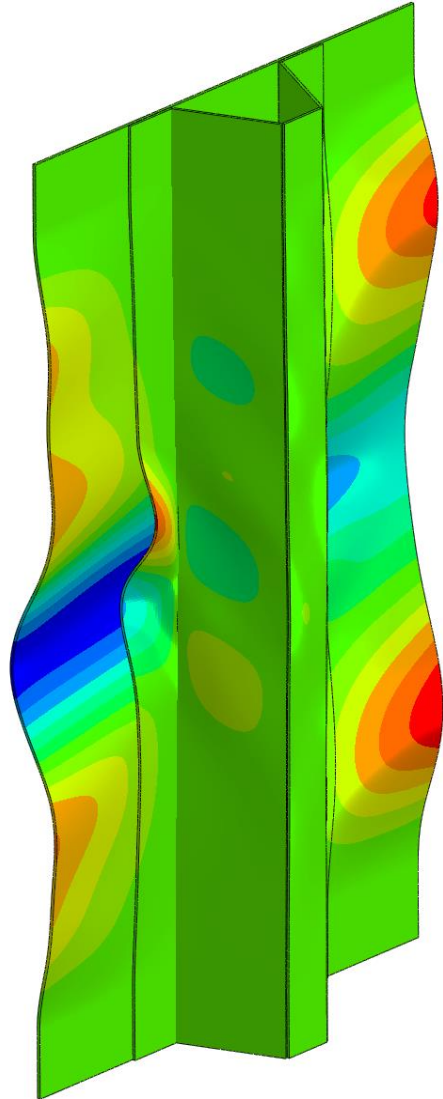


Damage Tolerance of Aircraft Structures Research in the NASA Advanced Composites Project



Carlos G. Dávila

Structural Mechanics and Concepts Branch
NASA Langley Research Center
Hampton, VA
USA

Institut Clément Ader
Toulouse, 17 Novembre 2016



Location of NASA Centers



NASA Headquarters
Washington, DC.

Ames Research Center



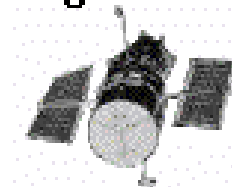
Lewis Research Center



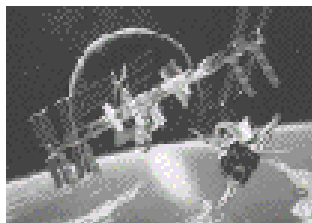
**Jet
Propulsion
Laboratory**



Goddard Space Flight Center

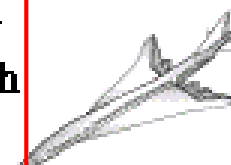


Dryden Flight Research Center

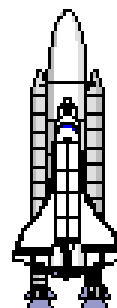


Capabilities
Distributed
Agencywide

**Langley
Research
Center**



Kennedy Space Center



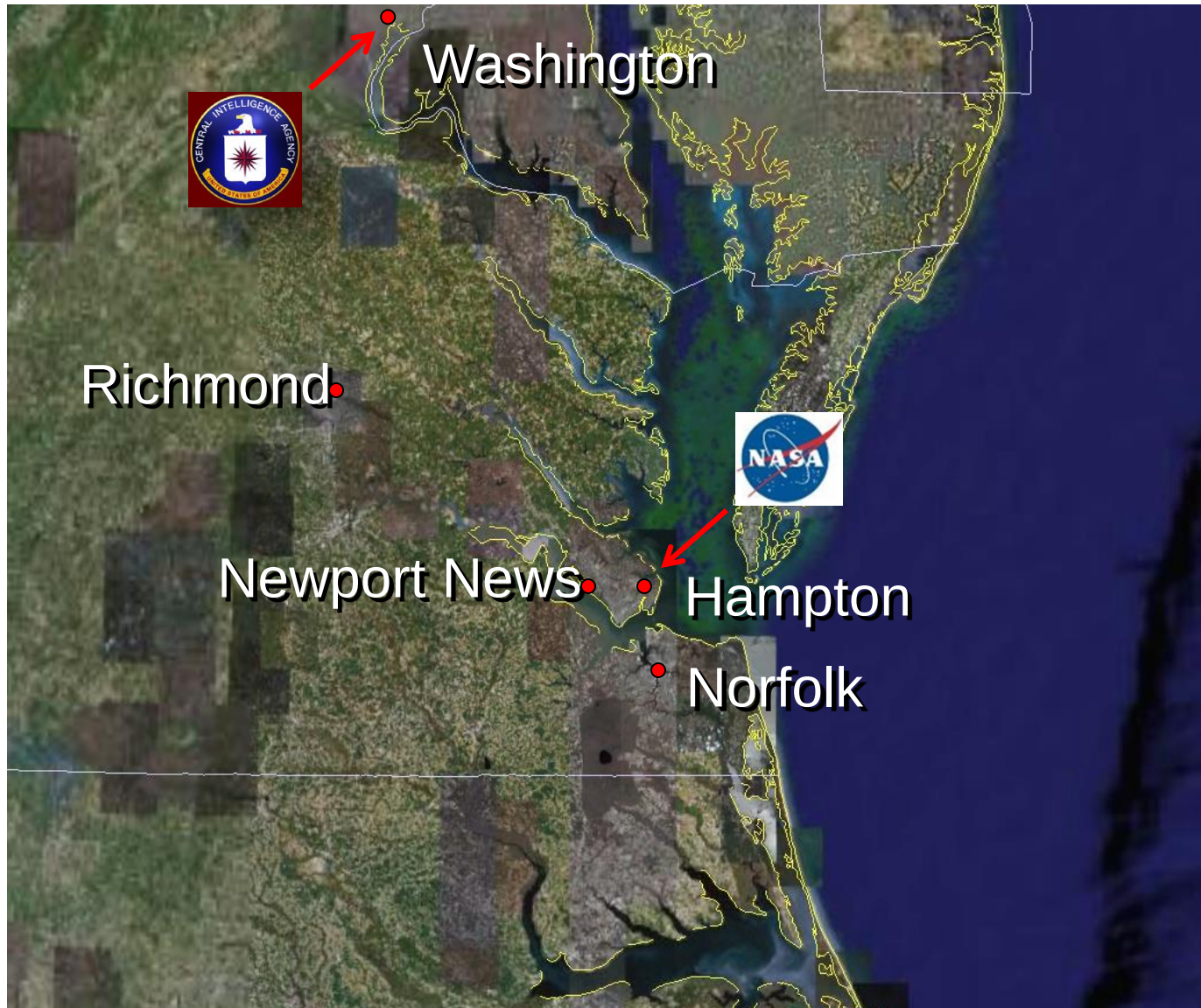
**Marshall
Space
Flight
Center**

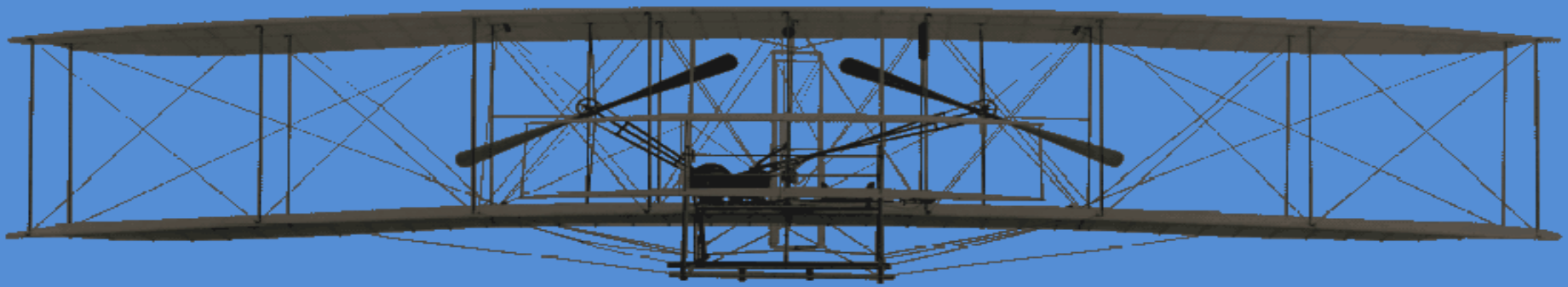


Johnson Space Center



NASA Langley Research Center





Brief Chronology of Early Aviation

- 1903** Wright brother's first powered, controlled flight in an airplane
- 1909** Improved Wright Flyer becomes 1st military plane
- 1909** Blériot crosses the English Channel in a monoplane
- 1910** Jorge Chavez (Peru) flies over the Alps in a Blériot
- 1914** US has no fighter aircraft ready for WWI combat!
- 1917** – **National Advisory Committee for Aeronautics** is formed

Created by Woodrow Wilson to organize American aeronautical research and raise it to the level of European aviation.

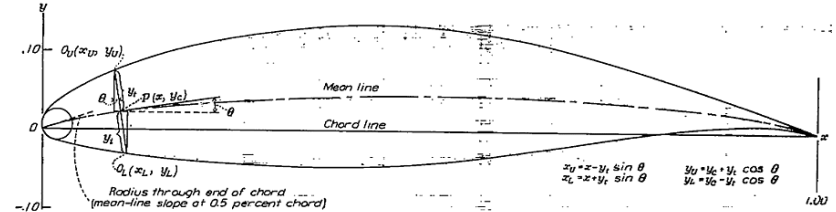
“Direct and conduct research and experimentation in aeronautics, with a view to their practical solution.”

Aerodynamics



1920

NACA



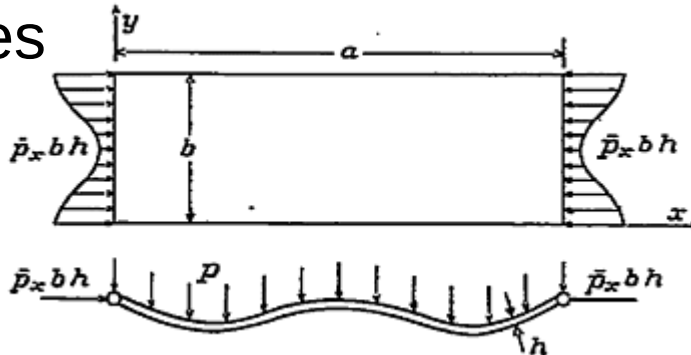
SAMPLE CALCULATIONS FOR DERIVATION OF THE NACA 65,3-618, $s=1.0$ AIRFOIL

x	$\bar{y}_1$	$\bar{y}_2$	$\tan \theta$	$\sin \theta$	$\cos \theta$	$y_1 \sin \theta$	$y_1 \cos \theta$	x_u	y_u	x_L	y_L
0	0	0	0	0	1	0	0	0	0	0	0
0.005	0.0124	0.0000	0.33696	0.31822	0.94765	0.00423	0.01245	-0.00077	0.01455	0.00923	-0.01055
0.05	0.0361	0.0000	0.33696	0.31822	0.94765	0.00423	0.01245	-0.00077	0.01455	0.00923	-0.01055
0.10	0.0602	0.0000	0.33696	0.31822	0.94765	0.00423	0.01245	-0.00077	0.01455	0.00923	-0.01055
0.25	0.0863	0.0000	0.33696	0.31822	0.94765	0.00423	0.01245	-0.00077	0.01455	0.00923	-0.01055
0.50	0.0863	0.01412	0	0	1.00000	0	0.08630	0.50000	0.00000	0.00000	-0.41811
0.75	0.0450	0.03850	0	0	1.00000	0	0.04500	0.75000	0.00000	0.00000	-0.35353
1.00	0	0	0	0	1.00000	0	0	1.00000	0	0	0

* Thickness distribution obtained from ordinates of the NACA 65,3-618 airfoil.
 * Ordinates of the mean line, 0.8 of the ordinate for $c_u=1.0$.
 * Slope of radius through end of chord.

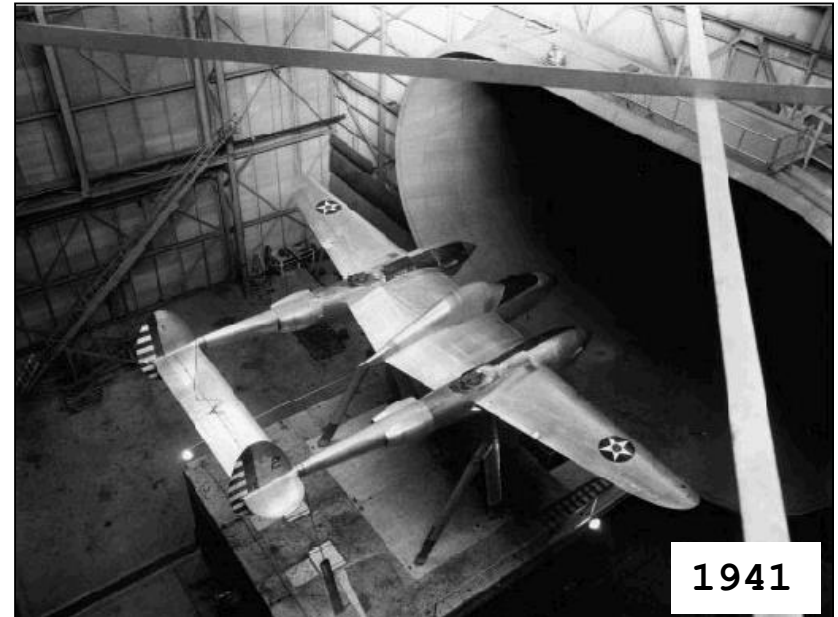
Flutter, engine performance

Structures



$$\epsilon_x^1 = \frac{1}{E} \left(\frac{\partial v}{\partial y} \frac{\partial F_x}{\partial x} - \nu \frac{\partial v}{\partial x} \frac{\partial F_x}{\partial y} \right)$$

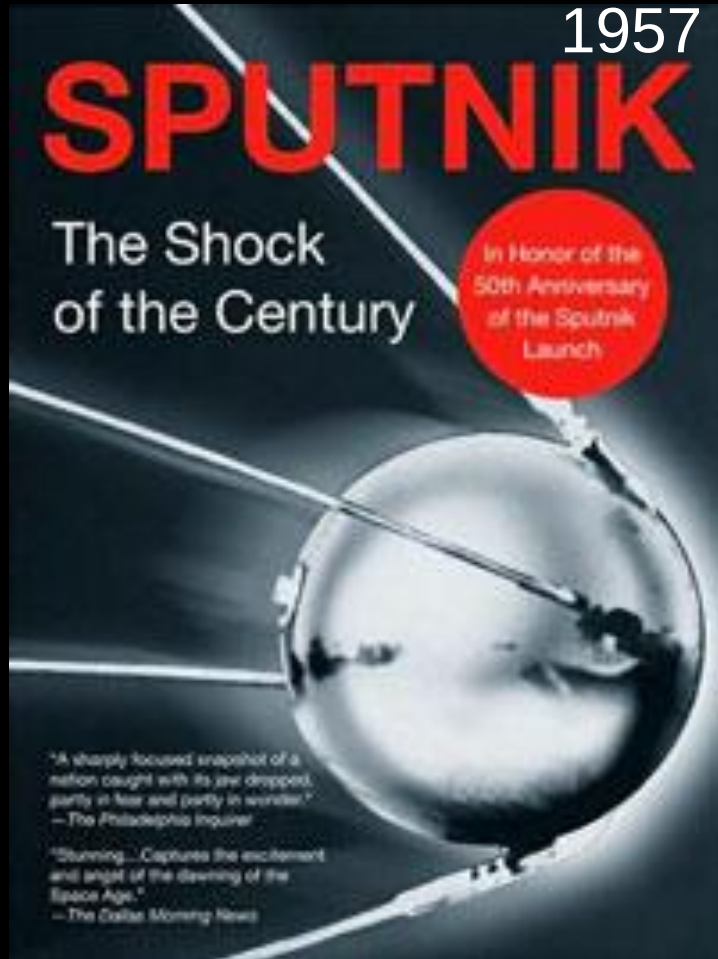
$$\epsilon_y^1 = \frac{1}{E} \left(\frac{\partial v}{\partial x} \frac{\partial F_y}{\partial x} - \nu \frac{\partial v}{\partial y} \frac{\partial F_y}{\partial y} \right)$$



1941



NACA to NASA



"...I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth."

J.F. Kennedy, May 25, 1961



NASA Langley Research Center



Neil Armstrong At The Lunar Landing Research Facility
NASA Langley Research Center

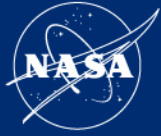
1/28/1970

Image # EL-1996-00192



Langley Snapshot

National Aeronautics and
Space Administration



CELEBRATING



NASA Langley Research Center 1917-2017



- 2016 budget: \$925 million
- 3,470 employees
- 300 hectares
- 150 buildings

A Storied Legacy, A Soaring Future



NASA's Focus Areas



Aeronautics



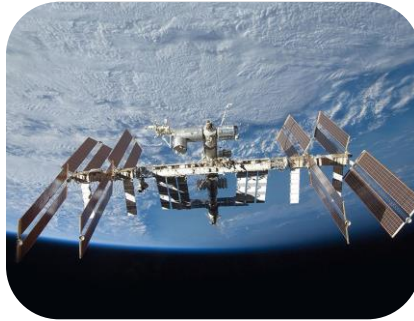
Mars



Technology



Earth



International
Space Station

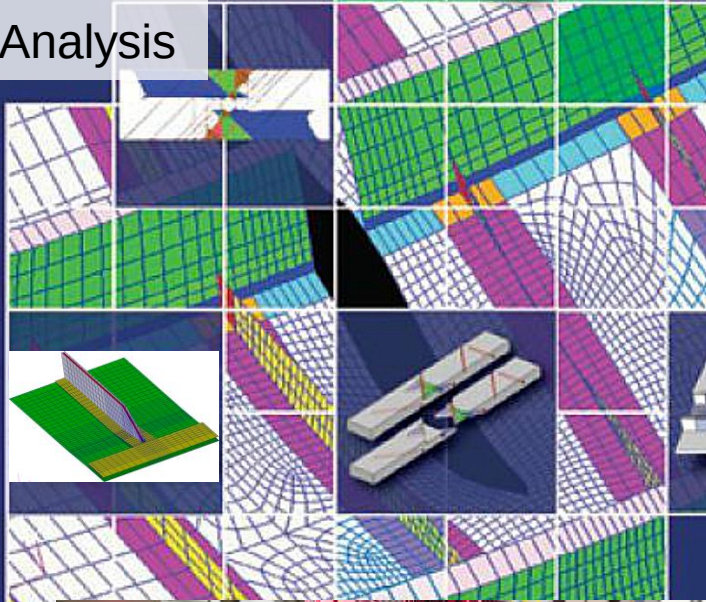


Solar System
& Beyond



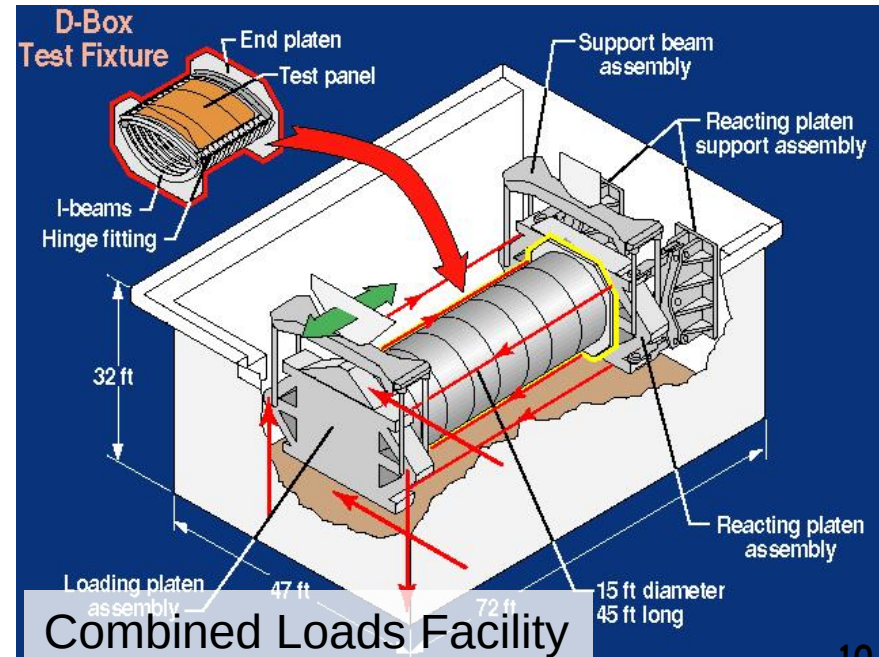
Composite Structures Research at LaRC

Analysis



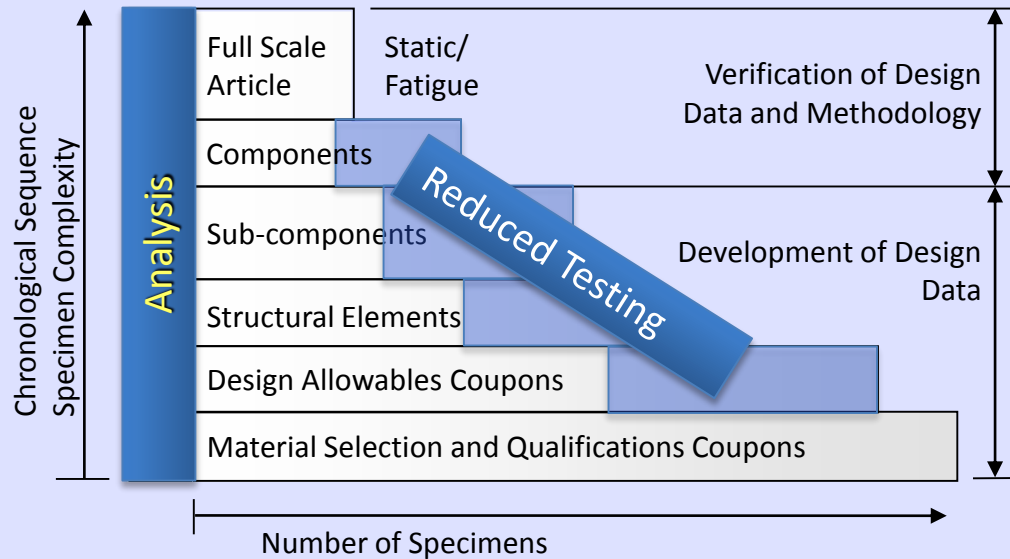
Structures and Materials Labs

ISAAC Manufacturing Testbed

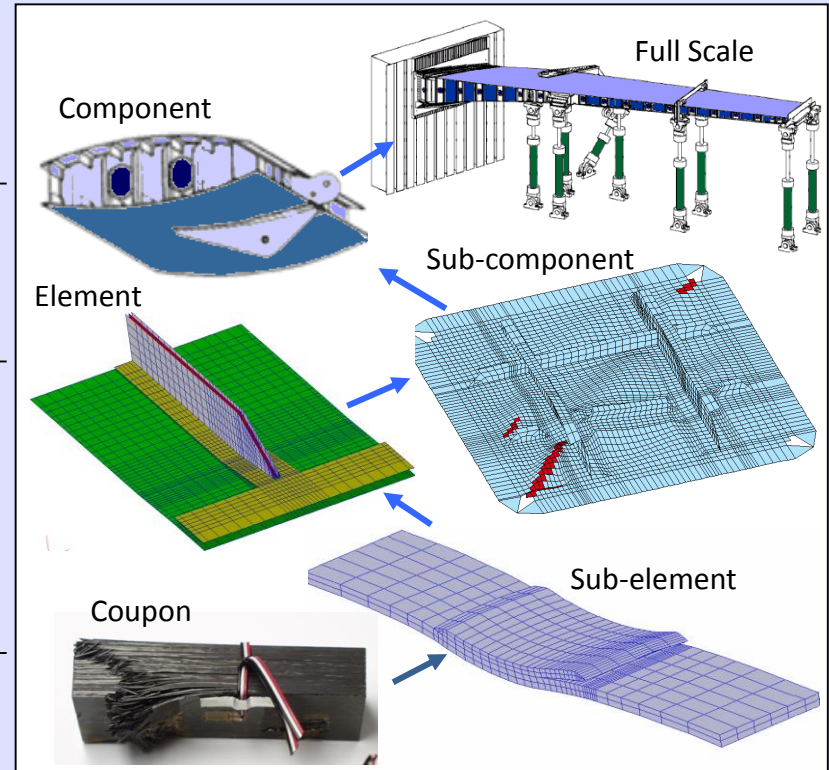


Structural Complexity and Building Block Approach

Building Block Integration *Certification Methodology (CMH-17)*



Levels of Structural Testing & Analysis

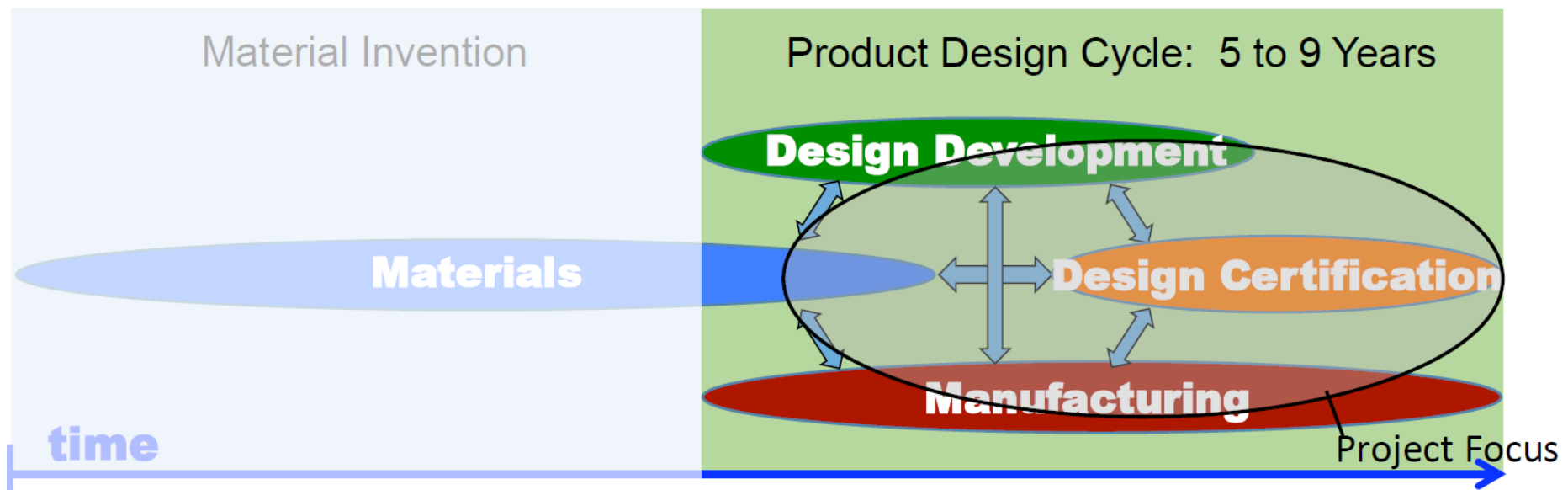


• High-fidelity Progressive Damage Analysis

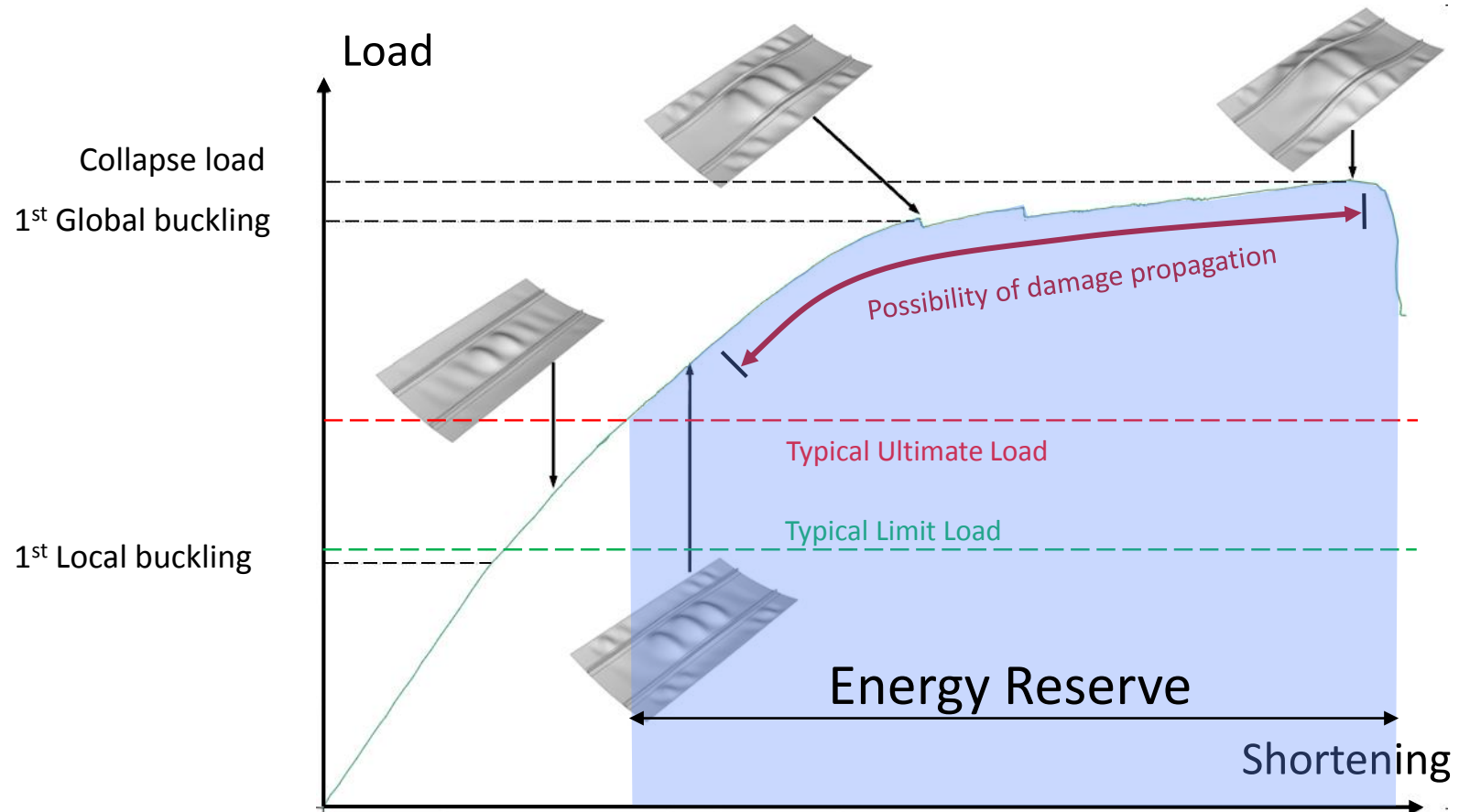
- Reduced reliance on testing
 - Faster design process
 - More accurate design tools
- } → reduced non-recurring costs
- reduced recurring costs

Goal and Scope

Focus on reducing the time to develop and certify composite materials and structures, helping American industry retain their global competitive advantage in aircraft manufacturing



Typical stages in a panel's postbuckling response



From: R. Degenhardt, DLR, 2008



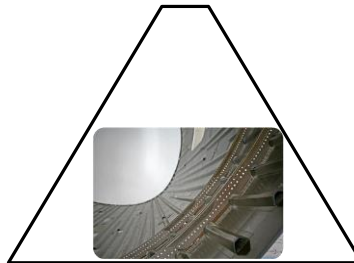
Post-Buckled Stringer-stiffened Panels with BVID

Fuselage Component:

- Candidate Material:
IM7/8552 Carbon Epoxy tape

Phase II FY17-19

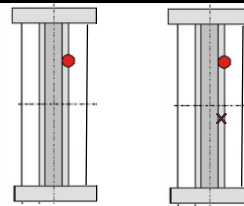
Subcomponents



Increasing complexity:

- Geometry and Loading
- Failure mode interaction

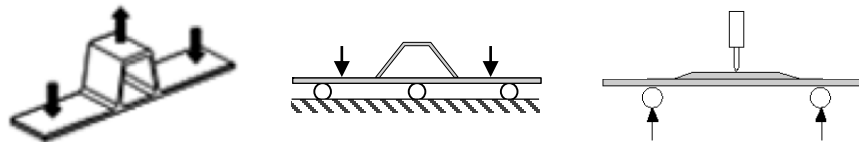
Elements



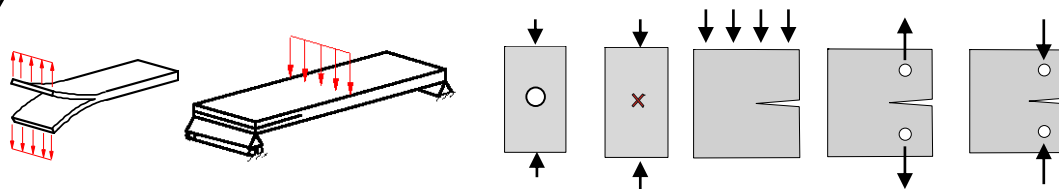
- Defect
- × Impact Site

Phase I FY15-16

Sub-elements

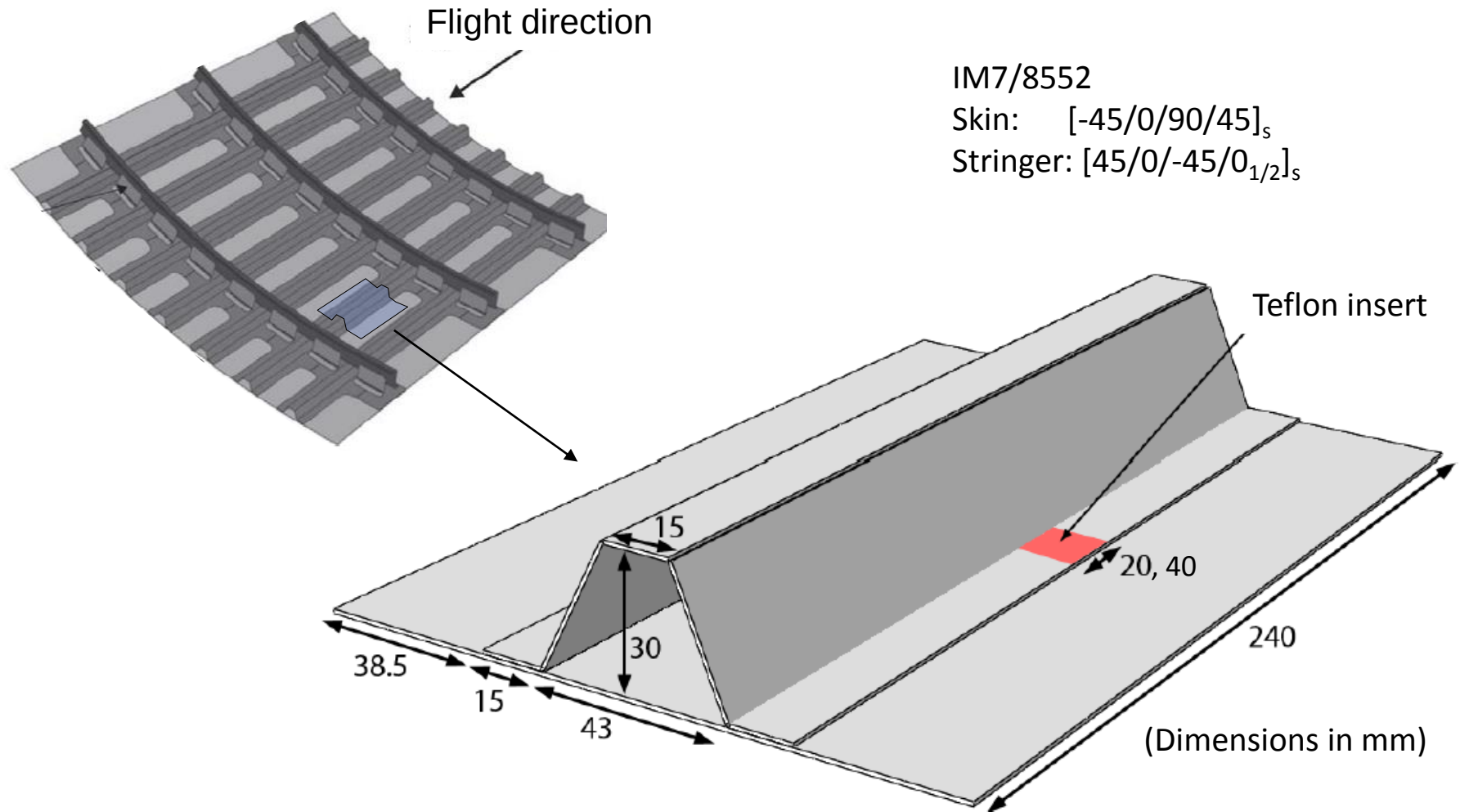


Coupons





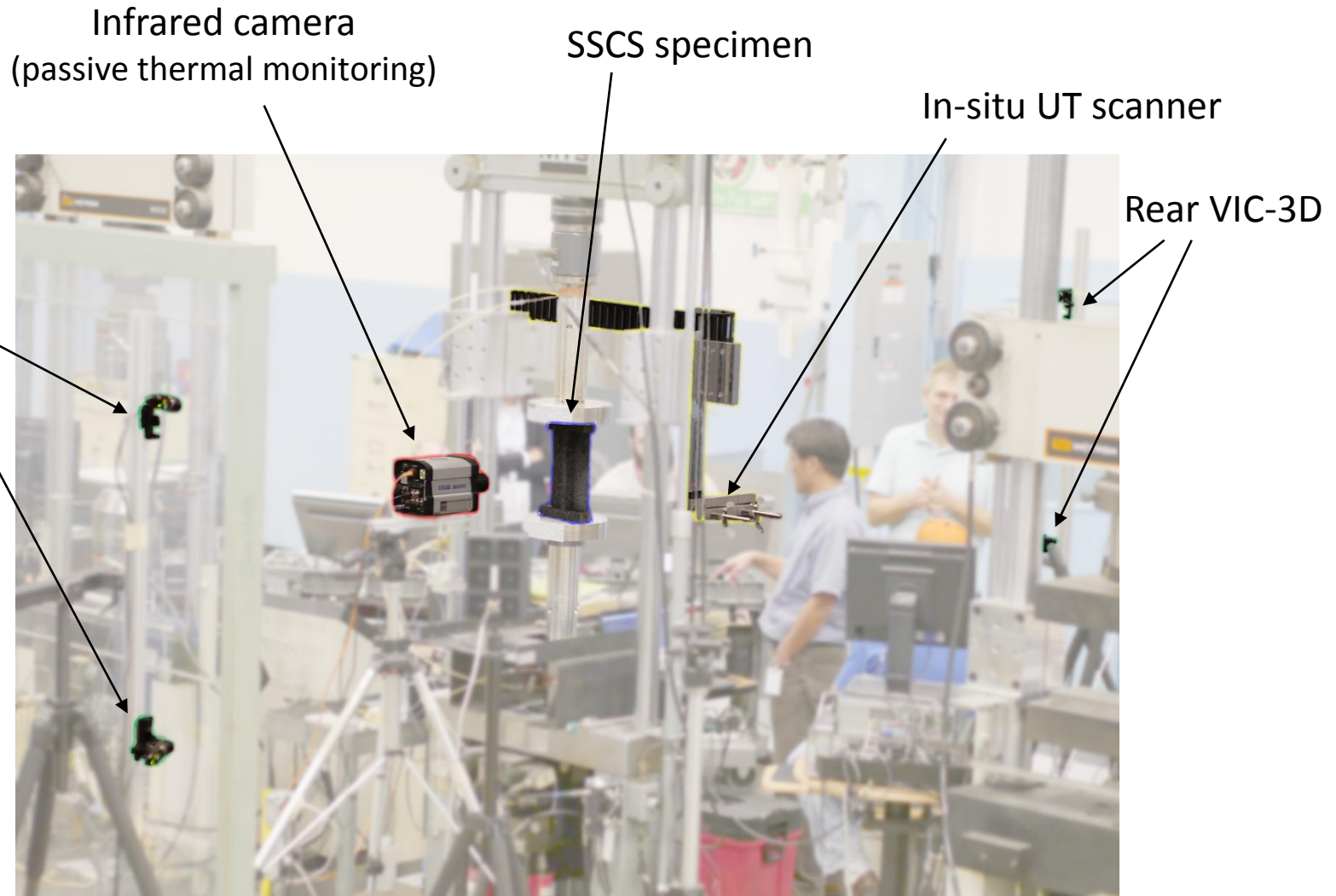
Single Stringer Compression Specimen (SSCS)



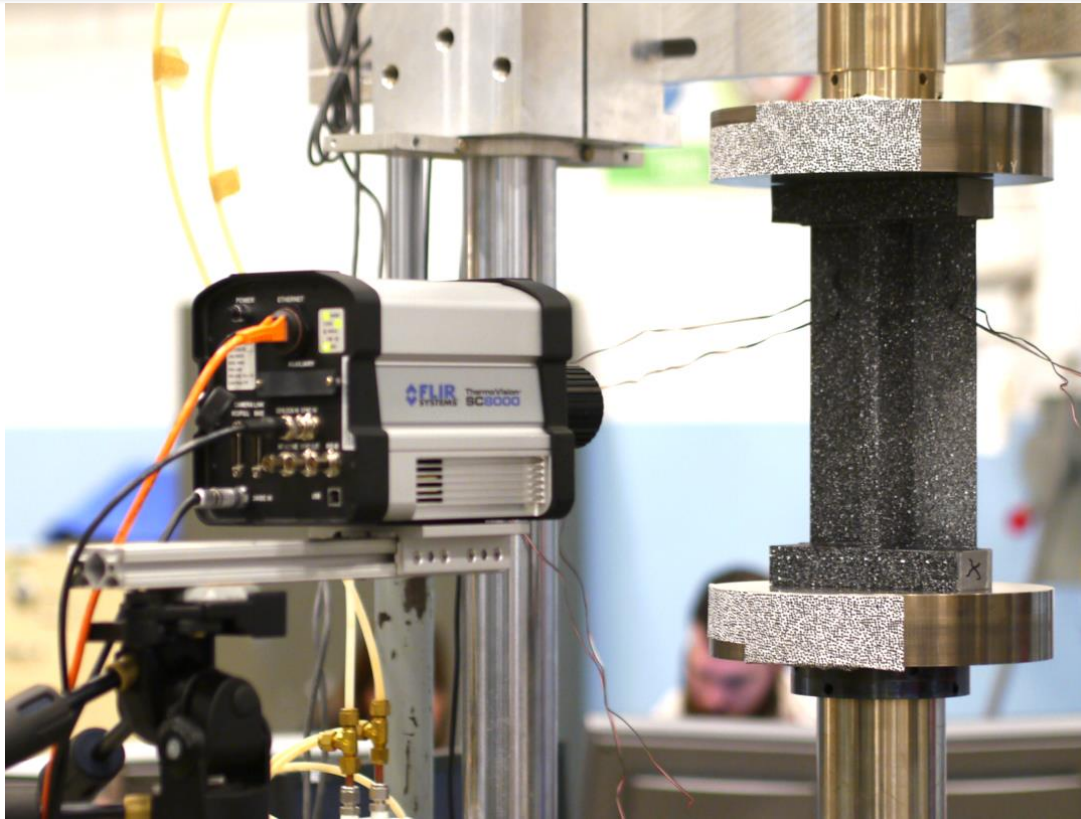
SSCS is designed to have response and damage tolerance characteristics similar to those of a multi-stringer panel



Instrumentation/Test Setup



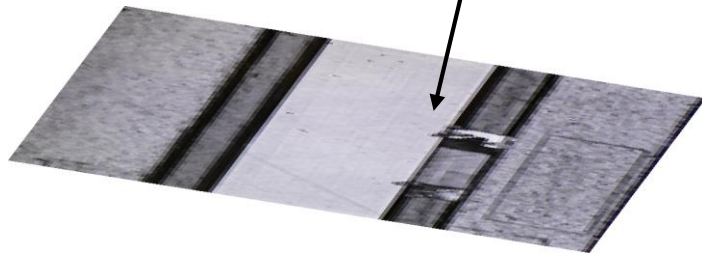
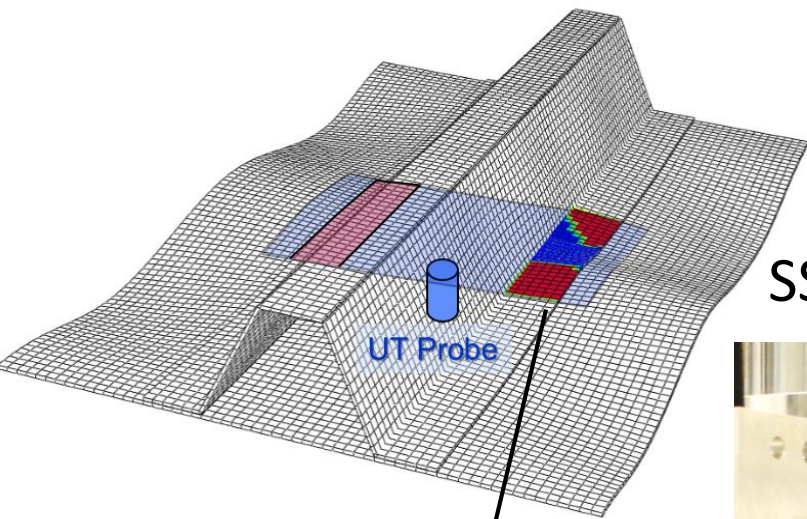
Passive Thermal Monitoring



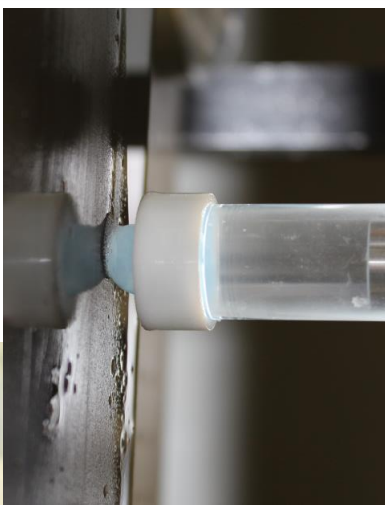
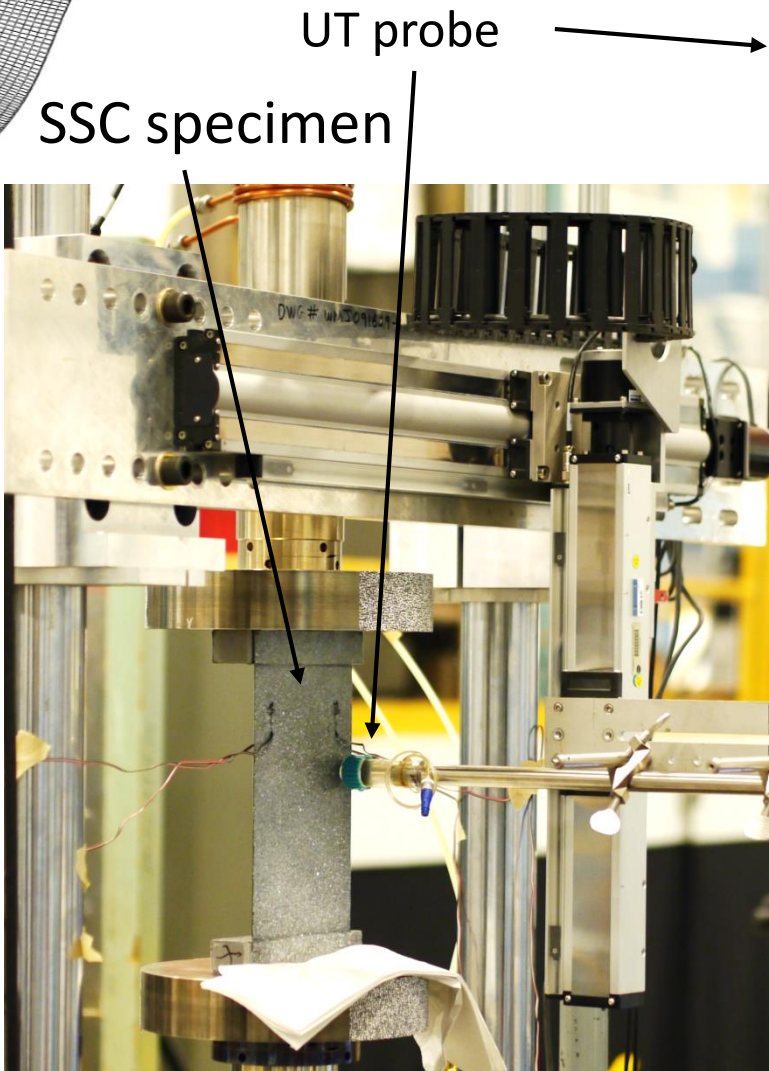
- Passive thermography can track the position of the delamination front during fatigue cycling
- Fatigue loading is stopped for UT scanning when changes are detected



In-situ Ultrasonic Testing (UT)



UT scan



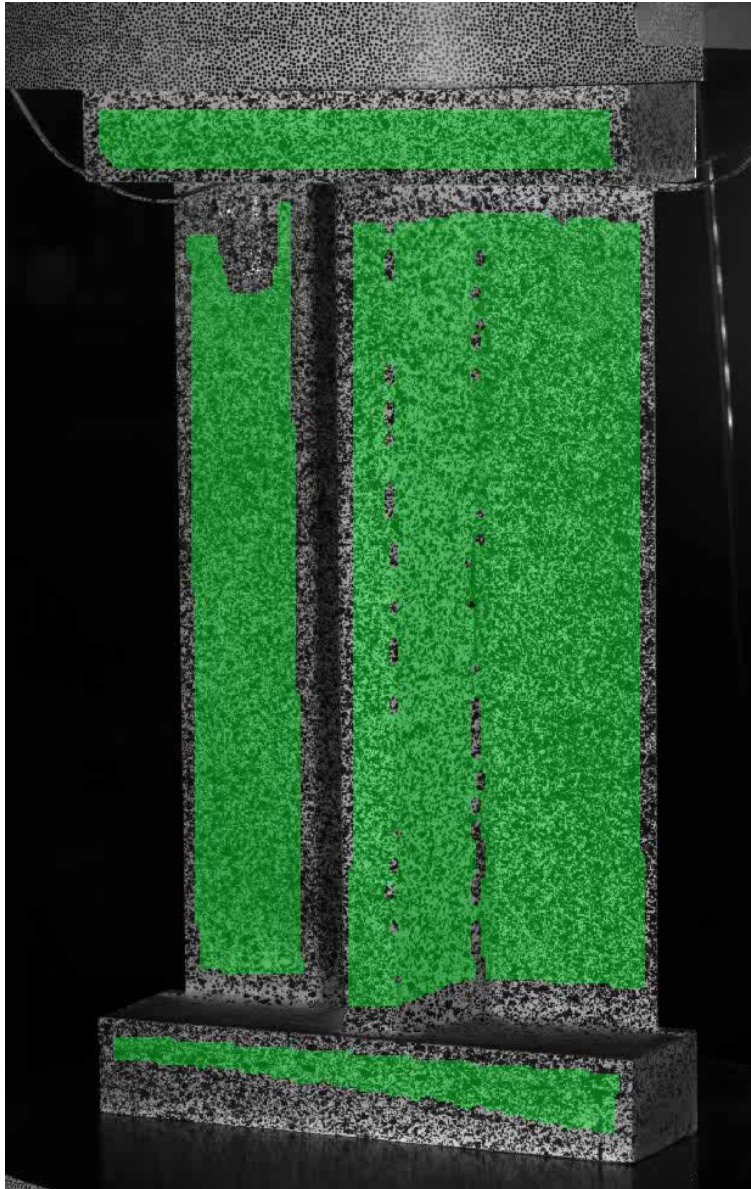


Quasi-static Test



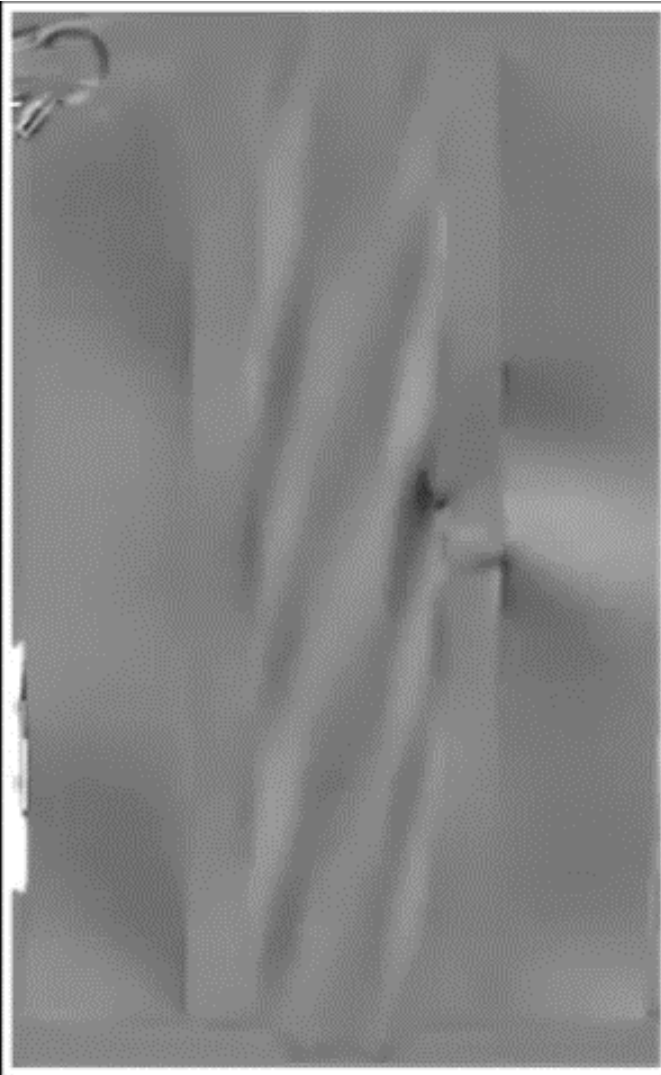


Quasi-static Test – DIC interpretation

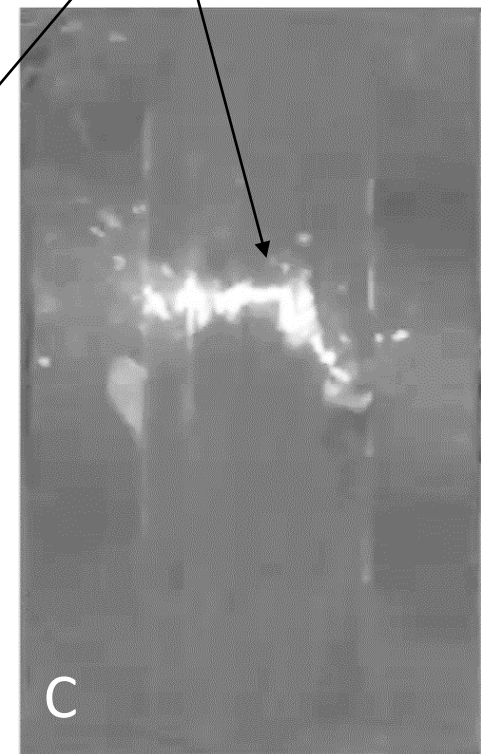
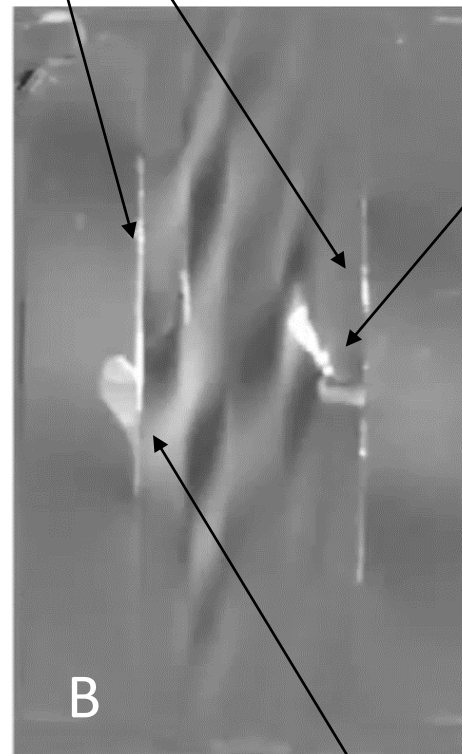
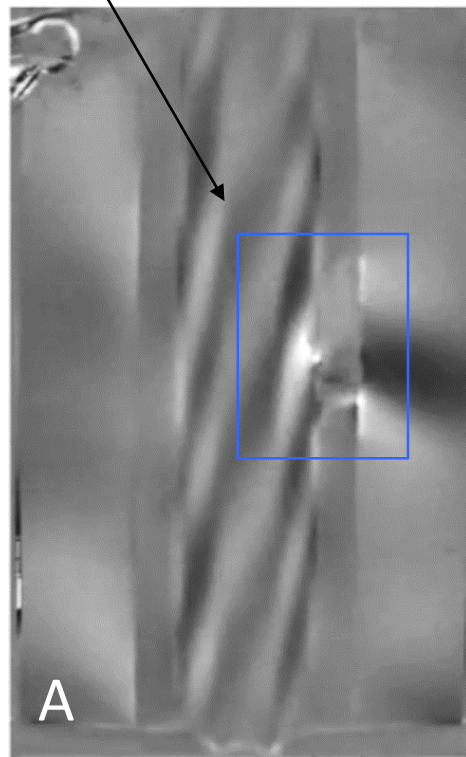
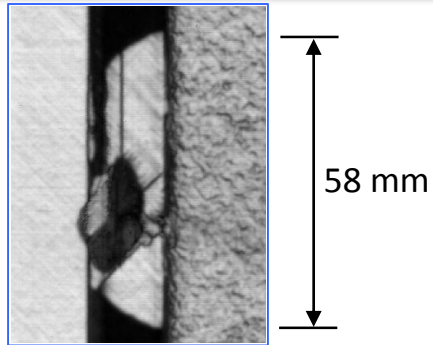




Passive Thermography: Collapse



Collapse Sequence

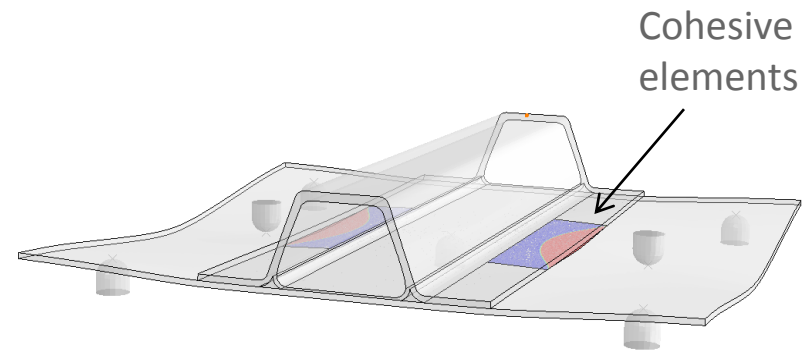
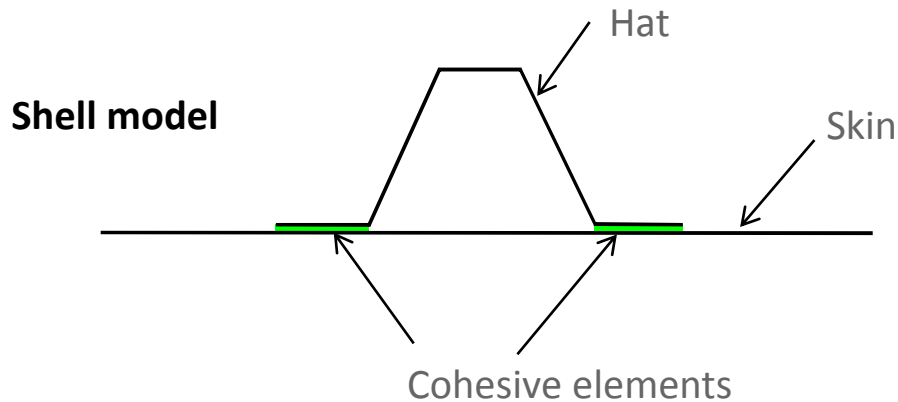


Flange debonding
and tunneling

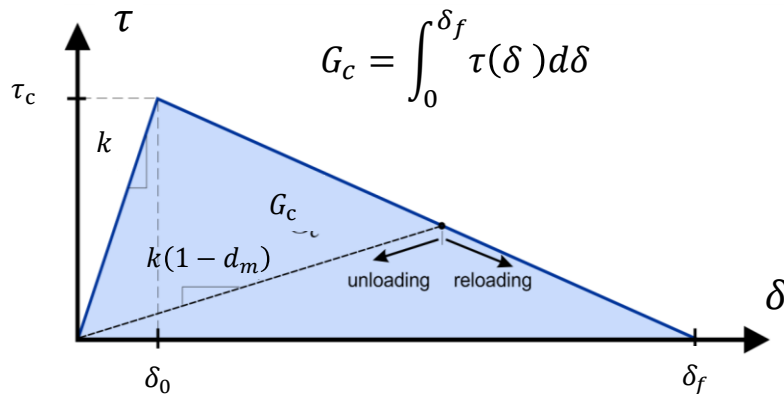
Stringer crippling

Delamination inside skin

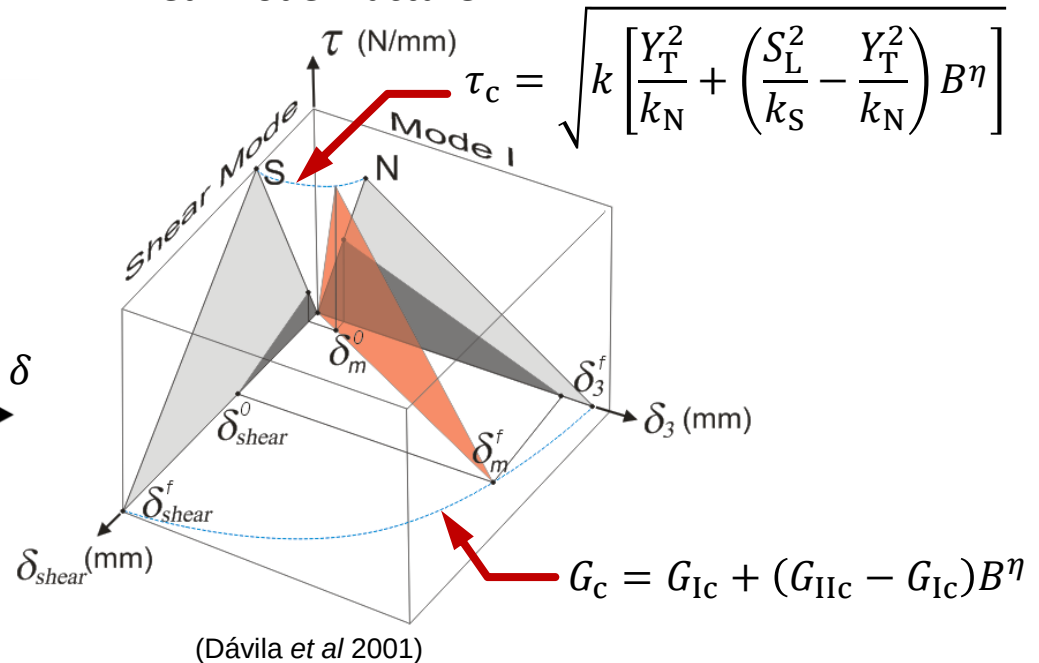
Analysis of Skin-Stringer Separation



Bilinear Traction-Displacement Law:



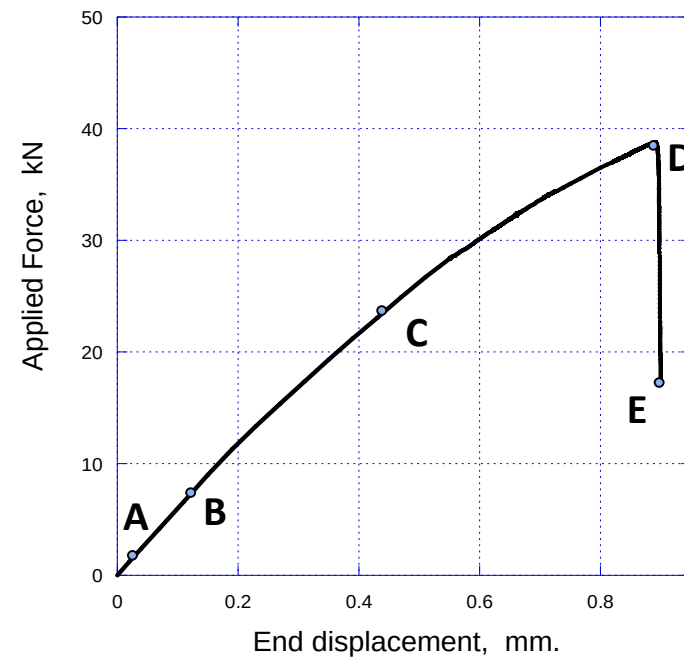
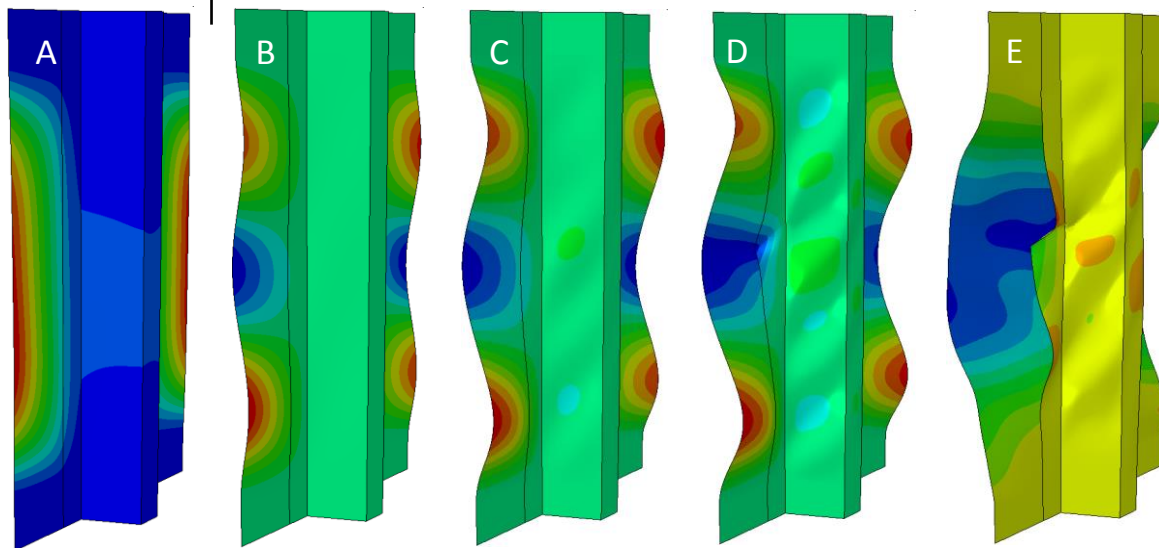
Mixed-Mode Fracture:



Predicted SSCS Response - Nominally Pristine Specimen

B.C. for potting applied

4X Magnification



Residual thermal deformation

First buckling

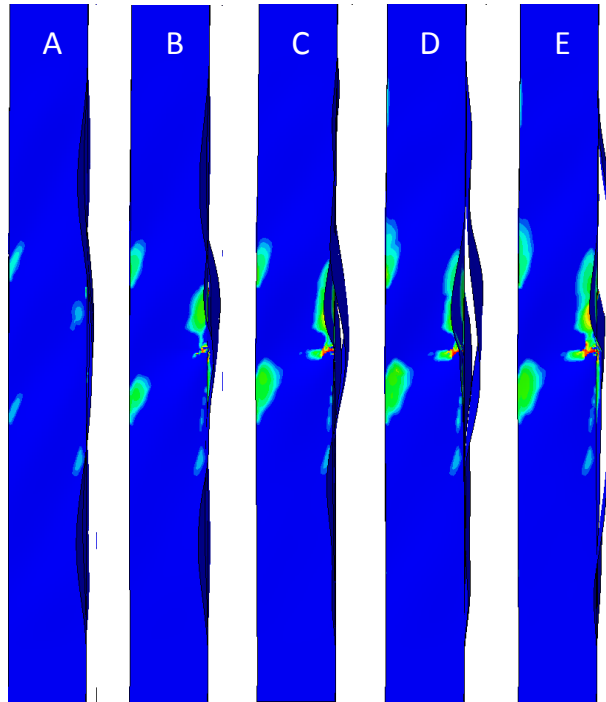
Initiation of matrix damage

Initiation of delamination

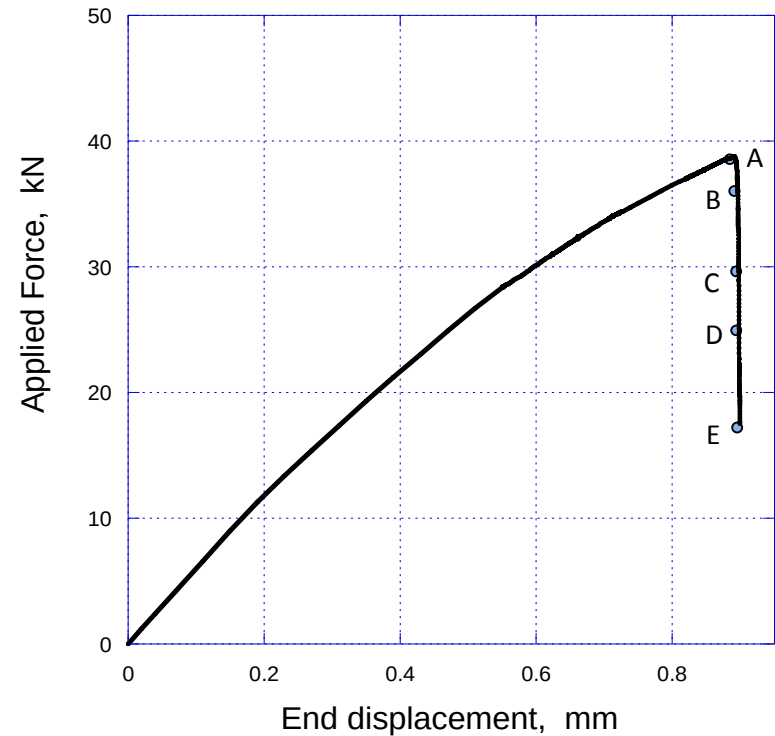
Collapse

Analysis of SSCS – Nominally Pristine Specimen

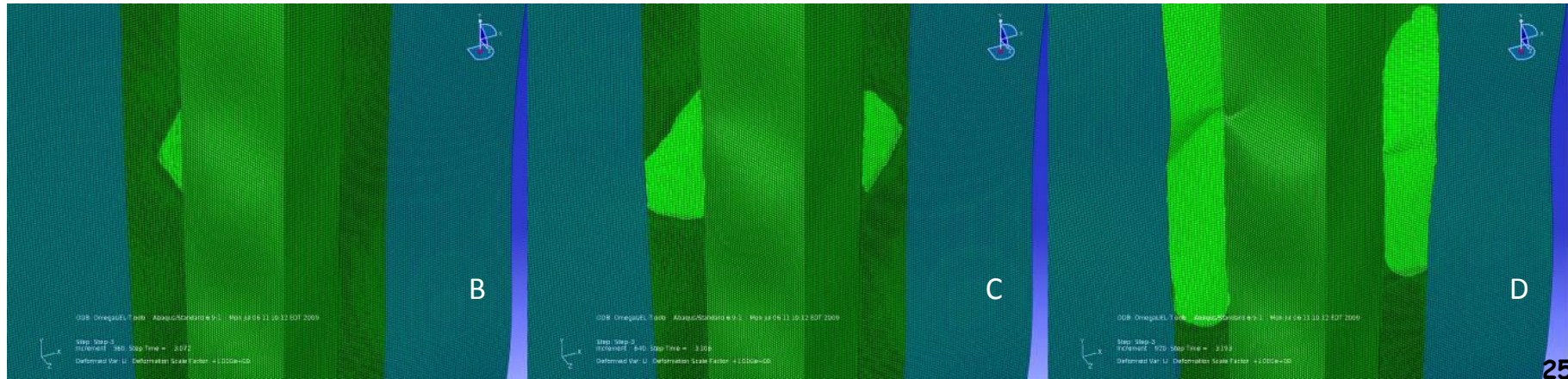
Delamination
Sequence
(edge view)



Matrix damage
shown



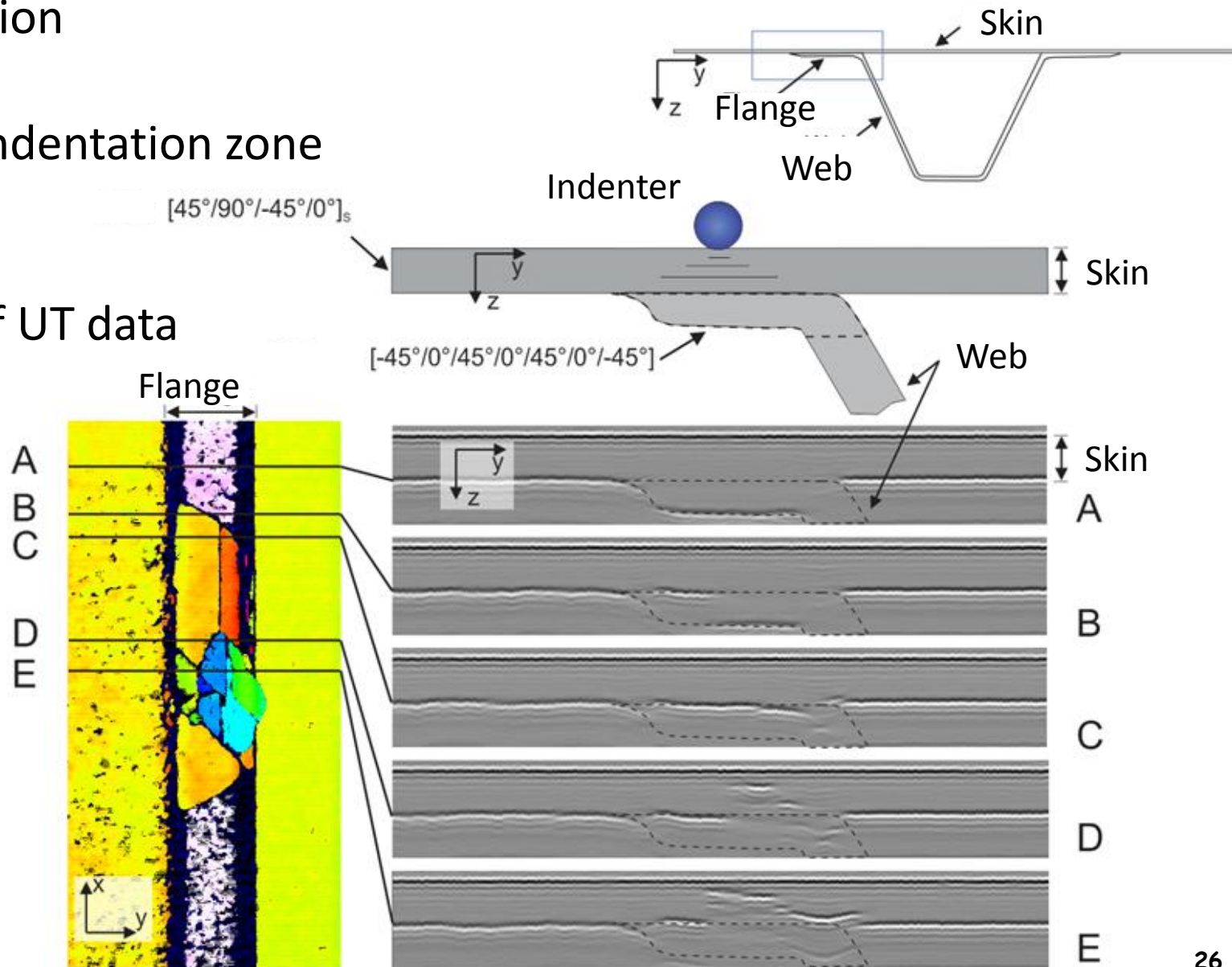
Predicted propagation of delamination (top view)



A. Cross-section

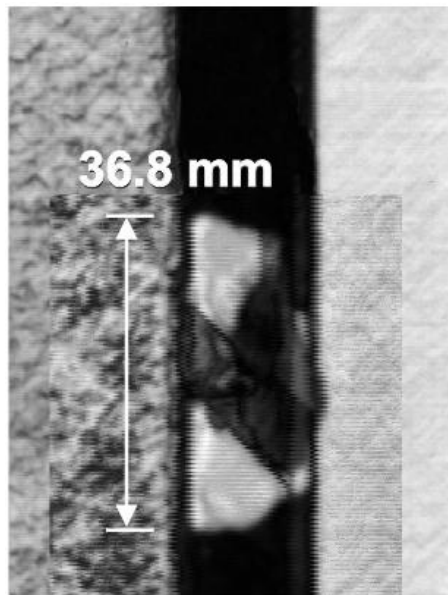
B. Detail of indentation zone

C. Analysis of UT data

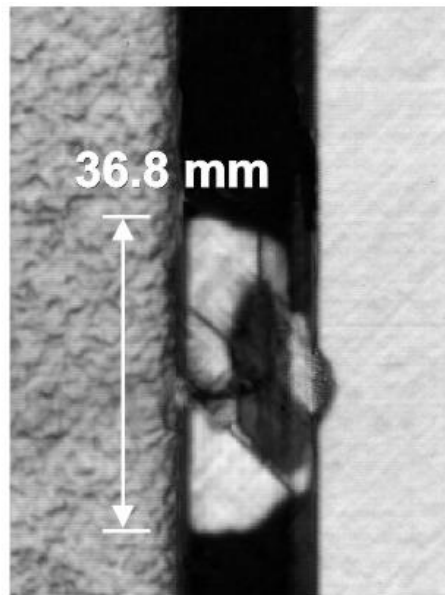


Fatigue Damage Propagation

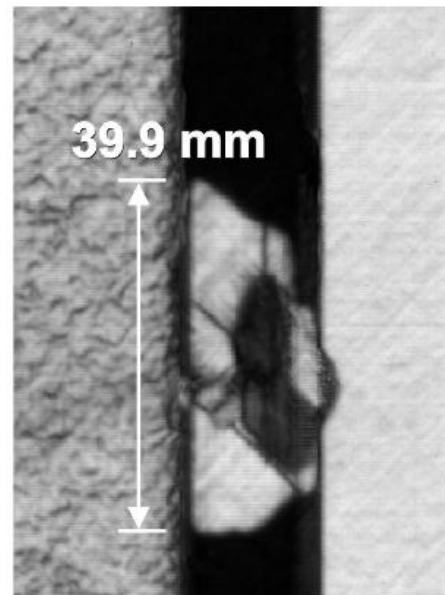
Typical fatigue propagation of indentation damage (center indent)



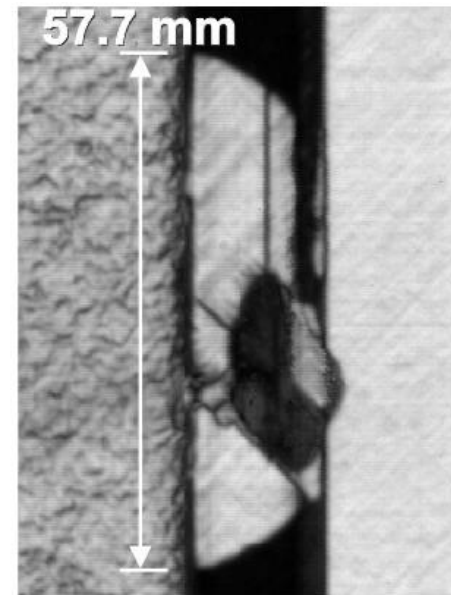
initial damage



12,000 cycles



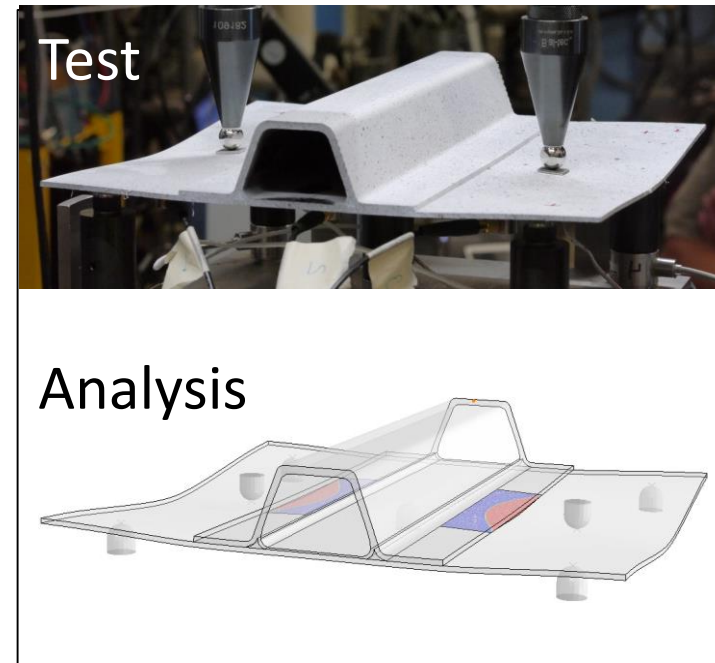
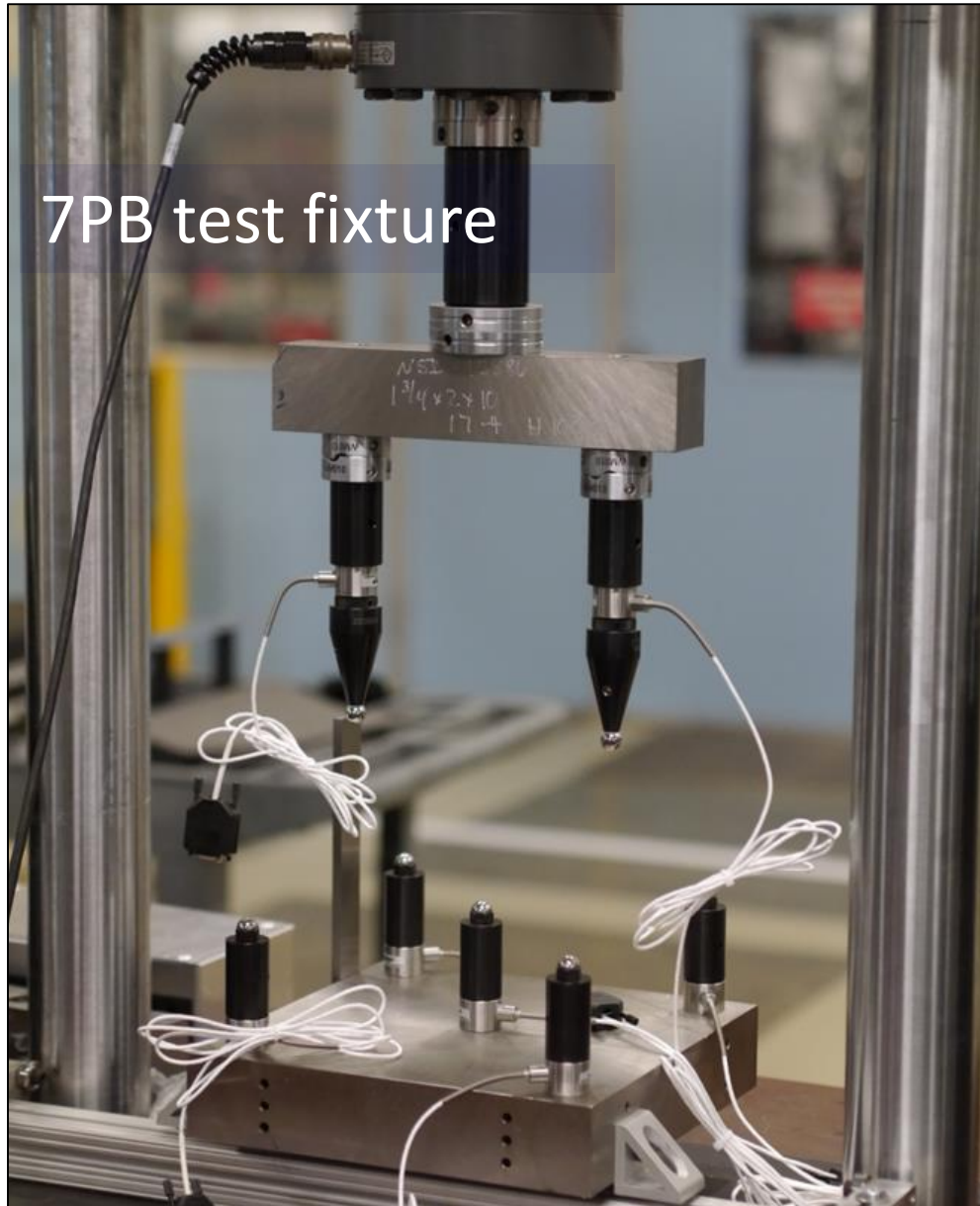
36,000 cycles



78,000 cycles

Collapse at 78,135 cycles

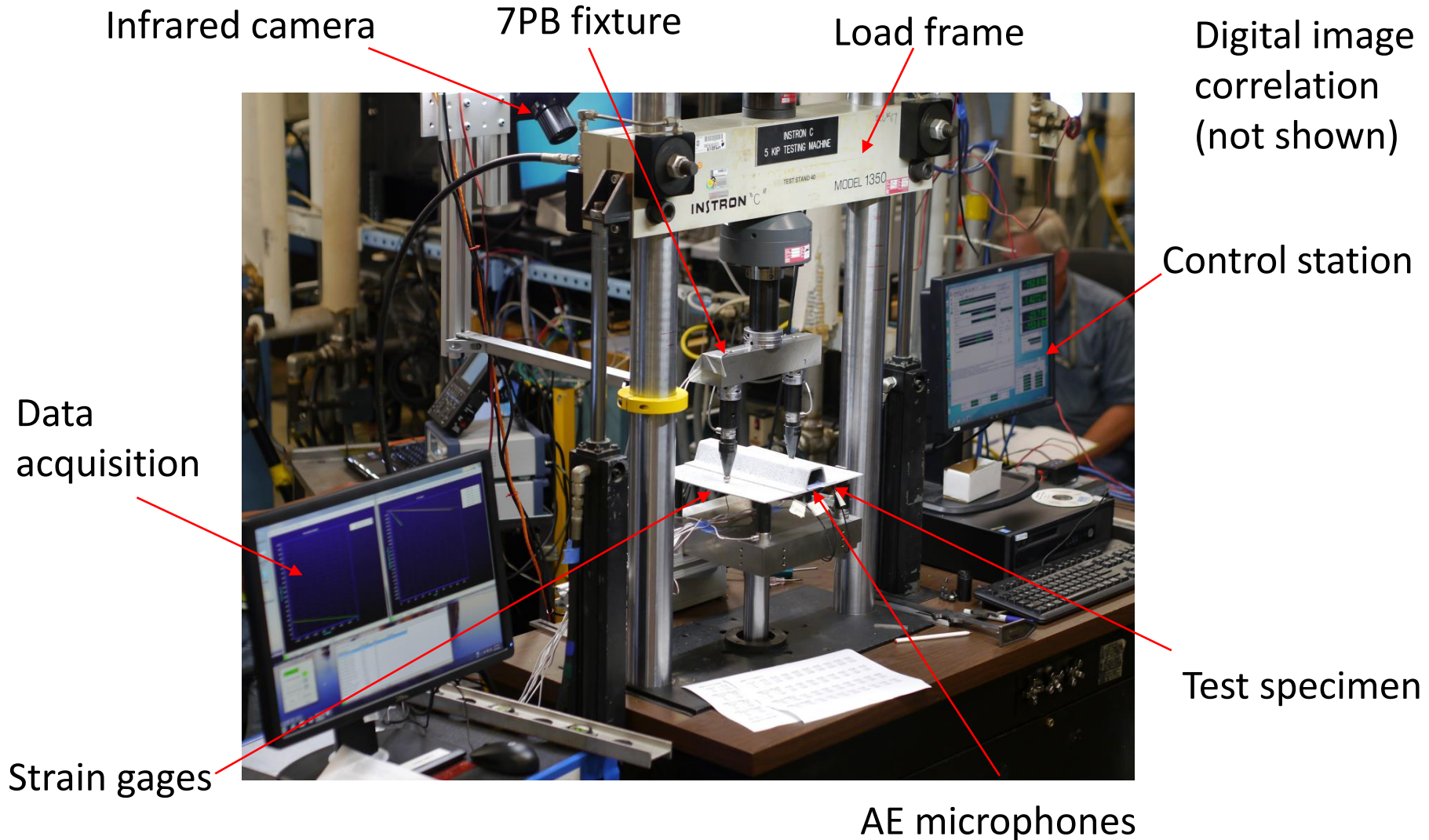
Seven Point Bend (7PB) Test





7PB Load Frame and Advanced Instrumentation

Seven Point Bend Test (7PB)



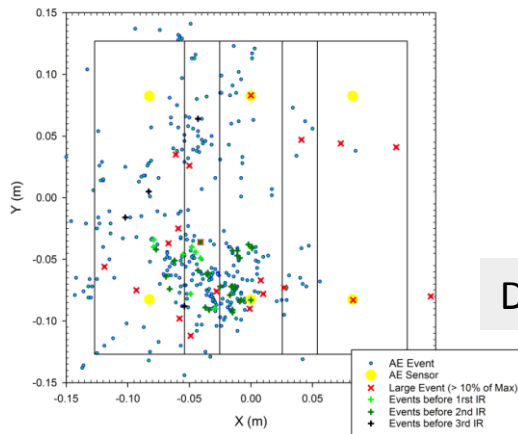
Seven Point Bend (7PB) Test

APPROACH:

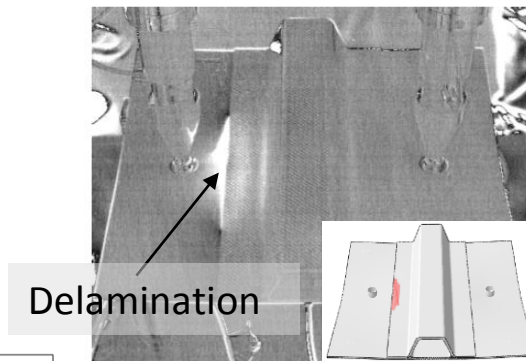
- A new seven point bend fixture (7PB) was designed that uses seven load cells for a precise interpretation of the response of the panel
- Top load points can be repositioned for symmetric and anti-symmetric loading

NDE to Monitor Damage Progression for Model Validation

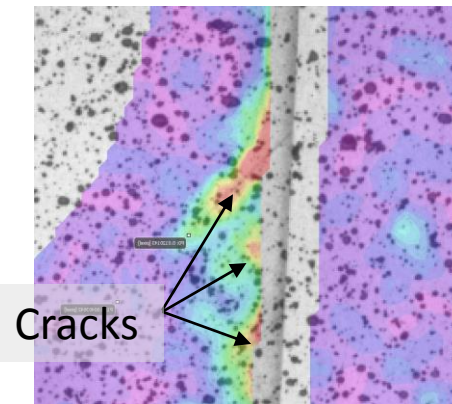
Acoustic Emission



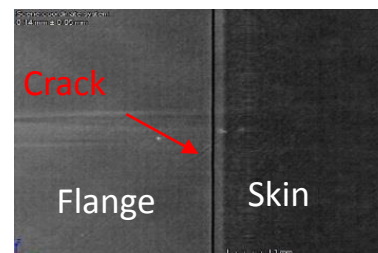
Passive Thermography



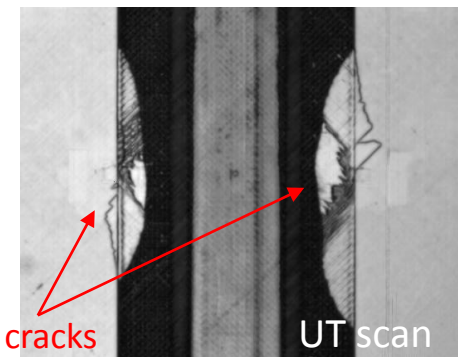
DIC



X-Ray/CT



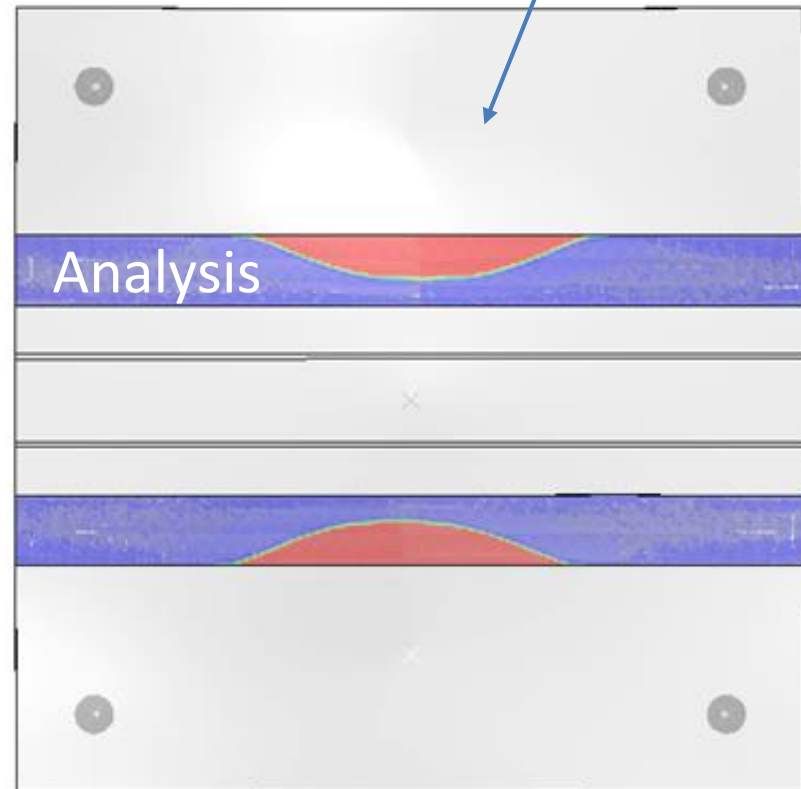
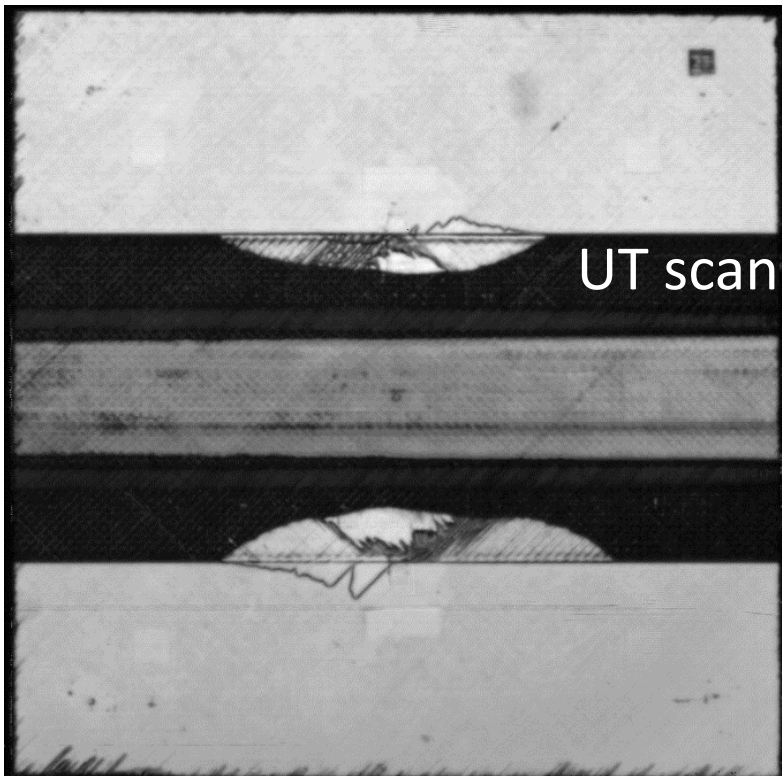
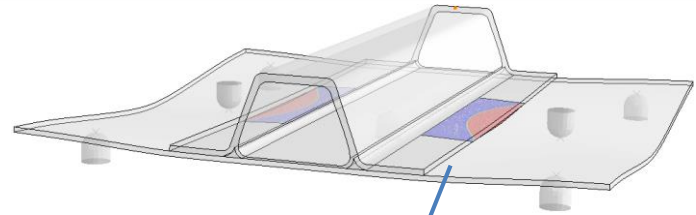
Ultrasonic Scan



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

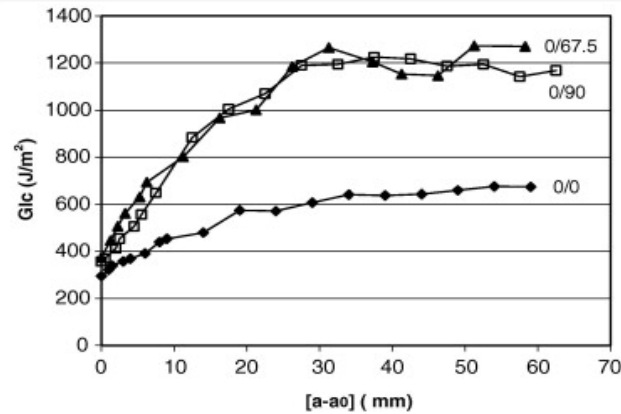
Seven Point Bend Test Results



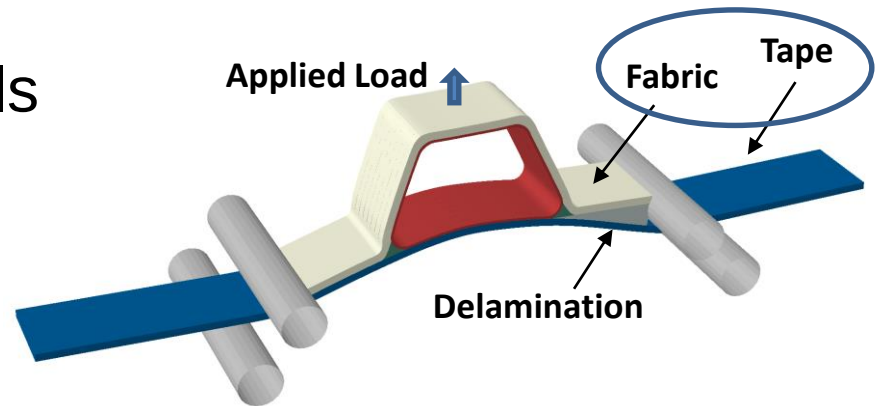
Can the detail features of the interface damage be ignored?

Complexities of Interfacial Damage

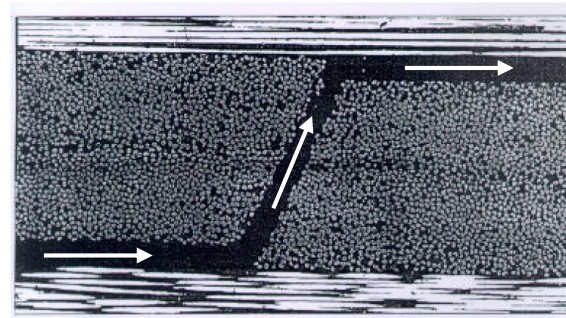
1. R-curve effects



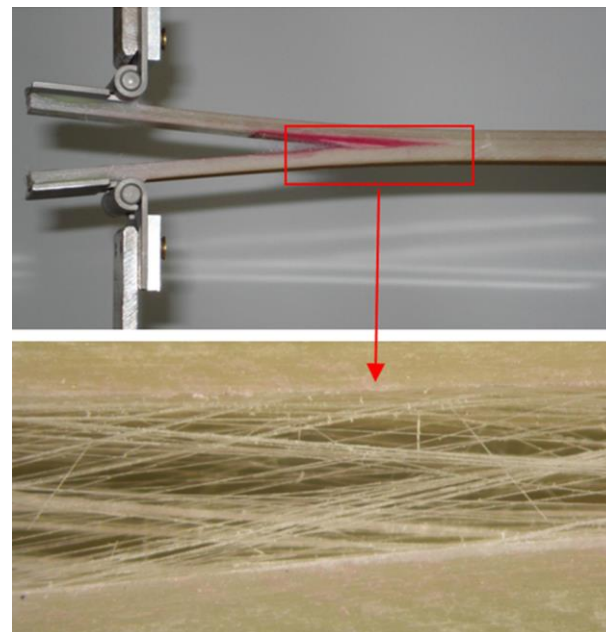
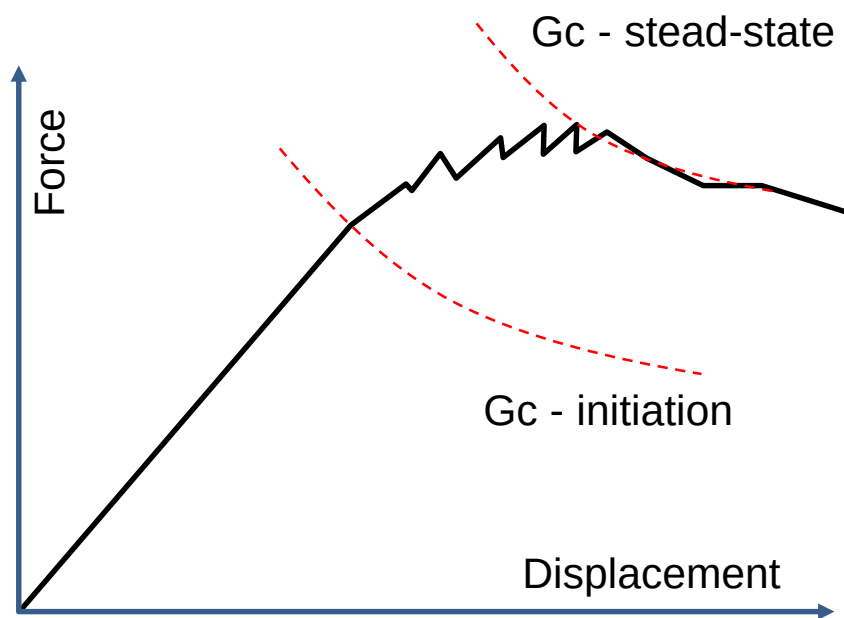
2. Complexities of interfaces between dissimilar materials



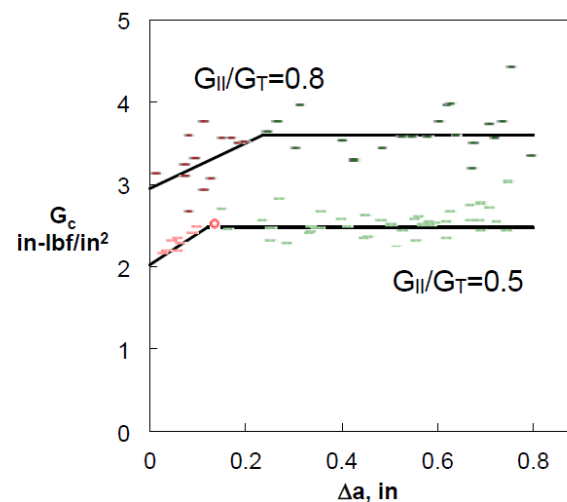
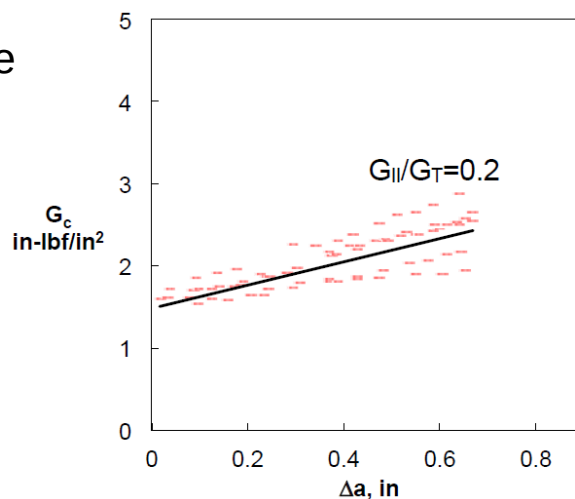
3. Migration of delamination



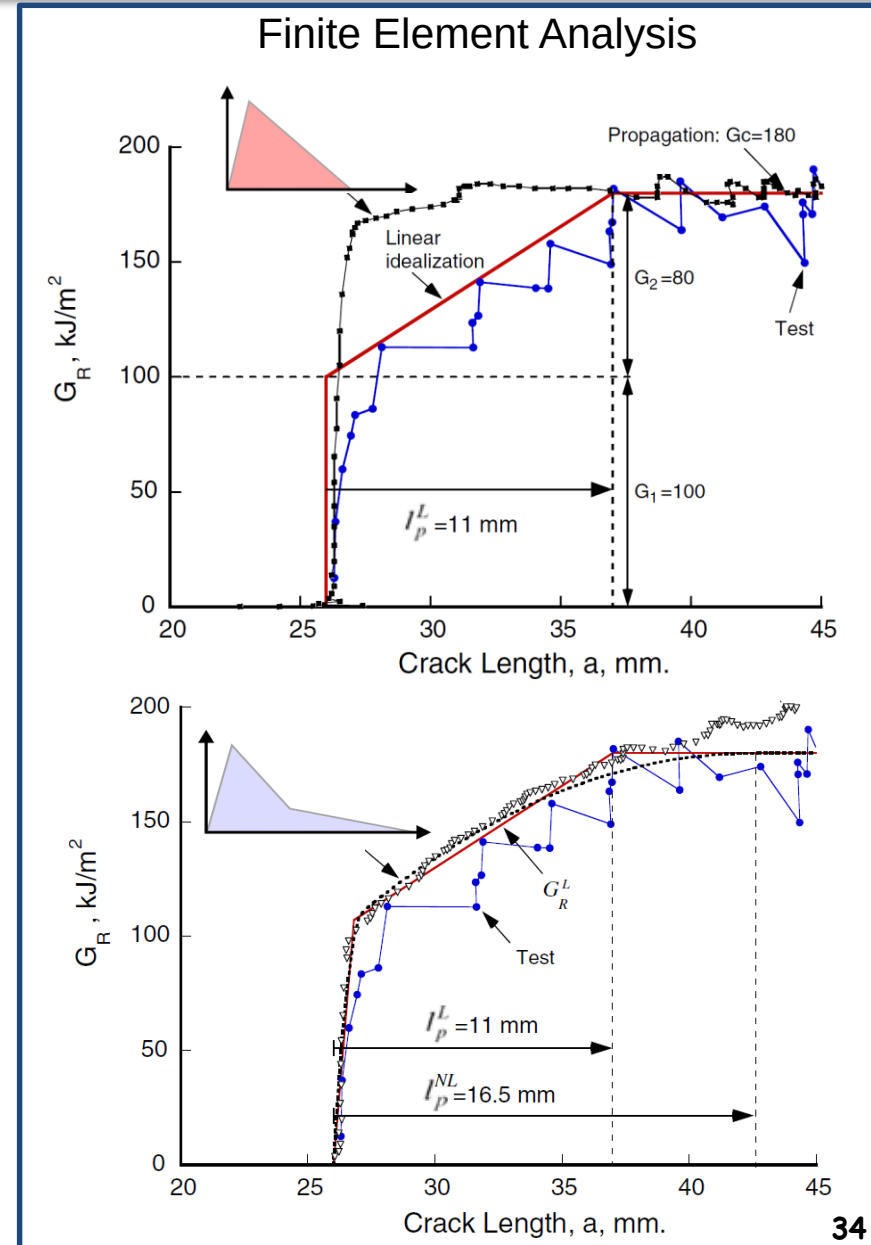
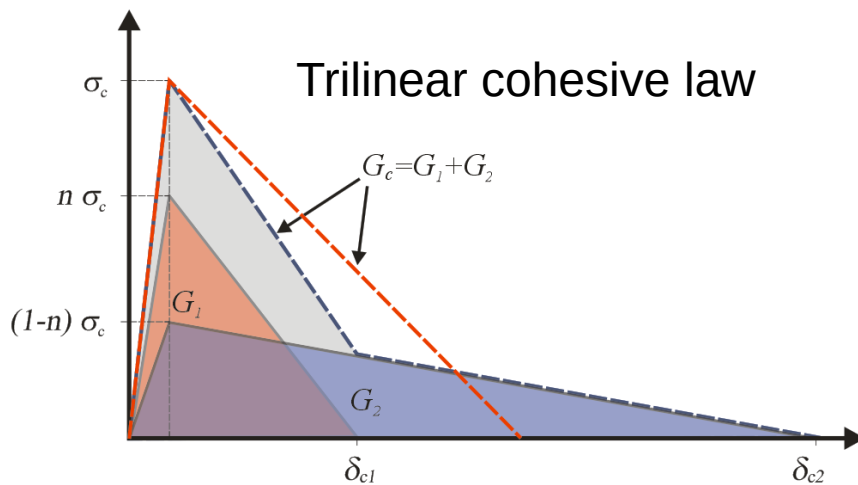
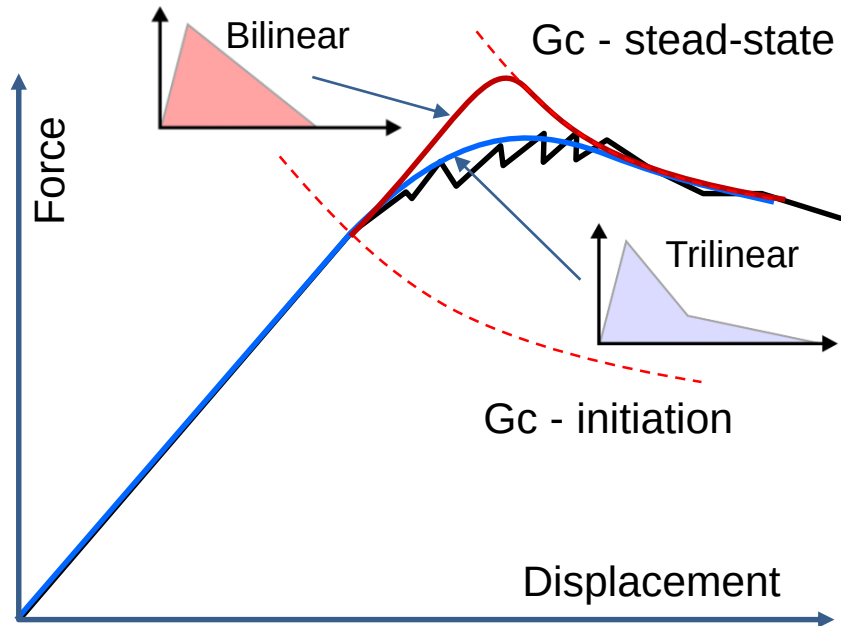
R-Curve Effect



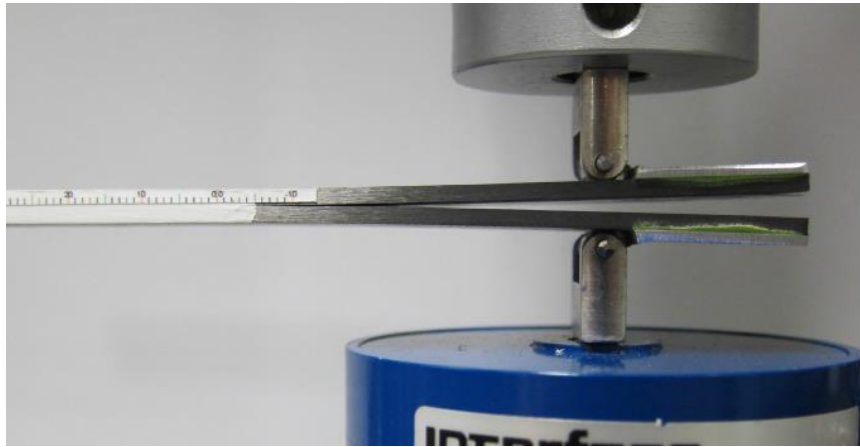
Delamination Resistance curves for mixed mode bending test (MMB)



Modeling the R-Curve Effect



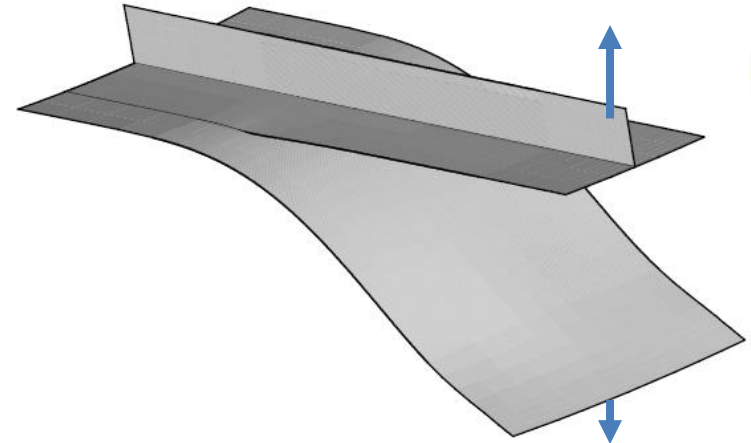
Standard Test 0/0 interface



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 Skin/Stringer interface



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!
↑

R-Curves for Multidirectional Laminates

4 times !

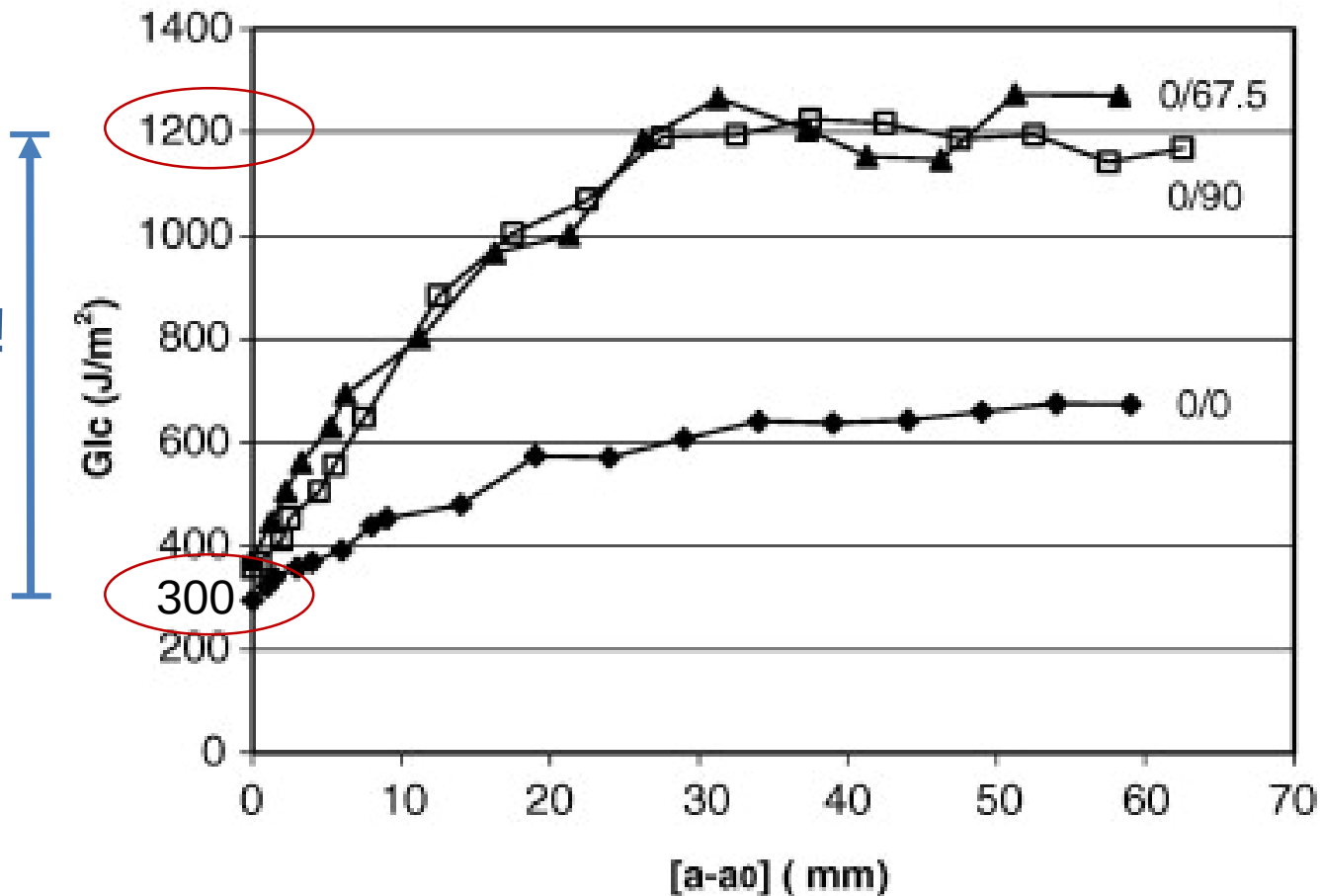
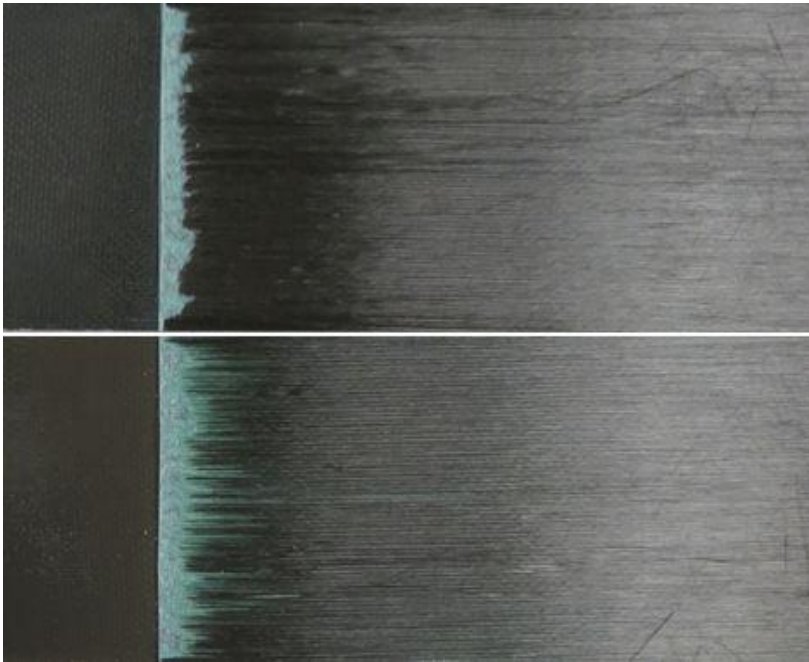


Fig. 14.

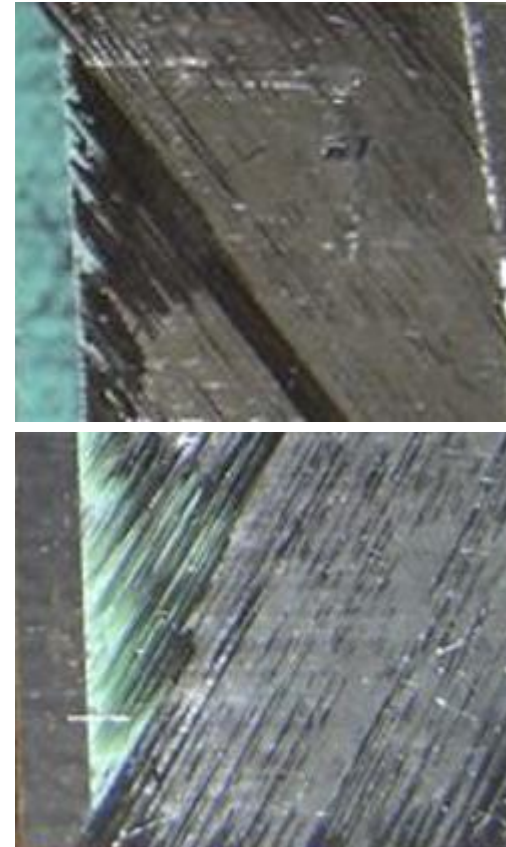
Typical *R*-curves of 0°/0°, 0°/67.5° and 0°/90° specimens.

Interface Surfaces

0/0 interface
(standard test)

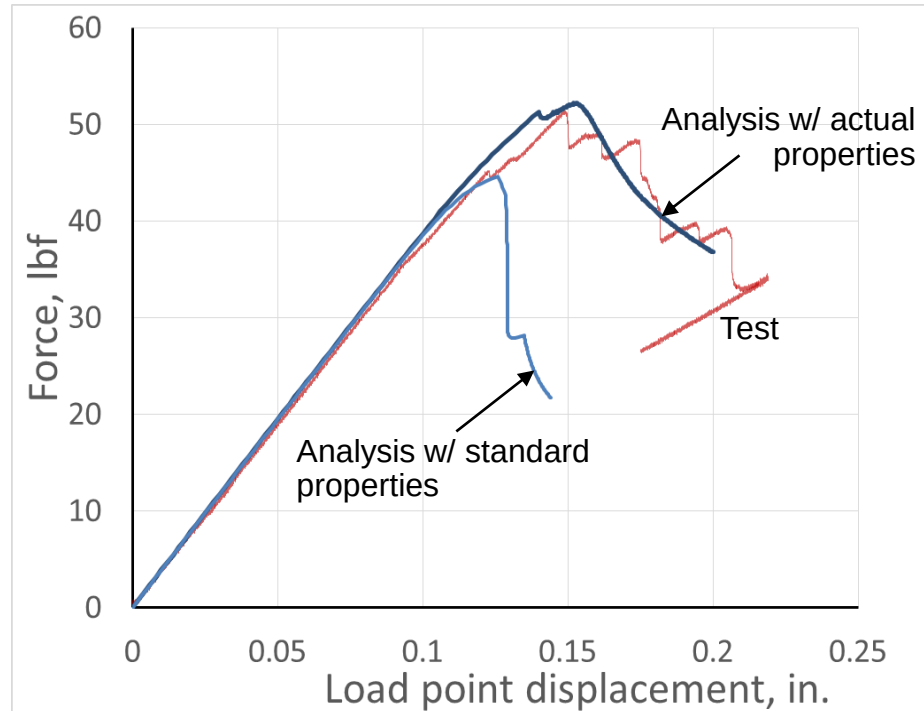
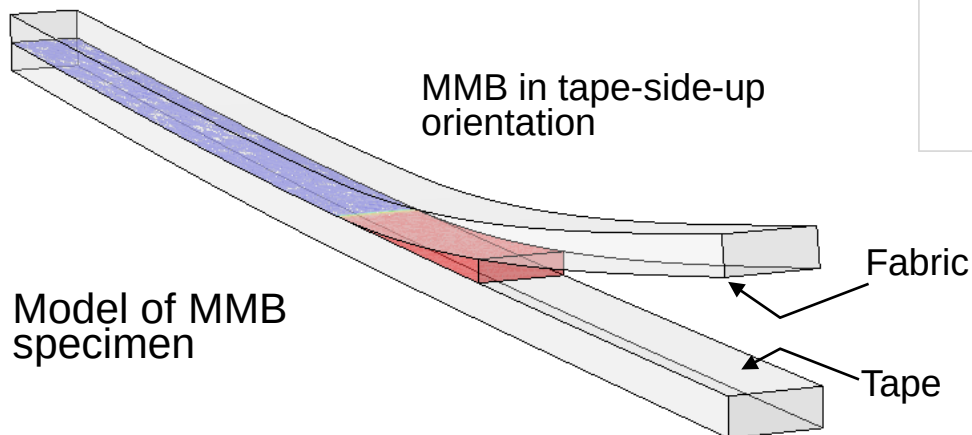
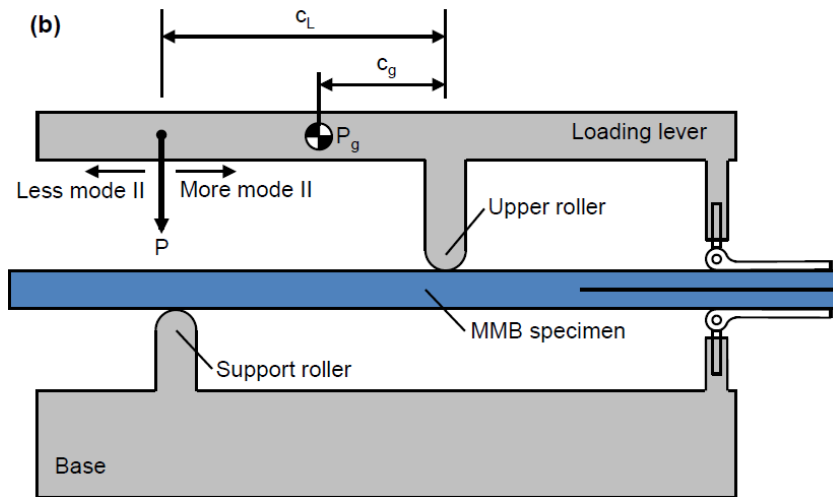


Typical structural
interface



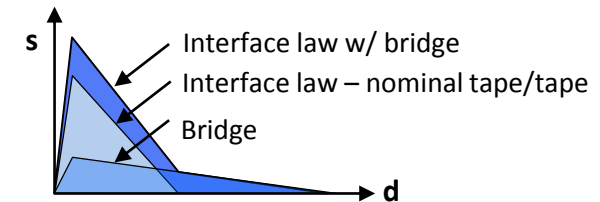
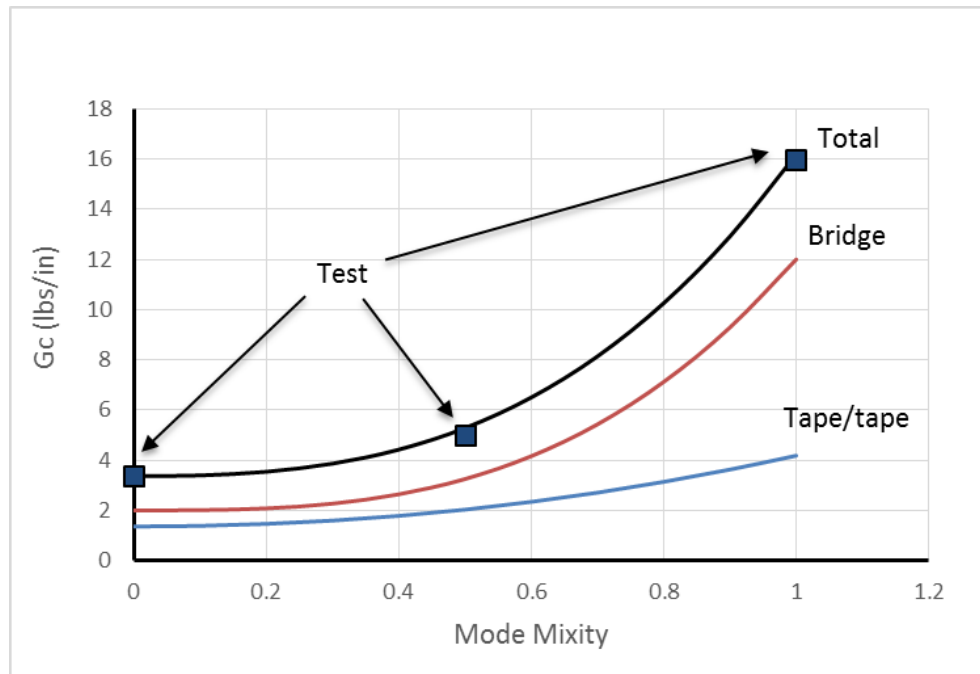
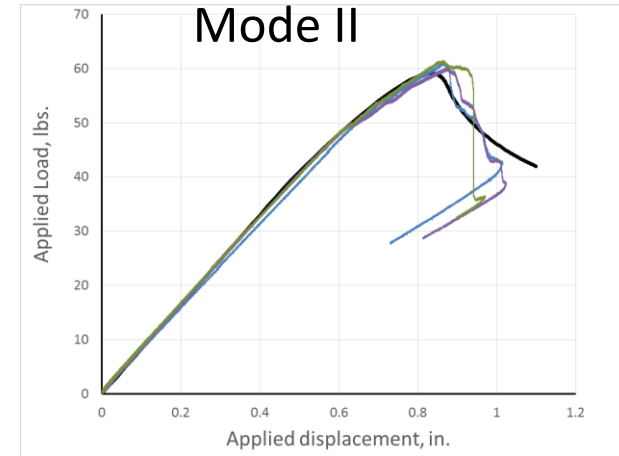
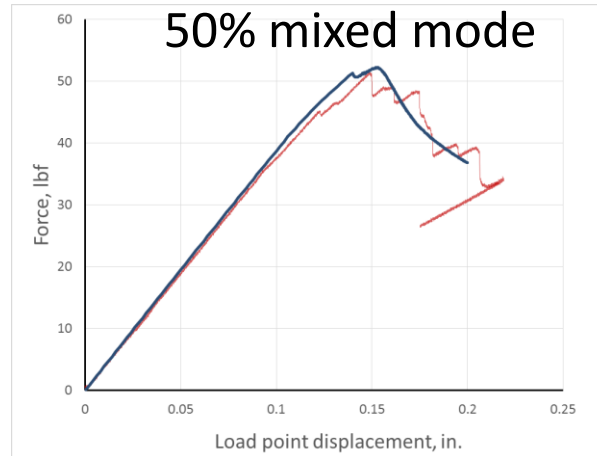
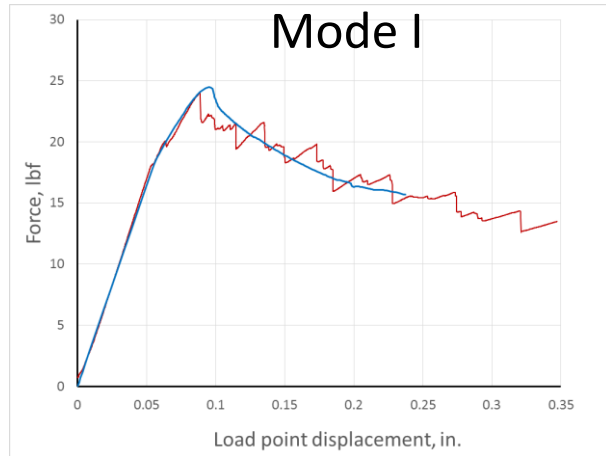
Is G_c the same?

Mixed Mode Bending (MMB)



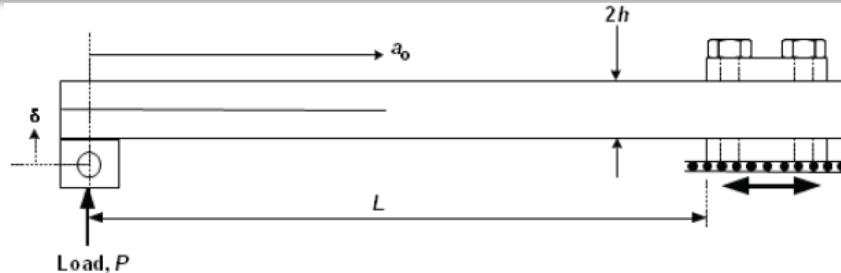
Characterization of Skin/Stiffener Interface Properties

Tests: J. Ratcliffe, 2016

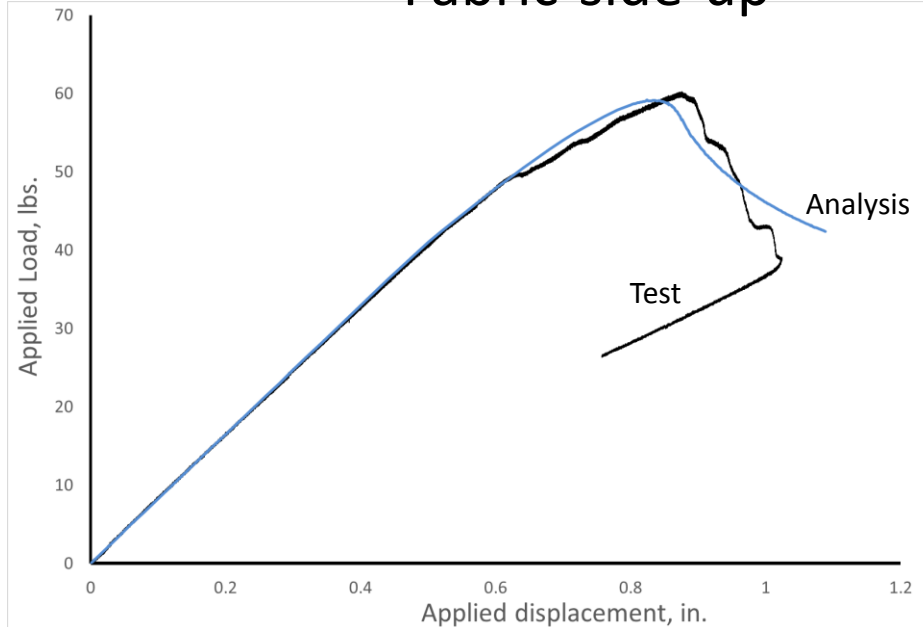


	Nominal	Bridging	
$G_{ic} =$	1.36	2	lb/in
$G_{IIc} =$	4.18	12	lb/in
$\text{Sig}_{33} =$	9040	1000	lb/in ²
$\text{Taush} =$	13490	3000	lb/in ²
$K_{33} =$	1.8E+08	2.E+07	lb/in ³
$K_{sh} =$	1.3E+08	3.E+07	lb/in ³
$BK =$	2.07	3	

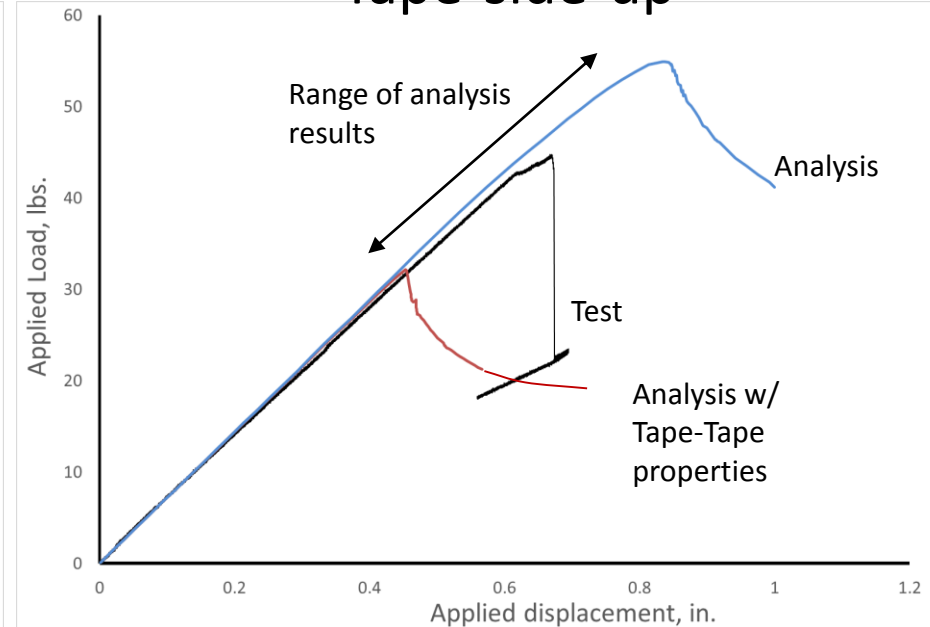
Mode II Tests: J. Ratcliffe, 2016



Fabric-side-up



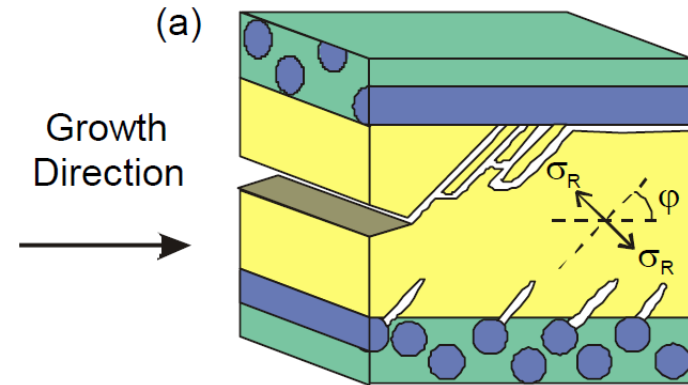
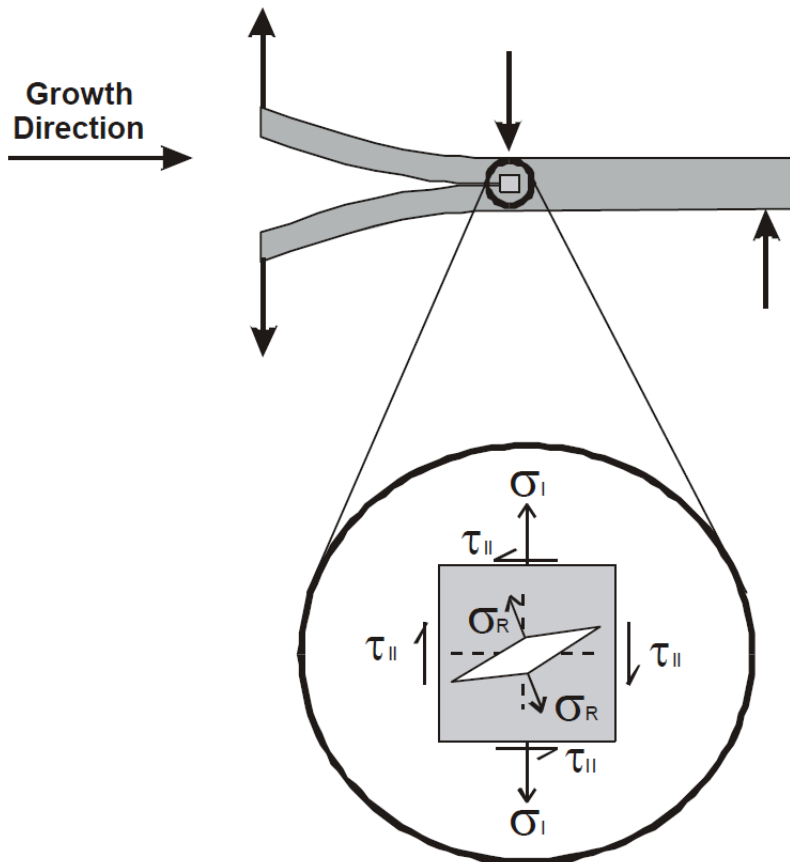
Tape-side-up



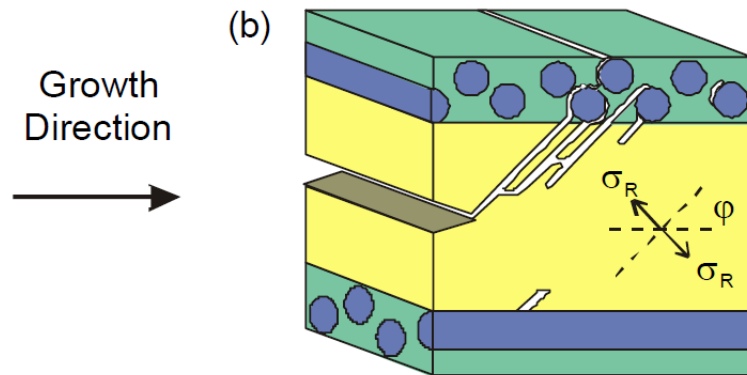
- The R-curves for the two orientations of the same interface are different
- The “tape-side-up” specimen exhibits unstable propagation

Migration of Delamination

Emile Greenhalgh, Imp. Coll., 2006



$0^\circ/\phi^\circ$ ply interface



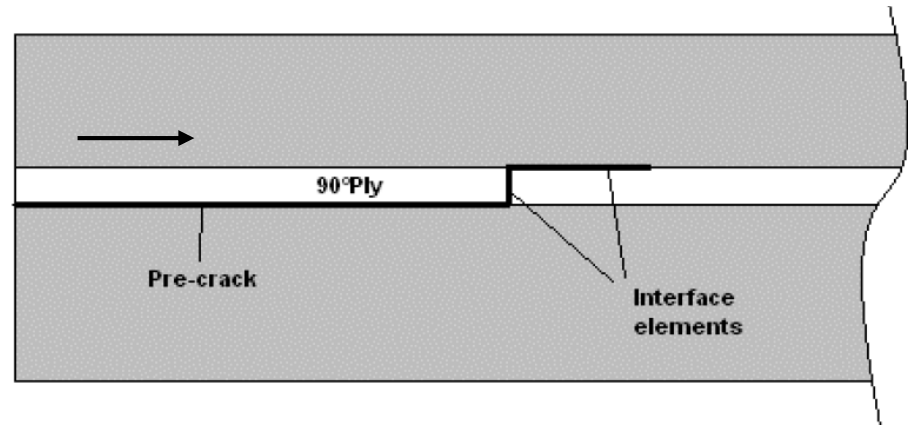
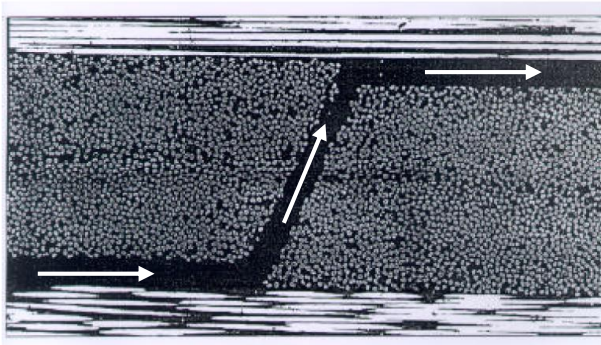
$\phi^\circ/0^\circ$ ply interface

The sign of the transverse shear determines the direction of propagation

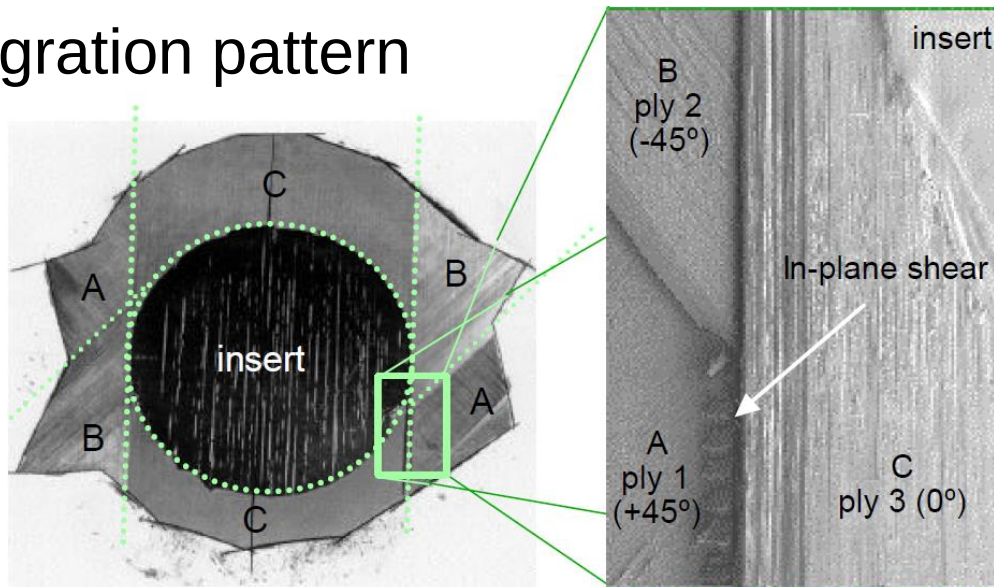
Migration of Delamination

Emile Greenhalgh, Imp. Coll., 2006

Simple migration pattern

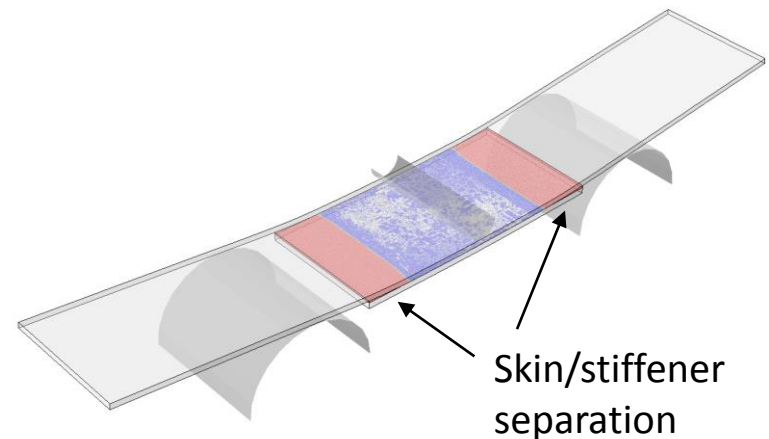
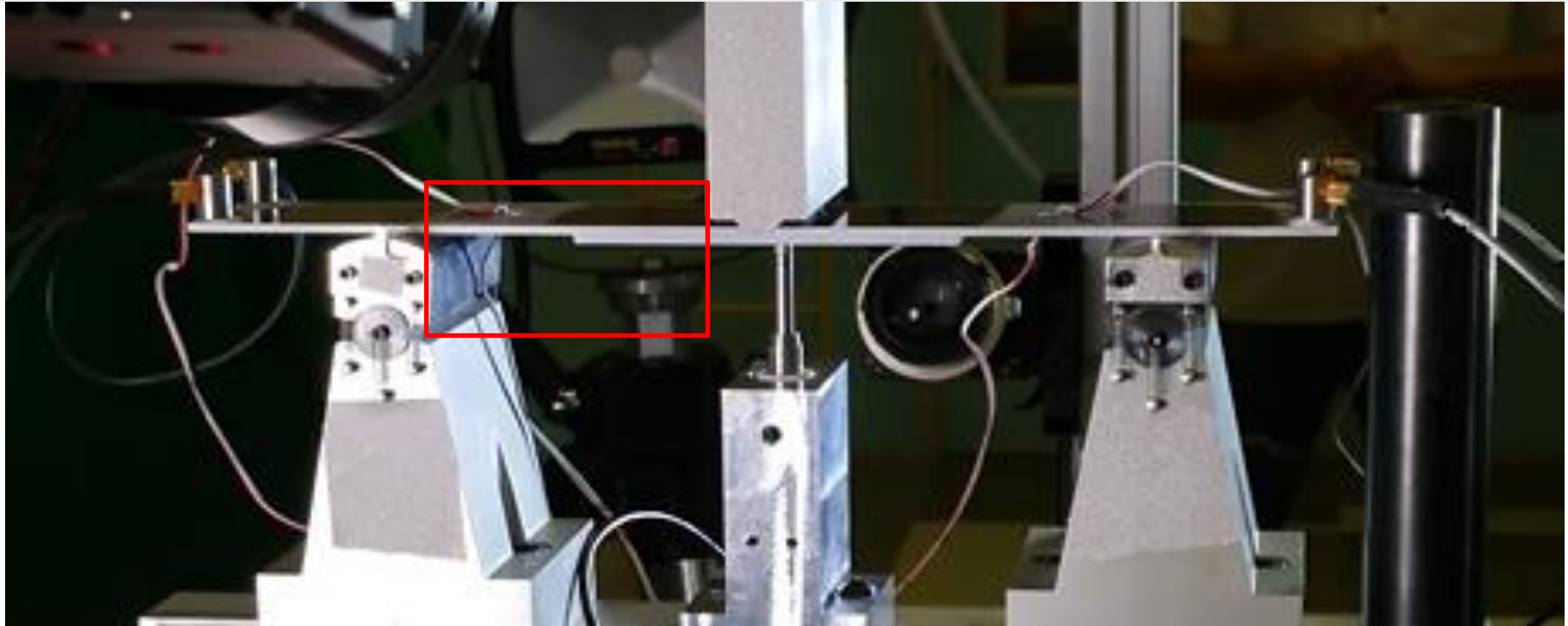


Complex migration pattern





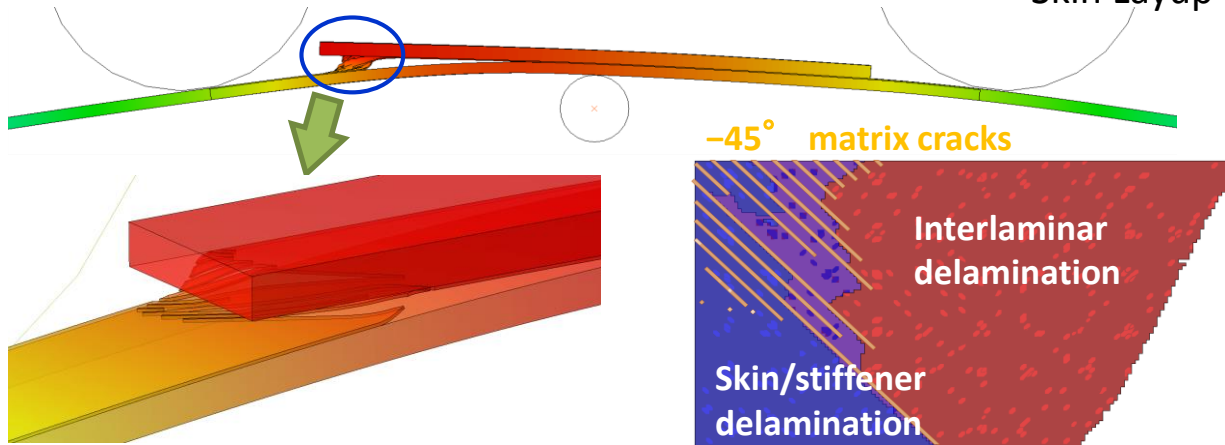
Three Point Bend (3PB) Doubler Specimen



3PB Specimen - Detailed 3D Models

1) CompDam_DGD

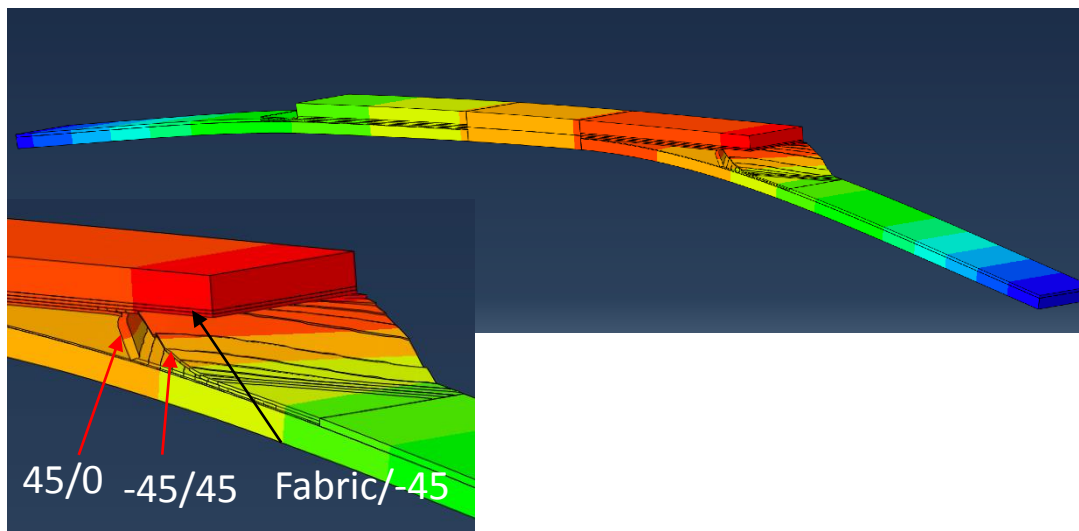
- Flange Layup – $[+45/0/-45/+45/-45/0]_s$ fabric
- Skin Layup – $[-45/+45/0/90/-45/+45]_s$ tape



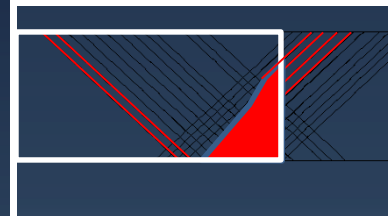
Failure Process:

- One side dominant
- Delamination predicted in different interfaces
- Transition occurs via matrix cracks

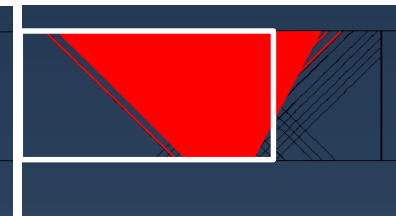
2) Floating Node Method - FNM



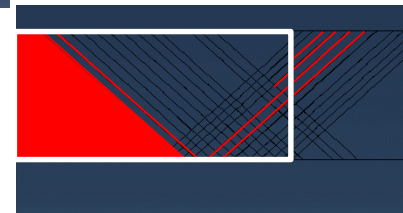
Fabric/-45



-45/45

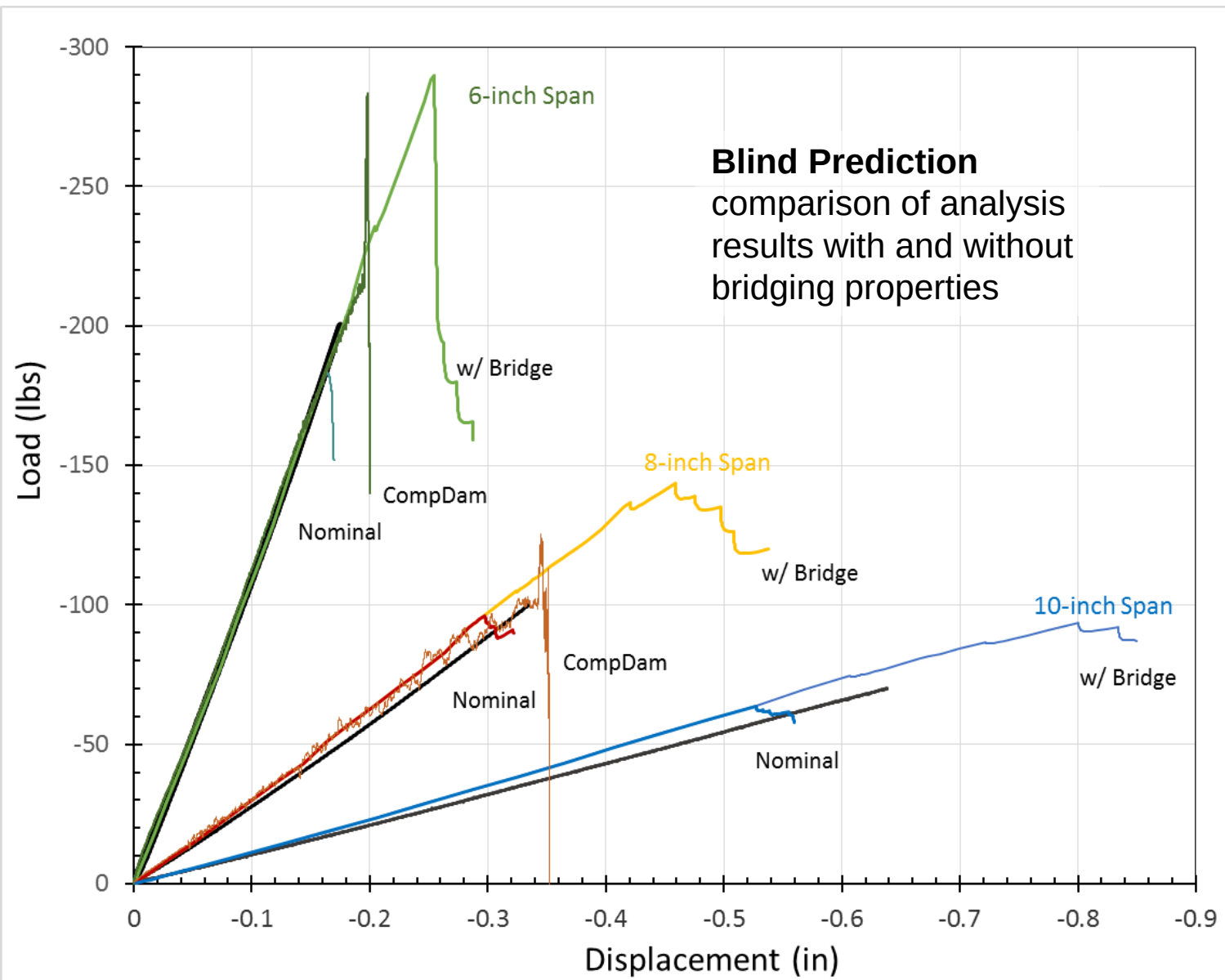


45/0





3PB Doubler Specimen Analysis Results





Concluding Remarks

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
- The level of fidelity required to model typical delaminations has not yet been established.
- Even the best analysis tools available may not account for all of the energy dissipation mechanisms that are required.



Questions?



#NASALangley100