Evaluation of Progressive Damage Analysis Methods for Damage Predictions in Stiffened Composite Structures

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Advanced Composites Project (ACP) Technical Challenge 1
Accurate Strength & Life Prediction

Technical Challenge Statement:
Develop validated strength and life prediction tools with known accuracy for complex composite structures and standardized procedures for their reliable use.

Progressive Damage Analysis (PDA) Tools

Validated high fidelity analysis methods to reliably predict the onset and progression of damage and benchmark cases, V&V processes and test data for tool development and usage.

High Energy Dynamic Impact (HEDI)

Validated high energy dynamic impact prediction methods, for accurate deformation, damage, and failure and benchmark cases, V&V processes and test data for tool development and usage.

Rapid Design Tools (RDT)

Rapid Analysis Tools accounting for possible in-service damage, and manufacturing defects and features.

Potential Impact:
- Reduce the number of design, analysis, test iterations during development
- Reduce the time to evaluate design options by using high fidelity progressive damage analysis methods to enable smarter more targeted physical testing
- Certification: earlier planning and shorter duration

Progressive Damage Analysis (PDA) Team Objective and Approach

Objective

- Evaluate/develop progressive damage and failure analysis (PDFA) methods for predicting the static strength and fatigue life of laminated composite structures
  - ***Post-buckled stiffened panel with barely visible impact damage (BVID)***
  - Blade spar component

Approach

- Assess predictive capabilities of existing PDFA methods
- Design and develop final sub-component validation articles with desired failure modes
- Perform incremental Verification and Validation (V&V) using building-block tests
  - Building-block test articles derived from sub-component designs; isolate fundamental failure modes/interactions
  - Develop validation data specific to failure modes of interest, including damage progression
  - Perform test and analysis at each incremental stage to develop modeling approaches, identify limitations in predictive capability
- Identify refinements to PDFA methods, other factors, required to address limitations

Progressive Damage Analysis (PDA) Team Members

Cheryl Rose (**Lead**)
Kevin O'Brien (**Lead**)
Andrew Bergan
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Nelson De Carvalho
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Wade Jackson
Will Johnston
Cyrus Kosztowny
Ronald Krueger
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Gerry Mabson
Lyle Deobald
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Stewart Boyd
Sara Murphy
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Brenna Feirer
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Addis Tessema
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Prabhakar Rao
Mark Gurvich
G.V. Srinivasan

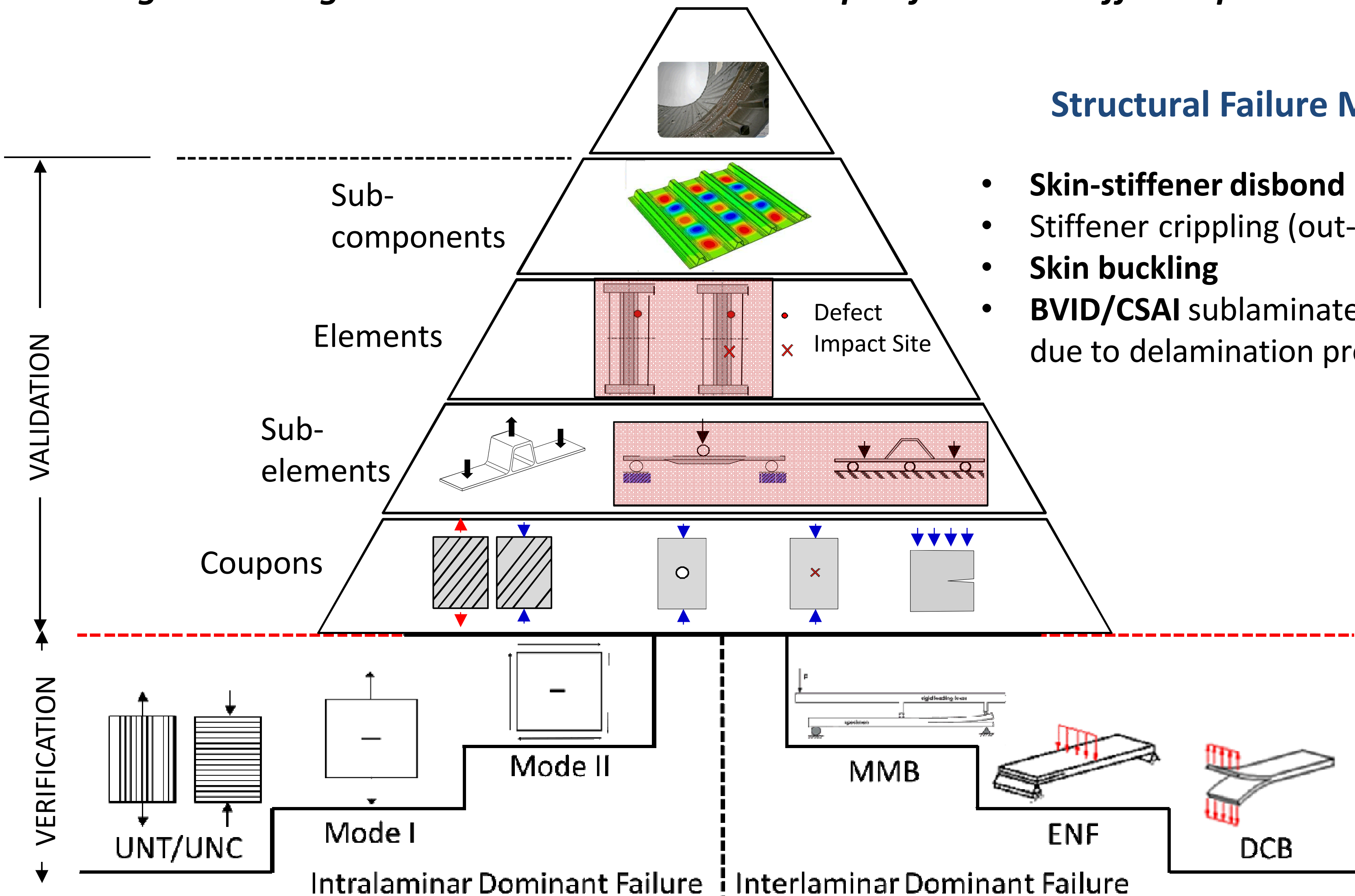
Waruna Seneviratne
Upul Palliyaguru
Shenal Perera
Garrett Smith

Endel Iarve
Kevin Hoos
Hari Adluru
Scott McQuien
Yu-Jui Liang

Hyonny Kim
Yuri Bazilevs
Andrew Ellison
Marco Pigazzini

Verification and Validation Building Block

Primary failure modes of interest were identified and categorized based off an overall panel design. Building-block validation matrix developed from hat-stiffened panel design.



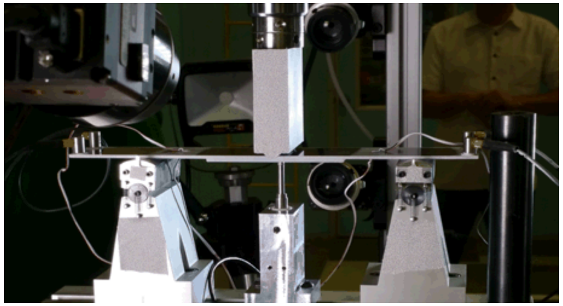
Structural Failure Modes

- **Skin-stiffener disbond**
- Stiffener crippling (out-of-scope)
- **Skin buckling**
- **BVID/CSAI** sublaminate **buckling** due to delamination propagation

Progressive Damage Analysis (PDA) Validation Tests

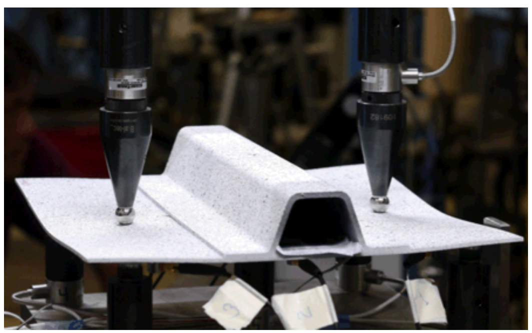
Post-buckled Stiffened Panel with Barely Visible Impact Damage

Three-Point Bend



Static, Fatigue

Seven-Point Bend



Static, Fatigue

- 4 nominally pristine
- 3 Teflon insert pre-damage
- 3 impact damaged

Single-Stringer Compression

Static (21), Fatigue (36)

- 3 nominally pristine
- 3 Teflon insert pre-damage
- 3 impact damaged

Multi-Stringer Compression

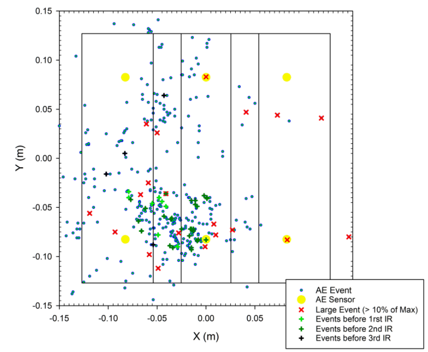
Static (8), Fatigue (15)

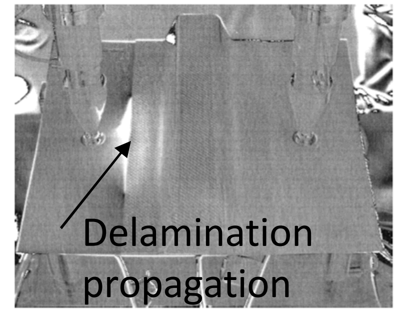
- Static – 4 with Teflon insert, 3 with impact damage
- Fatigue – 3 with impact damage

Experimental Methods

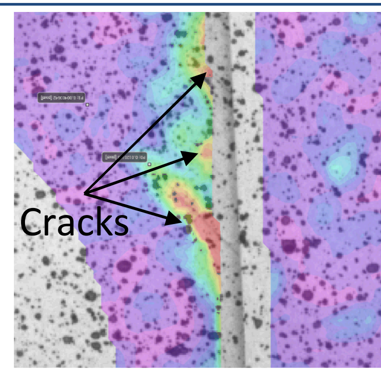
Test Interruption and Damage Characterization

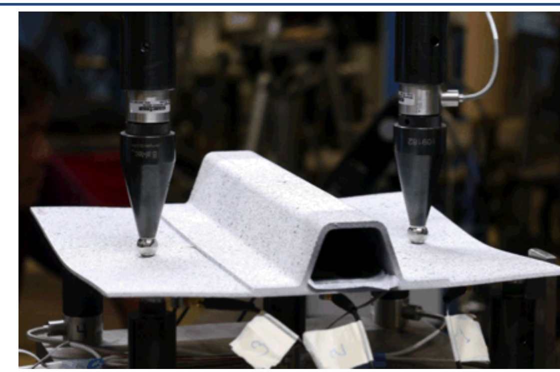
- Acoustic Emission (AE), Passive Thermography
  - Early damage detection
  - Rapid damage accumulation
  - Test interruption





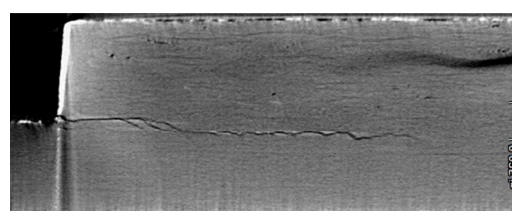
- Digital Image Correlation
  - Load introduction, boundary conditions, global response
  - Surface damage initiation and propagation

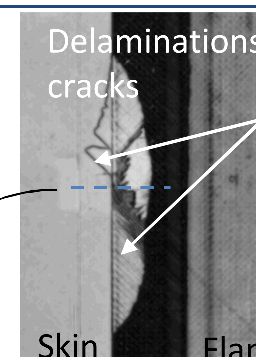




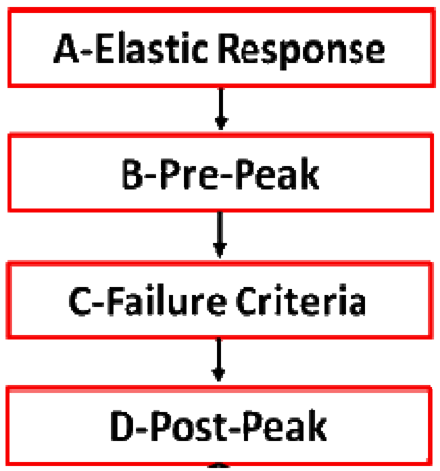
- Ultrasonic (UT), X-Ray/CT
  - In-situ damage assessment (UT)
  - Detailed pre and post-test assessment

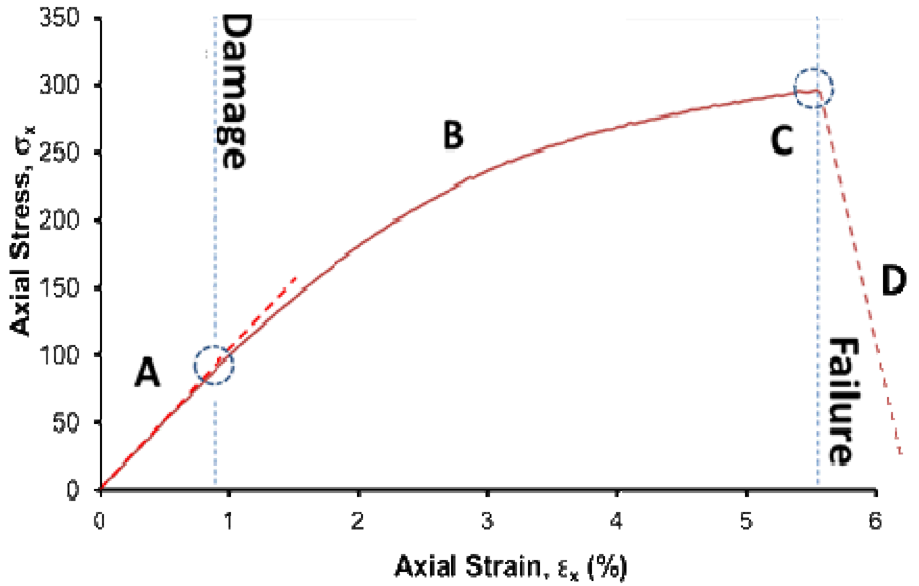
X-ray/CT





General Framework for Method Evaluation



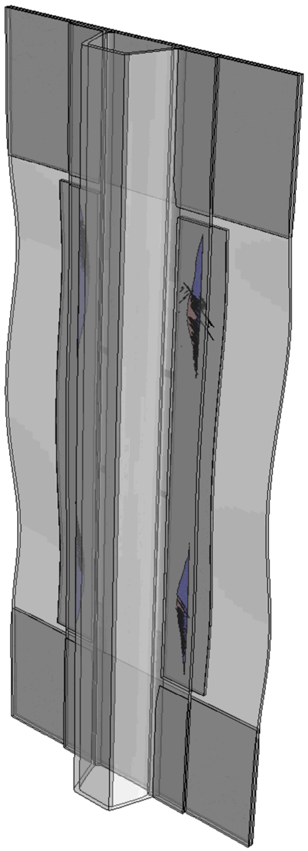


PDA methods:

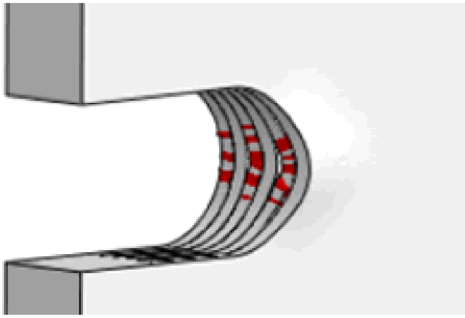
- Composite Damage (**CompDam**) Progressive Damage Analysis Software, NASA Langley Research Center
- Floating Node Method (**FNM**), NASA Langley Research Center
- Regularized Extended Finite Element Method (**Rx-FEM**), University of Texas at Arlington

CompDam – PDA Tool

Point of Contact: Frank Leone (NASA)



- **Description:**
  - ABAQUS VUMAT for predicting damage initiation and progression in graphite/epoxy unidirectional tape composite laminates in Abaqus/Explicit
    - Method based on continuum damage mechanics (CDM)
    - Recent developments involve deformation gradient decomposition method, matrix shear nonlinearity, fiber kink band modeling, code optimizations for parallel processing
  - Data includes material data, verification and validation (V&V) benchmark problems for code evaluation, publications with theory and applications, high-fidelity validation tests
  - Best practice guidelines for CompDam use
- **Capability:**
  - Complex damage processes of interacting matrix cracks and delaminations captured
  - Ultimate strength prediction within 15% of experimental average demonstrated
  - Progressive damage analysis of 15M DOF stiffened panels completed in ~16 hours on NASA K-cluster (75 cores)
- **Verification / Validation / Demonstration of Capability:**
  - Thorough verification of intralaminar project benchmarks for static loading
  - Residual strength of compression loaded four-stringer panel with impact damage
  - Blade spar sub-component level article with multiple ply-drops

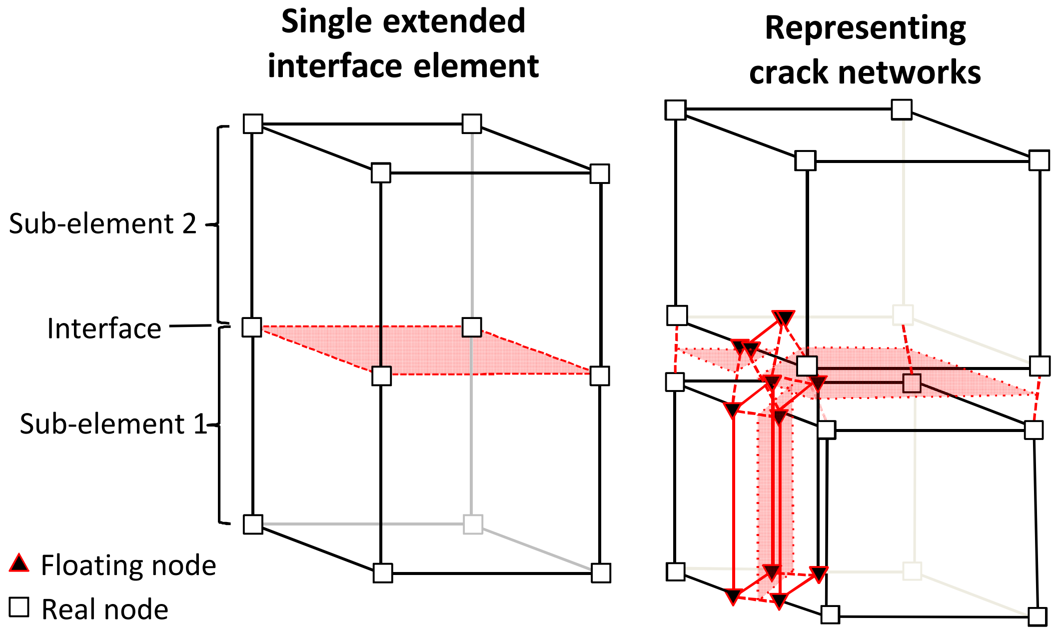


- **Transition Path:**
  - Open source release: https://github.com/nasa/CompDam_DGD
  - Extensive V&V in ACC 2C18 and example demonstration proposed for CMH-17

Floating Node Method (FNM) – PDA Tool

Point of Contact: Nelson DeCarvalho (National Institute of Aeronautics)

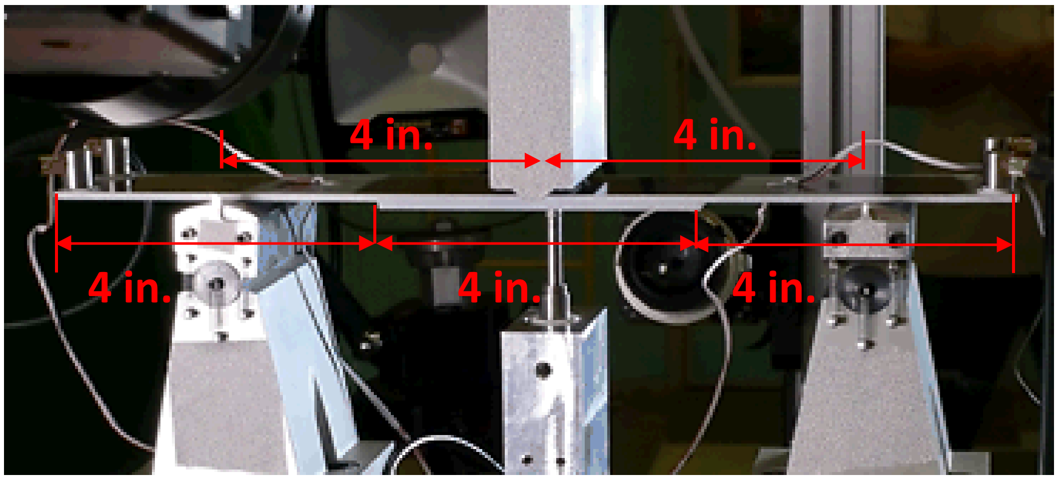
- **Description:**
  - ABAQUS UEL for predicting matrix damage initiation and progression
  - Discrete crack approach in Abaqus/Standard
  - Floating nodes are used to accommodate multiple crack interactions/intersections
  - Explicitly captures matrix crack/delamination interaction kinematics
  - No limit to crack spacing or number
  - Does not require fiber-aligned meshes
  - Cohesive (Static) and VCCT (Fatigue)

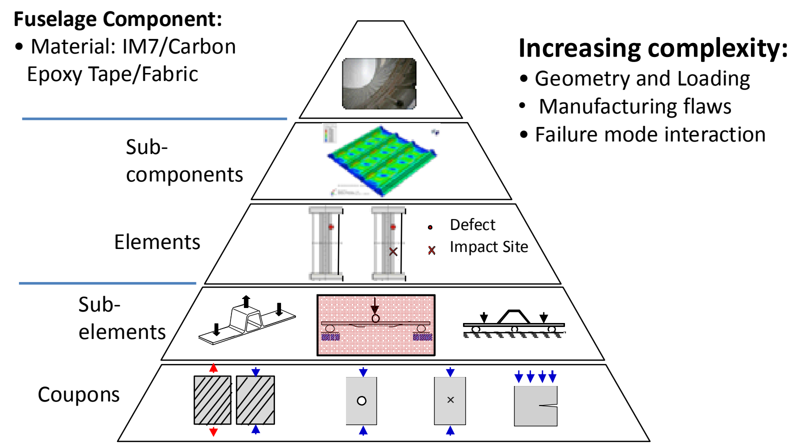


- **Capability:**
  - Static strength and fatigue life prediction capability
  - Complex damage processes of interacting matrix cracks and delaminations captured
  - Ultimate strength predictions and fatigue life predictions compared to experimental results
- **Verification / Validation / Demonstration of Capability:**
  - Thorough verification of interlaminar and intralaminar program benchmarks for static and fatigue
  - *Static test article*: Residual strength of stiffened compression panel with impact damage
  - *Fatigue test article*: Fatigue prediction of blade spar subcomponent article with multiple ply-drops
- **Transition Path:**
  - Unlimited release of code in US
  - Extensive V&V in ACC 2C18 and example demonstration proposed for CMH-17

Three-Point Bend (3PB) Validation Study

Objective: *Capture matrix crack and delamination growth and interactions near a flange termination under representative post-buckled stiffened panel deformations*

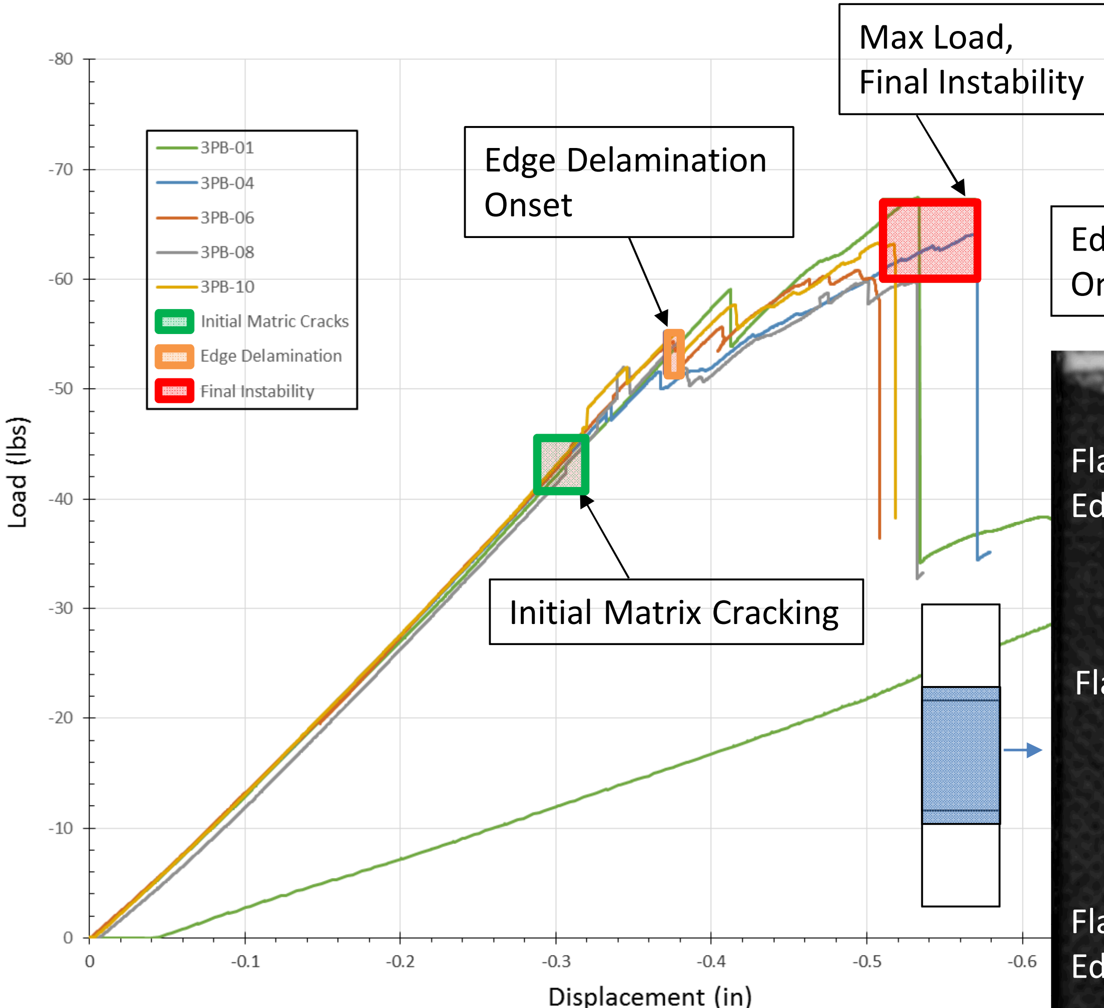




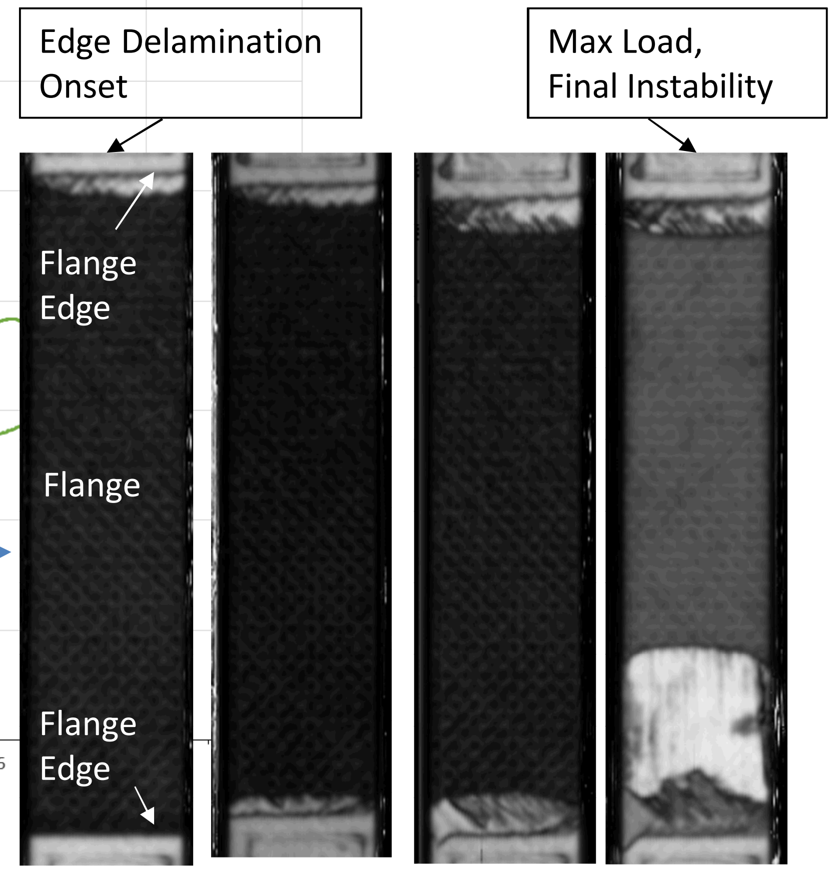
Challenges for modeling damage:

- Material properties
  - Strength properties, especially the Mode I matrix strength
  - Fracture toughness properties related to
    - Delamination between different materials
    - Delamination between differently oriented laminae
- Computational efficiency
  - Ply-to-ply level discretization is often needed for observed crack/delamination migration events

3PB Test Summary



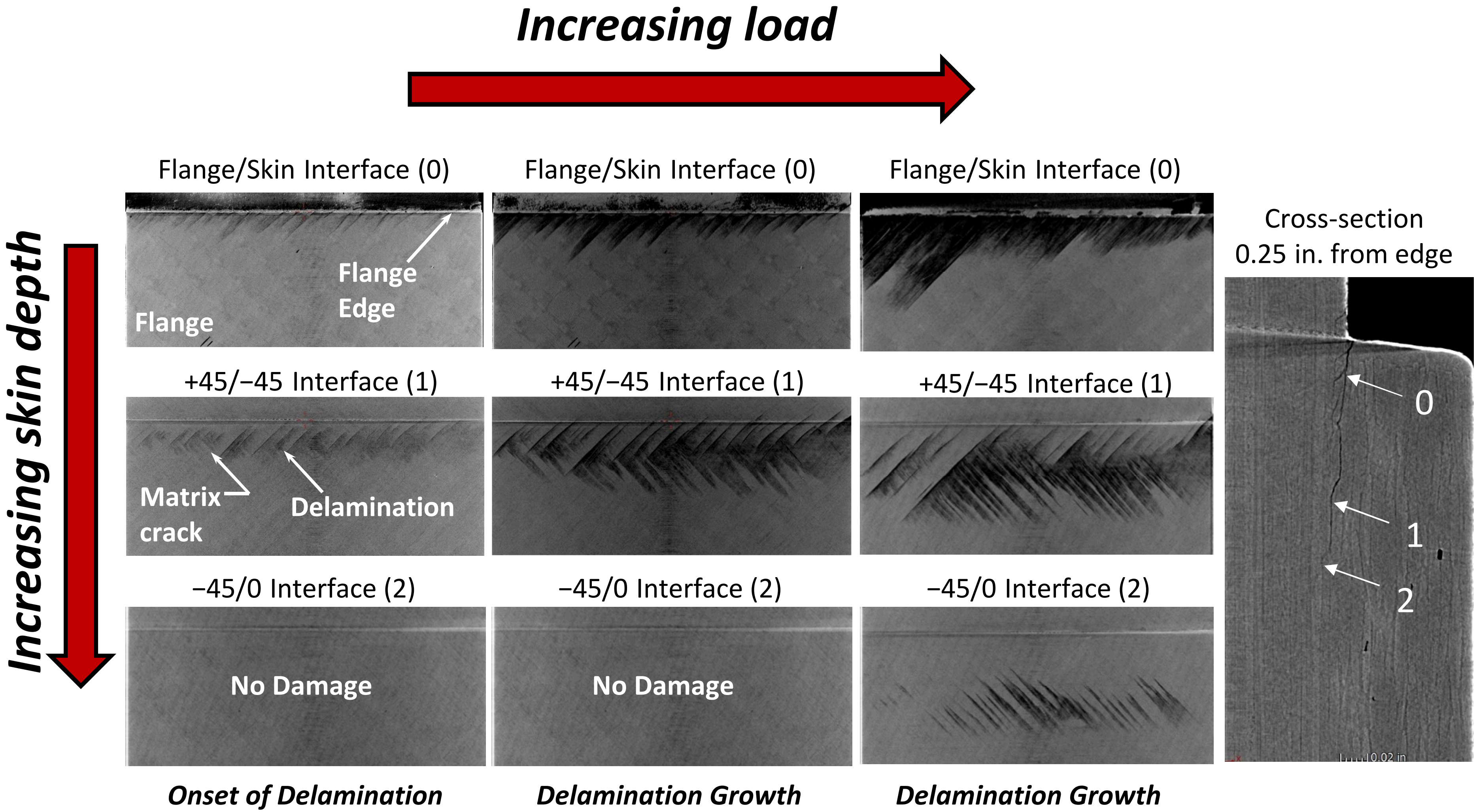
UT Images
Delamination growth from
the flange termination region



Specimens exhibit progressive matrix cracking and delamination growth from the flange termination regions

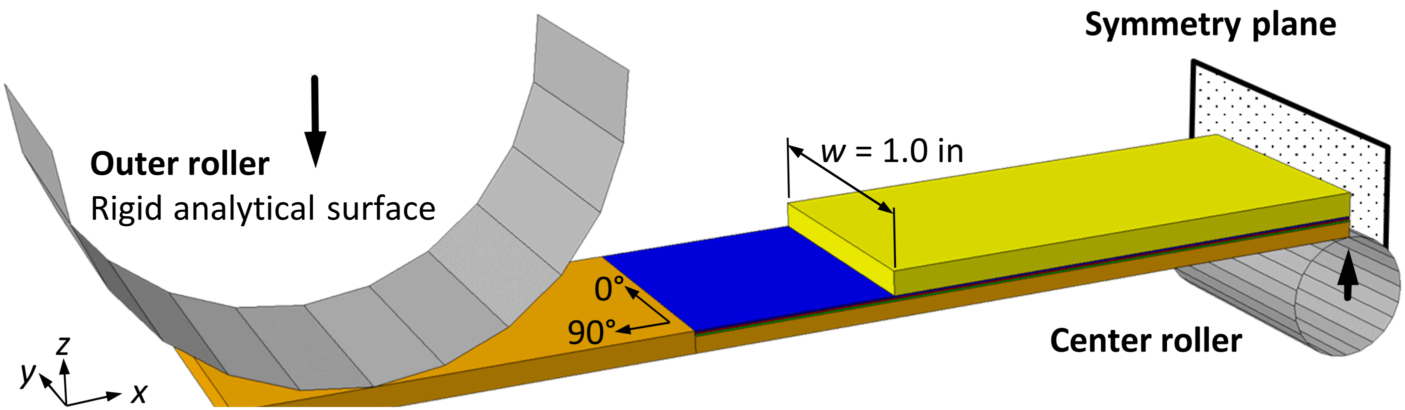
3PB Damage Details – Before Failure

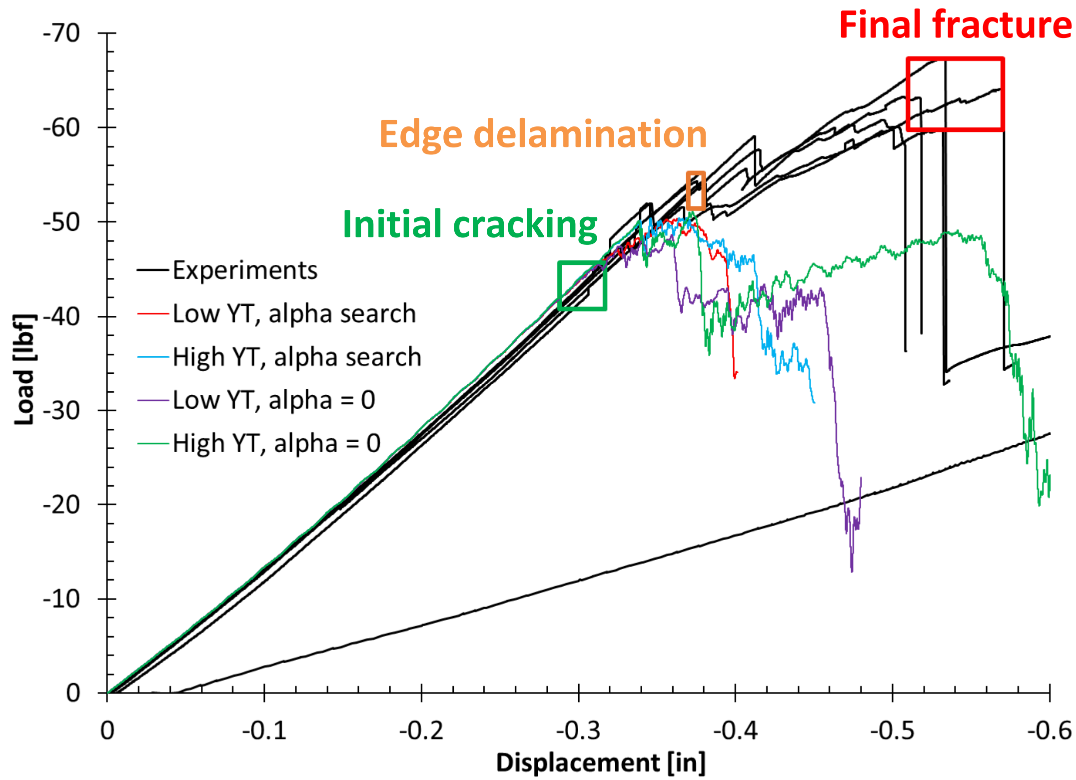
X-Ray CT Data



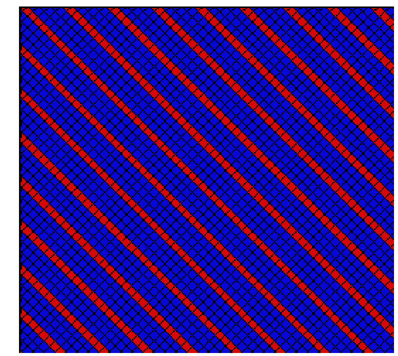
3PB Analyses

CompDam FE Model and Load/Displacement Response

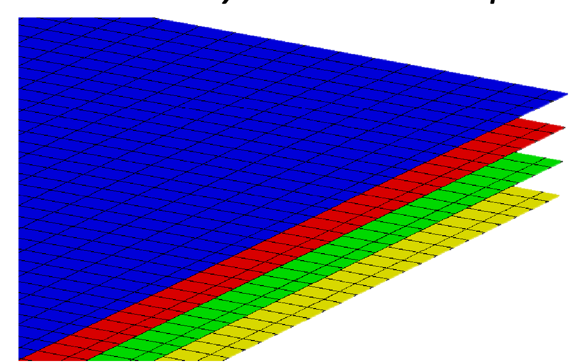




Fiber-aligned solid element plies



Cohesive layers between plies

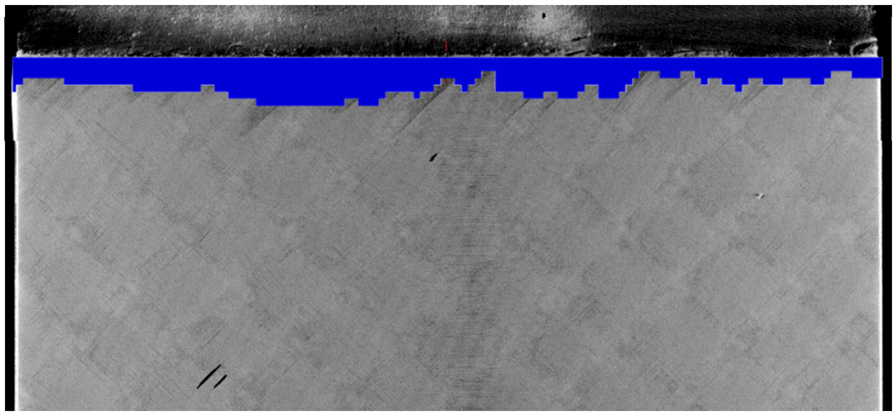


3PB Analyses

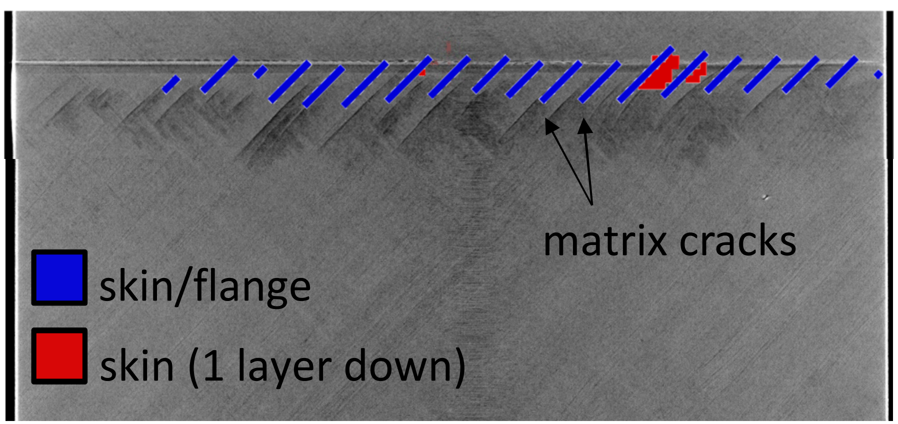
CompDam Damage Prediction Comparison to X-Ray/CT

Exp: Run 6, Peak Load – 53.9 lb
FE: Edge-to-Edge Delamination – 45.9 lb

Flange/Skin Interface

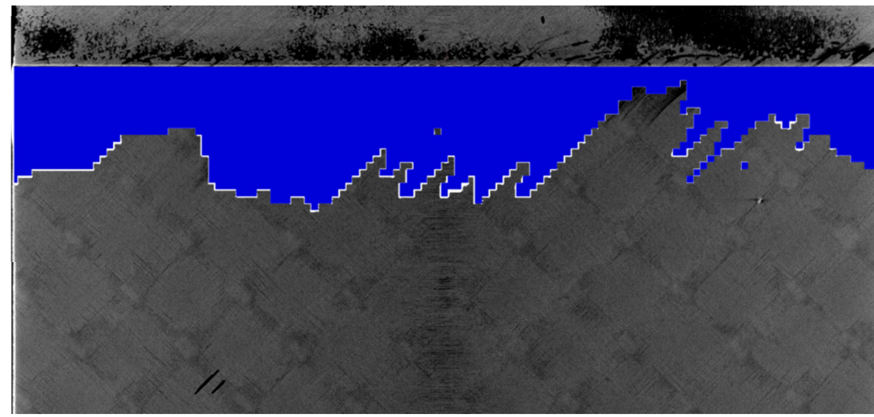


+45 Ply and +45/-45 Interface

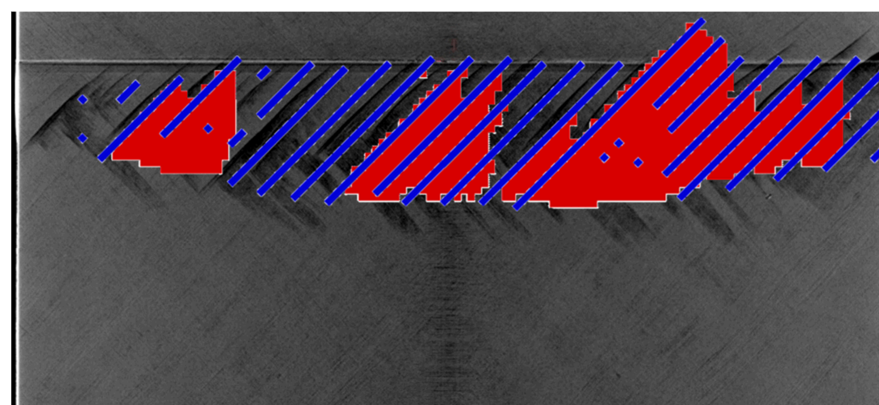


Exp: Run 7, Peak Load – 60.0 lb
FE: Peak Model Load – 50.4 lb

Flange/Skin Interface

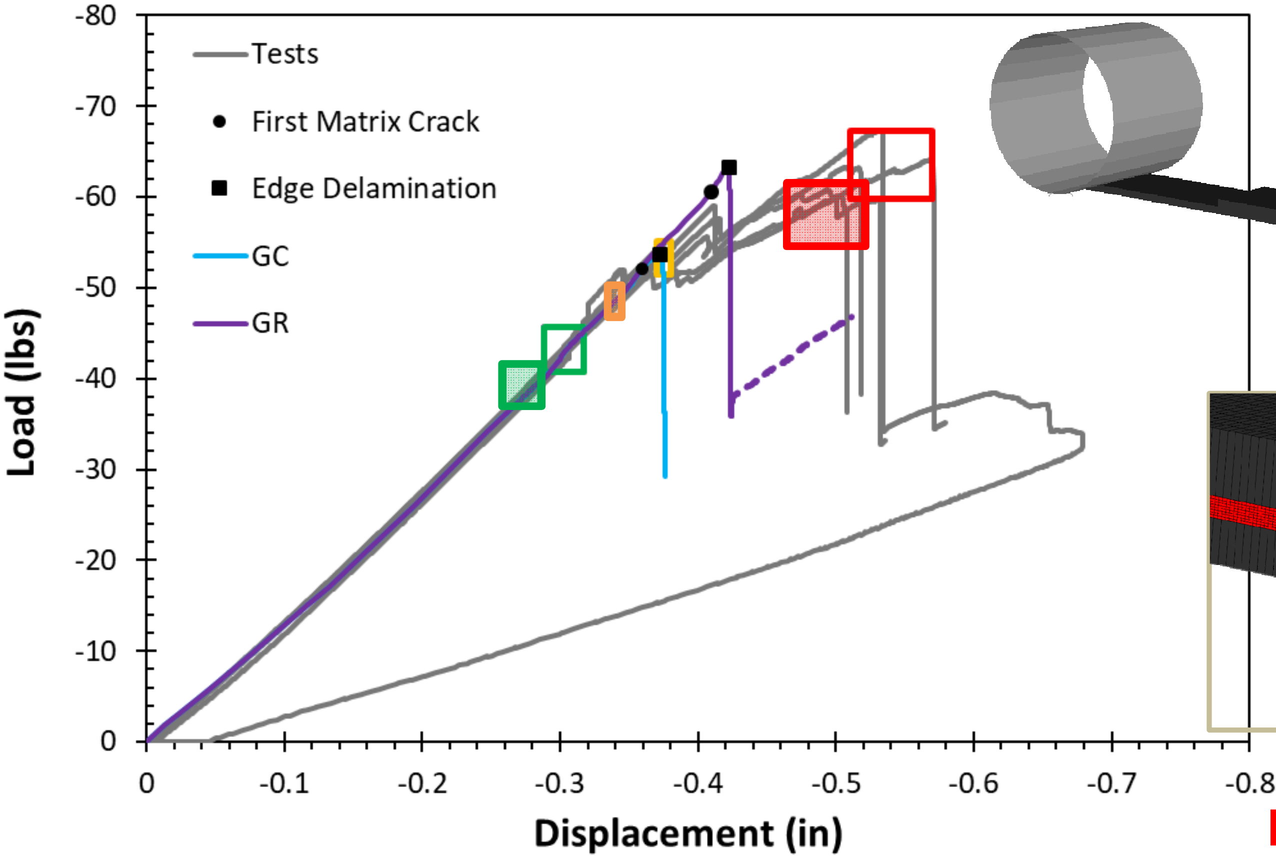


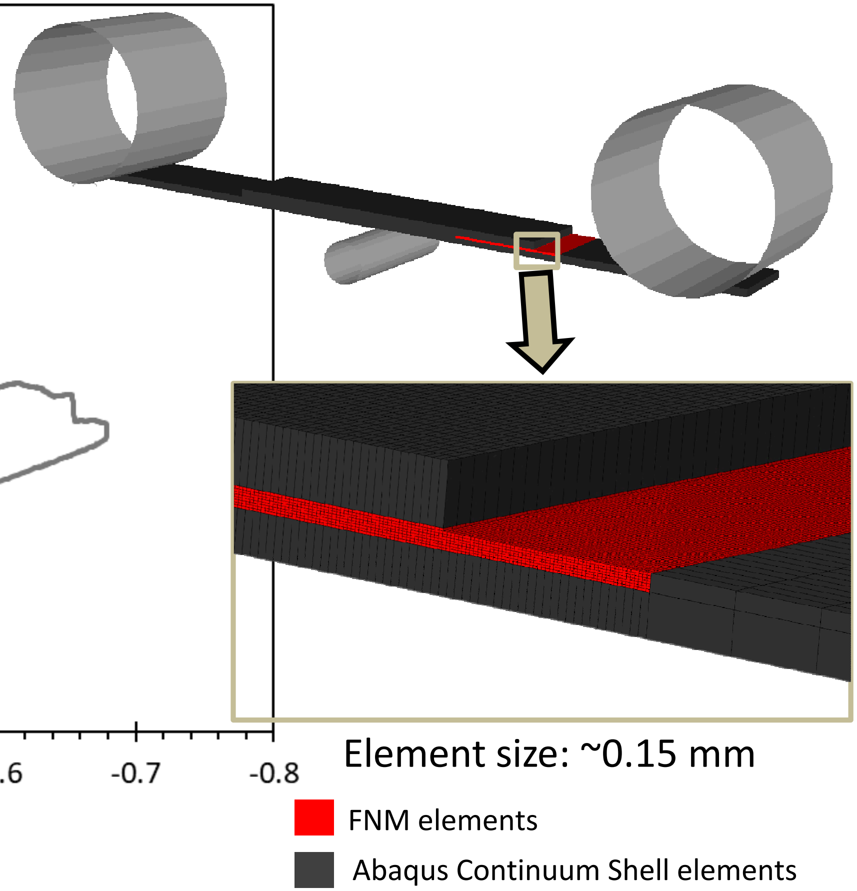
+45 Ply and +45/-45 Interface



3PB Analyses

FNM FE Model and Load/Displacement Response





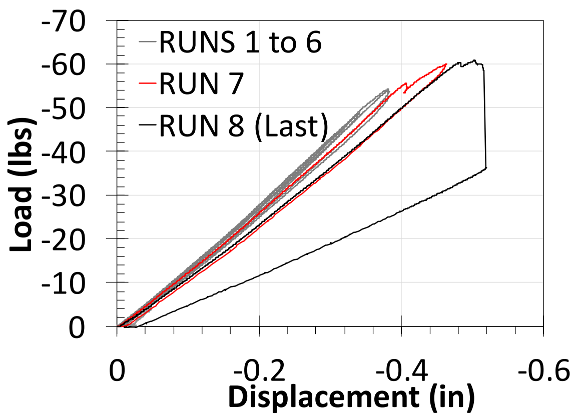
Observations:

- Maximum load/first load drop approximately within range predicted by G_C/G_R
- Load at which first cracks occur not captured
- Progressive nature of the unloading curves not captured

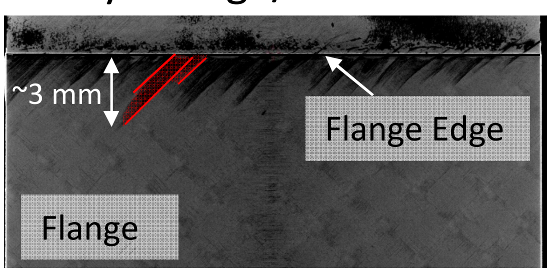
3PB Analyses

FNM Damage Prediction Comparison to X-Ray/CT

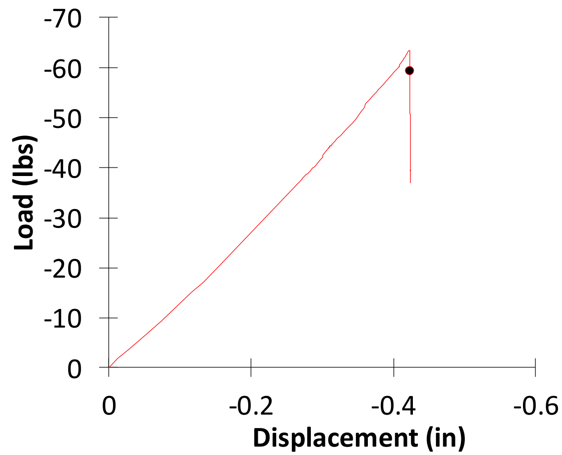
Interrupted Tests



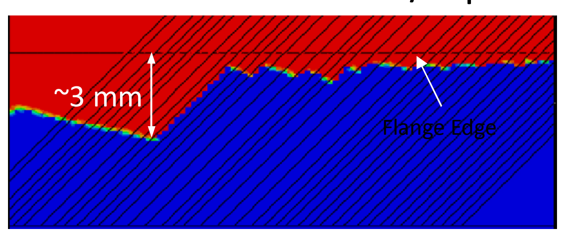
X-Ray: Flange/skin interface



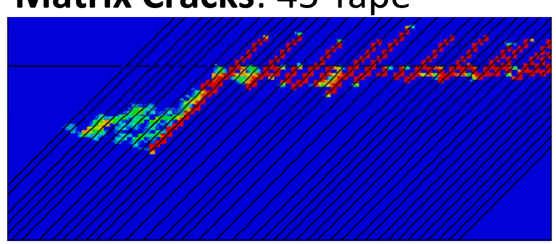
G_R – Fabric/Tape



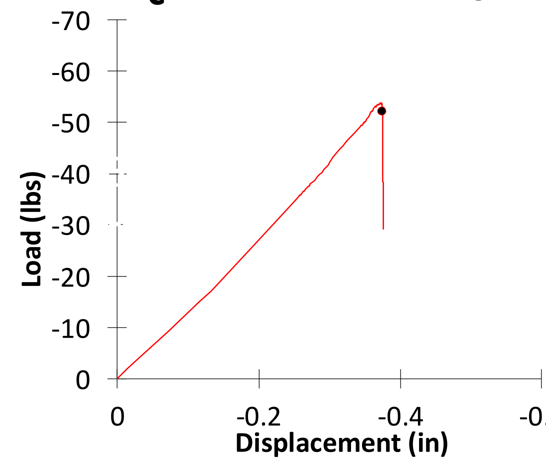
Delamination: Fabric 45/Tape 45



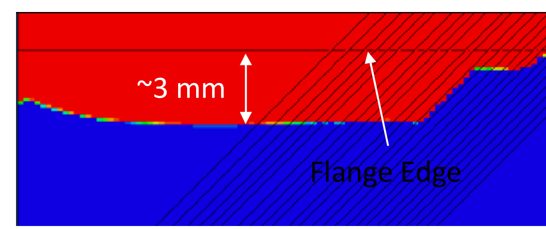
Matrix Cracks: 45 Tape



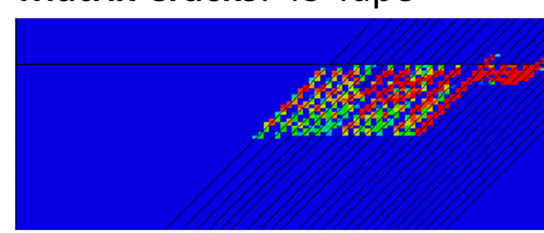
G_c – Fabric/Tape



Delamination: Fabric 45/Tape 45

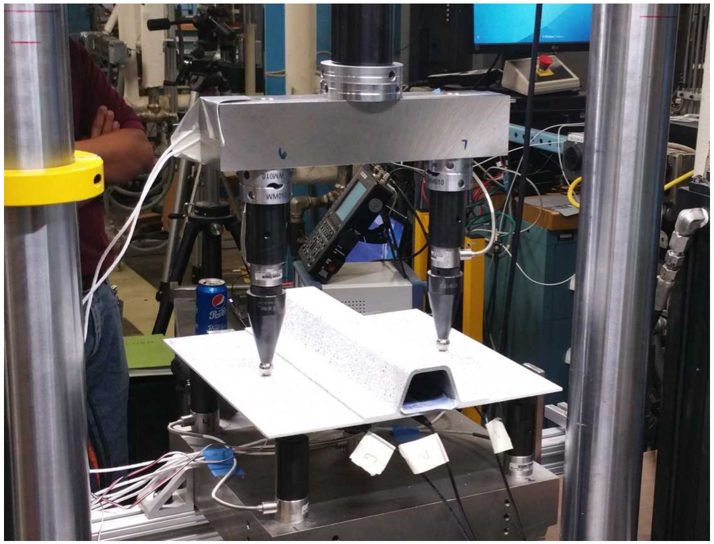


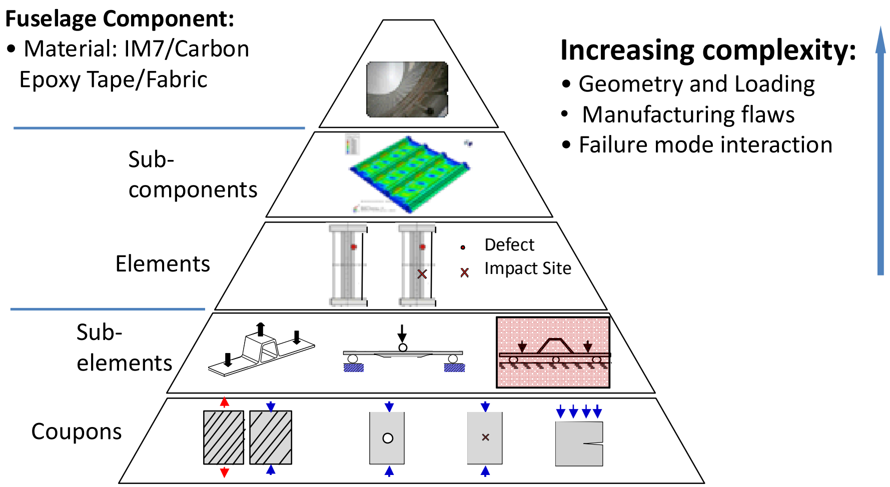
Matrix Cracks: 45 Tape



Seven-Point Bend (7PB) Validation Study

Objective: *Measure and characterize matrix crack and delamination growth and interactions near a flange termination in a post-buckled stiffened panel*

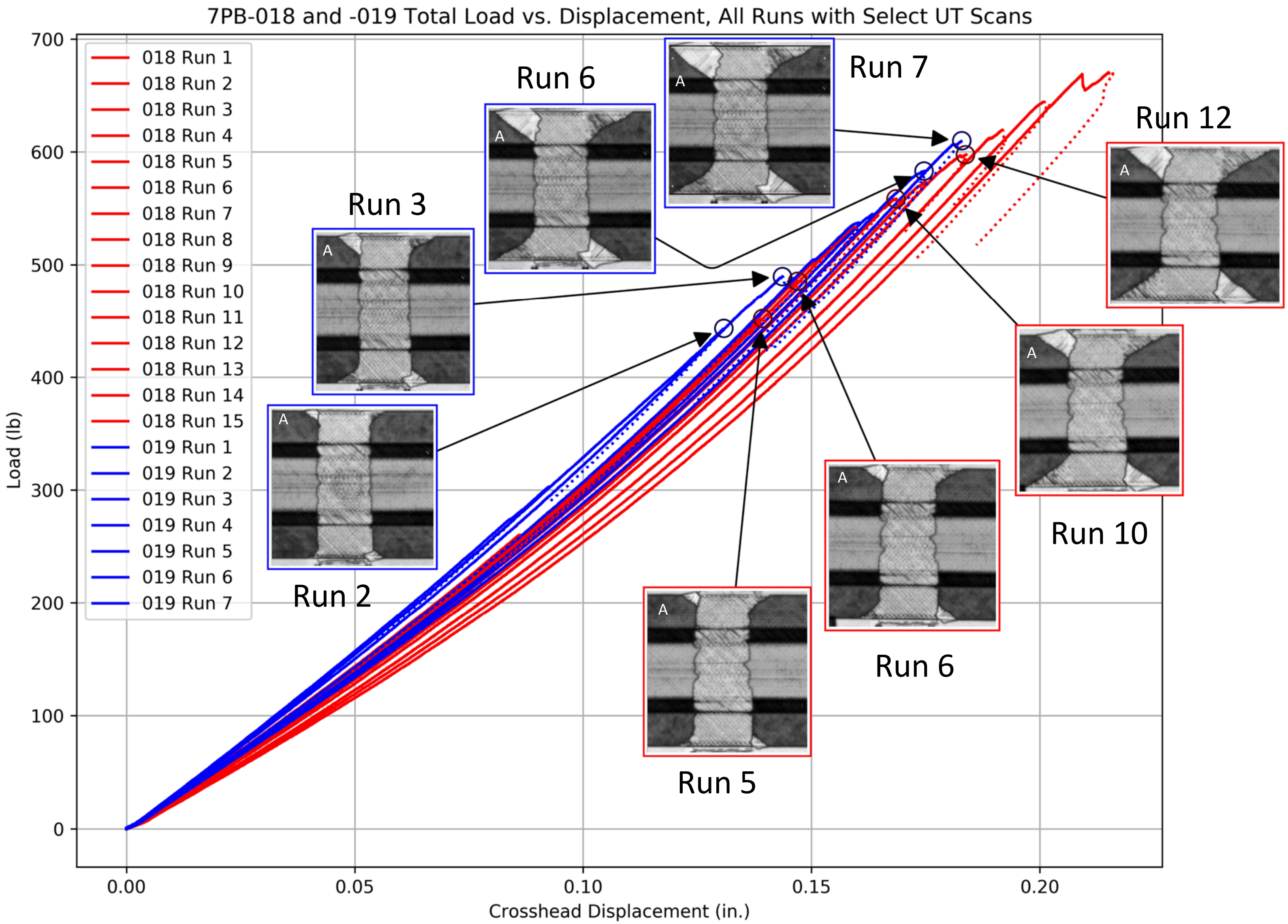




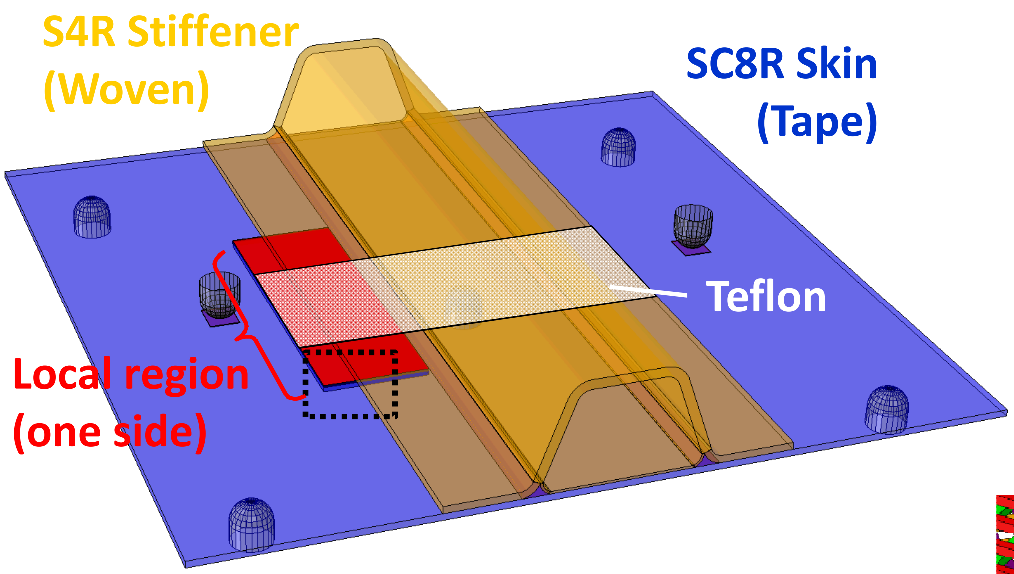
Challenges for modeling damage:

- Material properties
- Large Out-of-Plane Deformation
  - Finite deformations may require consideration of geometric nonlinearity
- Computational efficiency
  - Experimentally observed damage spans significant portions of geometry
  - Ply-to-ply level discretization is often needed for observed crack/delamination migration events

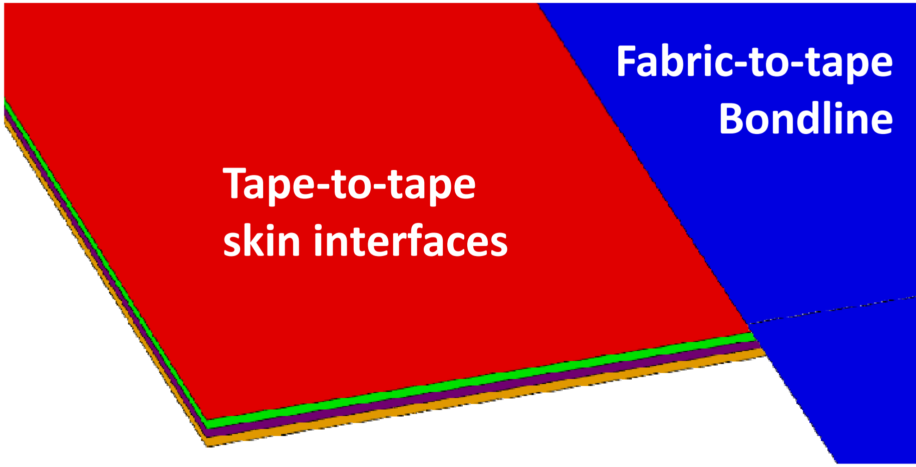
7PB Load/Displacement History with UT Scans



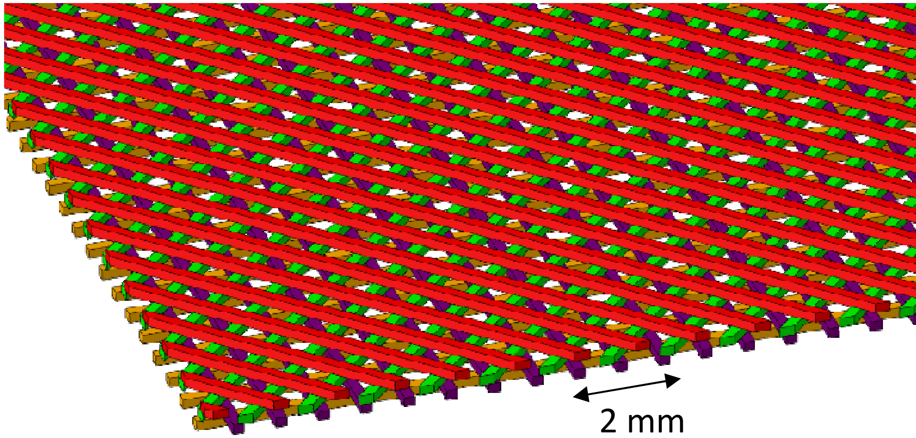
7PB Analyses – CompDam Finite Element Model



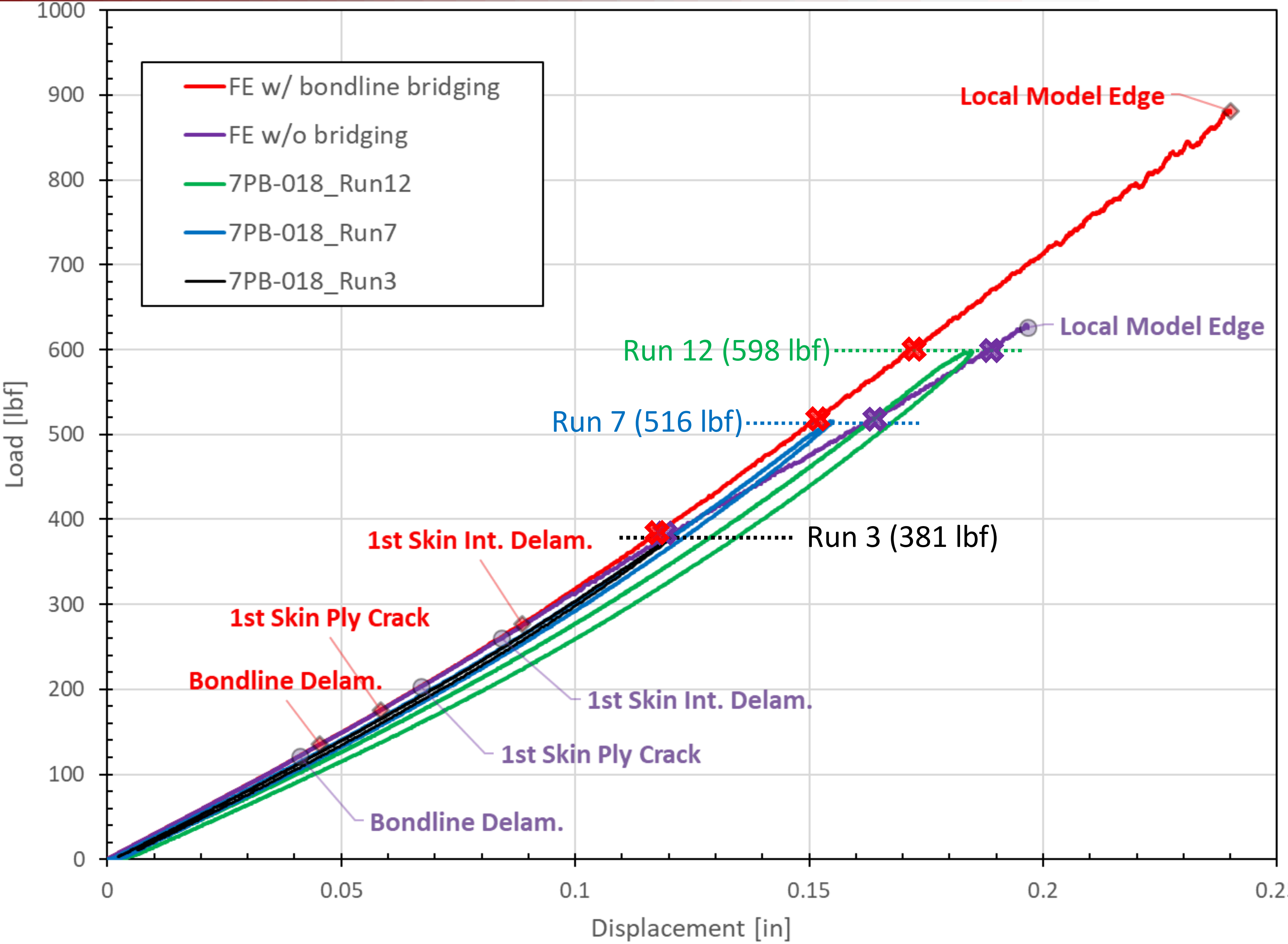
Cohesive element layers



Fiber-aligned solid element
layers for intralaminar damage

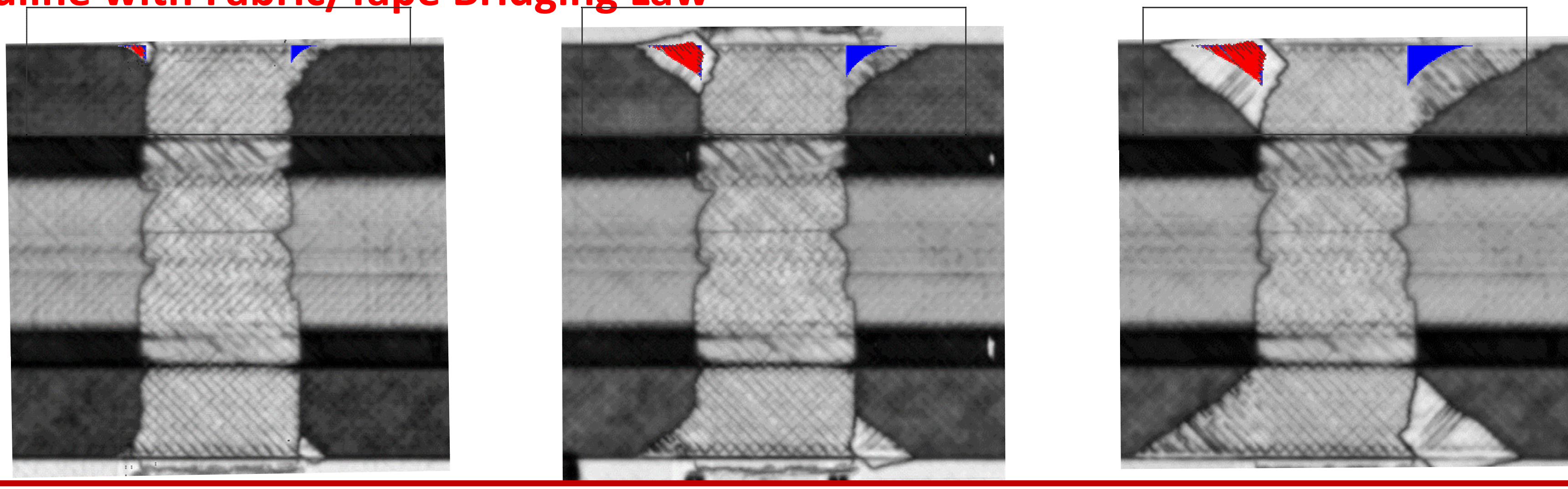


7PB Analyses – CompDam Load/Displacement

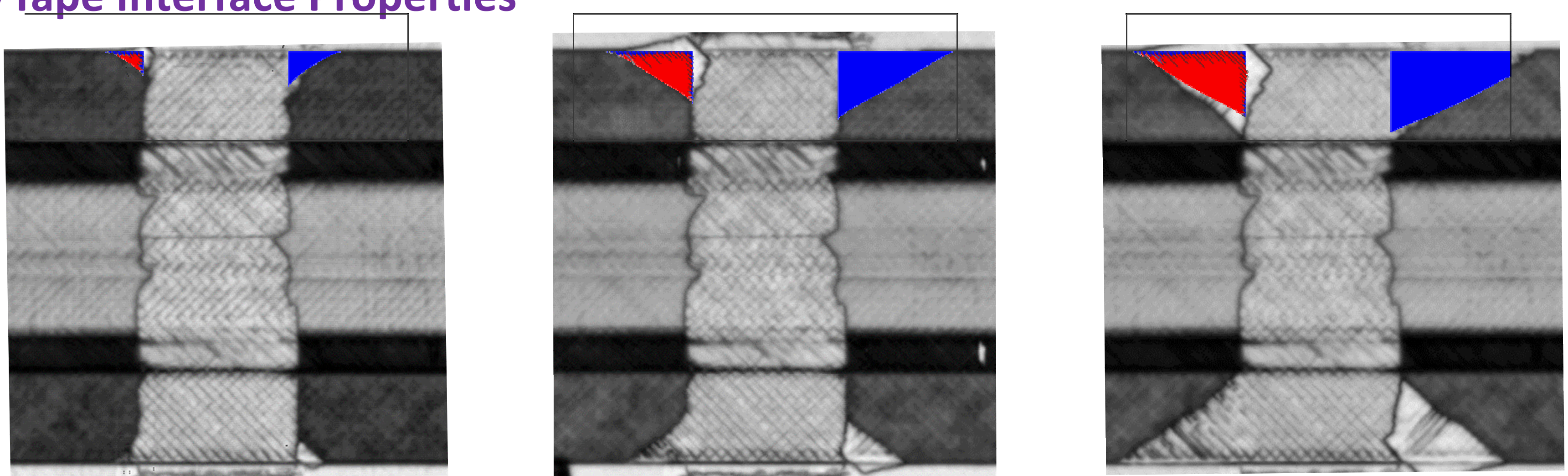


7PB Analyses – CompDam Damage Evolution

Bondline with Fabric/Tape Bridging Law



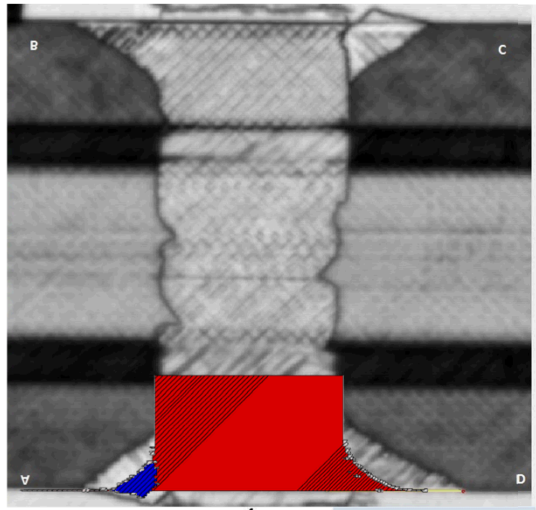
Tape/Tape Interface Properties

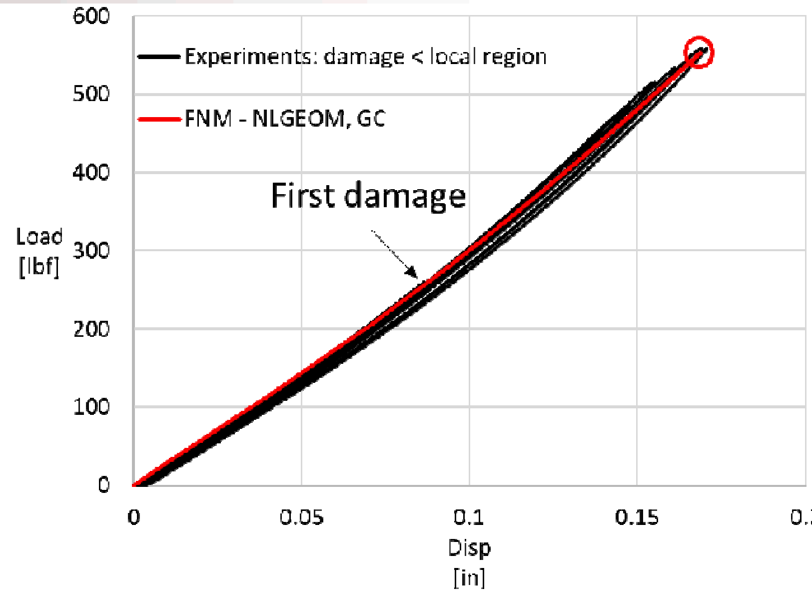


Run 3 (381 lbf) | Run 7 (516 lbf) | Run 12 (598 lbf)

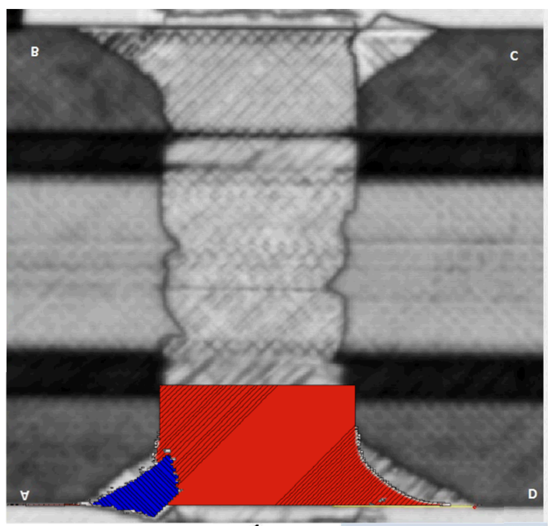
7PB Analyses – FNM Damage Evolution

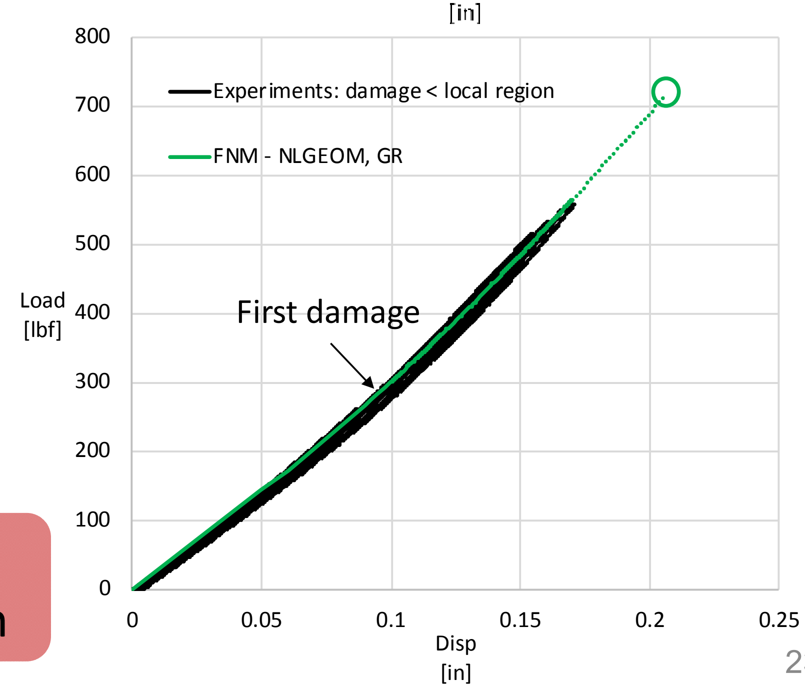
$G_{c\text{-}Tape/Fabric}$





$G_{R\text{-}Tape/Fabric}$



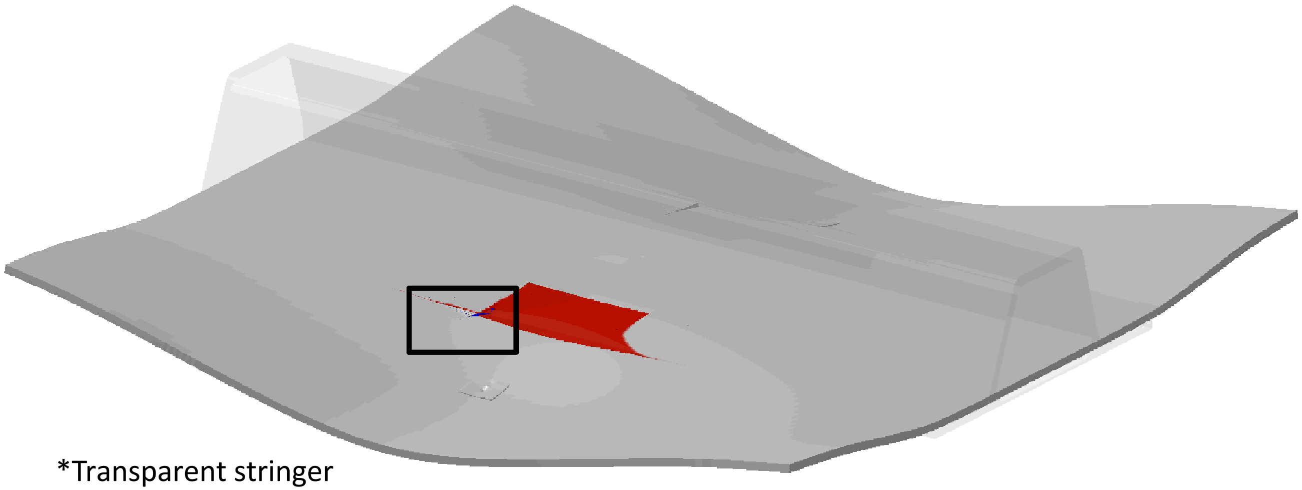


skin/flange

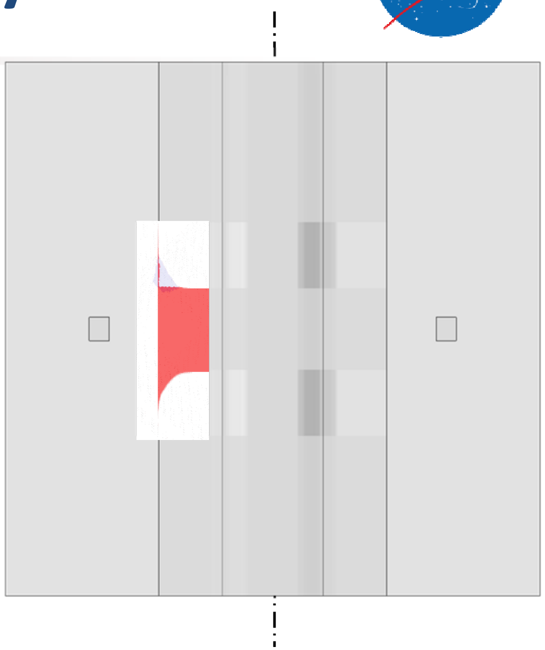
skin (1 layer down)

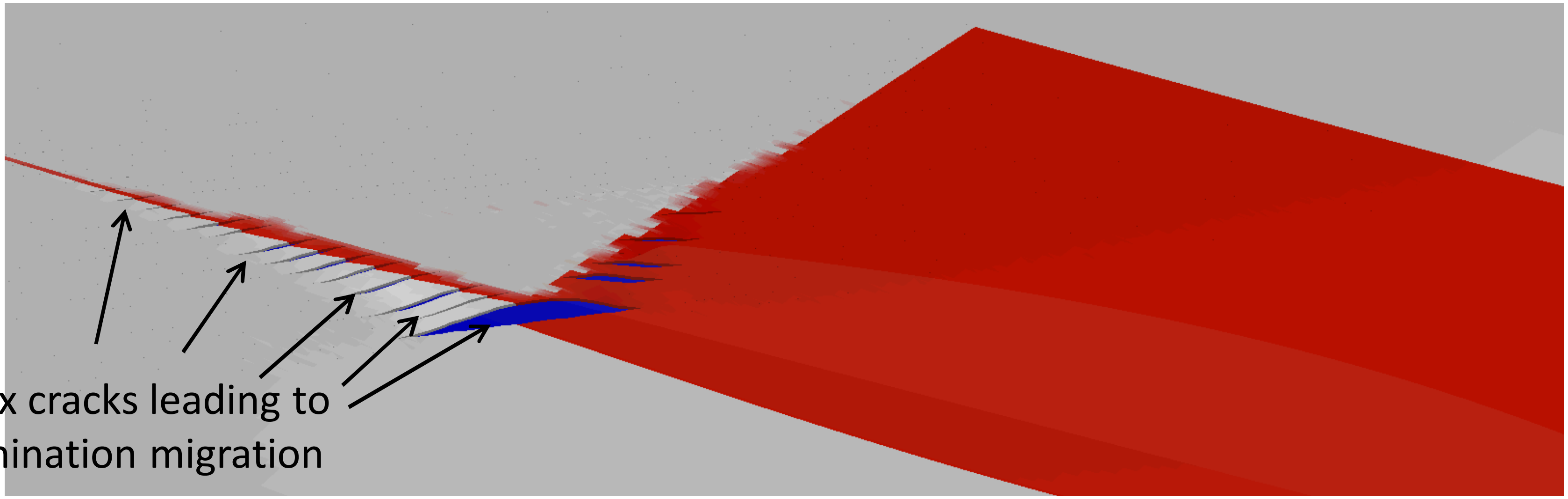
- Correct morphology
- Slower simulated growth

7PB Analyses – FNM Damage Morphology



*Transparent stringer



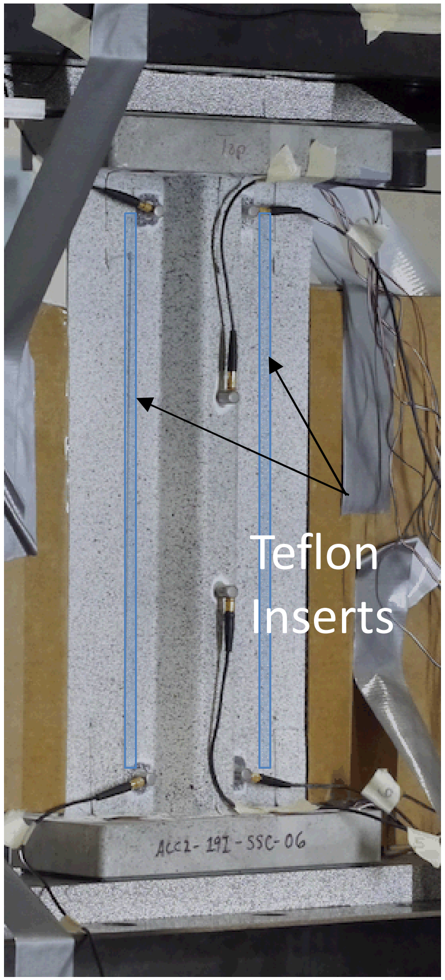


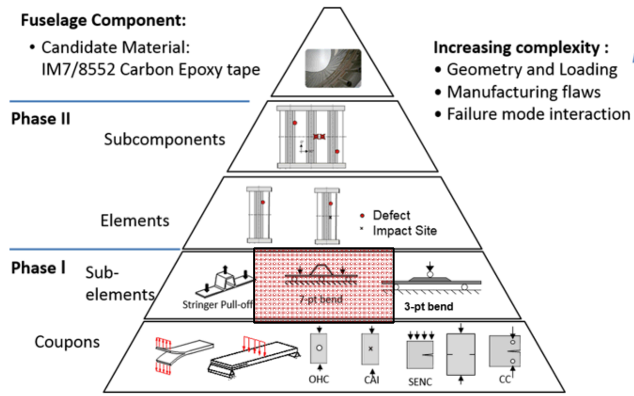
delamination between skin/flange

delamination within the skin (1 layer down)

Single Stringer Compression (SSC) Validation Study

Objective: *Measure and characterize matrix crack and delamination growth and interactions near a flange termination in a post-buckled stiffened panel*

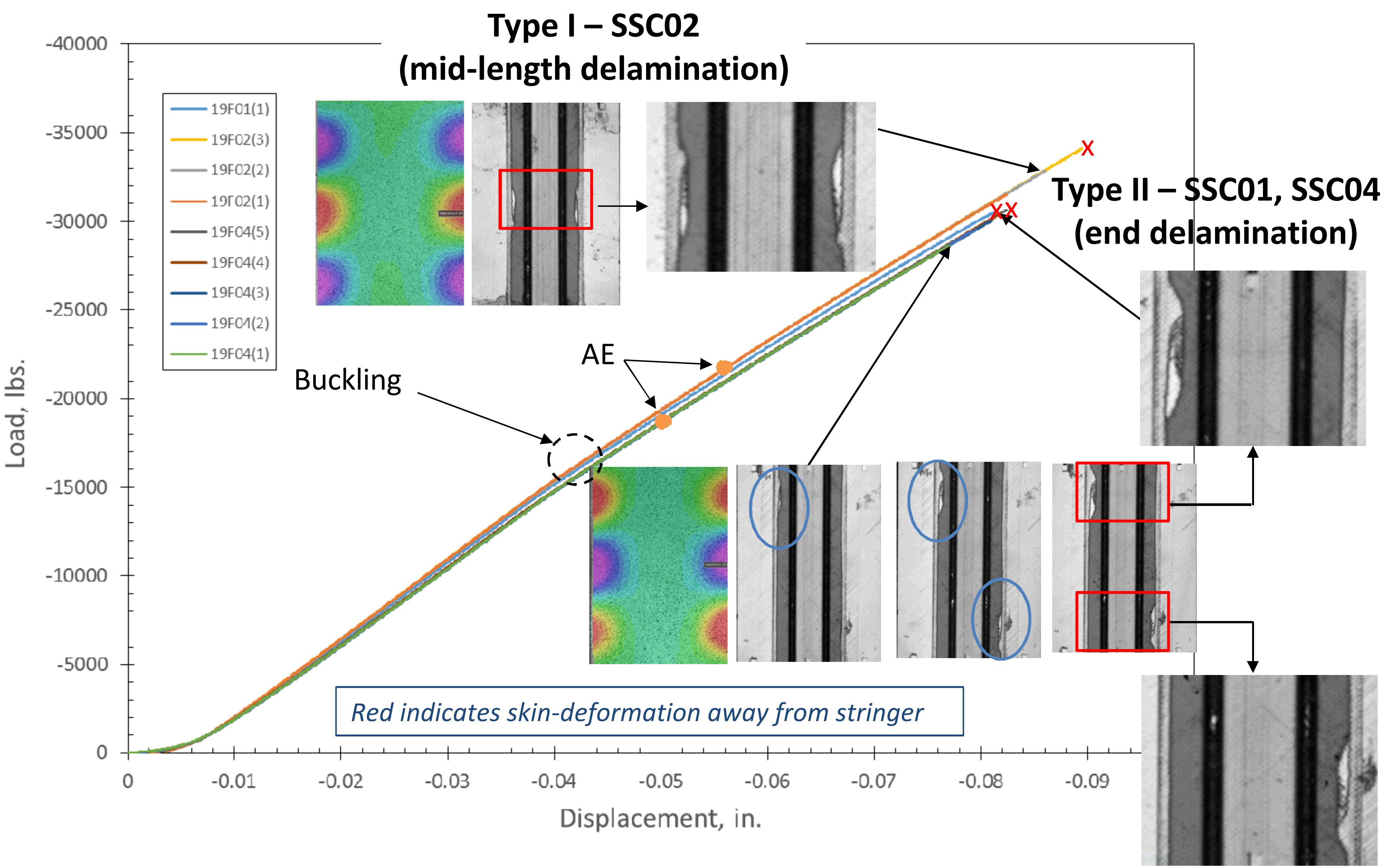




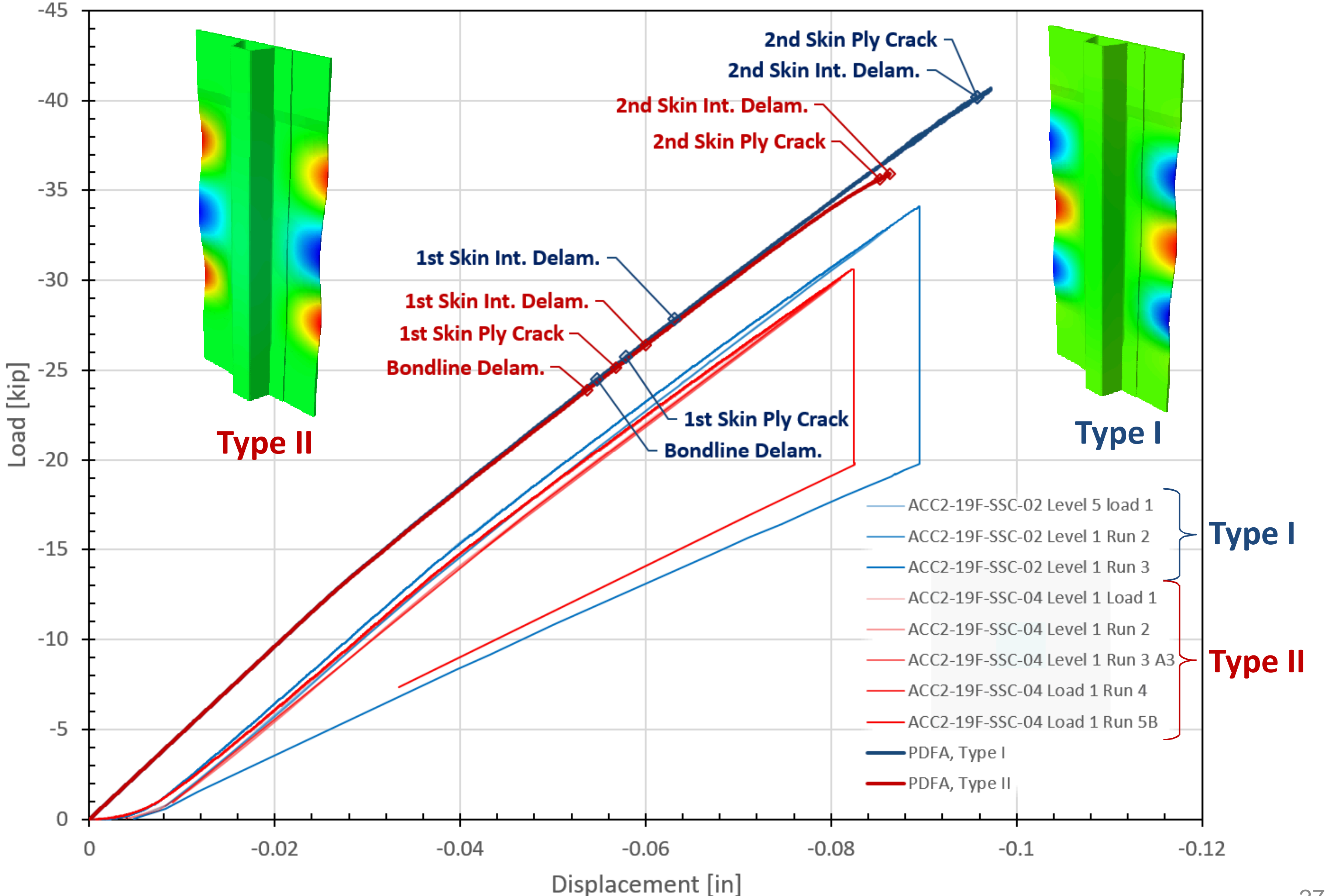
Challenges for modeling damage:

- Material properties
- Post-buckled deformation
  - Finite deformations may require consideration of geometric nonlinearity
  - In stiffened compression tests, buckling mode depends on:
    - Residual thermal deformations
    - Geometric imperfections
    - Experimental test conditions
- Computational efficiency

SSC Load/Displacement History with UT Scans



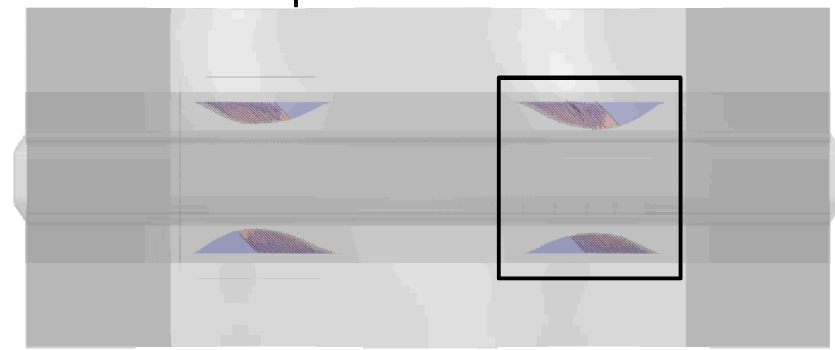
SSC Analyses – CompDam Load/Displacement



SSC Analyses – CompDam Damage Evolution, Type II

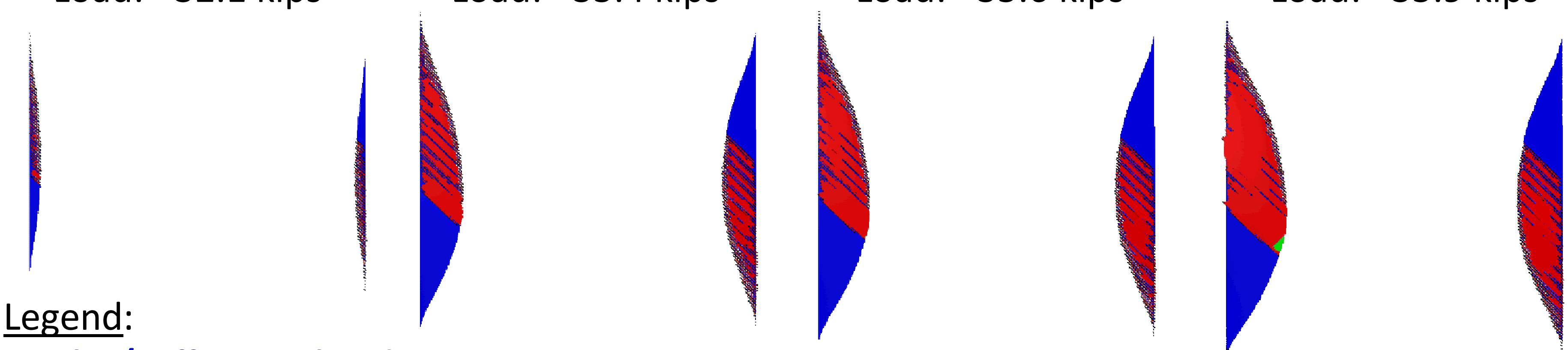
Initiates where Skin Buckles Away from Hat
Load: −23.9 kips

Final Damage State
Load: −35.9 kips



Damage Close-up Views:

Load: −32.1 kips   Load: −35.4 kips   Load: −35.6 kips   Load: −35.9 kips



Legend:
- Skin/Stiffener Debond
- 1st Skin Interface Delamination
- 2nd Skin Interface Delamination

(Viewed from skin-side)

Rapid damage growth

Summary

- **Verification:**
  - Multiple verification benchmark problems/solutions developed and executed
  - Codes are working as they should be
  - Modeling best practices established
- **Sub-element Validation:**
  - Validation articles provide baseline of damage modes of importance in larger scale structure; confidence to proceed to larger scale validation articles
  - Predicted observed damage modes and sequence of damage events
  - Damage extent and peak loads under- or over-predicted, potentially due to sub-ply damage mechanisms, complex migration
  - Fatigue analysis and test efforts ongoing
- **Element, Sub-Component Validation:**
  - Analysis and test efforts ongoing on single-stringer and multi-stringer validation articles
  - Fatigue test efforts ongoing at all levels

Value Added in Progressive Damage Analysis by ACP

- Improved VCCT module for ABAQUS
  - Variable mode-mixity as delamination grows
  - Order of magnitude reduction in computation
- General V&V framework developed, applicable to other PDA methods
  - Multiple benchmark verification problems/solutions
  - Building block validation test matrices and metrics for focus problems
  - High-fidelity test data generated for model validation
- New characterization tests and materials property database for more representative analysis input
- PDA codes evaluated at multiple levels of V&V building block
  - Developments include matrix shear nonlinearity, fiber compression damage model, stochastic intralaminar strength (decrease in small crack error from up to ~90% to ~15%)
  - Complex damage processes of interacting matrix cracks and delaminations captured
  - Modeling and analysis best practices established
  - Limitations in predictive capability identified; future developments identified