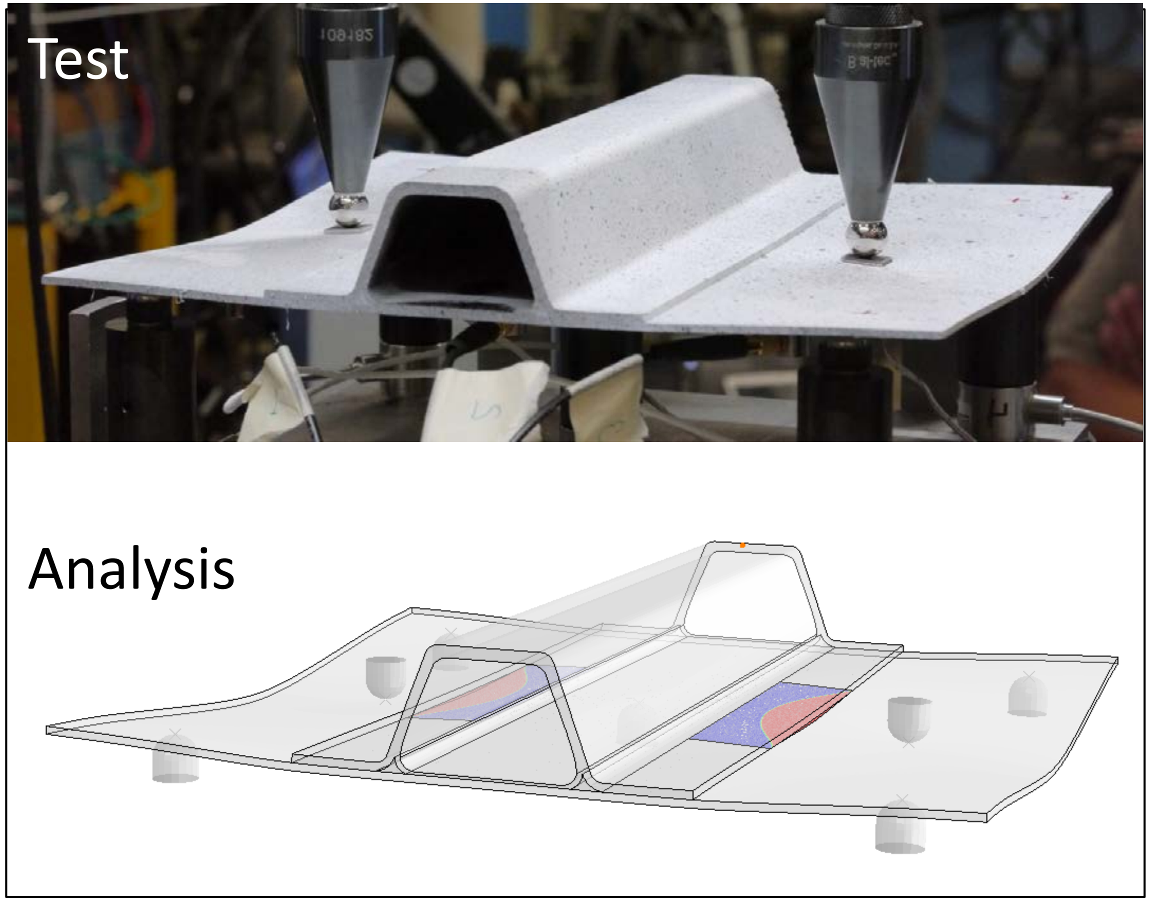
Initiation and Propagation of Skin/Stiffener Separation in Postbuckled Structures Subjected to Cyclic Loads



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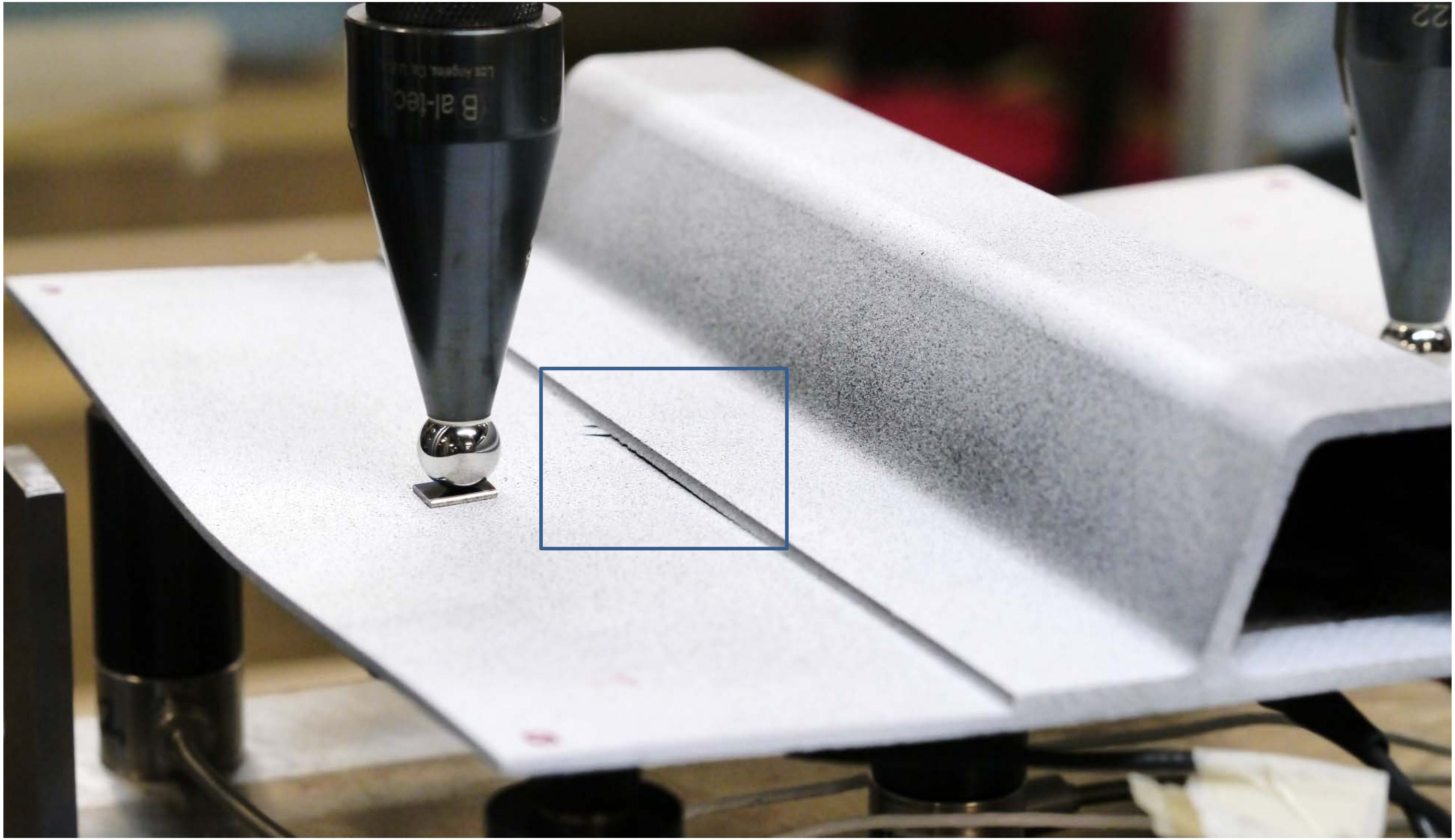
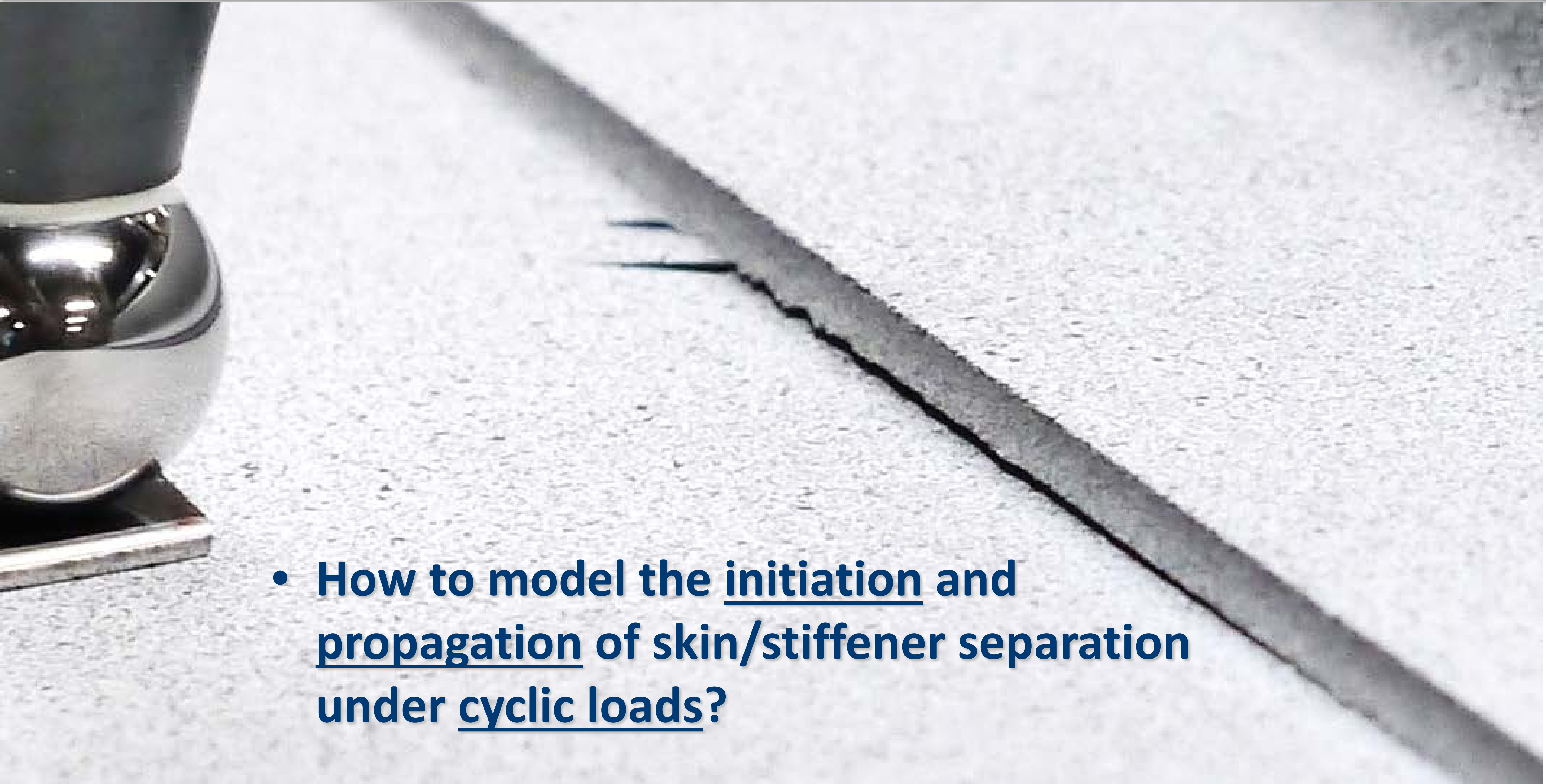
SciTech 2021 Conference

Skin/Stiffener Separation



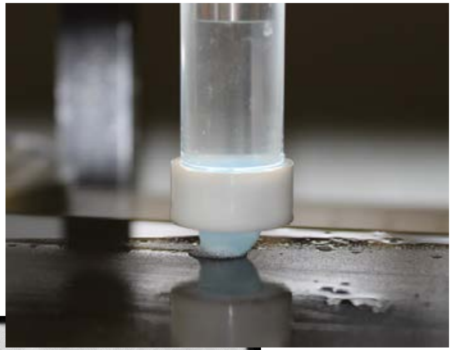
Fatigue: Skin/Stiffener Separation

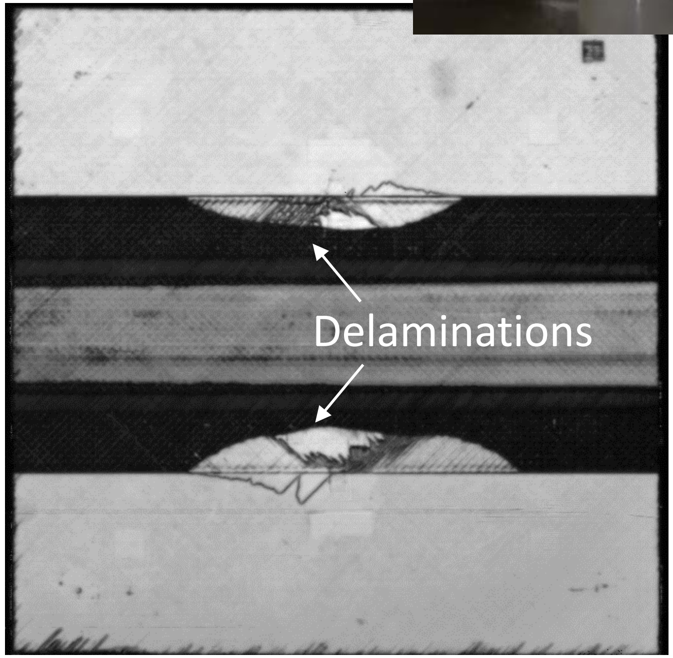


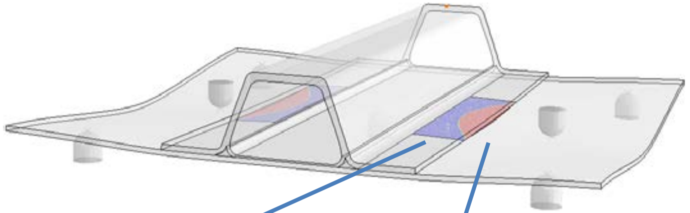
- **How to model the initiation and propagation of skin/stiffener separation under cyclic loads?**

Nondestructive Evaluation (NDE) Techniques

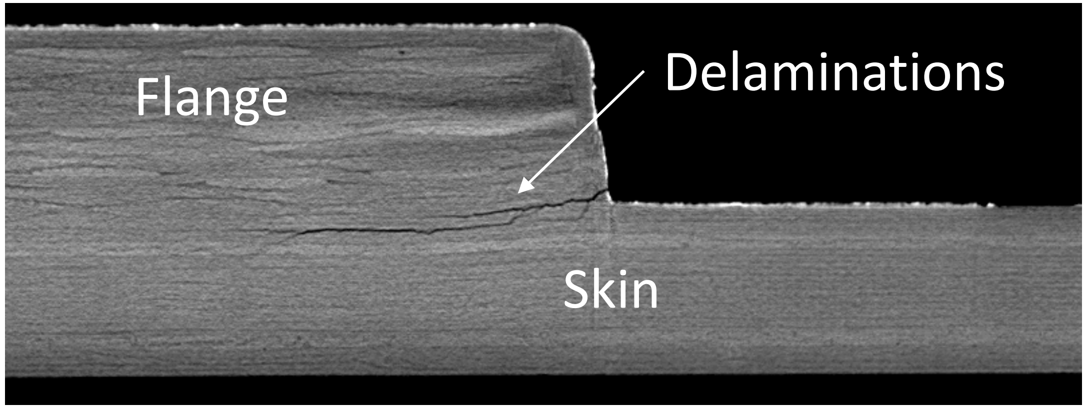
Ultrasonic C-scanning (UT)





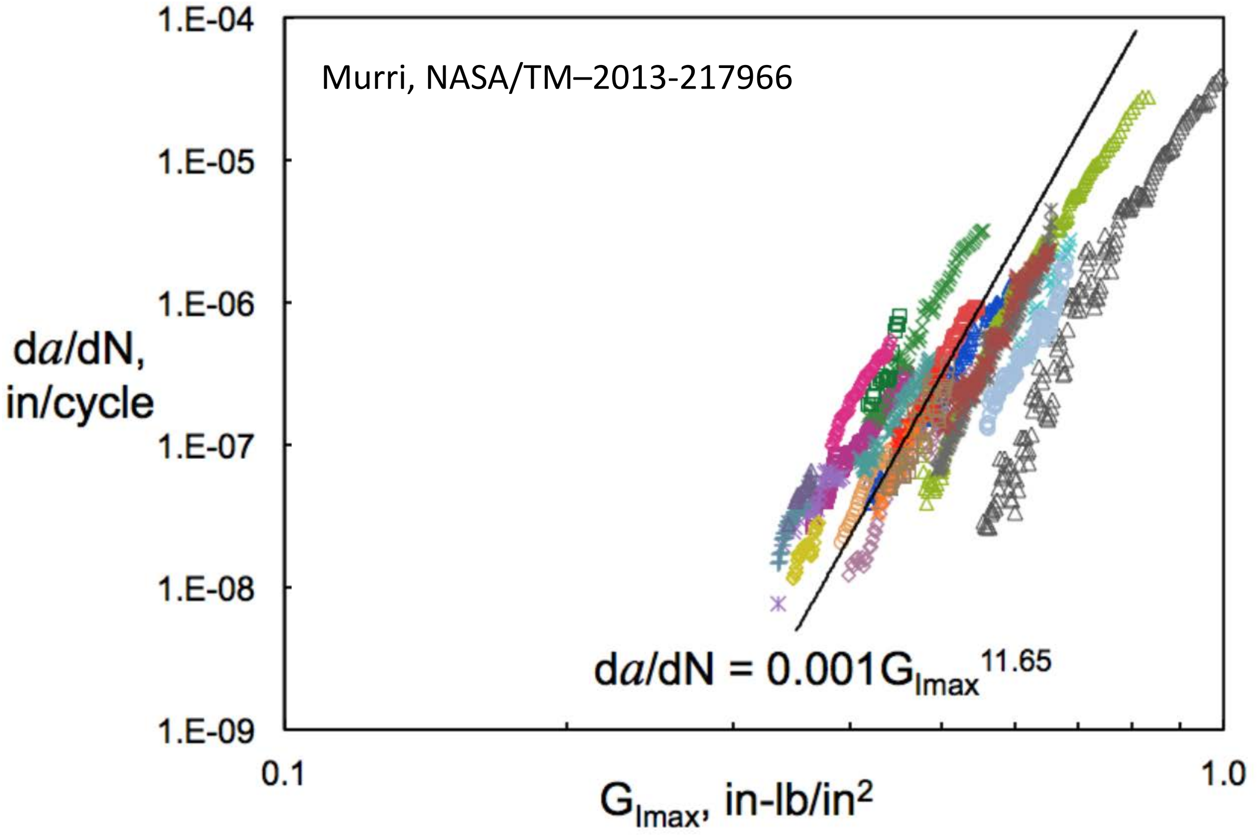


X-Ray Computed Tomography (CT)



Fatigue Propagation Rate Using the Paris Law

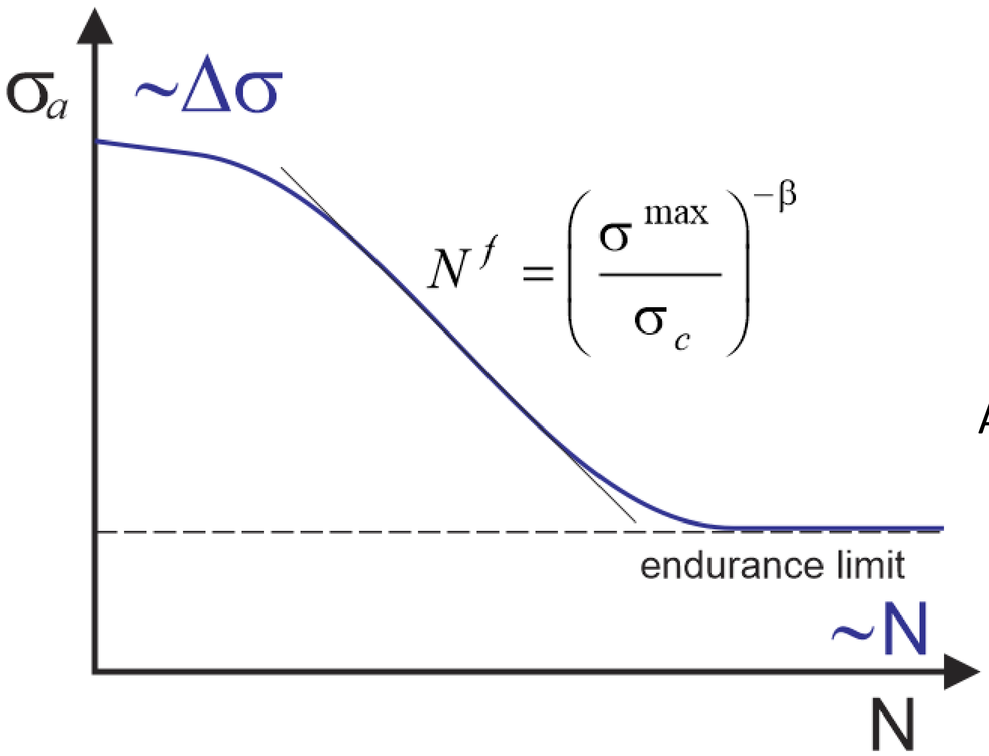
$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left(G_{\max}\right)^{m}$$



- Paris data is not useful for crack initiation.
- These tests are slow and expensive to conduct.
- R-curve effects produce multiple Paris laws.
- Tests must be conducted at different stress ratios R and mode mixities B.
- Implementation into a cohesive law is difficult.

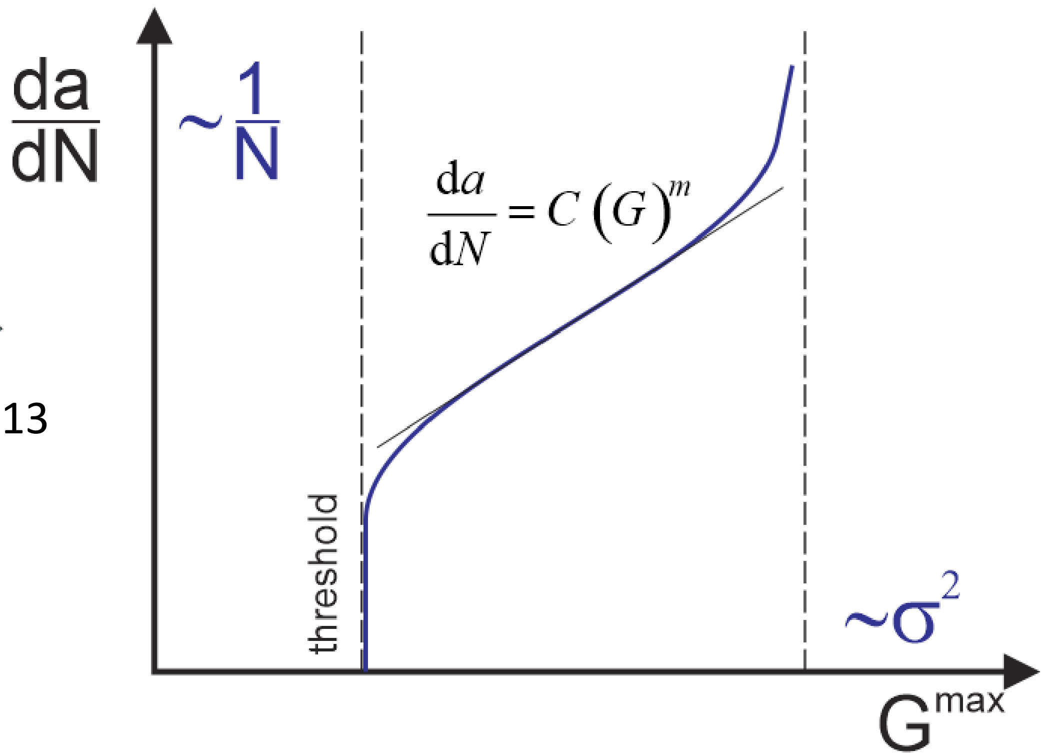
Fatigue: S-N or Paris Law?

S-N Curve



Allegri, 2013

Paris Law

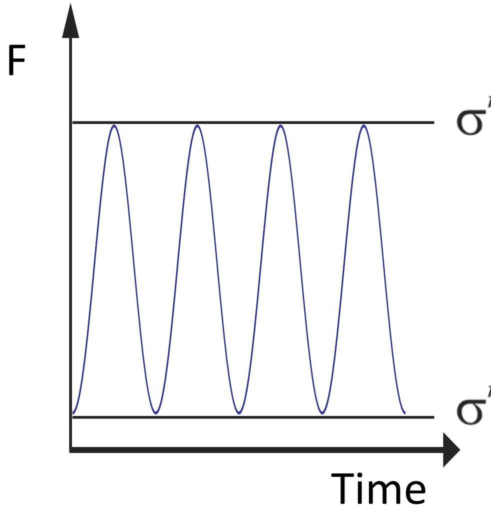


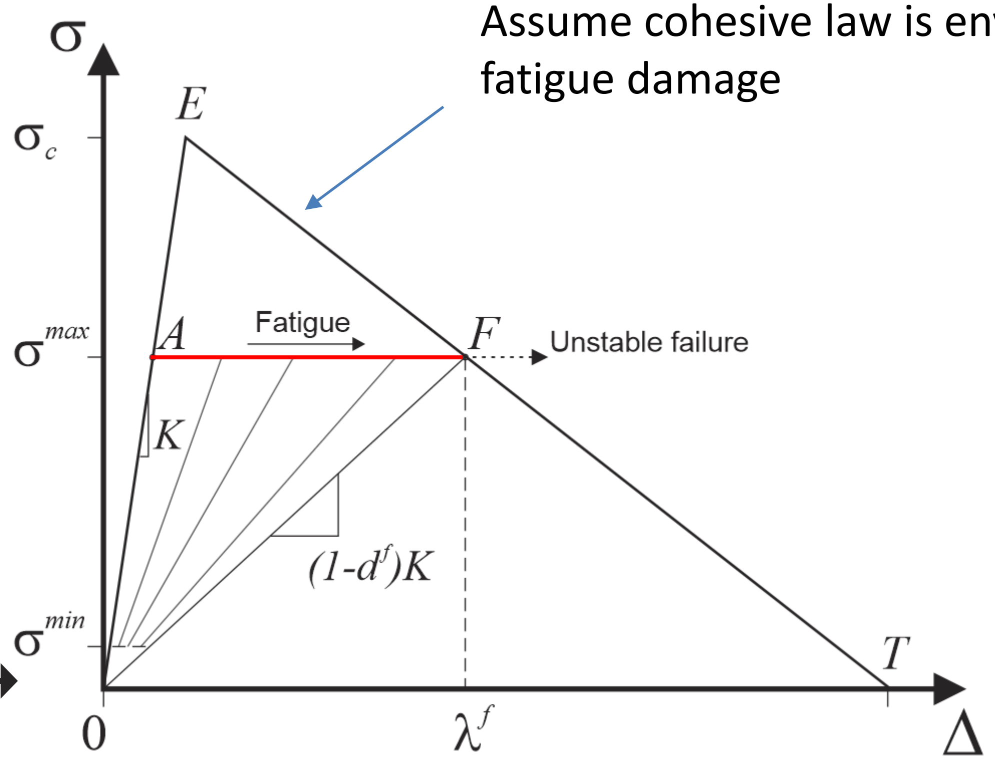
S-N Curve and Paris law are related: $\beta = 2m$

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

S-N Cohesive Fatigue Damage Model (Dávila 2020)

Consider case of bar subjected to cyclic load





Assume cohesive law is envelope of fatigue damage

What damage law?

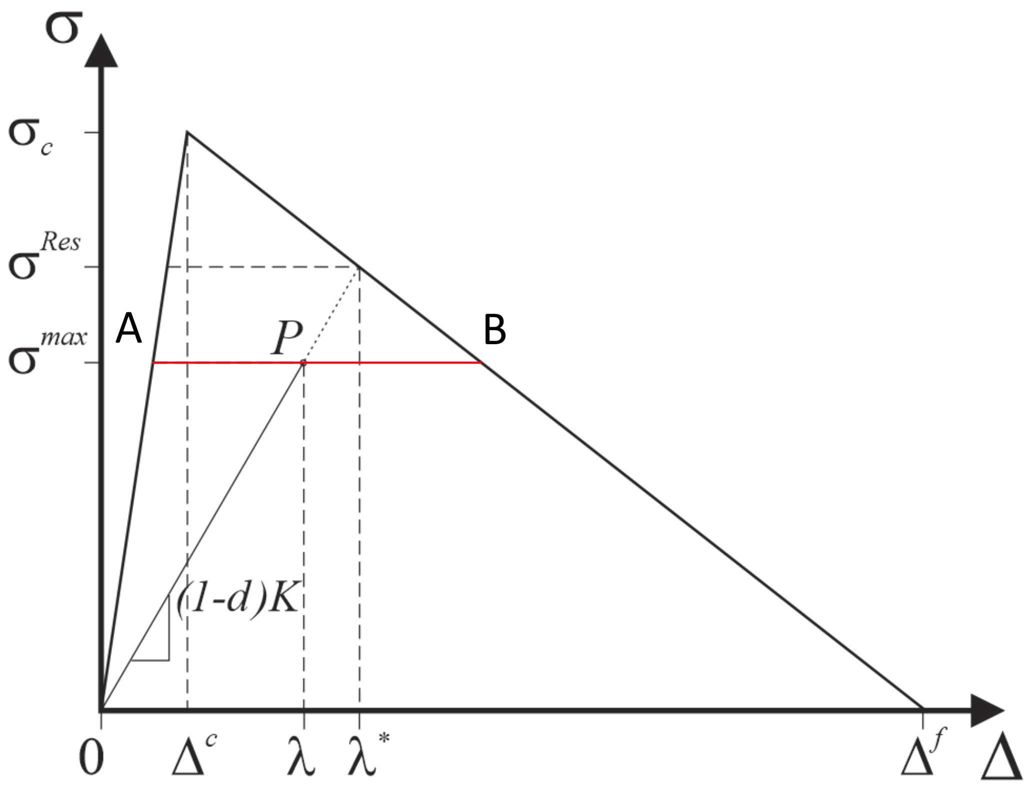
Cohesive Fatigue Damage Model (Dávila 2020)

Consider damage accumulation function at point P:

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

Dávila et al. NASA/TP–2020-220584

$$D = \frac{\lambda^* - \Delta^c}{\Delta^f - \Delta^c}$$



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

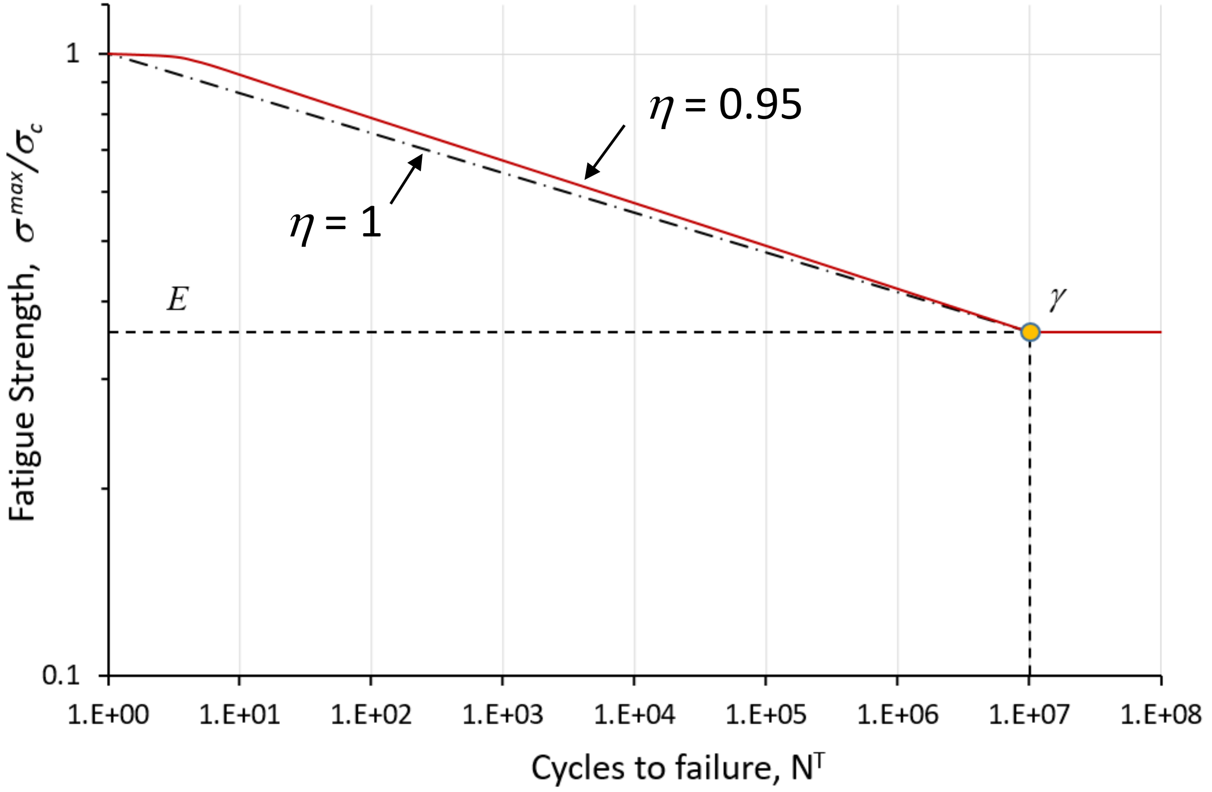
$$N^T = \gamma E^{\beta} \left(\frac{\sigma^{\max}}{\sigma_c}\right)^{-\beta} \left(1 - \left(\frac{\sigma^{\max}}{\sigma_c}\right)^{p+1}\right) + 1$$

≈ 1

S-N curve

Determination of Damage Model Parameters

$$N^T \approx \gamma E^{\beta}\left(\frac{\sigma^{\max}}{\sigma_c}\right)^{-\beta} + 1$$



Endurance (Goodman diagram)

$$E = \frac{\sigma_e^{max}}{\sigma_c} = \frac{2C_L\varepsilon}{C_L\varepsilon + 1 + \left(C_L\varepsilon - 1\right)R}$$

Endurance @ R=-1

Stress ratio

(Mixed-mode correction)

$$C_L = 1 - 0.42\,B$$

Mode mixity

$$\beta = \frac{-7\eta}{\log E}$$

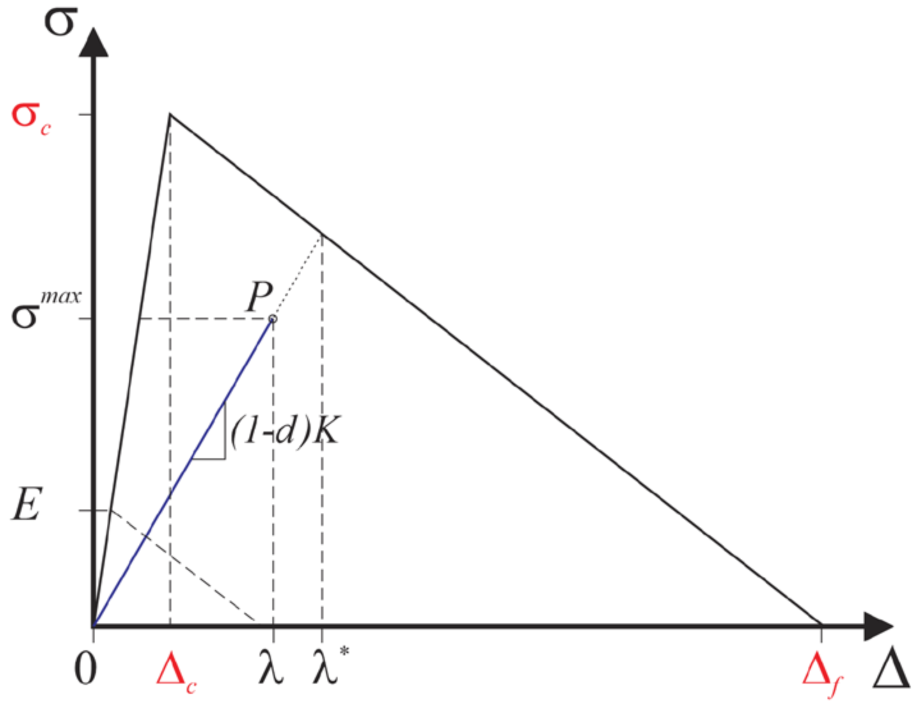
Brittleness

Damage model entirely defined by parameters η, ε, and p

Affects slope of S-N and Paris law

Affects pre-factor "C" of Paris law

UMAT Subroutine



$D, \lambda, \Delta N$

QS mixed-mode parameters

$\sigma_c, K, \Delta_c, \Delta_f$ (Turon)

Quasi-static tearing damage

$$D^T = \frac{\lambda - \Delta_c}{\Delta_f - \Delta_c}$$

Update damage

$$D = Max\left(D^T; D\right)$$

Loss of constitutive stiffness

$$1-d = \frac{(1-D)\Delta_c}{D\,\Delta_f + (1-D)\Delta_c}$$

$D, (1-d)$

Fatigue damage

Fatigue parameters

$$E = \frac{2C_L\,\varepsilon}{C_L\,\varepsilon + 1 + (C_L\,\varepsilon - 1)R} \qquad \beta = \frac{-7\eta}{\log E}$$

Relative displacement jump

$$\frac{\lambda}{\lambda^*} = \frac{\lambda}{D\,\Delta_f + (1-D)\Delta_c}$$

Calculate incremental fatigue damage

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

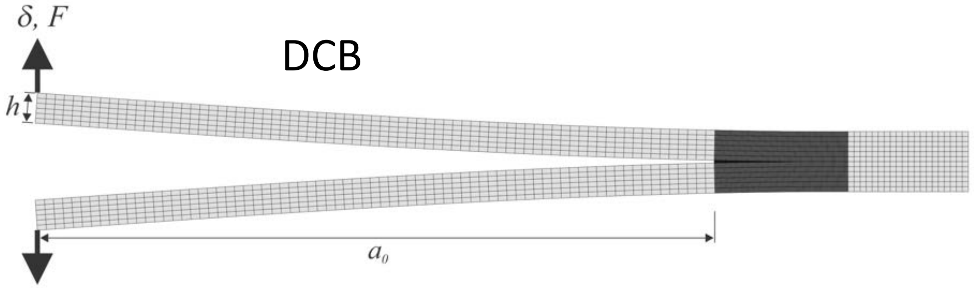
Update damage with fatigue

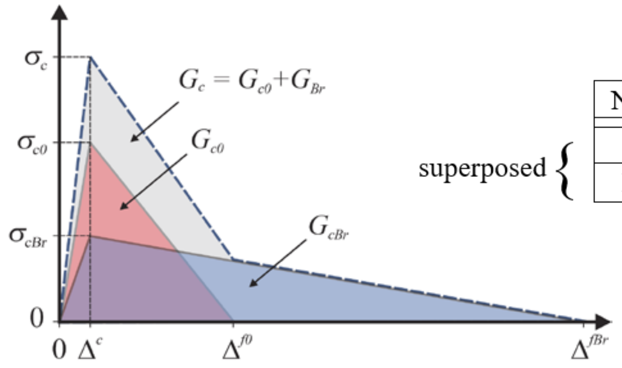
$$D^{fat} = D + \Delta D$$

Update damage

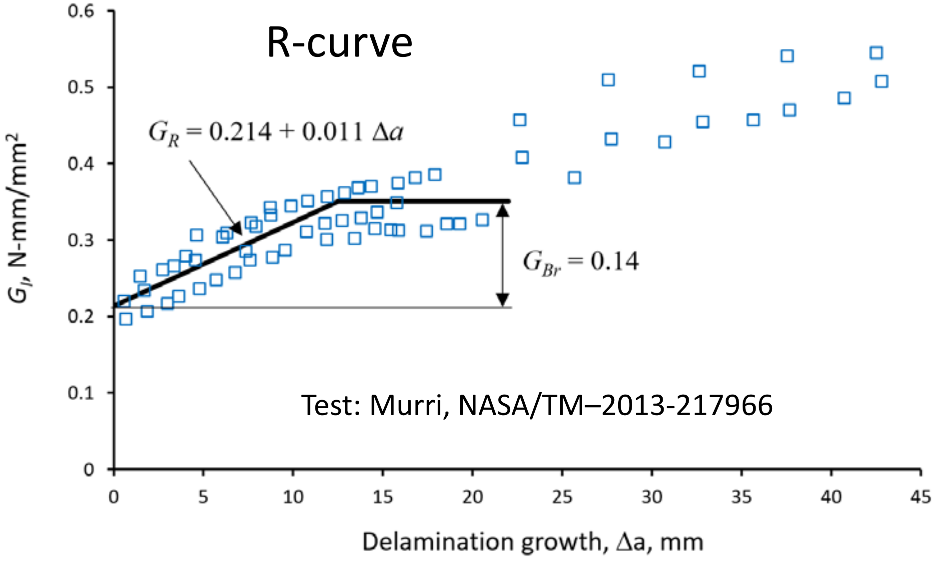
$$D = Max\left(D^T; D^{fat}\right)$$

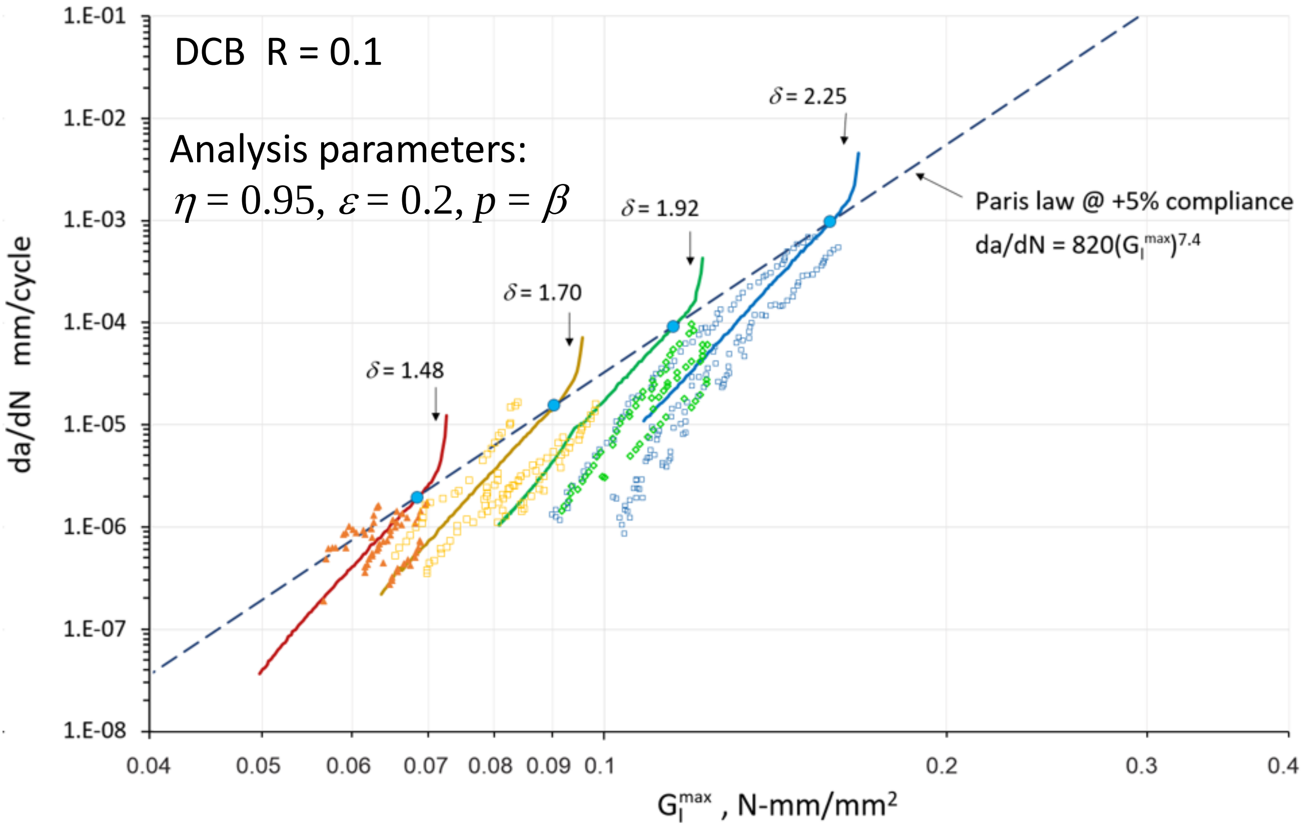
R-Curve Effects





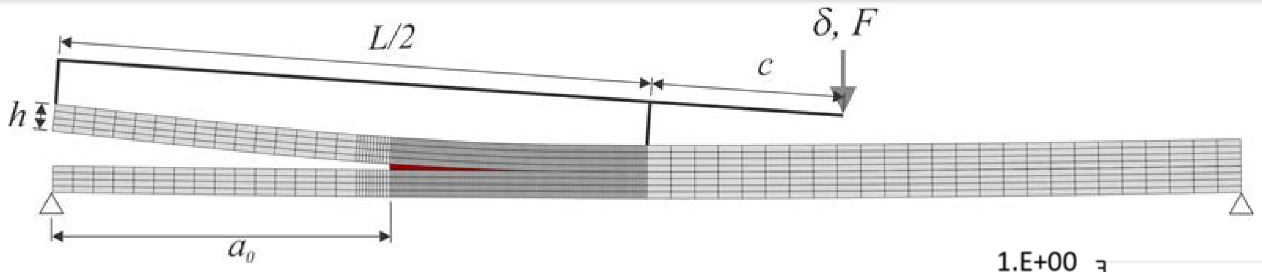
	G_c (N/mm)	σ_c (MPa)	K (N/mm³)
Nominal	0.240	80.1	2. 10⁵
superposed { Base	0.214	80.1	2. 10⁵
superposed { Bridge	0.140	0.8	2. 10³



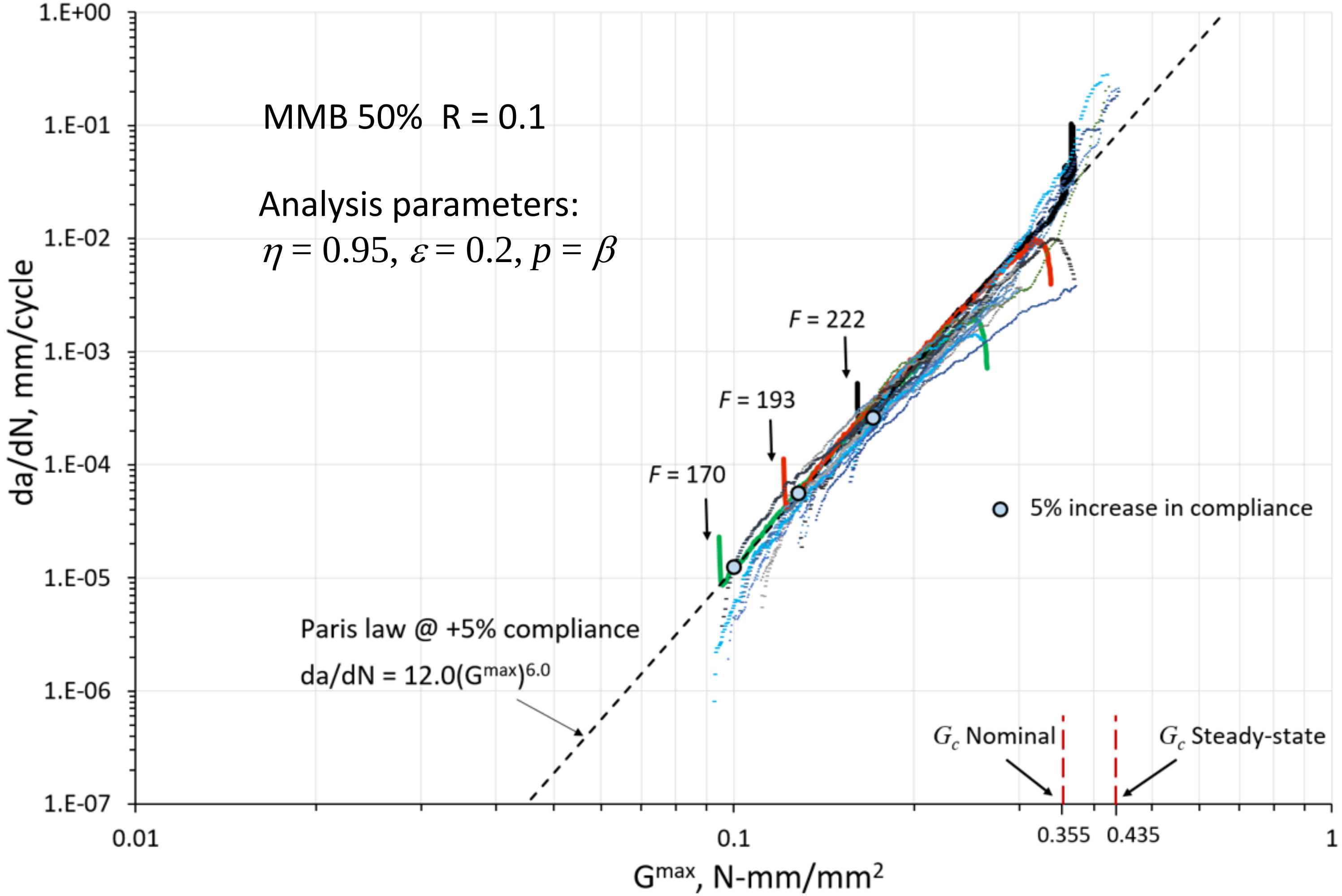


R-curve is capture by superposing two layers of elements with bilinear cohesive laws.

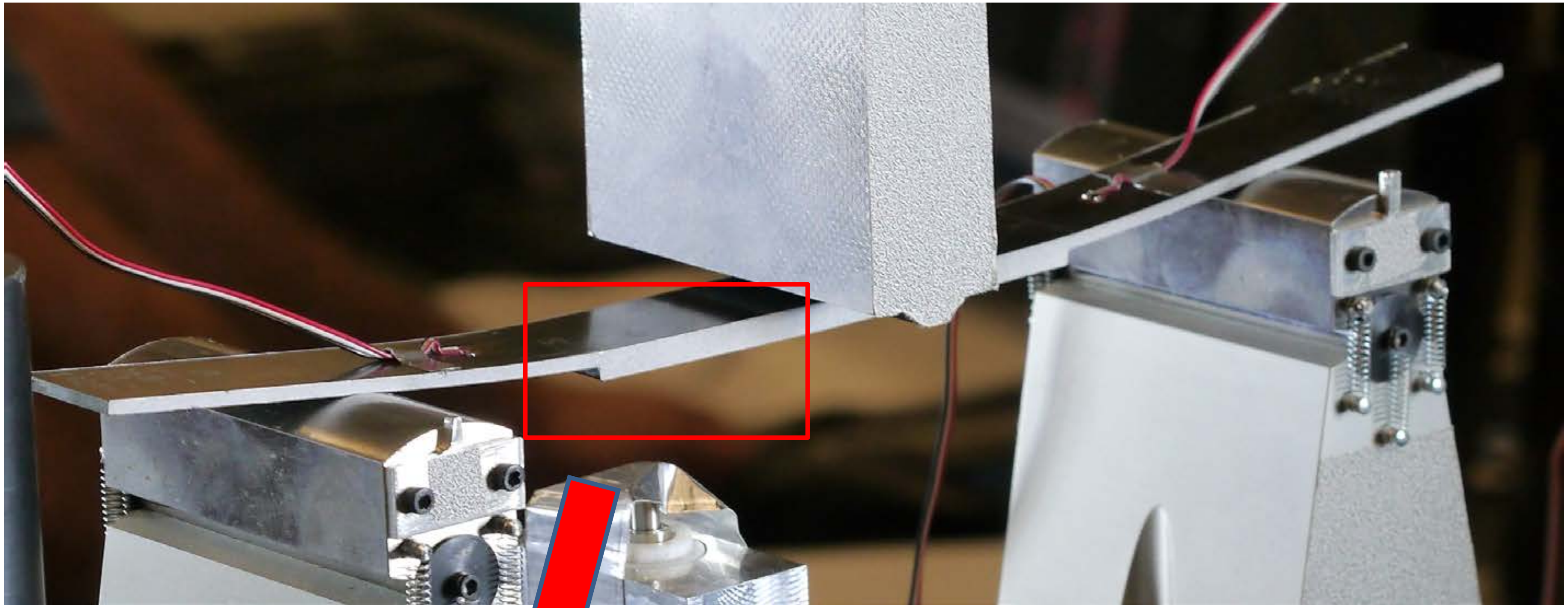
Example 1 – Prediction of MMB Test

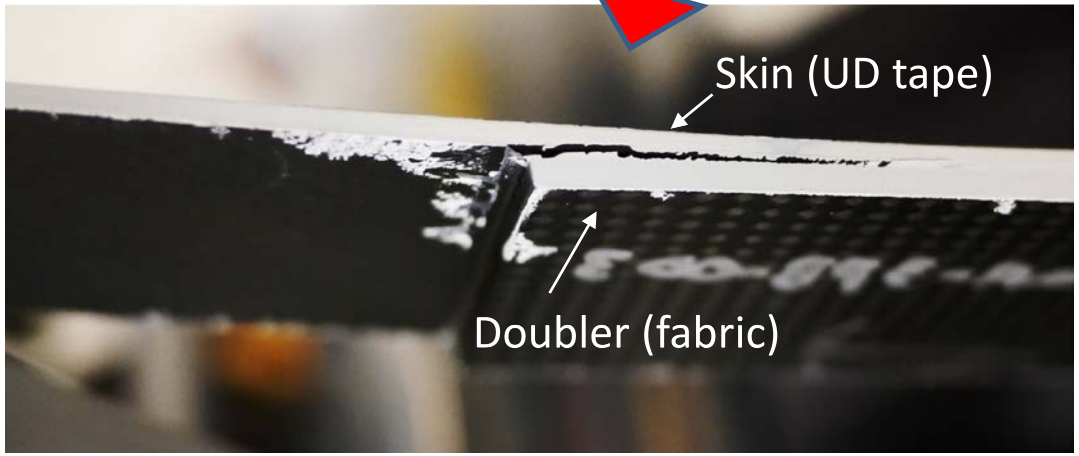


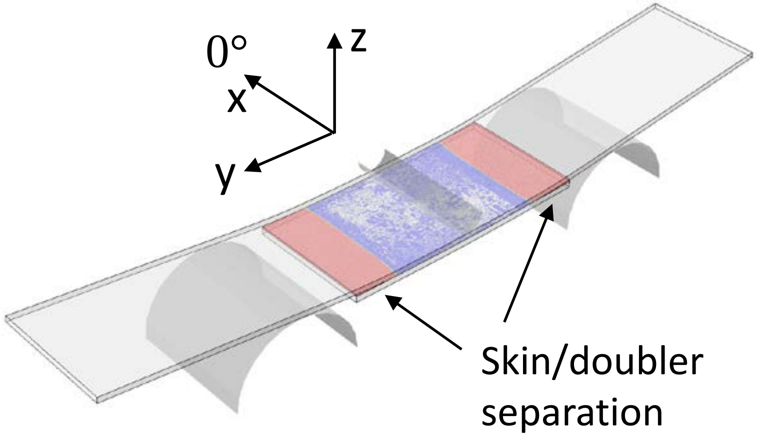
Test conducted under force control. R = 0.1



Three Point Bend (3PB) Doubler Specimen

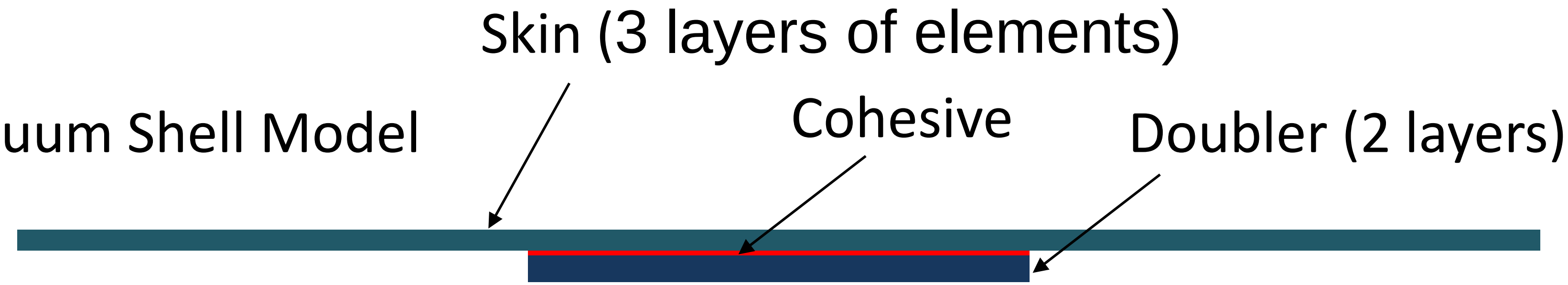




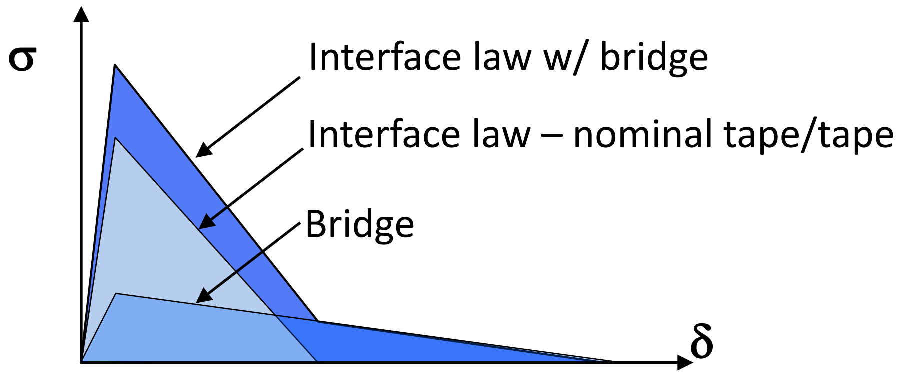


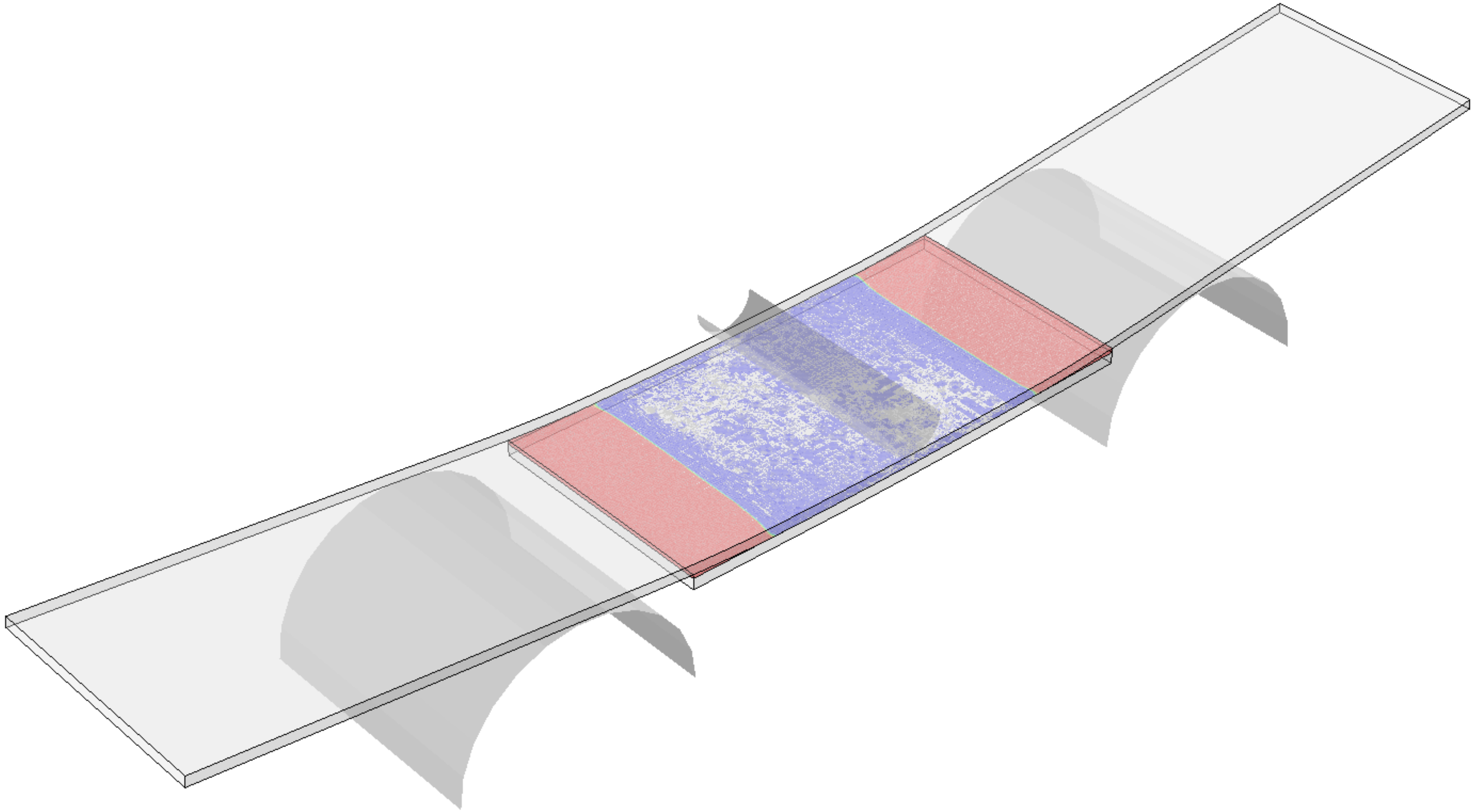
Simplified Shell Model of 3PB Specimen

Continuum Shell Model



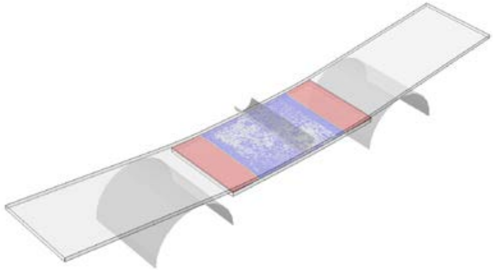
Empirical cohesive properties capture the effects of all damage mechanisms



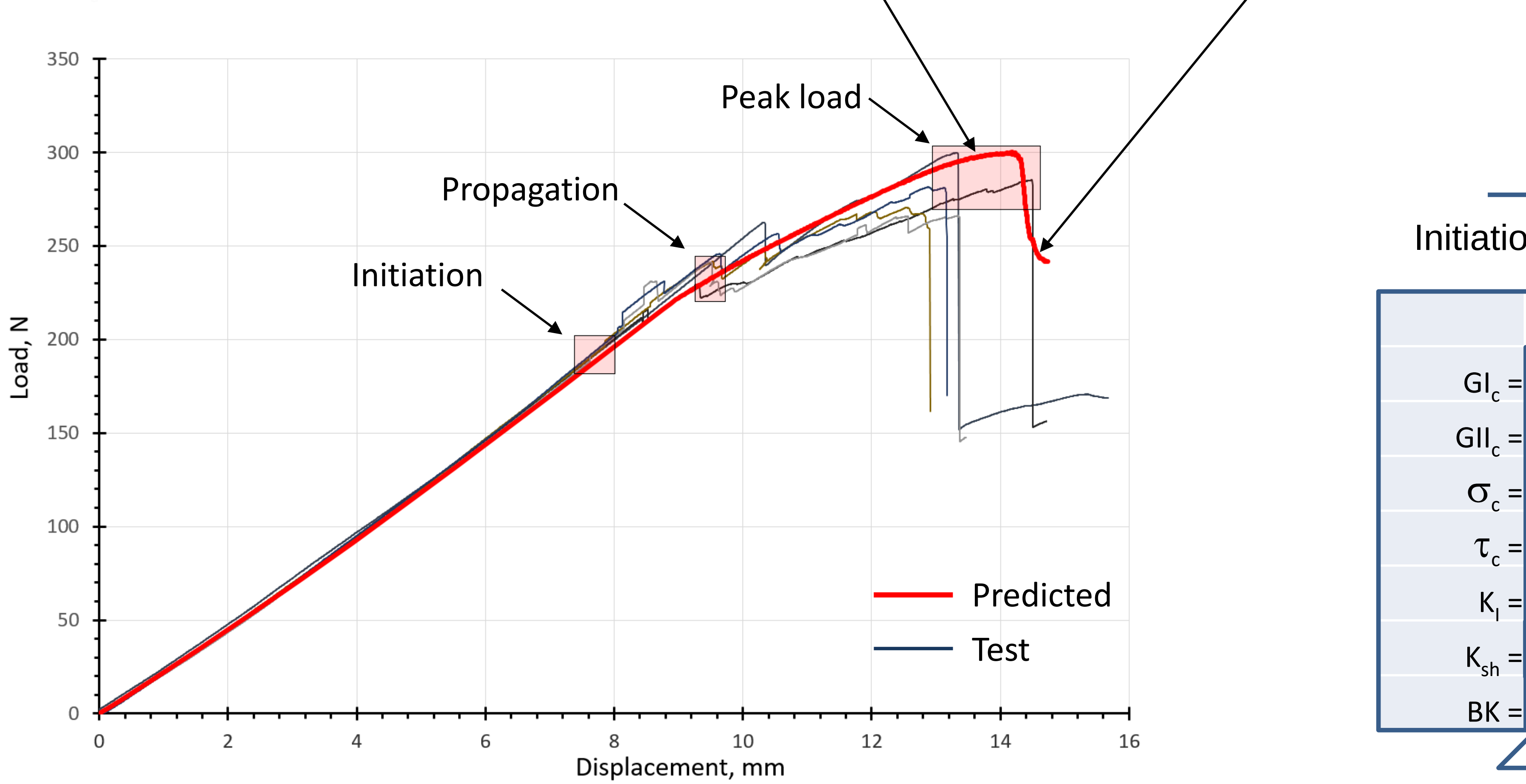


Simplified Shell Model of 3PB Specimen

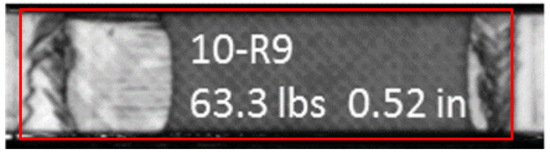
Shell Model



Before peak load
(symmetric)
After peak load
(unsymmetric)



Test



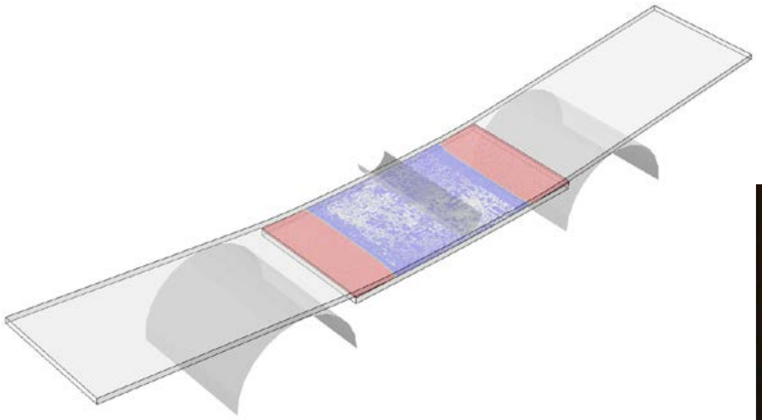
Analysis

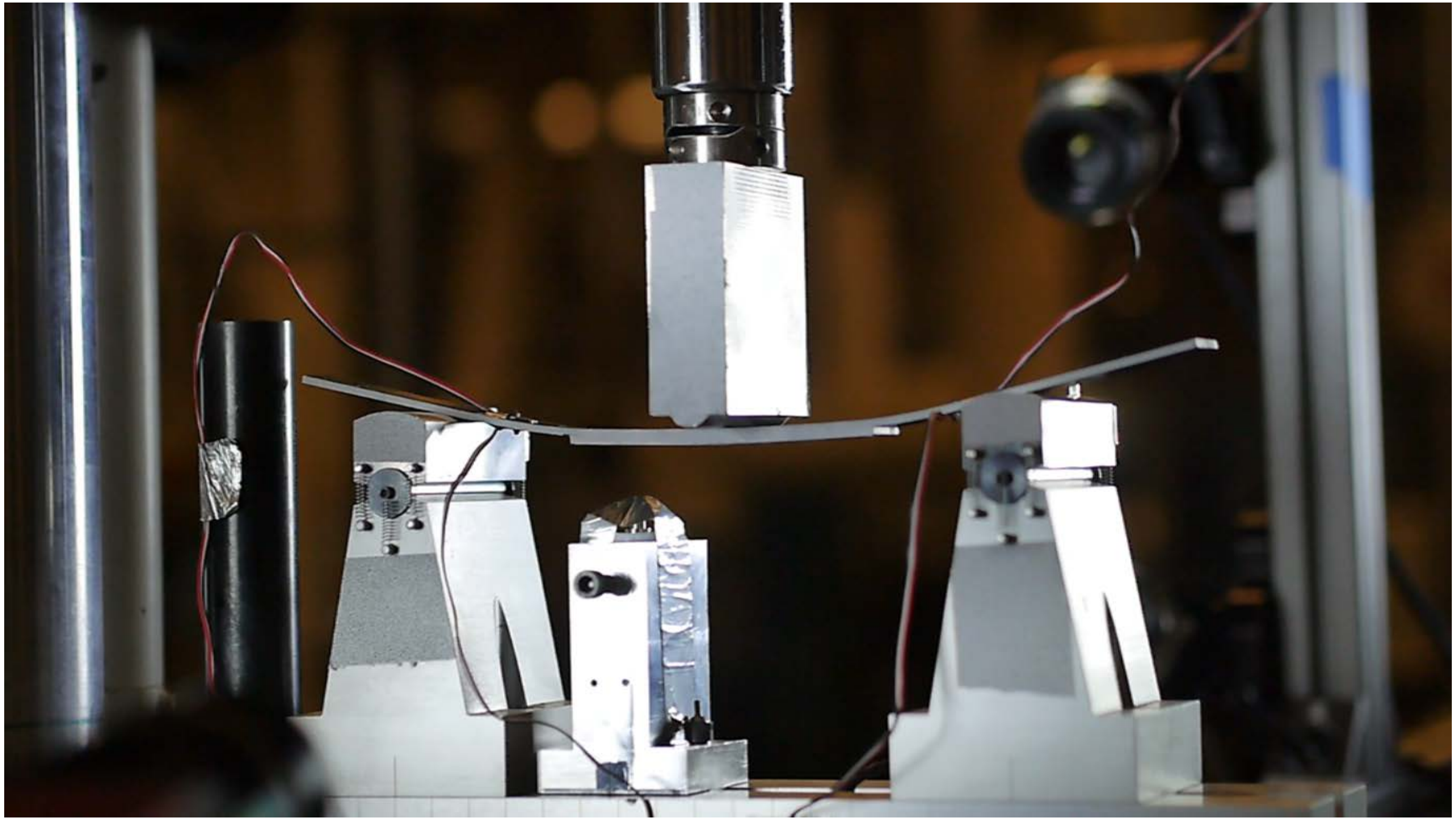
Initiation → Base; Propagation → Bridge

	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	

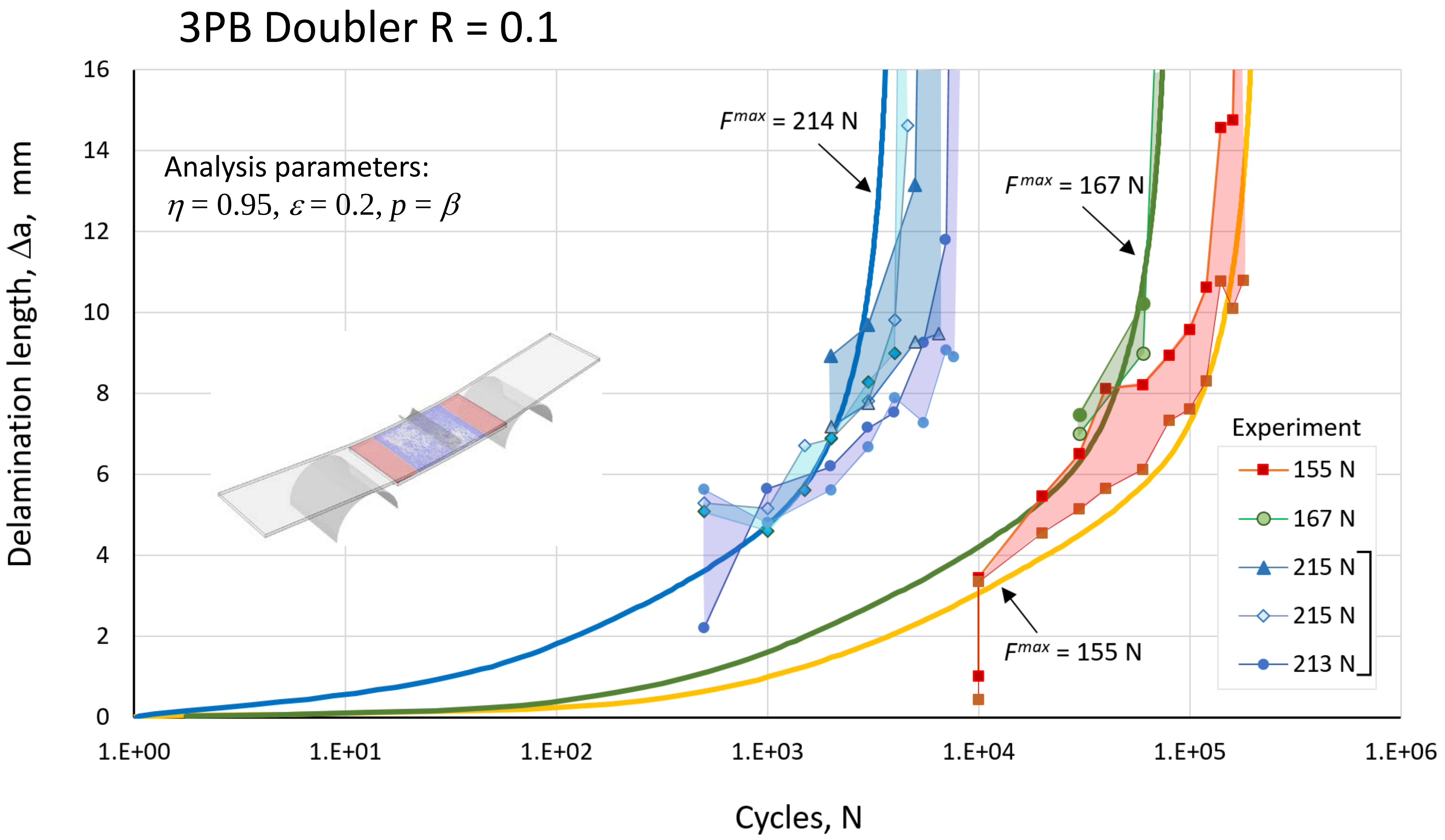
Computed (Turon's constraints)

3PB Fatigue – Experimental Results

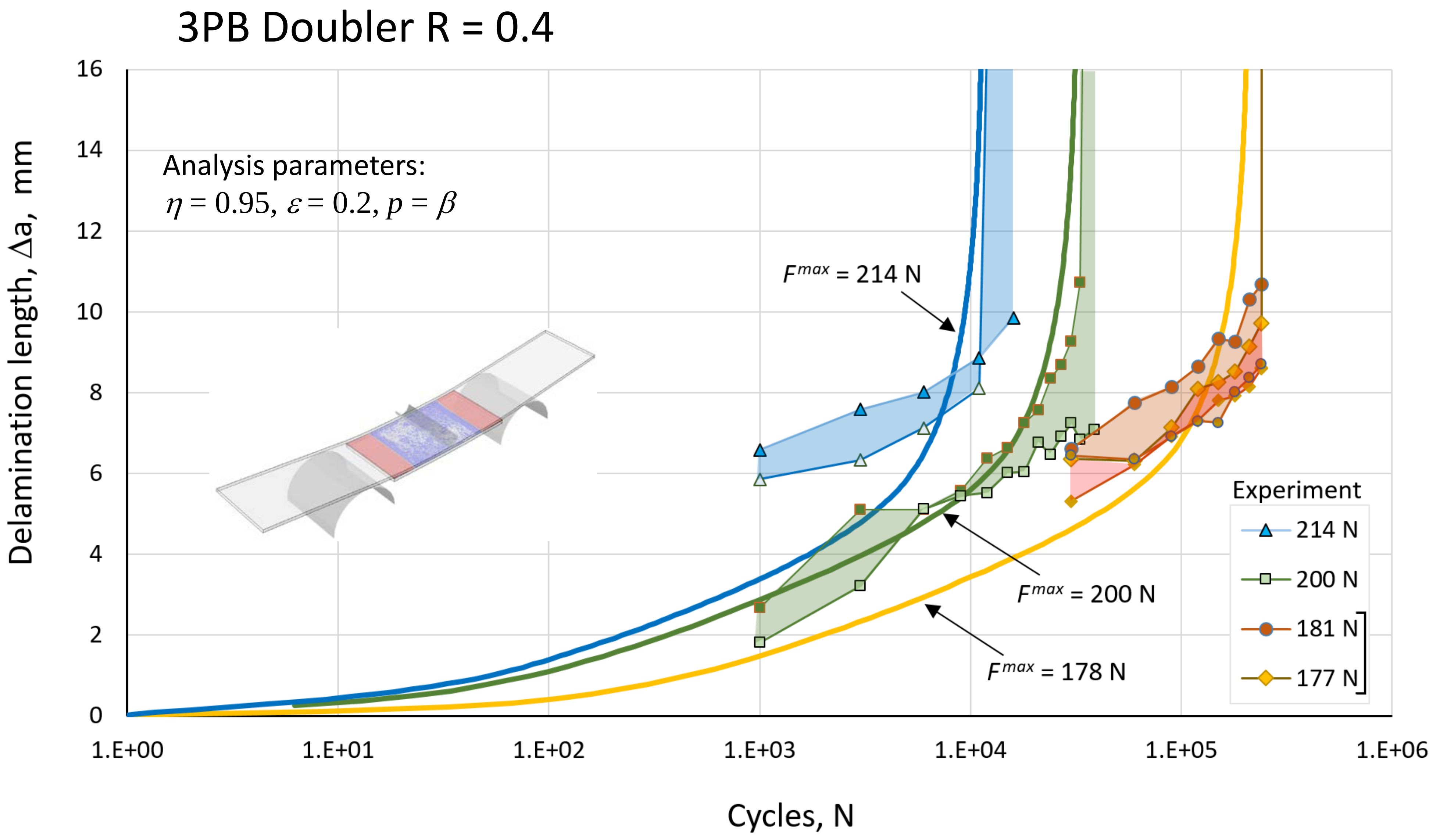




Delamination length in 3PB Doubler



Delamination length in 3PB Doubler



Concluding Remarks

Fatigue Cohesive Constitutive Model:

- Based on S-N curve rather than Paris law.
- Relies on relationship between S-N and Paris.
- Simplified loading procedure keeps load constant during analysis.
- Fatigue model parameters obtained from DCB test data.
- Same fatigue parameters were used in all analyses ($\eta = 0.95$, $\varepsilon = 0.2$, $p = \beta$).
- **Very simple to implement on top of a UMAT of a bilinear cohesive law**

R-Curve Effects Modeled Using Cohesive Superposition

- R-curve is intended to capture effect of blunting, delving, bridging, and migrations.
- Shift in Paris lines is predicted.

Skin/Stiffener Spearation: 3PB Doubler Test

- Specimen is initially pristine.
- Interface characterized by quasi-static R-curve.