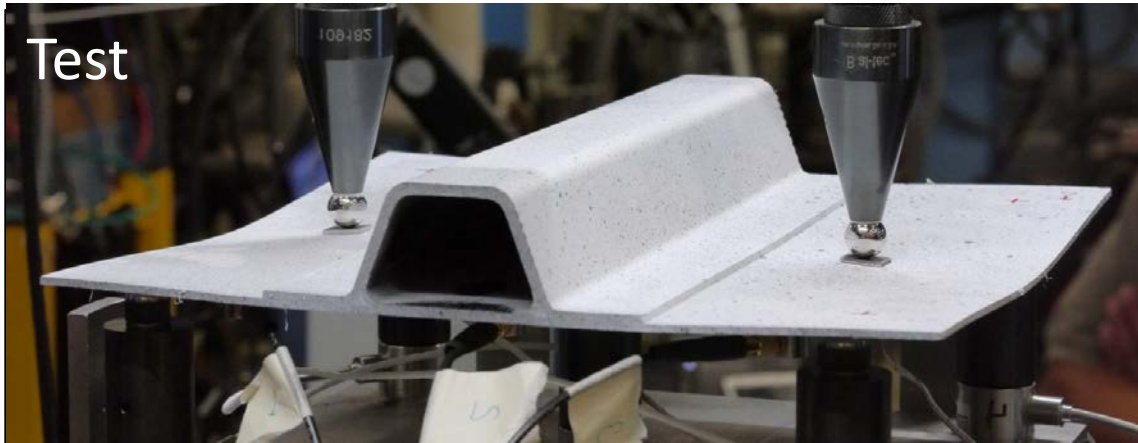
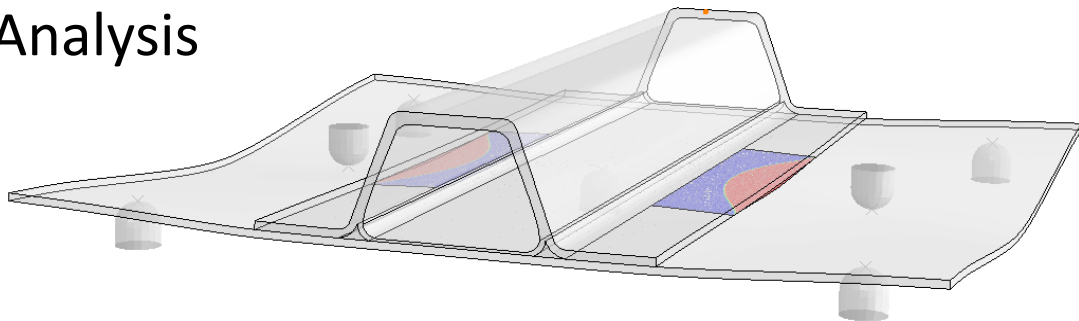


Cohesive Analysis of Skin-Stiffener Separation under Quasi-Static and Cyclic Loads

Test



Analysis



Carlos G Dávila
William M Johnston
Cheryl A Rose

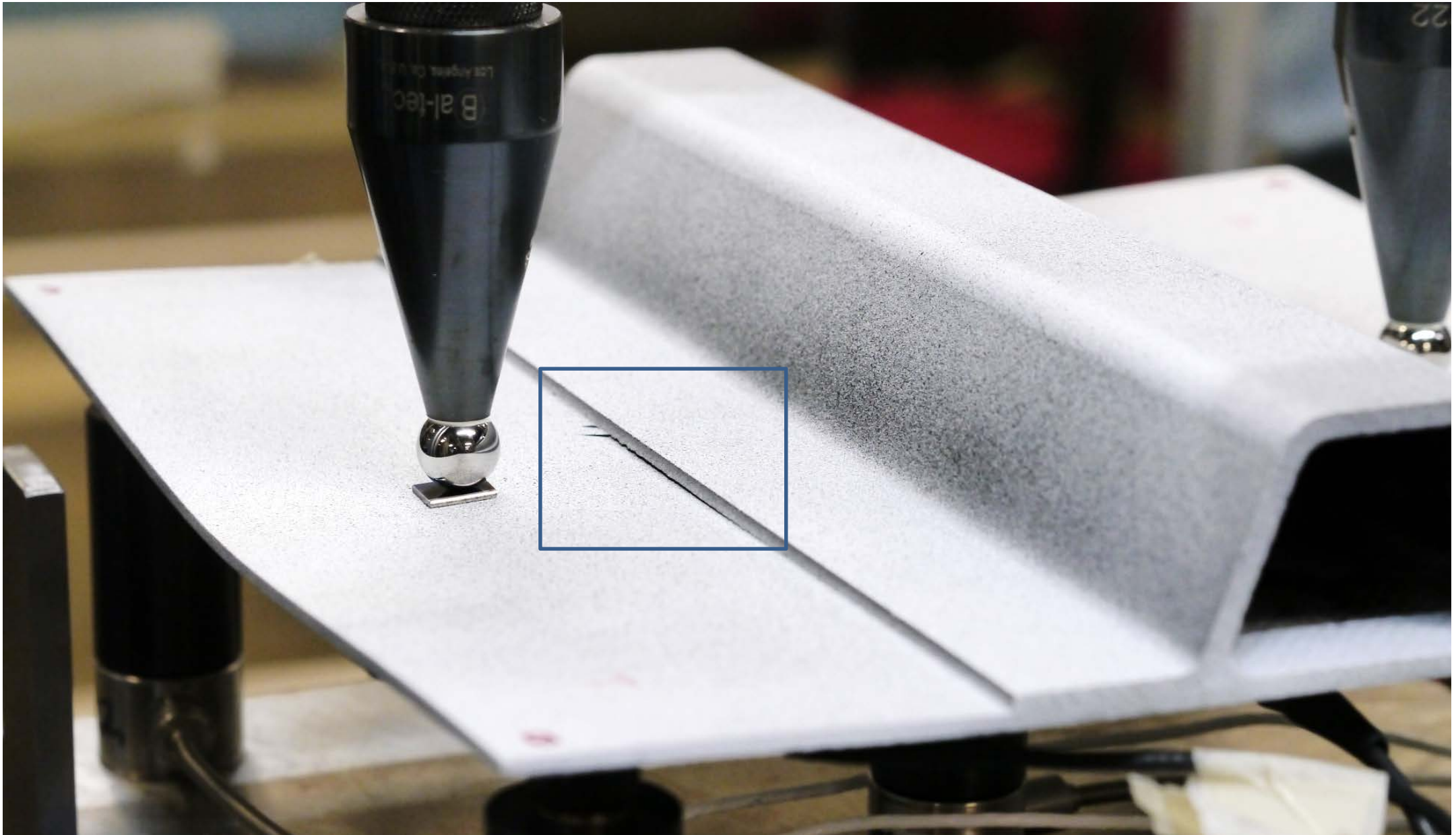


**Durability, Damage Tolerance
and Reliability Branch**

**NASA Langley Research Center
Hampton, VA**

ECCOMAS Composites 2019 Conference
Girona, September 18-20, 2019

Skin/Stiffener Separation



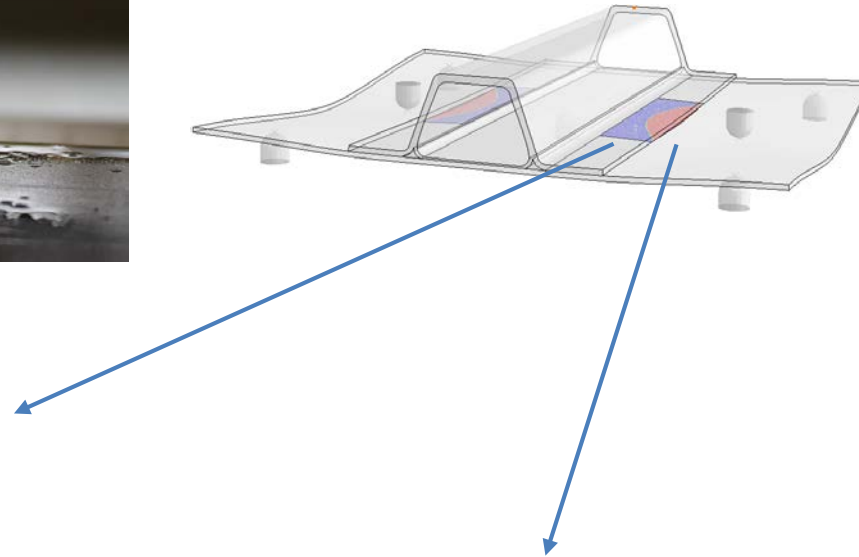
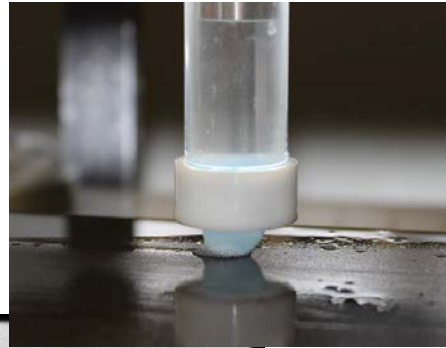
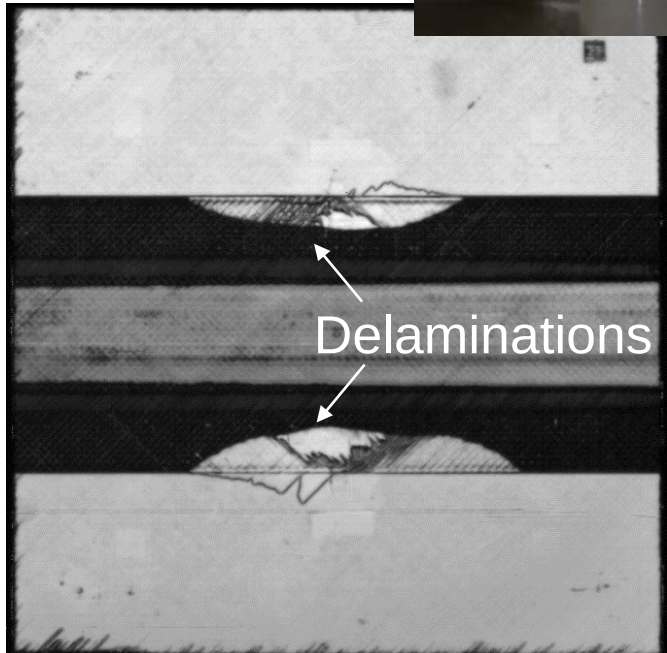
Skin/Stiffener Separation



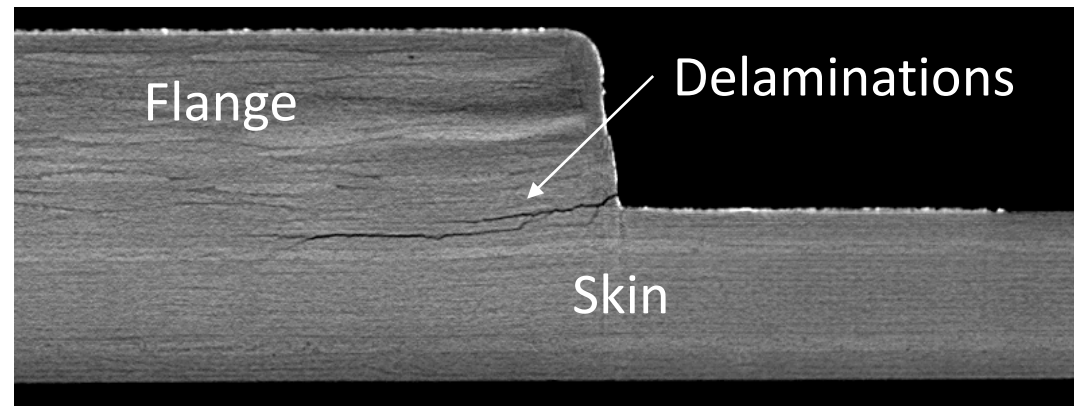
- How to model “real” delaminations?
- Can the detail features of the interface damage be ignored?
- What material properties should we use?

Nondestructive Evaluation (NDE) Techniques

Ultrasonic C-scanning
(UT)

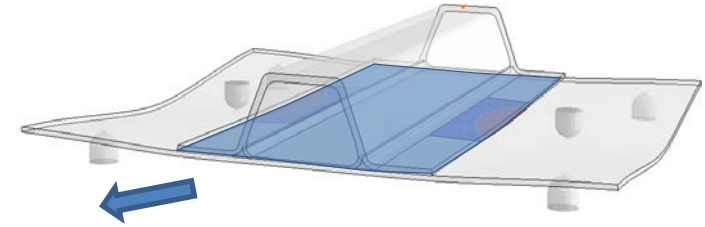
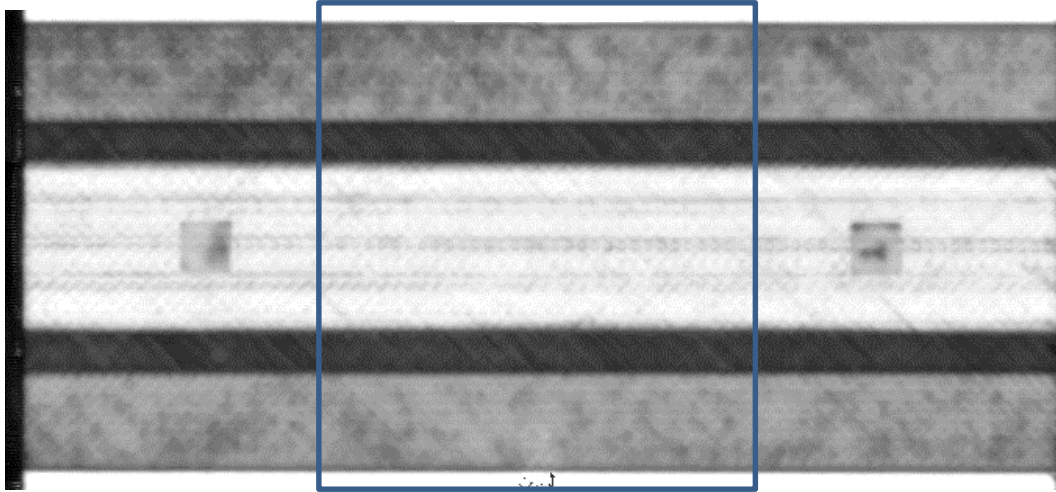


X-Ray Computed Tomography (CT)



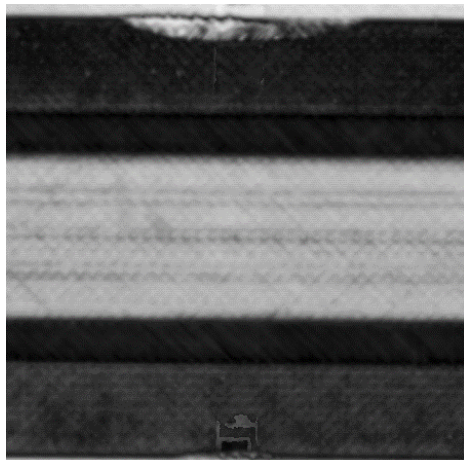
Propagation of Interface Damage

Pristine Specimen

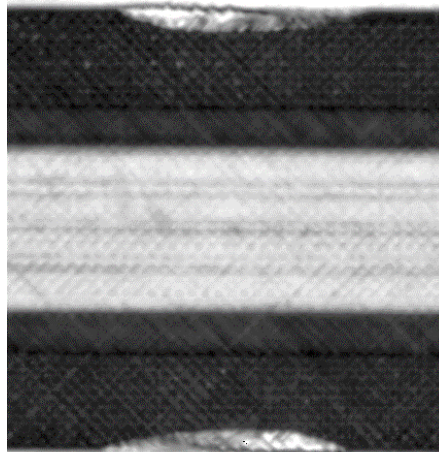


Damage growth

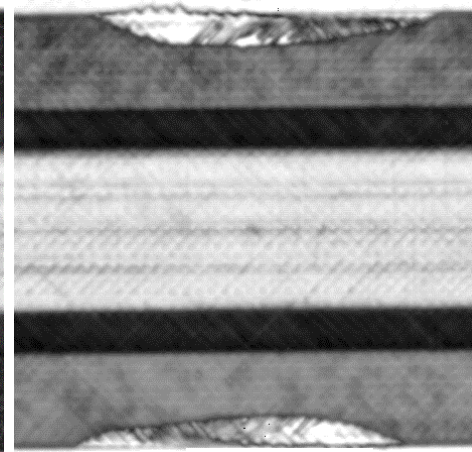
3477 N



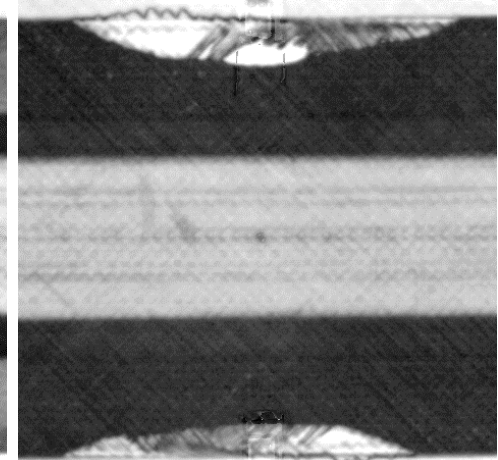
3497 N



3931 N

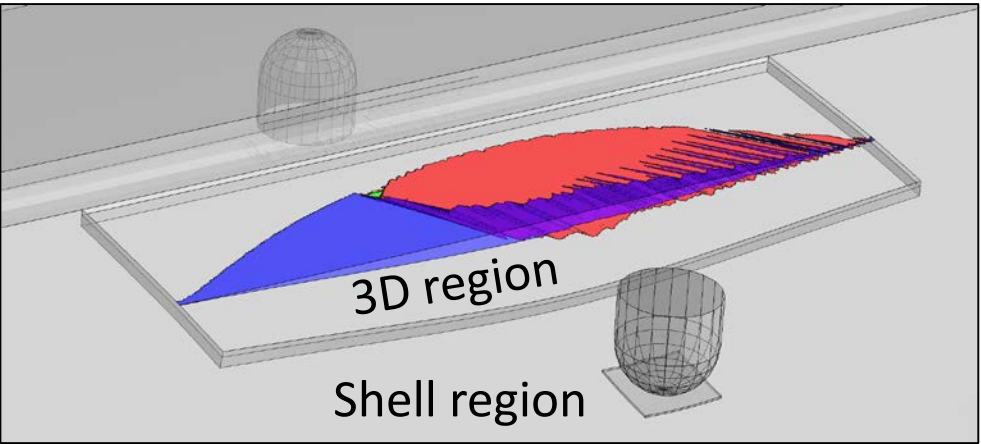


4204 N



Seven Point Bend Test Results

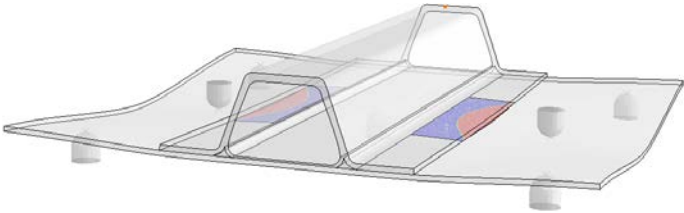
Shell/3D Detailed Analysis



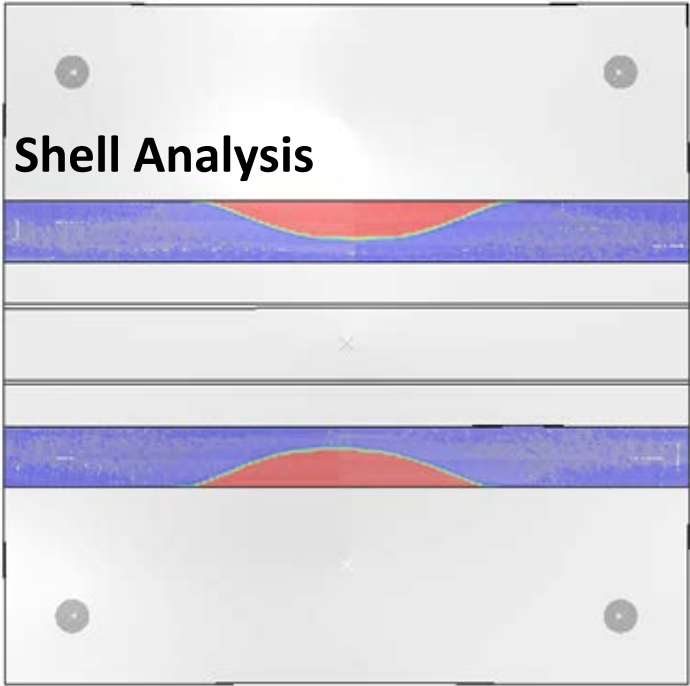
3D model with multiple interfaces, interlaminar and intralaminar failure modes

Shell model with single cohesive interface

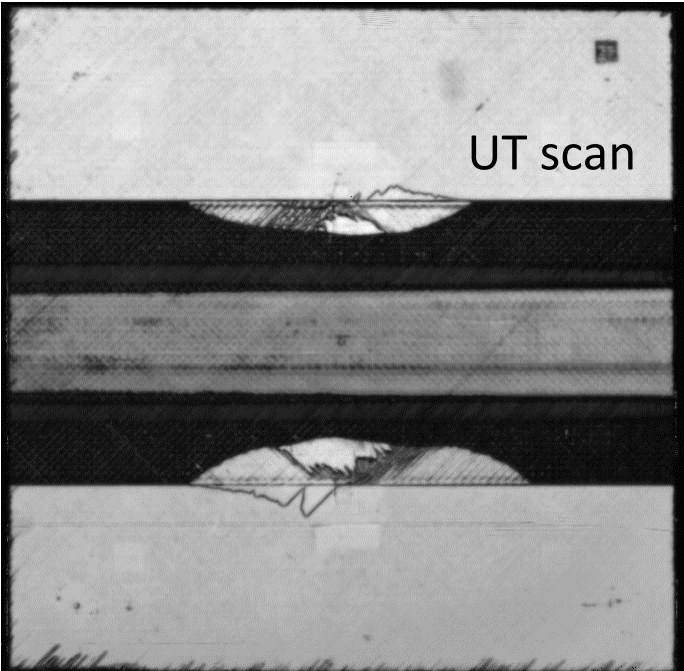
What level of fidelity is required?



Shell Analysis

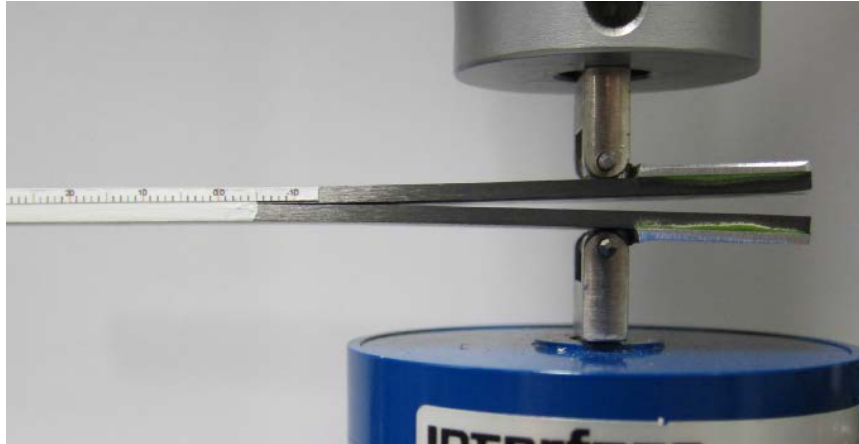


UT scan



G_c : Standard Tests vs. Structural Interfaces

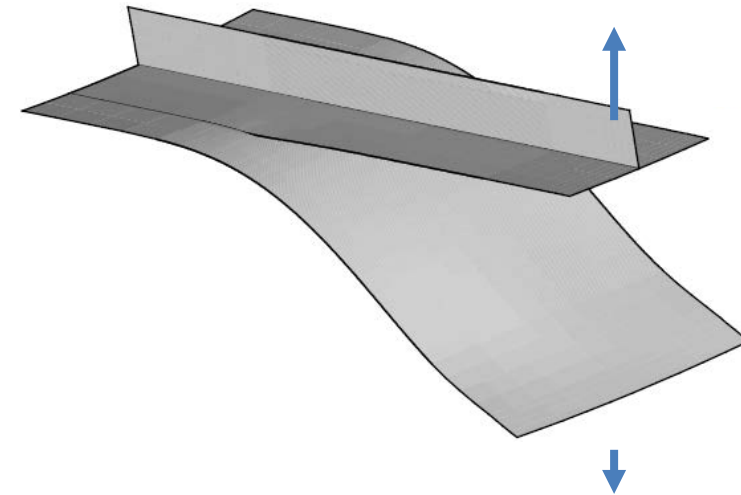
DCB test



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

Skin/stiffener separation test



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!

R-Curves for Multidirectional Laminates

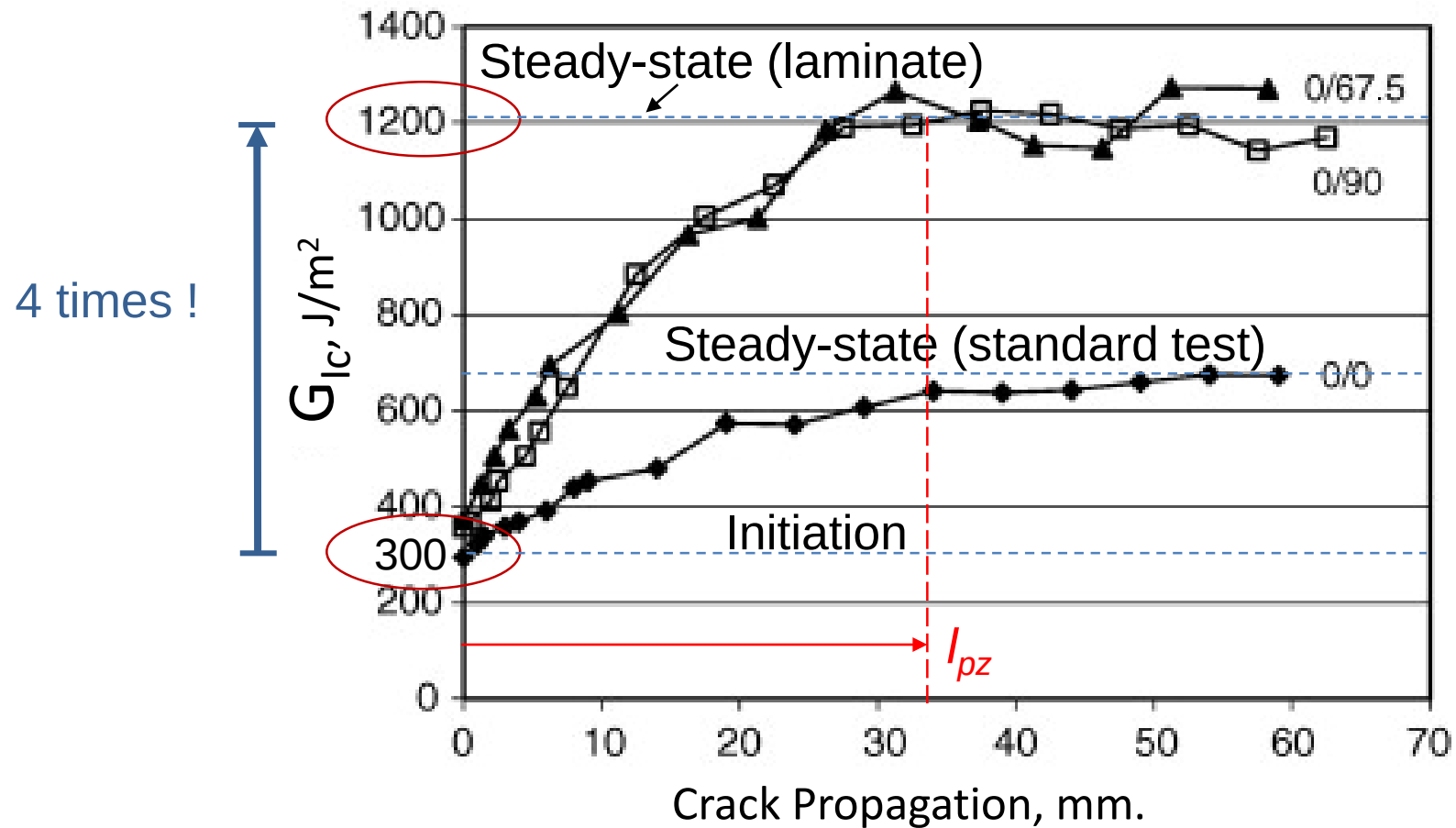
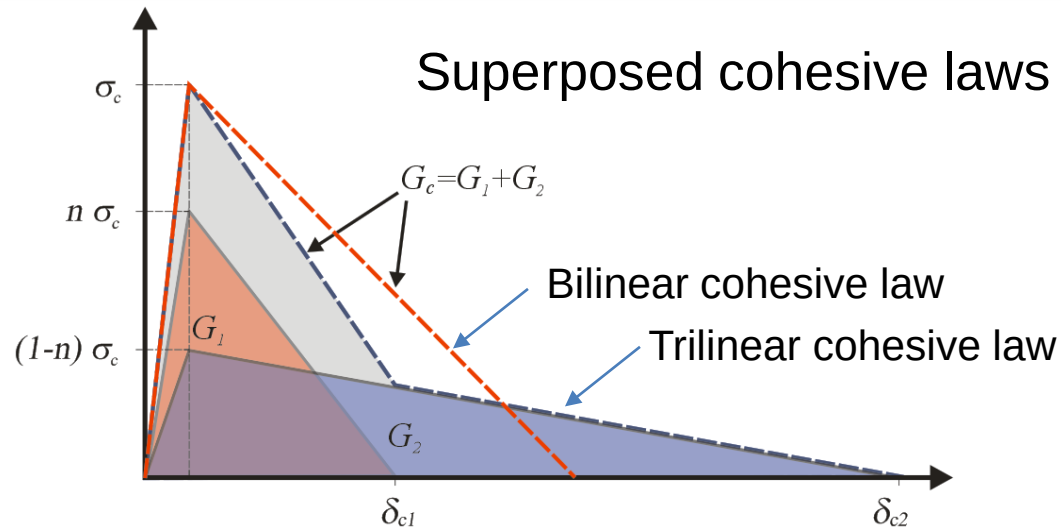


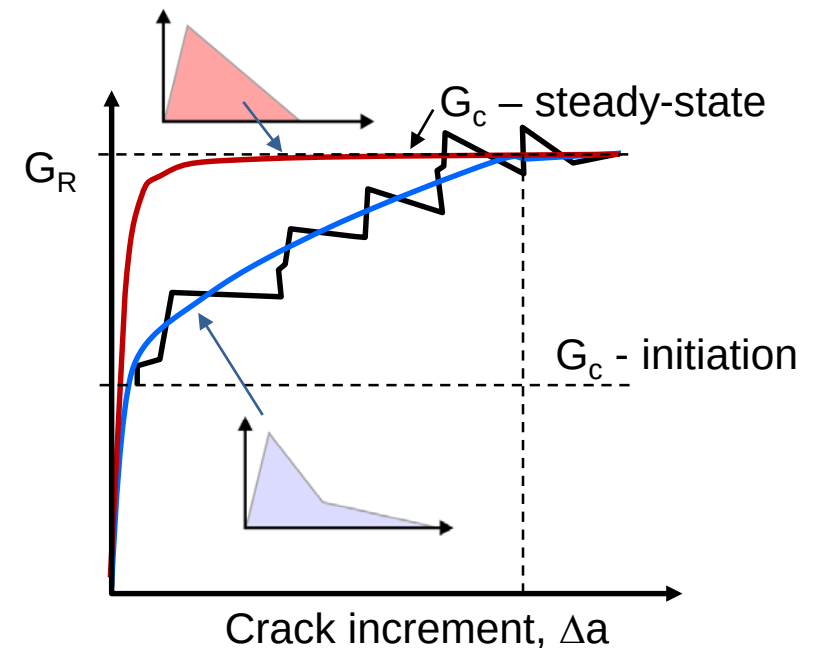
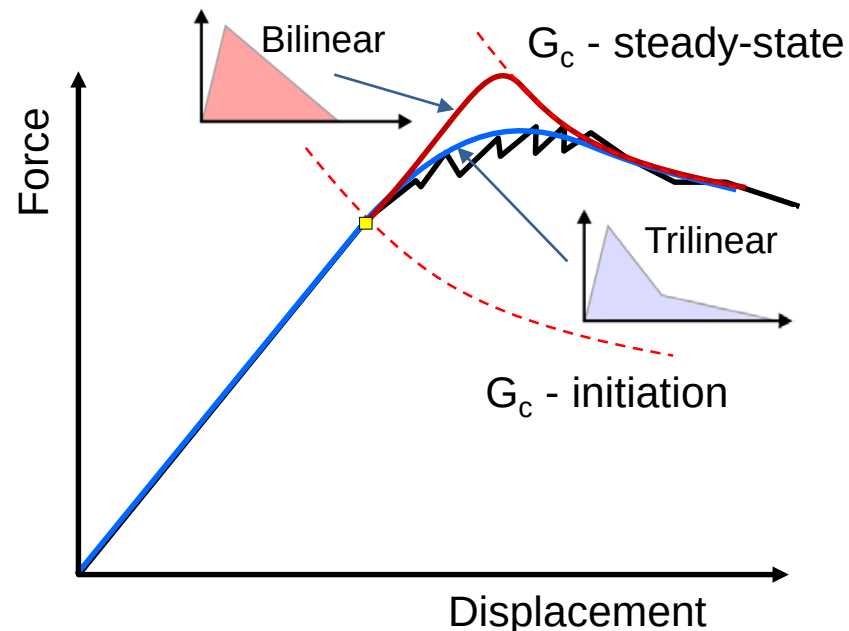
Fig. 14.

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

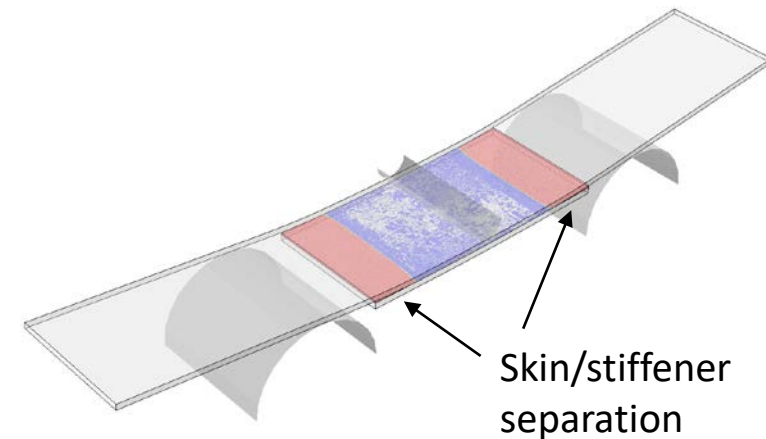
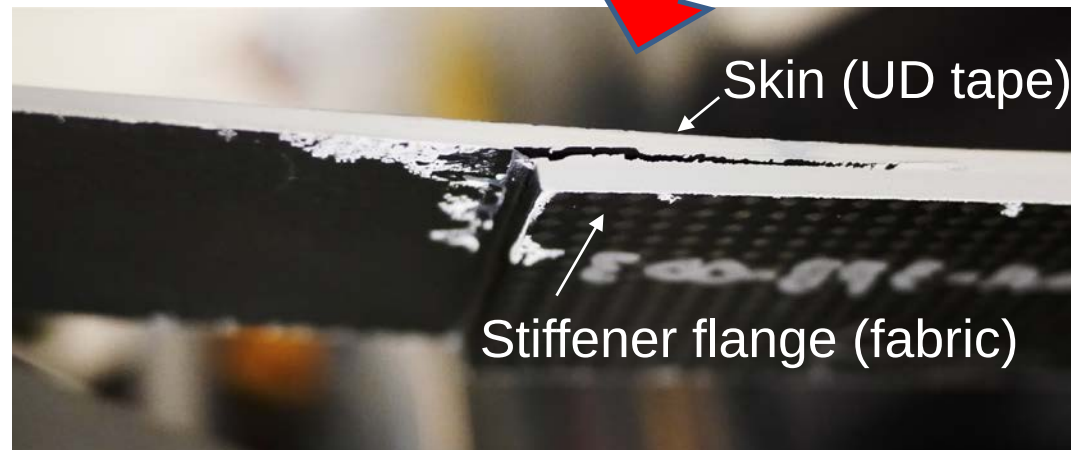
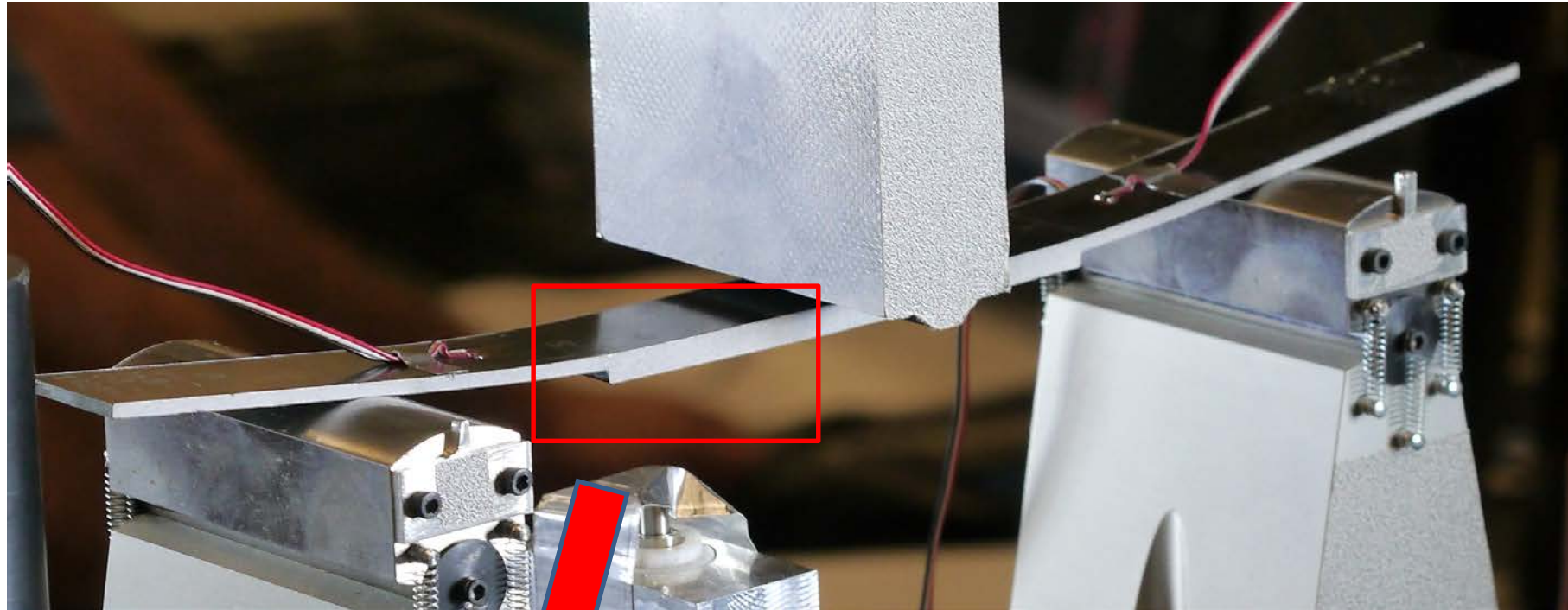
Modeling the R-Curve Effect



Trilinear cohesive laws can represent a number of R-curve effects such as fiber bridging, blunting, delving, migration, and the combined effect of crack networks.

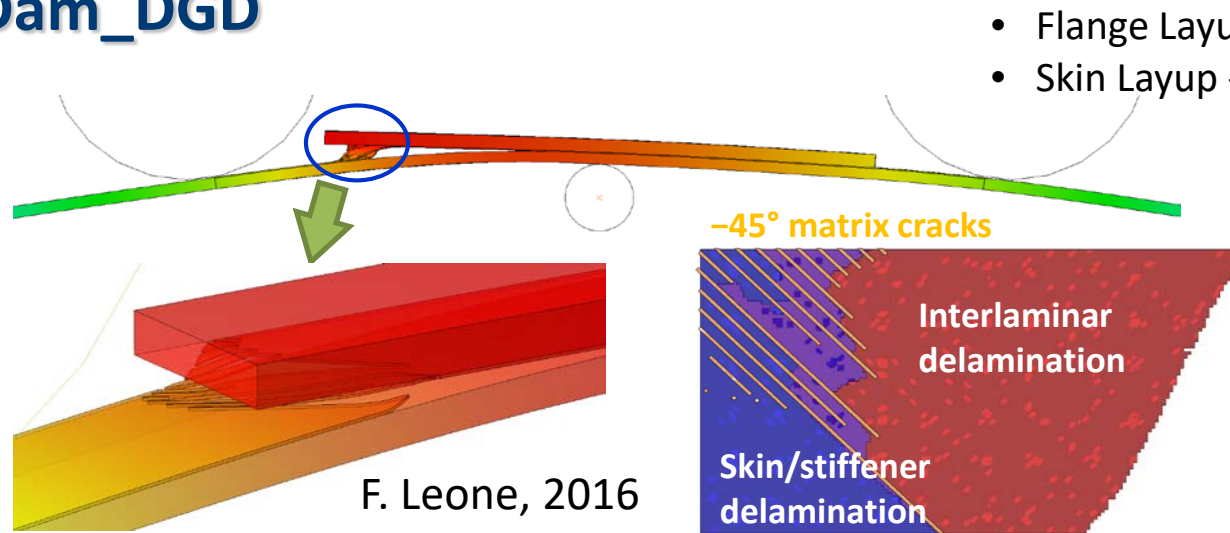


Three Point Bend (3PB) Doubler Specimen



3PB Specimen - Detailed “3D Models”

1) CompDam_DGD

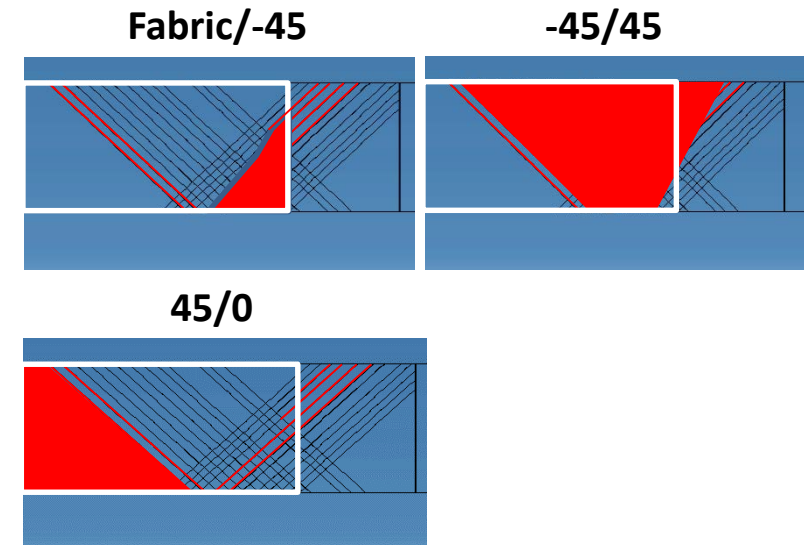
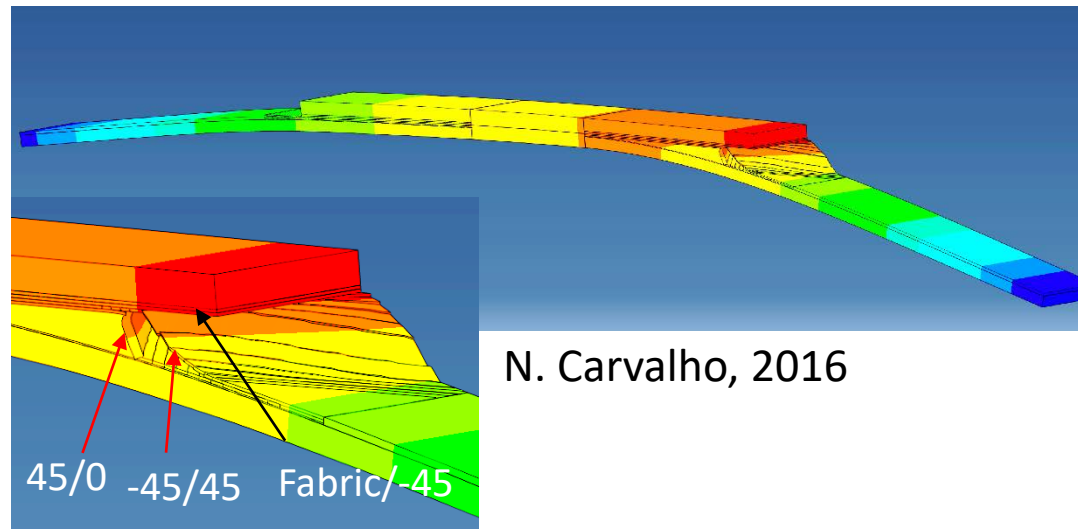


- Flange Layup – $[+45/0/-45/+45/-45/0]_s$ fabric
- Skin Layup - $[-45/+45/0/90/-45/+45]_s$ tape

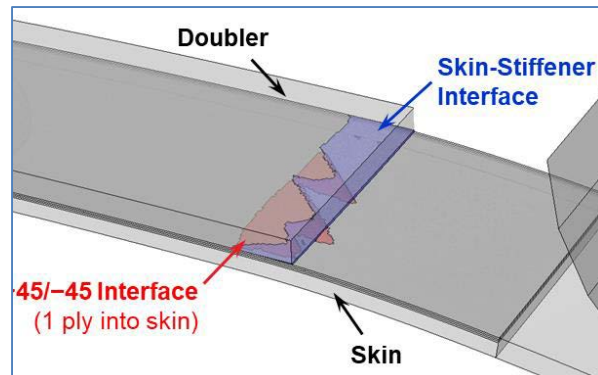
Failure Process:

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

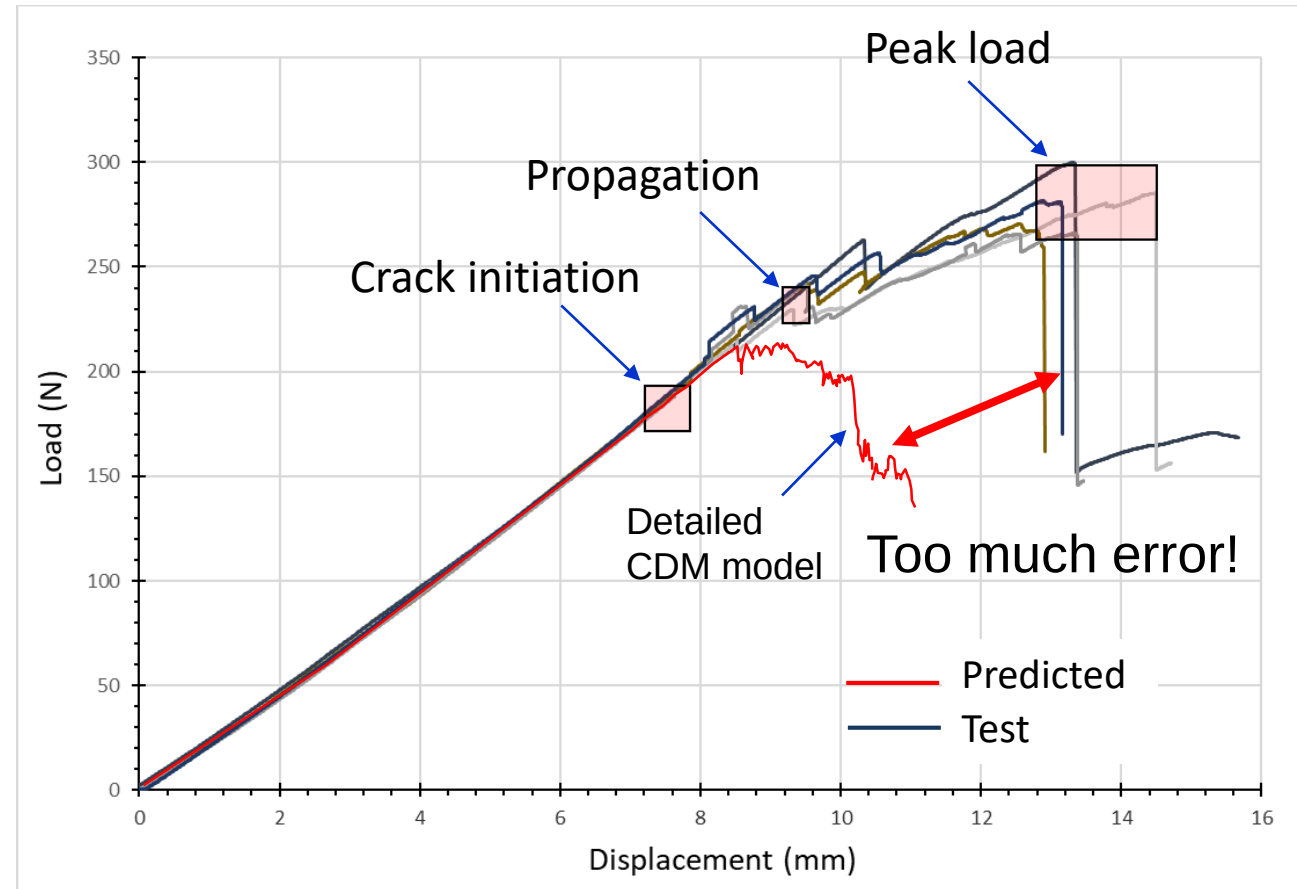
2) Floating Node Method (FNM)



3PB Specimen: Predicted Response

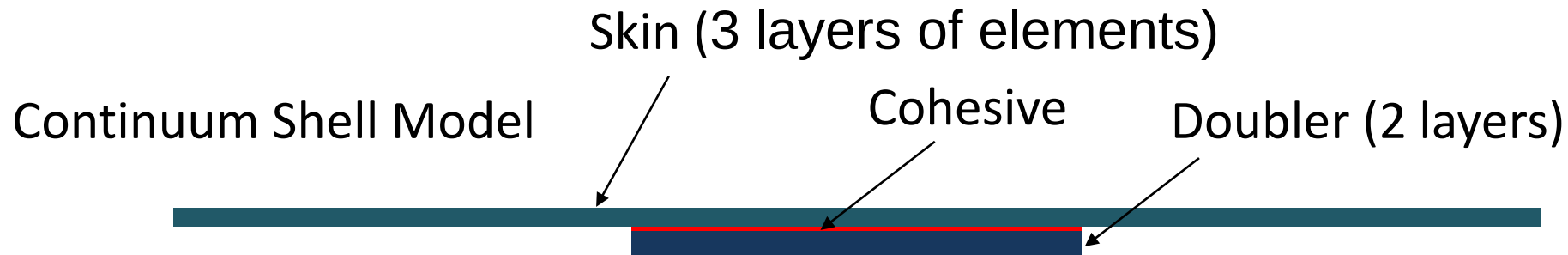


CompDam Model

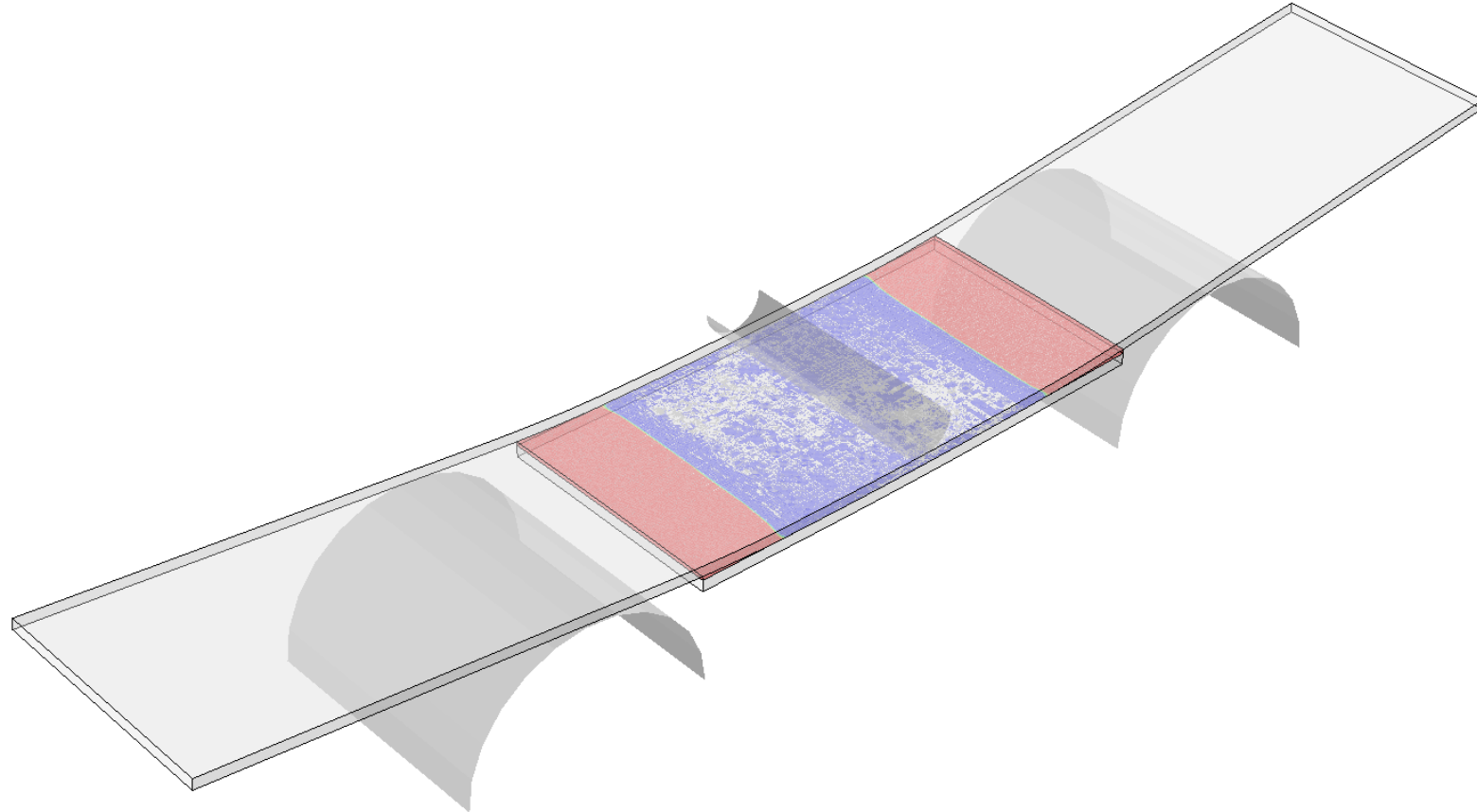
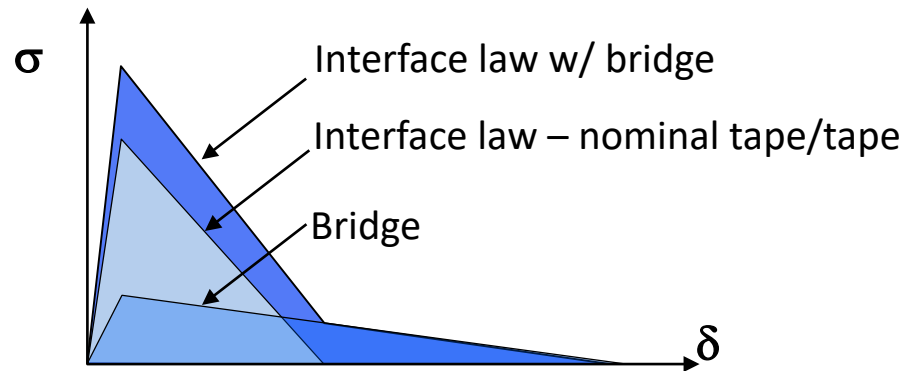


- Predicted morphology of damage is excellent, but response is too brittle
- It appears that “standard” material properties are not satisfactory for damage propagation

Simplified Shell Model of 3PB Specimen



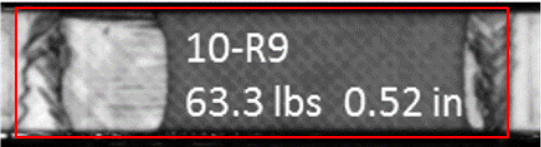
Empirical cohesive properties capture the effects of all damage mechanisms





Simplified Shell Model of 3PB Specimen

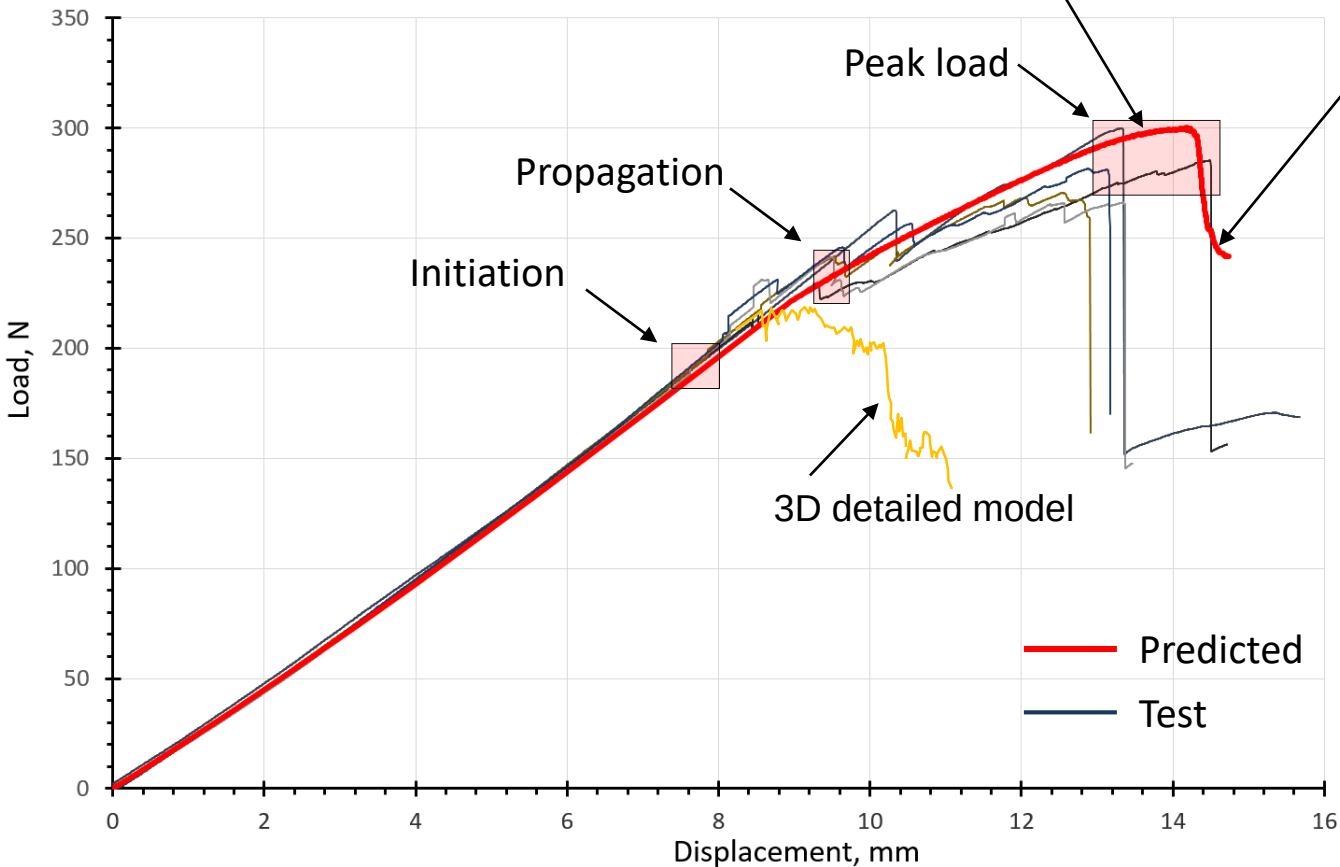
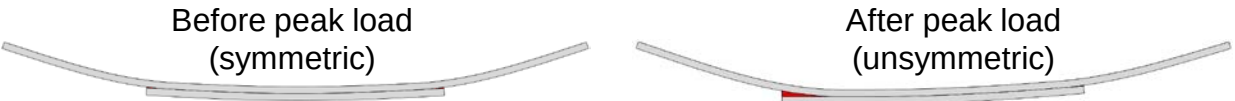
Test



Analysis



Shell Model



Initiation

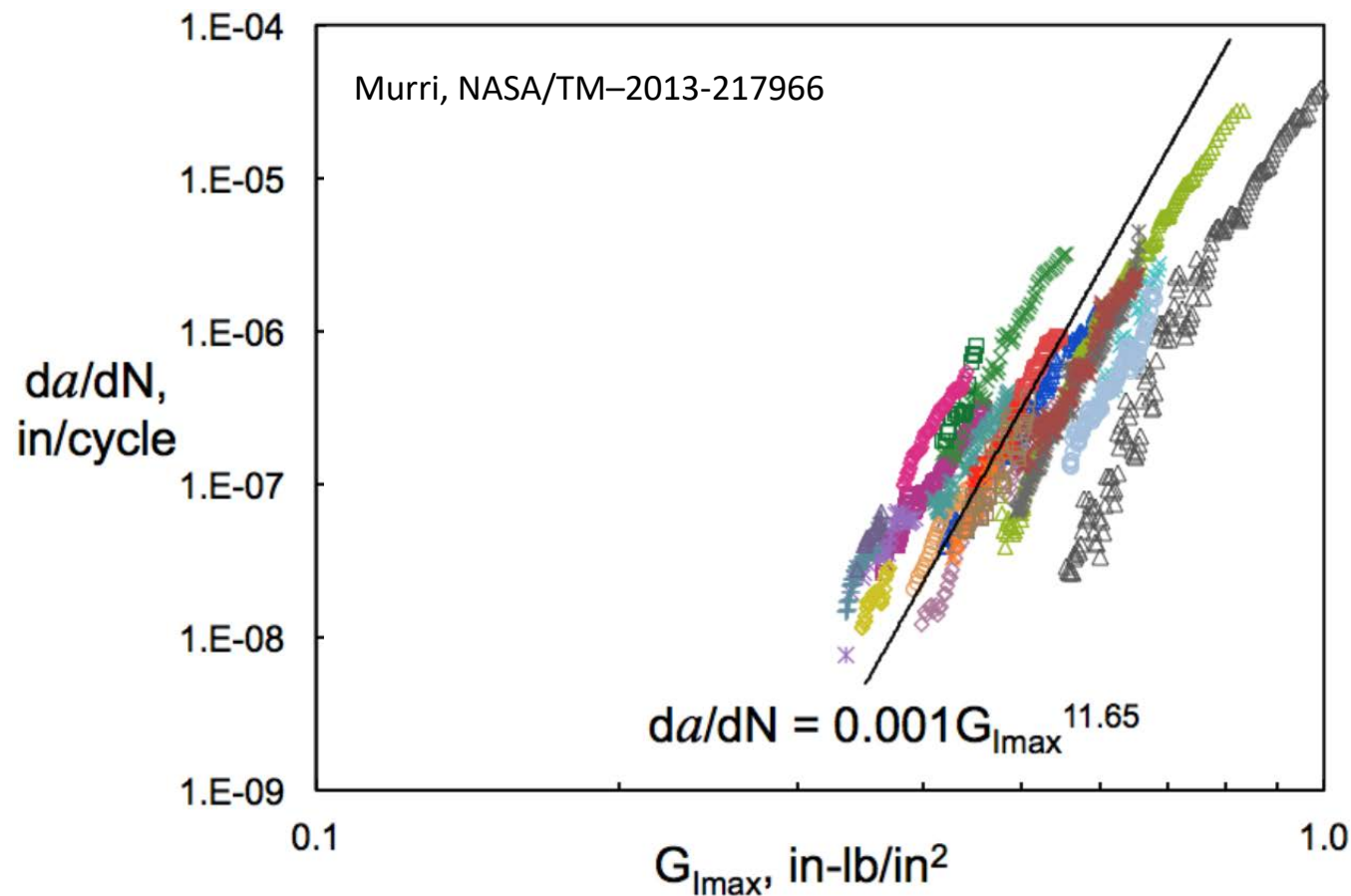
Propagation

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

Computed (Turon's constraints)

Fatigue Propagation Rate Using the Paris Law

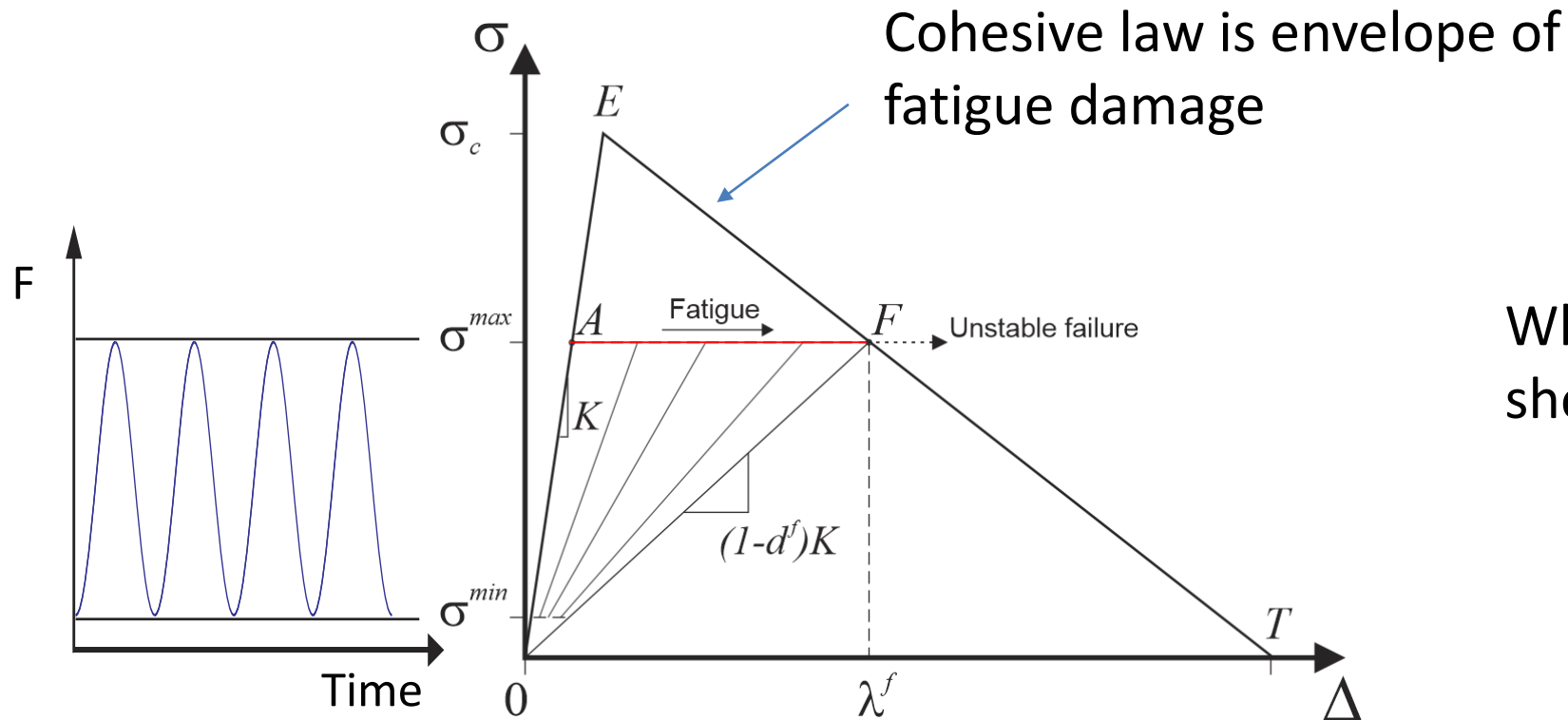
Paris law
$$\frac{da}{dN} = C (G_{\max})^m$$



- da/dN tests are expensive.
- Implementation into a cohesive formulation is difficult (nonlocal).
- Paris law does not account for R-curve effects.
- Paris data does not apply to crack initiation or to short cracks.

Cohesive Fatigue Damage Model (S-N)

Consider case of bar subjected to cyclic load



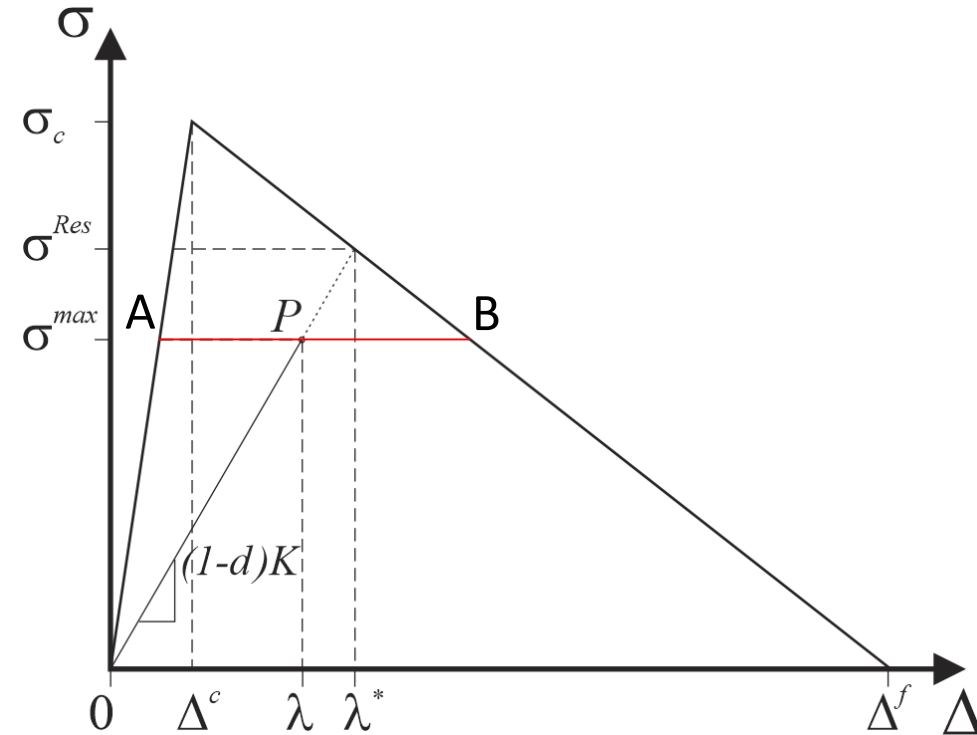
What damage law should be used?

Cohesive Fatigue Damage Model

Consider damage law at point P:

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

where damage is: $D = \frac{\lambda^* - \Delta^c}{\Delta^f - \Delta^c}$



Number of cycles to failure obtained by integrating dN from A to B

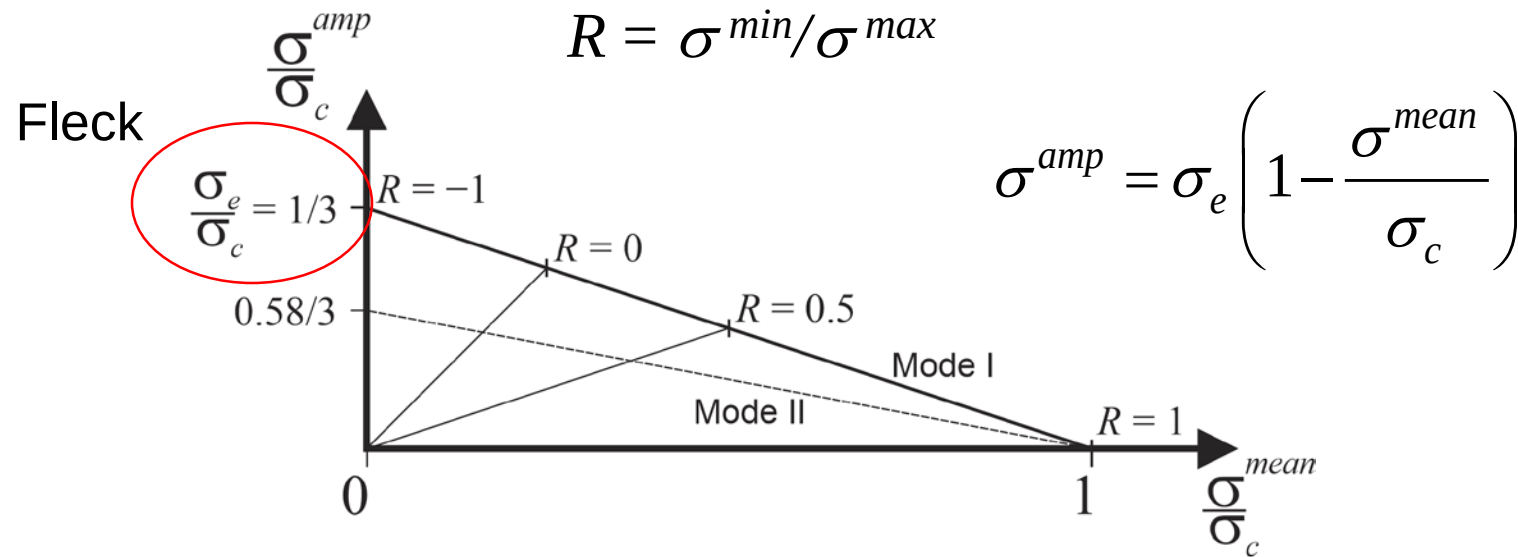
$$\Rightarrow N^f = \underbrace{\left(\frac{\sigma_c}{\sigma^{\max}} \right)^\beta \int_0^{D^F} \frac{(1-D)^{-\beta}}{D + \gamma} dD}_{\text{S-N curve}}$$

Get β and γ from:

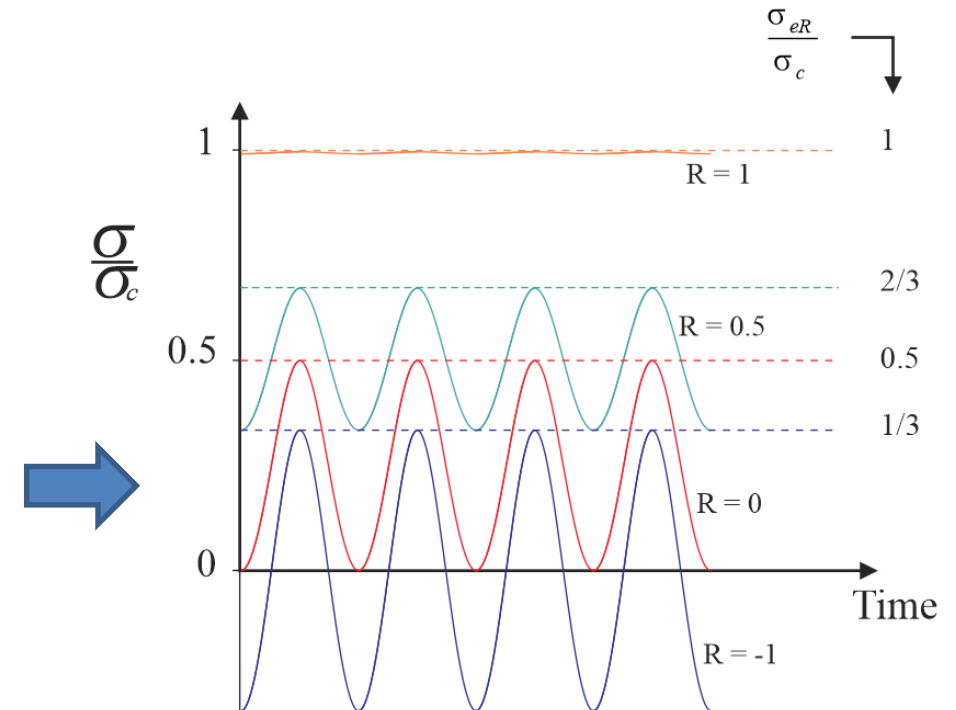
experimental S-N
or
idealized S-N

Goodman Diagram (GD)

The GD is design tool that represents the locus of stress states corresponding to a runout stress or a given number of cycles to failure



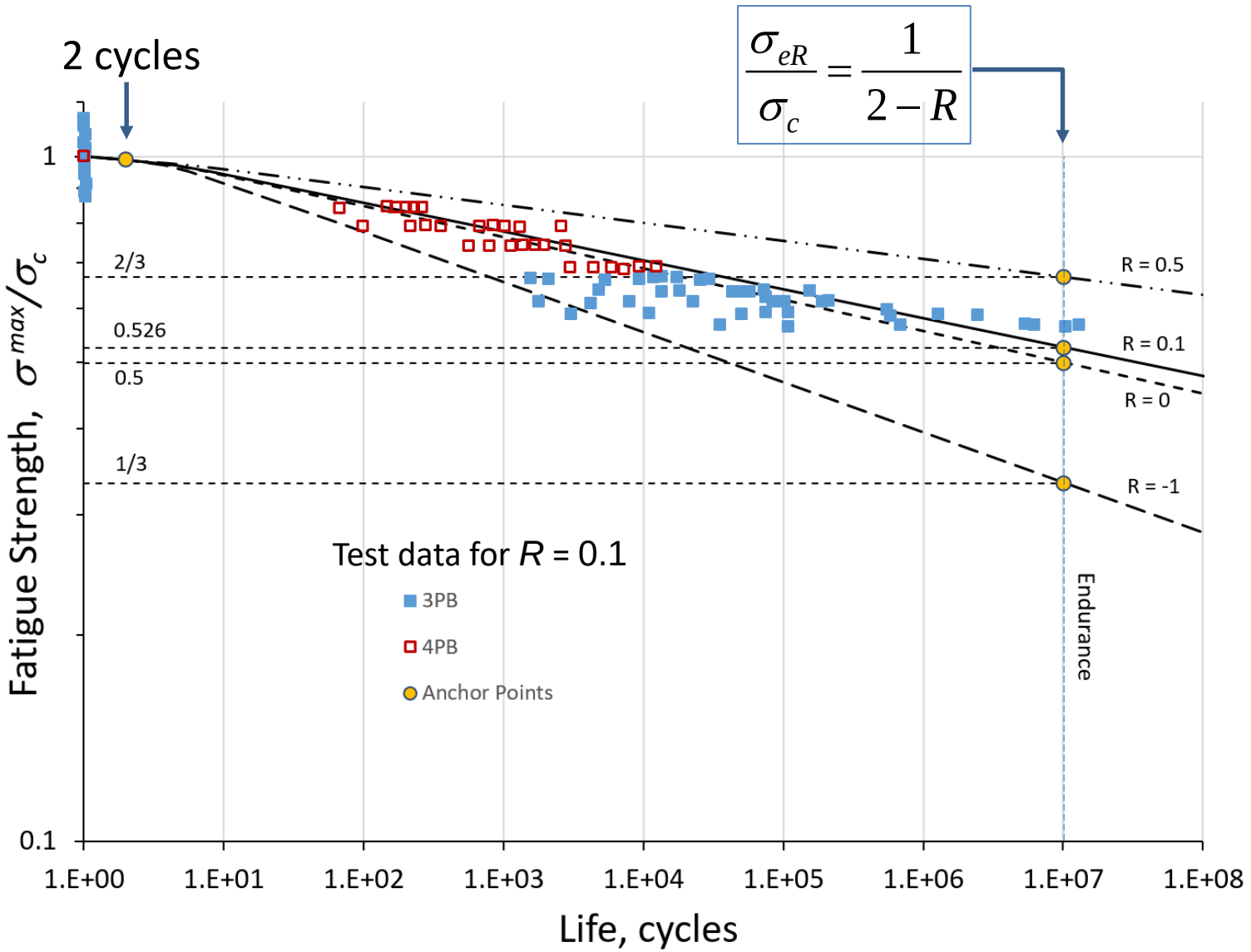
$$\frac{\sigma_{eR}}{\sigma_c} = \frac{1}{2 - R}$$





S-N curves for Different R Ratios

S-N curves are “anchored” at two points



Solve two equation for 2 unknowns β, γ

$$N_1^f = 2 = (0.99)^{-\beta} \int_0^{D_1^F} \frac{(1-D)^\beta}{D+\gamma} dD$$
$$N_2^f = 10^7 = \left(\frac{1}{2-R} \right)^{-\beta} \int_0^{D_2^F} \frac{(1-D)^\beta}{D+\gamma} dD$$

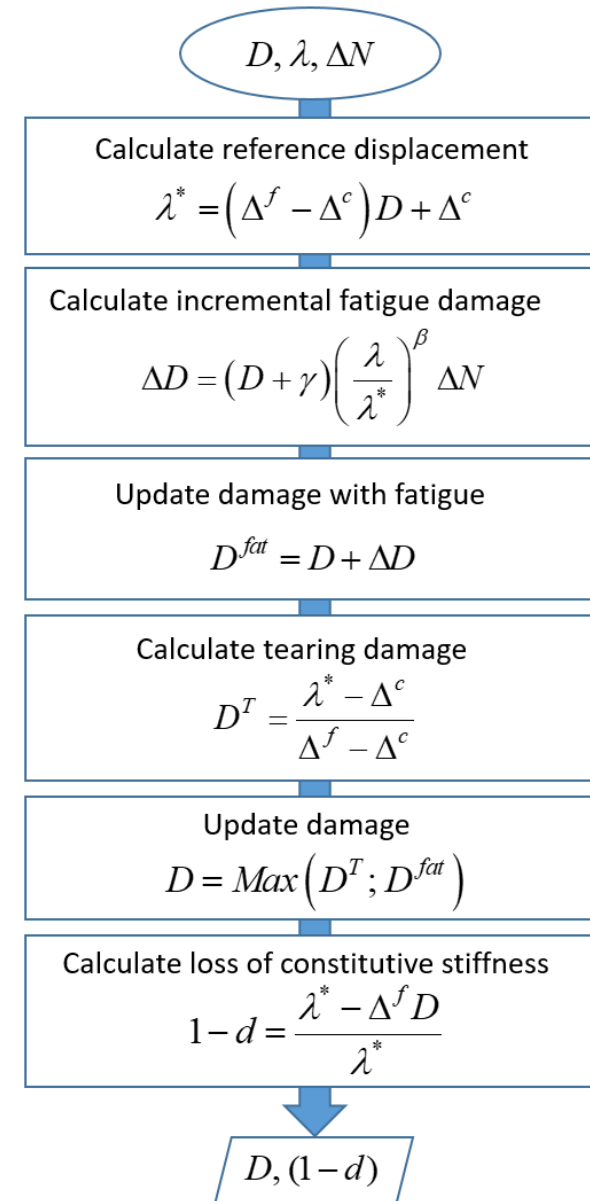


Coefficients ($\beta; \gamma$) for several values of the stress ratio.

R	β	γ
-1	13.611	0.001911
0	21.842	0.002142
0.1	23.649	0.002194
0.5	38.033	0.002643

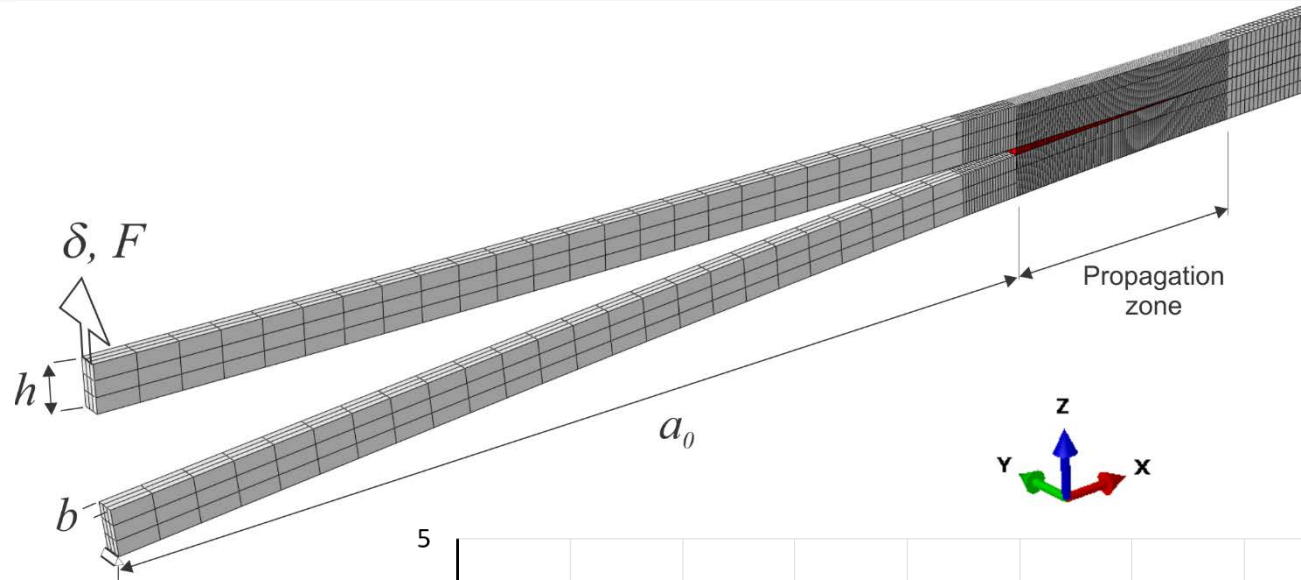
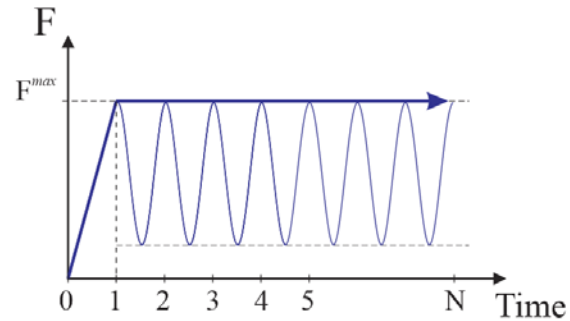
Flowchart of UMAT

Fatigue model was implemented as a UMAT user-written material subroutine for Abaqus cohesive elements

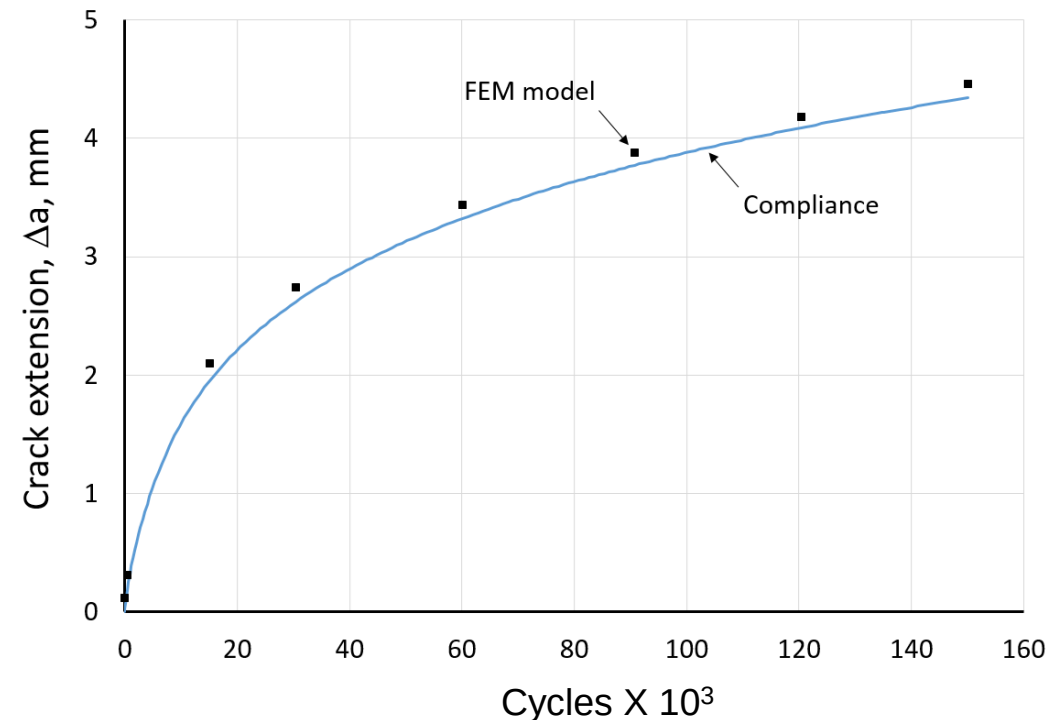


Analysis of Double Cantilever Beam Specimen (DCB)

Applied load remains constant

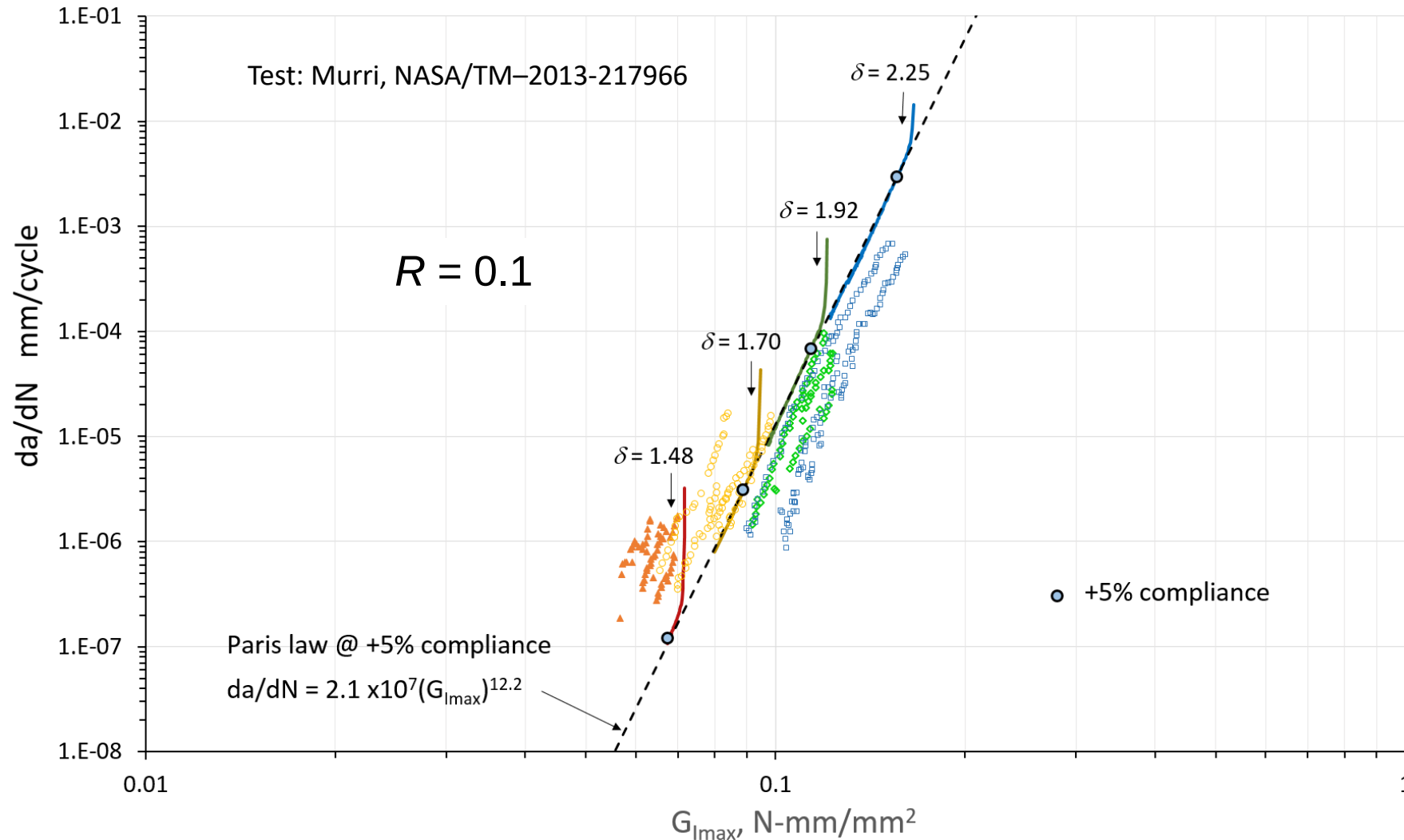


Detail of propagation zone

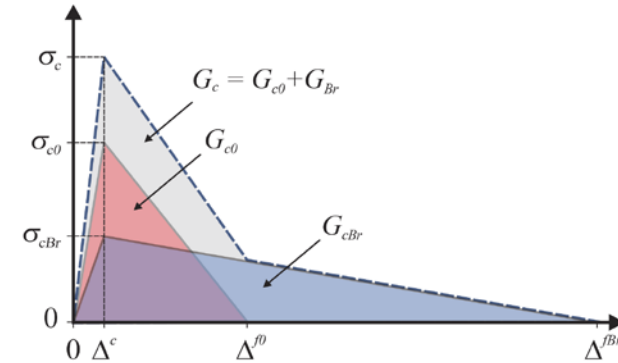
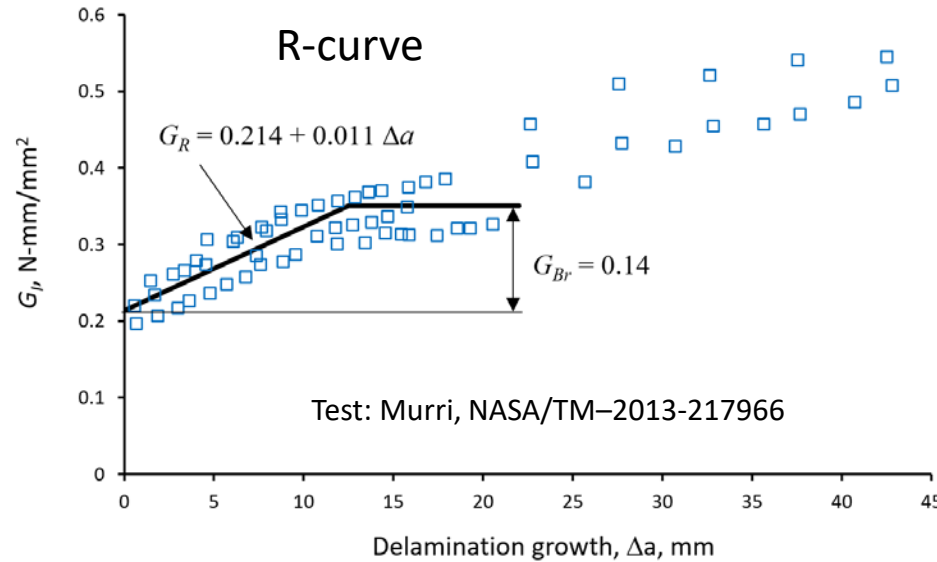


Propagation Rates for DCB Specimen

Analyses of DCB were conducted with 4 different applied loads (displacement control)



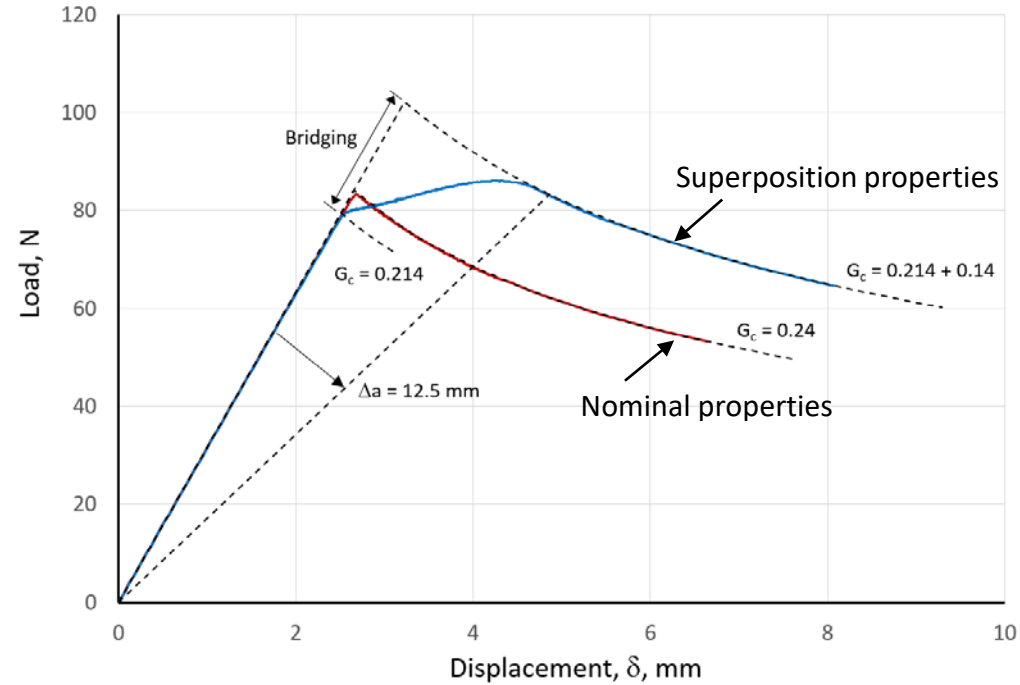
R-Curve Effect on DCB Specimen



	G_c (N/mm)	σ_c (MPa)	K (N/mm ³)
Nominal	0.240	80.1	$2 \cdot 10^5$
Base	0.214	80.1	$2 \cdot 10^5$
Bridge	0.140	0.8	$2 \cdot 10^3$

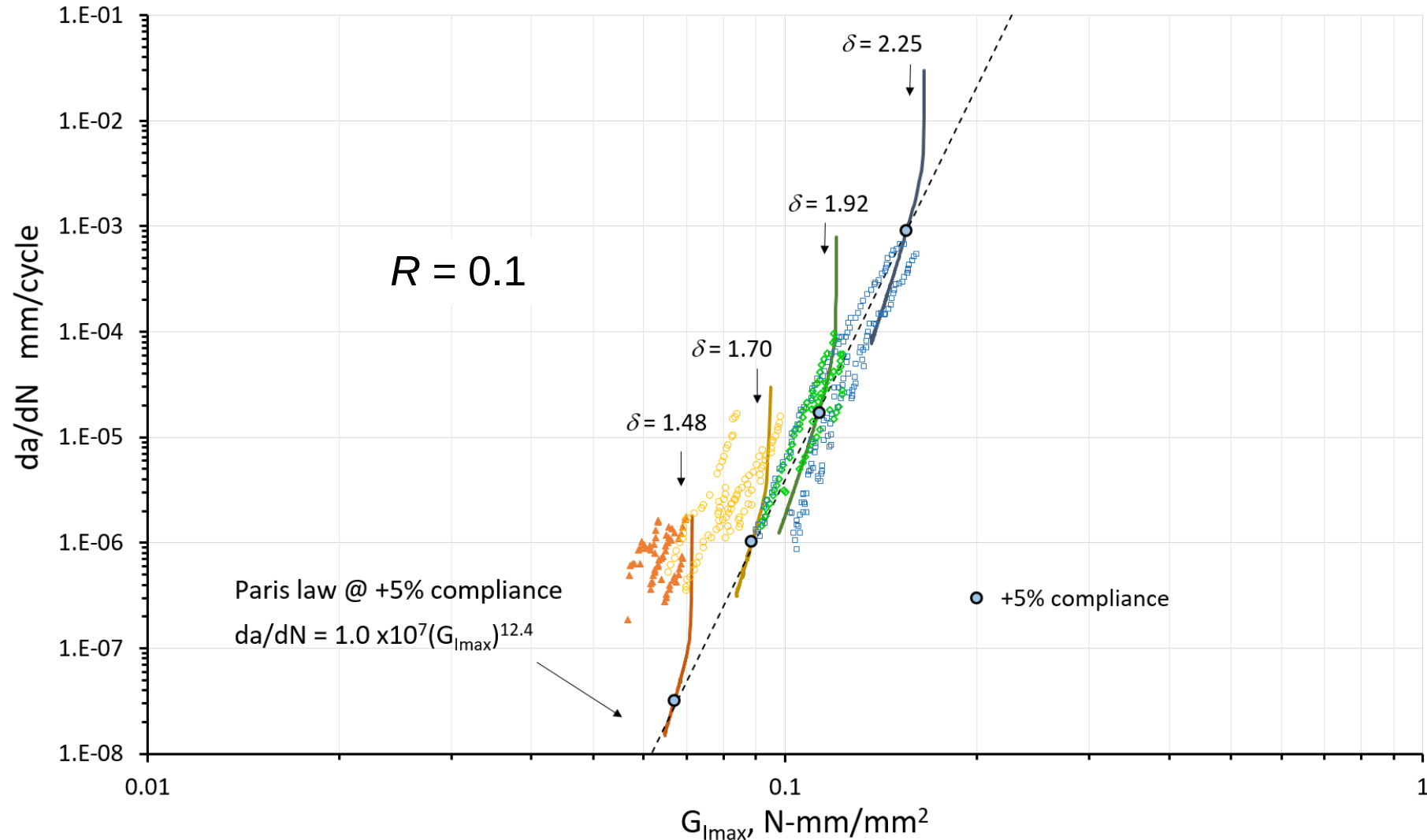
superposed {

Quasi-static response of DCB using superposition of bridging laws

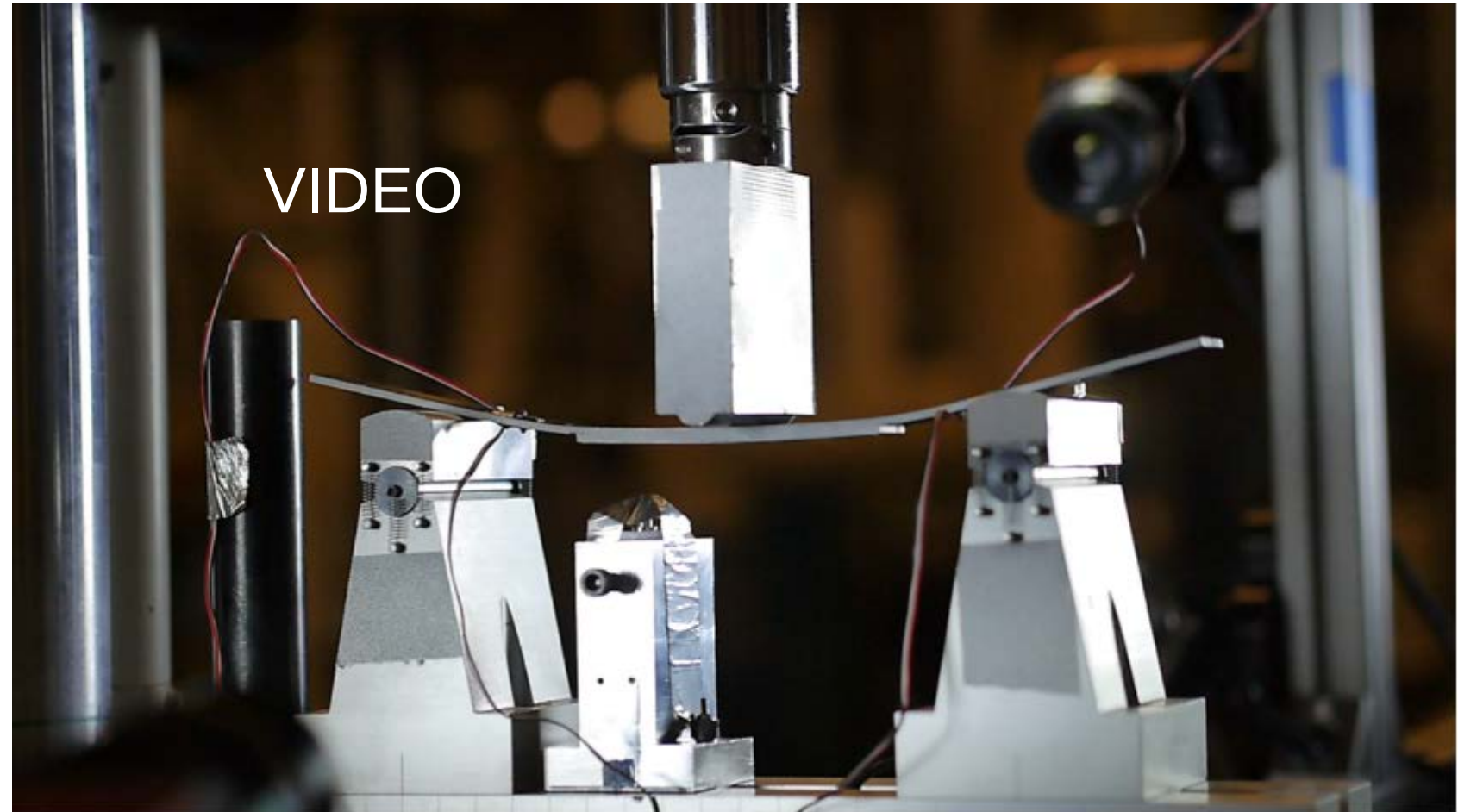
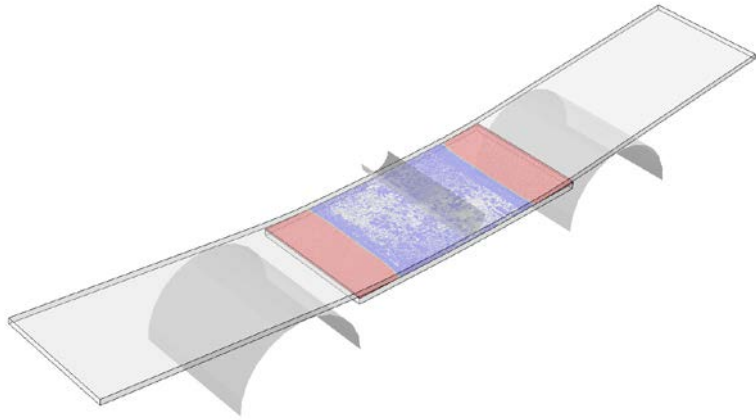


Delamination Propagation Rates for DCB with R-Curve

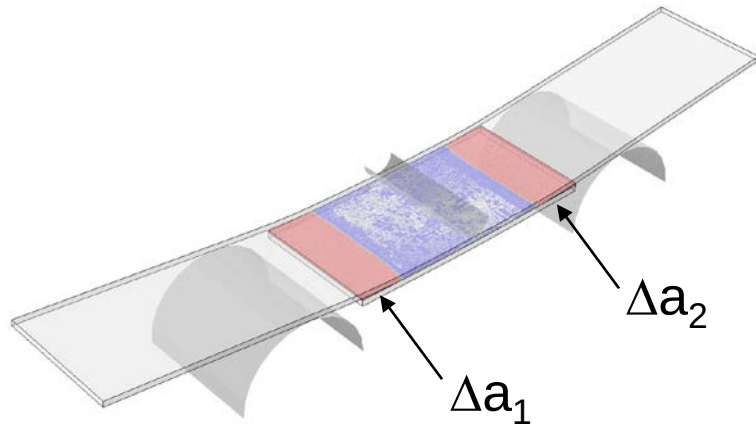
Comparison of predicted delamination growth rates with
R-curve bridging included with experimental results



3PB Fatigue – Experimental Results



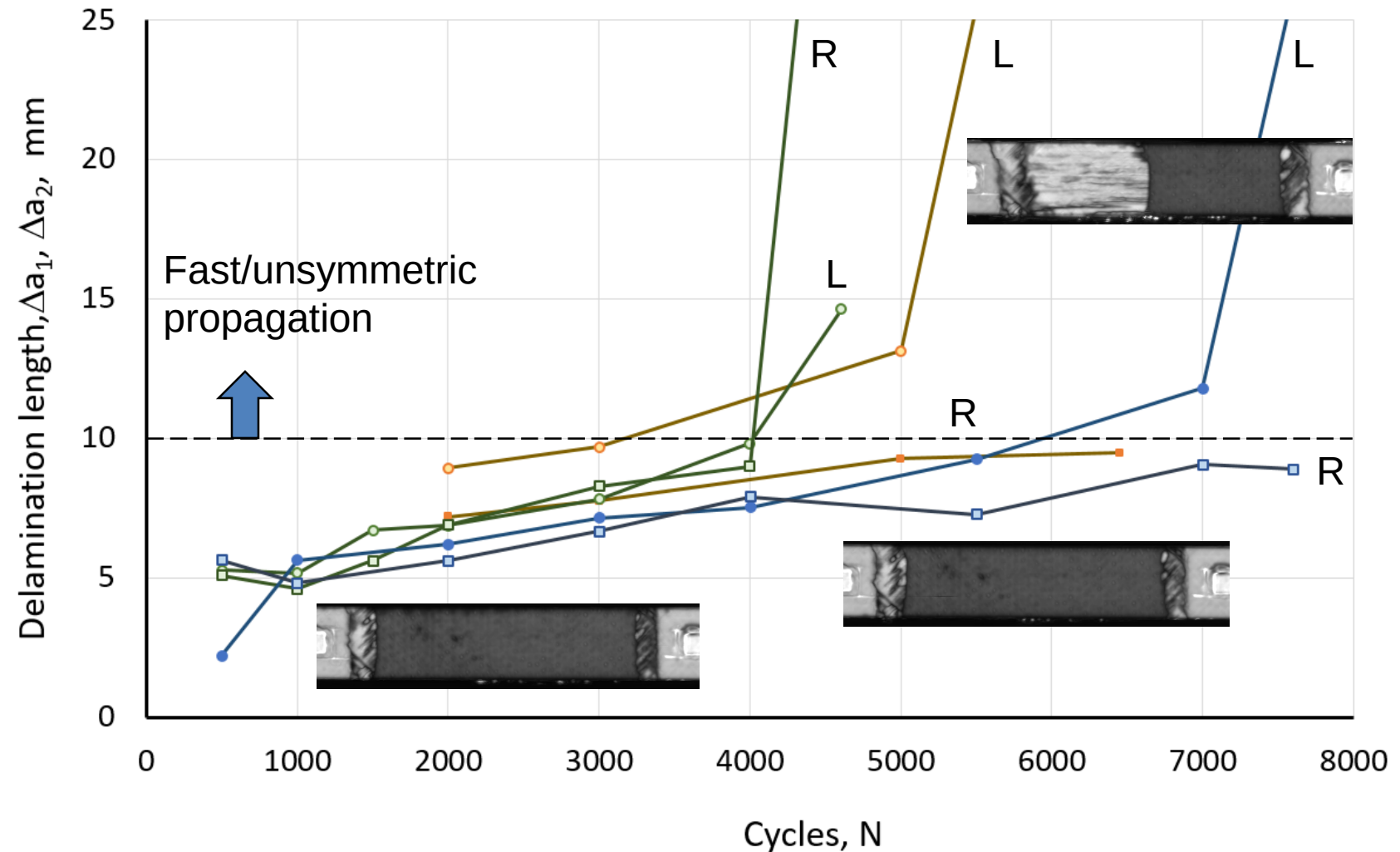
3PB Fatigue – Experimental Results



Delamination initially grows equally on both ends.

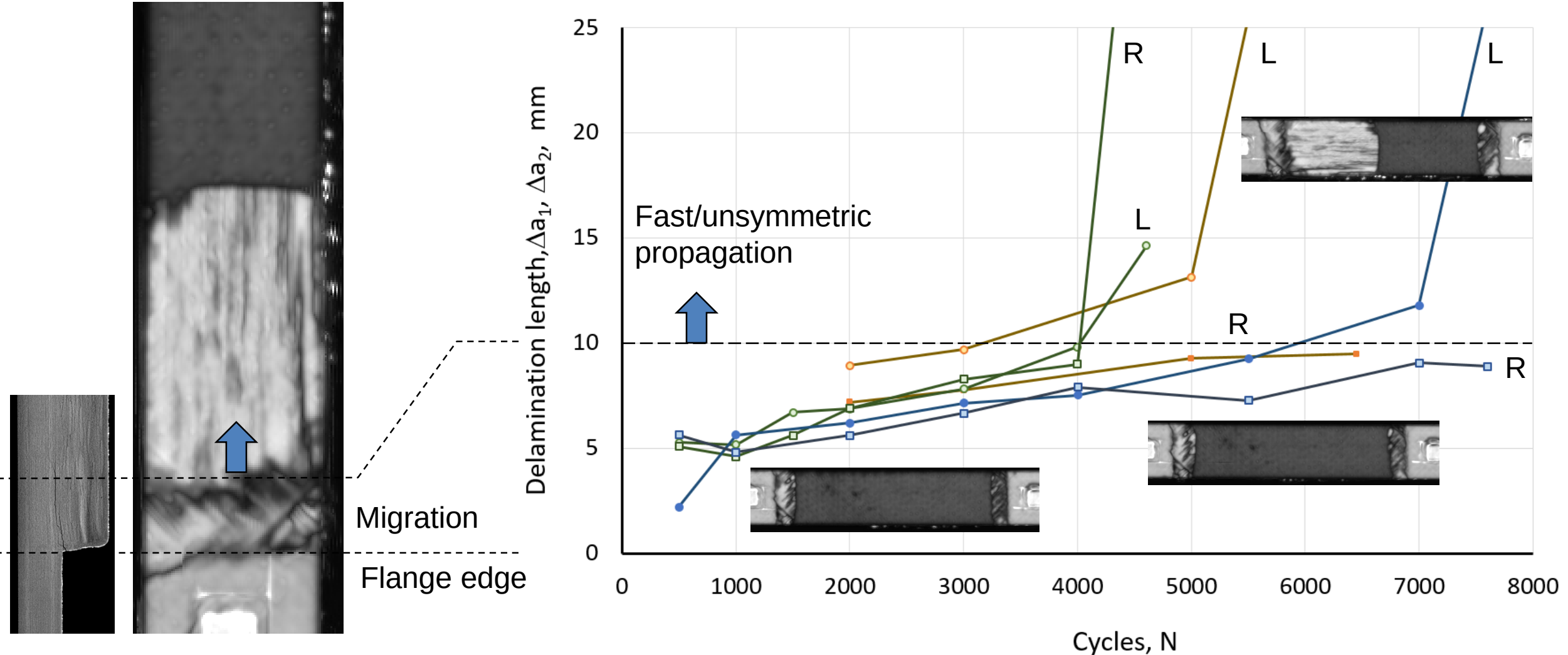
After about 10 mm, the delamination on one side of the specimen grows rapidly.

Loading: $F = 214 \text{ N}$, $R = 0.1$

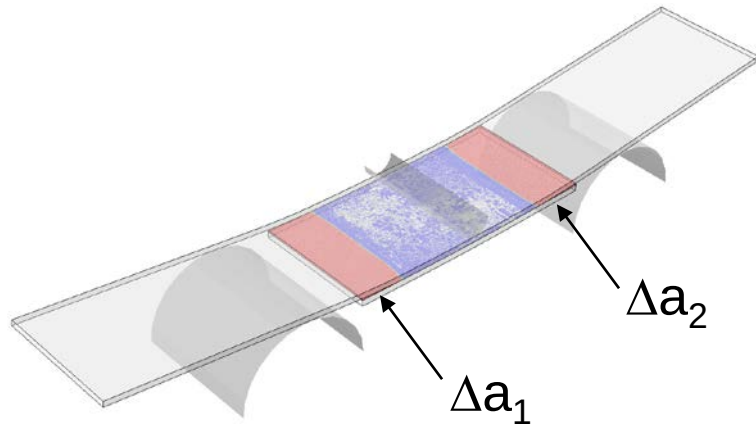


3PB Fatigue – Experimental Results

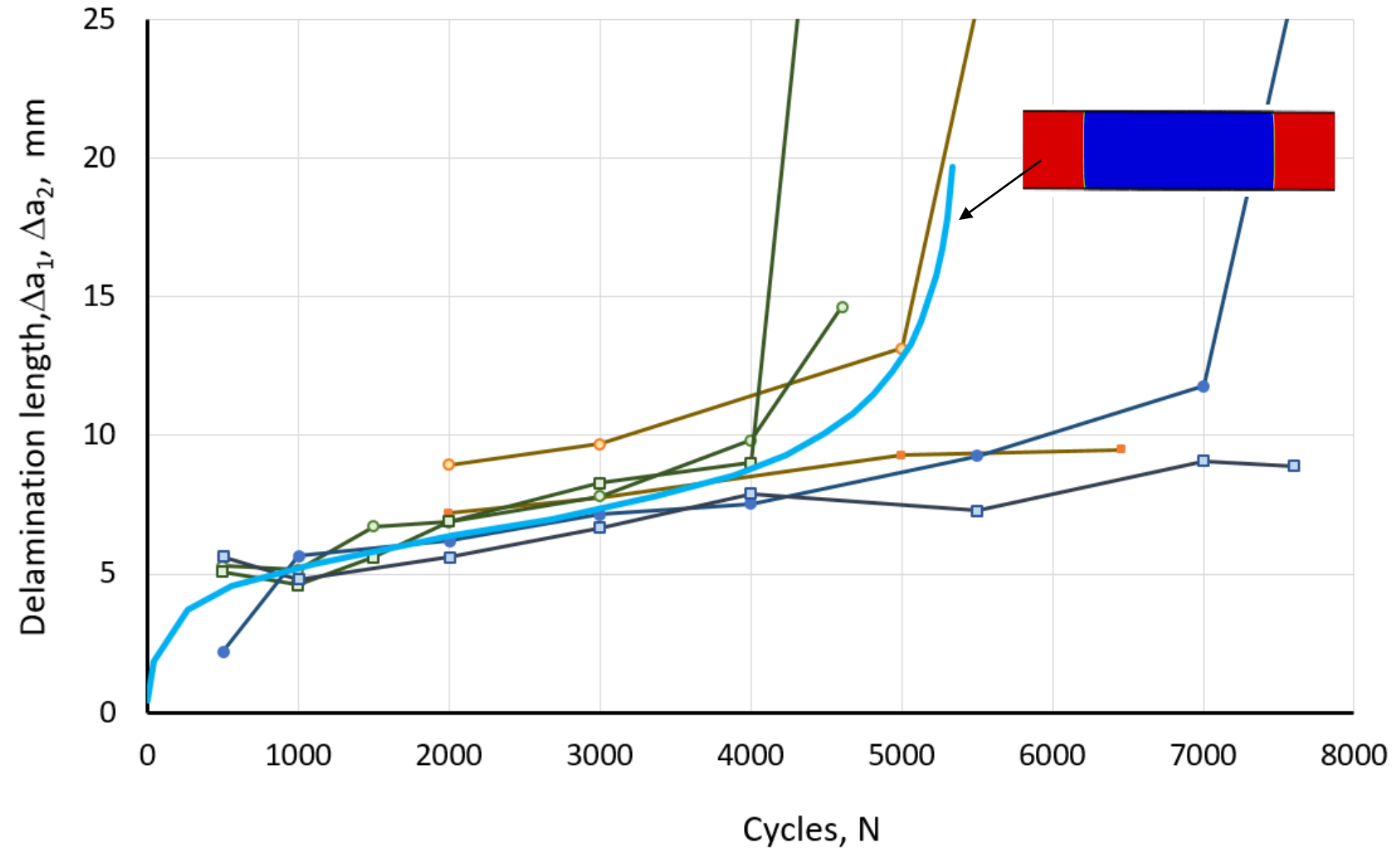
Loading: $F = 214 \text{ N}$, $R = 0.1$



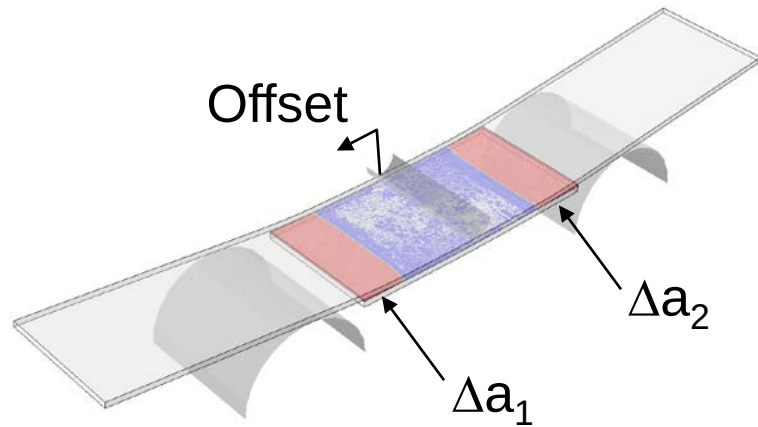
3PB Fatigue – Analysis Results



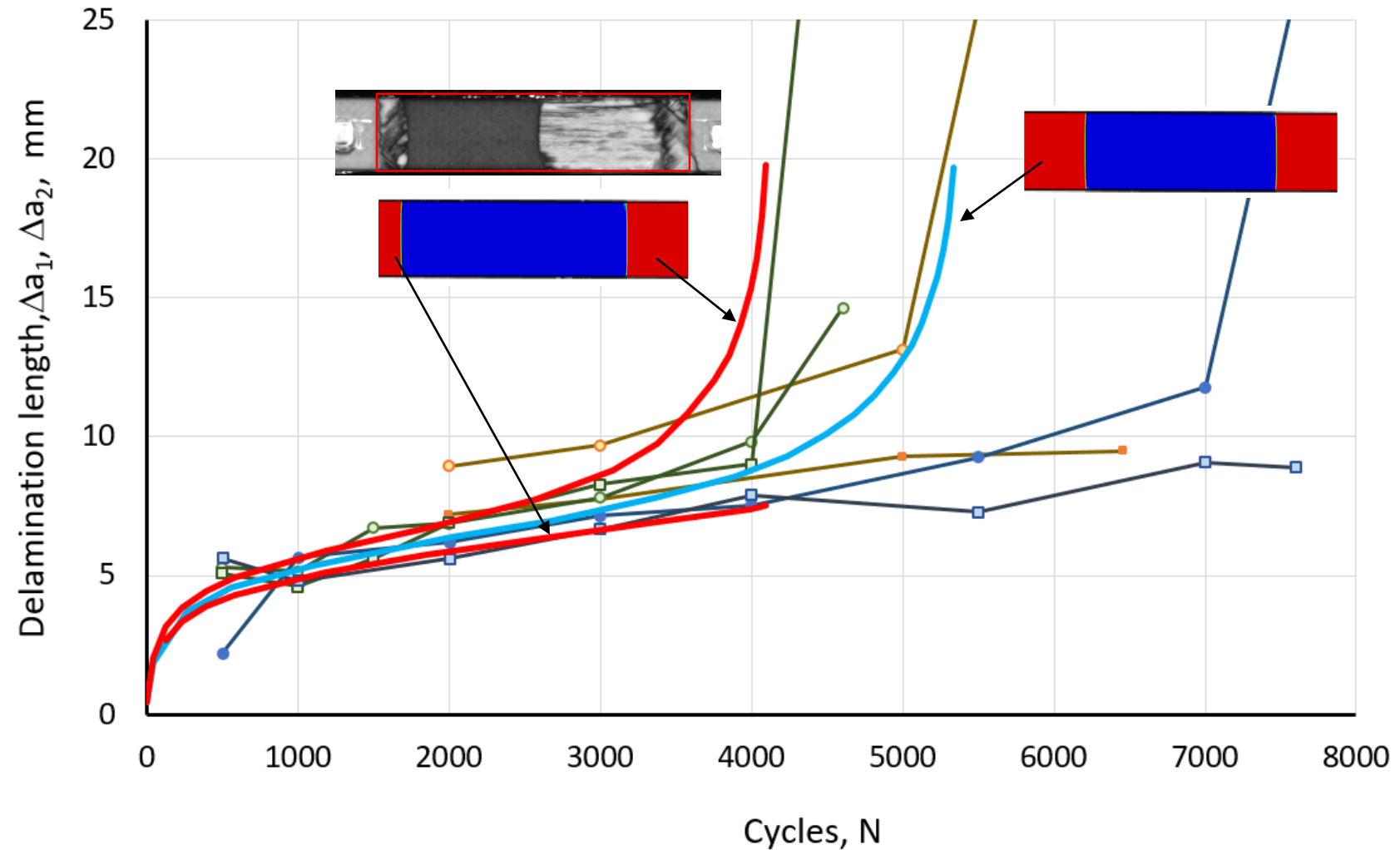
Symmetric results



3PB Fatigue – Analysis Results



Unsymmetric model:
1.1 mm offset in center roller



Concluding Remarks

- Cohesive models can account for R-curve effects that result from complex kinematics of migration and bridging
- New cohesive fatigue model works well with simplified interfaces:
 - model based on S-N rather than Paris law
 - assumes that quasi-static R-curve applies to fatigue
 - appears capable of predicting crack initiation and propagation
 - fatigue-specific input data was not used
- The level of fidelity required to model typical delaminations has not yet been established