

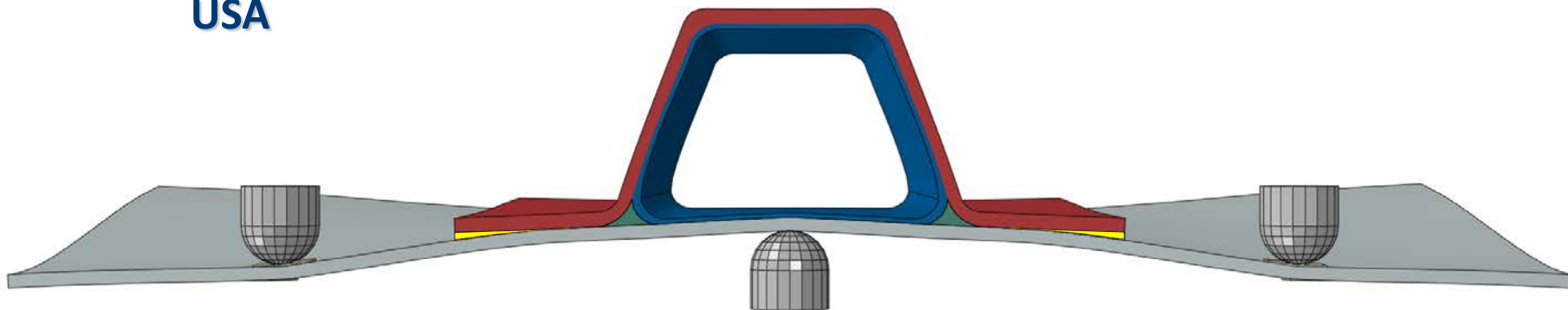


NASA Advanced Composites Program

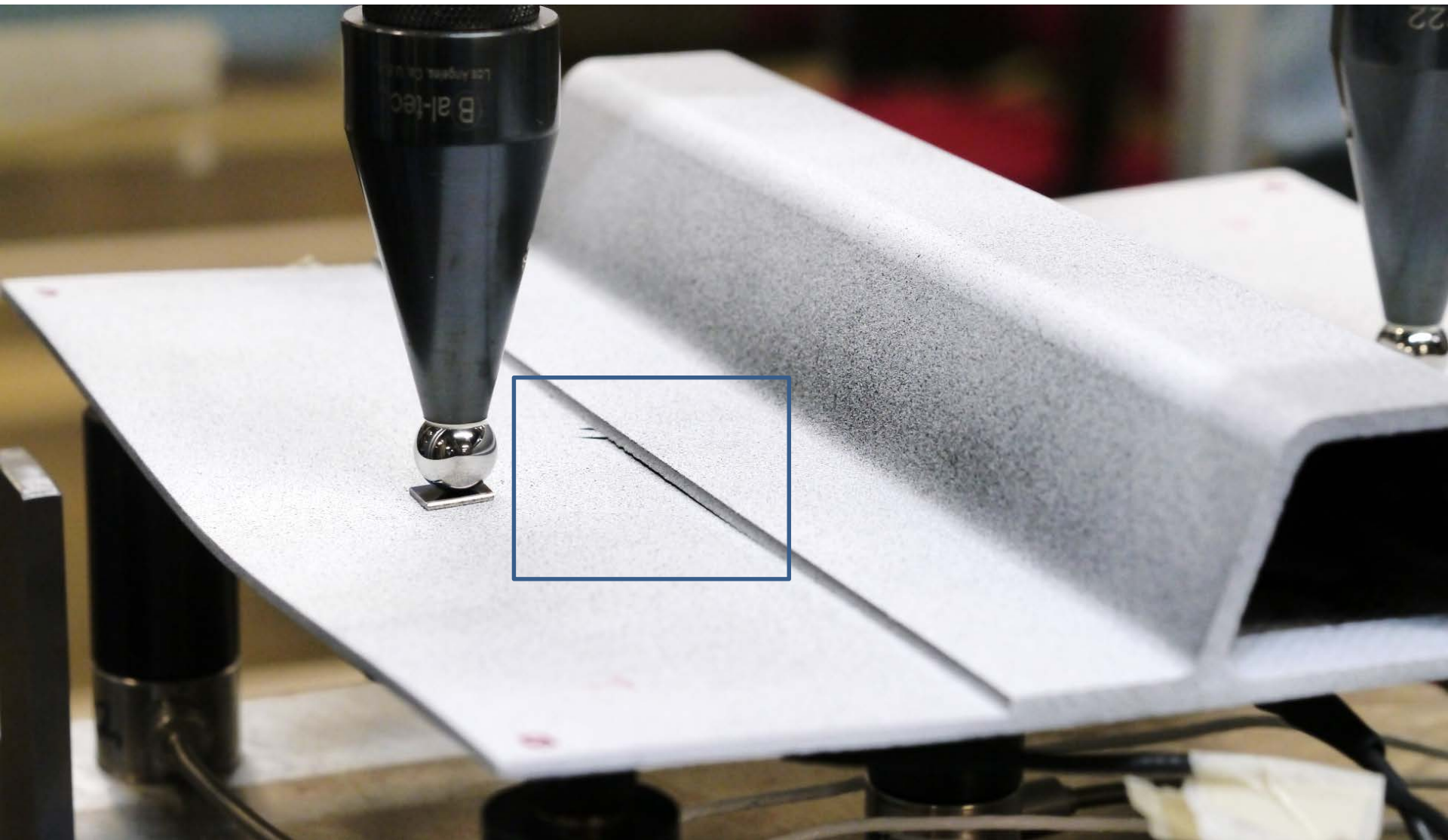
Cohesive Solutions for Structural Integrity and Fatigue Life Prediction

Carlos G. Dávila

**Durability, Damage Tolerance, and Reliability Branch
NASA Langley Research Center
Hampton VA
USA**



Skin/Stiffener Separation in Seven Point Bend (7PB) Test



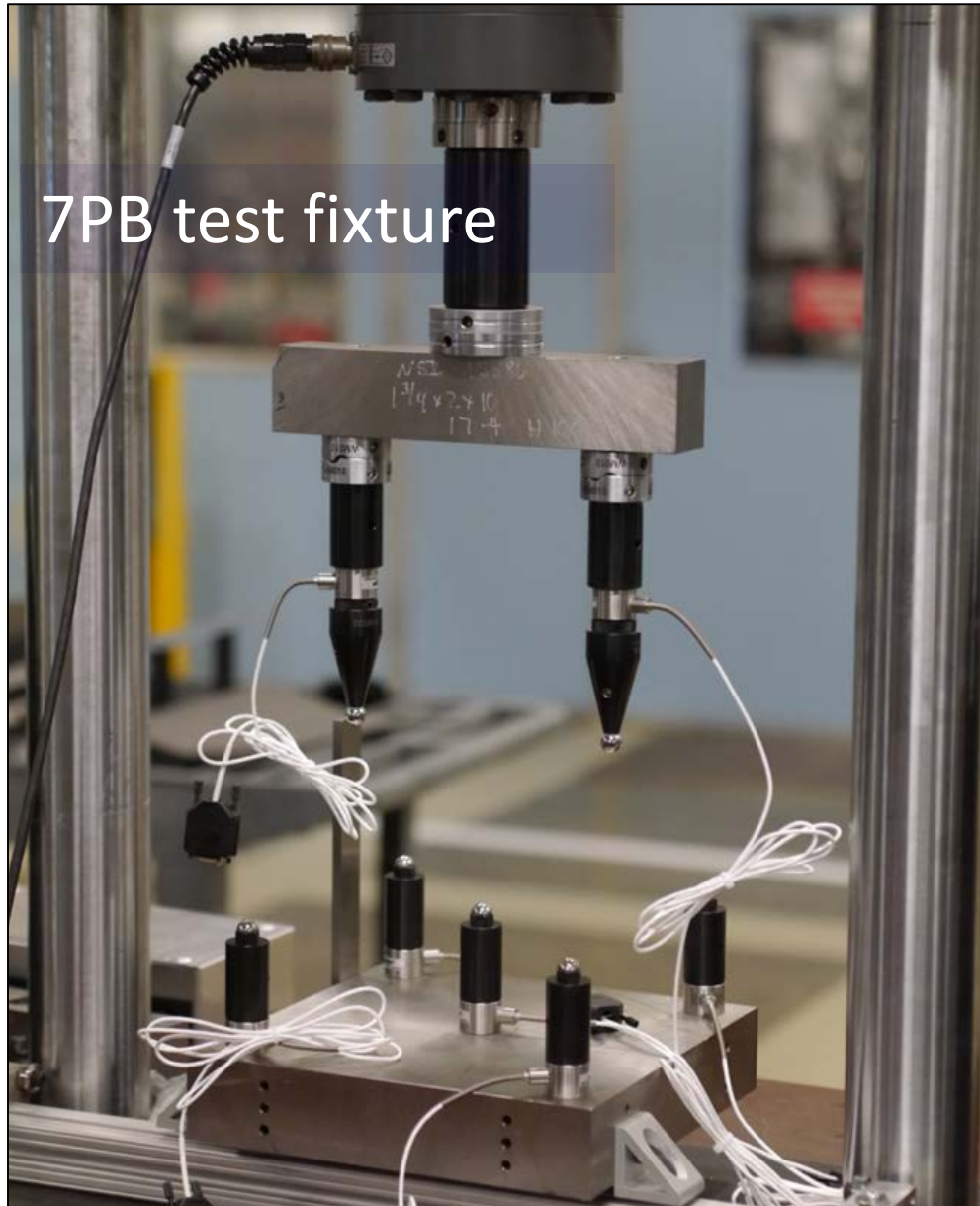


Seven Point Bend (7PB) Test

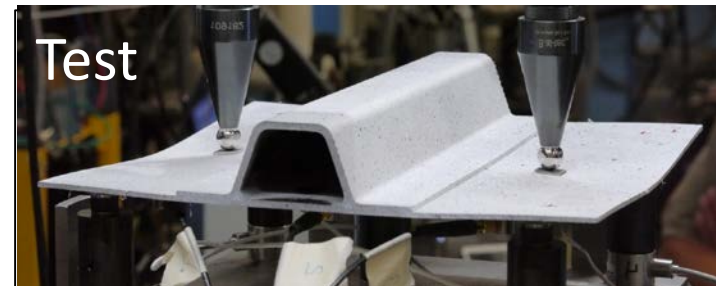


- How to model “real” delaminations?
- Can the detail features of the interface damage be ignored?
- What material properties should we use?

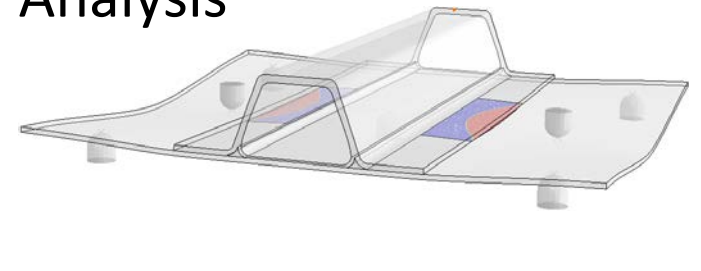
Seven Point Bend (7PB) Test



In the 7PB, skin/stiffener separation can be introduced in a controlled manner.



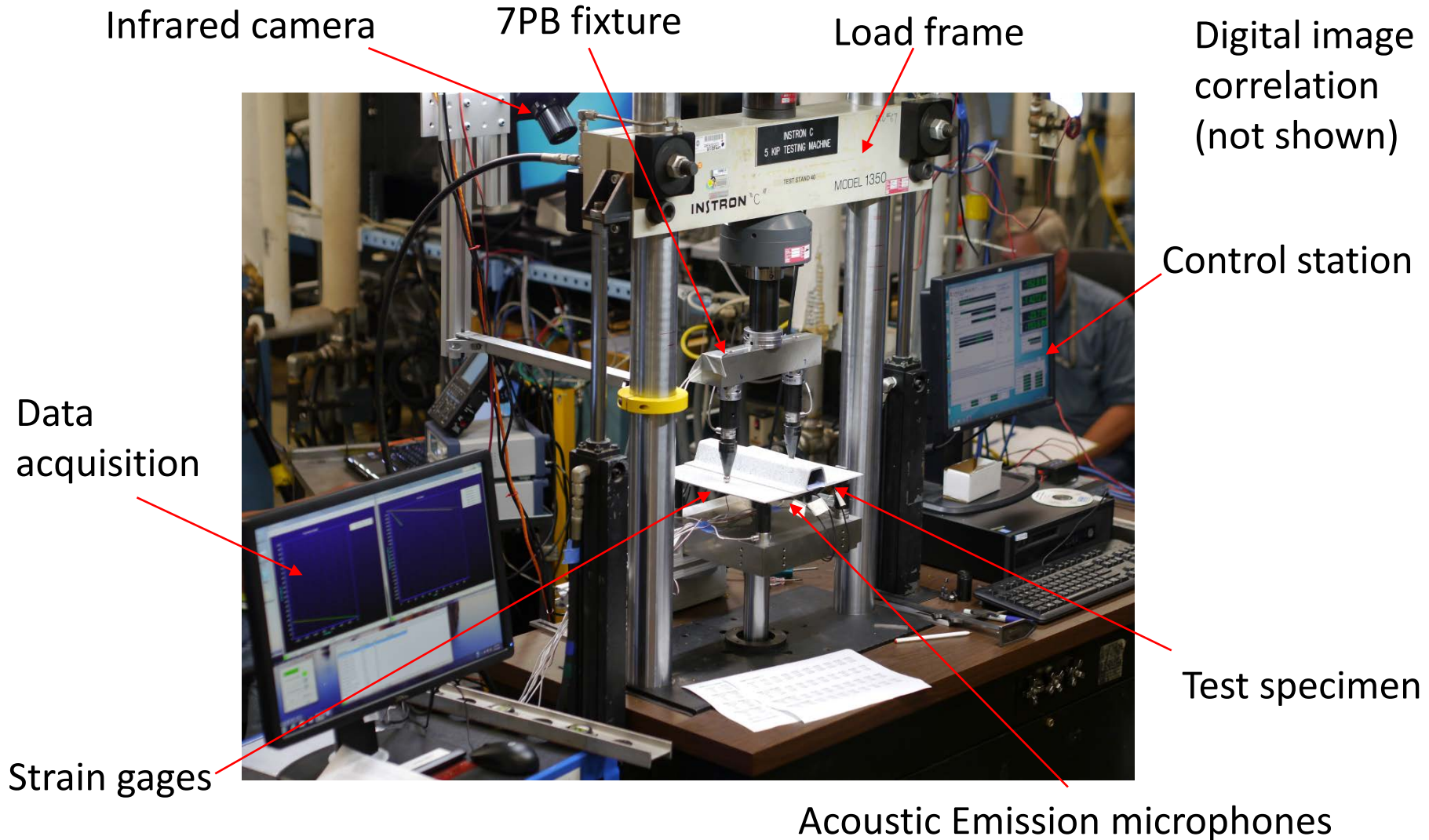
Analysis





7PB Load Frame and Advanced Instrumentation

Seven Point Bend Test (7PB)



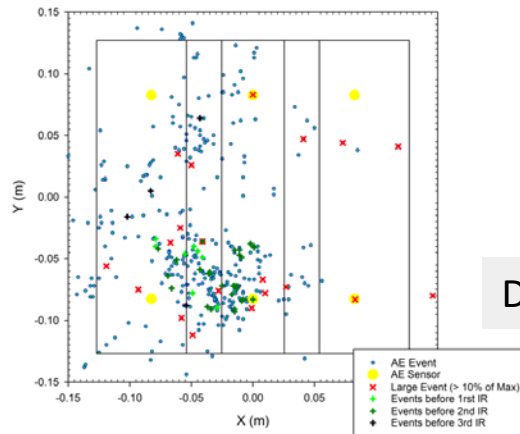
7PB Test Instrumentation

APPROACH:

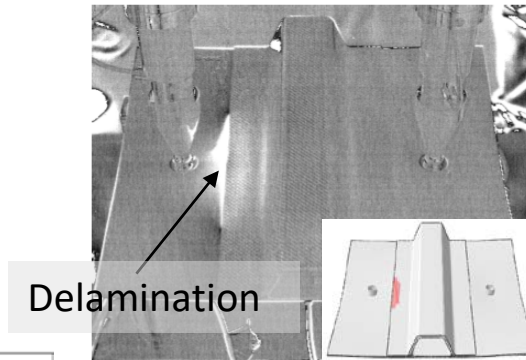
- A seven point bend fixture (7PB) was designed that uses seven load cells for a precise loading of the panel into a simulated postbuckled shape
- Top load points can be repositioned for symmetric and anti-symmetric loading

Monitor Damage Progression for Model Validation

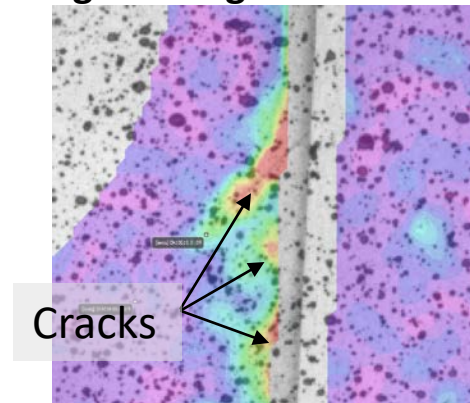
Acoustic Emission



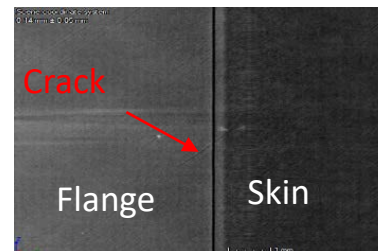
Passive Thermography



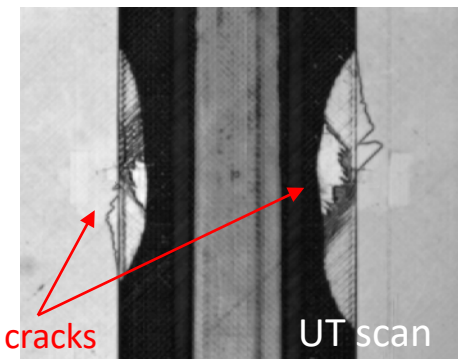
Digital Image Correlation



X-Ray/Computed Tomography



Ultrasonic Scan



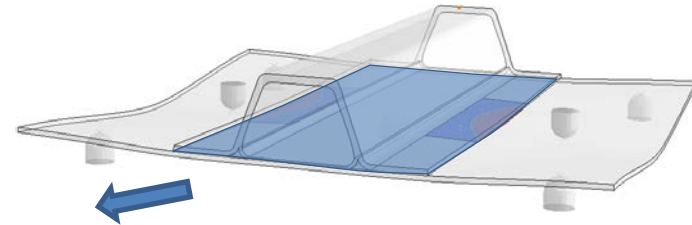
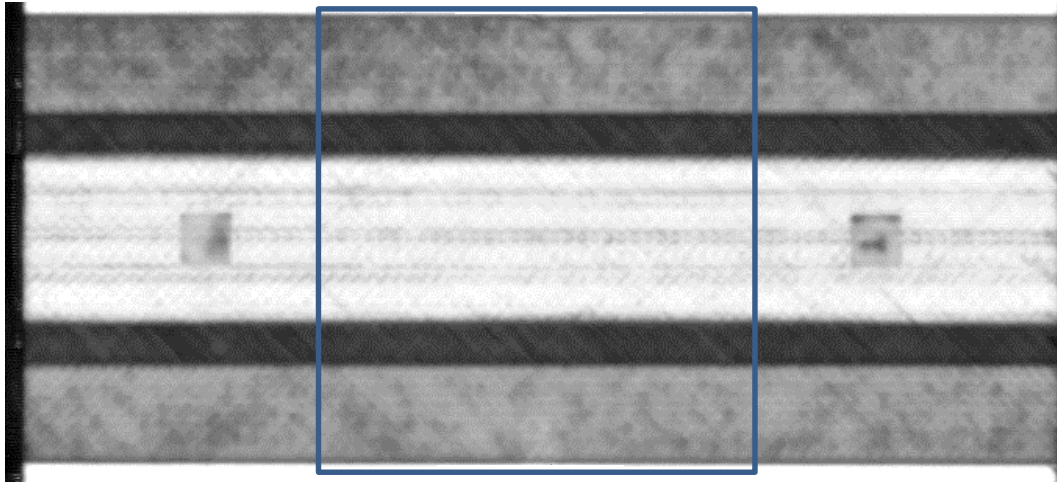
The 7PB test specimen exhibits deformations and damage similar to postbuckled panels, but in a controlled environment that allows detailed observations for method validation.

Delaminations / cracks

UT scan

Propagation of Interface Damage

Pristine – Specimen 7PB-010

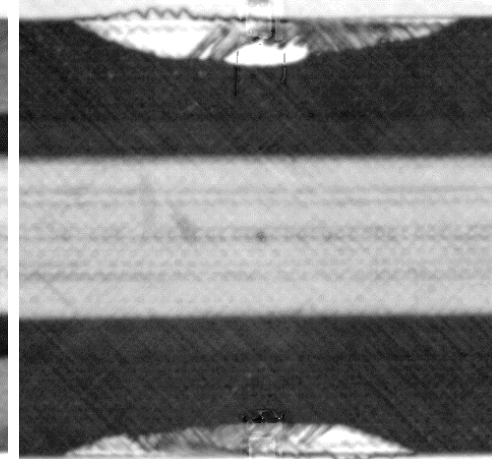
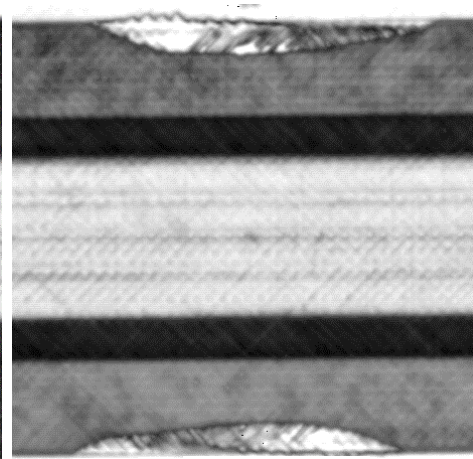
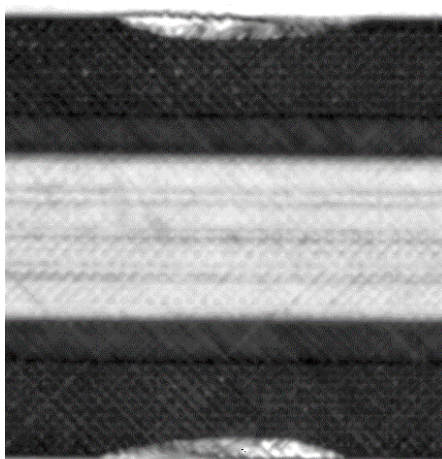
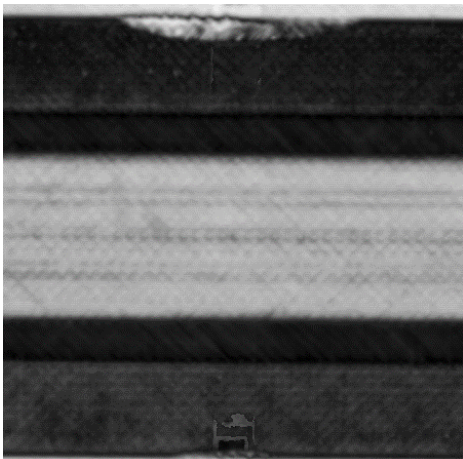


3477 N

3497 N

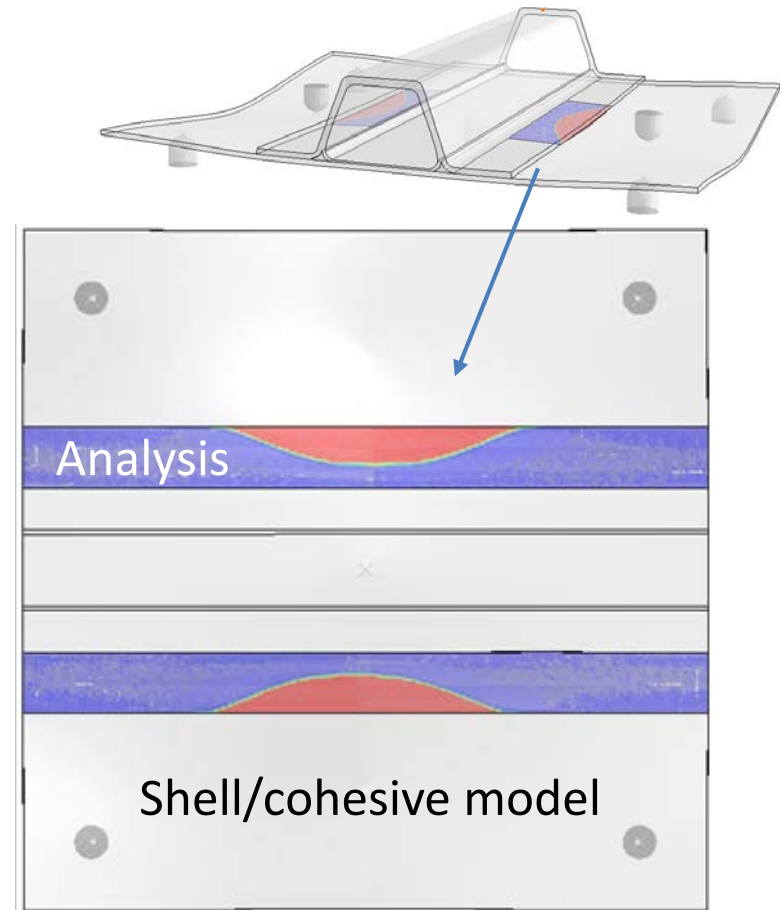
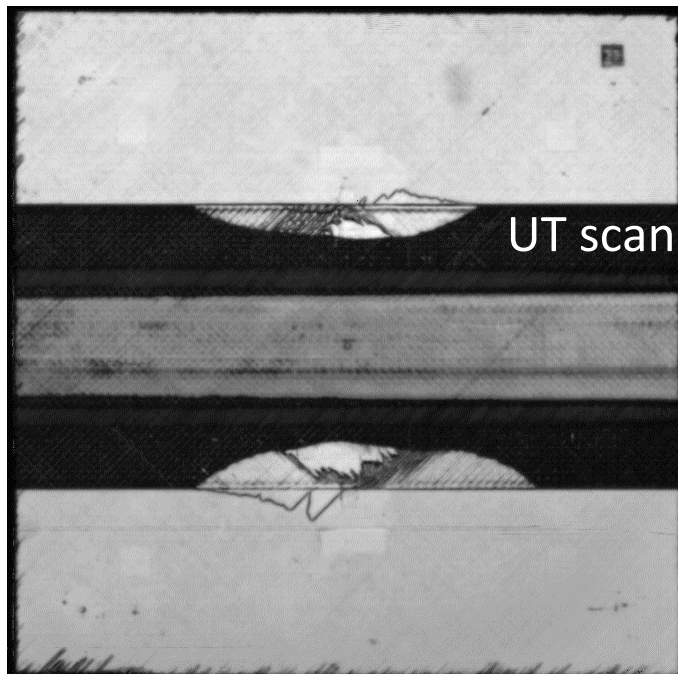
3931 N

4204 N



Seven Point Bend Test Results

- Can skin/stiffener be modeled with a single interface?



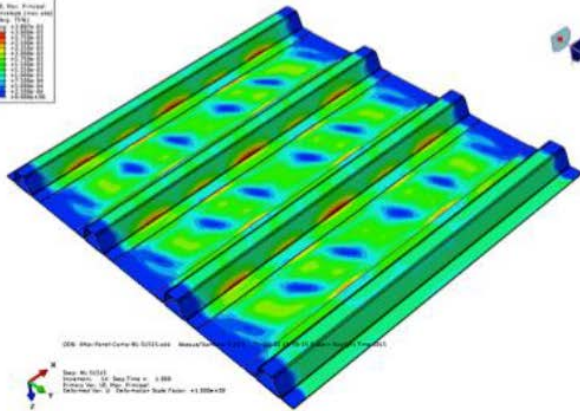
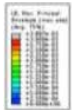


Advanced Composites Project (ACP)

Postbuckled Panel with BVID, Strength and Life



LOCKHEED MARTIN



Technical Challenge 1:

Accurate Strength and Life Prediction

The NASA ACP seeks to reduce the timeline required for development and certification of new aircraft.

High fidelity analysis methods can reduce the testing requirements of primary aircraft structures.

A compression-loaded skin-stringer panel was selected as the basis of method validation.



Building Block: Compression-Loaded Skin-Stringer Panel

Fuselage Component:

- Candidate Material:
IM7/8552 Carbon Epoxy tape

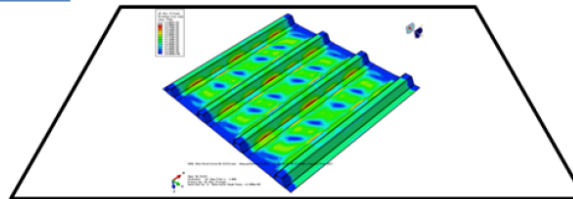
Increasing complexity:

- Geometry and Loading
- Failure mode interaction

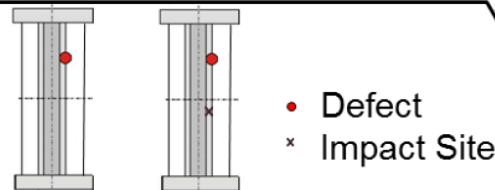


Phase II FY17-19

Subcomponents

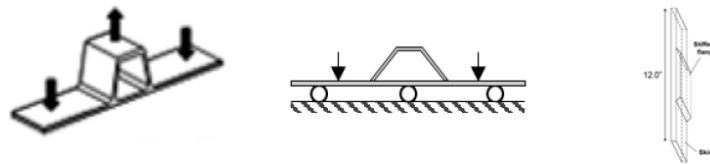


Elements

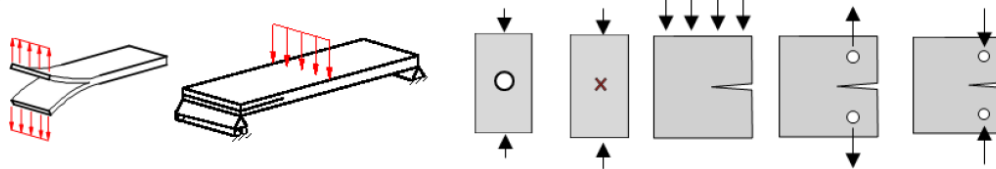


Phase I FY15-16

Sub-elements



Coupons



Material properties



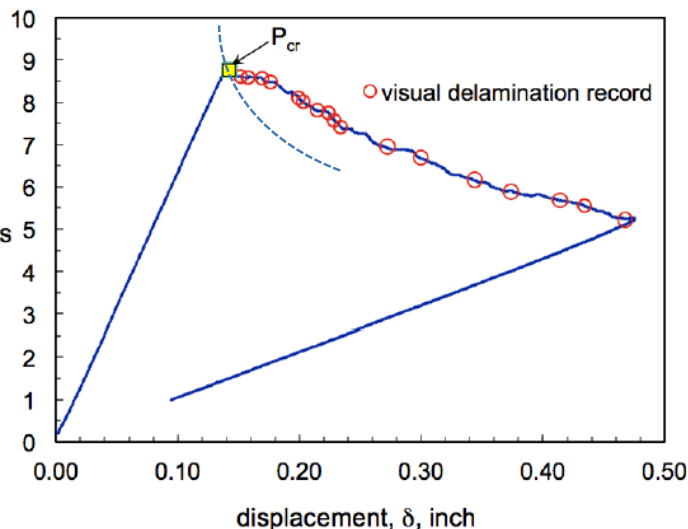
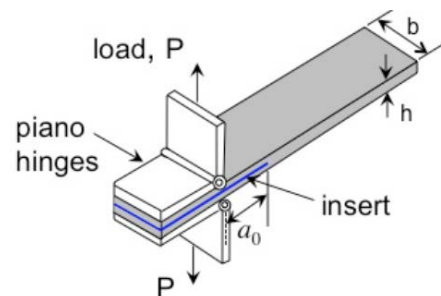
Characterization of material properties based on “first principles”

Characterization of Fracture Properties

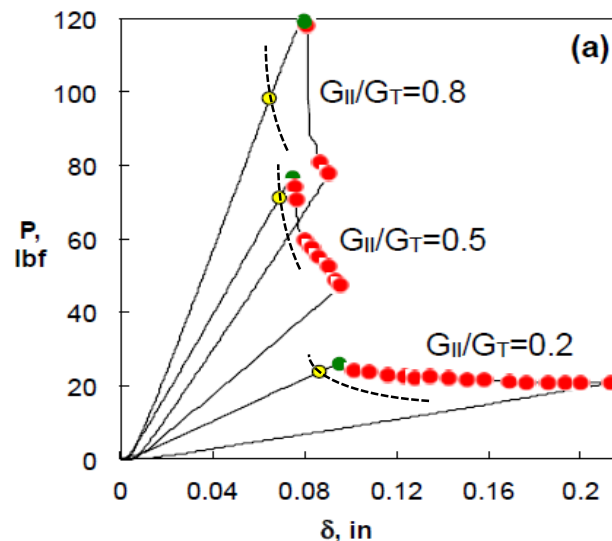
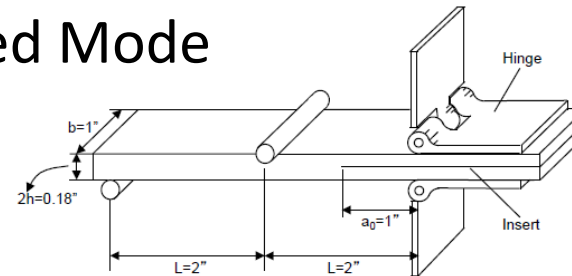
Characterization of fracture properties based on “first principles”:

- Initiation values represent pure fracture properties
- R-curve effects result from bridging, crack migrations, and other mechanisms

Mode I

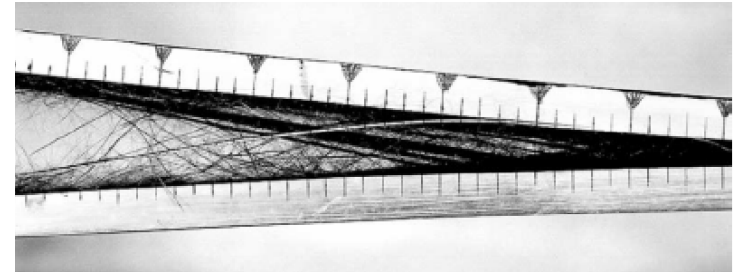
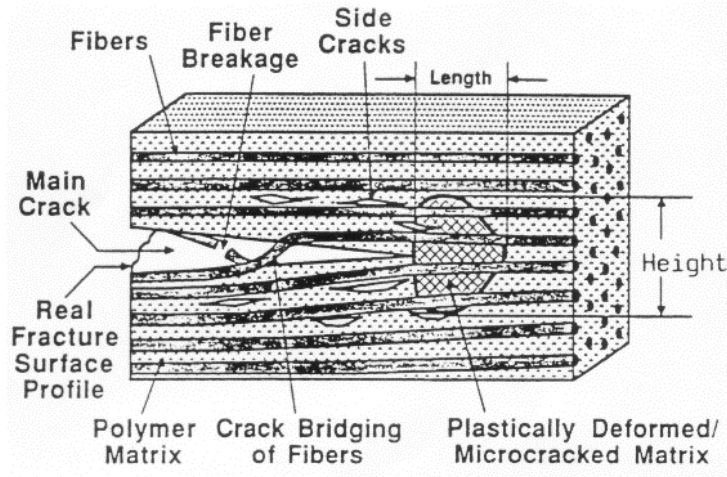


Mixed Mode



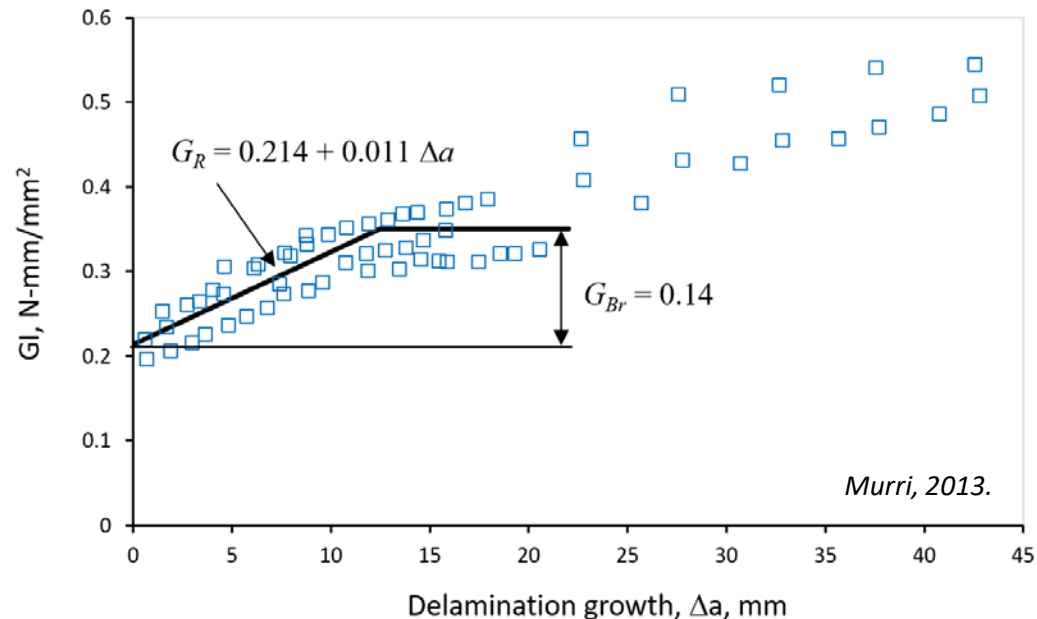
→ G_{Ic}, G_{IIc}, η

Fracture is a combination of interacting discrete and diffuse damage mechanisms



Tamuzs, 2001.

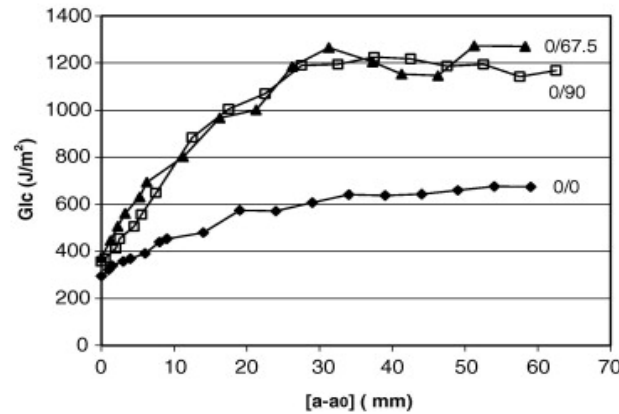
*Bloodworth, V., PhD Dissertation,
Imperial College, UK, 2008.*



Murri, 2013.

Complexities of Interfacial Damage

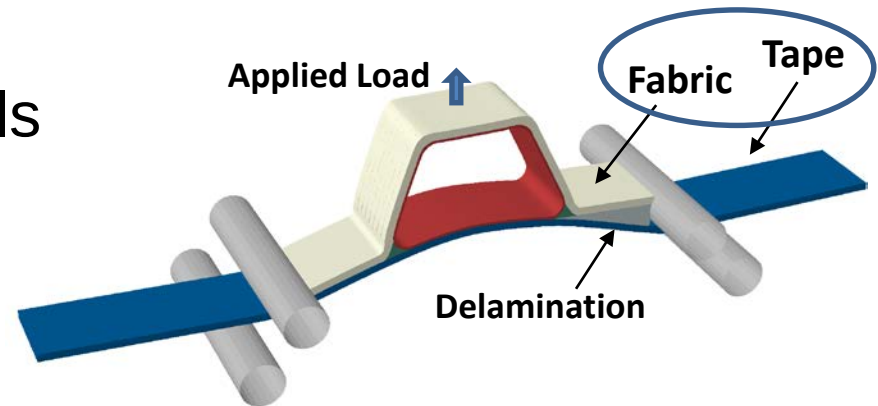
1. R-curve effects



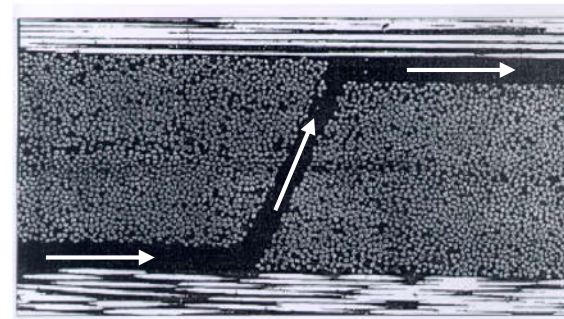
Causes:

- Bridging
- Delving
- Other damage modes

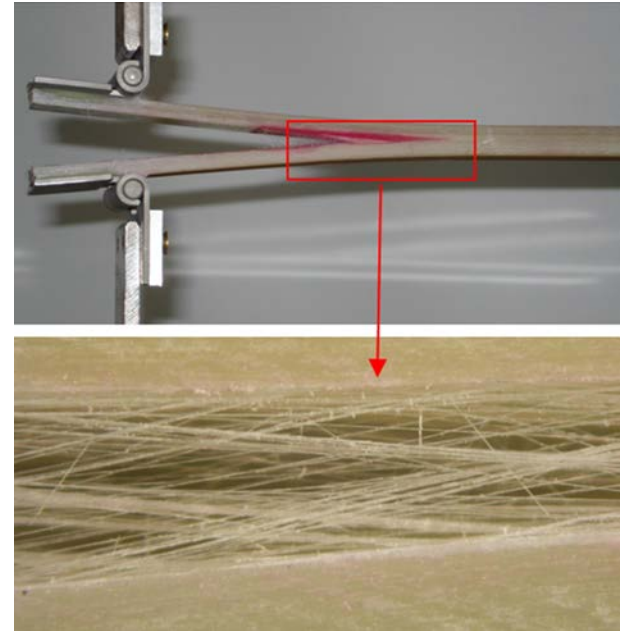
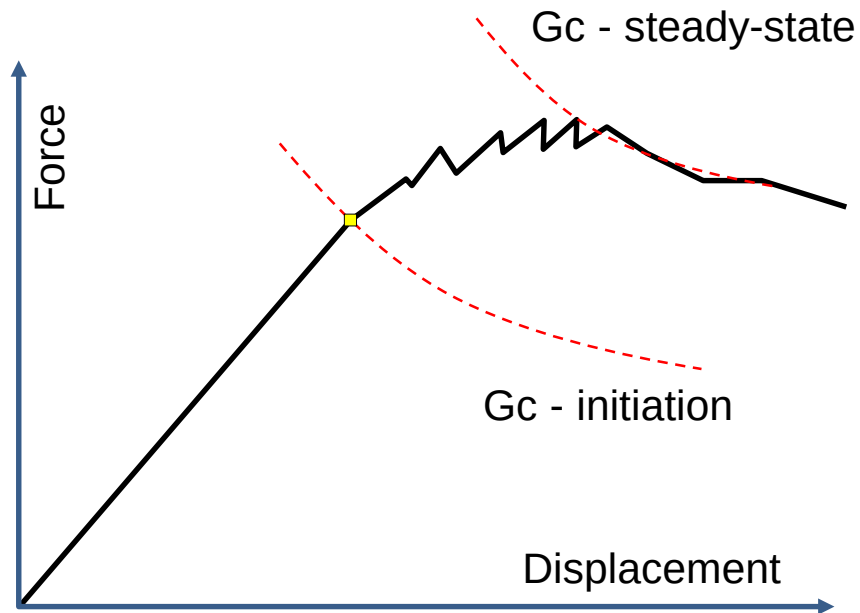
2. Complexities of interfaces between dissimilar materials



3. Migration of delamination

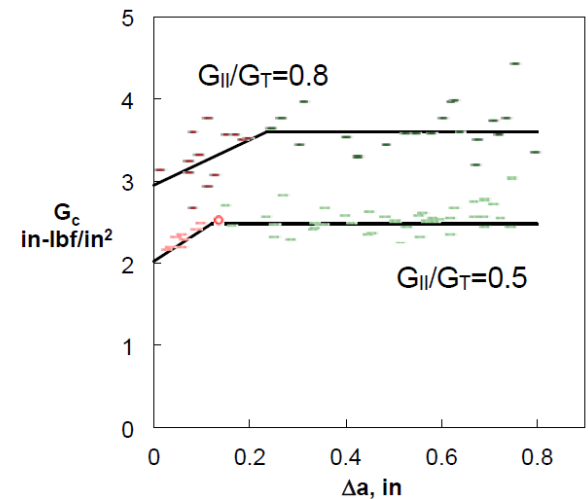
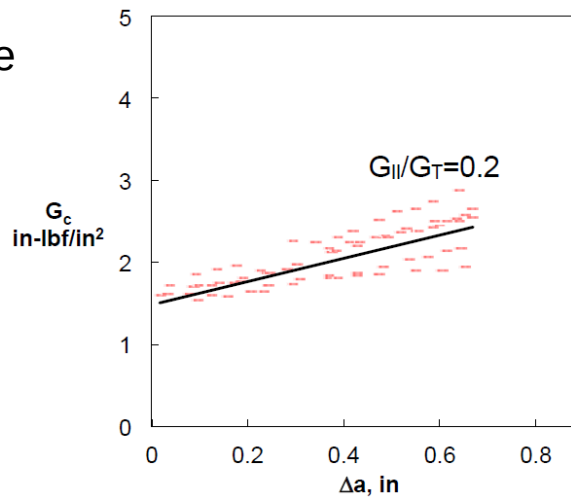


R-Curve Effect

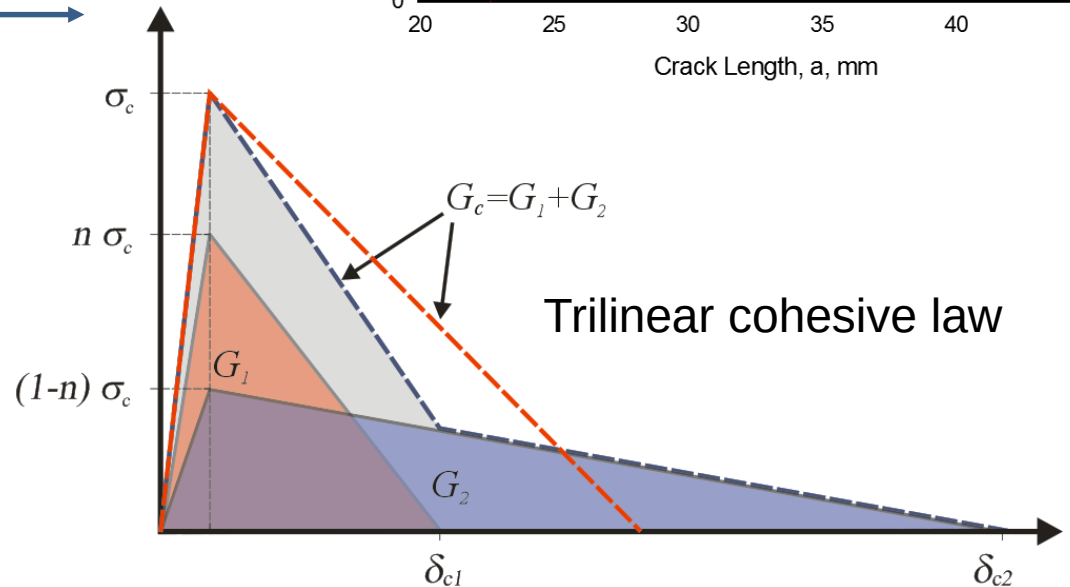
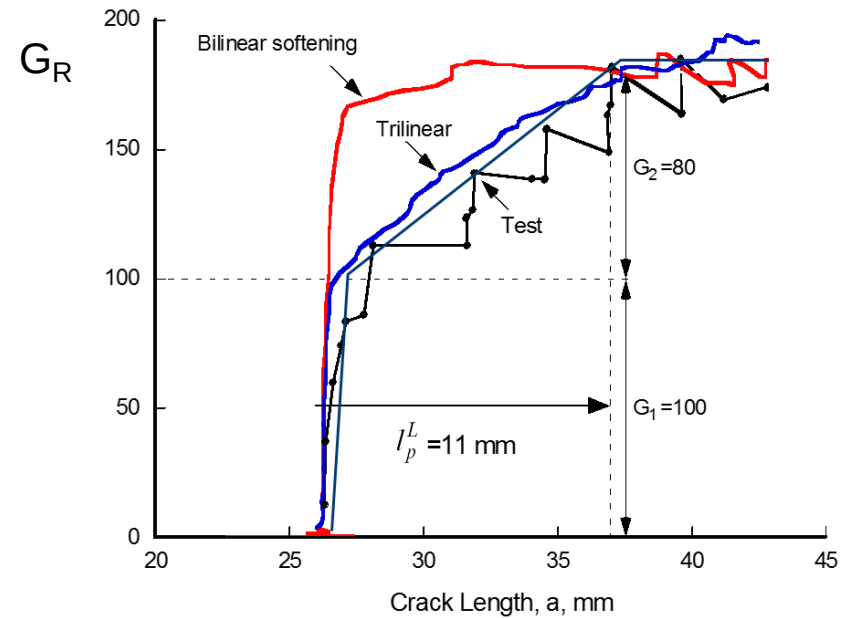
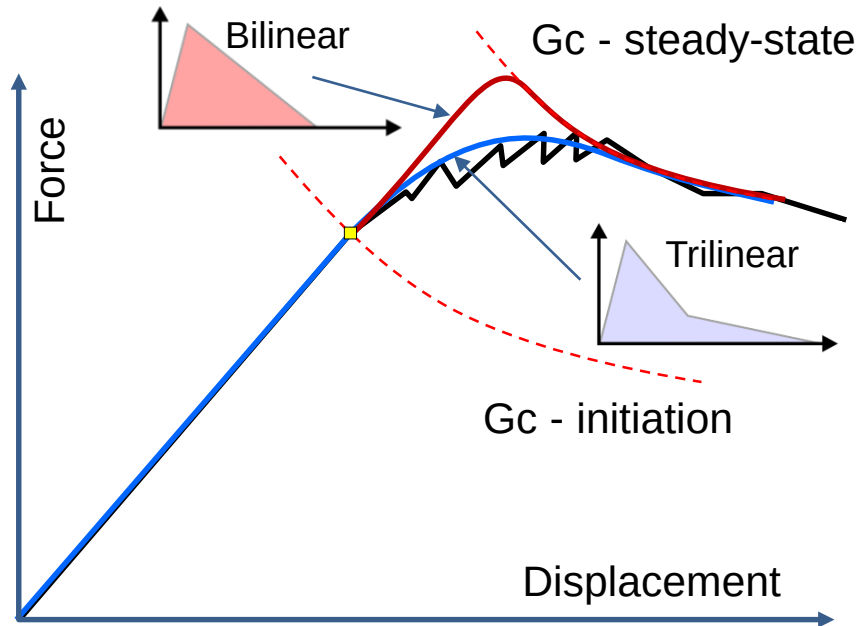


Delamination Resistance curves for MMB Test

Ratcliffe, 2016

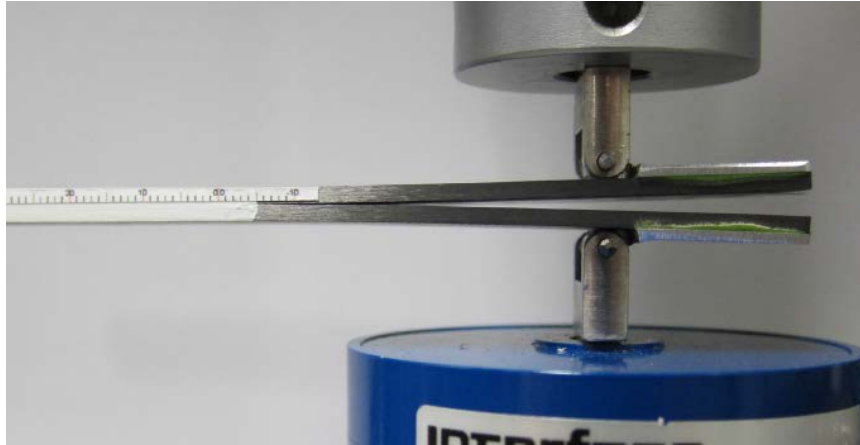


Modeling the R-Curve Effect



Standard Tests and Structural Interfaces

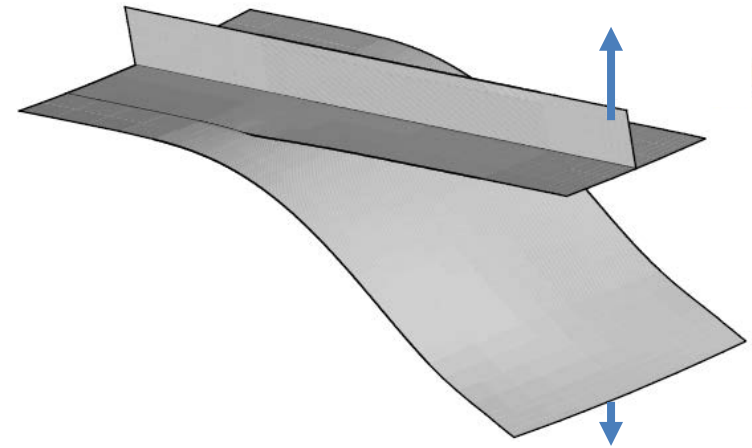
MMB



Interlaminar mechanical properties of IM7/8552

σ_0 (N/mm ²)	τ_0 (N/mm ²)	G_{Ic} (N/mm)
51.0	115.7	0.270

Structural Interface



Wagner, W., and Balzani, C., *Computers and Structures*, 2008

Properties for the interface between skin and stiffener made of IM7/8552

σ_0 (N/mm ²)	τ_0 (N/mm ²)	G_c (N/mm)
51.0	115.7	1.103/0.875

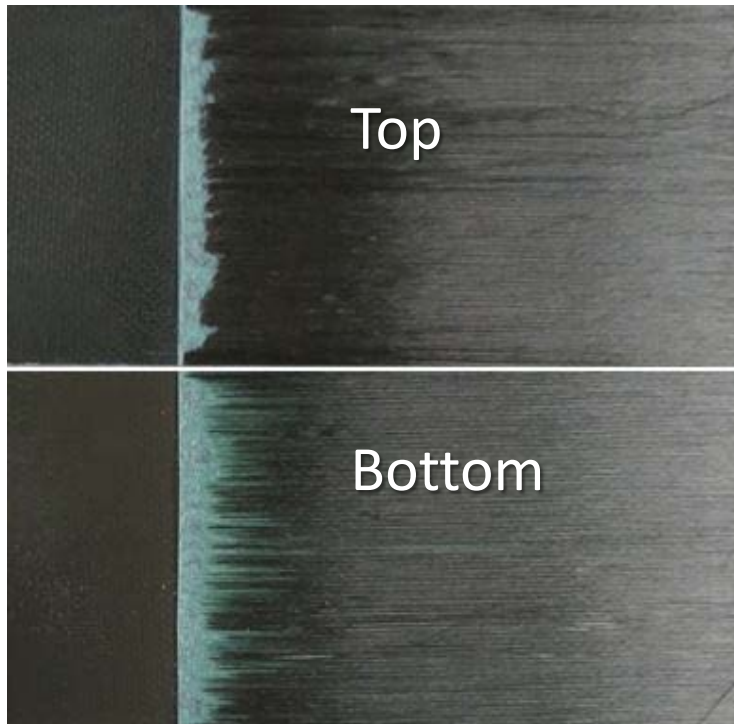


4 times!

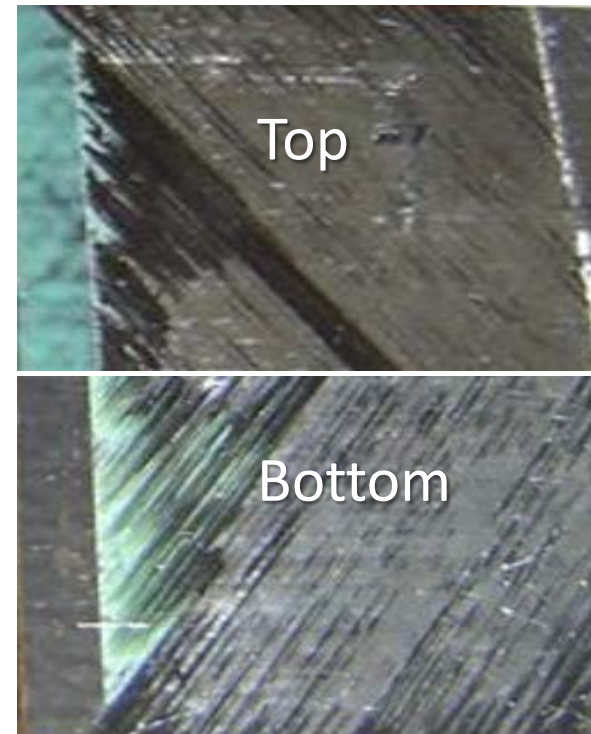
$$G_{c_interface} \approx 4 \times G_{c_tape}$$

Interface Surfaces

0/0 interface
(standard test)



Typical structural
interface



Is G_c the same?

R-Curves for Multidirectional Laminates

4 times !

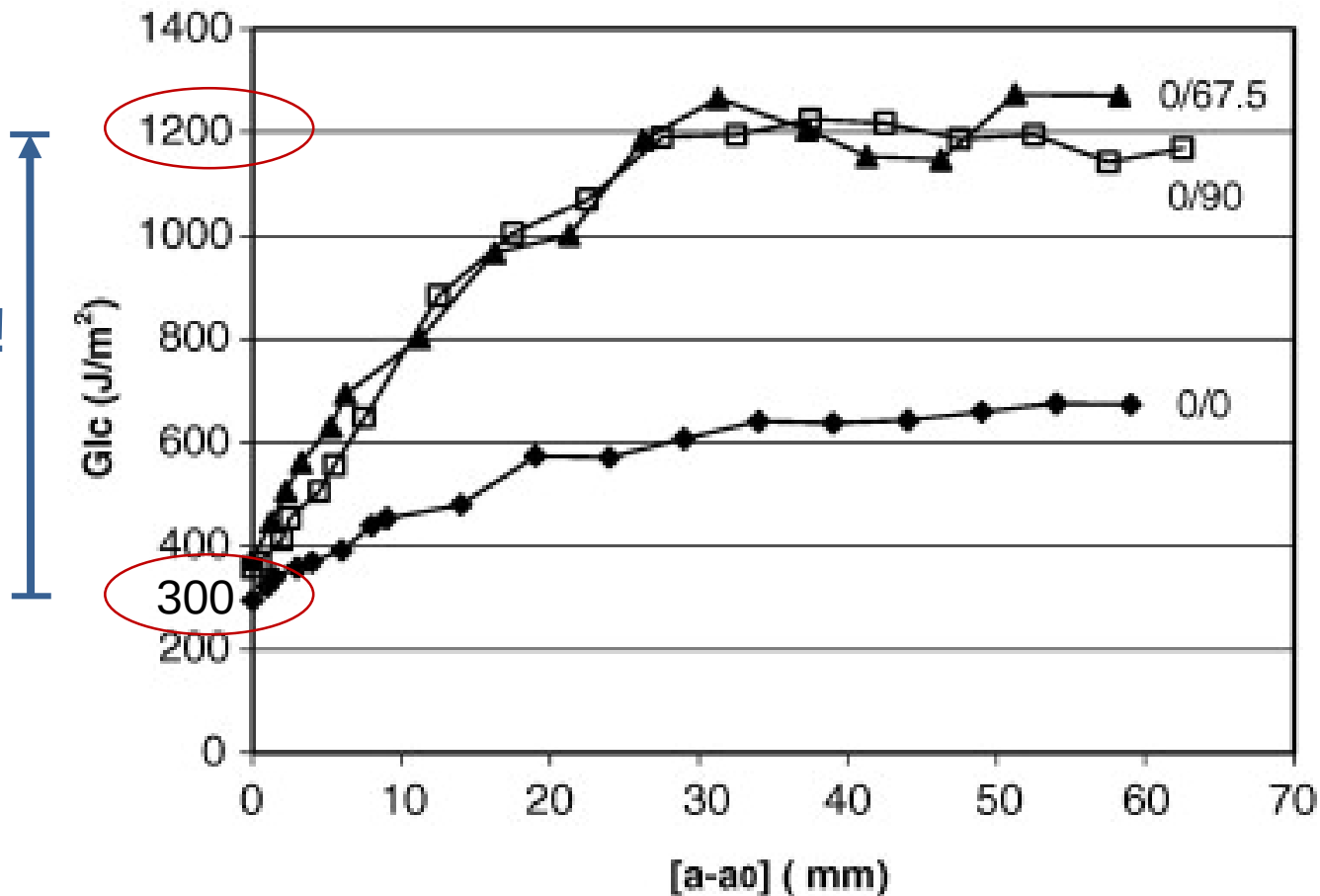
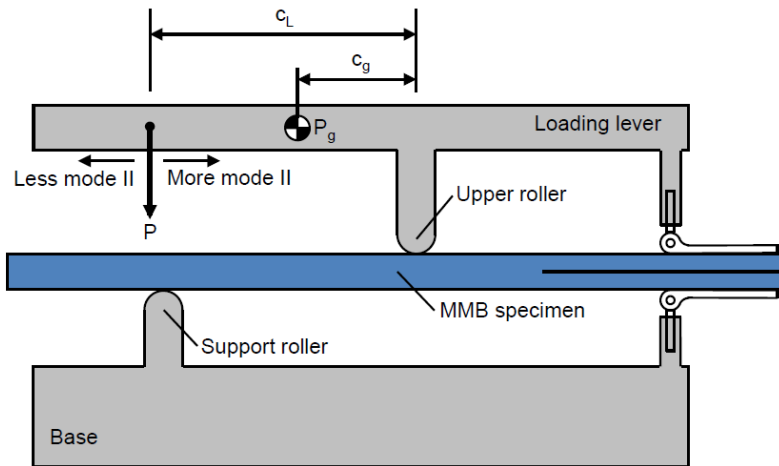


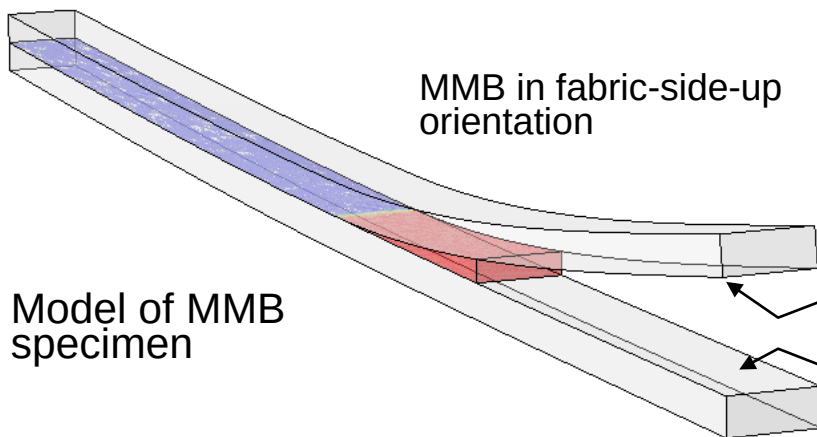
Fig. 14.

Typical *R*-curves of 0°/0°, 0°/67.5° and 0°/90° specimens.

Tape/fabric interface



Mixed Mode Bending (MMB)

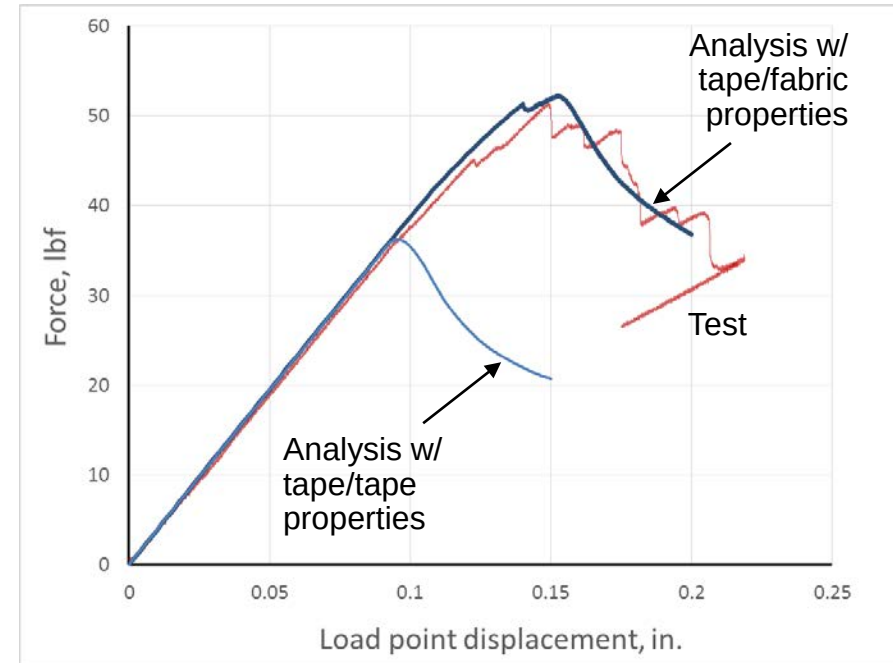


MMB in fabric-side-up orientation

Model of MMB specimen

Fabric $[0_f]/[0_t]_7/[0_f]$

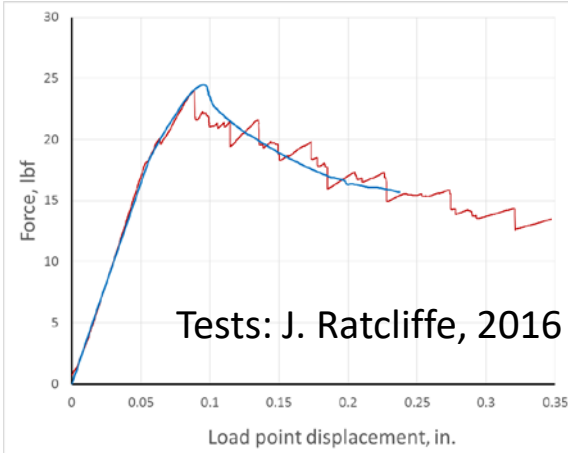
Tape $[0_t]/[0_f]/[0_t]_5/[0_f]/[0_t]$



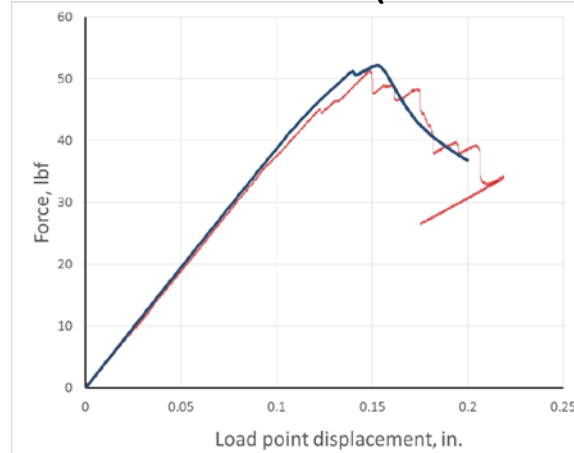


Characterization of Skin/Stiffener Interface Properties

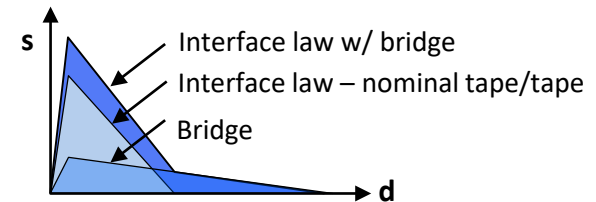
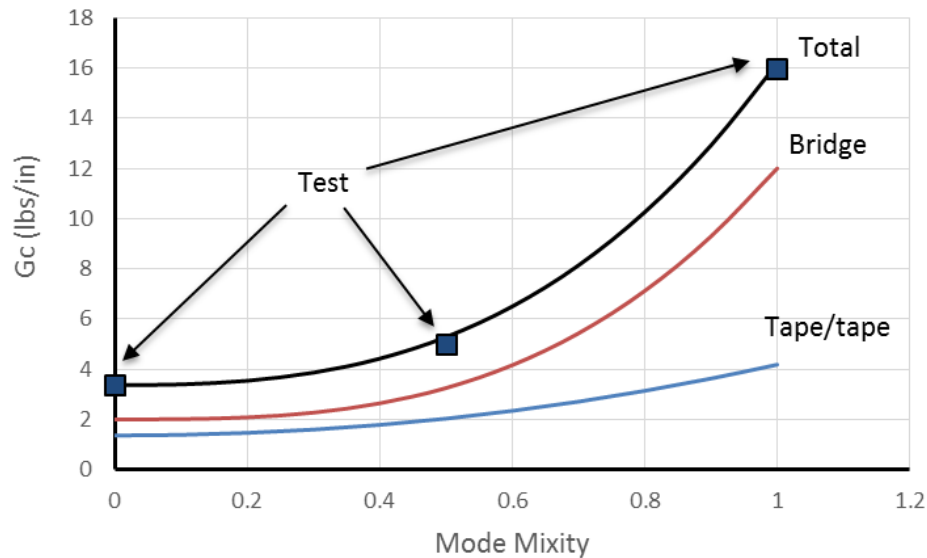
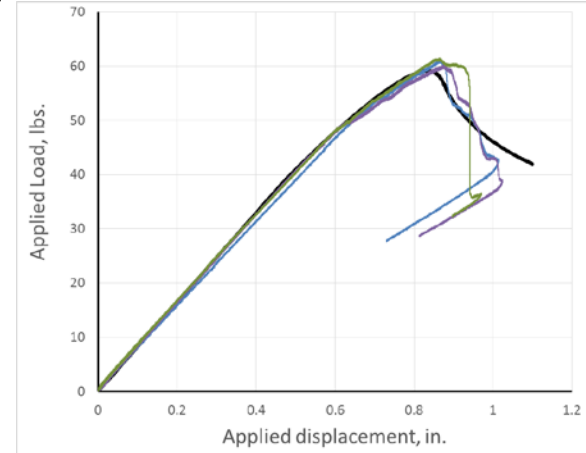
Mode I (DCB)



Mixed Mode (MMB 50%)



Mode II (ELS)

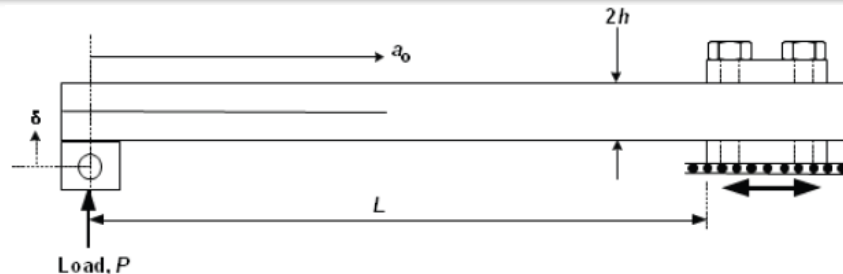


	Nominal	Bridging	
Gic=	1.36	2	lb/in
GIIc=	4.18	12	lb/in
Sig33=	9040	1000	lb/in ²
Taush=	13490	3000	lb/in ²
K33=	1.8E+08	2.E+07	lb/in ³
Ksh=	1.3E+08	3.E+07	lb/in ³
BK=	2.07	3	

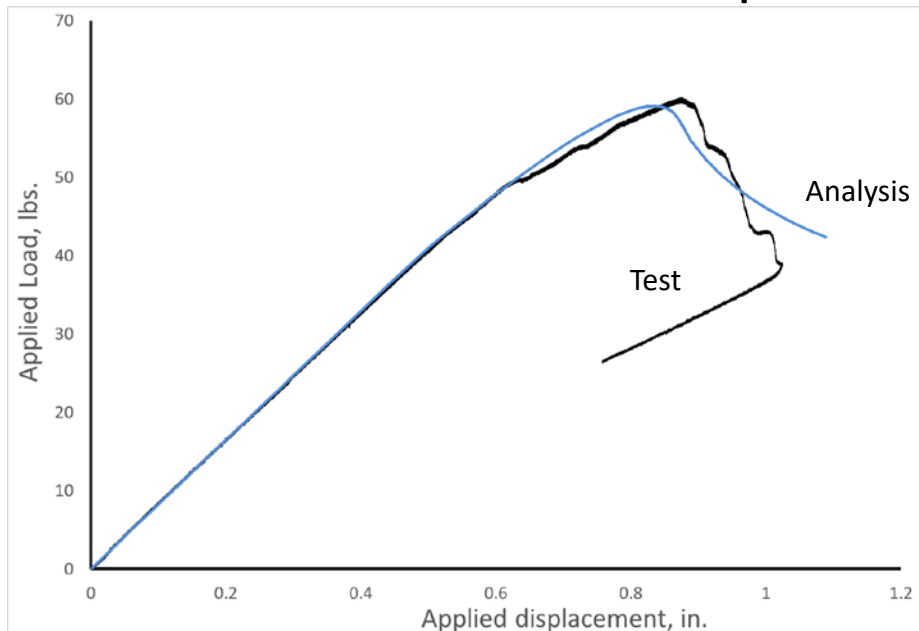


Characterization of Skin/Stiffener Interface Properties

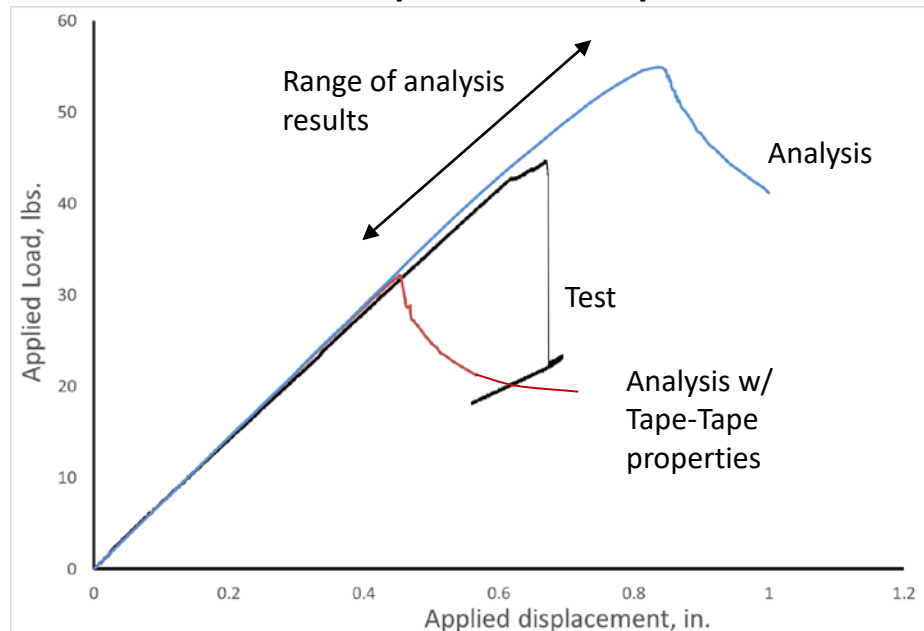
ELS Tests: J. Ratcliffe, 2016



Fabric-side-up



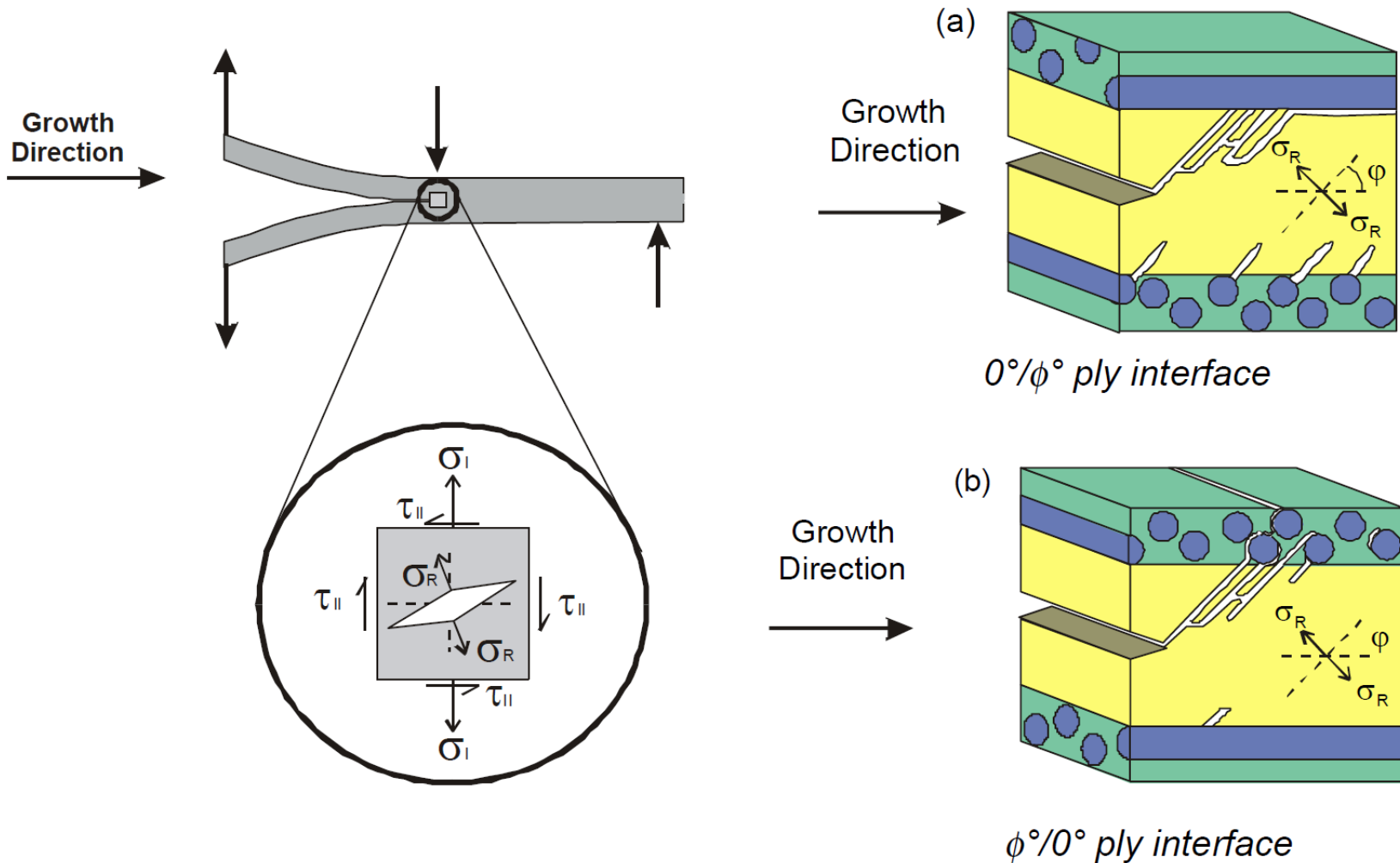
Tape-side-up



- The R-curves for the two orientations of the same interface are different
- The “tape-side-up” specimen exhibits unstable propagation

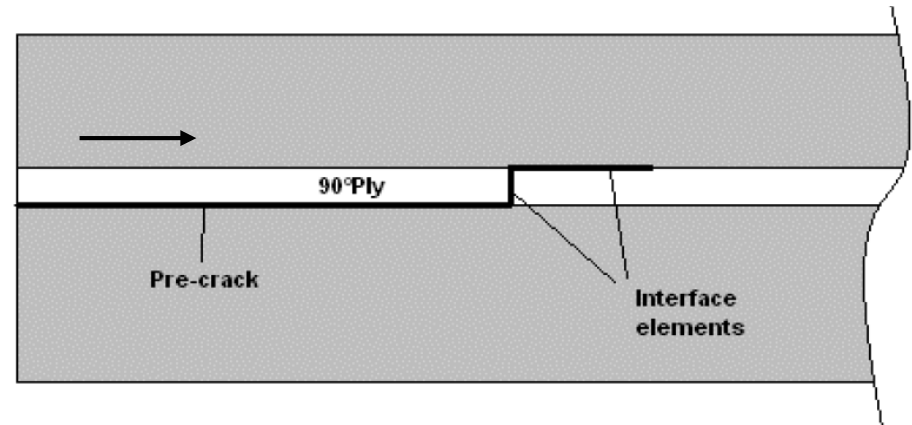
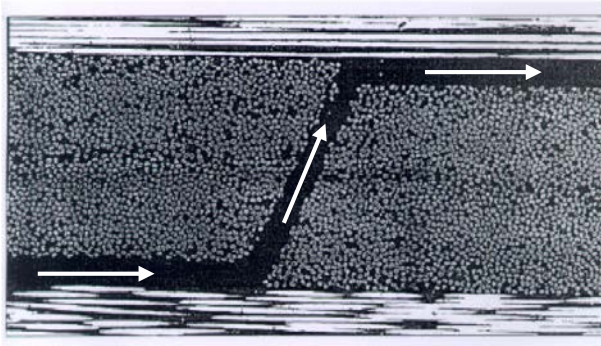
Migration of Delamination

Emile Greenhalgh, 2006

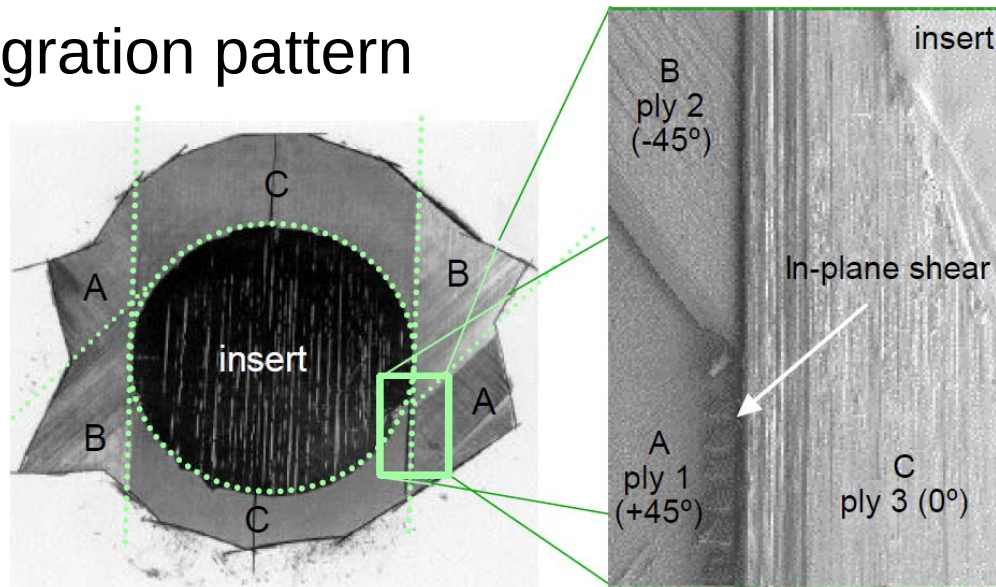


The sign of the transverse shear determines the direction of propagation

Simple migration pattern

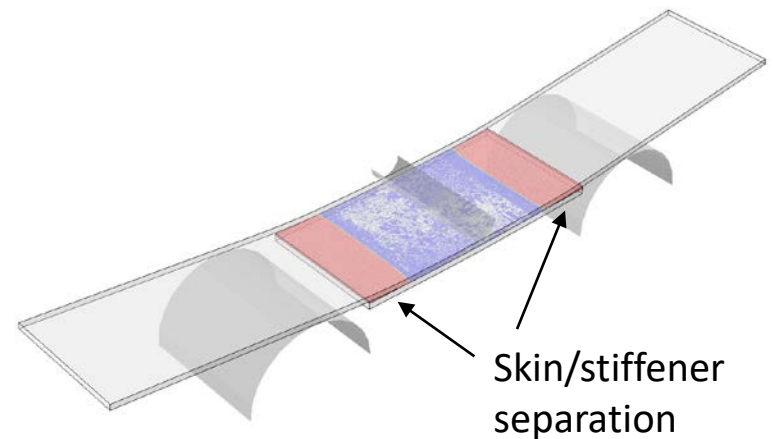
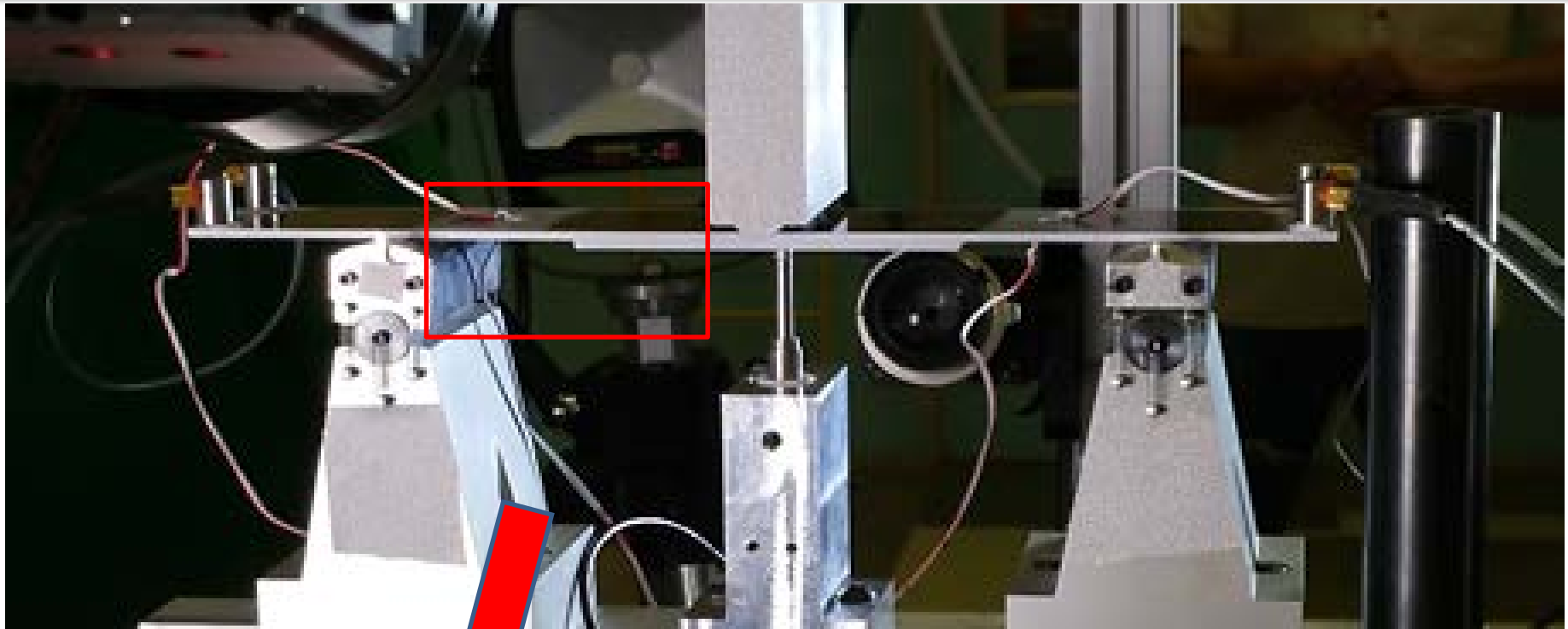


Complex migration pattern





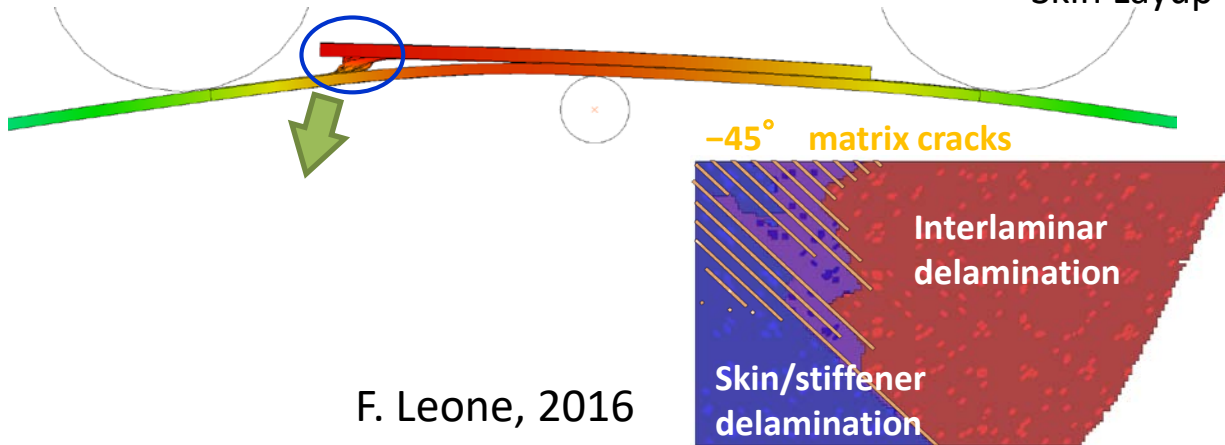
Three Point Bend (3PB) Doubler Specimen



3PB Specimen - Detailed 3D Models

1) CompDam_DGD

- Flange Layup – $[+45/0/-45/+45/-45/0]_s$ fabric
- Skin Layup – $[-45/+45/0/90/-45/+45]_s$ tape

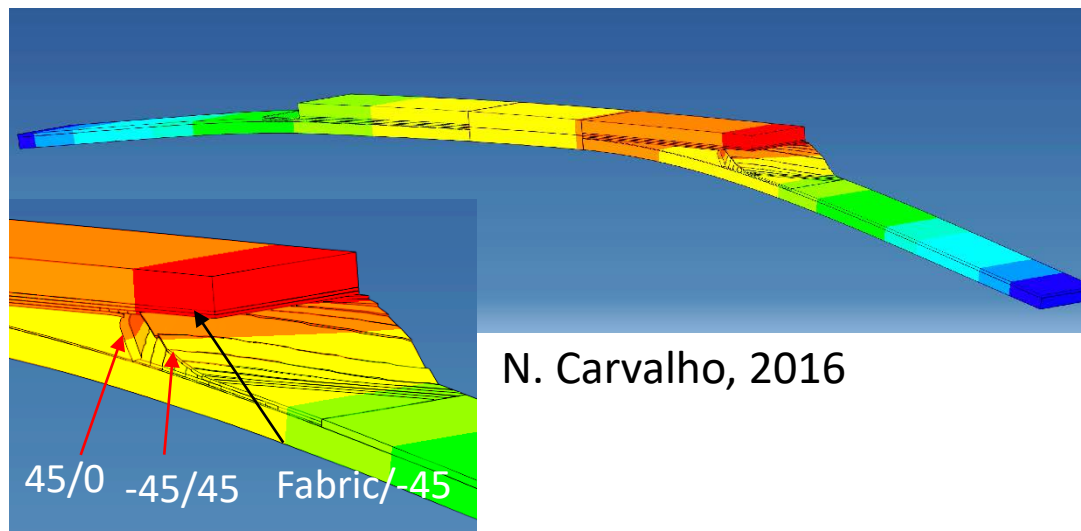


F. Leone, 2016

Failure Process:

- Delamination predicted in different interfaces.
- Delamination migration and bridging occurs via matrix cracks.

2) Floating Node Method - FNM



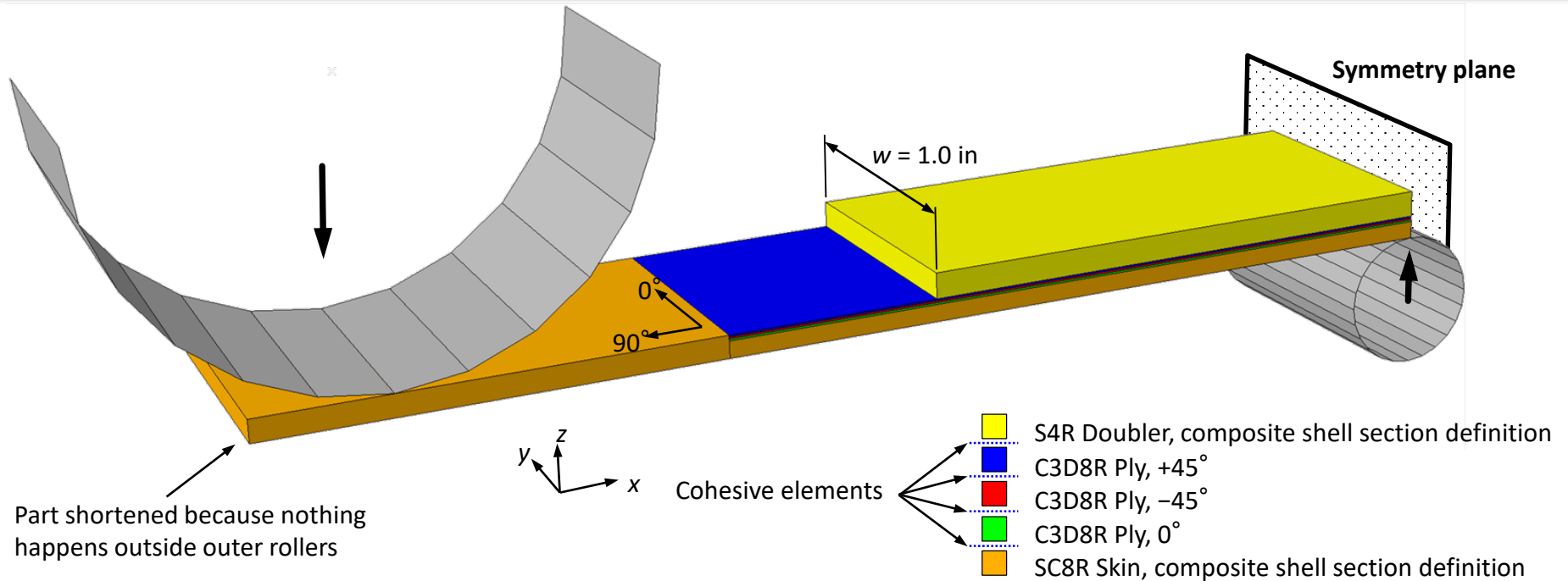
N. Carvalho, 2016

Fabric/-45

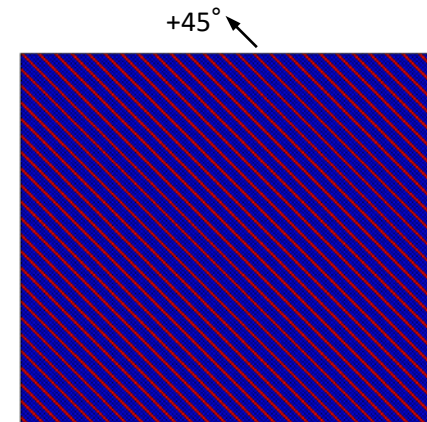
-45/45

45/0

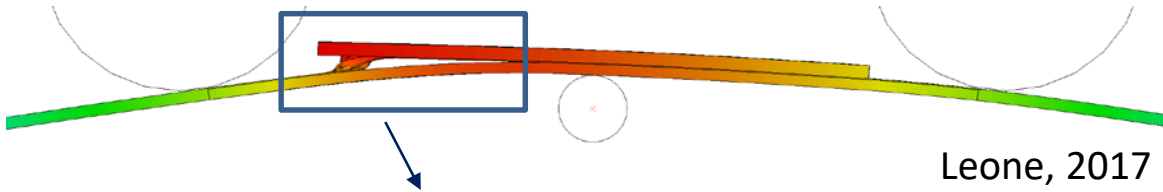
Global view of finite element model



- CompDam_DGD version 2.1.0 used for all solid elements
- Fiber tensile damage, matrix damage, and friction turned on
- In-plane element size = 0.2 mm
- Matrix damage allowed only in every fourth row of elements, oriented parallel to the material fiber direction, i.e., minimum matrix crack spacing of 0.8 mm



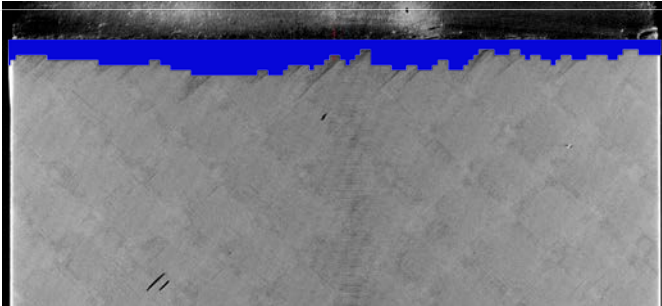
Comparison with X-Ray/CT Data



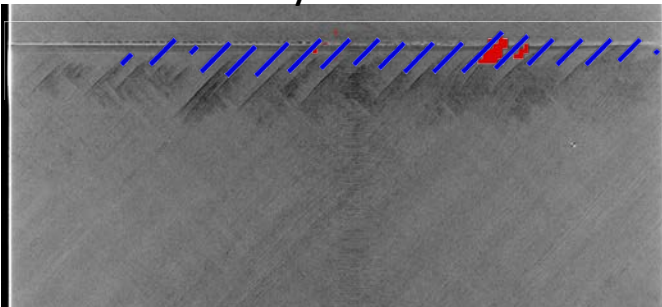
Exp: Run 6, Peak Load – 53.9 lb
FE: Edge-to-Edge Delam – 45.9 lb

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

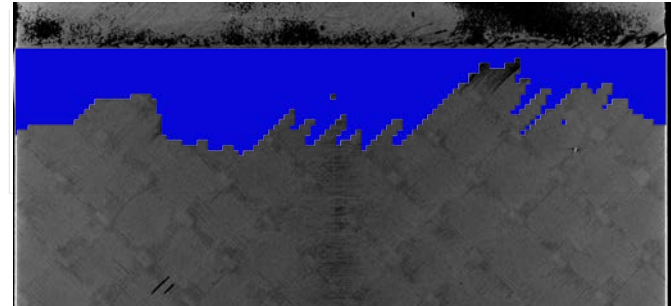
-0.50 Interface 0 0.50



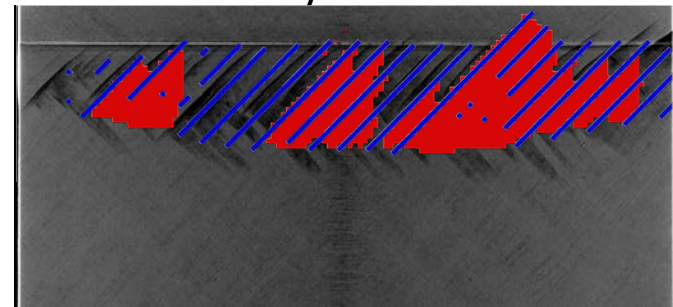
+45 Ply and Interface 1



-0.50 Interface 0 0.50

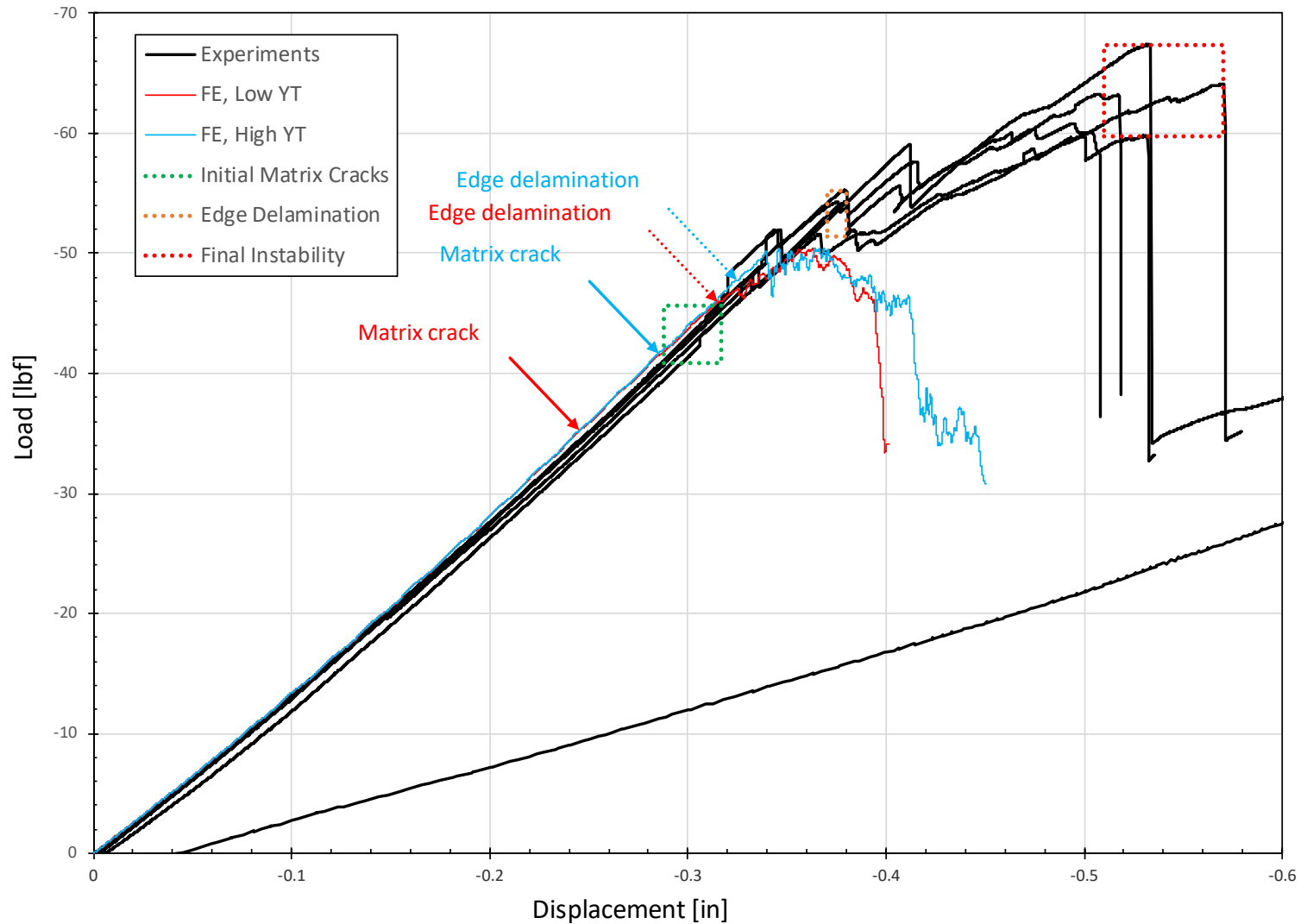


+45 Ply and Interface 1



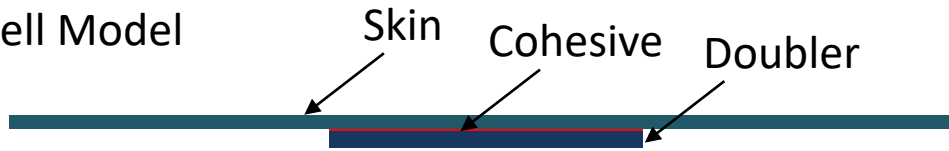
Load/Displacement, α not prescribed

Leone, 2017

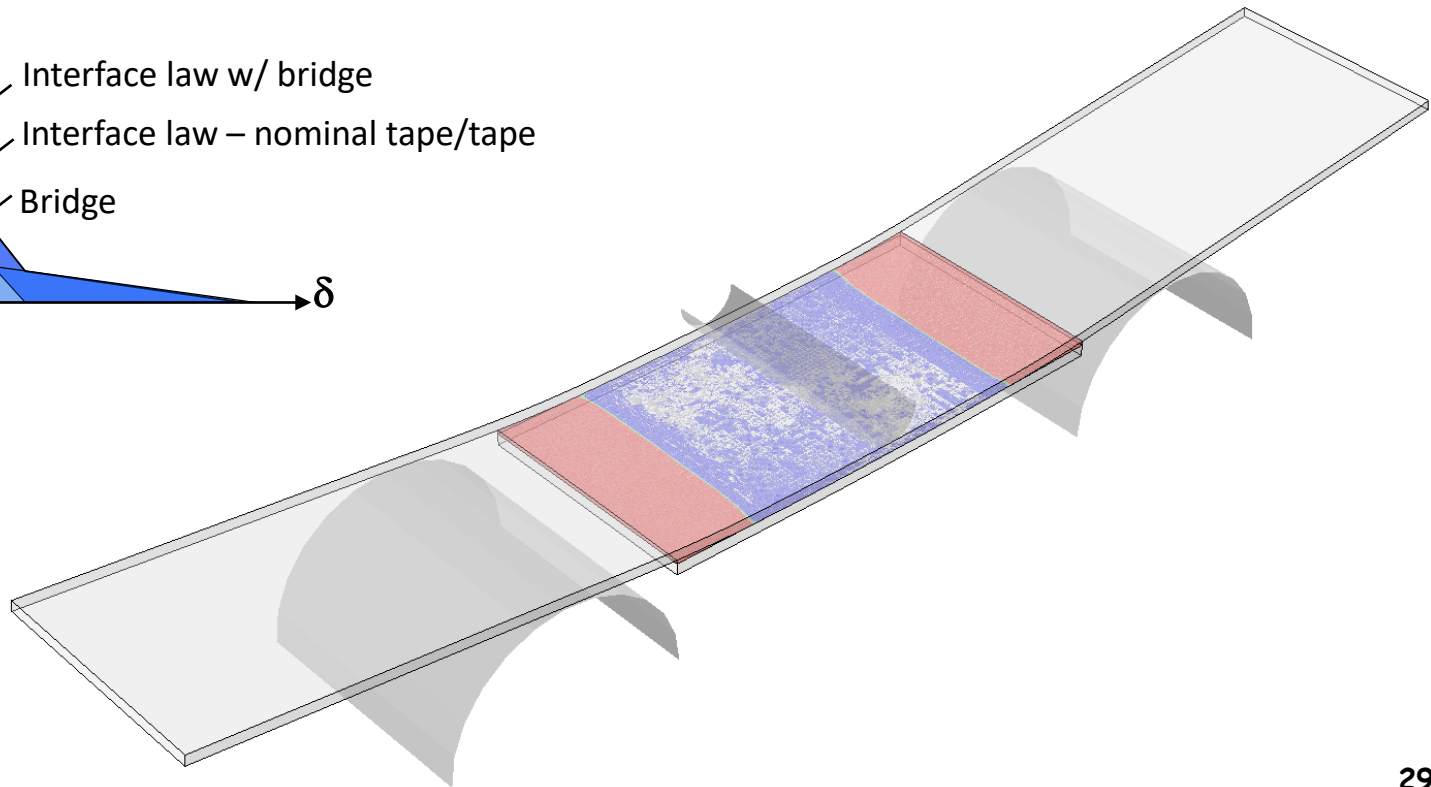
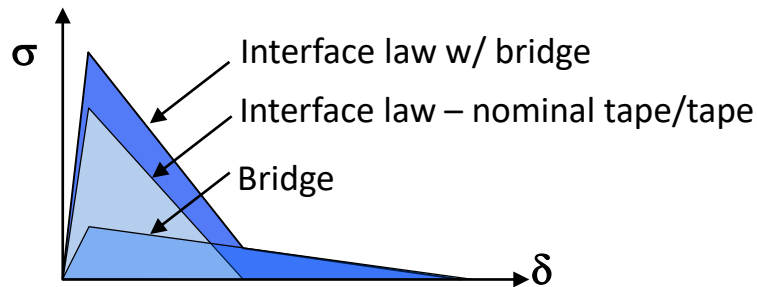


Shell Model of 3PB Doubler Specimen

Shell Model

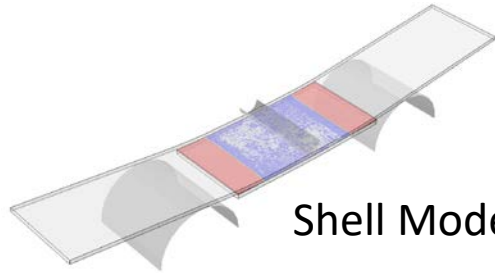


Cohesive law captures the effects of all damage mechanisms contributing to the energy release rate

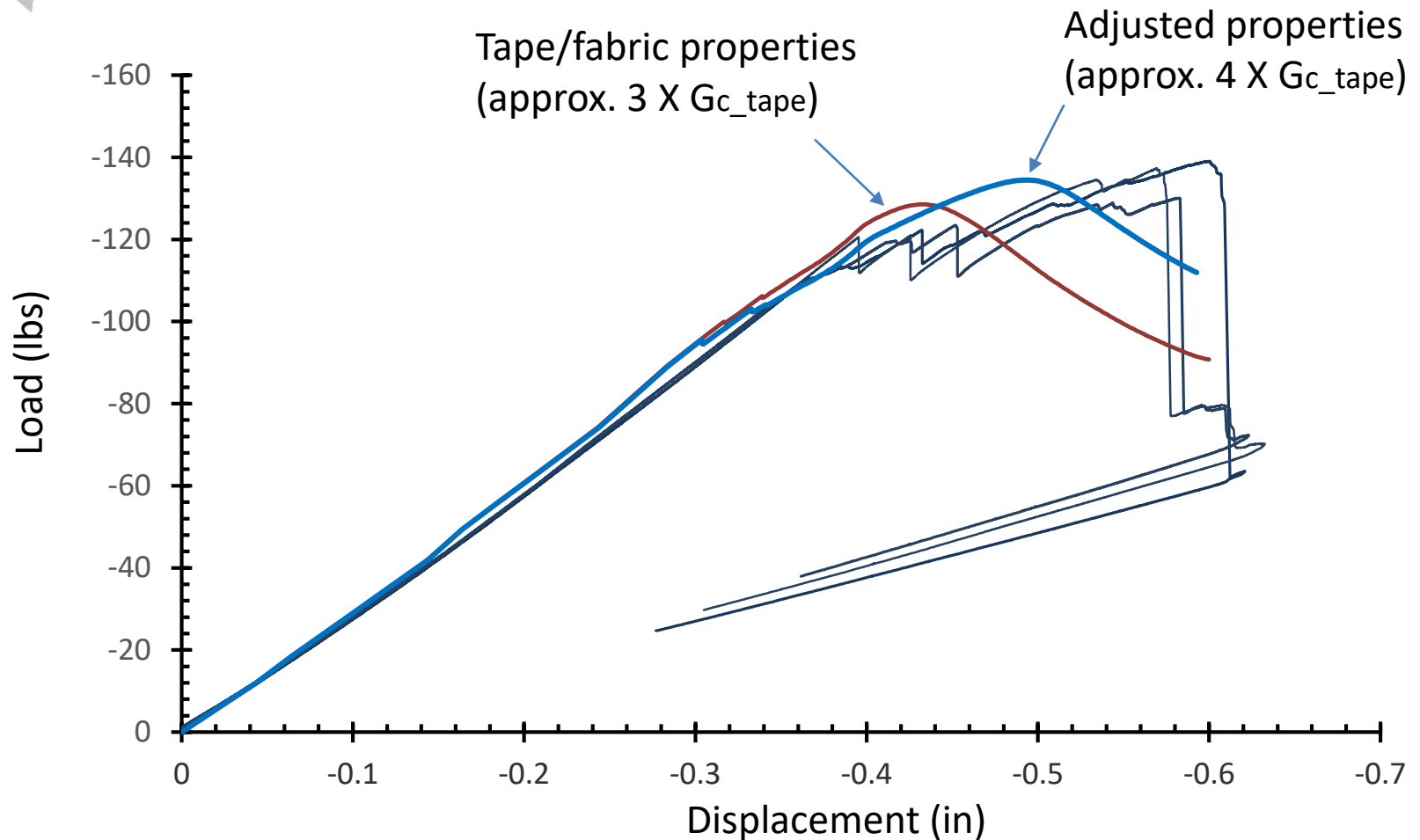
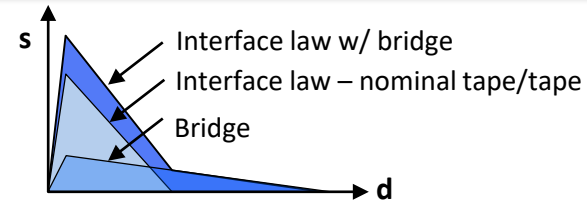




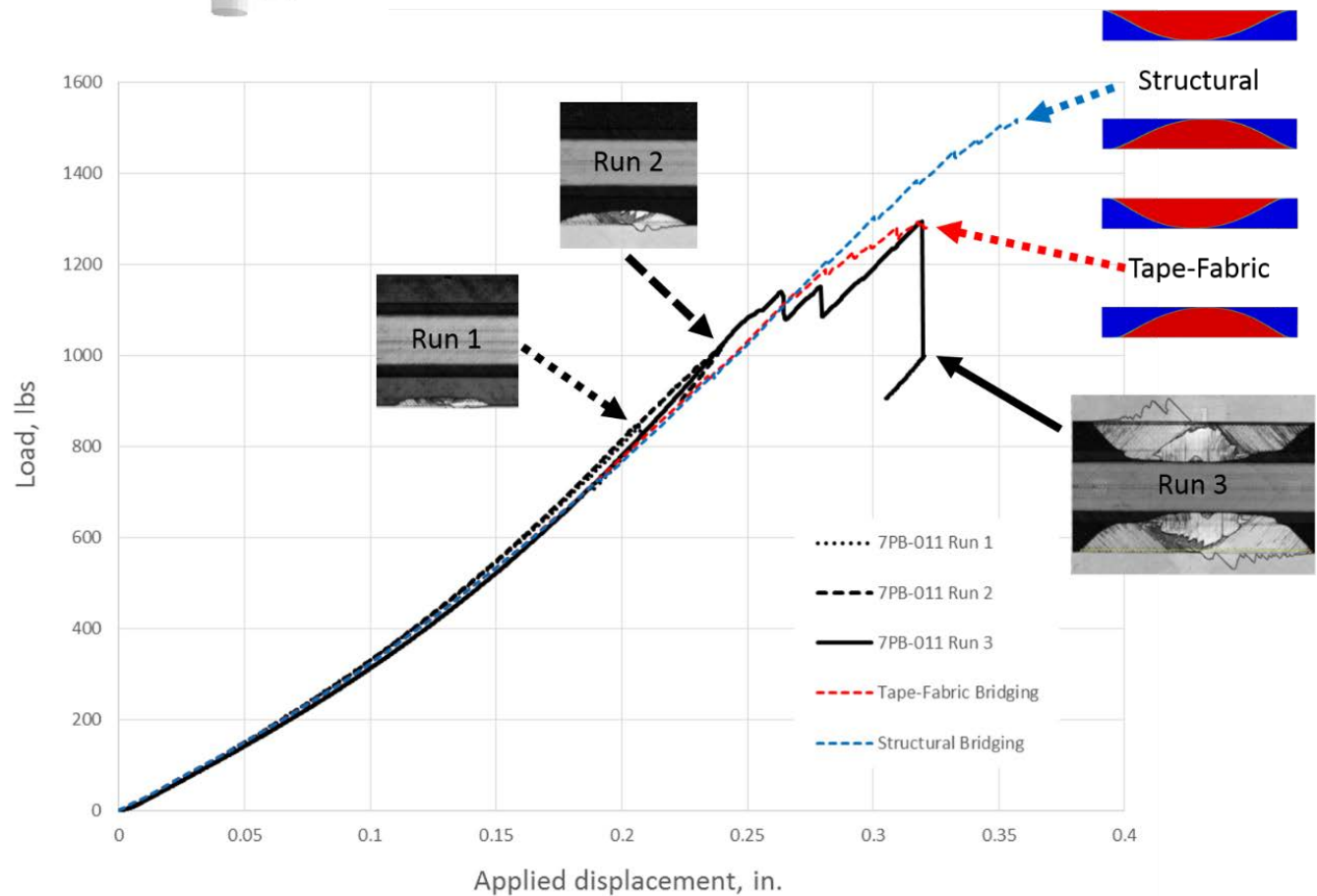
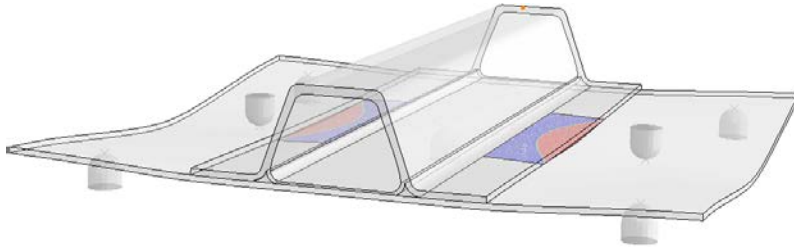
3PB Doubler Specimen Analysis Results



Shell Model



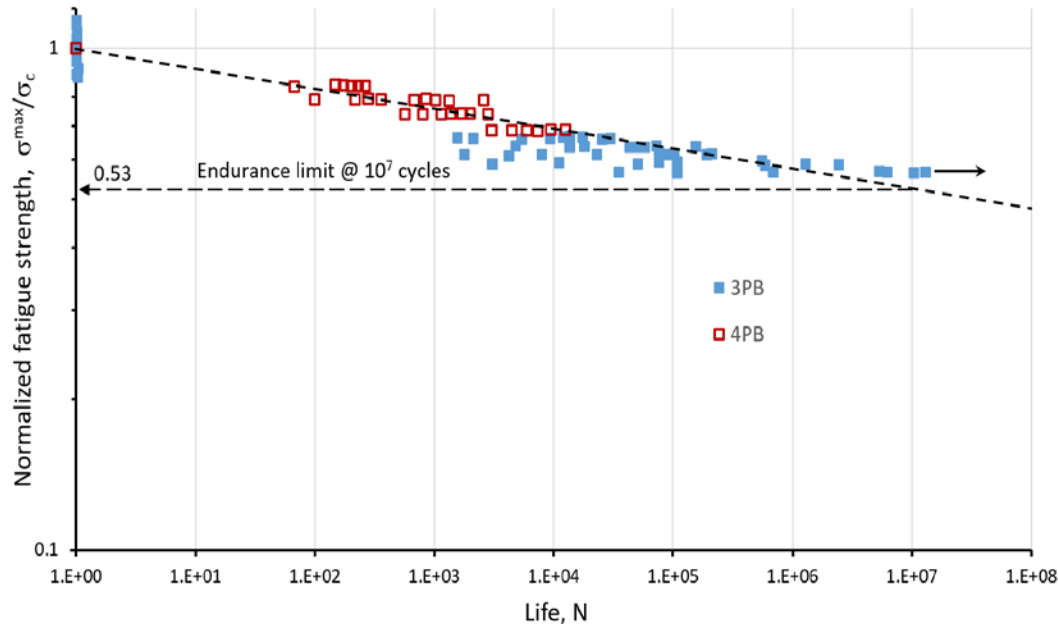
Shell Model of 7PB Specimen



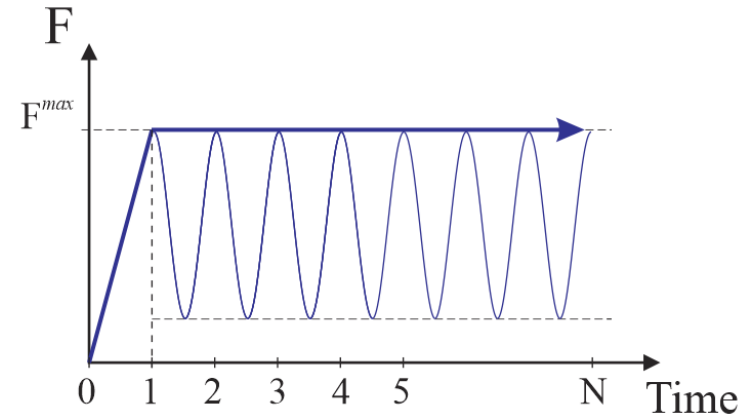


Emerging Technology: Cohesive Fatigue Model

1) S-N diagram



2) Simplified cyclic load

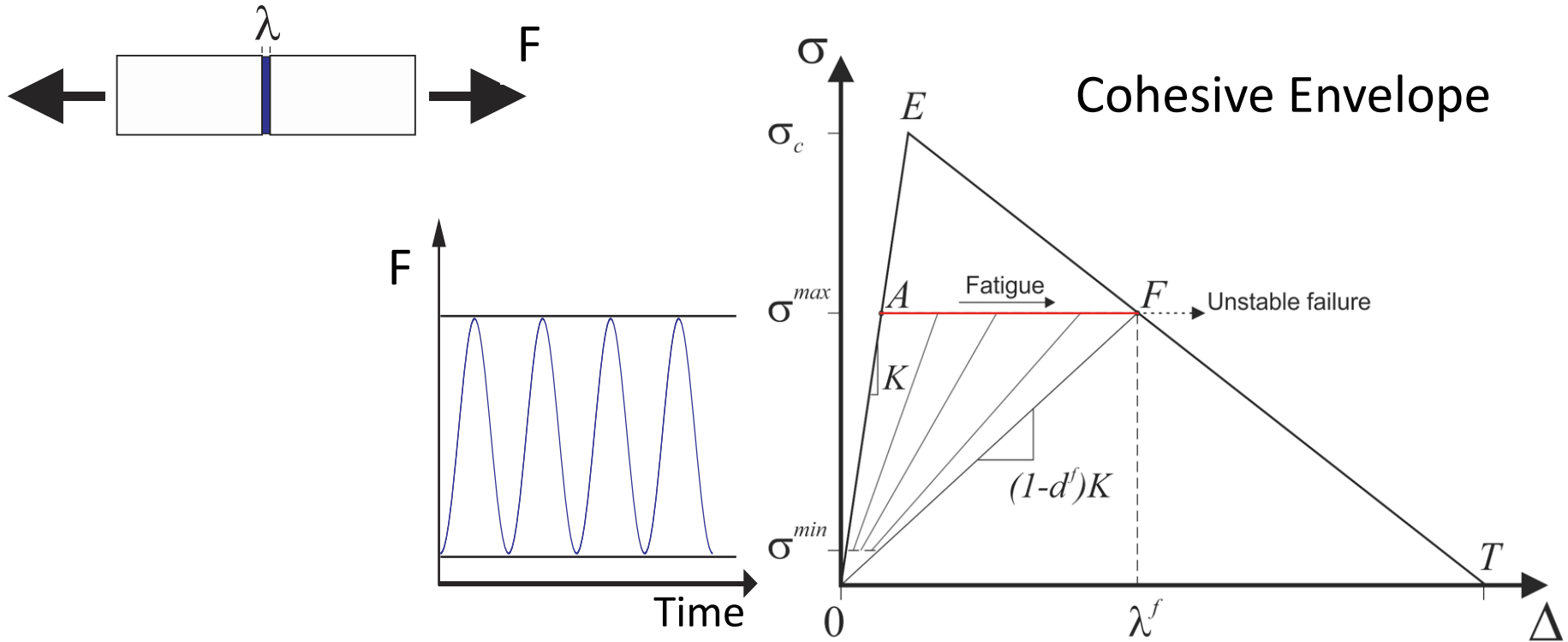


3) Damage accumulation law

$$\frac{dd}{dN} = f(d) \left(\frac{\sigma^{\max}}{\sigma_c} \right)^{\beta}$$

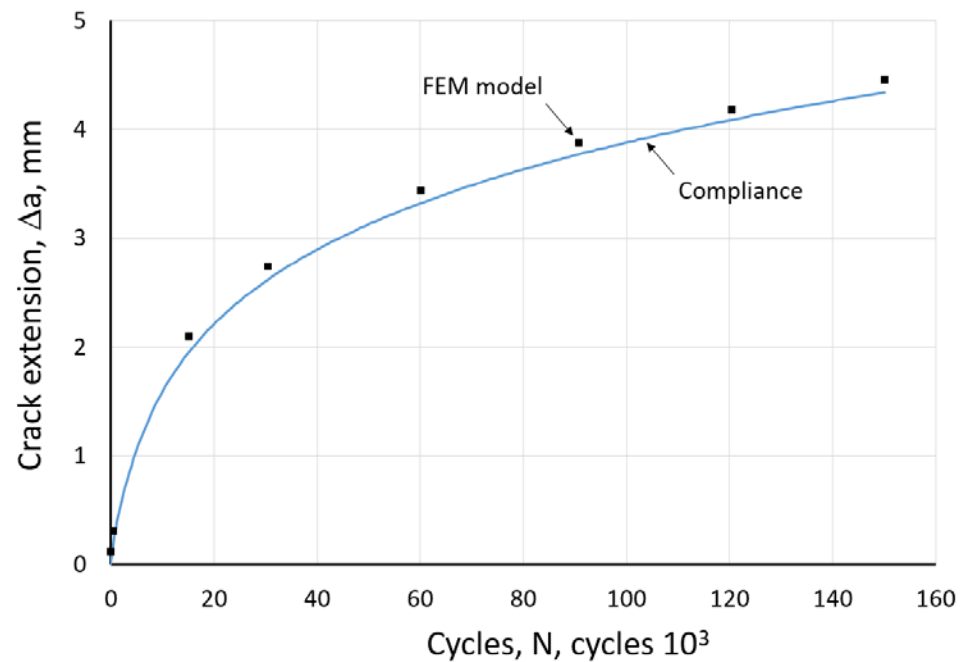
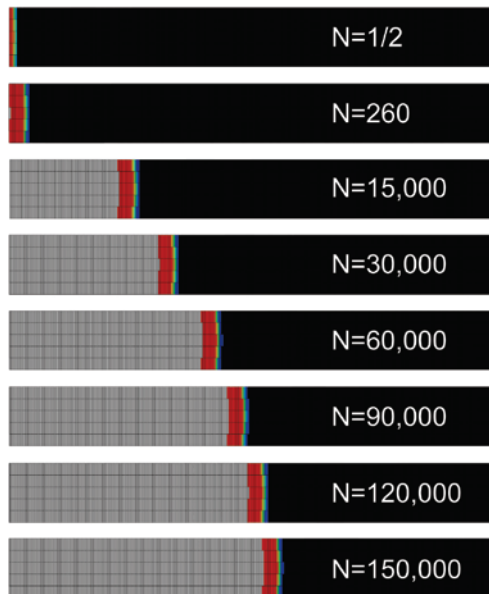
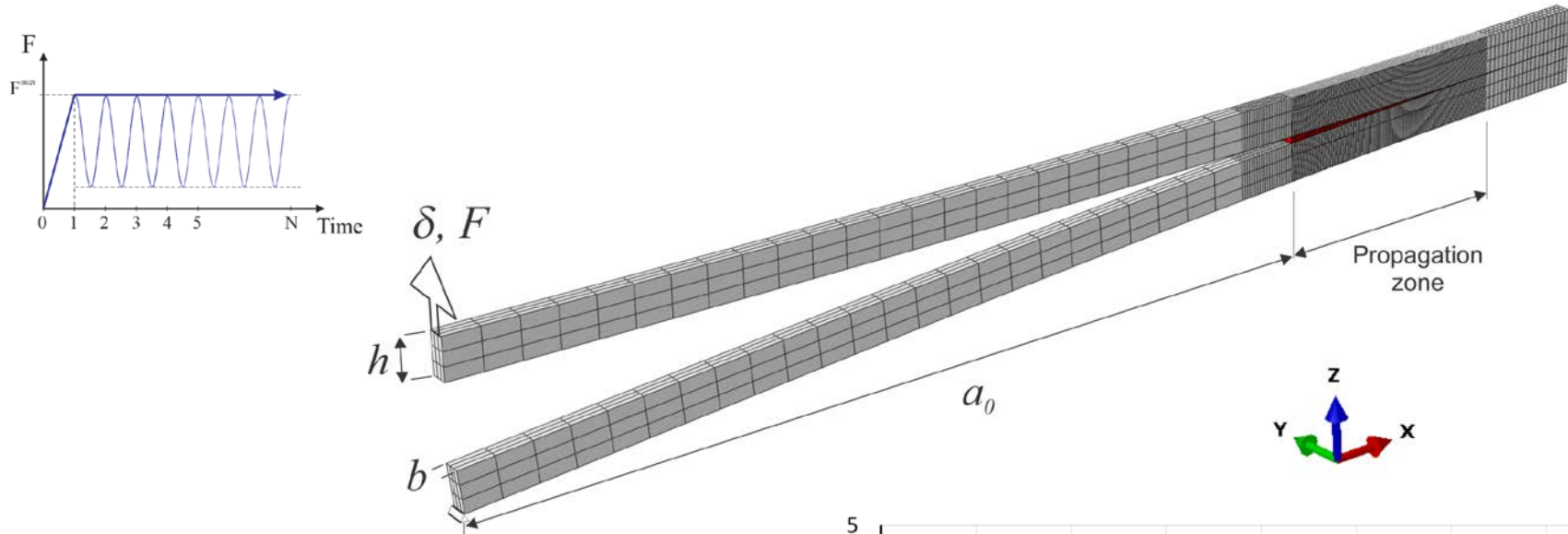


Emerging Technology: Cohesive Fatigue Model



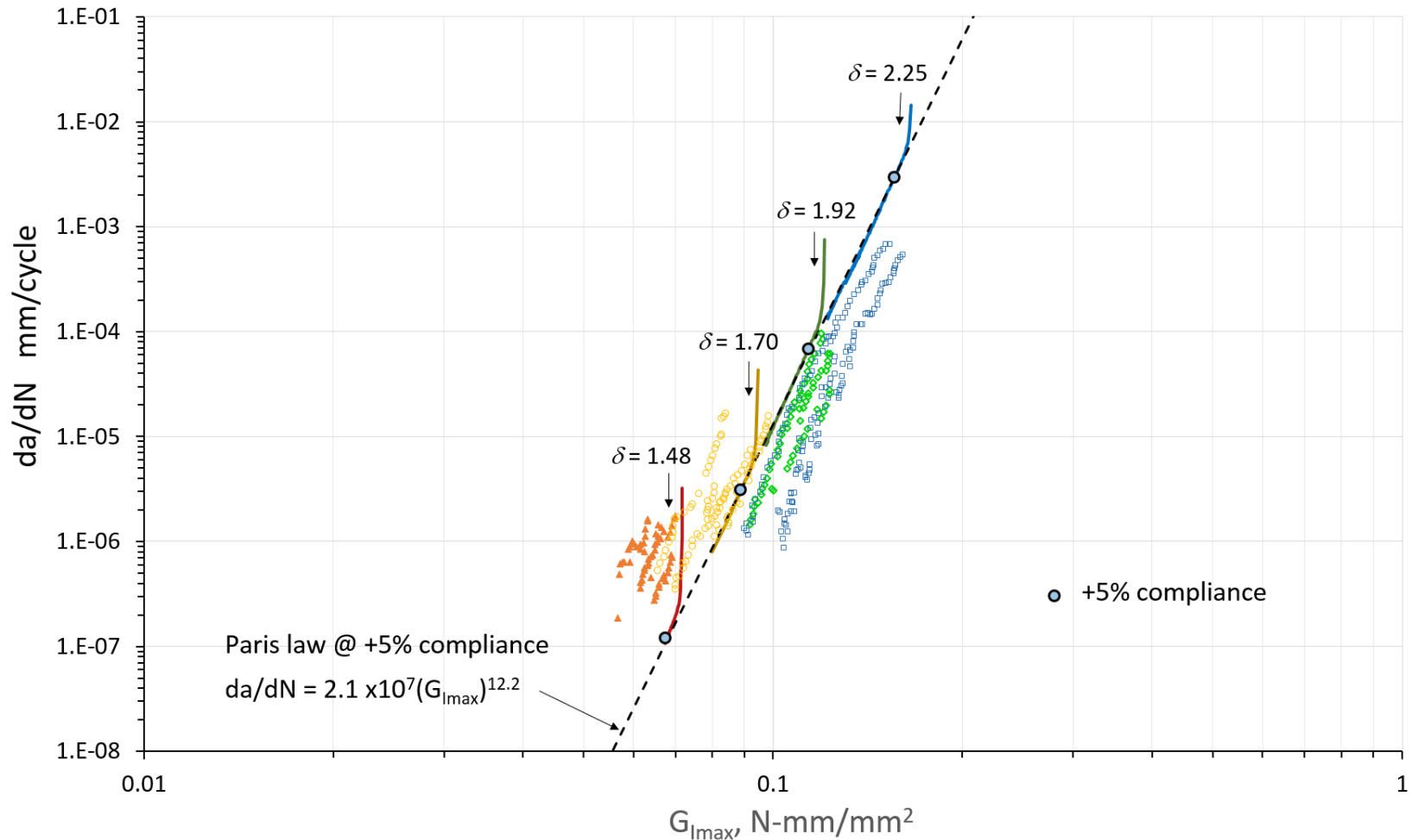
$$dd = f(d) \left(\frac{\sigma_{max}}{\sigma_c} \right)^\beta dN \quad \Rightarrow \quad \underbrace{N^f = g(d) \left(\frac{\sigma_{max}}{\sigma_c} \right)^{-\beta}}_{\text{S-N}} \quad \text{Solve for } \beta$$

Fatigue: Fatigue Delamination Propagation





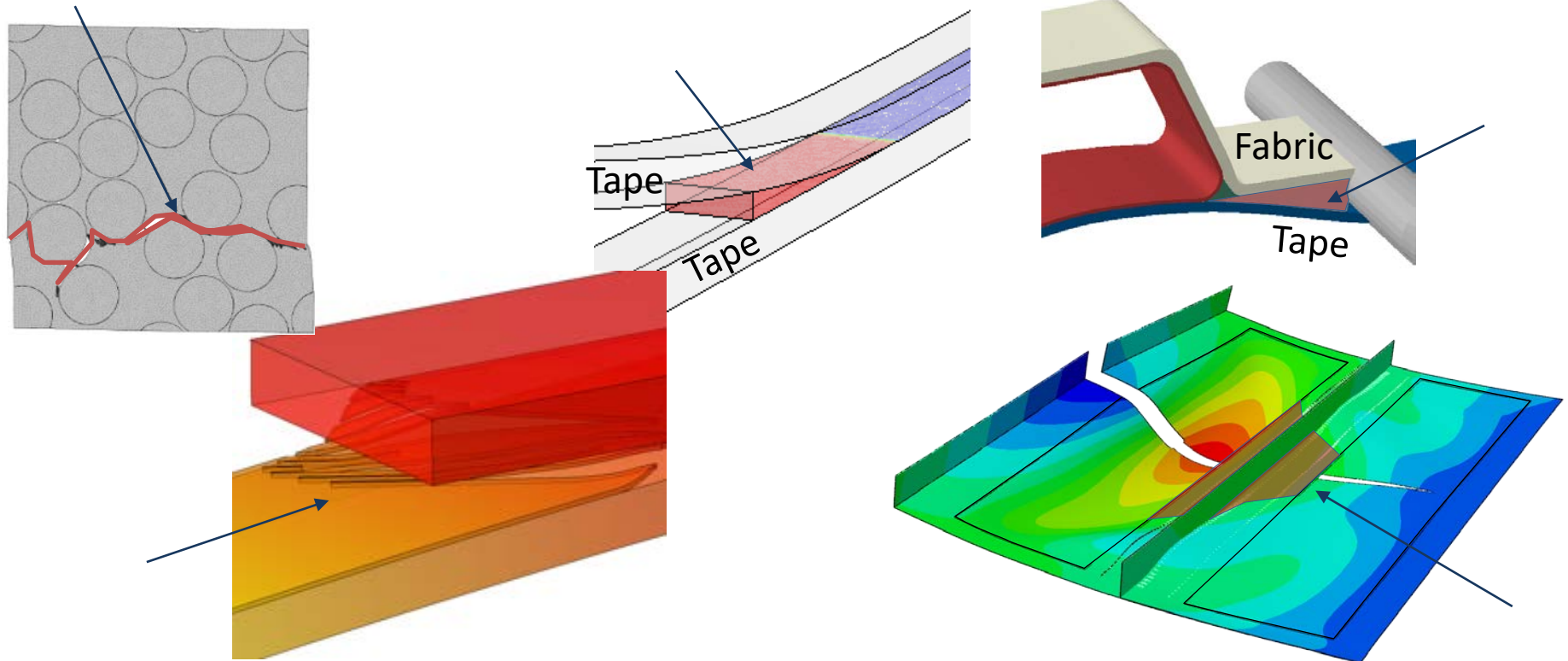
Cohesive Fatigue: Predicted Paris Law



Dávila, C. G., "From S-N to the Paris Law with a New Mixed-Mode Cohesive Fatigue Model,"
Technical Report NASA-TP-2018-219838, Hampton, VA, June 2018.

Limitations of Standard Interface Properties

- G_{Ic} and G_{IIc} do not account for R-curve toughening effects.
- Fracture toughness is a scale-dependent property that involves the morphology of the damage surfaces and the interactions with other damage modes.





Concluding Remarks (2)

Interface Separation

- The collapse of postbuckled structures is usually the result of skin/stringer separation.
- Interfacial damage is not well understood.

Modeling delamination

- Models must account for:
 - R-curve effects
 - Complexities of interfaces between dissimilar materials
 - Migration of delamination.



Concluding Remarks (3)

Modeling Delamination

- The level of fidelity required to model typical delaminations has not yet been established.
- Even the most detailed models available may not account for all of the energy dissipation mechanisms that are required.
- In many cases, models with a single interface using empirical material properties may be able to predict the response and failure of real interfaces with complex failure modes.
- As a first approximation, the G_c of a structural interface can be assumed to be 3 to 4 times the G_c of tape/tape.