Tools For Simulating Damage and Fracture in Composite Materials: How Should NASA Research Groups Better Communicate Updates to NASA Engineering?

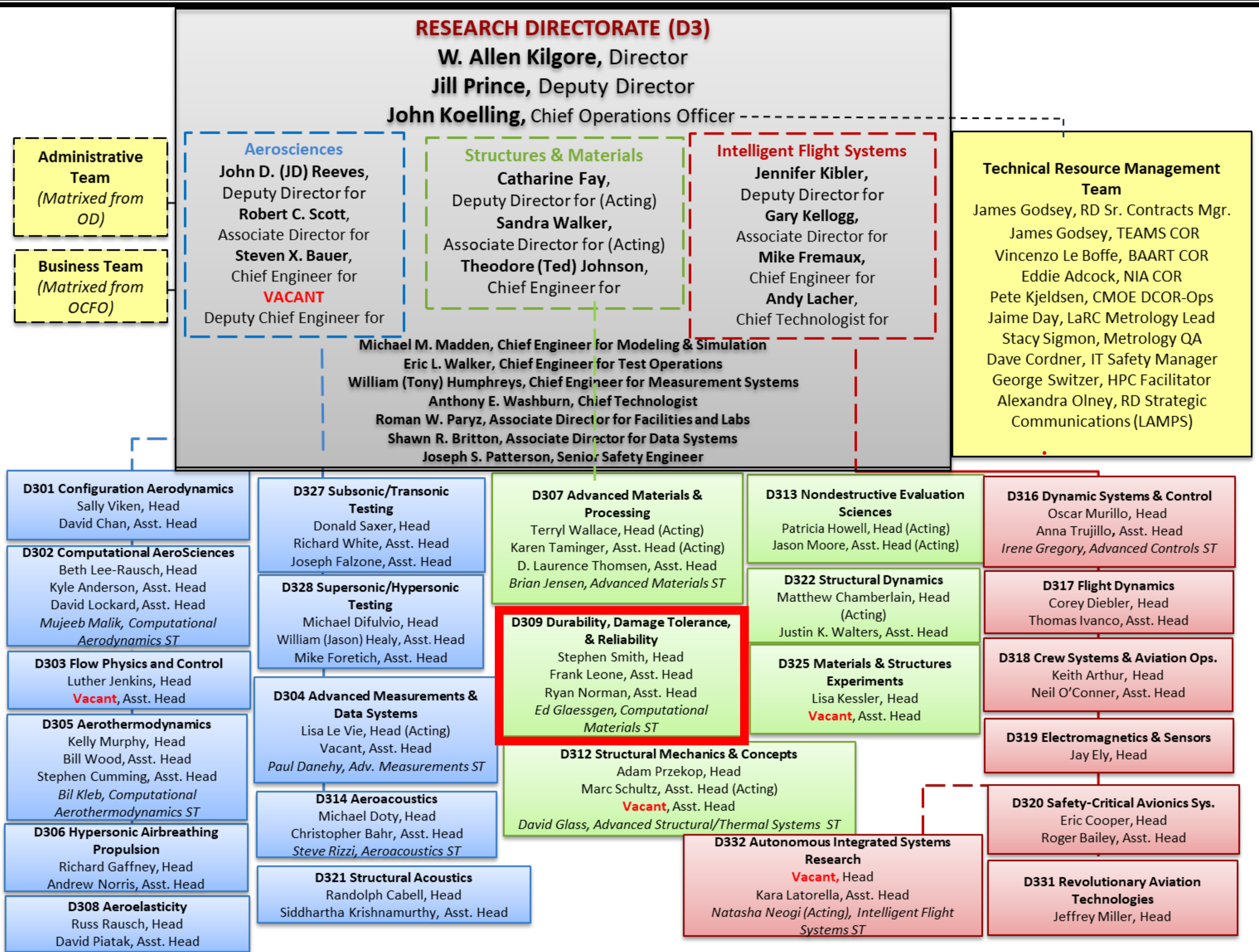
Composites Group
Durability, Damage Tolerance, and Reliability Branch
NASA Langley Research Center, Hampton, VA

Presenters
Nelson Carvalho, Carlos Davila, Ronald Krueger,
Frank Leone, James Ratcliffe, Cheryl Rose

Outline

- **Background**
- **Objective and Approach**
- **NASA Langley Research Center (LaRC) Composites Group Analysis Tools**
- **Closing Remarks**

Composites Group in the Durability, Damage Tolerance, and Reliability Branch



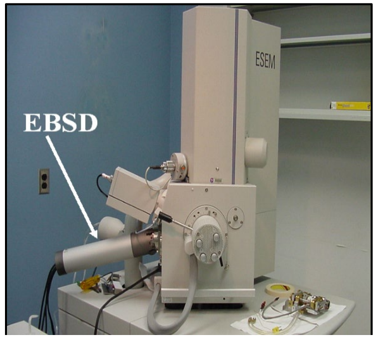
D309 Capabilities

- Damage mechanics of metallic materials
- Testing and evaluation of damage processes in metallic materials
- Developing multiscale computational codes and methods
- Reliability-based design
- Radiation risk assessment for long-duration space missions
- Radiation shielding and design
- Modeling space environments

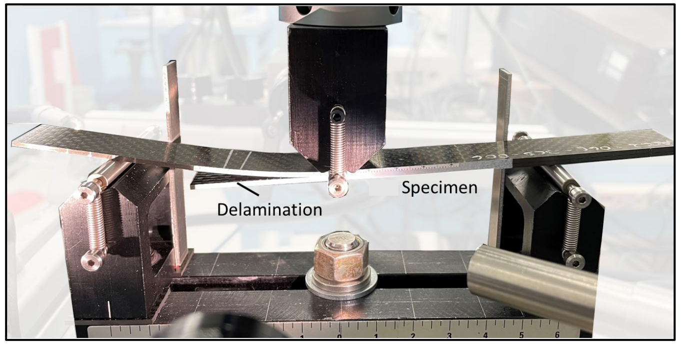
Composites Group Focus

- Damage mechanics of composite materials
- Testing and evaluation of damage processes in composite materials

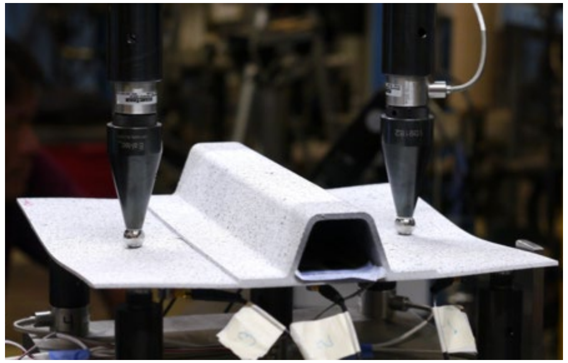
Composites Group Facilities



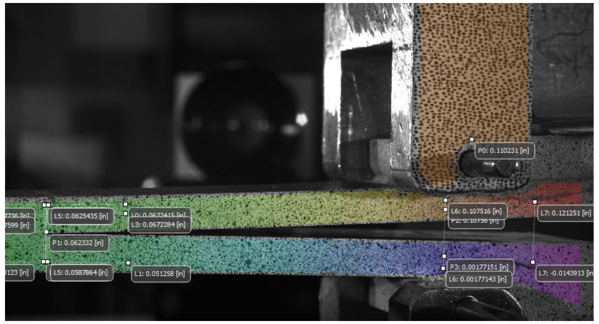
Inspection equipment
Microscopy, UT*, X-ray/CT

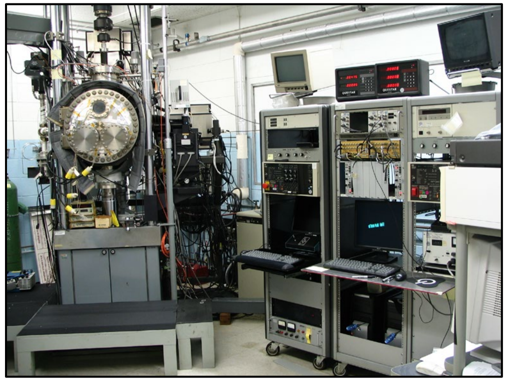


Materials Characterization


Validation Testing


Multi-axial testing


Far-field data measurement


Environmental Testing

*UT – Ultrasonic Transmission, CT – Computed Tomography


Thermal Testing

Composites Group Members

- **Andrew Bergan**: Composite Damage (CompDam) progressive damage analysis software
- **Nelson Carvalho:** Floating Node Method (FNM). Virtual Crack Closure Technique (VCCT). Cohesive zone modelling (CZM)
- **Carlos Davila**: CompDam, CZM
- **Wade Jackson**: Experimental methods. Inspection techniques
- **William Johnston**: General experimental methods
- **Ronald Krueger**: VCCT. Analysis benchmarking
- **Frank Leone**: CompDam. Assistant Branch Head
- **James Ratcliffe**: Materials characterization. NASA Engineering Safety Center (NESC) Materials Technical Discipline Team (TDT)
- **James Reeder:** Materials characterization. NESC Structures TDT and Materials TDT
- **Cheryl Rose**: CompDam. Validation test methodologies
- **Banavara “Sesh” Seshadri:** Progressive damage analysis (PDA)
- **Austin Smith:** FNM. Materials characterization

Motivation for This Presentation

New analysis tools emerging that may be of help to NASA engineering

Future investigations/engineering studies may be aided by a comprehensive knowledge of new composites analysis tools

Dissemination of updates on research tools to NASA engineering is not presently optimal

Objective / Approach

Objective

Communicate new tool development on a regular basis for awareness and feedback

Approach

- Provide regular updates of new tools at NASA forums: NESC, LaRC Engineering Directorate (ED), others
- Encourage updates from all agency tool developers
- Publish evolving document containing details of new tools in a format guided by NASA engineering
- Improve understanding of possible NASA engineering applications
- Obtain technical and operational feedback from NASA engineering community

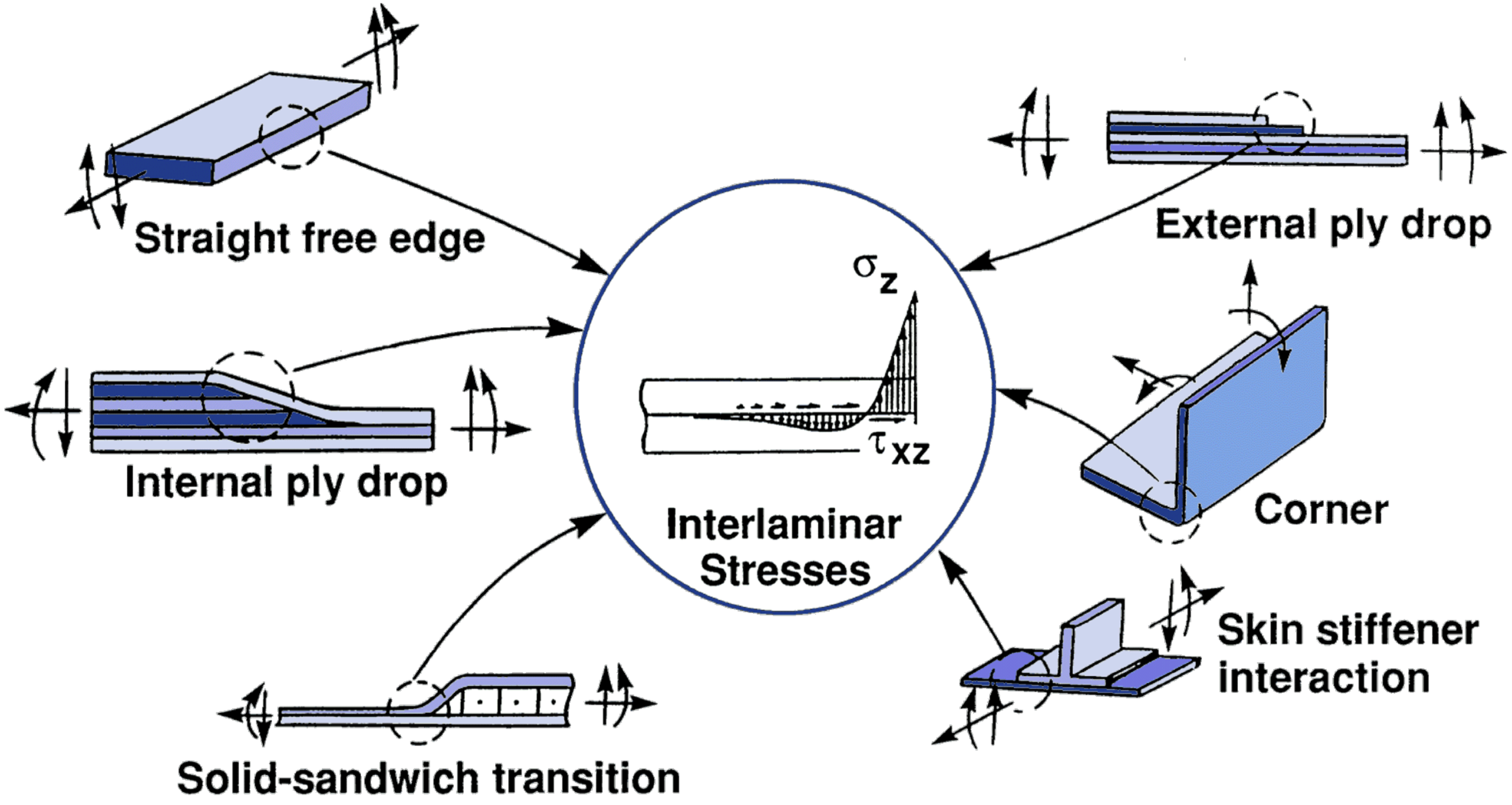
Composites Group Analysis Tools

- Virtual Crack Closure Technique and Progressive Release Explicit VCCT
- Composites Damage Progressive Damage Analysis
- Composite Fatigue Life Prediction
  - A User Material Subroutine for Cohesive Analysis
- Experimentation supporting PDA
  - Validation test methods
  - Material property input

Virtual Crack Closure Technique: Outline

- **Background: Delamination in composite materials**
- **Fracture mechanics methodology**
- **Virtual crack closure technique based tools – abbreviated timeline**
- **Progressive release explicit Virtual Crack Closure Technique (PRX – VCCT)**
- **Benchmark example**
- **Concluding remarks**

Background: Delamination in Composite Materials

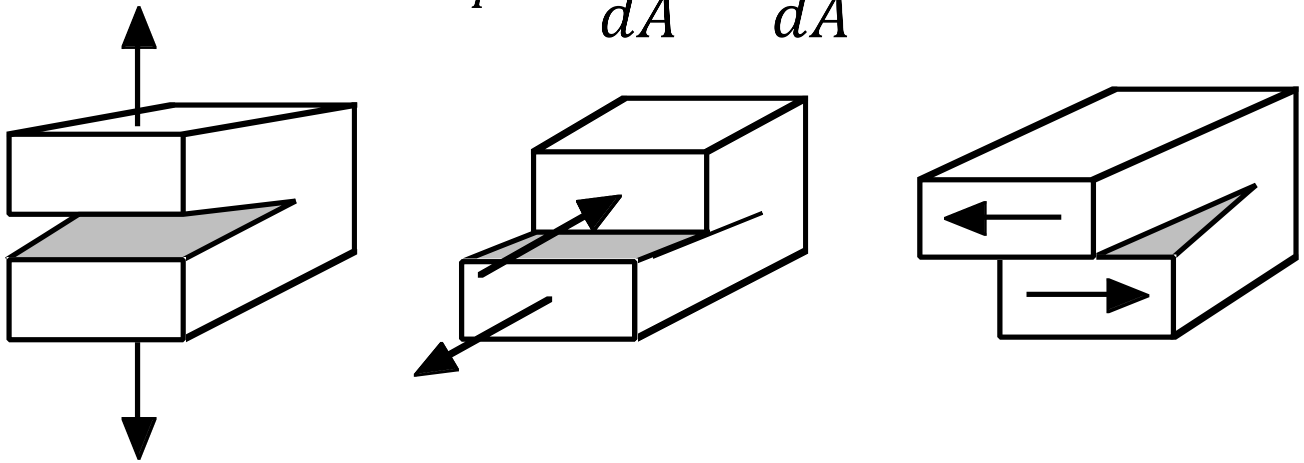


- **Delaminations pose a complex problem**
- **Difficult to model and predict**

Linear Elastic Fracture Mechanics Methodology: VCCT

- **Energy Release Rate**

$$G_T = \frac{dW}{dA} - \frac{dU}{dA}$$

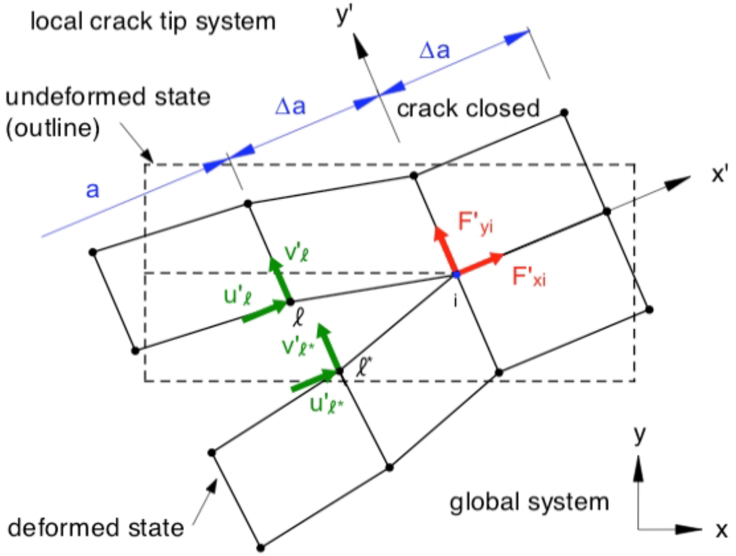


crack opening mode I | **in-plane shear mode II** | **tearing mode III**

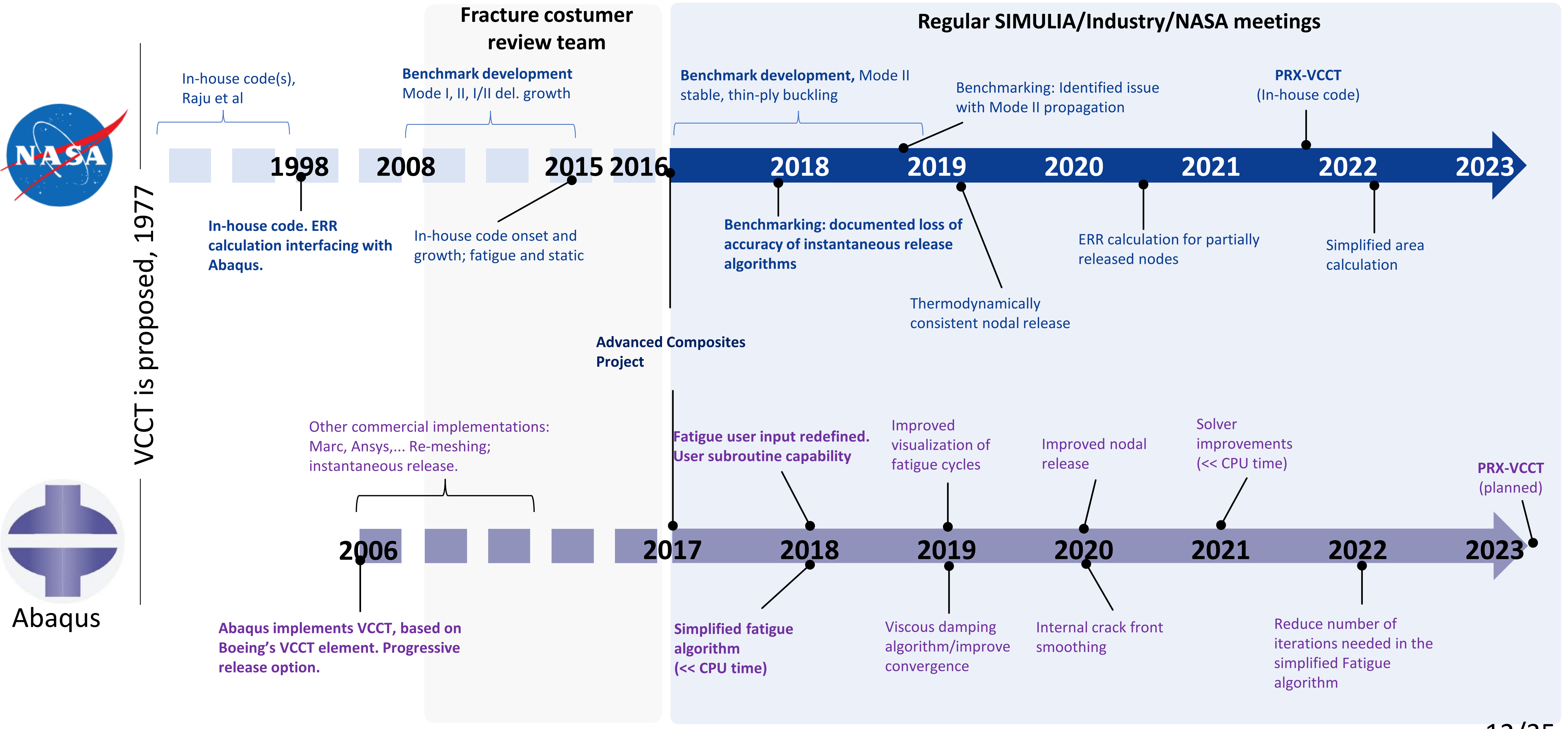
$$G_T = G_I + G_{II} + G_{III}$$

- **Static case: Propagation occurs if local mixed-mode energy release rate exceeds fracture toughness**
- **Fatigue case: Growth follows Paris Law**

- **Virtual Crack Closure Technique**
  - Two-dimensional (2-D) and three-dimensional (3-D) analysis
  - Nonlinear analysis
  - Arbitrarily shaped delamination front



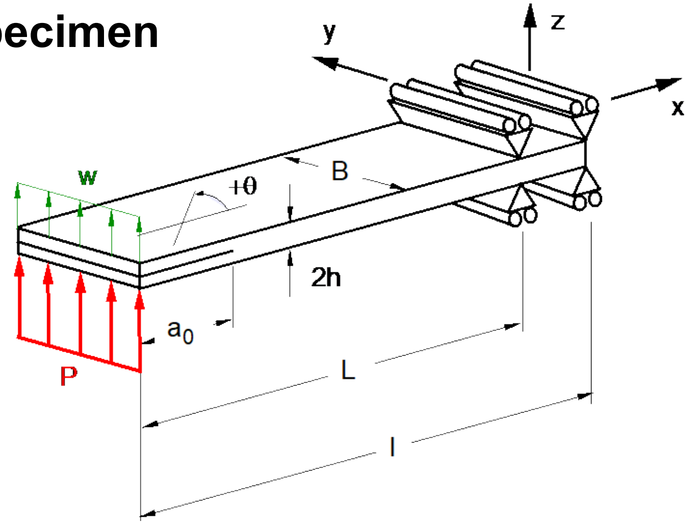
VCCT Based Tools: Abbreviated time-line
Emphasis on recent work (2017 – 2023)



Benchmark Problem Example: Calibrated-Loaded Split Specimen

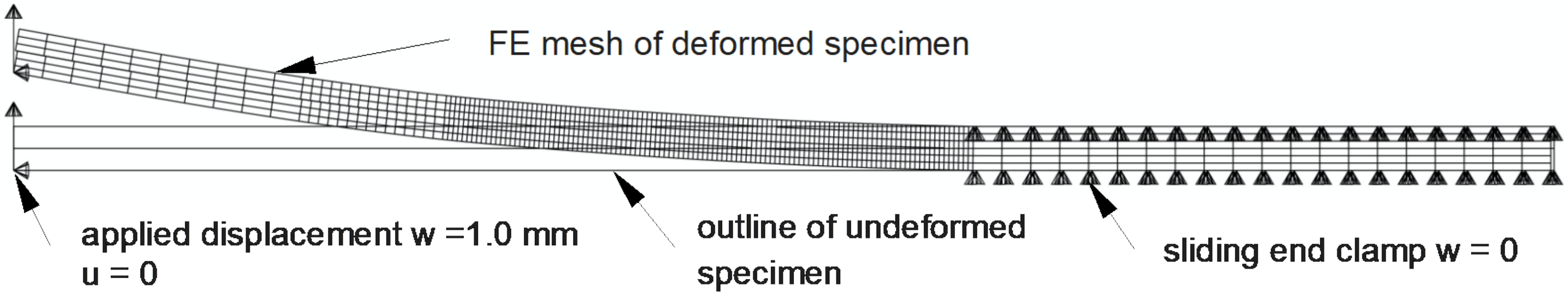
- **Calibrated End-Loaded Split (C-ELS) specimen**

B	25.4 mm
2h	4.5 mm (12 plies each)
L	100.0 mm
L	160.0 mm
a_0	50.0 mm



Material and Layup: IM7/8552
$[0]_{12}//[0]_{12}$

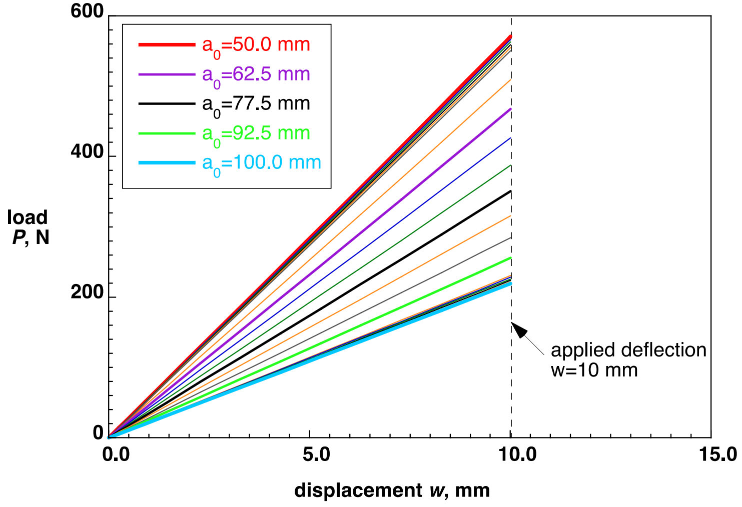
- **2-D Finite Element (FE) model - Abaqus 2021**
  - CPE4I
  - **Δa = 0.5mm**



Benchmark Cases for Static Loading Condition:

Development of C-ELS specimen based benchmark case

- **Results for multiple different crack lengths a_0**

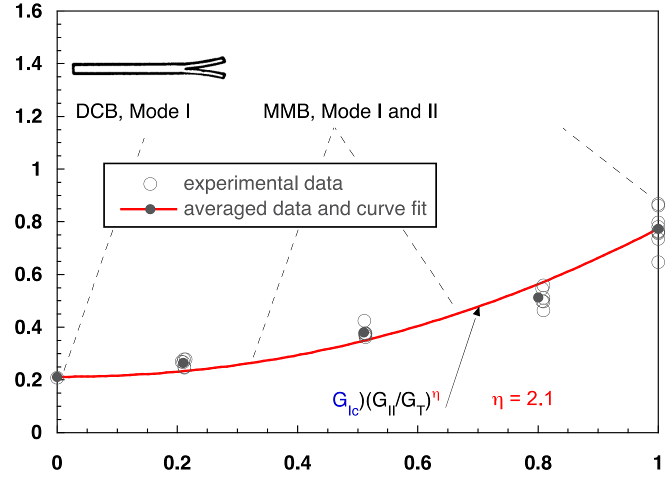


1. Models with multiple crack lengths a_0 (50.0 mm ≤ a_0 ≤ 100.0 mm)
2. Compute load P versus applied displacement w
3. Compute energy release rate G_T and G_{II}/G_T using VCCT for $w_{applied}$ = 10.0 mm
4. Obtain G_{IIc} from Benzeggagh- Kenane (BK) law
5. Calculate P_c and w_c for each a_0 using

$$\frac{G_T}{G_c} = \frac{P^2}{P_c^2} \Rightarrow P_c = P\sqrt{\frac{G_c}{G_T}}$$

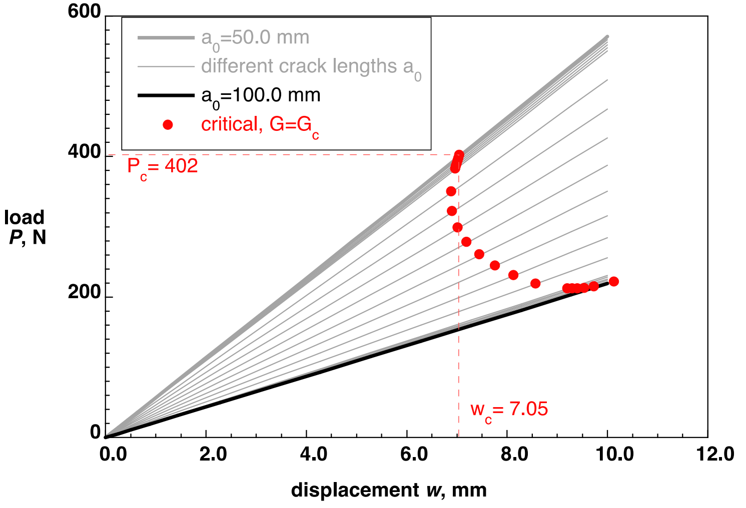
$$\text{and} \quad \frac{w_c}{2} = \frac{w}{2}\sqrt{\frac{G_c}{G_T}}$$

- **BK-law for IM7-8552**

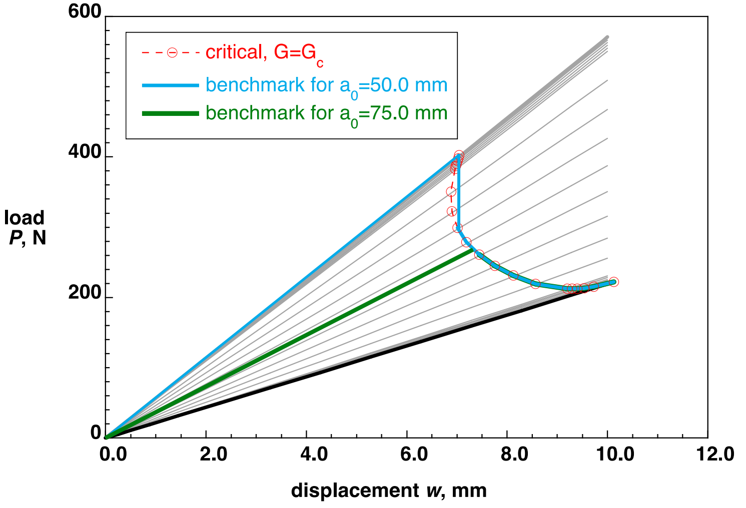


- **Results from automated growth analysis expected to follow benchmarks**

- **Critical loads and displacements**



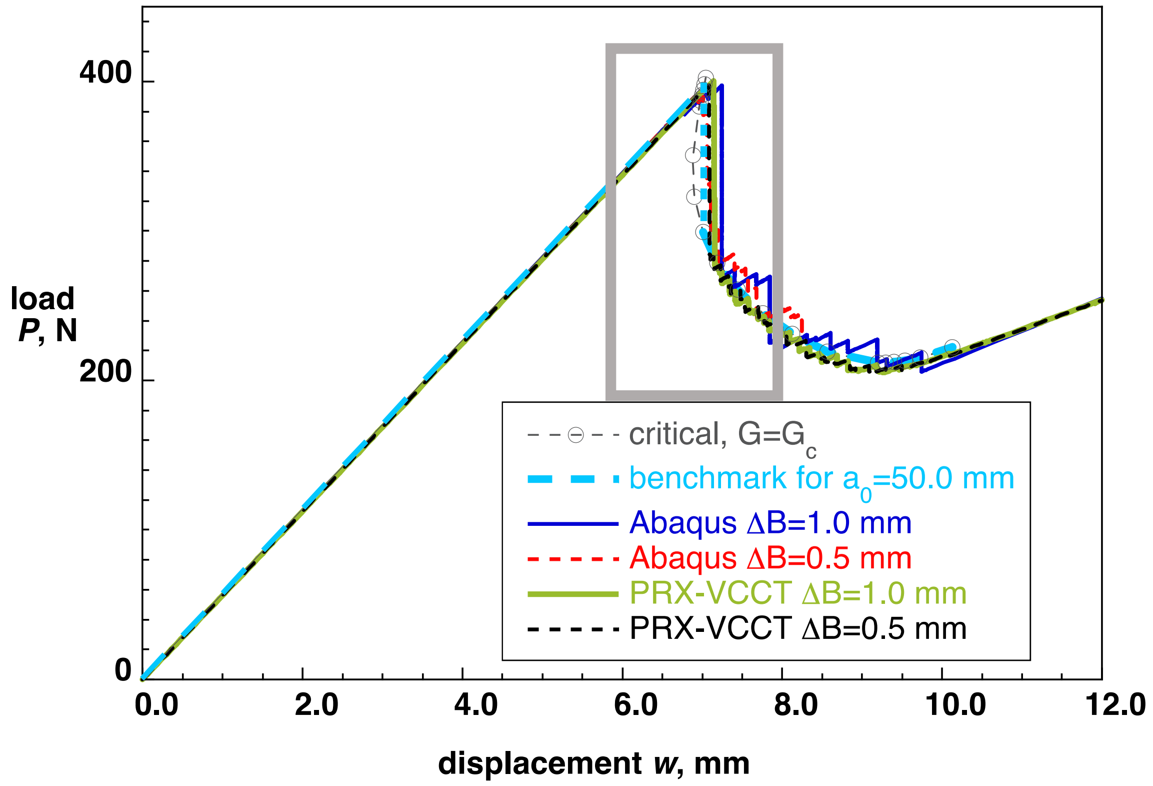
- **Benchmarks for a_0 = 50 mm and 75 mm**



Assessment of Automated Growth Analysis:

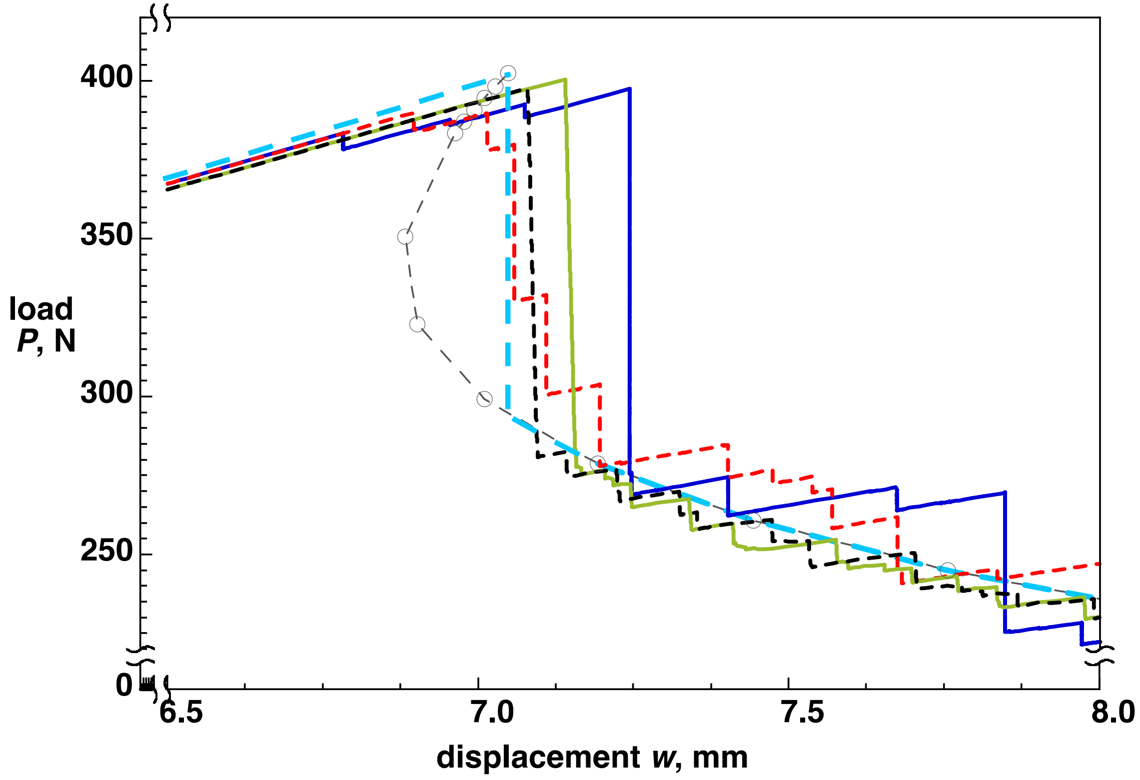
Results from 3-D analysis of C-ELS specimen – a_0 = 50.0 mm

- **Results obtained from aligned meshes**



- **Computed results slightly exceeded critical point**
- **Unstable growth part captured as expected**
- **Computed results dropped slightly below the benchmark**
- **Results oscillated around the critical path**

- **Detail**

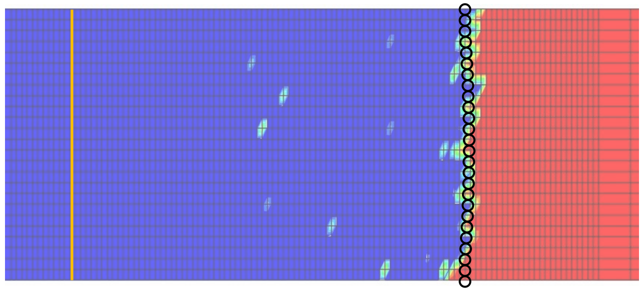


- **Oscillations less pronounced for refined mesh**
- **Results for PRX-VCCT appear smoother and closer to the benchmark**

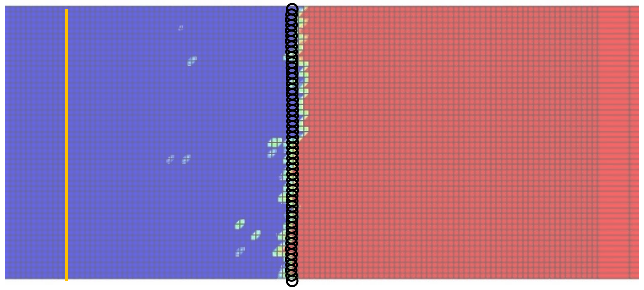
Assessment of Automated Growth Analysis:

Computed delamination front contours – a_0 = 50.0 mm

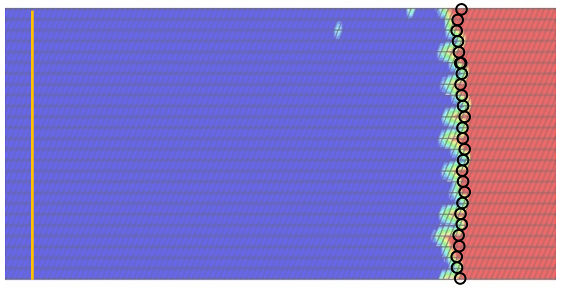
- **Aligned mesh**
  Δa = 0.5 mm, ΔB = 1.0 mm
  increment:
  Abaqus= 5000
  PRX-VCCT = 910



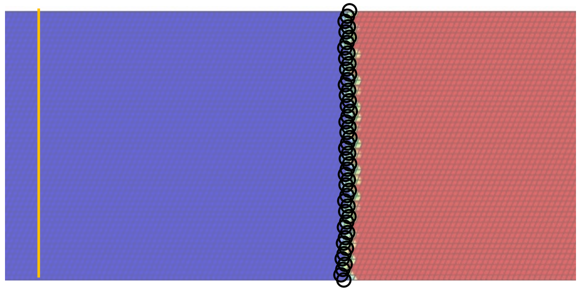
- **Aligned mesh**
  Δa = 0.5 mm, ΔB = 0.5 mm
  increment:
  Abaqus= 6000
  PRX-VCCT= 457



- **Misaligned mesh**
  Δa = 0.5 mm, ΔB = 1.0 mm
  increment:
  Abaqus= 5010
  PRX-VCCT= 1648



- **Misaligned mesh**
  Δa = 0.5 mm, ΔB = 0.5 mm
  increment:
  Abaqus= 6150
  PRX-VCCT= 1533



Legend

initial front

Abaqus: fully failed, partially failed, pristine

PRX-VCCT: ○ computed front

- **For Abaqus contours showed zig-zag behavior with unreleased elements developing (islands)**

- **For PRX-VCCT front appeared continuous and smooth Formation of islands in the wake not observed**
- **Results obtained with relatively low number of increments**

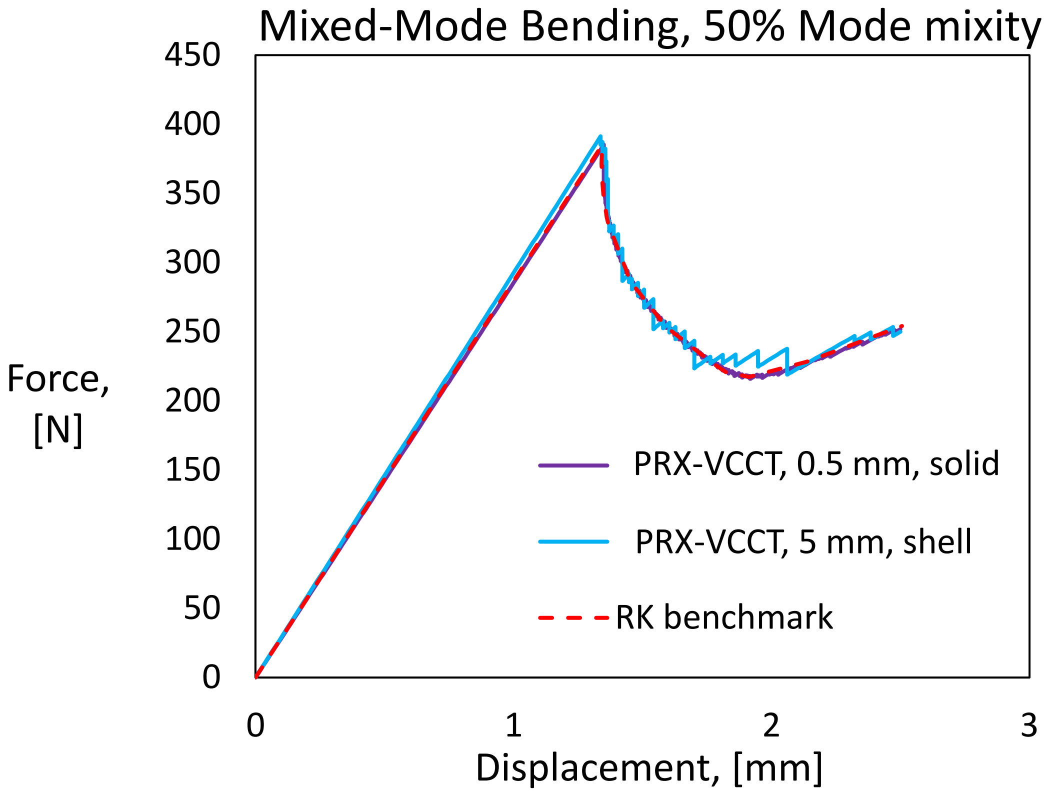
PRX - VCCT

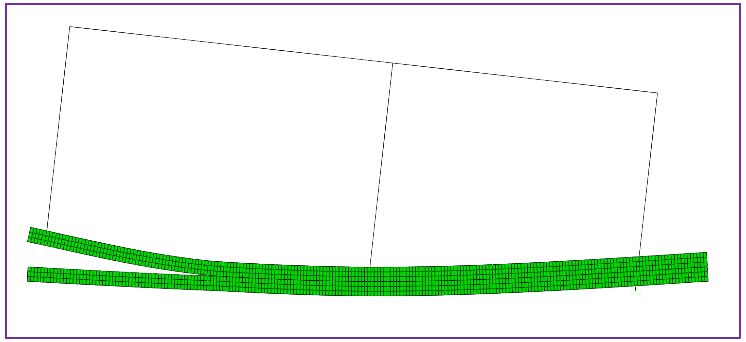
Key features:

- Energy release rate calculation based on VCCT consistent with Linear Elestic Fracture Mechanics (LEFM)
- Growth simulation; no re-meshing
- Fatigue/Static
- No convergence difficulties
  - Implicit solver; explicit propagation
- Structural elements
- Multiple fracture planes

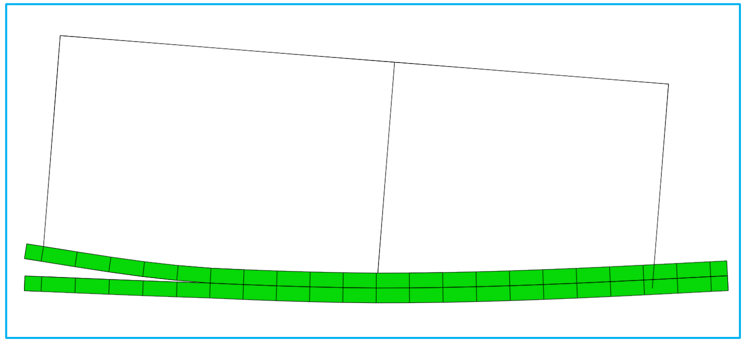
Limitations:

- Pre-defined plane
- Initial pre-crack(s)
- LEFM
  - E.g. R-curves are specimen dependent
- Structured meshes
  - Similar element sizes/nodal grids above and below the fracture plane



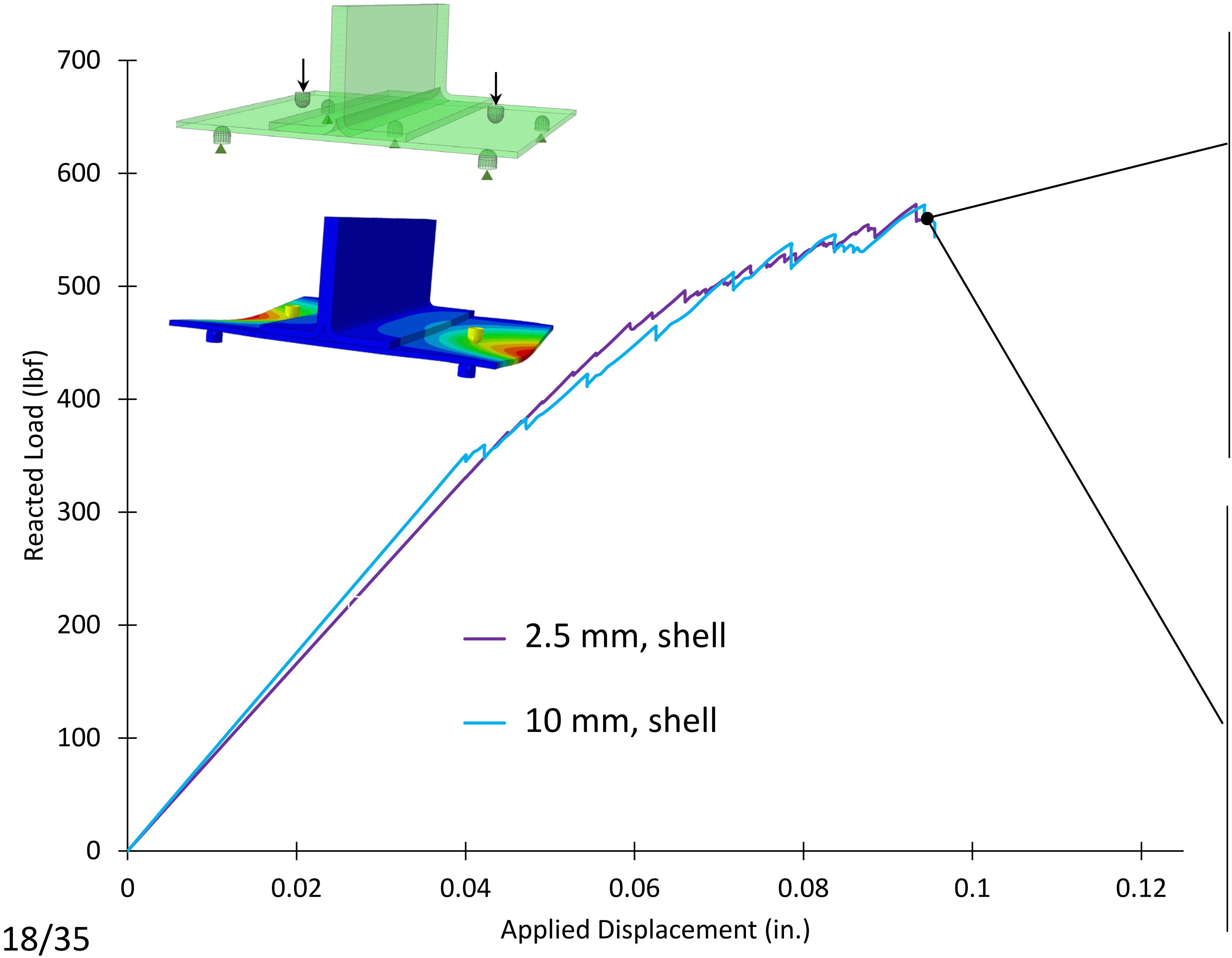


PRX-VCCT, 0.5 mm, solid



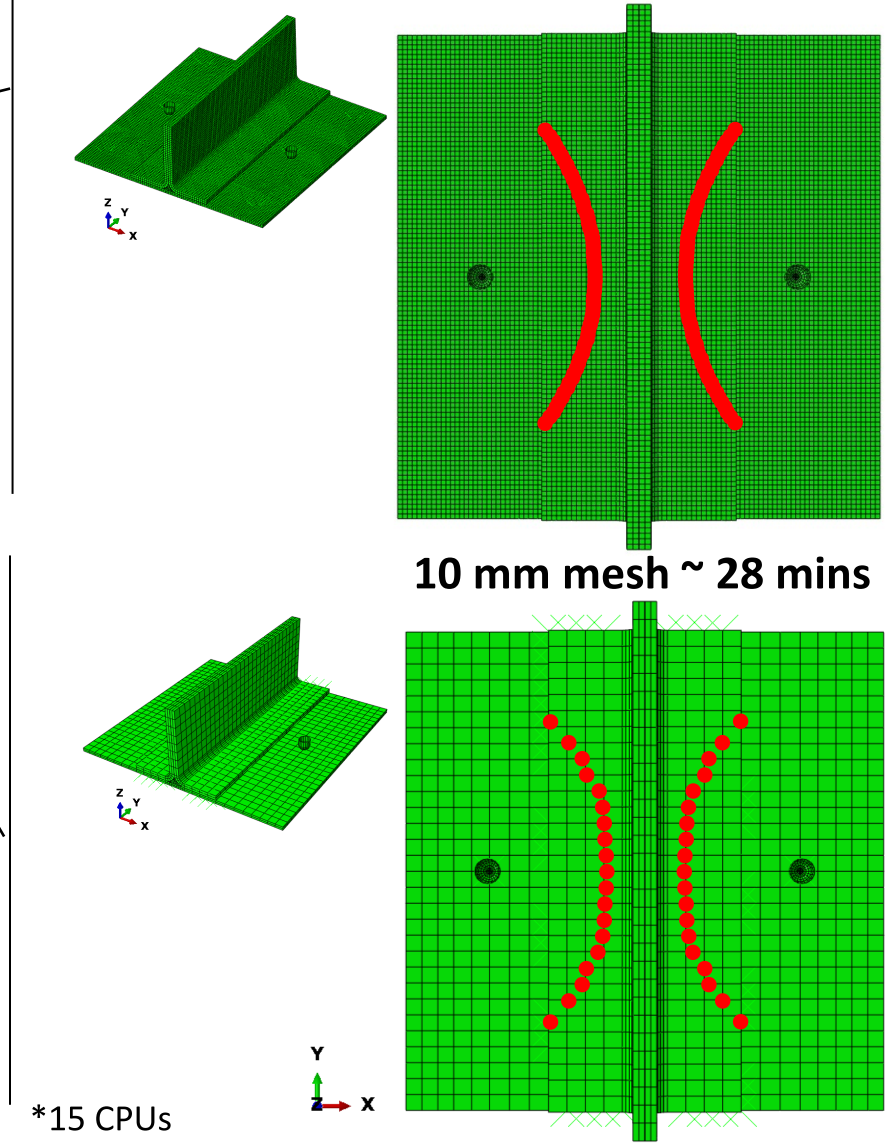
PRX-VCCT, 5 mm, shell

PRX-VCCT: Structural example – 7-point bending



Simulated del. Fronts:

2.5 mm mesh ~ 2h*



*15 CPUs

VCCT Summary

- **Benchmarking**
  - **Benchmark example based on the C-ELS specimen created using LEFM and VCCT**
  - **Analysis benchmarking was successfully used to assess the performance and identify critical differences**
  - **Benchmarking is key to help users and developers understand and improve codes**
  - **Adopt as standard practice when evaluating novel approaches/software**
  - **Benchmarks proposed span fracture modes (Mode I, II and I/II) and loadings (static, fatigue, buckling)**
- **PRX-VCCT**
  - **Energy Release Rate (ERR) calculation; growth simulation**
  - **Large element sizes; no convergence issues**
  - **Static and fatigue**
  - **Enables damage tolerance assessments using “structural” meshes**
  - **Damage tolerance can be assessed earlier in the design process**

CompDam PDA: Development History

2001–08 Cohesive zone elements (with Camanho, Turon, et al.)

2003–05 LaRC Failure Criteria (with Camanho, Pinho, et al.)

2006–11 P. Maimí's Abaqus[1] UMAT subroutine continuum damage mechanics (CDM) material model

2011 Change to Abaqus/Explicit VUMAT subroutine material model

2012–15 Deformation Gradient Decomposition (DGD) method for matrix cracks

2016 Initial open-source release during the Advanced Composites Project (ACP)

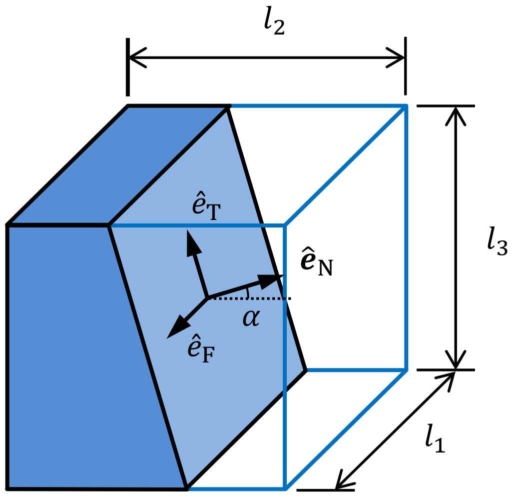
2017–19 Multiple collaboratively developed feature releases during the ACP

1. Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available

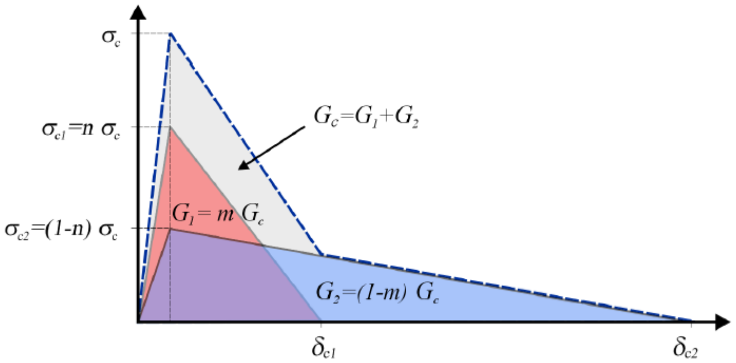
* Years are approximate, representing either conceptual development through release or years of related publications

CompDam: Interlaminar Failure Modes

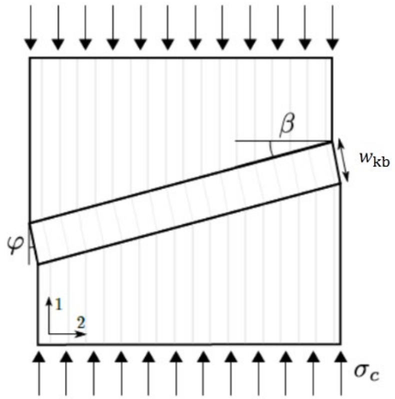
- **Matrix cracks**
  - Represented by cohesive surfaces, inserted with the DGD method
  - Cohesive surfaces use typical mixed-mode cohesive laws for damage evolution for linear traction-displacement softening laws
  - Transverse crack orientations α are set at initiation and tracked
  - Friction acts on the cracked portion of failure surfaces



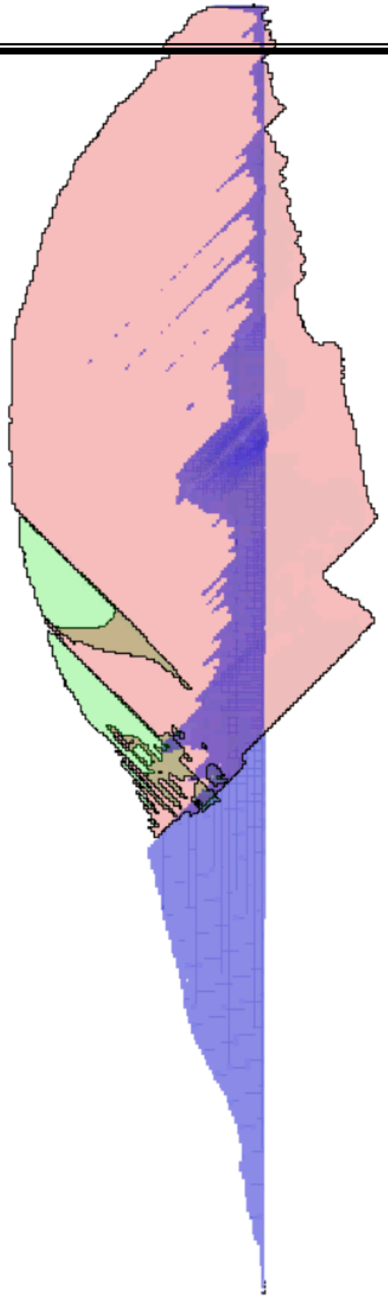
- **Fiber tension**
  - Maximum strain failure criterion for failure initiation
  - Bi-linear stress-strain CDM softening law for damage evolution



- **Fiber kink bands**
  - Based on Budiansky's fiber kinking theory
  - Kink band kinematics are explicitly modeled at the mesoscale
  - Response is governed by the pre-peak nonlinearity response and the initial fiber misalignments



CompDam: Interlaminar Fracture (Delamination)

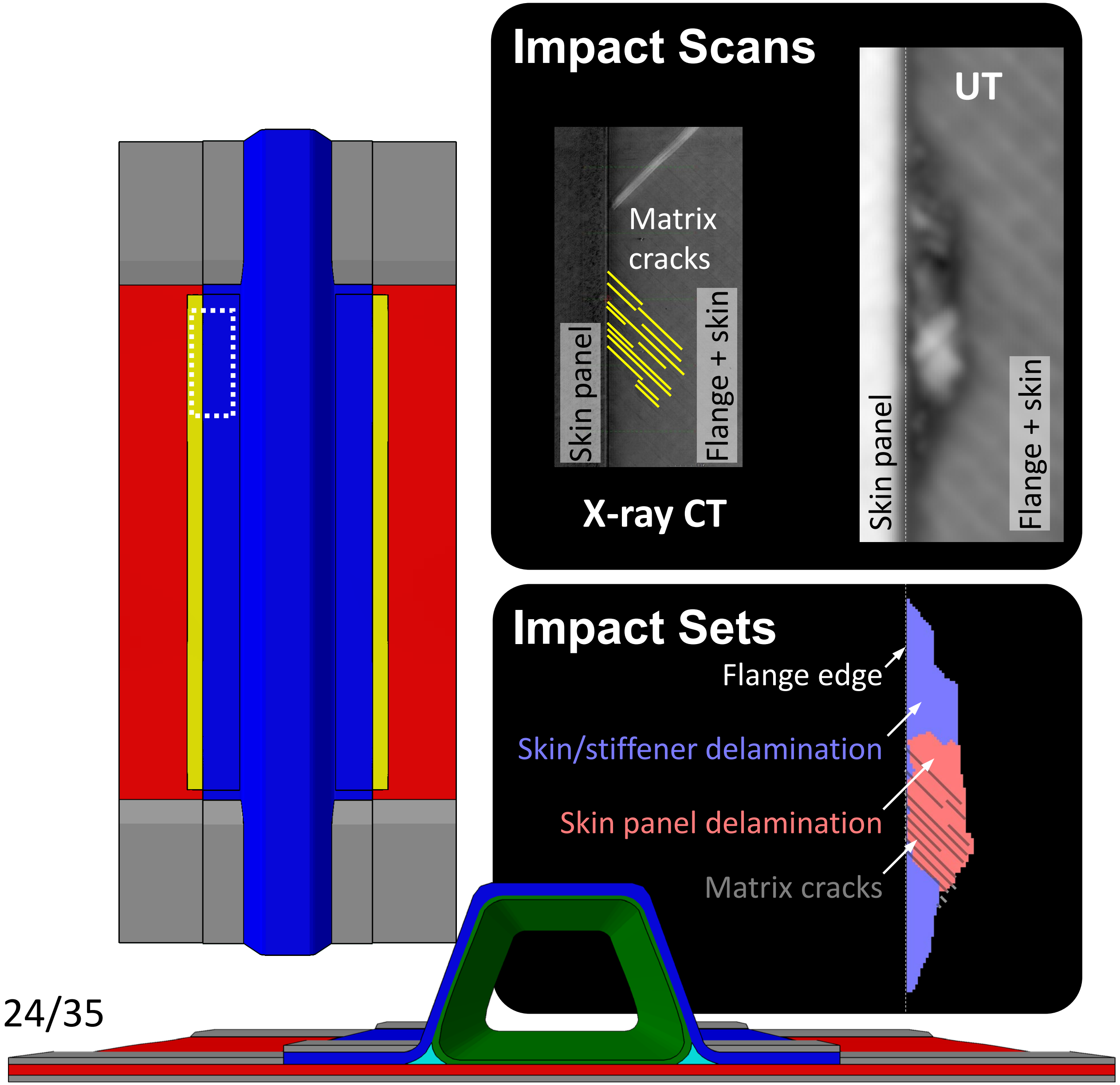


- Matrix cracks and delaminations use same cohesive law logic in the CompDam material subroutines
- Mode mixity defined according to Benzeggagh-Kenane
- Linear softening laws in traction-displacement space
- Shear strengths depend on normal compressive load, according to LaRC04 failure criteria
- Friction acts on delaminated portions of cohesive surfaces
- Interlaminar materials are defined using user subroutine material cards, and are used with Abaqus cohesive elements
  - Three-dimensional, eight-node COH3D8 elements
  - Two-dimensional, four-node COH2D4 elements

CompDam: Material Property Input Data

- 3-D orthotropic stiffness terms : E_1, E_2, G_{12}, ν_{12}, ν_{23}
- Coefficients of thermal expansion
- Nonlinearity of pre-peak responses
  - Fiber-direction
  - Matrix
- Strengths (fiber tension, fiber compression, matrix tension, matrix compression, matrix shear)
- Mixed-mode matrix fracture toughness : G_{Ic}, G_{IIc}, η_{BK}
- Matrix compression fracture angle : α_0
- Coefficient of friction for cracked matrix material
- Fiber fracture toughness, including R-curve
- Fiber kink band width

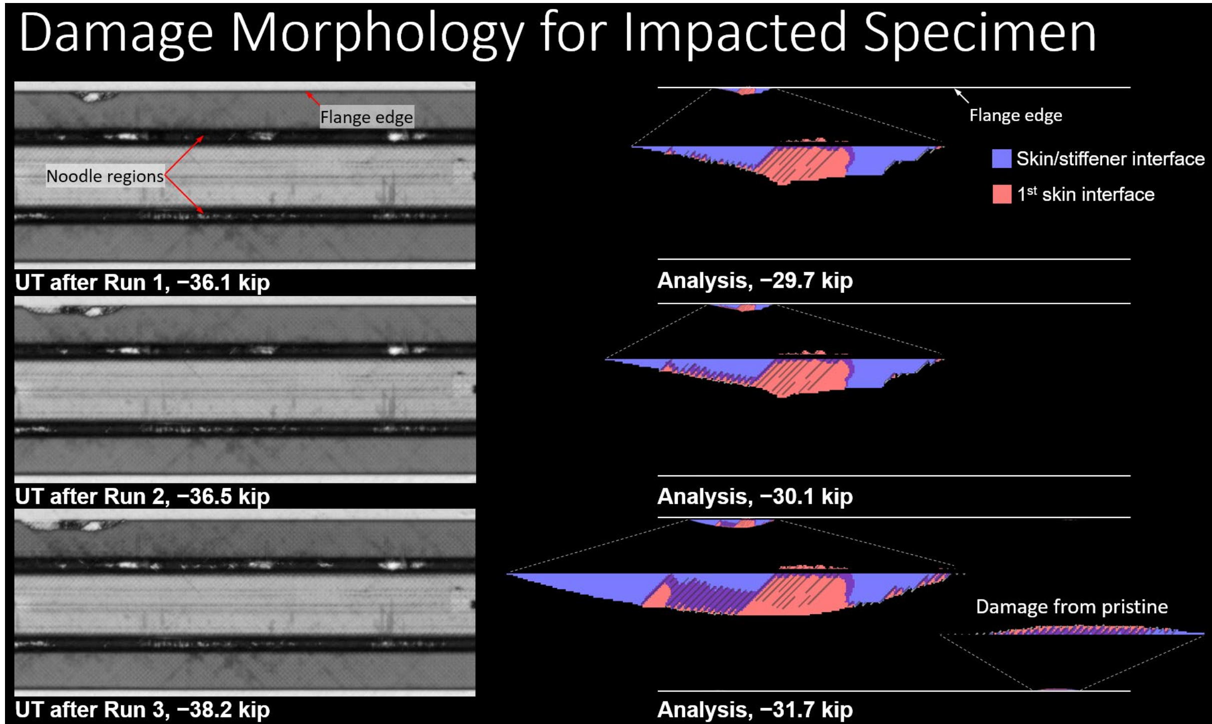
CompDam: Validation Testing



Seven-point bending and single-stringer compression specimens with low-velocity impacts were evaluated

Damage manually mapped from UT and X-ray CT data

Damage morphology matched well, but growth rates were over-predicted

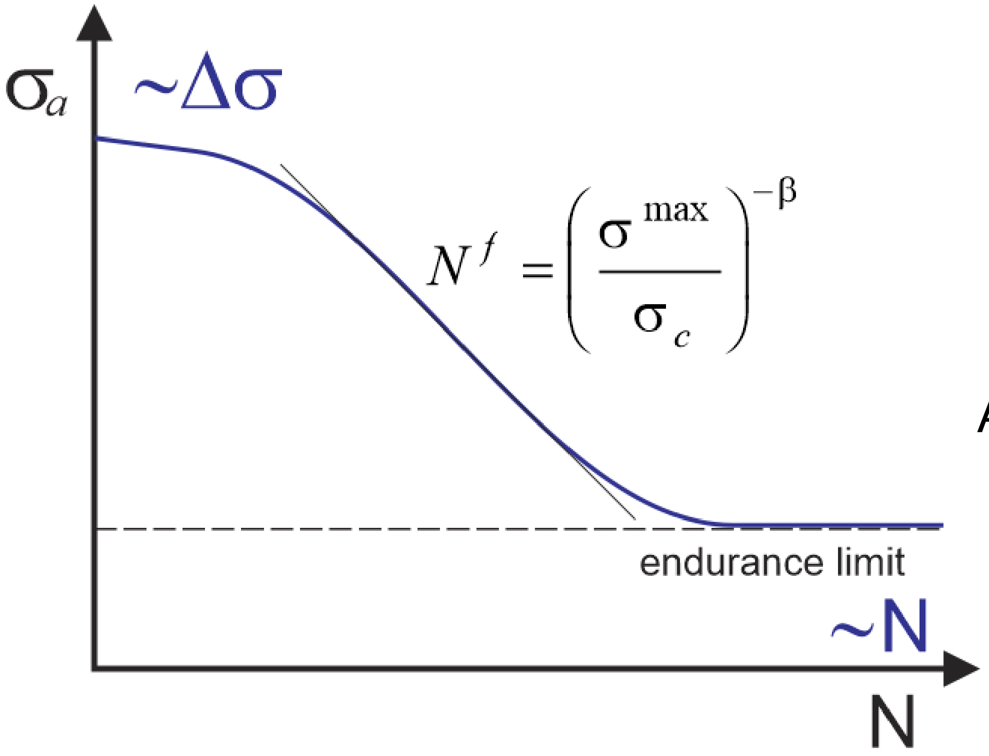


Composite Fatigue Life Prediction

– A User Material Subroutine for Cohesive Analysis

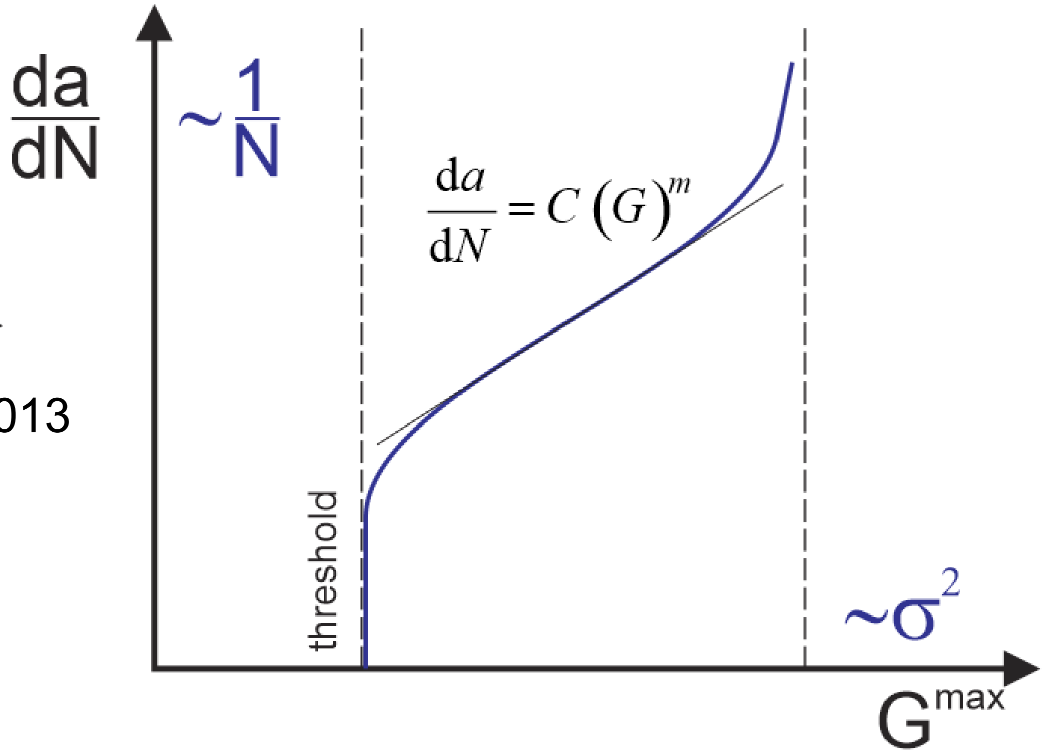
Fatigue: (Cyclic stress to failure) S-N or Paris Law?

S-N Curve



Allegri, 2013

Paris Law

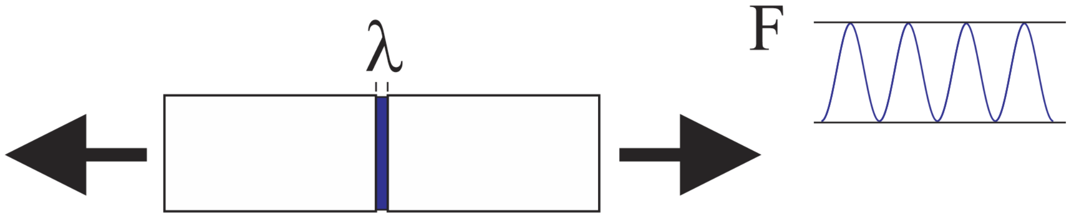


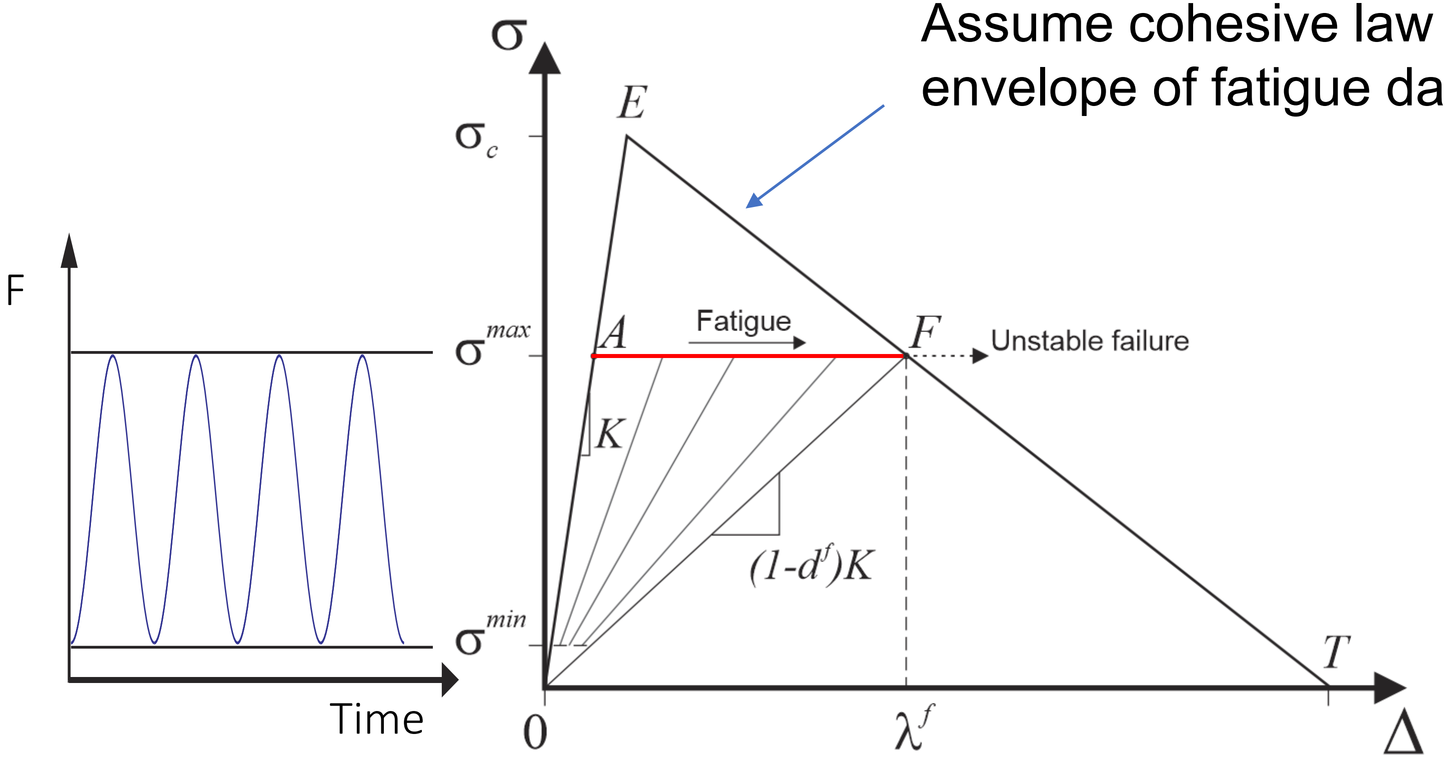
S-N Curve and Paris law are related: $\beta = 2m$

Can we develop a cohesive model based on S-N that can also predict crack propagation?

S-N Cohesive Fatigue Damage Model

Consider case of bar subjected to cyclic load





Assume cohesive law is envelope of fatigue damage

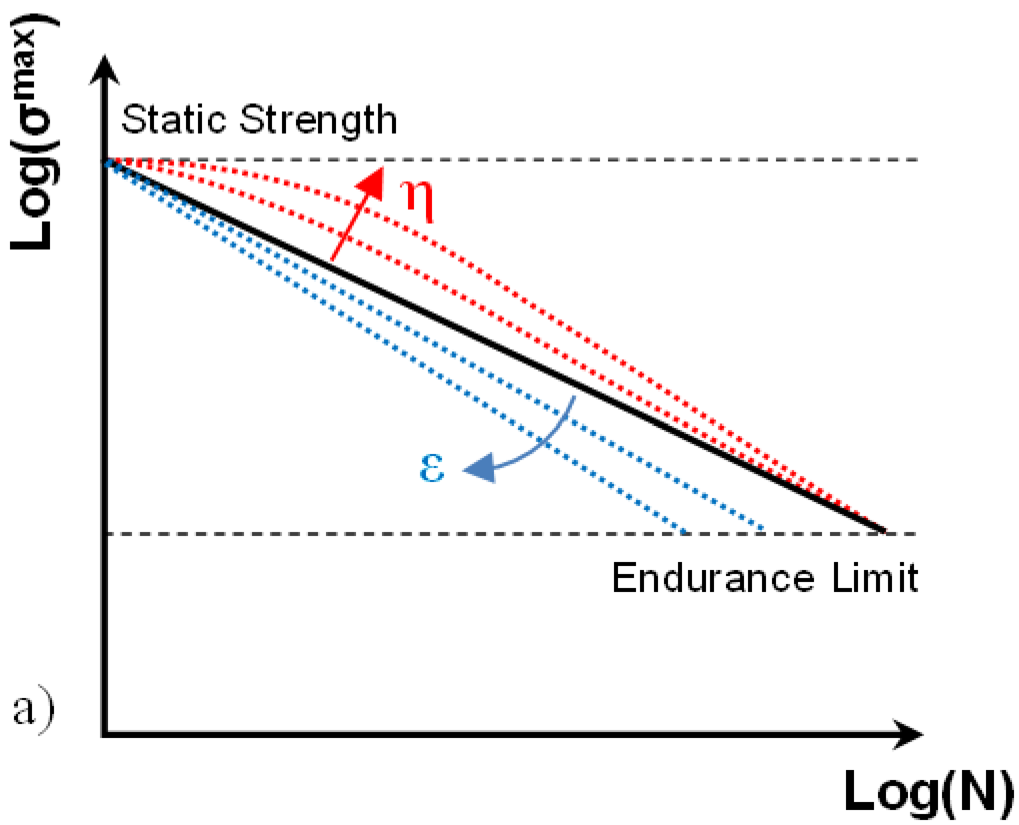
What damage law?

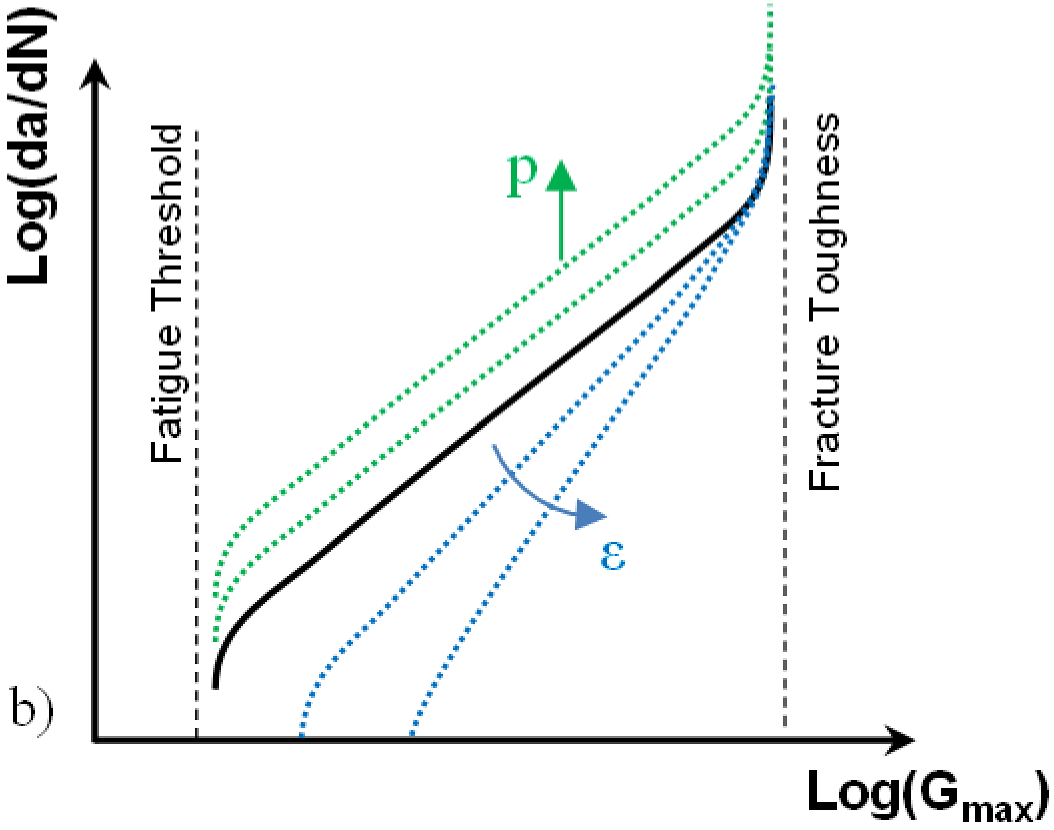
$$\frac{dD}{dN} = \frac{1}{\gamma}\frac{(1-D)^{\beta-p}}{E^{\beta}(p+1)}\left(\frac{\lambda}{\lambda^*}\right)^{\beta}$$

Dávila et al. NASA/TP–2020-220584

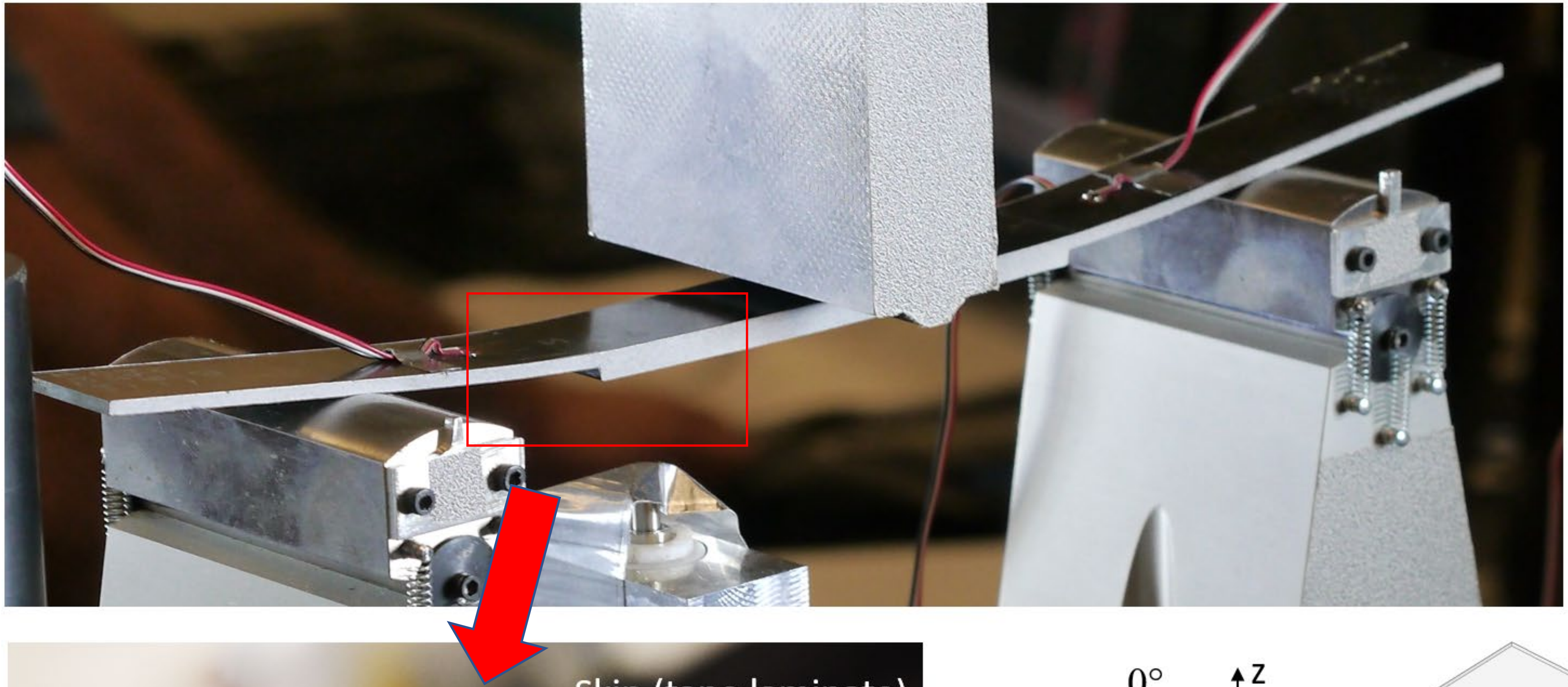
Effect of Damage Model Parameters

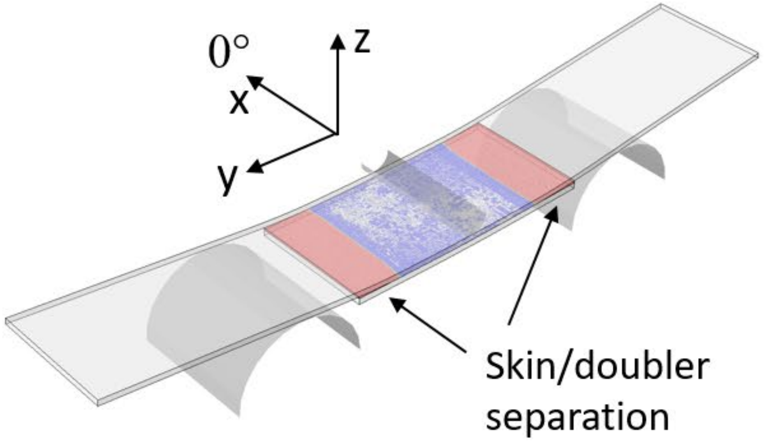
Effect of the model parameters *η, ε* and *p* on: a) S-N diagram; b) crack propagation curve





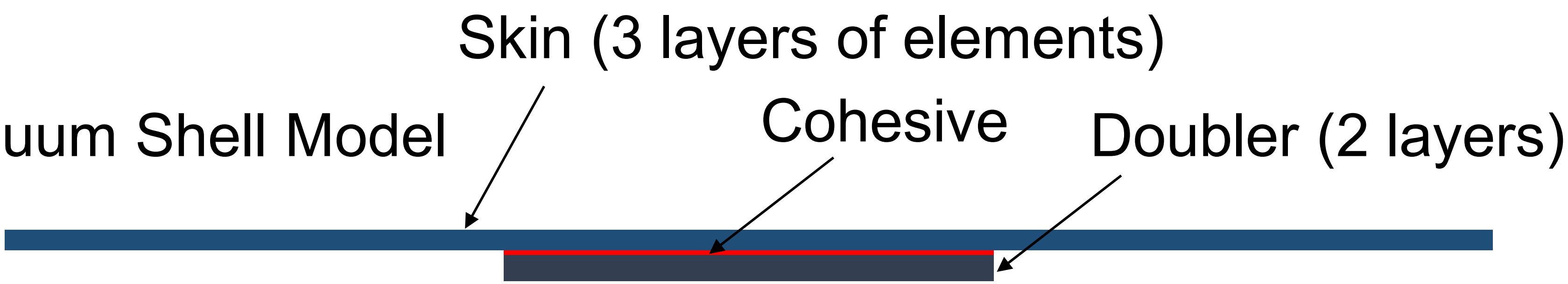
Validation Test: Three-Point Bend (3PB) Doubler Specimen



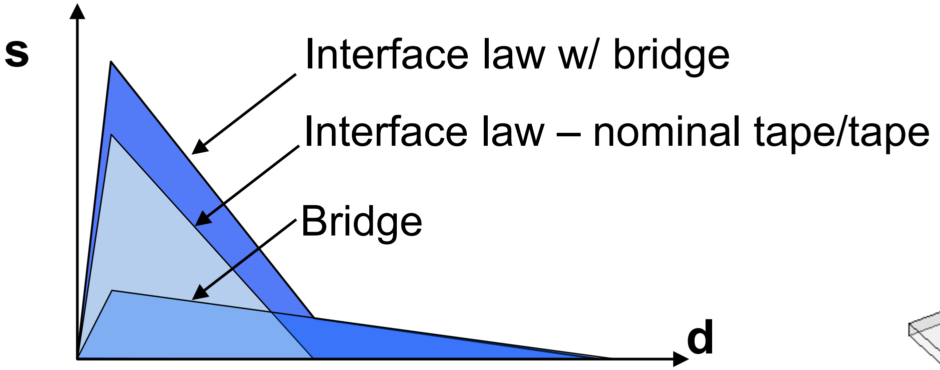


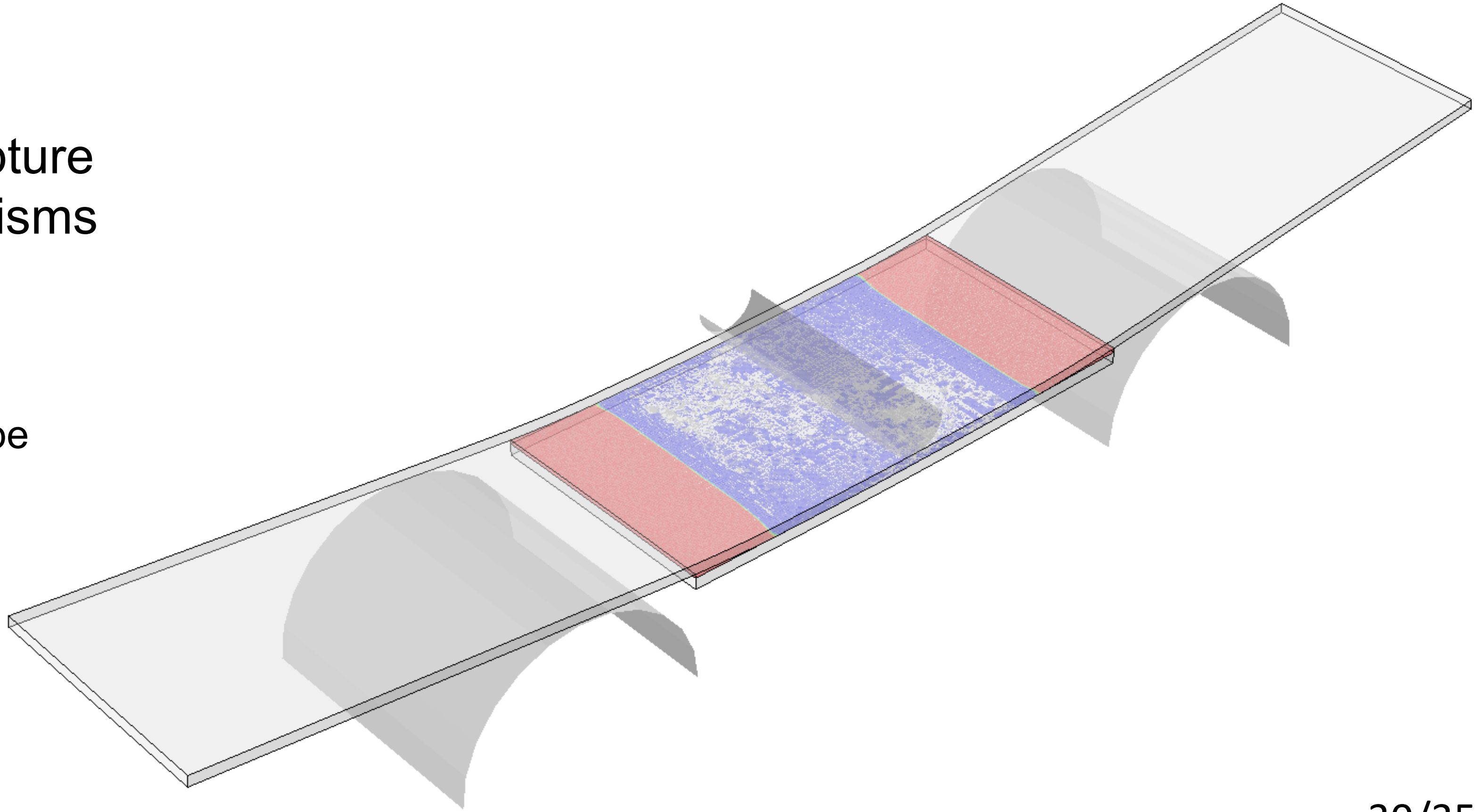
Validation Test: Simplified Shell Model of 3PB Specimen

Continuum Shell Model

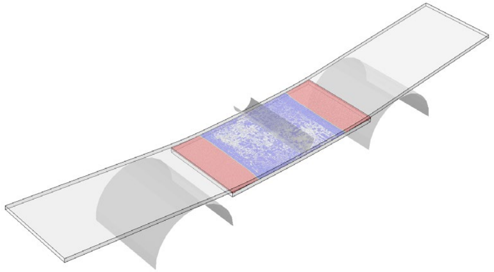


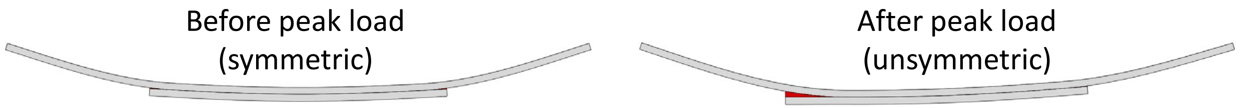
Empirical cohesive properties capture the effects of all damage mechanisms

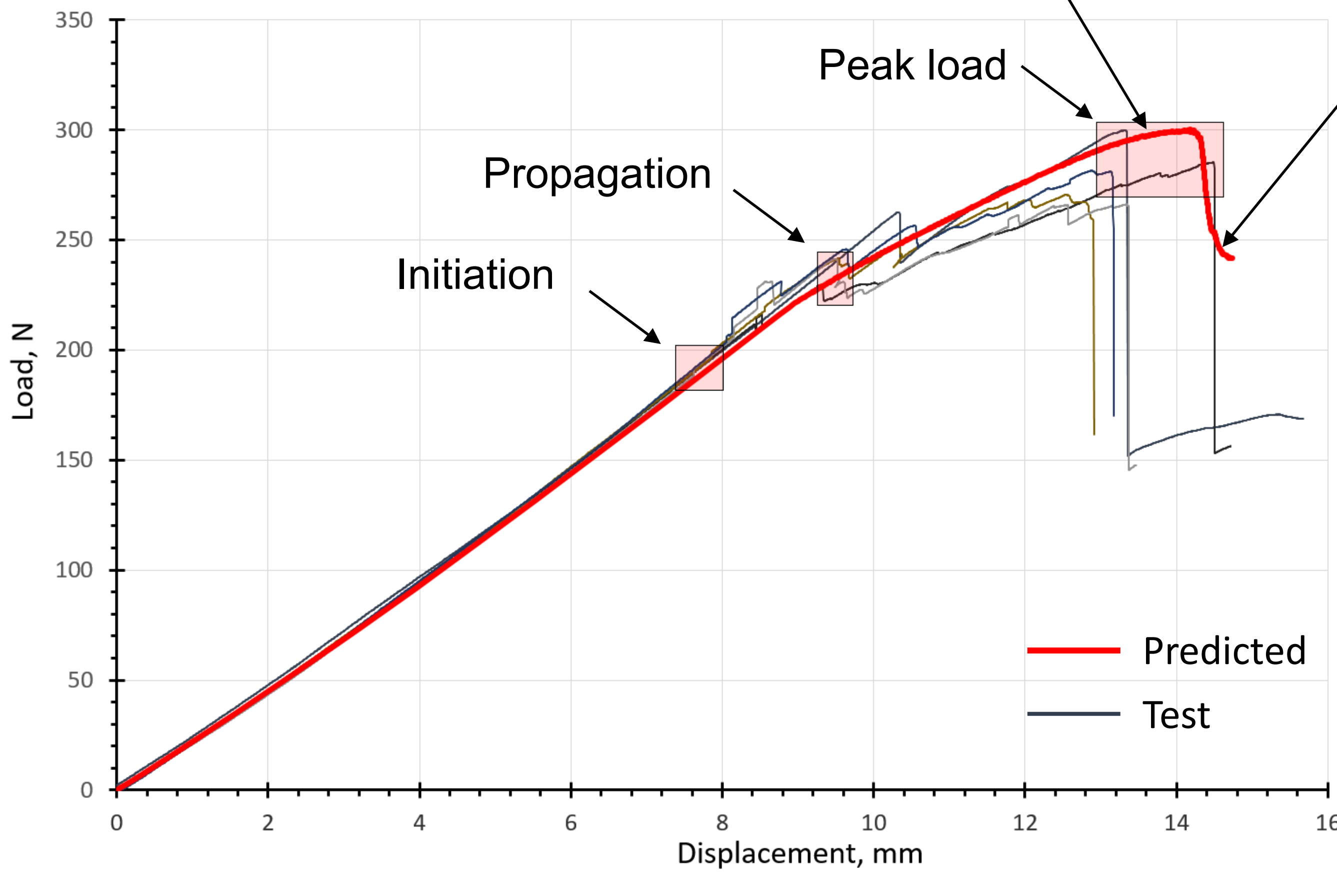




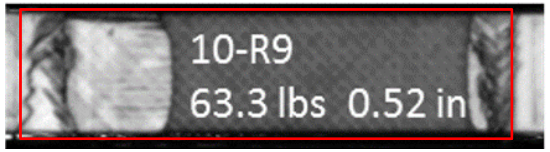
Validation Test: Simplified Shell Model of 3PB Specimen



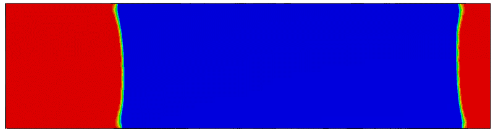




Test



Analysis

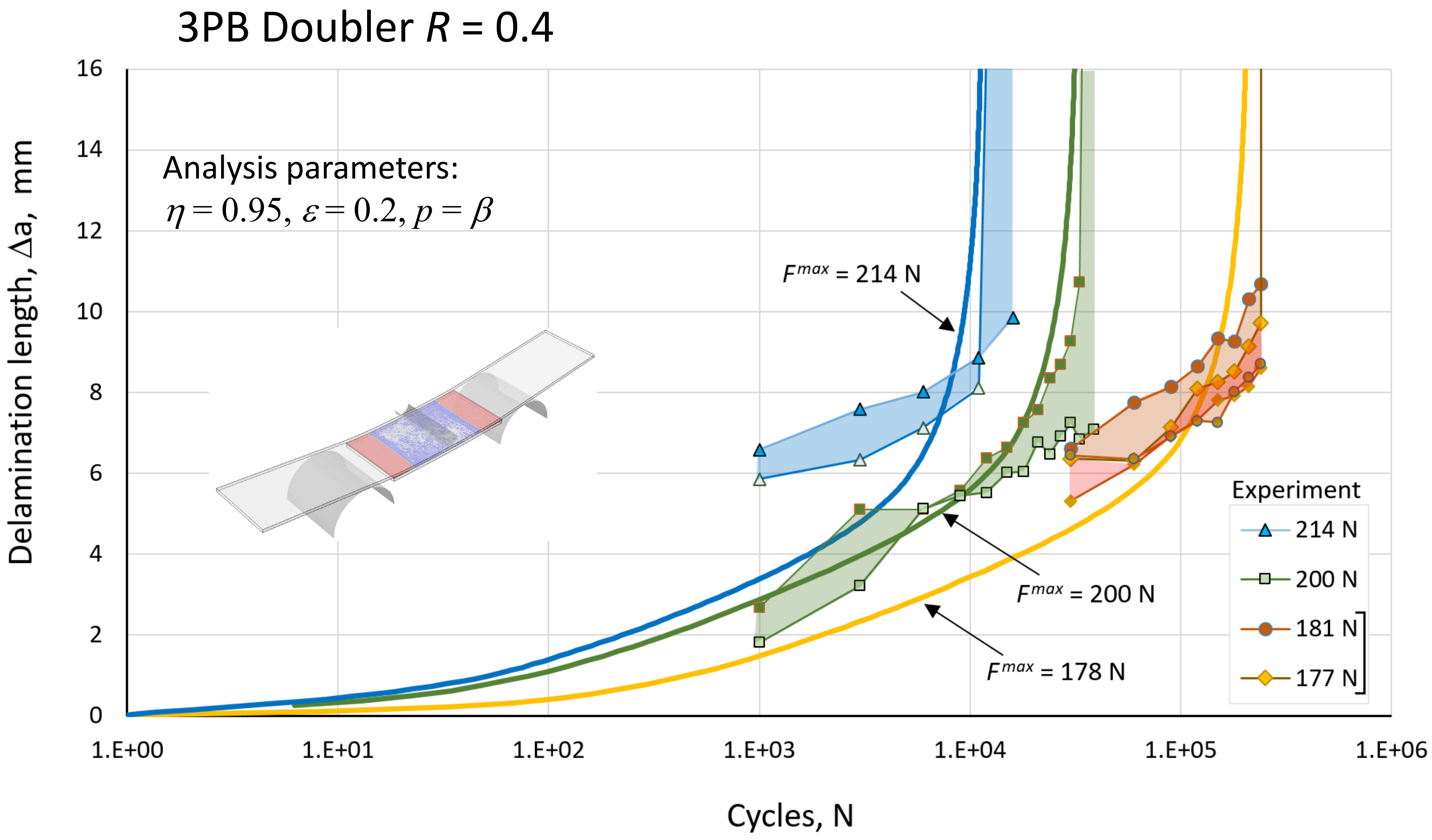


Initiation → Base; Propagation → Bridge

	Base	Bridge	
GI_c =	0.45	0.60	N/mm
GII_c =	1.1	4.50	N/mm
σ_c =	105	3.5	MPa
τ_c =	97	10.	MPa
K_I =	5E+05	1.8E+04	N/mm³
K_{sh} =	1.6E+05	3.0E+04	N/mm³
BK =	2.07	3	

Computed (Turon's constraints)

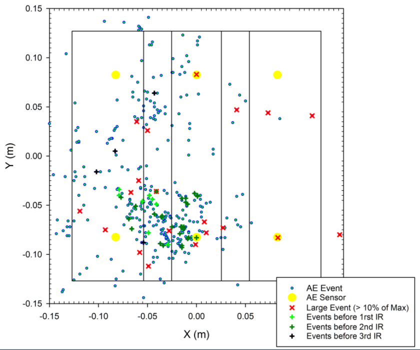
Validation Test: Predicted Versus Measured Delamination Growth

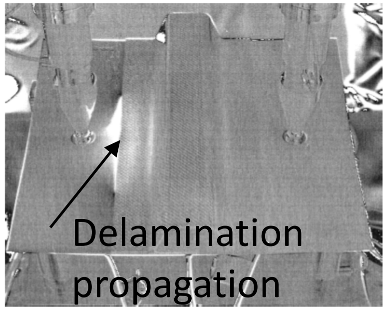


Validation Testing: Experimental Methods

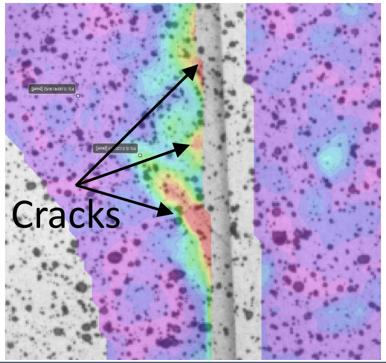
Objective: *Generate sufficient data on the initiation and evolution of damage to make thorough comparisons with progressive damage analysis predictions*

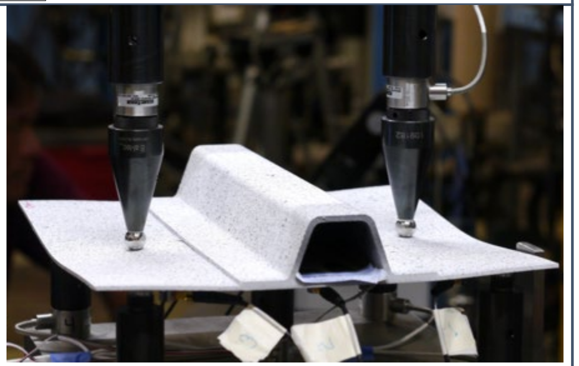
- Acoustic Emission (AE), Passive Thermography
  - Early damage detection
  - Rapid damage accumulation
  - Test interruption





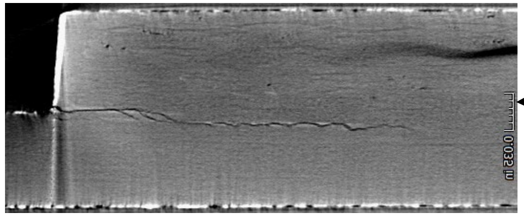
- Digital Image Correlation
  - Load introduction, boundary conditions, global response
  - Surface damage initiation and propagation

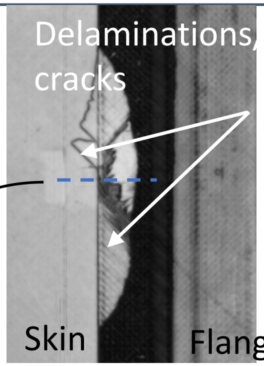




- Ultrasonic (UT), X-Ray/CT
  - In-situ damage assessment (UT)
  - Detailed pre and post-test assessment

X-ray/CT





PDA Analysis Material Property Input

Problem

PDA tools for simulating damage in laminated composites rely on specific empirical input data. Established standardized test methods not equipped to provide information necessary for PDA input:

- Crack growth resistance and fatigue delamination growth rates at non-unidirectional ply interfaces and in hybrid laminates
- Strength components subjected to volumetric scaling effects
- Traction separation law measurements

Action

Modification of existing standard test methods and development of new standards to provide reliable PDA input property data

Closing Remarks

Optimizing Tool Availability and Assessing Tool Suitability

- Better communication with NASA engineering
- Document candidate tool applications and complexity associated with use, including additional requisite experimental data
- Document examples of extra-agency tool application
- Conduct retrospective application of tools