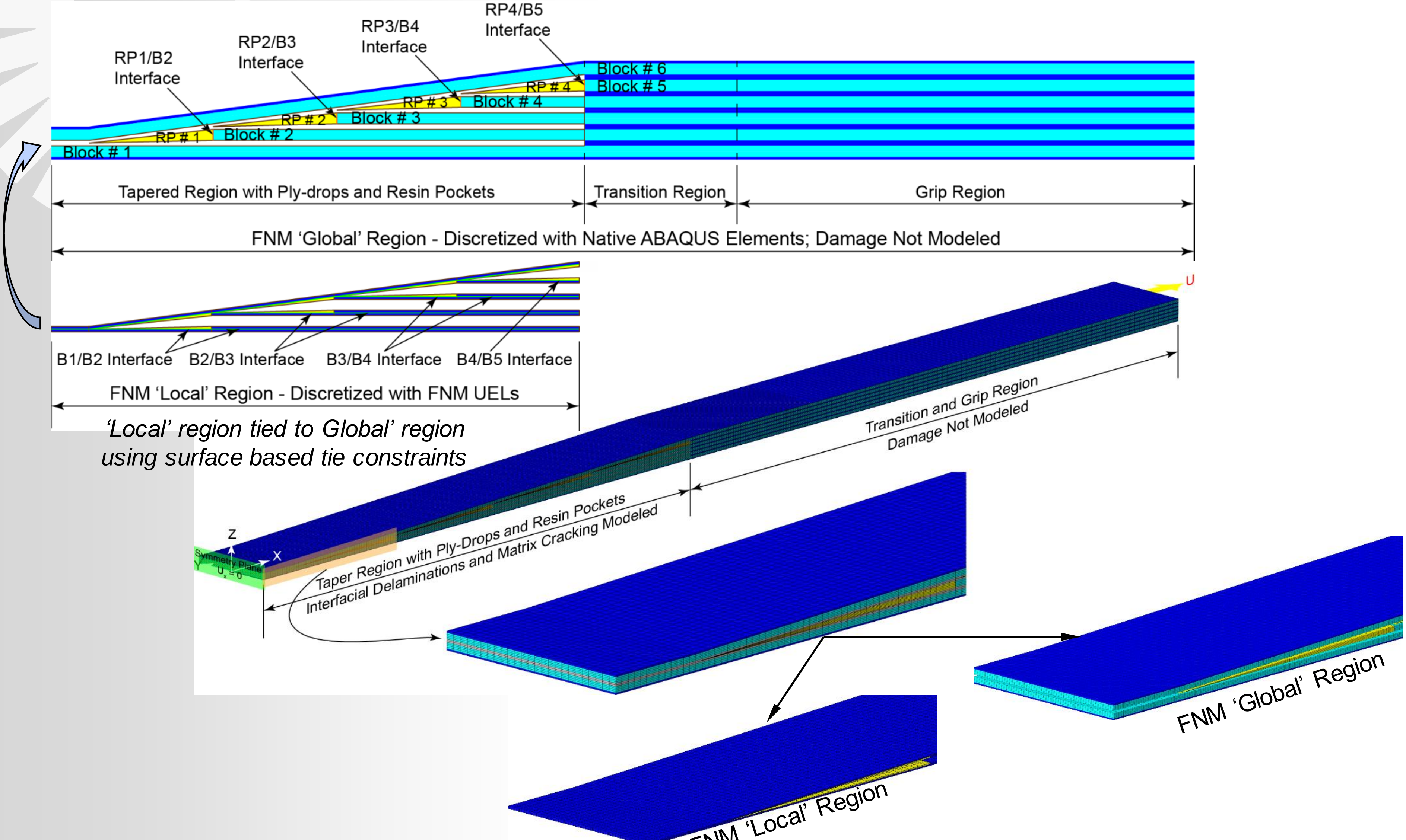


Element representing matrix cracks

- Fracture mechanics based Discrete Damage Mechanics (DDM) code
  - Matrix crack kinematics modeled by splitting finite elements representing deformable bulk material
  - Details: Chen, B.Y. et al. "*A Floating Node Method for the Modelling of Discontinuities in Composites.*" Engineering Fracture Mechanics, Vol. 127:104–134, 2014.
- Implemented as a 48-node Extended Interface User Element (UEL) in ABAQUS/Standard
  - Each UEL is composed of two solid sub-elements and an embedded interface element
  - Additional nodes (Floating Nodes) and additional degrees of freedom (Floating Degrees of Freedom) added to regular finite elements
  - Floating Nodes and Floating Degrees of Freedom linked to the crack path within the element
- Models static crack growth using traction-separation cohesive laws; fatigue crack growth based on Paris Law
- **Requires** user-defined finite element mesh generation programs to insert UELs in model input files

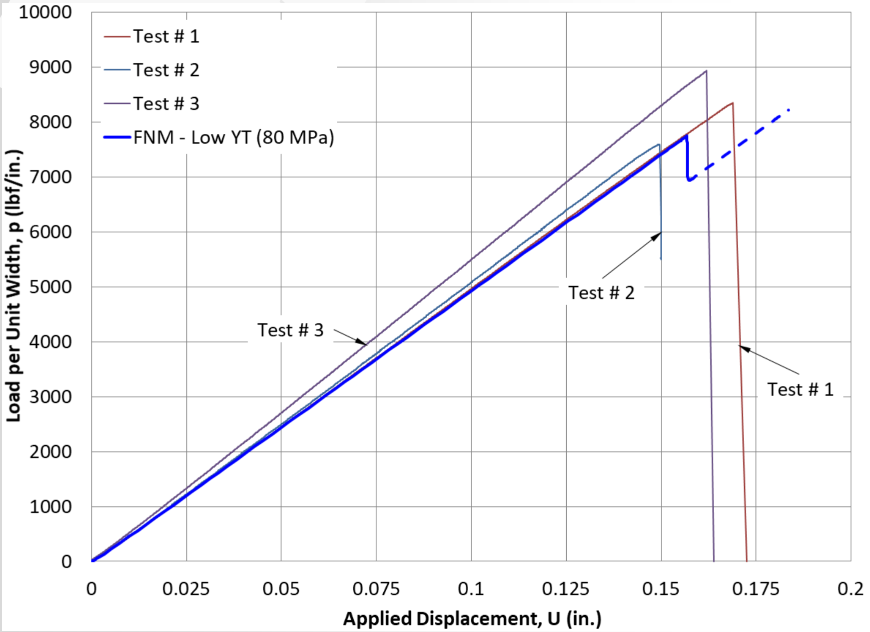
Pathfinder FNM Model

Global-Local model of pristine pathfinder specimen

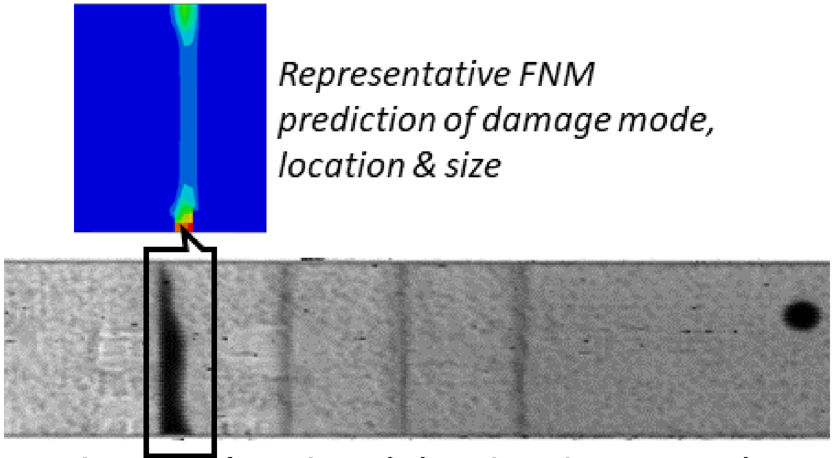


Pathfinder Static Correlations – FNM

Successful correlations of stiffness, and peak load; preliminary correlations of damage mode, location and size



Dotted line indicates FNM code predicts delamination arrest – result attributable to the modeling techniques implemented; <u>not a limitation of the code</u> and also not consistent with experiments



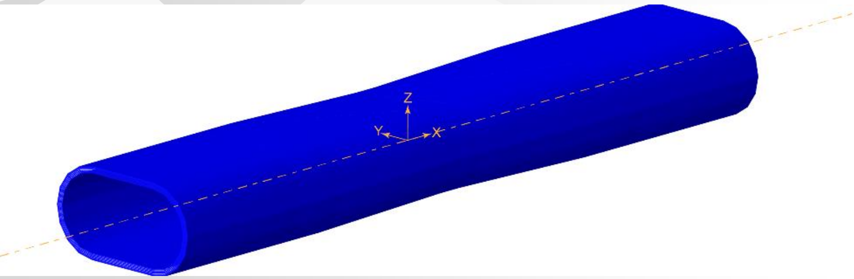
Representative FNM prediction of damage mode, location & size

UT image showing delamination growth

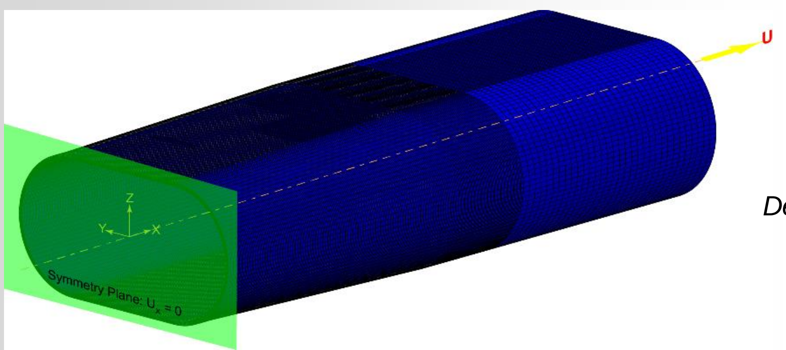
WORK-IN-PROGRESS

Blade Spar Static Blind Predictions – ABQ/COHESIVE

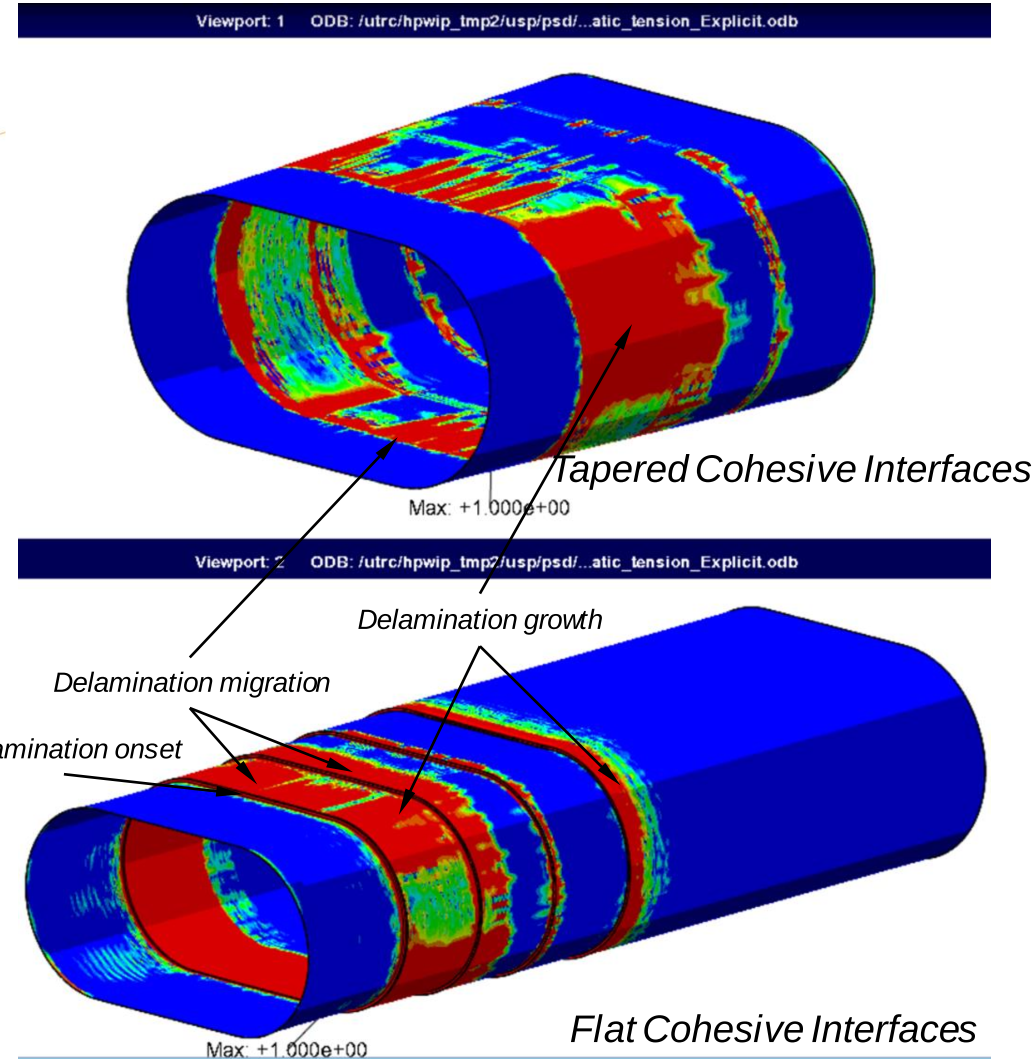
Preliminary simulation showing delamination growth from ply-drop regions



Full ABAQUS/CAE 3D Model



Half-Symmetric ABAQUS/COHESIVE 3D Model



Simulation successfully captures delamination onset, migration and growth

Summary

- Progressive delamination growth under static and fatigue loading documented with UT scans
- Validated quantitative metrics against experimental data
  - Successful correlations of stiffness, peak load, damage location, size and growth
- Work-in-progress
  - Fatigue simulations on the pathfinder models with the FNM code
  - Pre-test blind predictions of failure loads, damage mode, location and growth in 3D blade spar validation test article
  - Fabrication and testing of 3D blade spar validation article at NIAR