

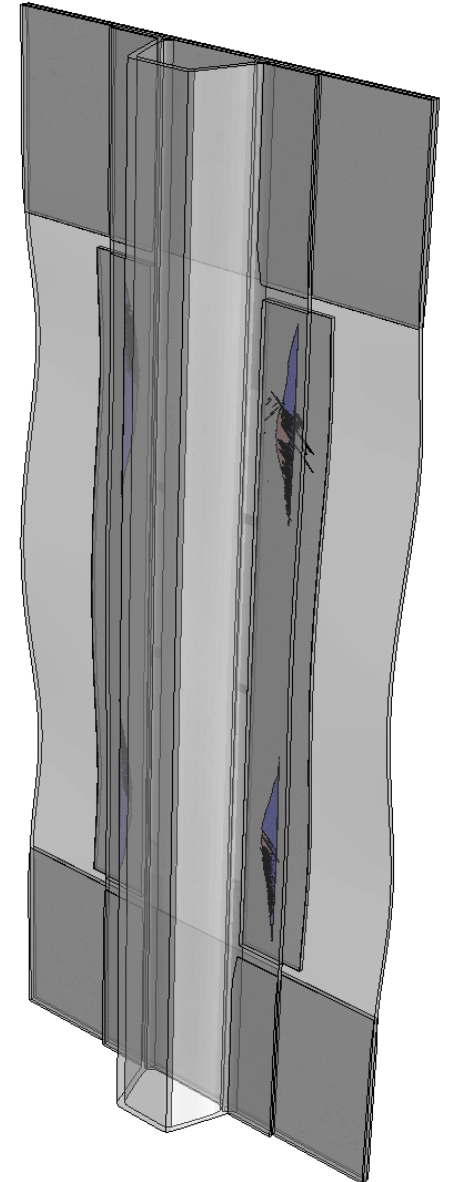
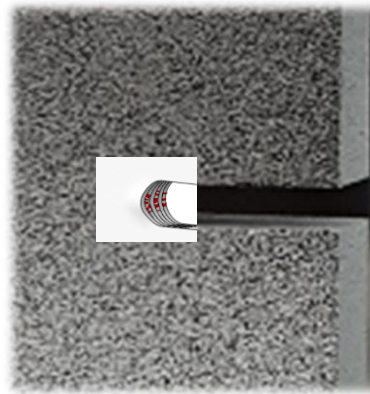
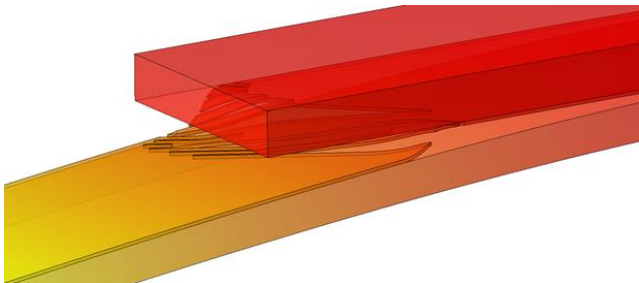
Establishing Predictive Capability for Progressive Damage and Failure in Composite Structures: *A Perspective on Virtual Testing*

Andrew Bergan

Durability, Damage Tolerance and Reliability Branch
NASA Langley Research Center

May 20, 2018

IMDEA Materials Institute





- About NASA
- Composites manufacturing and test labs at LaRC
- Advanced Composites Project (ACP)
- Three steps toward predictive capability
 - Material science
 - Verification
 - Validation
- Practical challenges in virtual testing
- Concluding remarks

NASA Missions



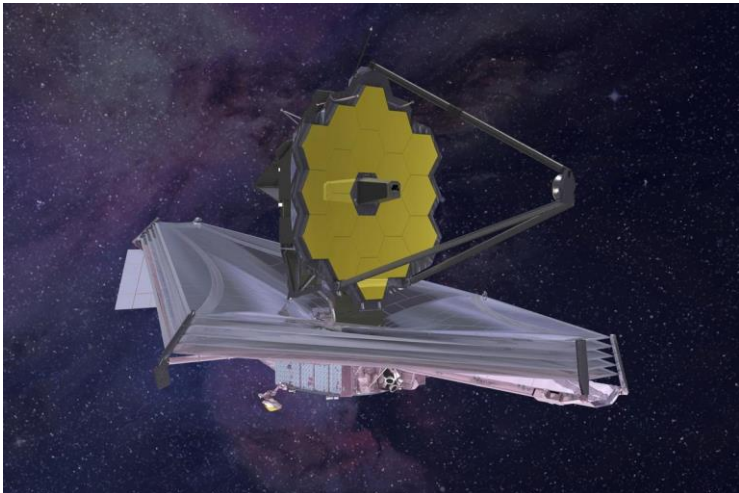
Aeronautics Research



Space Technology



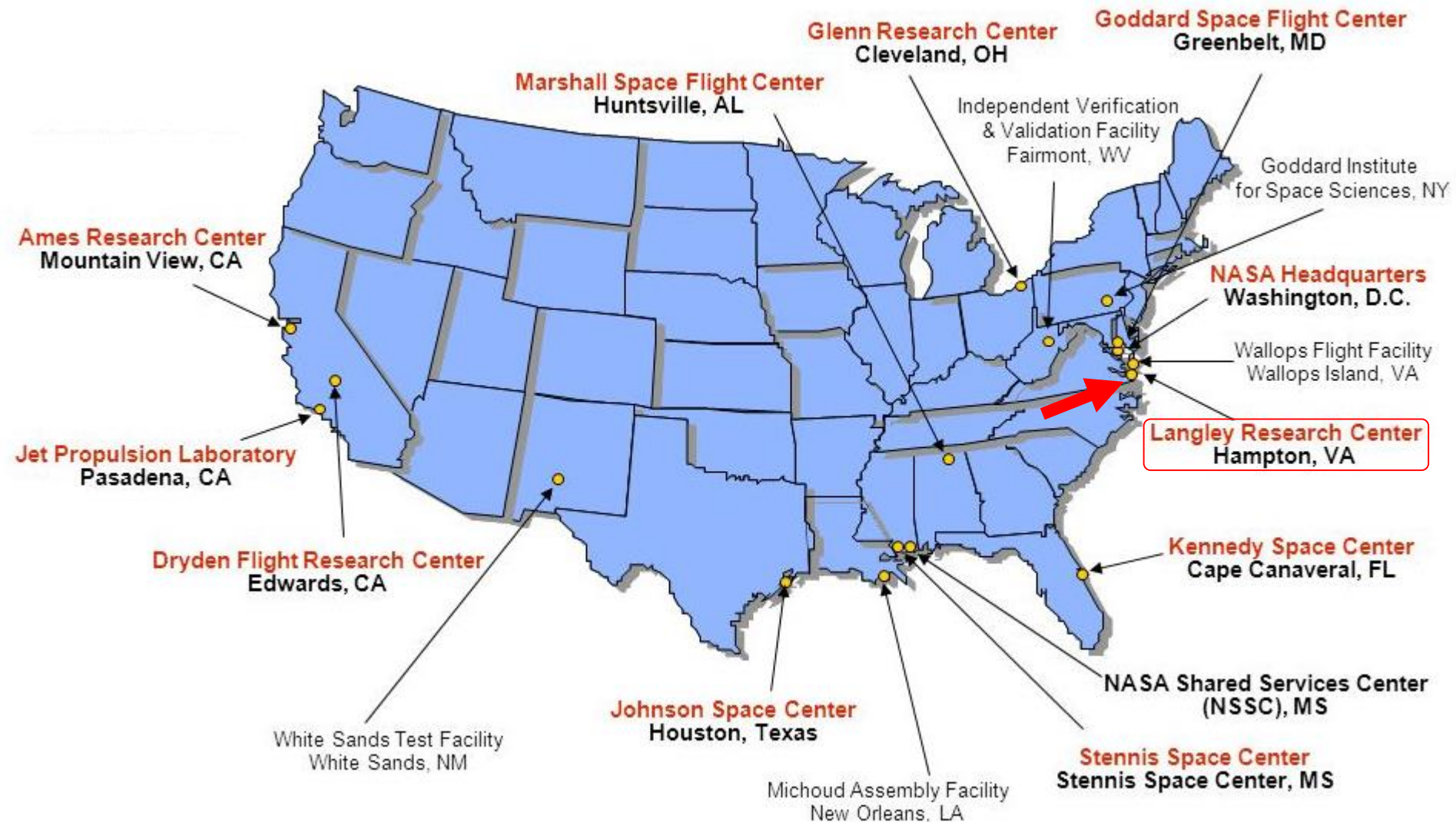
Science



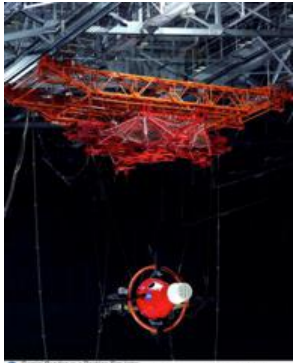
Human Exploration and Operations



NASA Centers



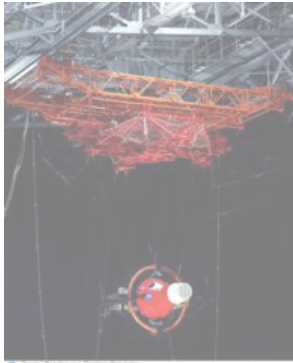
NASA Langley Research Center



Orion Transonic Landing Simulator
NASA Langley Research Center
5/1/1984 Image # EL-1999-00088



NASA Langley Research Center



Space Shuttle Landing Simulator
NASA Langley Research Center
5/1/1984 Image # EL 1989-00088



Core Competencies

Aerosciences
Research



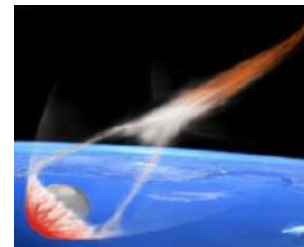
Characterization
of Atmospheres



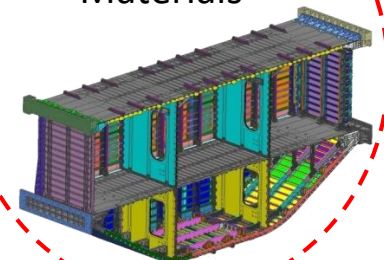
Aerospace
Systems



Entry, Descent,
& Landing



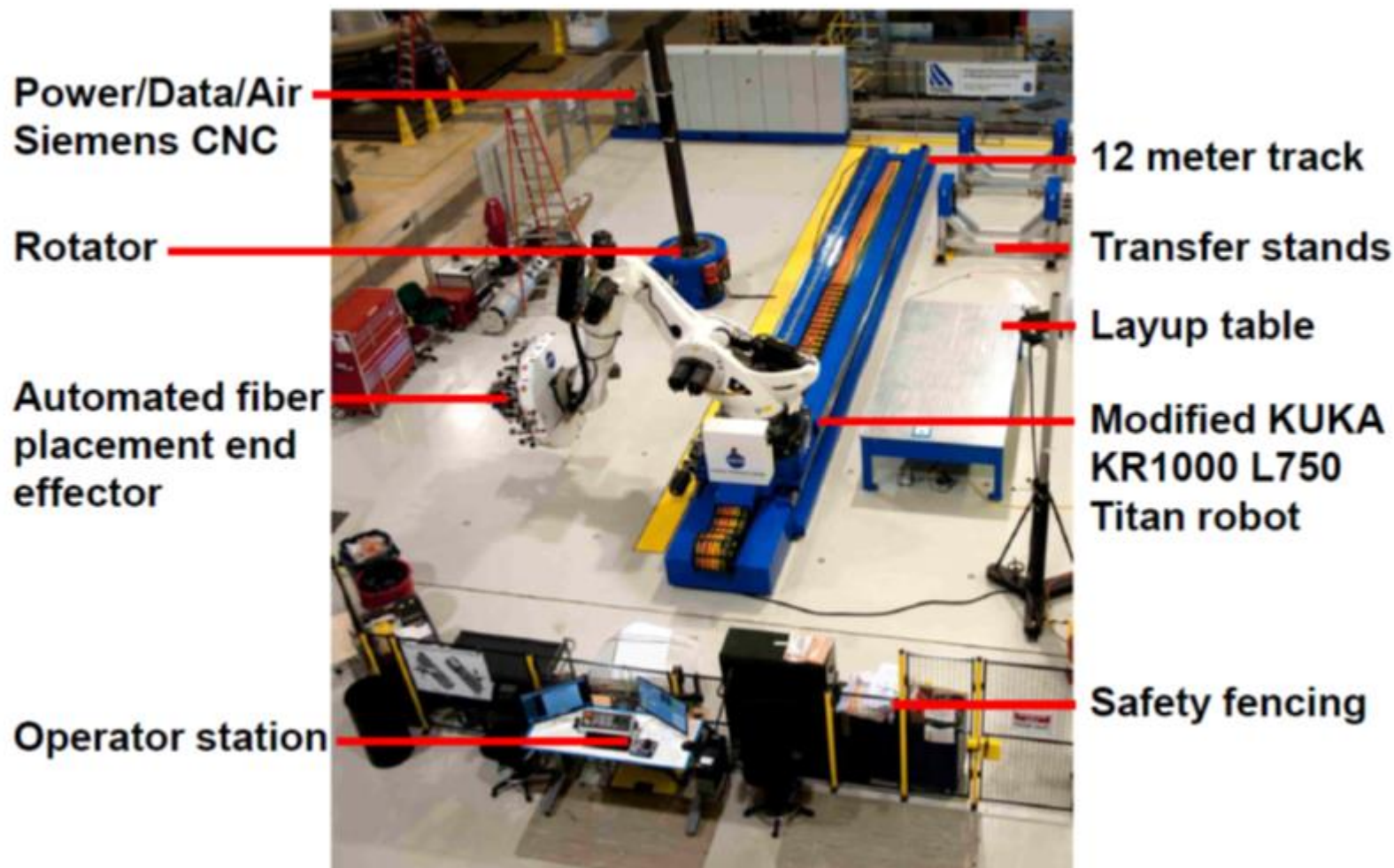
Structures and
Materials





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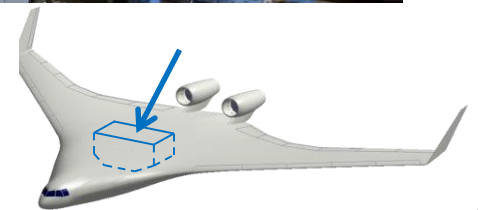
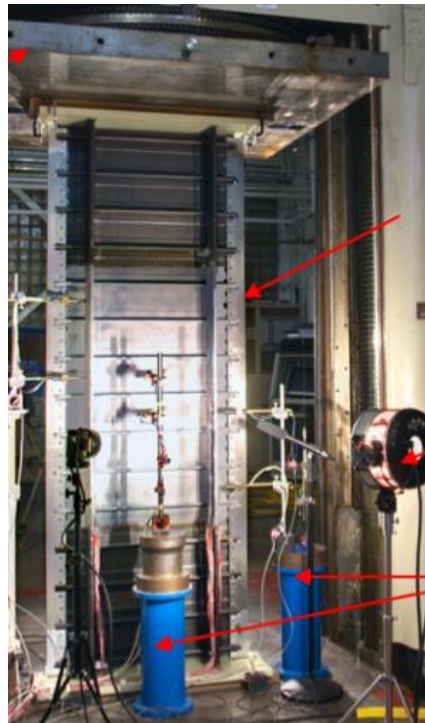
Integrated Structural Assembly of Advanced Composites (ISAAC)



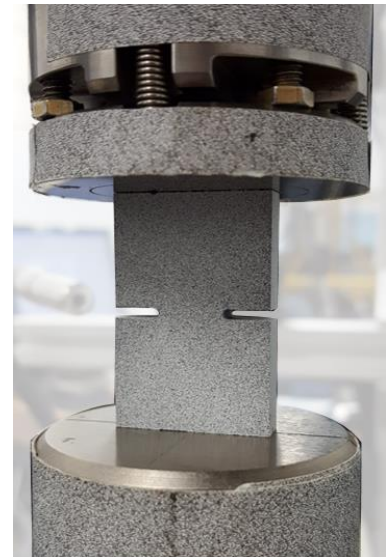
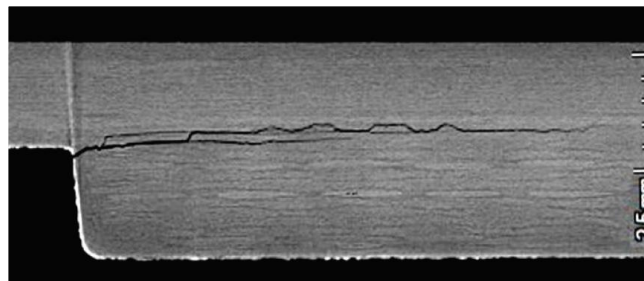
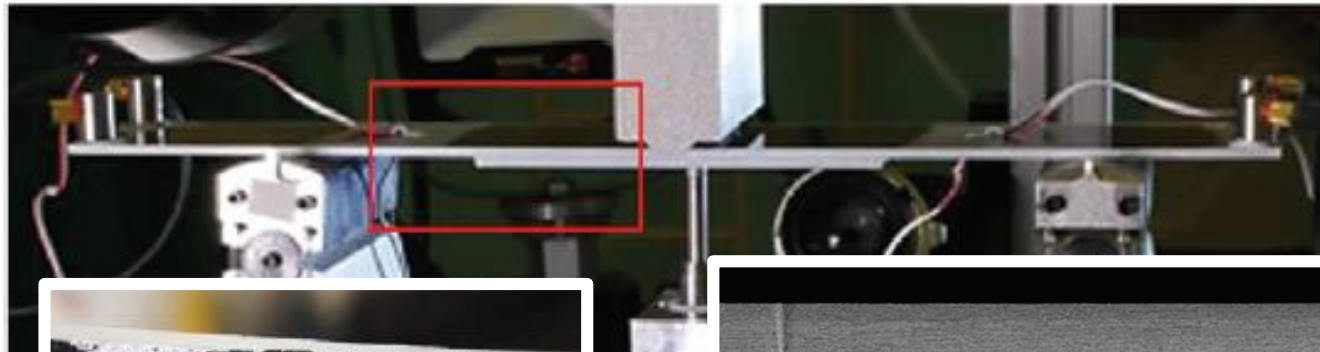
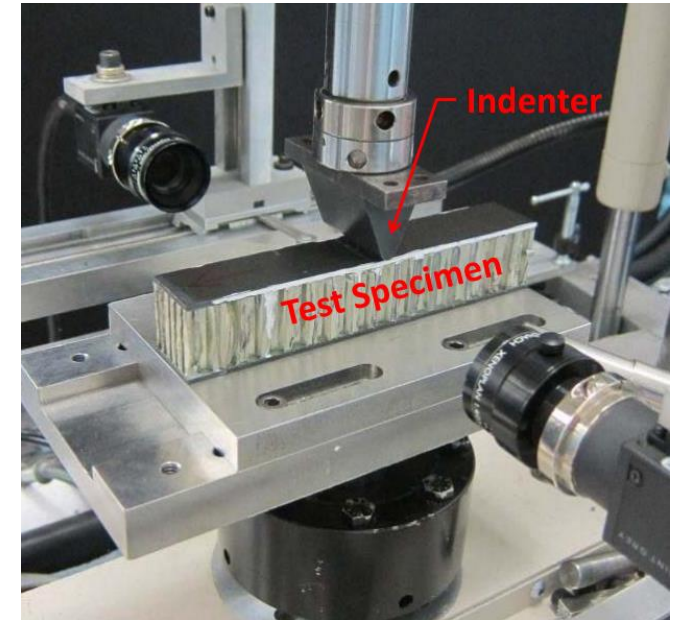
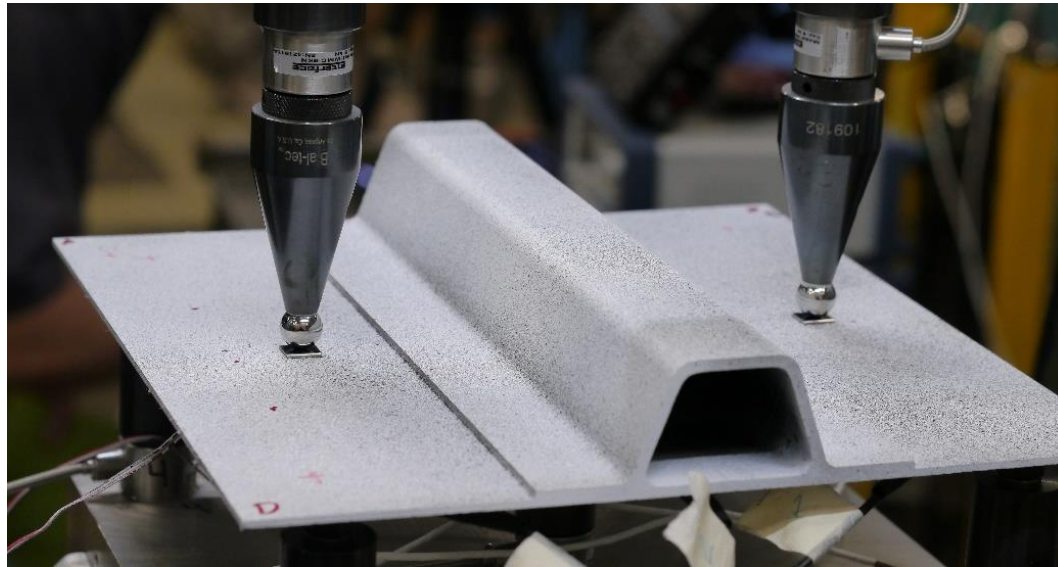
Materials and Structures Research Labs



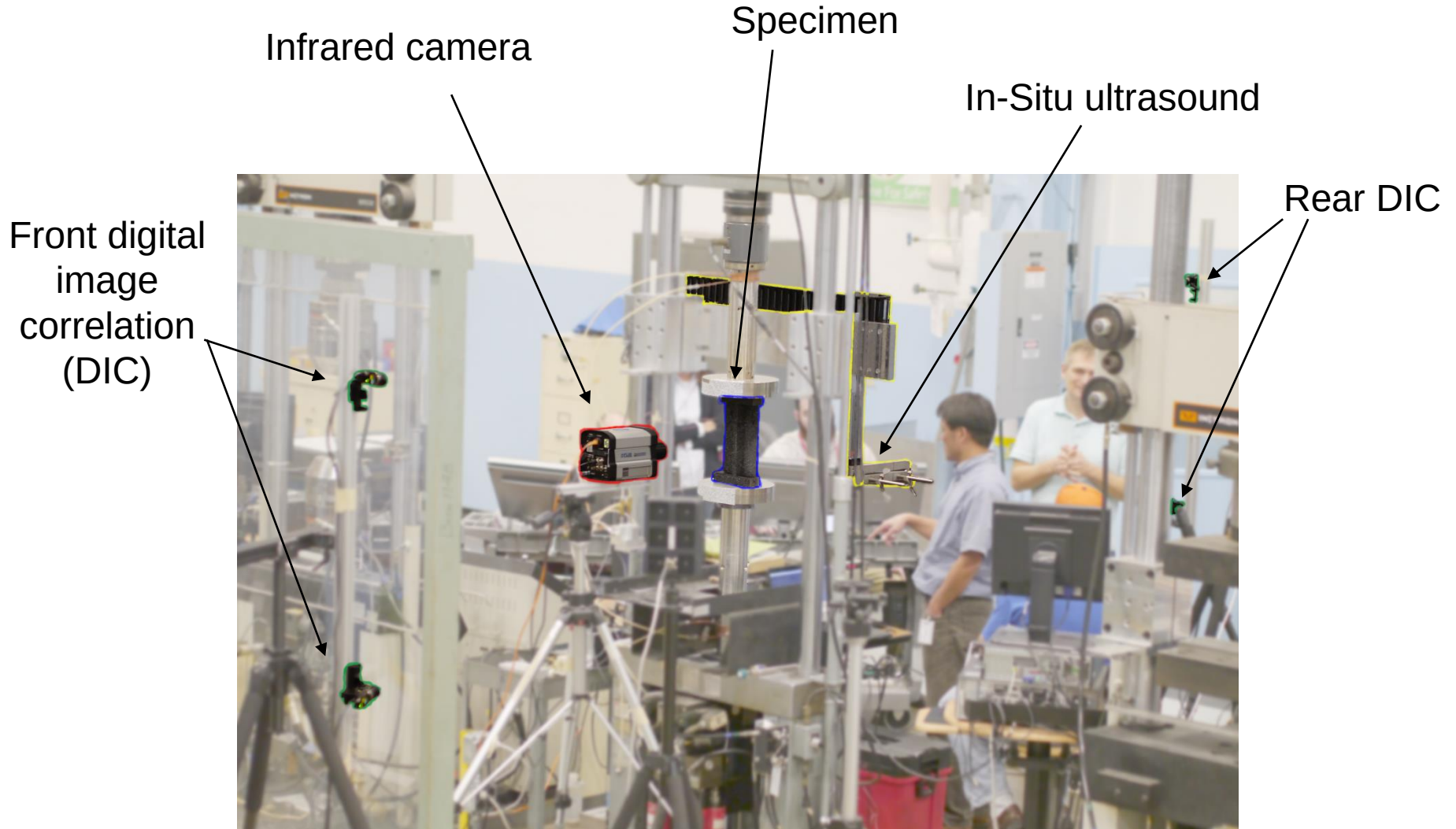
Large-Scale Structural Test Articles



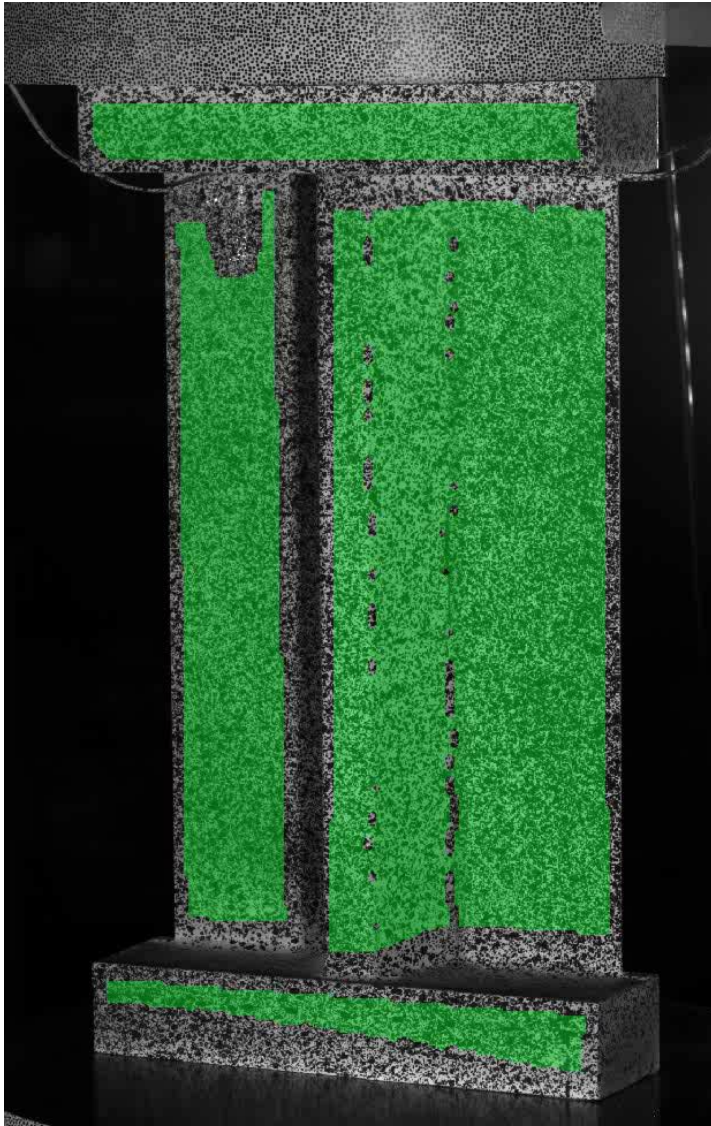
Element Scale Structural Test Articles



A Highly Instrumented Structural Test



Example Test Result



Dávila and Bisagni 2017



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Advanced Composites Project: Overview



Motivation: Growing use of composites



Boeing 787



Lockheed Martin F-35

- **Benefits of composites:** lightweight, durable, low cost
- **Challenges:** Immature capabilities limit use and rate of innovation

Challenges with Composites

- Complexity: parameters; failure modes; variability
- Strength and life cannot be predicted reliably
- Empirical and iterative 'trial and error' methods
- NDE is painfully manual (human factors); expensive
- Redesigns and reworks: largest single factor in development time
- Simulation tools: Long lag for confidence

Team: Advanced Composites Consortium



Focus Areas

1. Accurate strength & life prediction
 - Reduce design and testing effort / time
 - Robust high-fidelity analysis for damage
 - Better preliminary design, fewer redesigns
2. Rapid inspection and characterization
3. Efficient manufacturing process development

Charter: Reduce the time to develop and certify composite materials and structures

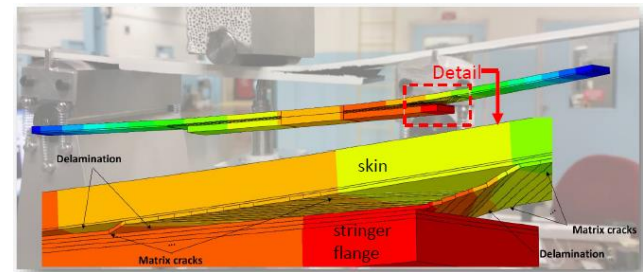
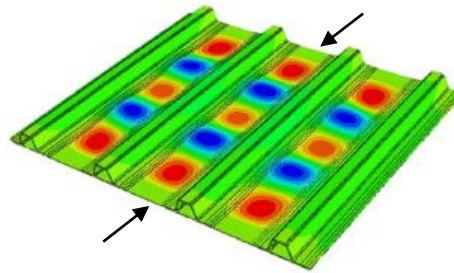
Accurate Strength and Life Prediction Task



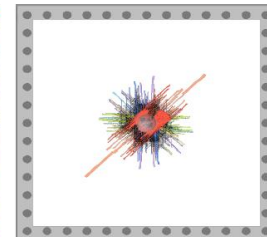
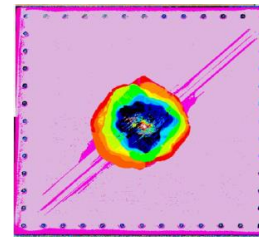
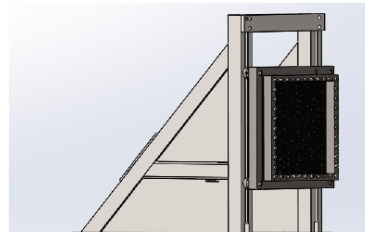
Technical Challenge Statement:

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



High Energy Dynamic Impact (HEDI)

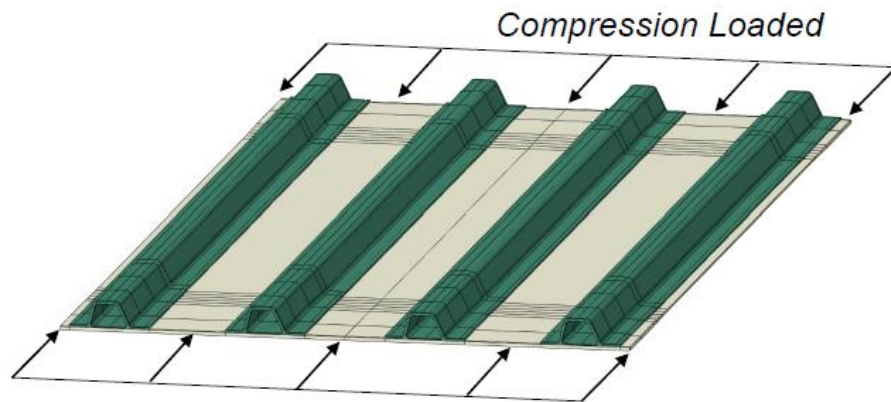


Rapid design tools

Postbuckled Panel: Strength & Life Prediction



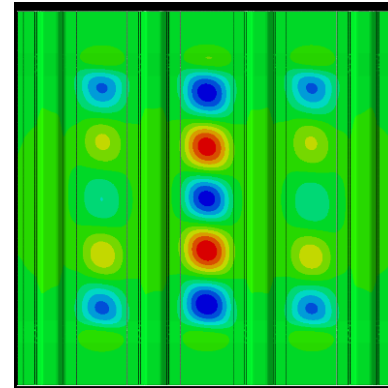
Problem statement: Designing a skin stiffened panel to post-buckle is expensive since numerous panel level tests are required (no predictive analysis capability)



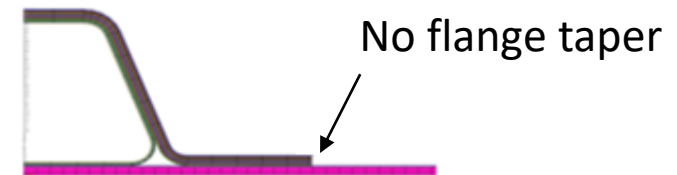
Stiffened panel failure modes (compression):

- Skin/stiffener disbonding
- Stiffener crippling

Carefully designed validation test article



- Design drives buckling & delamination to center
- All specimens included impact damage or Teflon inserts to localize damage

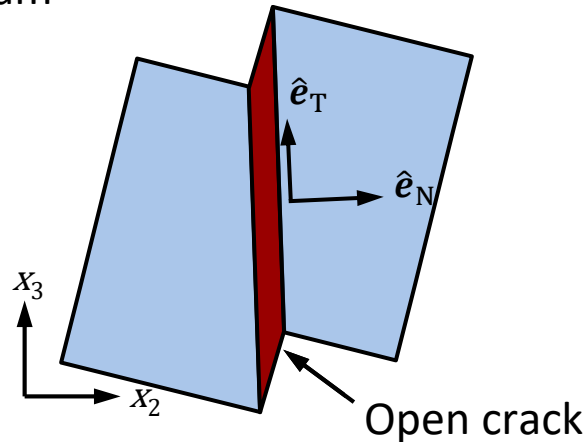


Validation test article
designed to **isolate**
skin/stiffener failure mode

Progressive Damage Codes



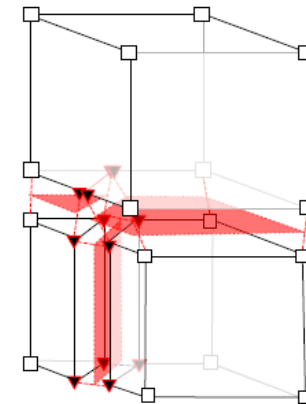
CompDam



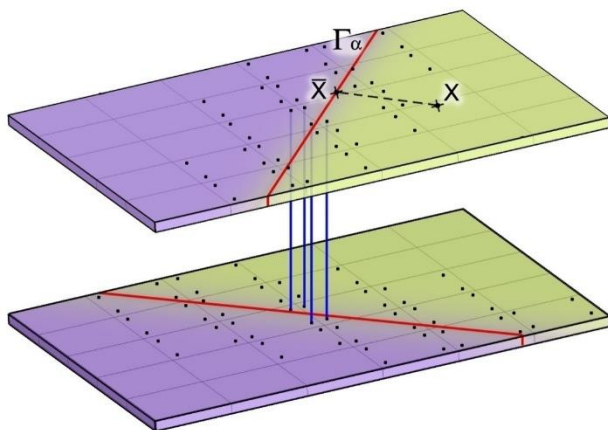
https://github.com/nasa/CompDam_DGD

Floating Node Method (FNM)

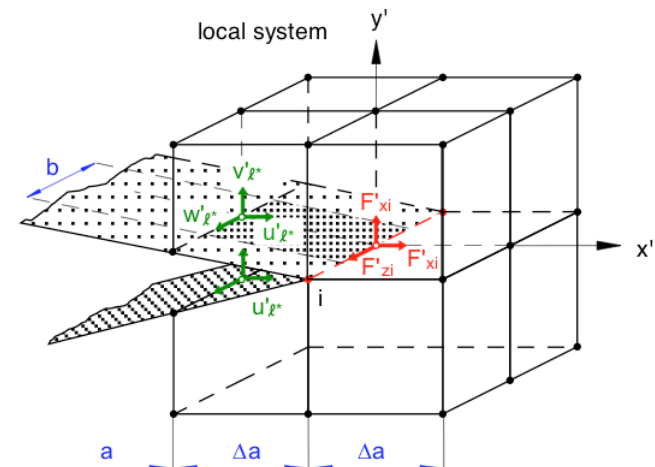
▲ Floating node
□ Real node



Regularized XFEM (RXFEM)



Virtual Crack Closure Technique (VCCT)



Establishing Predictive Capability Through Verification and Validation (V&V)



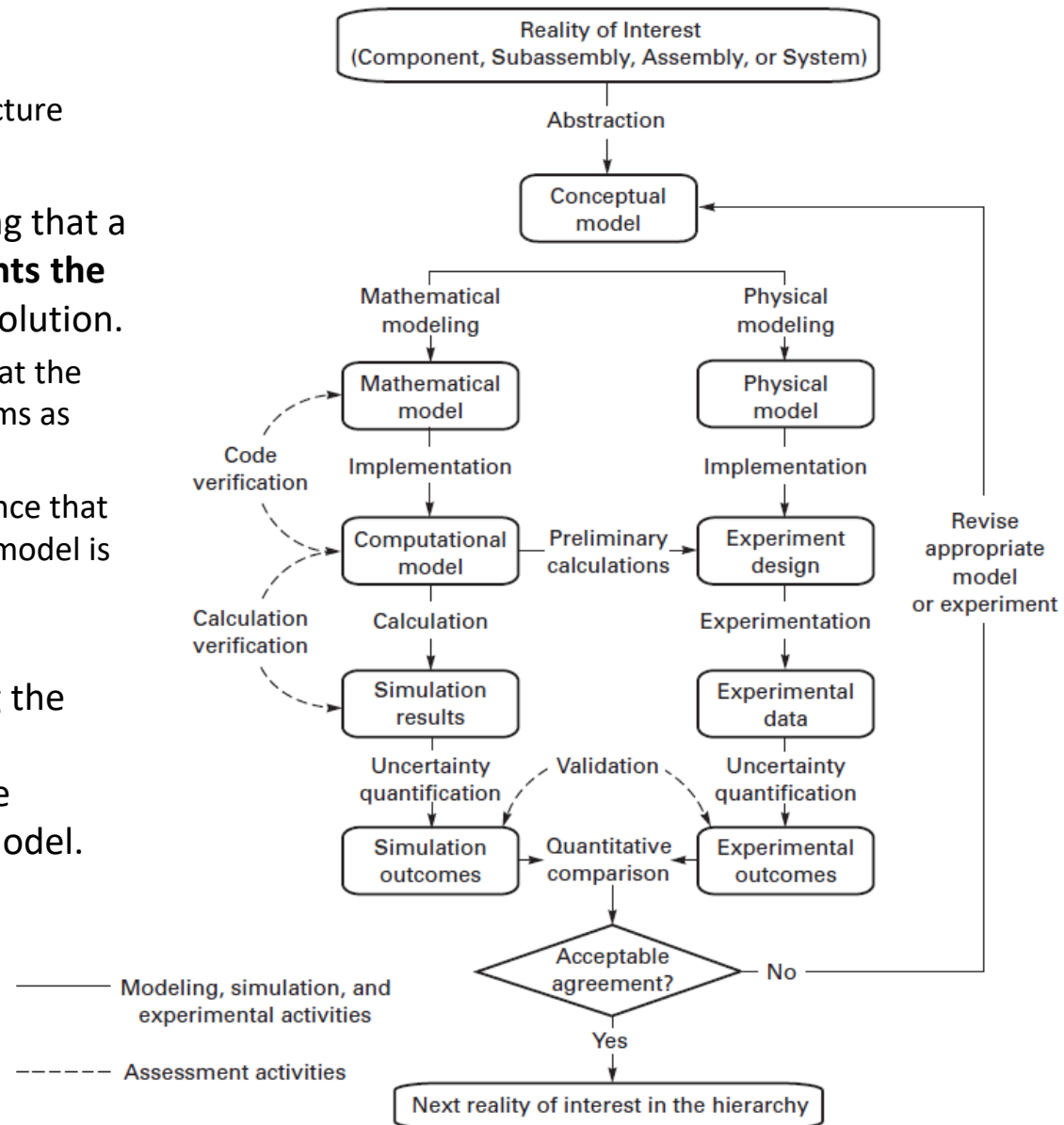
1. Material Science vs. Material Model

- Skin/Stiffener separation: mixed mode fracture

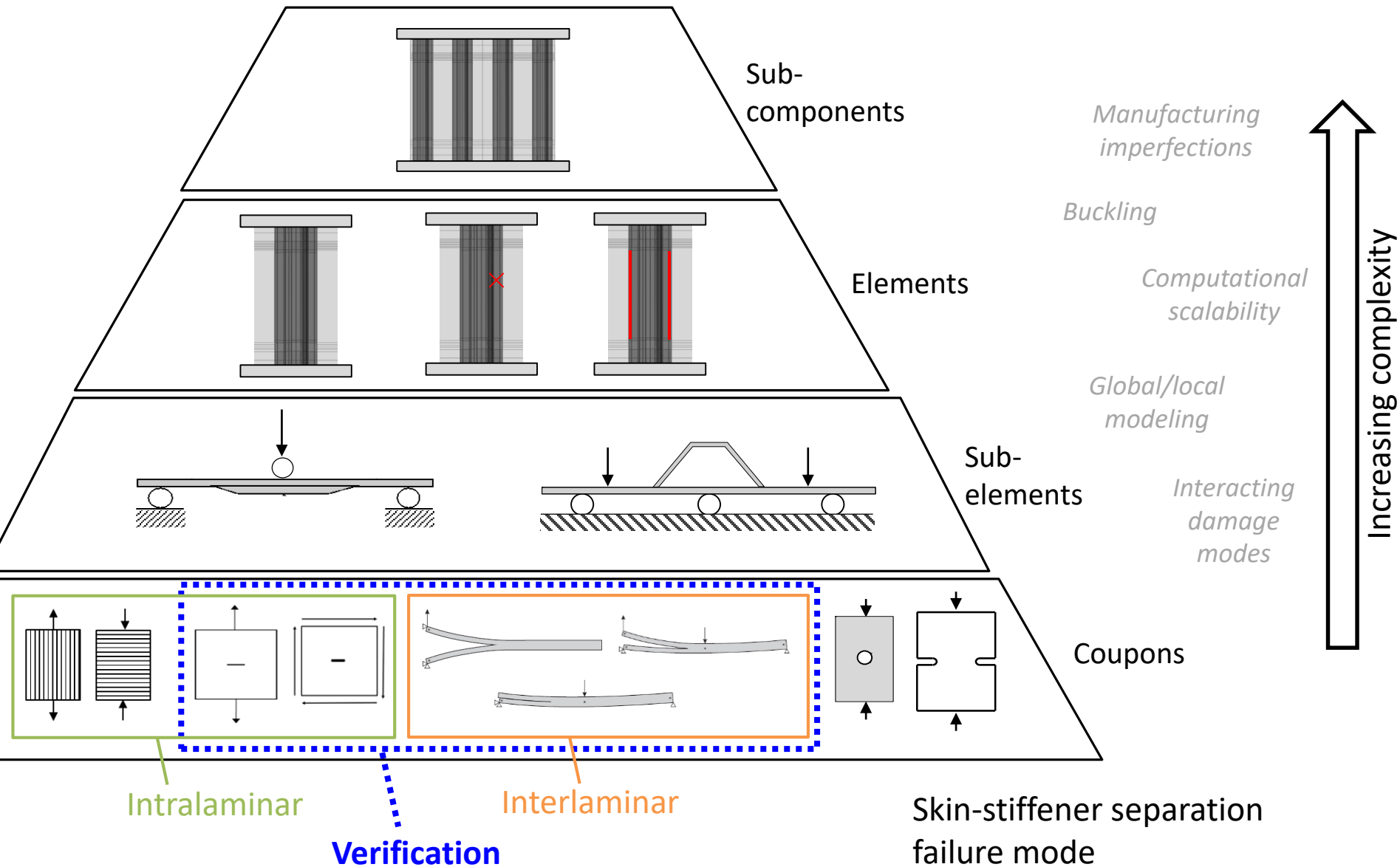
2. Verification: The process of determining that a computational model **accurately represents the underlying mathematical model** and its solution.

- *Code Verification* – establish confidence that the mathematical model and solution algorithms as implemented are working correctly.
- *Calculation Verification* - establish confidence that the discrete solution of the mathematical model is accurate.

3. Validation: The process of determining the degree to which a model is an **accurate representation of the real world** from the perspective of the intended uses of the model.



Building Block Approach for V&V Postbuckled Stiffened Panel





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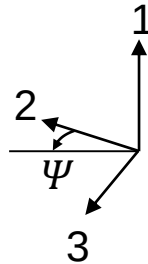
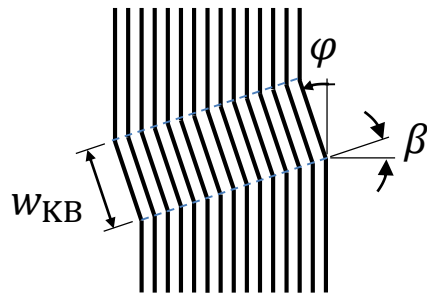
Introduction: Longitudinal Compression Damage



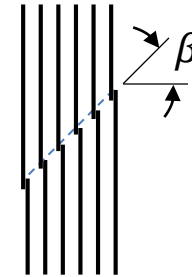
- Damage mechanisms of interest:

1. Fiber kinking

(kink band, plastic microbuckling)



2. Shear driven fiber failure



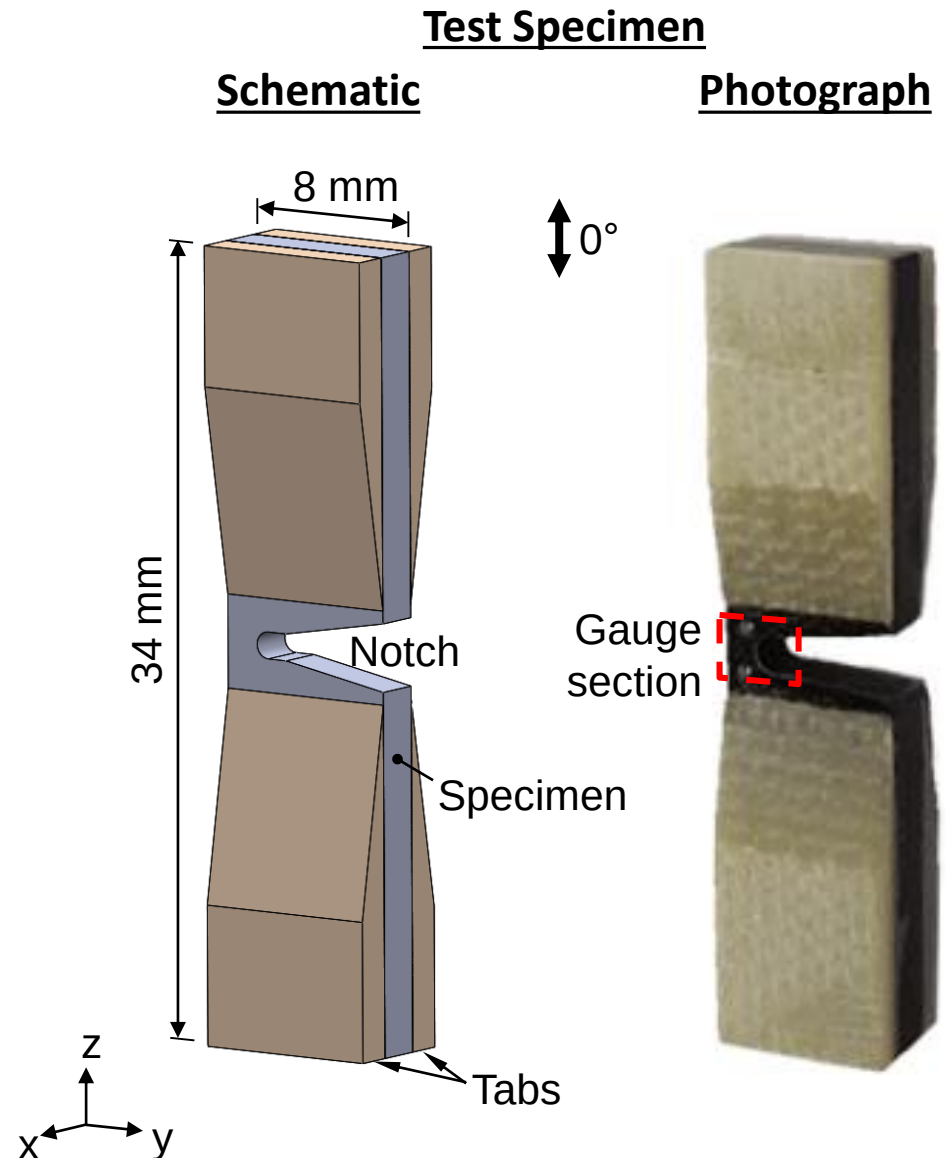
- Limited understanding of the physics governing these mechanisms due to:

- Competition of failure modes
- Unstable collapse
- Most investigations have used two dimensional destructive inspections

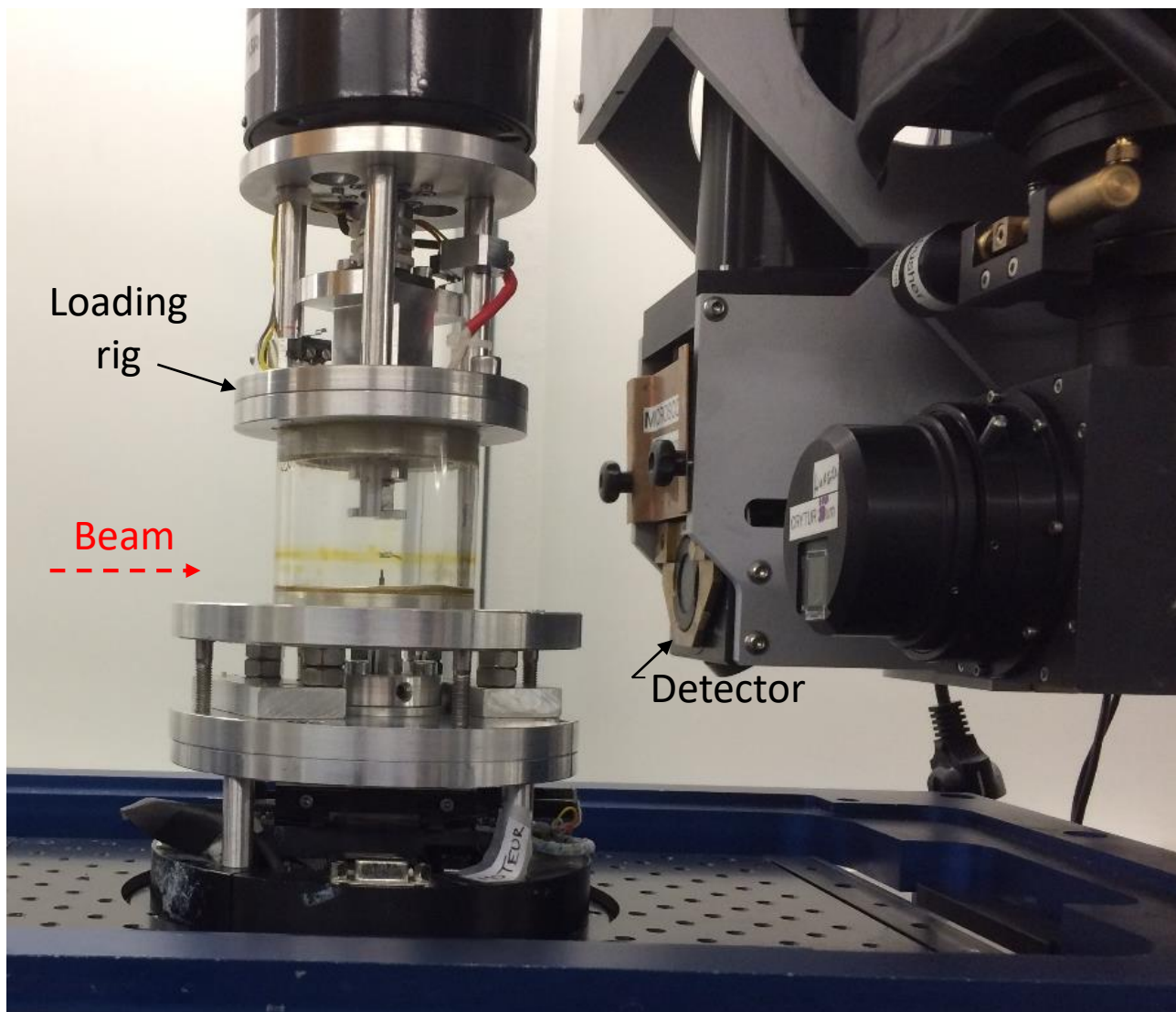
Test Specimen Configuration



- Material: IM7-8552, 190 GSM
- Layup: $[(90/0)_3/90/(0/90)_3]$
- Anti-buckling guides (not shown) and fiberglass tabs used to prevent buckling
- Two replicates tested; presentation focuses on one replicate



Test Setup and Imaging

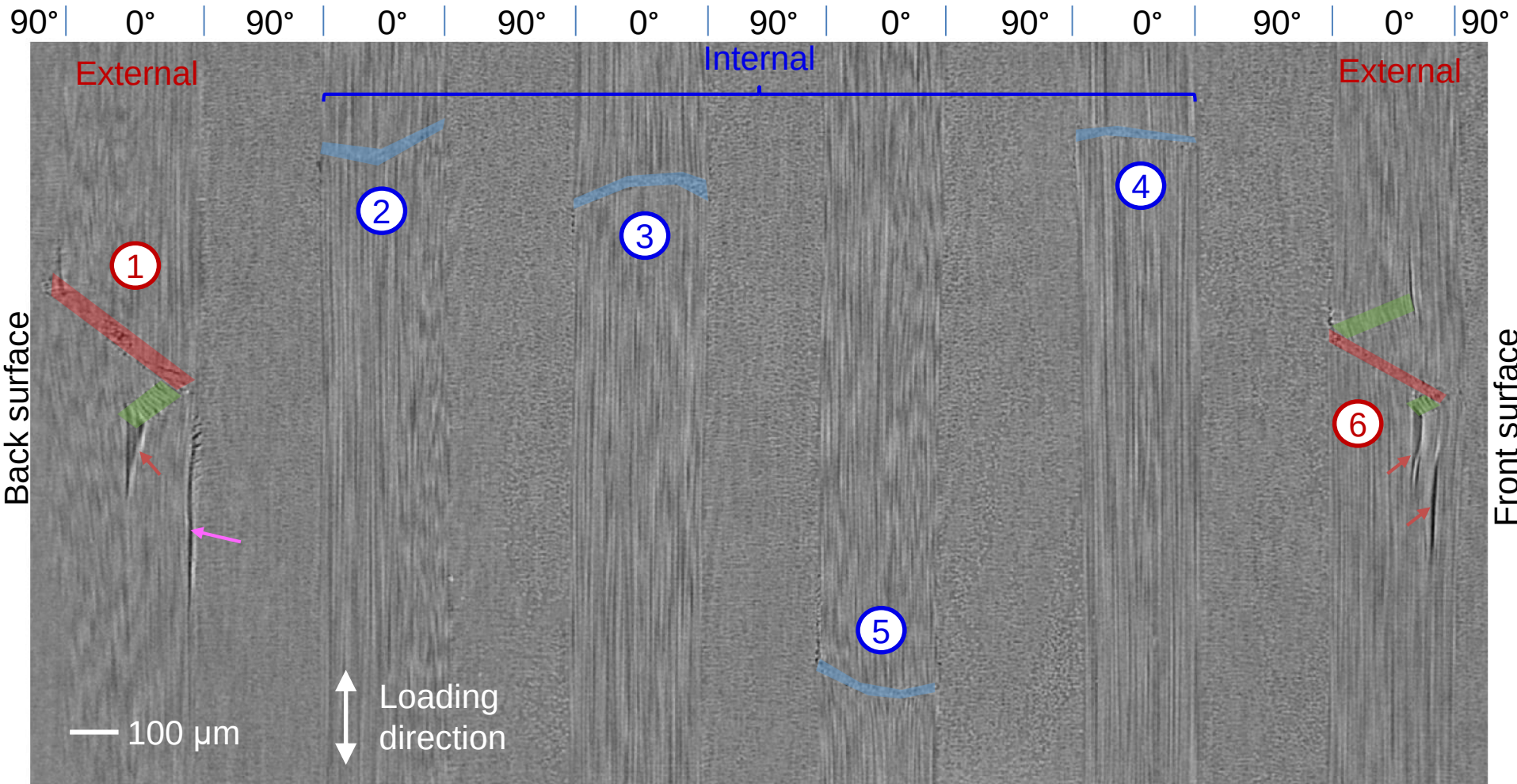


In-Situ Synchrotron Radiation Computed Tomography

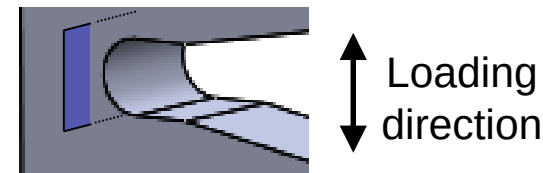
- Temporal resolution: 2.4 s
- Spatial resolution: 1.1 $\mu\text{m}/\text{voxel}$

TOMCAT-X02DA beamline, PSI, Villigen, Switzerland

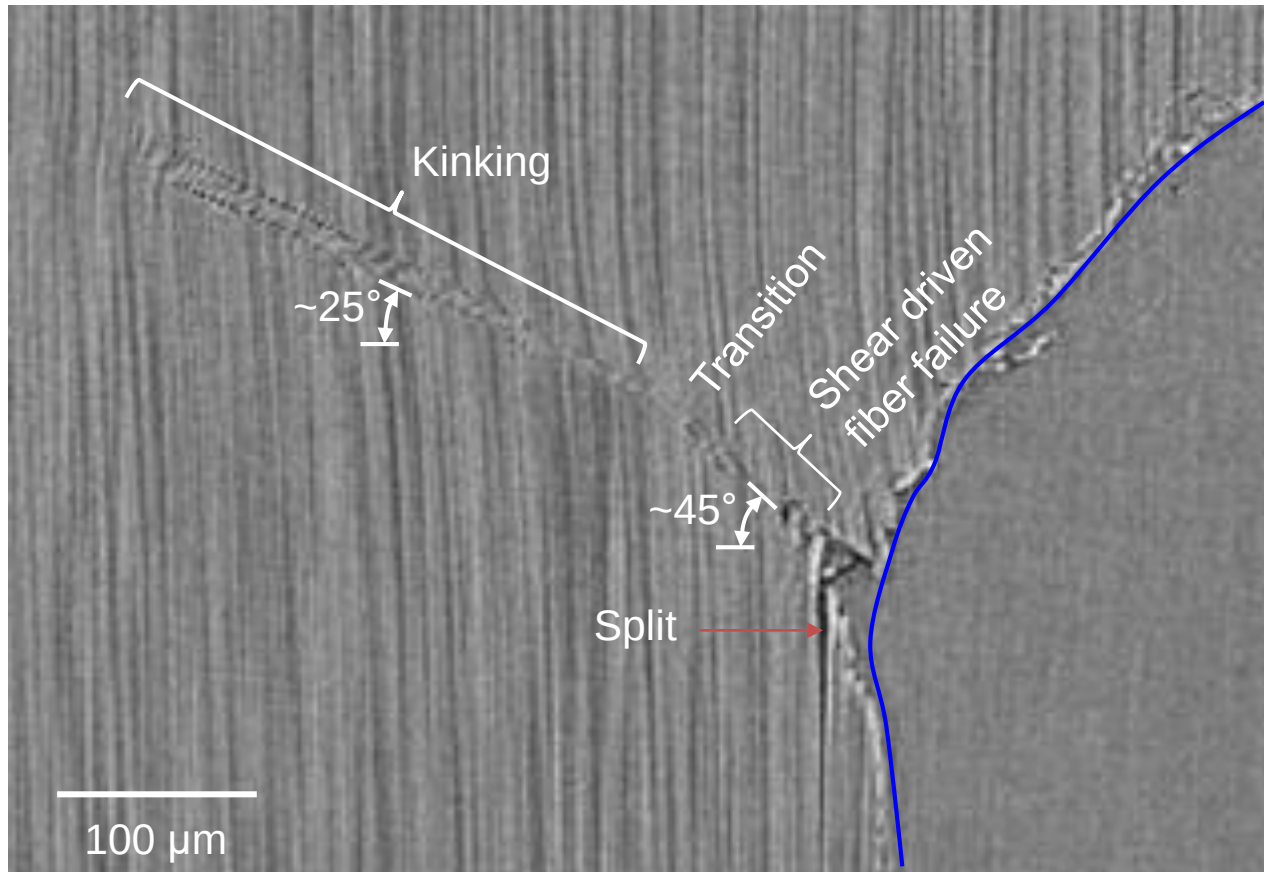
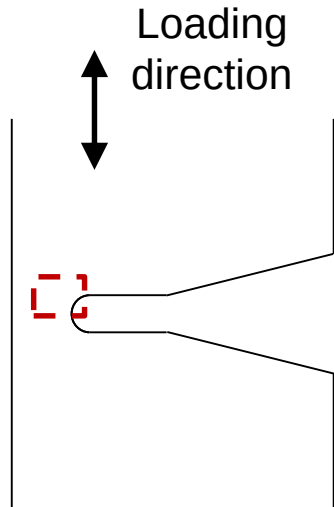
Sequence of 0° ply failures



- Image shows damage just before collapse
- Kink bands initiated from back to front through-thickness
- Exterior most 0° plies kinked **out-of-plane**; interior kinked **in-plane**
- Out-of-plane kinks are accompanied by **larger** delaminations and splits than in-plane kinks

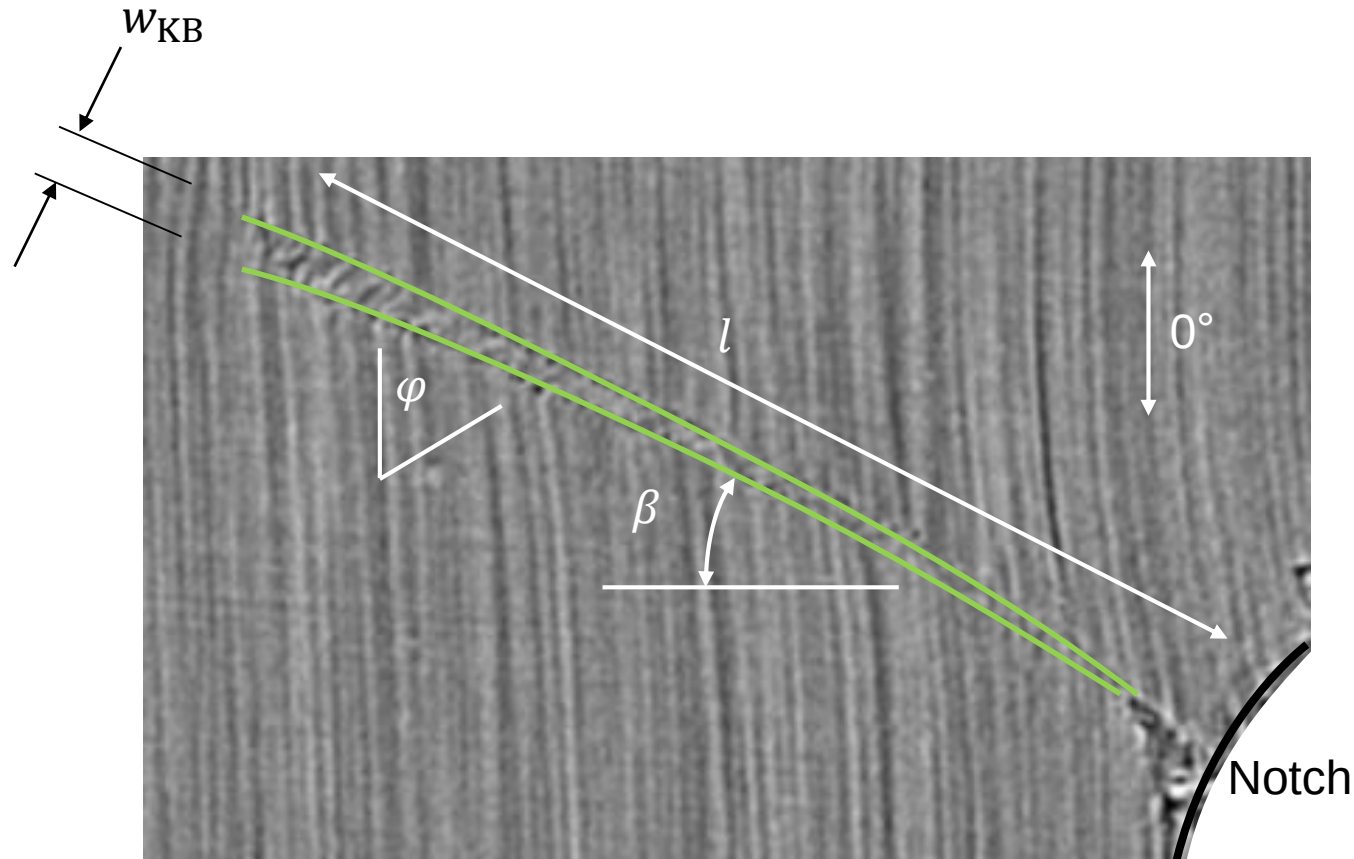


In-Plane Kink Band



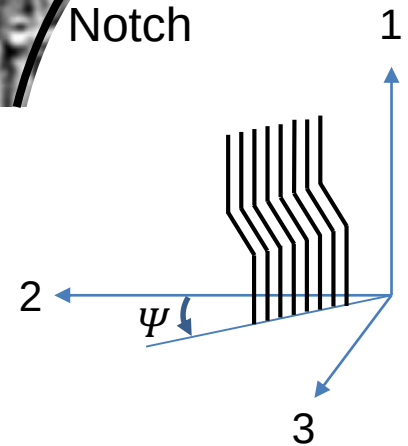
- Image captured after load drop but before final propagation and collapse (~ 940 N)
- In-plane kink bands all show evidence of shear driven fiber failure at the notch tip
- Kink band widths are ~ 3 -5 fiber diameters

Segmentation Overview

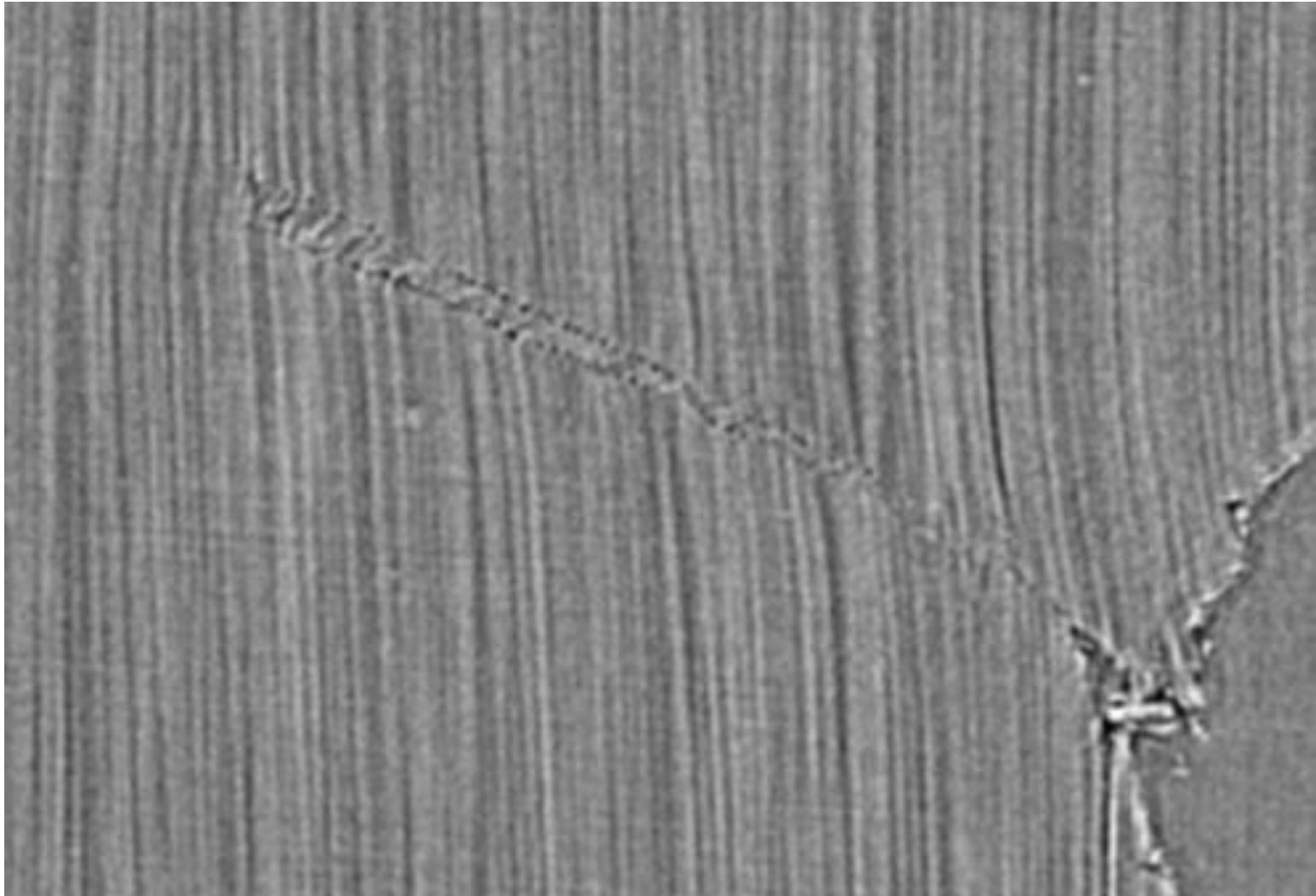


- Why use segmentation:

- Characterize the morphology of kink bands
- Quantify the evolution of kink band features through loading



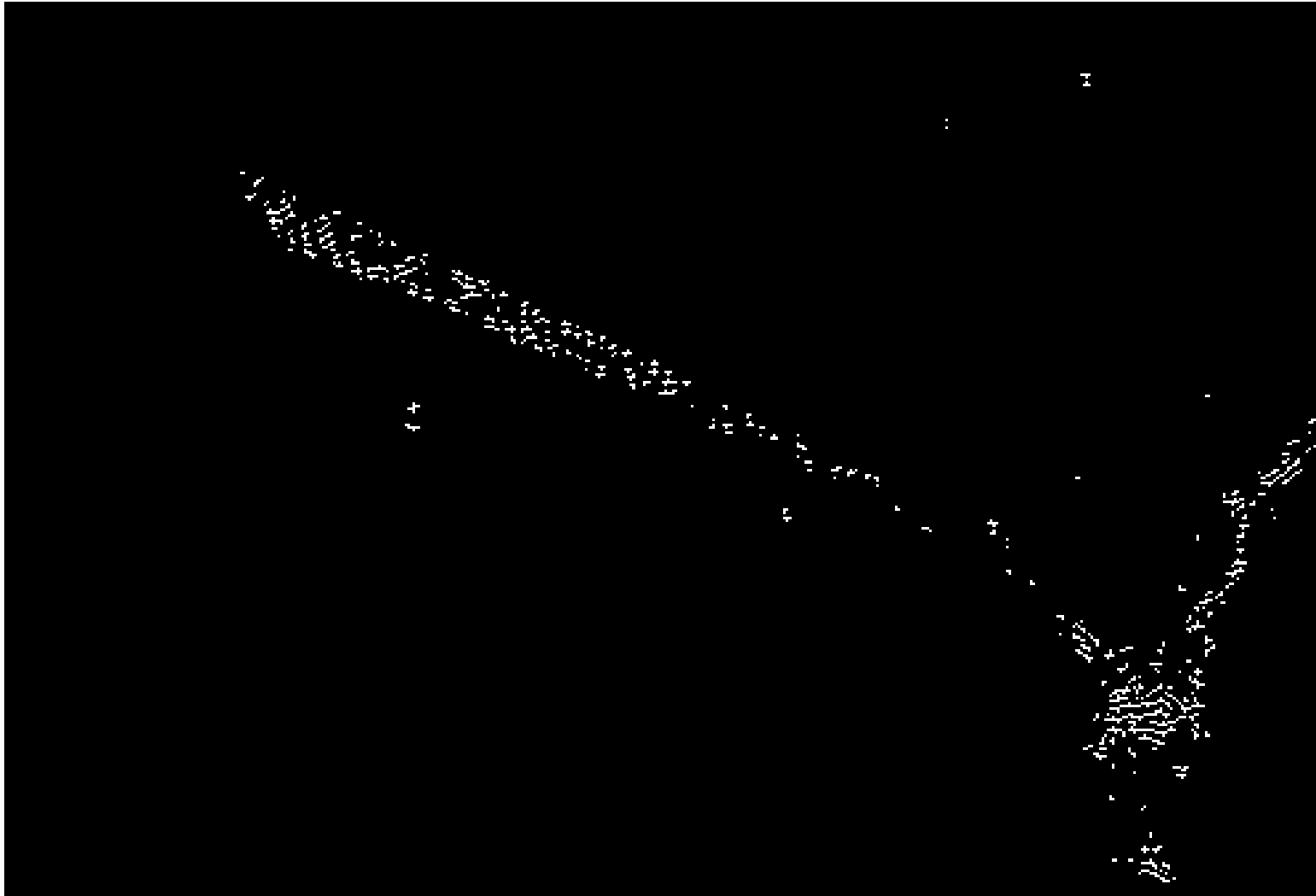
Segmentation Procedure: Sample Image



Segmentation Procedure: Sobel Edge Detection



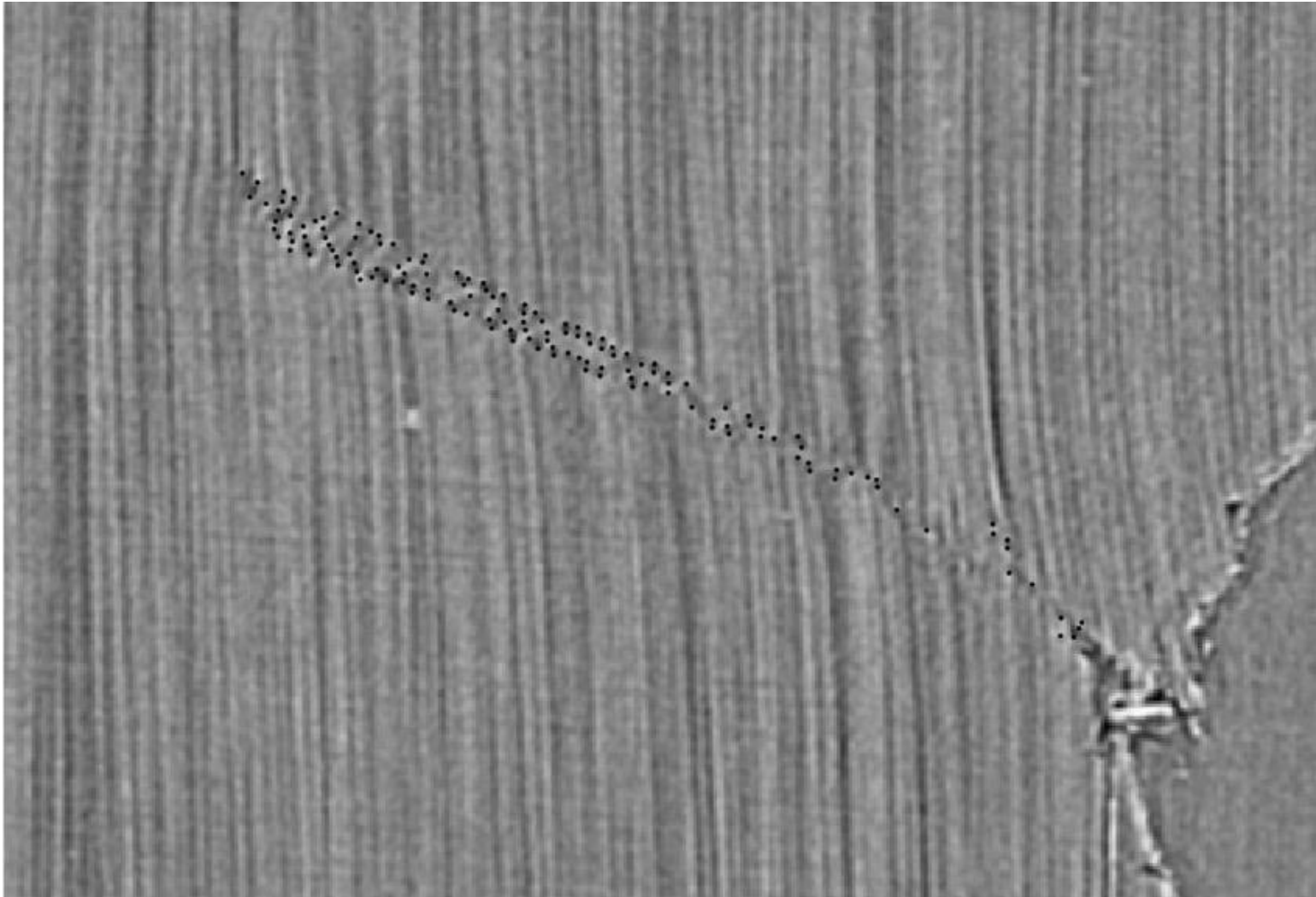
Horizontal edge detection is effective at identifying points of interest



Segmentation Procedure: Final Points of Interest



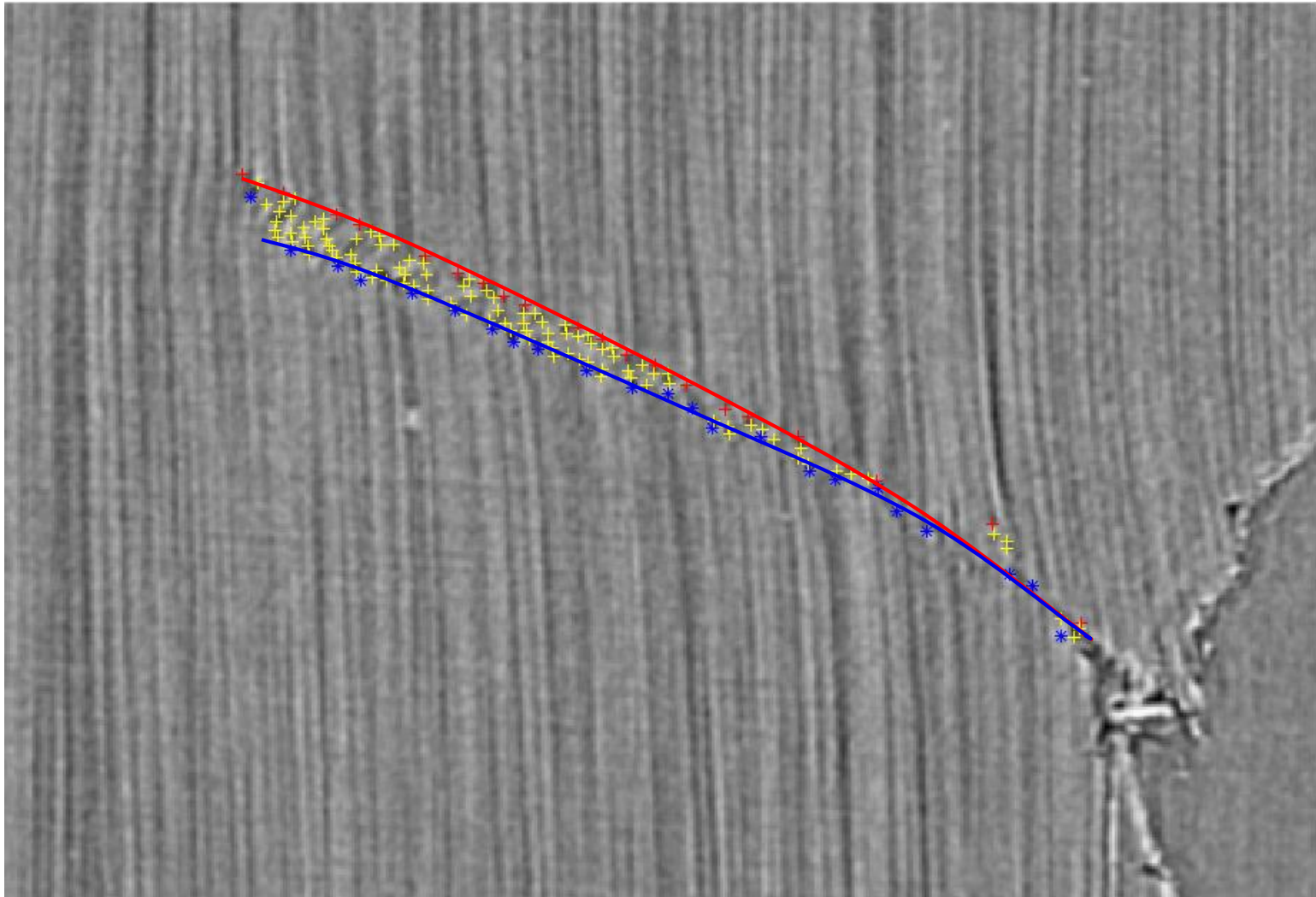
Centroids of points of interest are overlaid on the original image



Segmentation Procedure: Kink Band Surfaces



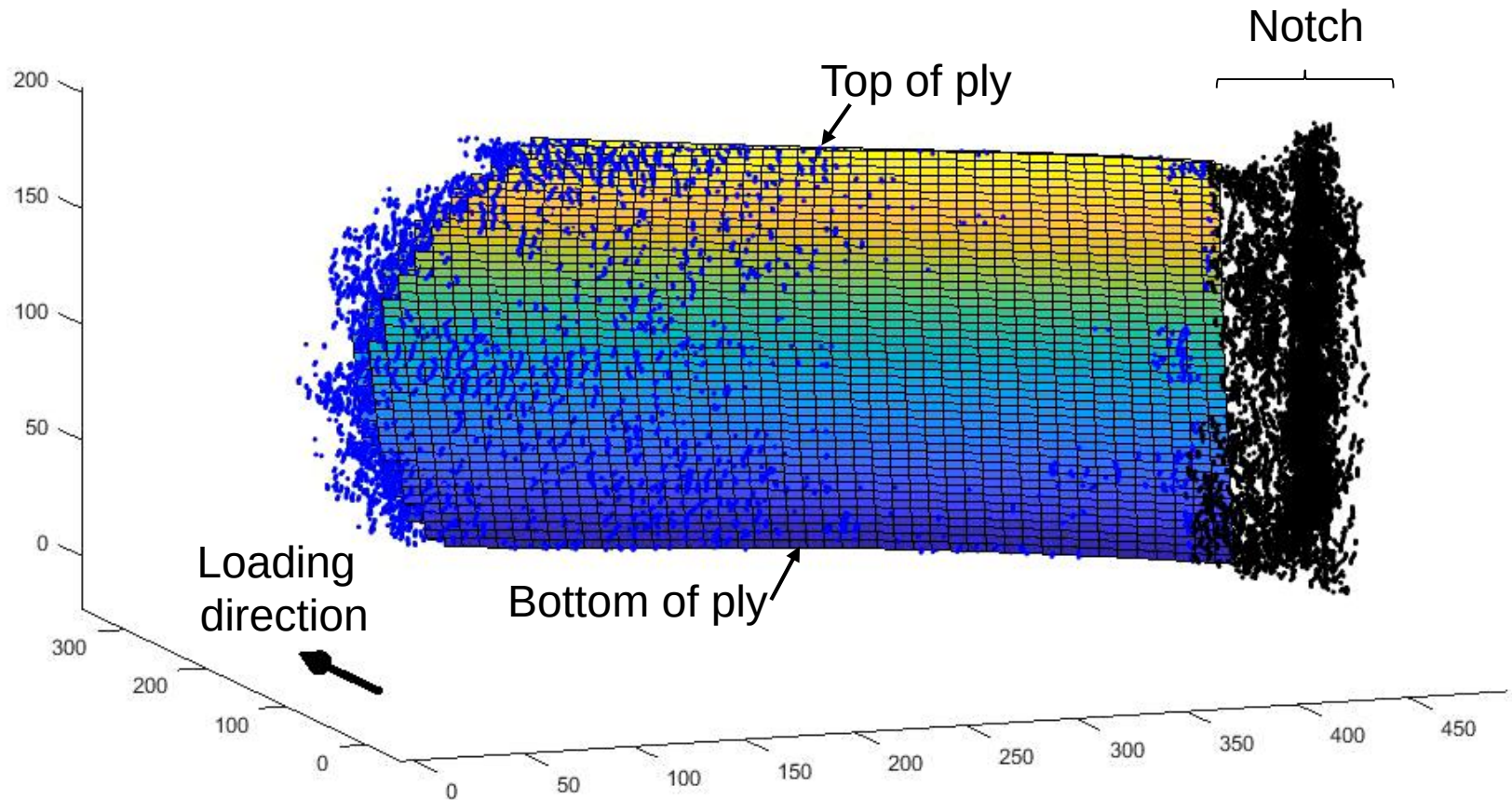
- Categorize the points belonging to the **top surface** or **bottom surface**
- Remaining points are considered **interior to the kink**
- Lines (surfaces) are fit through each set of kink surface points (top and bottom)

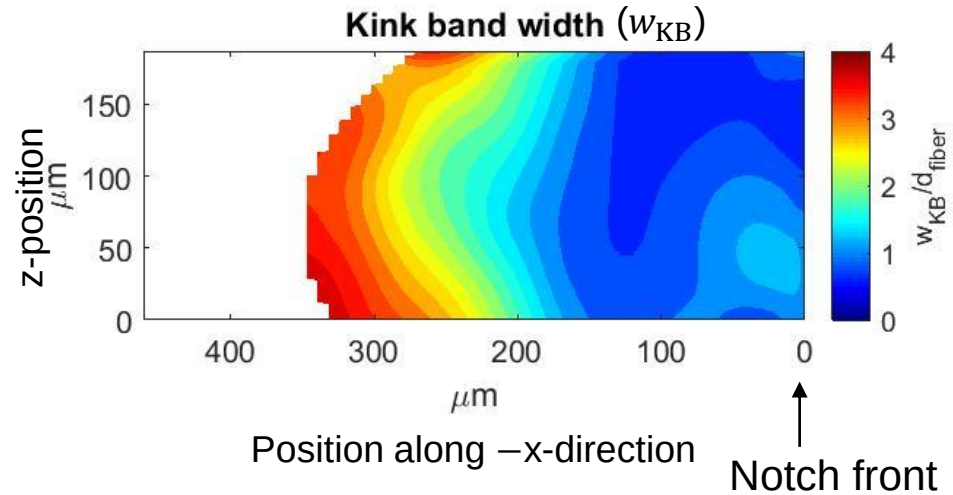
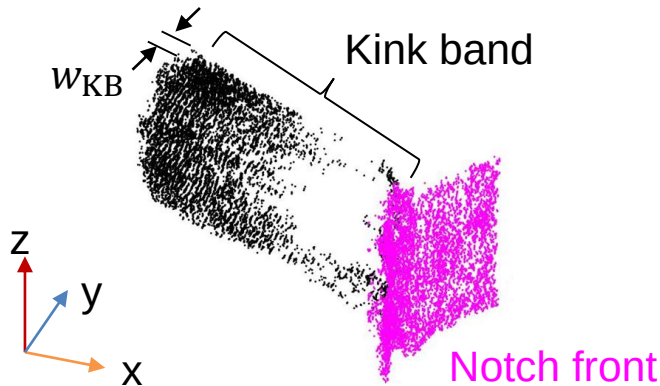


Point Cloud and Kink Surfaces: Animation



- Kink •
- Notch •





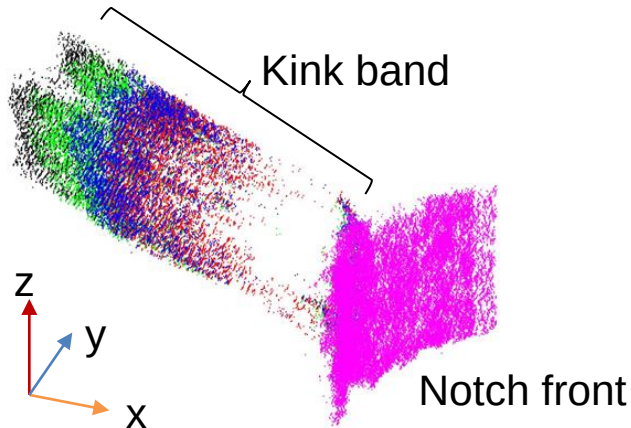
- 34

Quantifying Kink Band Propagation

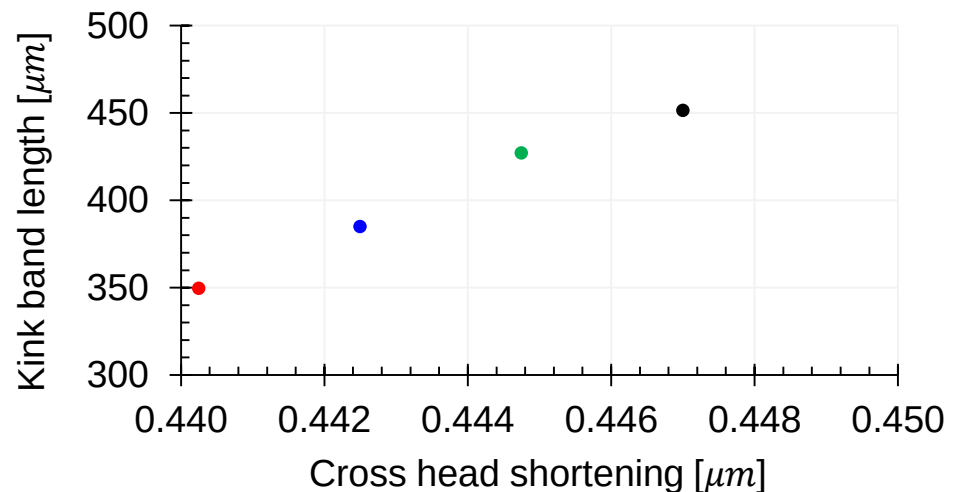
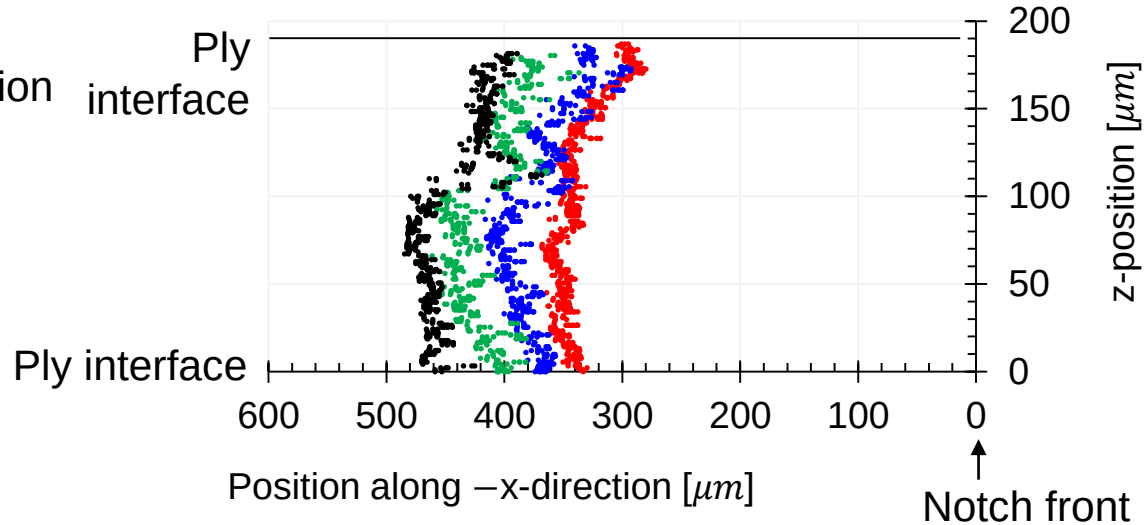


- Overlay kinks from several scans (load levels) in order to visualize and quantify propagation
- Use notch front data for registration

Overlaid kink band point clouds



Scan 36 • Scan 38 •
Scan 37 • Scan 39 •



- Propagation 'tunnels' through the ply; suggesting that delamination follows kinking



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Intralaminar Matrix Crack Propagation



Objective

Compare the results of finite element progressive damage analysis (PDA) methods to closed-form linear elastic fracture mechanics (LEFM) solutions for unidirectional (UD) fiber-reinforced cracked plates subject to pure mode 1 and mode 2 loading

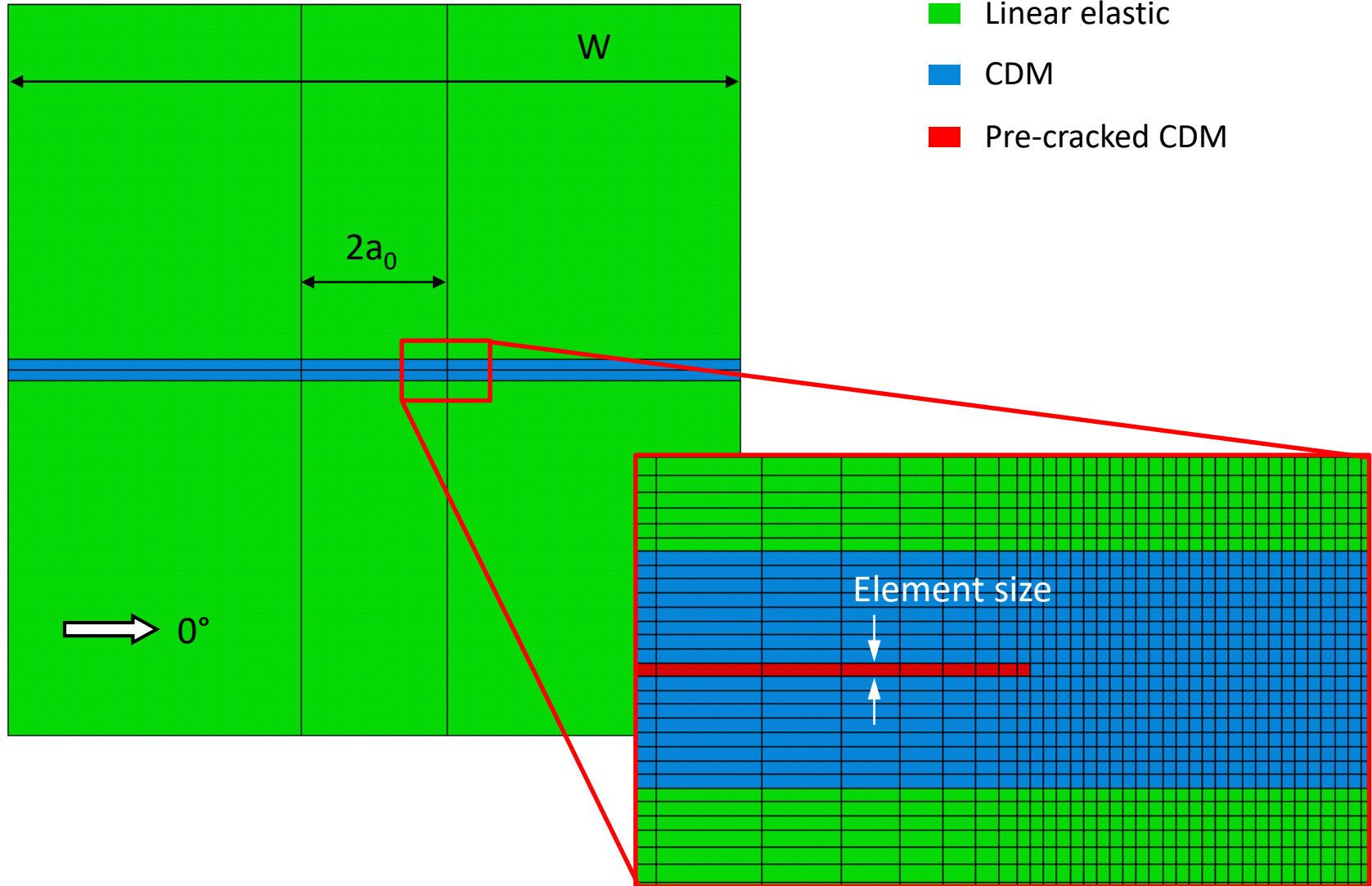
Continuum Damage Mechanics Codes

- Abaqus built-in
 - Softens terms of the material stiffness tensor to represent damage (e.g., E_2 and G_{12} for matrix cracks)
 - Hooke's law applied using conventional strains with softened stiffness
- CompDam
 - Matrix cracks are represented by sub-integration point cohesive laws
 - Special attention given to kinematics and geometric nonlinearity

Approach

Analyze center cracked unidirectional plate with different element sizes

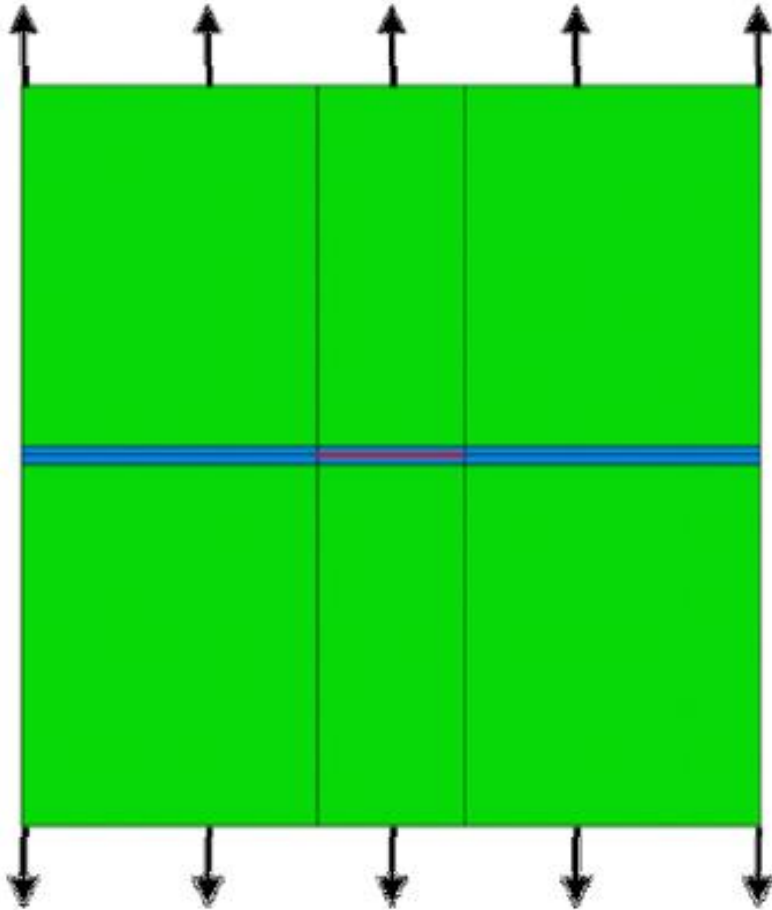
Geometry and Mesh



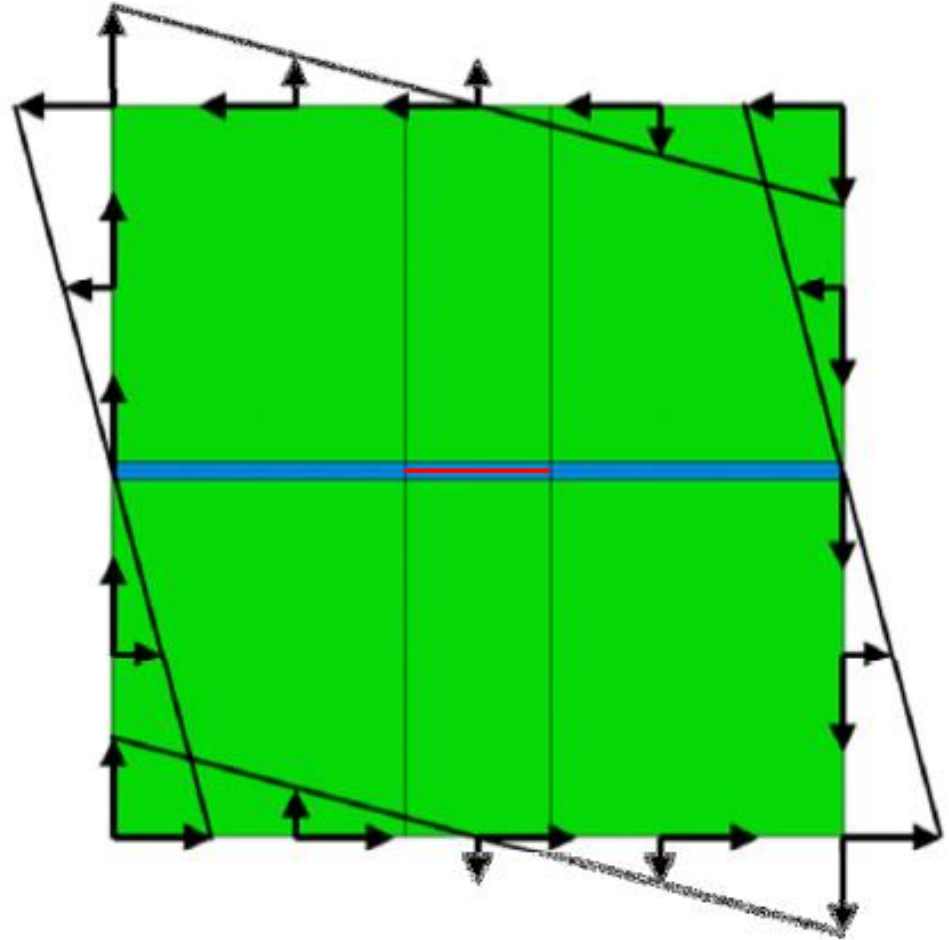
Loads and Boundary Conditions



Mode I



Mode II



Post Processing Definitions

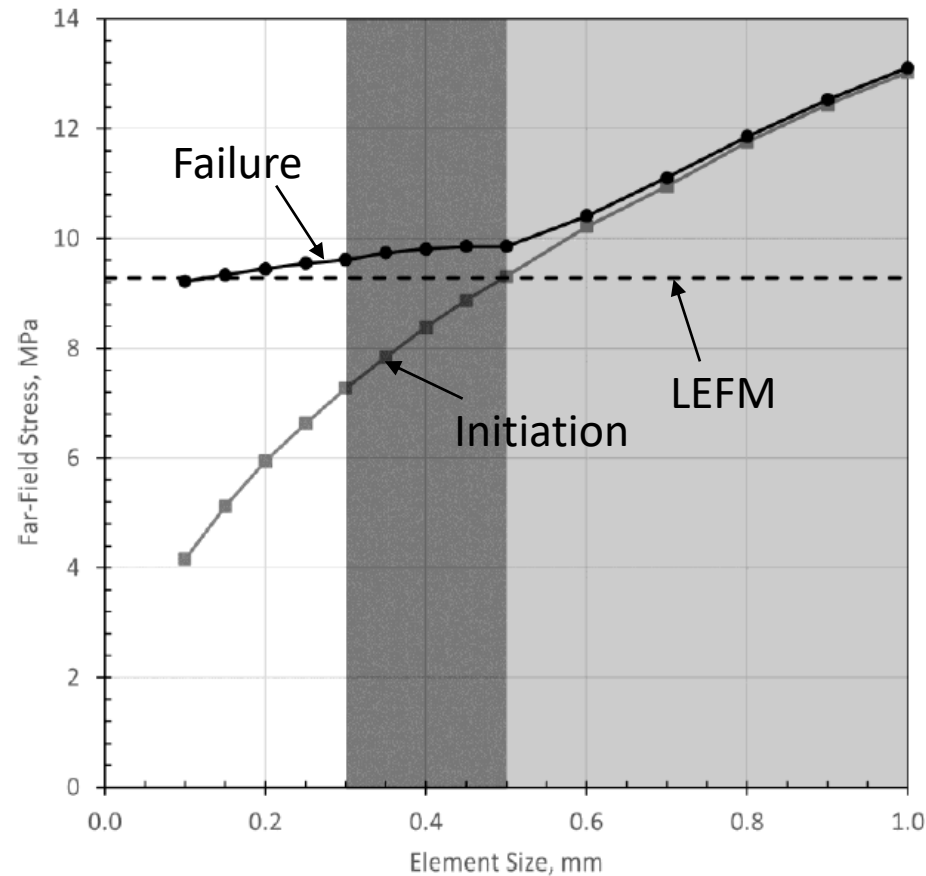


- **Damage Initiation** is defined as the first instance of a CDM damage state variable being greater than zero at the crack tip
- **Final failure** is defined as the start of unstable crack growth, usually coinciding with the full development of the fracture process zone ahead of the initial crack
- The **fracture process zone** (FPZ) is the adjacent elements ahead of a crack with damage state variables between zero and one

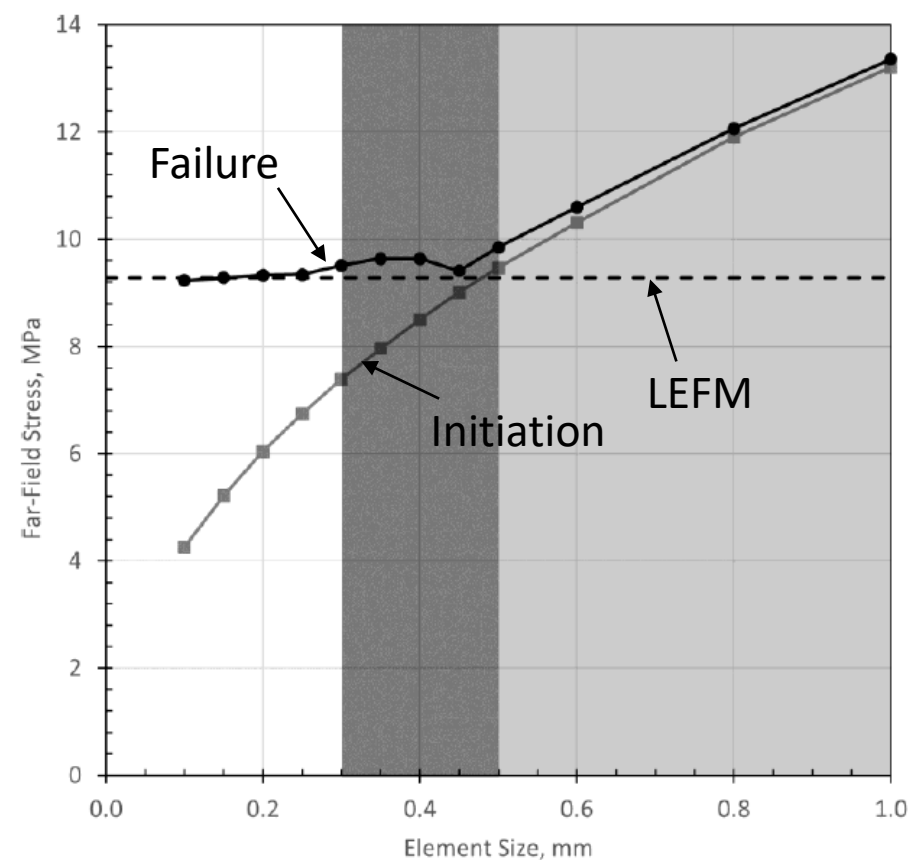
Mode I



Abaqus CDM



CompDam



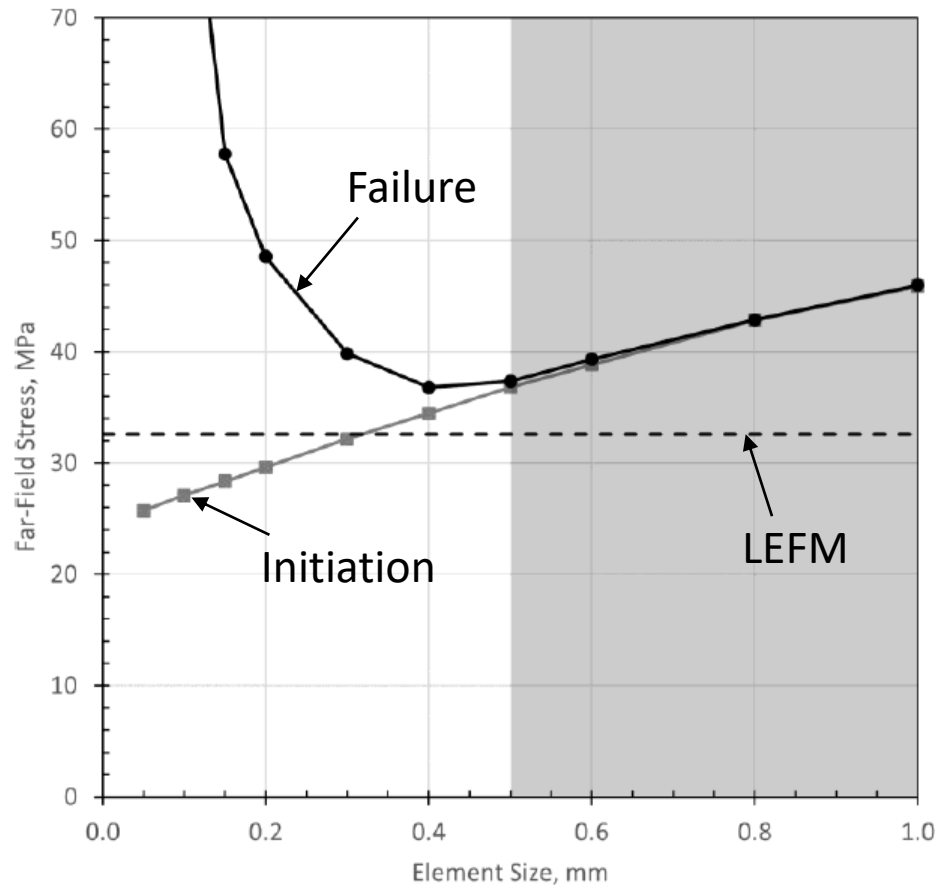
- Reproduced results from Mabson et al 2012
- Both models predict LEFM propagation for sufficiently small elements
- Snap back element size: 1.3 mm

$$L_{e, \text{snap back}} = \frac{2G_{Ic}E_y}{\sigma_c^2} = 1.3 \text{ mm (mode I)}$$

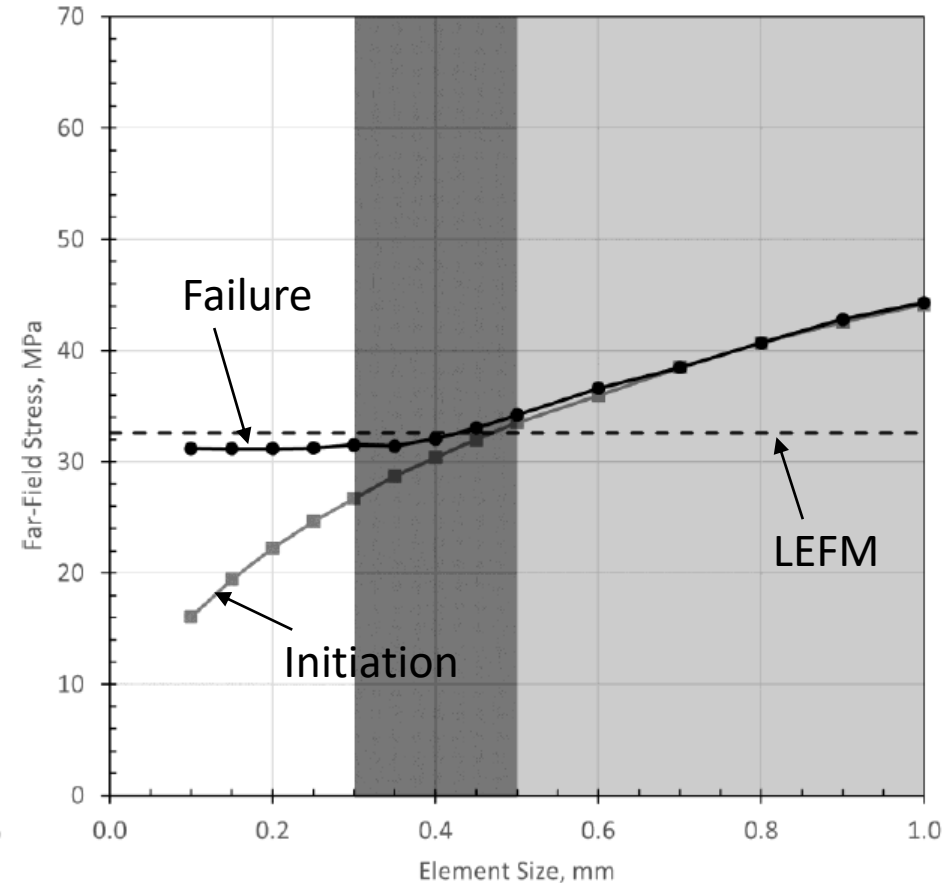
Mode II



Abaqus CDM



CompDam



- CompDam predicts LEFM propagation for sufficiently small elements
- Snap back element size: 0.98 mm

$$L_{e,\text{snap back}} = \frac{2G_{IIc}G_{xy}}{\tau_c^2} = 0.98 \text{ mm (mode II)}$$

Element size requirement is more severe than the snap back condition



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Overview: Two Examples of Test/Analysis Validation

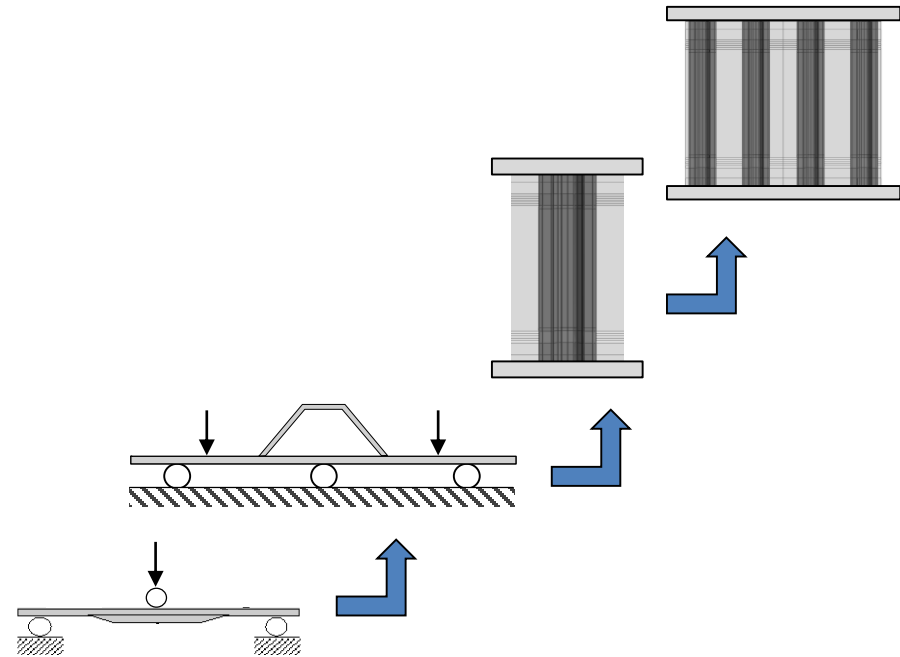


Traditional engineering test



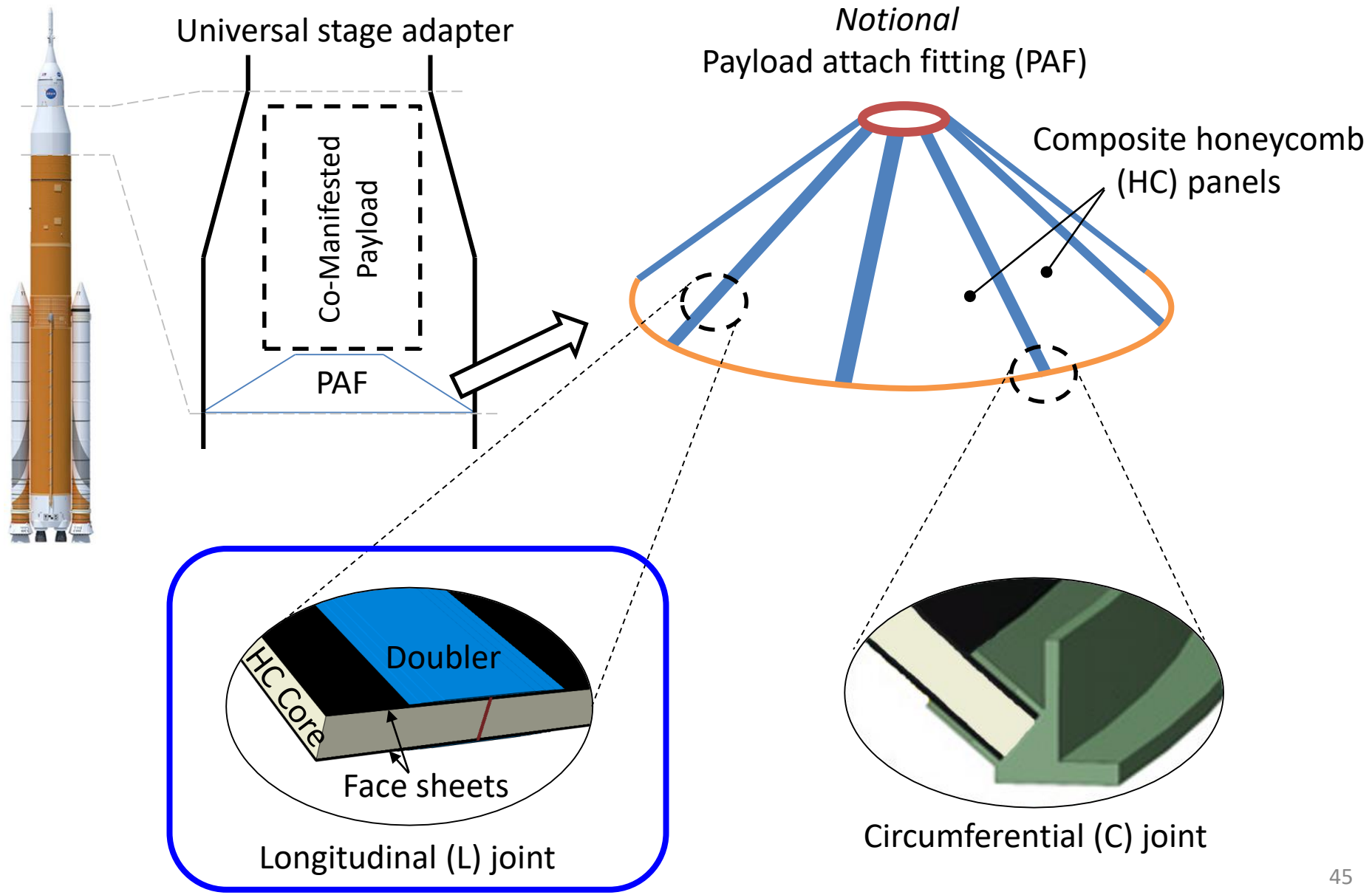
- Test article representative of flight design
- Competing failure modes
- Minimal instrumentation
- Minimal NDE
- Uninterrupted load to failure

Bespoke validation test program

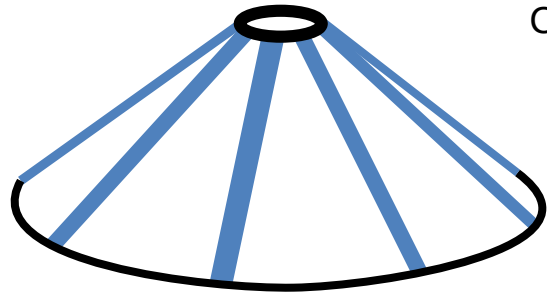


- Building block tests; started with simplified configurations
- Test articles designed for separation of failure modes
- Highly instrumented
- Interrupted loadings with NDE

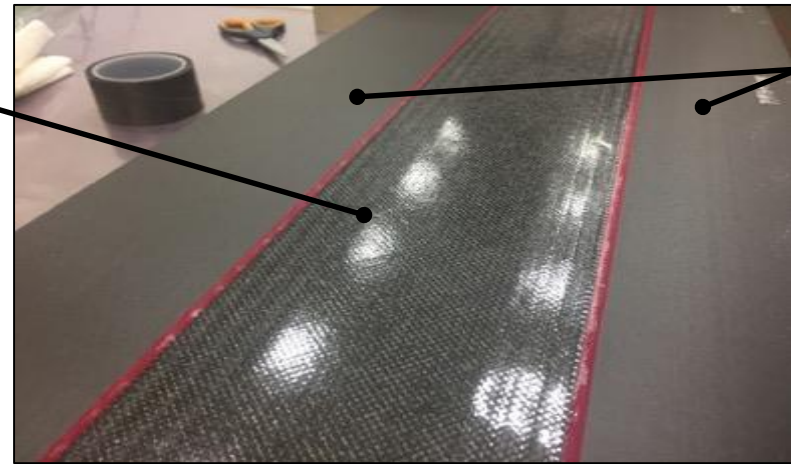
Example 1: Bonded Composites Joints for Launch Vehicles



L-Joint: Double Lap Configuration

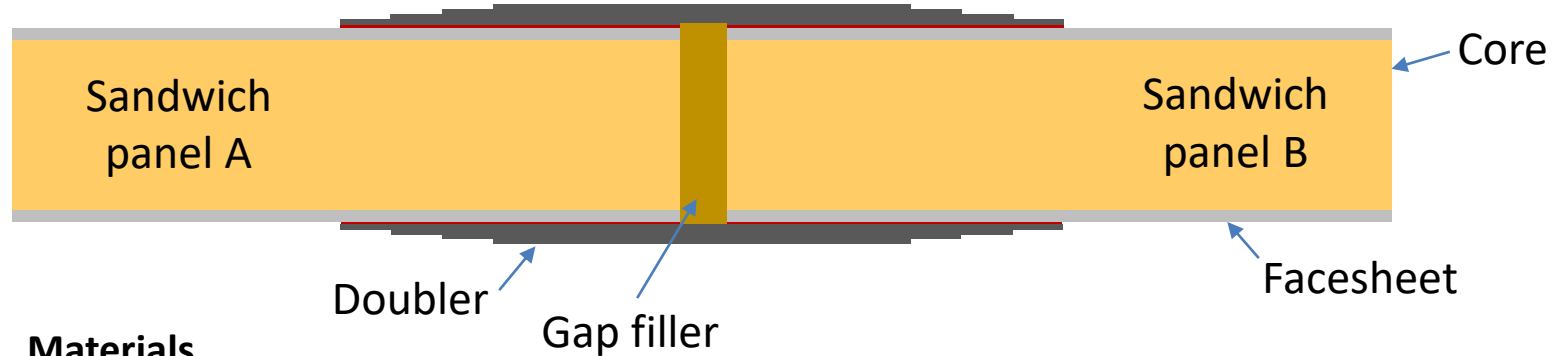


Co-bonded out-of-autoclave doubler



Pre-cured acreage sandwich panels

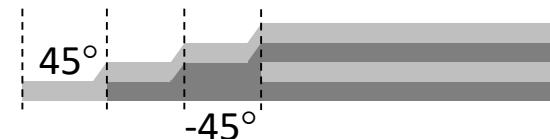
Section view



Materials

- IM7/8552-1 (8 ply)
- T650/5320-1 (4 ply)
- Plascore 3/16 in 3.1 pcf
- Film Adhesive
- EA9396-MD epoxy glue

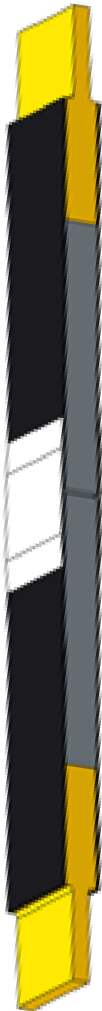
Taper



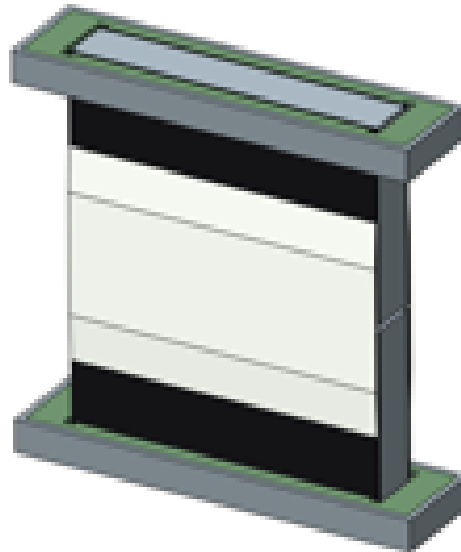
Element-Scale Test Specimens



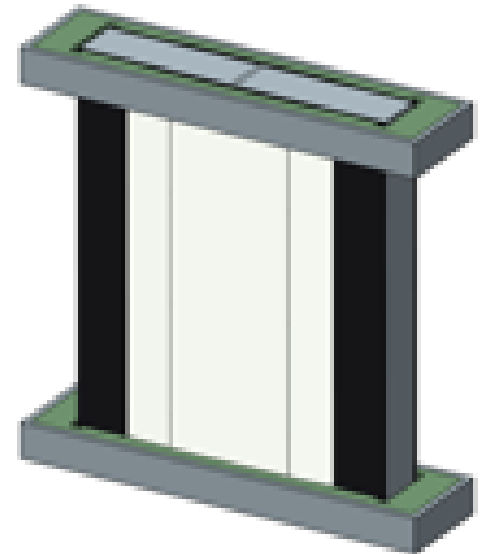
Circumferential
tension



Circumferential compression

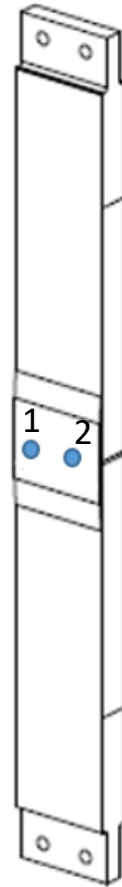
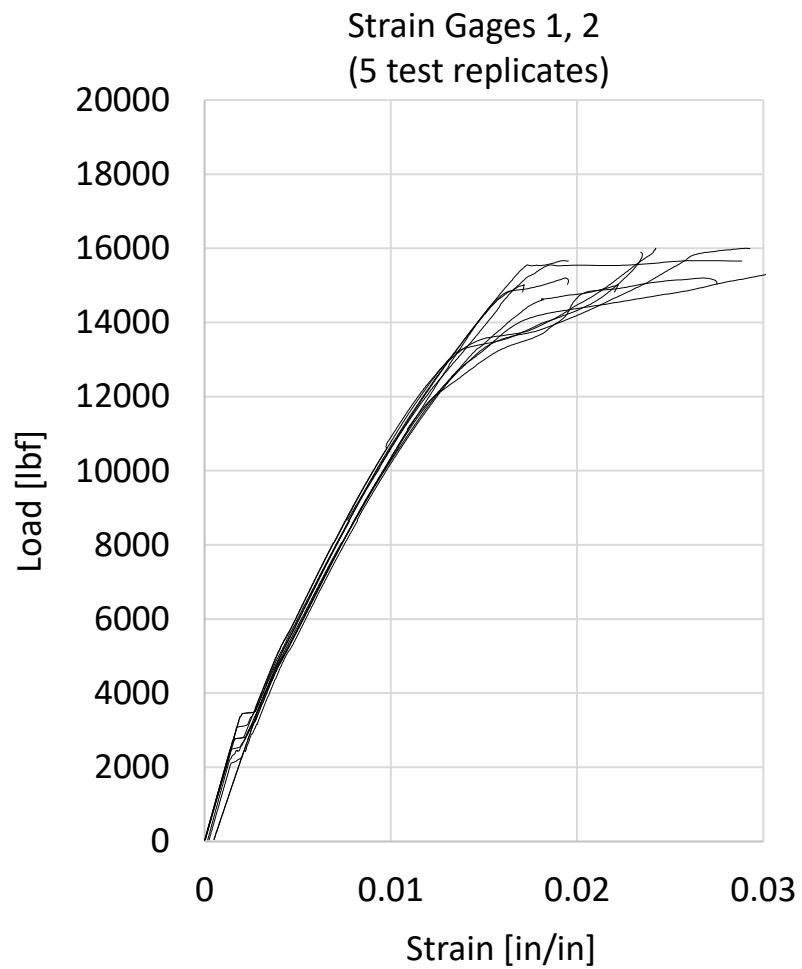


Axial compression

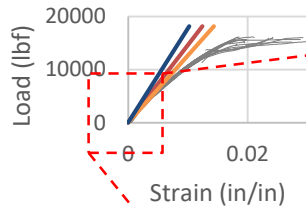


- Each loading configuration included specimens from 2 panels
- Tested as-manufactured and with impact damage
- Engineering style tests (pull and break)
- Instrumentation: Load, displacement, strain, digital image correlation

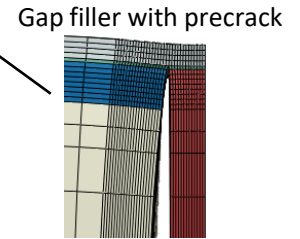
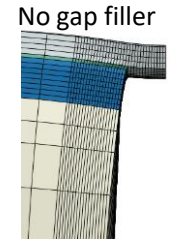
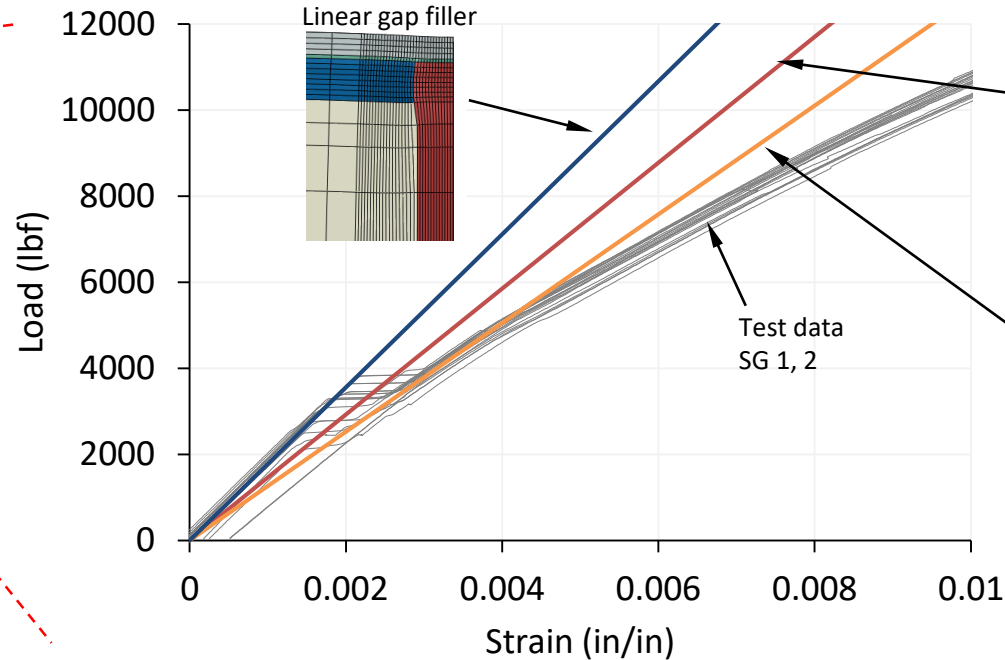
Typical Result



Gap Filler Cracking Analysis

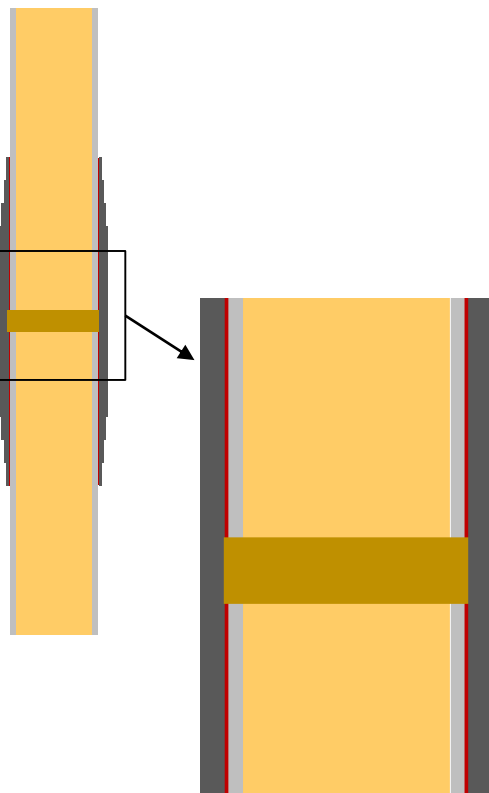


-  Doubler
-  Adhesive
-  Facesheet
-  Core
-  Gap filler



- Analysis results show that gap filler cracking explains the jump in stiffness in the local strain gage results

Damage Progression



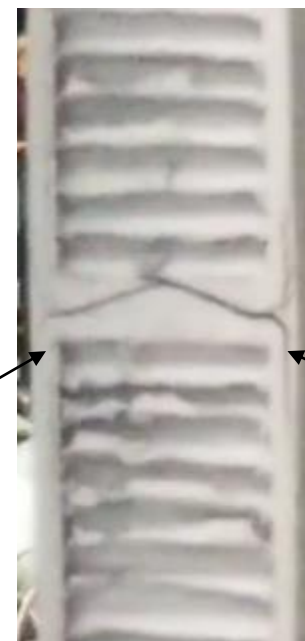
~25% peak load



~50% peak load

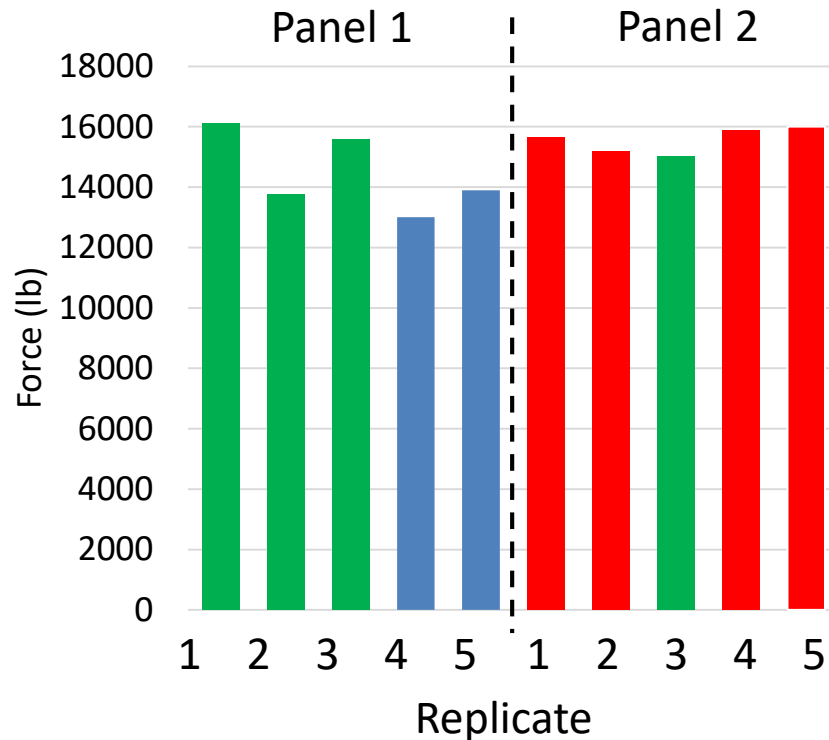


Just before failure



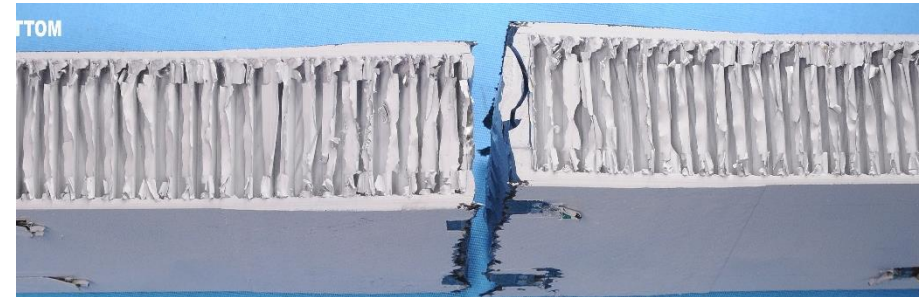
- Source of asymmetry in damage is unclear
- No fracture data available for gap filler; was assumed to be structurally insignificant
- Gap filler crack turning/interacting with delamination poorly understood

Competition Between Failure Modes

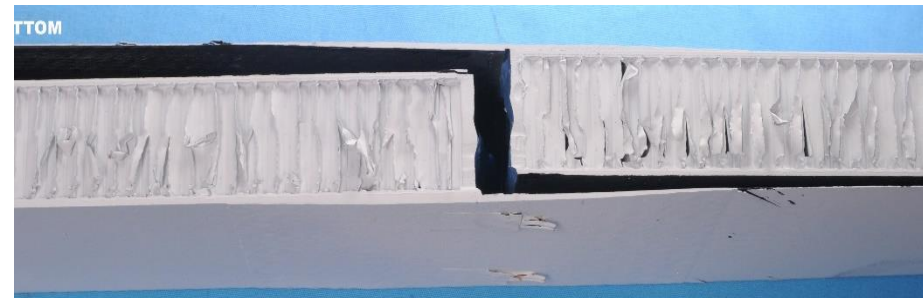


- Triggers/sensitivities for different failure modes unclear
- Validated damage models for isolated failure modes are needed before attempting to predict competition between failure modes!

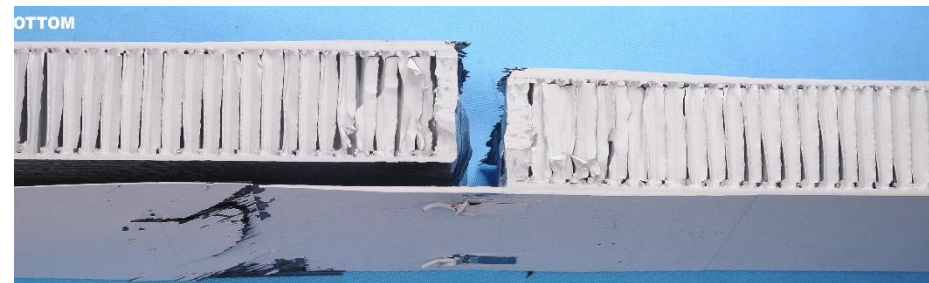
Red – Net section failure



Blue – Delamination



Green – Mixed



Overview: Two Examples of Test/Analysis Validation

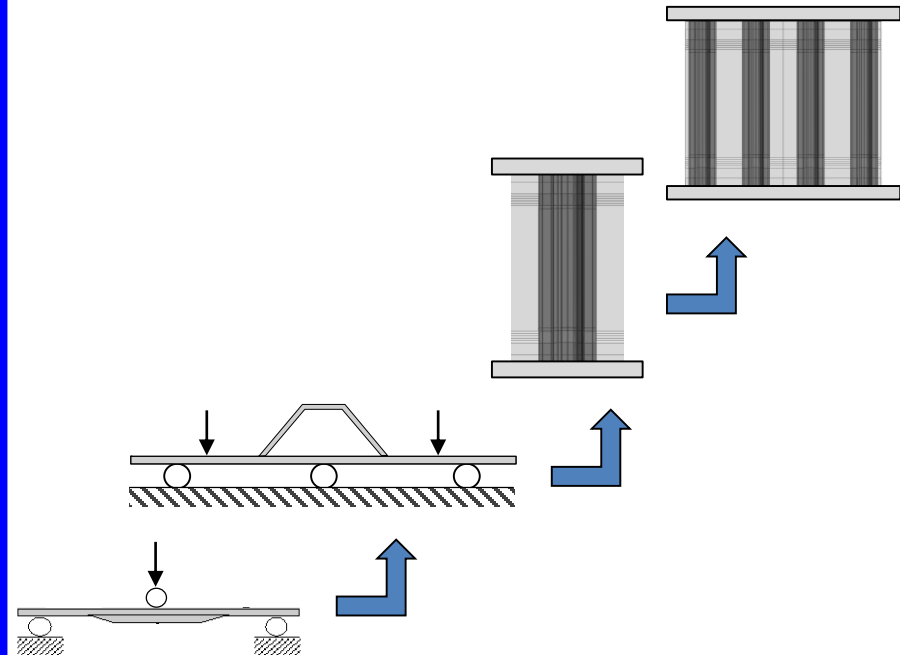


Traditional engineering test



- Test article representative of flight design
- Competing failure modes
- Minimal instrumentation
- Minimal NDE
- Uninterrupted load to failure

Bespoke validation test program

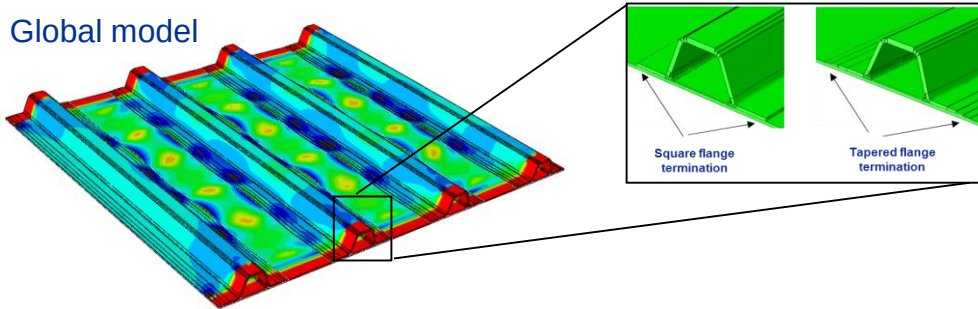


- Building block tests; started with simplified configurations
- Test articles designed for separation of failure modes
- Highly instrumented
- Interrupted loadings with NDE

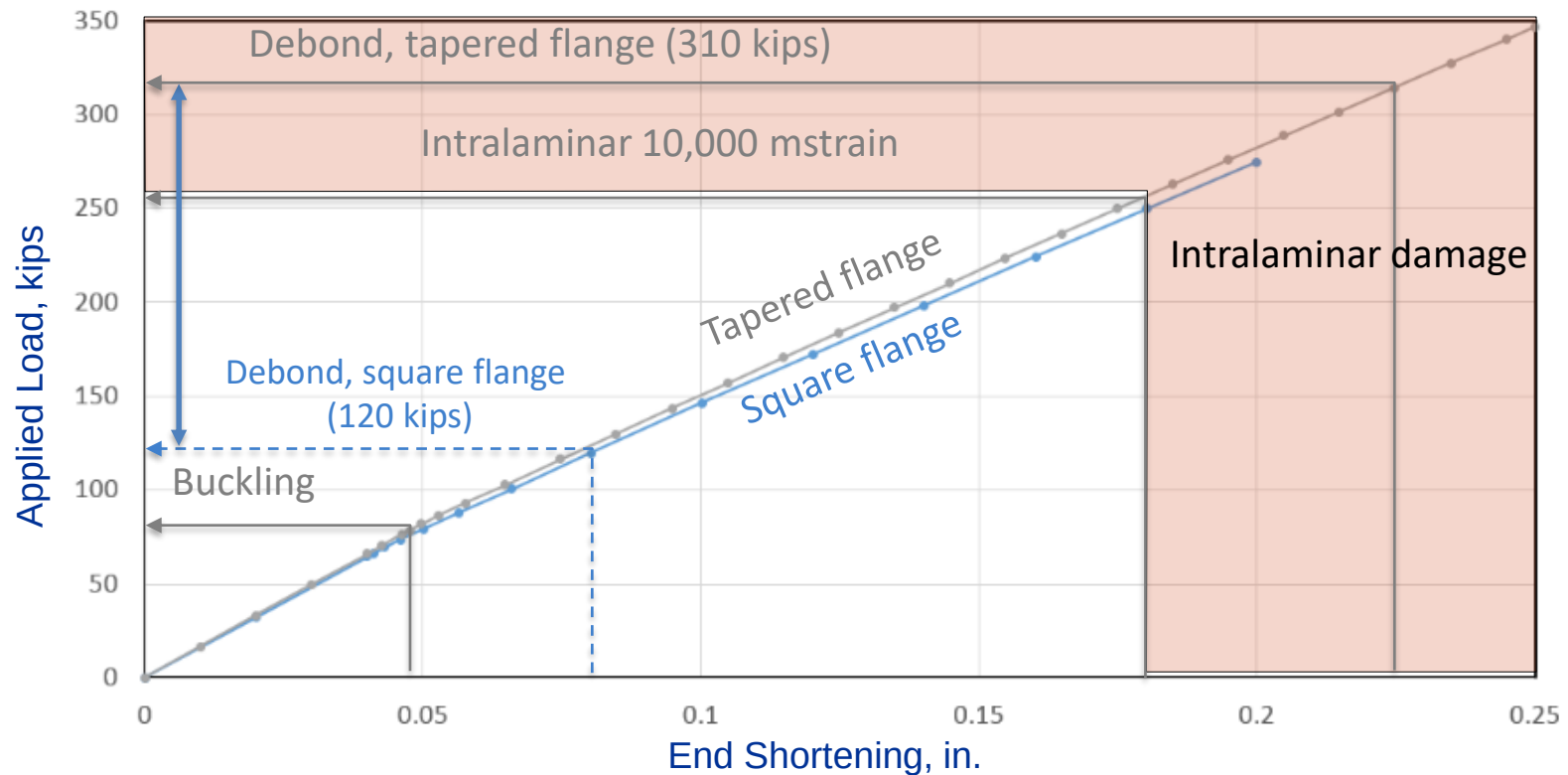
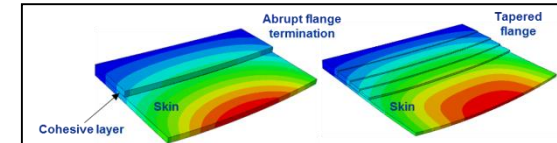
Example 2: Four-Stringer Panel



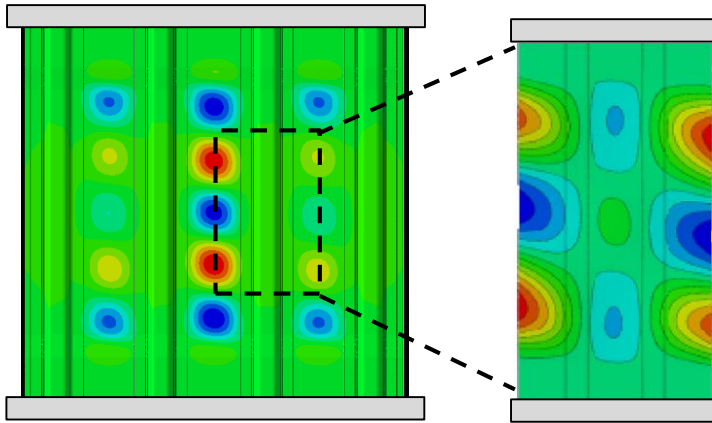
Global model



Local models

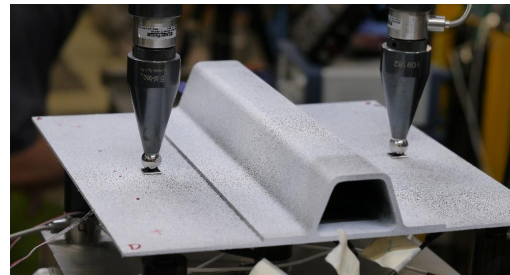
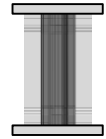


Simplified Test Articles



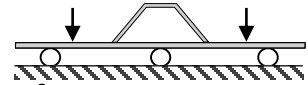
Single stringer

- Similar postbuckling skin/stiffener interactions
- Multiple buckling modes



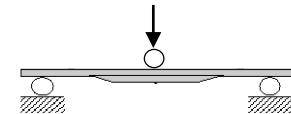
Seven-point bend

- Stable postbuckle-like deformation



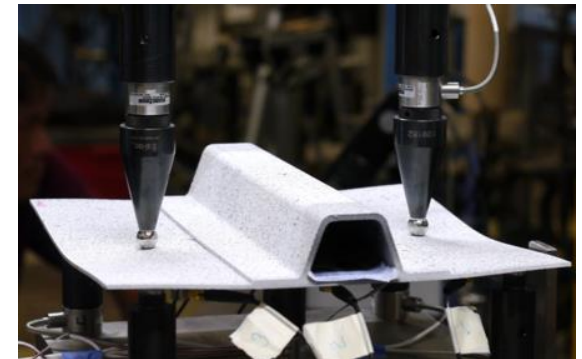
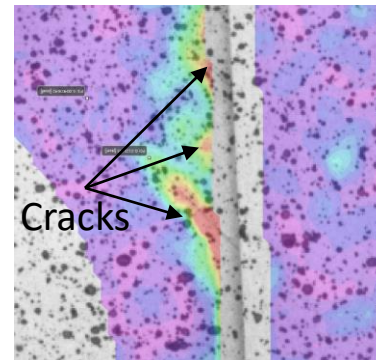
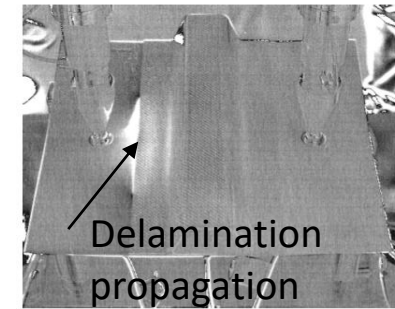
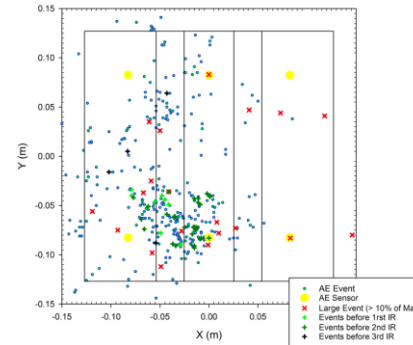
Three-point bend

- Mimics loading at flange edge
- Simple load introduction

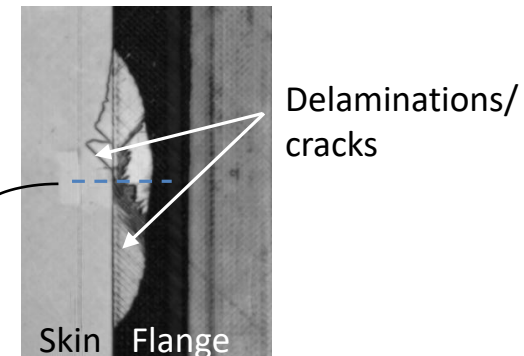
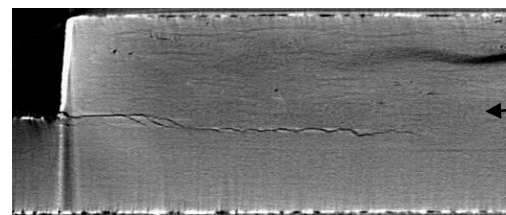


Reduced size, cost, & complexity

- 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



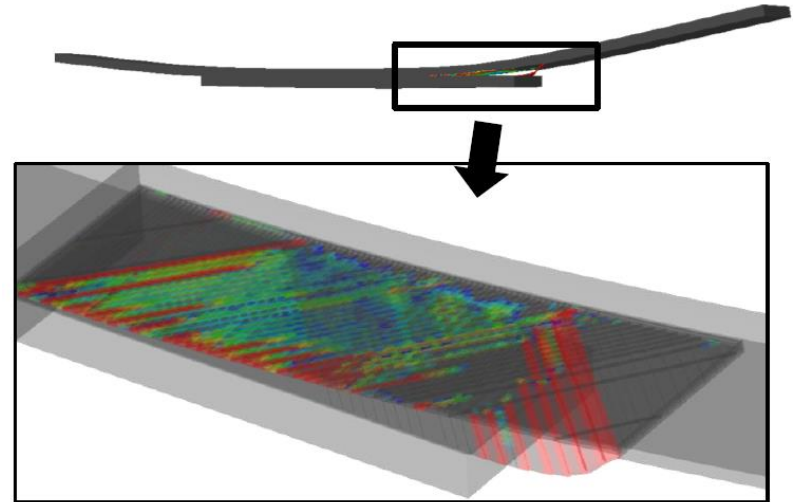
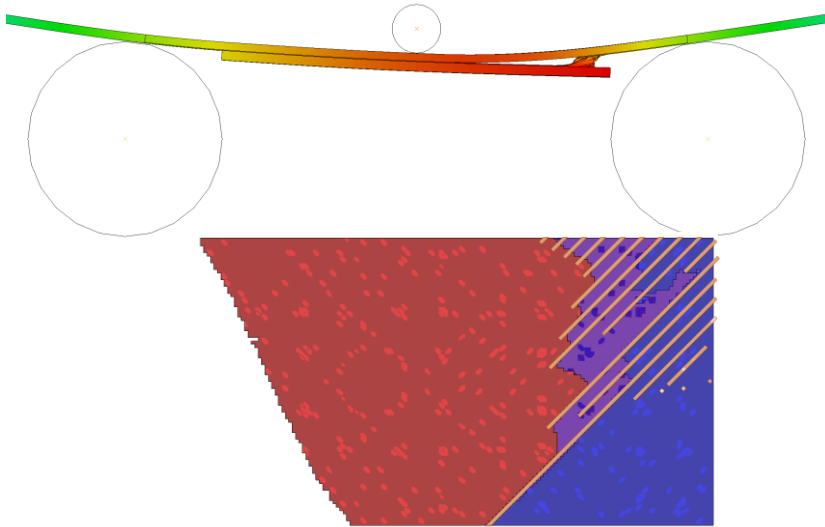
X-ray/CT



Example of Test/Analysis Correlation

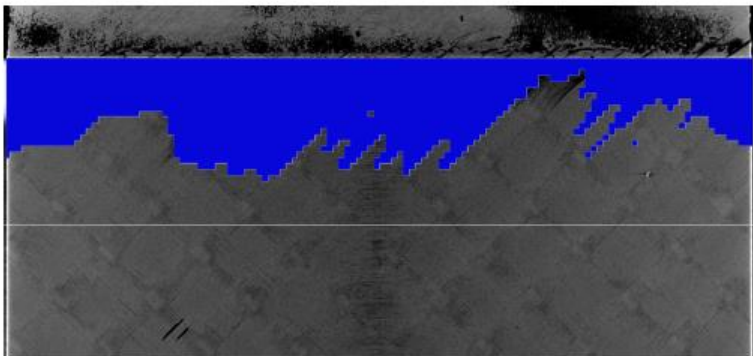


Typical model predictions

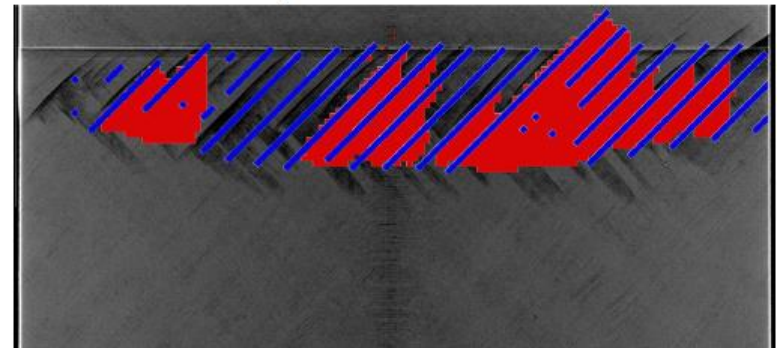


Analysis results overlaid on X-Ray CT

Flange/Skin Interface



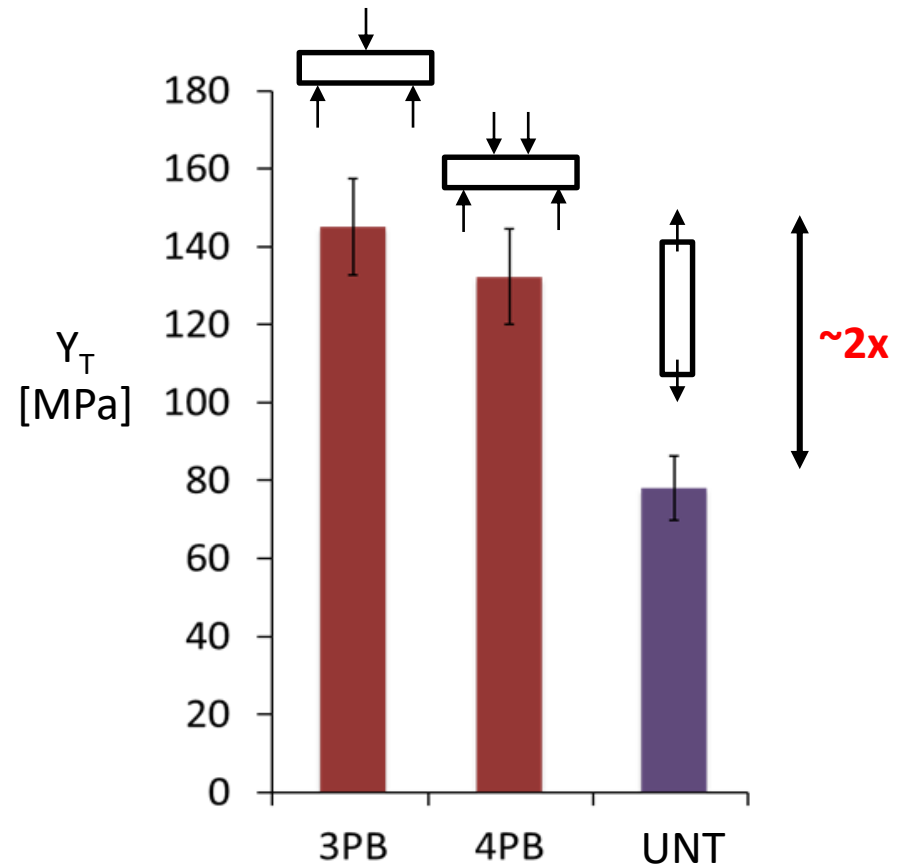
+45 Ply and +45/-45 Interface





- About NASA
- Composites manufacturing and test labs at LaRC
- Advanced Composites Project (ACP)
- Three steps toward predictive capability
 - Material science
 - Verification
 - Validation
- **Practical challenges in virtual testing**
- Concluding remarks

- Transverse tensile strength depends on test configuration
- Not explained by Weibull scaling
- Validation studies show certain problems are very sensitive to Y_T
- 'High Y_T ' creates numerical challenges; extremely small elements required

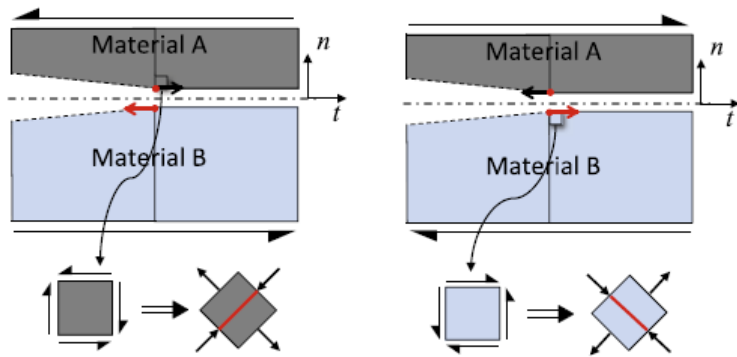


Material Characterization: Fracture Toughness

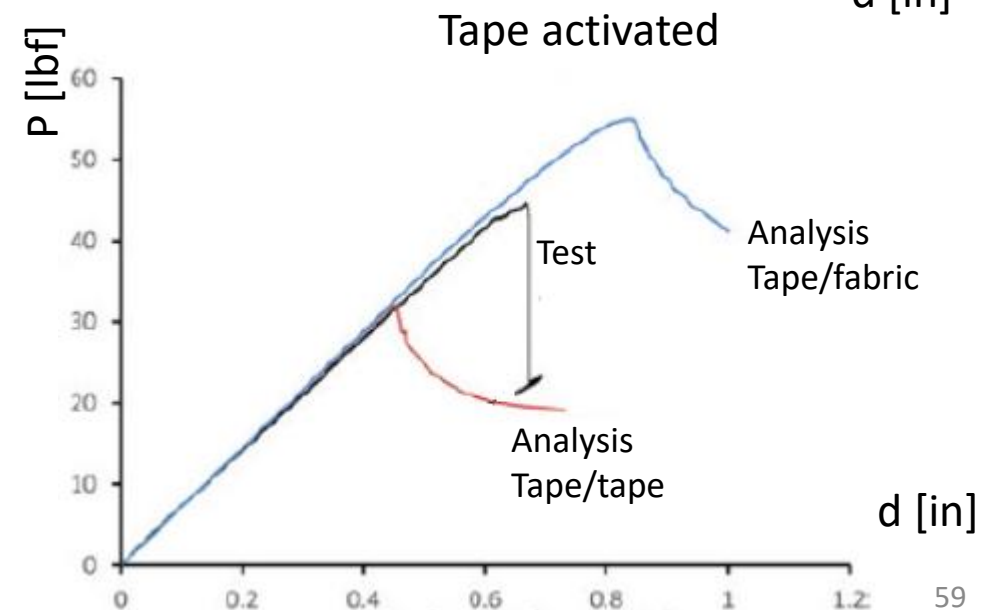
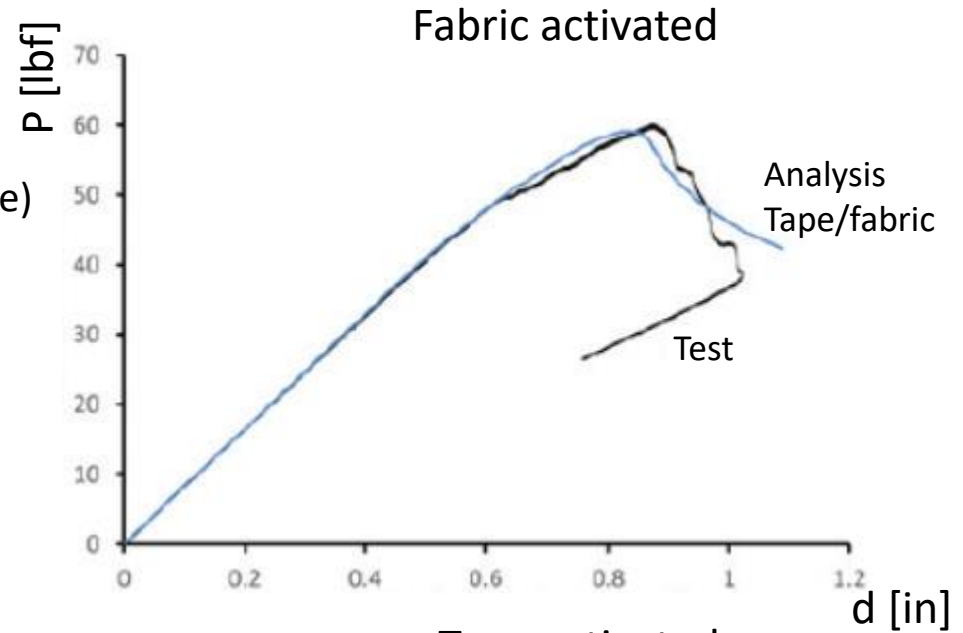
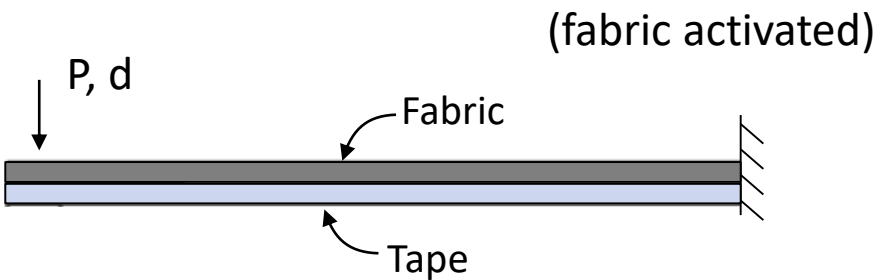


Fabric (flange)

Tape (skin)



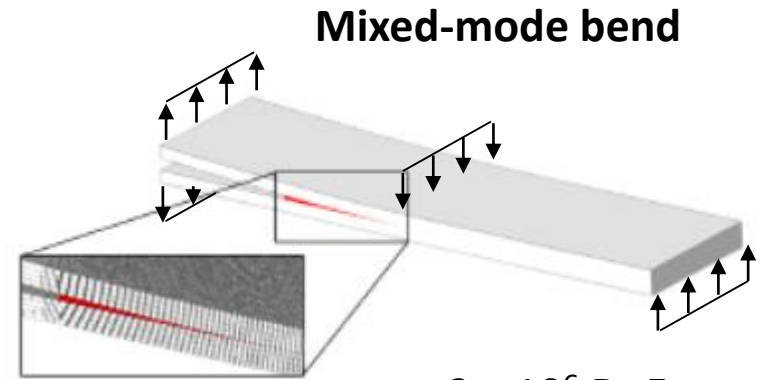
De Carvalho 2015



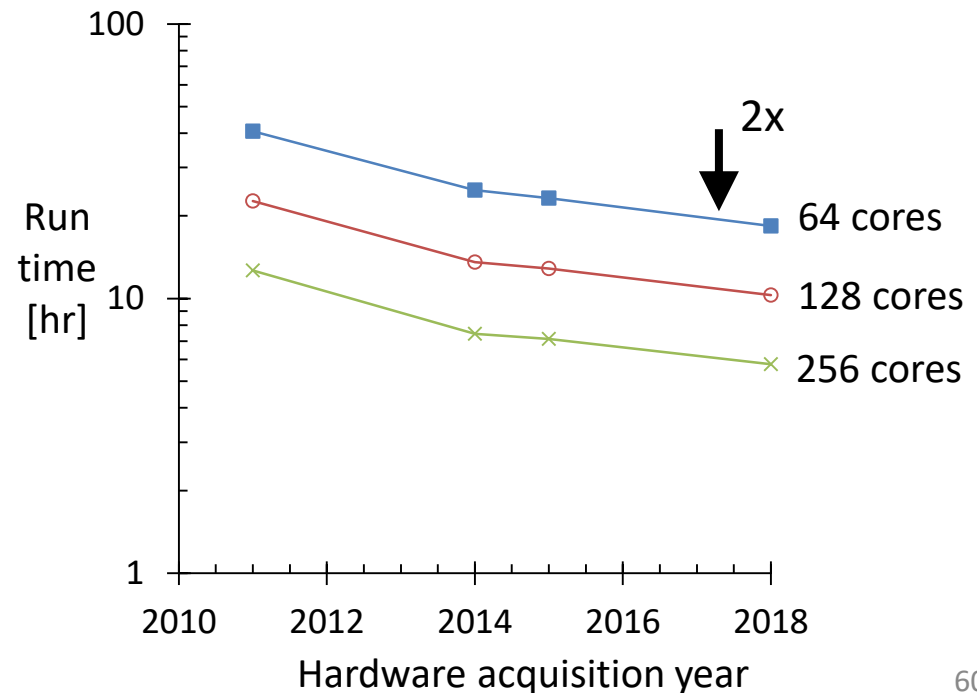
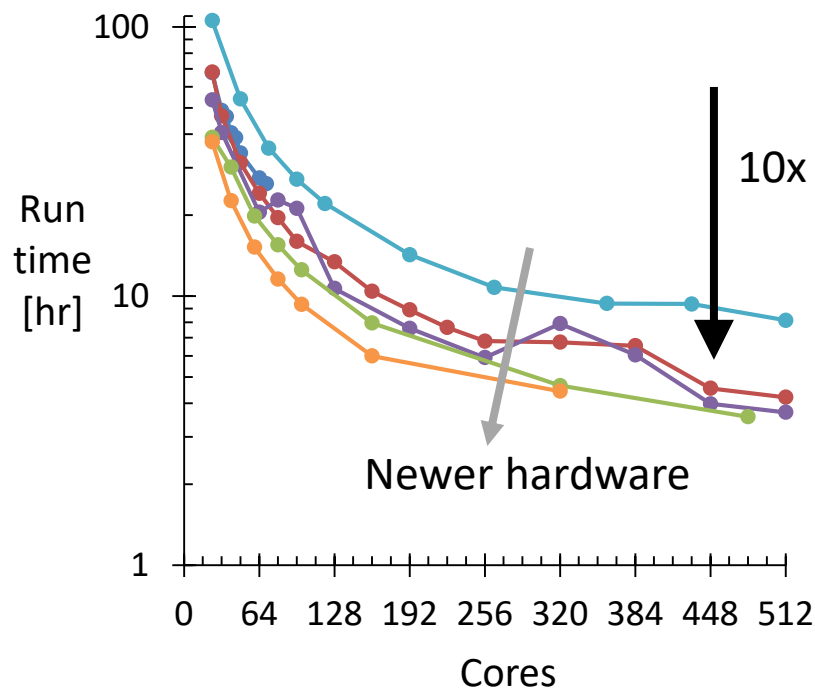
Computational Scaling



- Computational size of models
 - Typical coupon (3 pt bend): 10×10^6 DoF
 - Element (single stringer): 40×10^6 DoF
 - Sub-component (4 stringer panel): 75×10^6 DoF
- Abaqus/Explicit scales well in parallel
 - Typically used ~ 24 cores
 - 10x computational speed up can be obtained using 512 cores



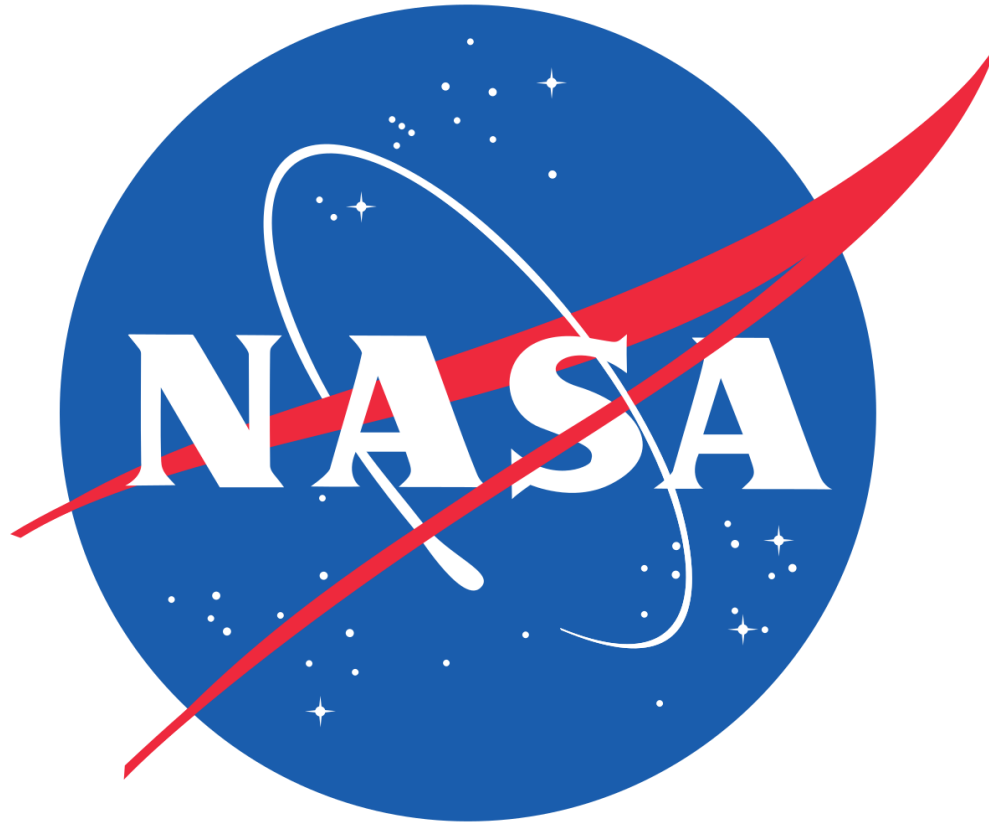
- 3×10^6 DoF
- Cohesive elements





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- **Concluding remarks**

- Rigorous verification & validation is needed to establish virtual testing capabilities
 - Foundation is a theory of damage initiation and evolution (material science)
 - Verification: Is the computational implementation correct?
 - Validation: Do the physics in the model capture the experimental trends for load, displacements, strain, damage evolution, damage initiation?
- Open challenges
 - Material characterization: strength, fracture
 - Test article designs that isolate damage mechanisms
 - High fidelity test methods: observations of damage formation, evolution, and interactions
 - Robust & general computational methods



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