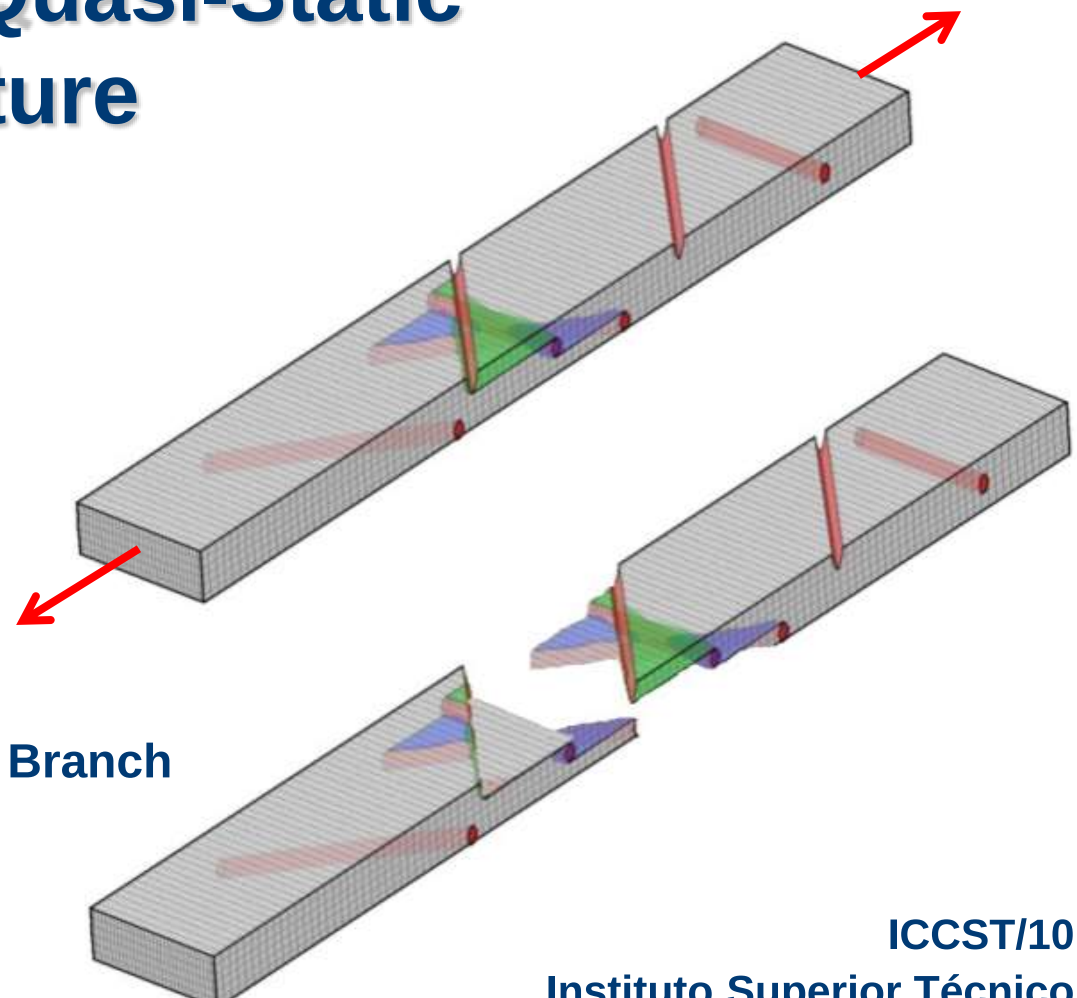
Damage Instability and Transition from Quasi-Static to Dynamic Fracture



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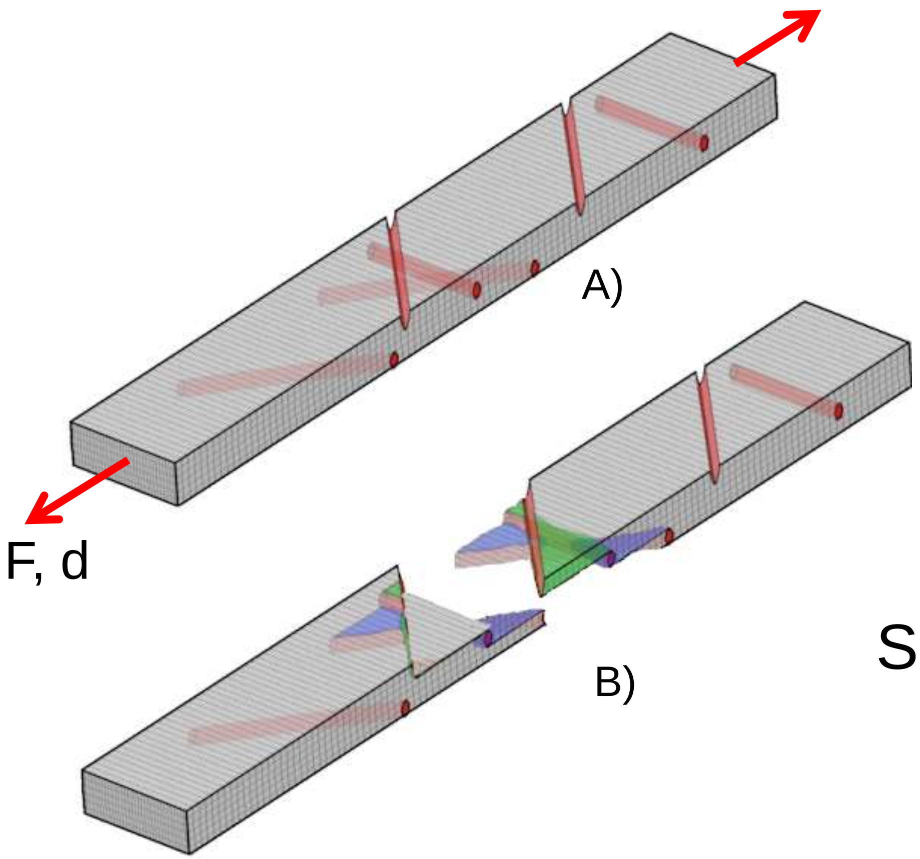
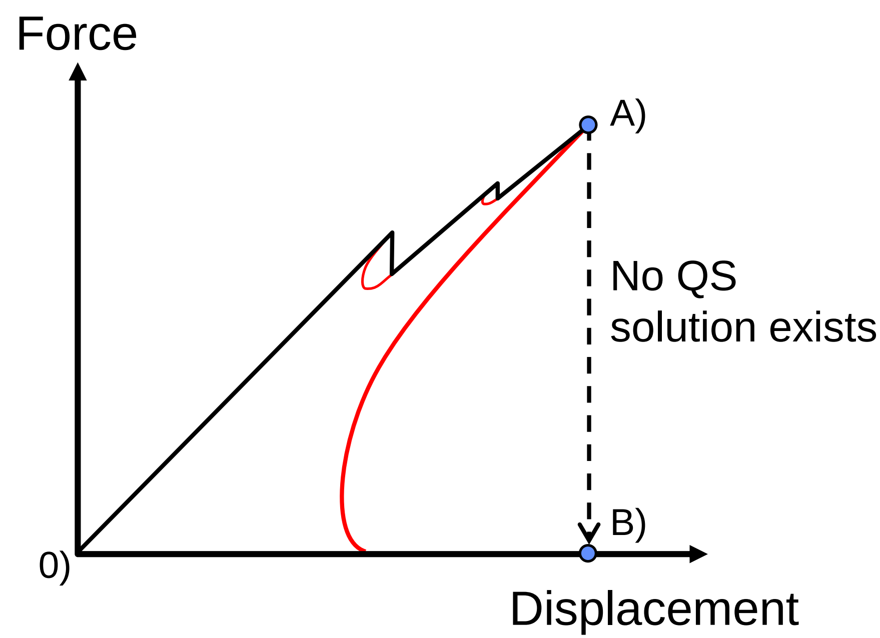
Lisbon, Portugal, 2-4 September 2015

Quasi-Static Loading and Rupture

Loading Phases:

- 0) to A) – Quasi-static (QS) loading
- A) to B) – Dynamic response



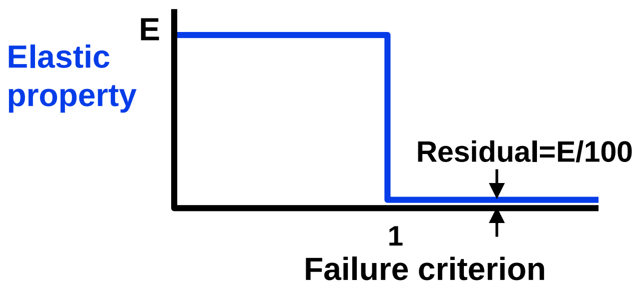


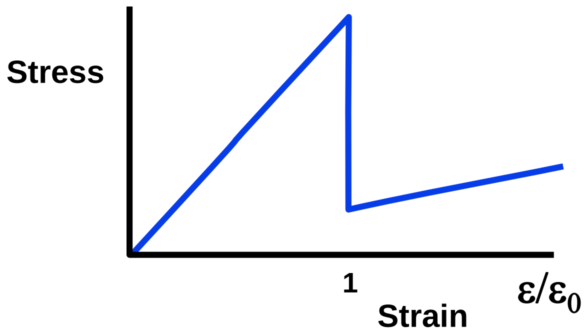
Snapback behavior:

- More strain energy available than necessary for fracture

Failure Criteria and Material Degradation

Progressive Failure Analysis



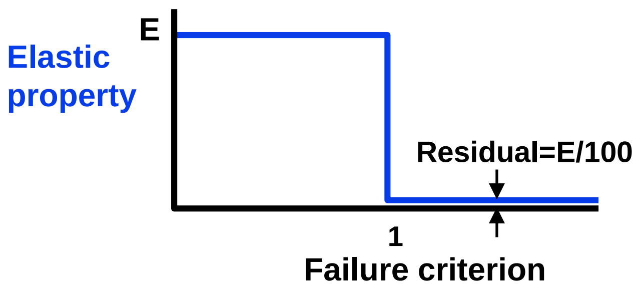


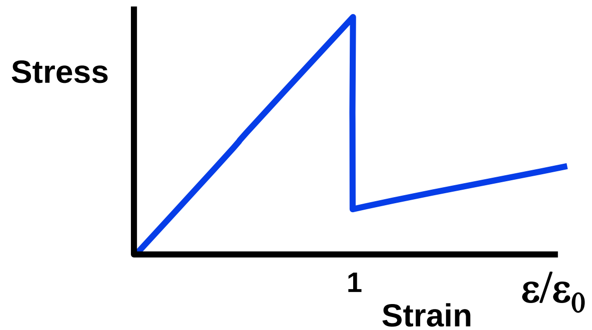
Benefits
- Simplicity (no programming needed)
- Convergence of equilibrium iterations

Drawbacks
- Mesh dependence
- Dependence on load increment
- Ad-hoc property degradation
- Large strains can cause reloading
- Errors due to improper load redistributions

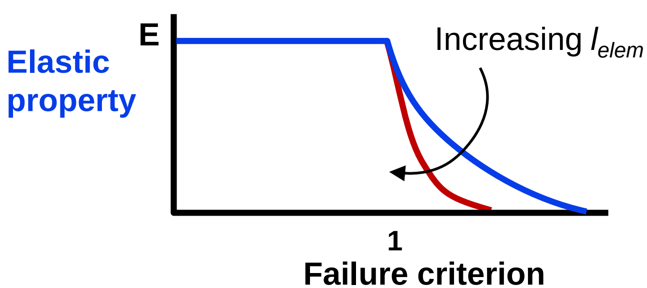
Failure Criteria and Material Degradation

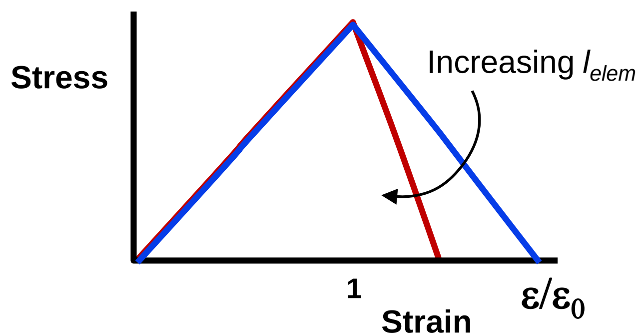
Progressive Failure Analysis



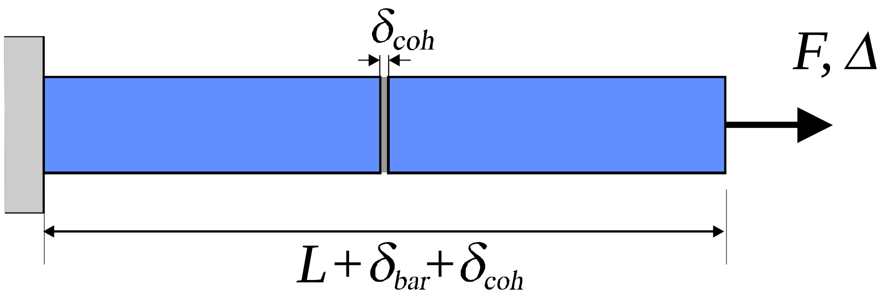


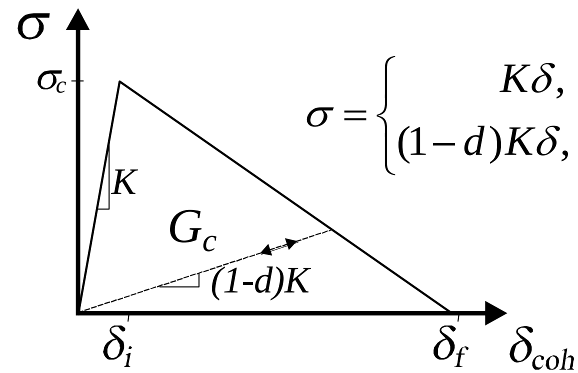
Progressive Damage Analysis – Regularized Softening Laws





Strength-Dominated Failure





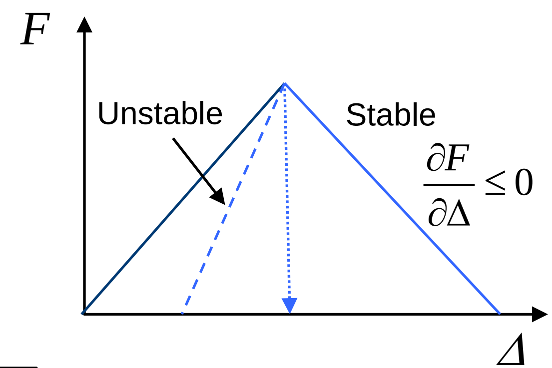
$$\sigma = \begin{cases} K\delta, & \delta < \delta_i \\ (1-d)K\delta, & \delta_i \le \delta < \delta_f \end{cases}$$

Before damage

$$F = A\sigma = EA\frac{\Delta}{L + \dfrac{E}{K}}$$

After damage

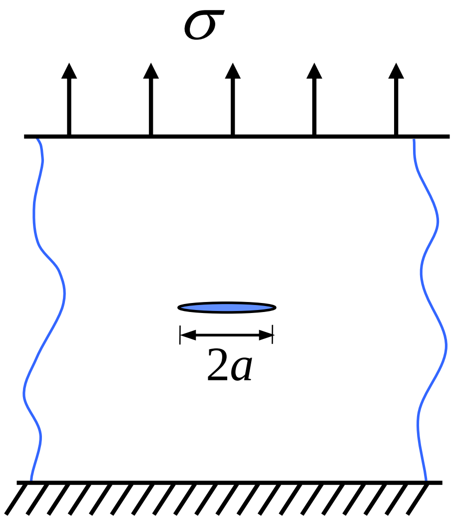
$$F = A\sigma = EA\frac{\Delta - \dfrac{2G_c}{\sigma_c}}{L - \dfrac{2EG_c}{\sigma_c^2} + \dfrac{E}{K}}$$



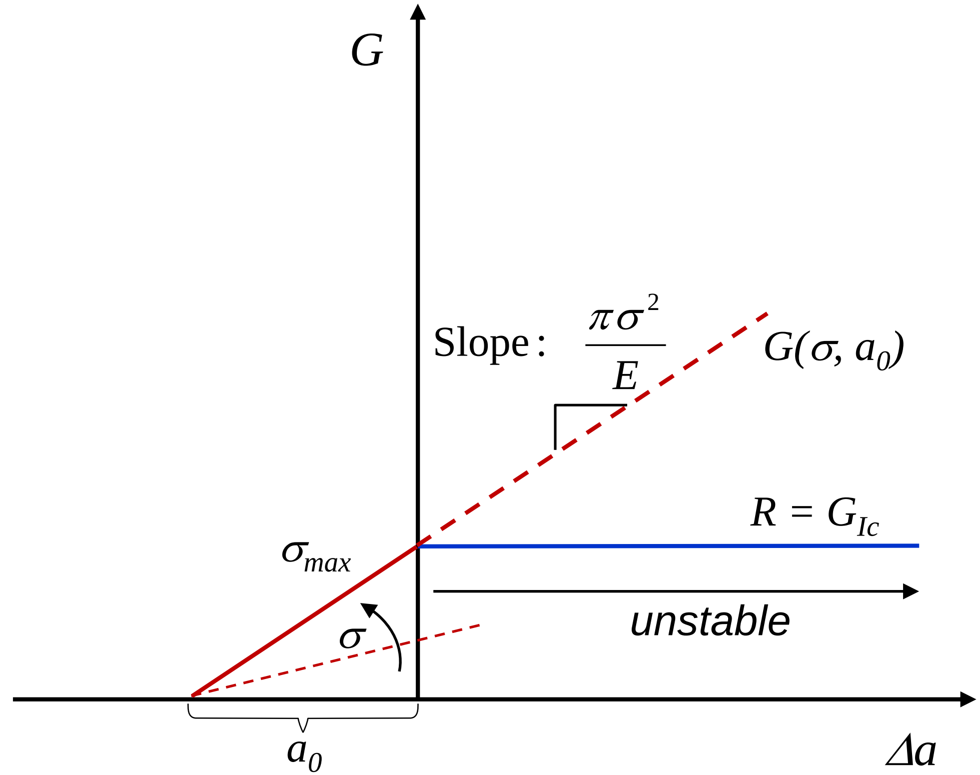
For <u>stable</u> fracture under Δ control: $\dfrac{\partial F}{\partial \Delta} \le 0$ ⇨ $\boxed{L \le \dfrac{2EG_c}{\sigma_c^2}}$

For “long” beams, the response is <u>unstable</u>, dynamic, and independent of Gc

Fracture-Dominated Failure

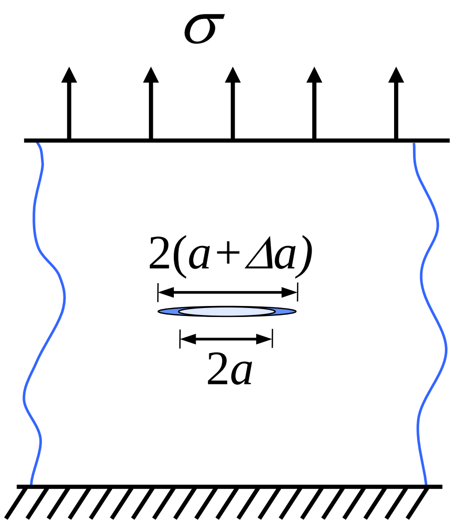


$$G = \frac{\pi \sigma^2 a}{E}$$

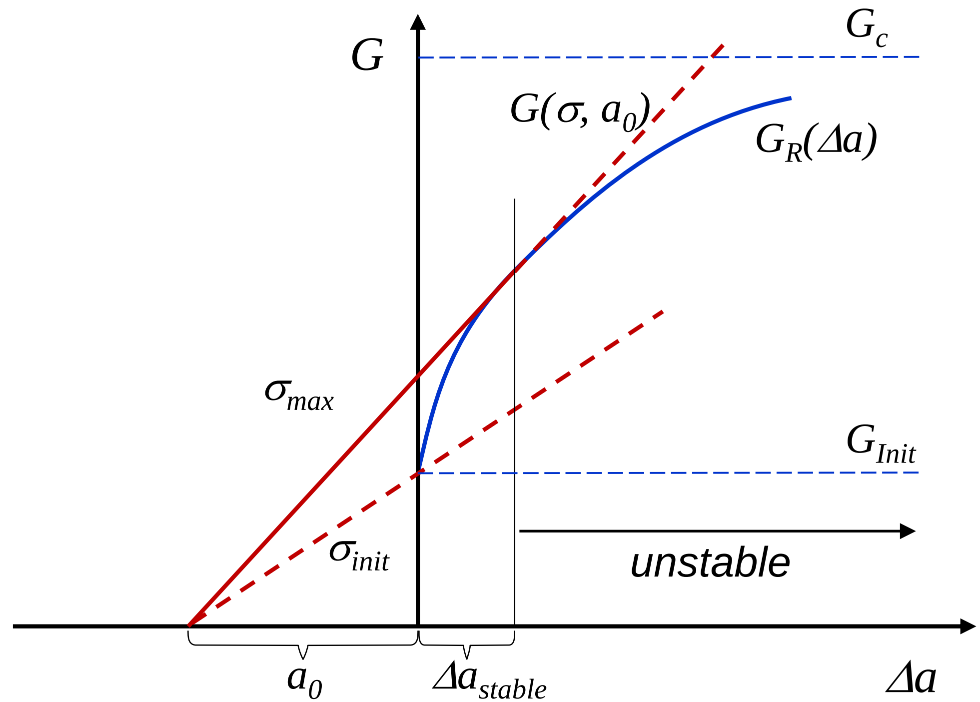


Crack propagates unstably once driving force $G(\sigma, a_0)$ reaches G_{Ic}

Fracture-Dominated Failure



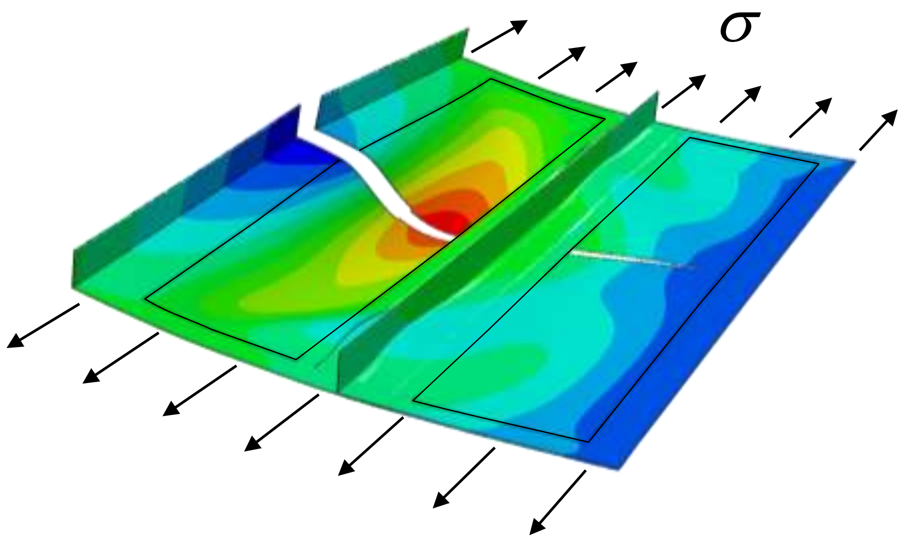
$$G = \frac{\pi \sigma^2 a}{E}$$

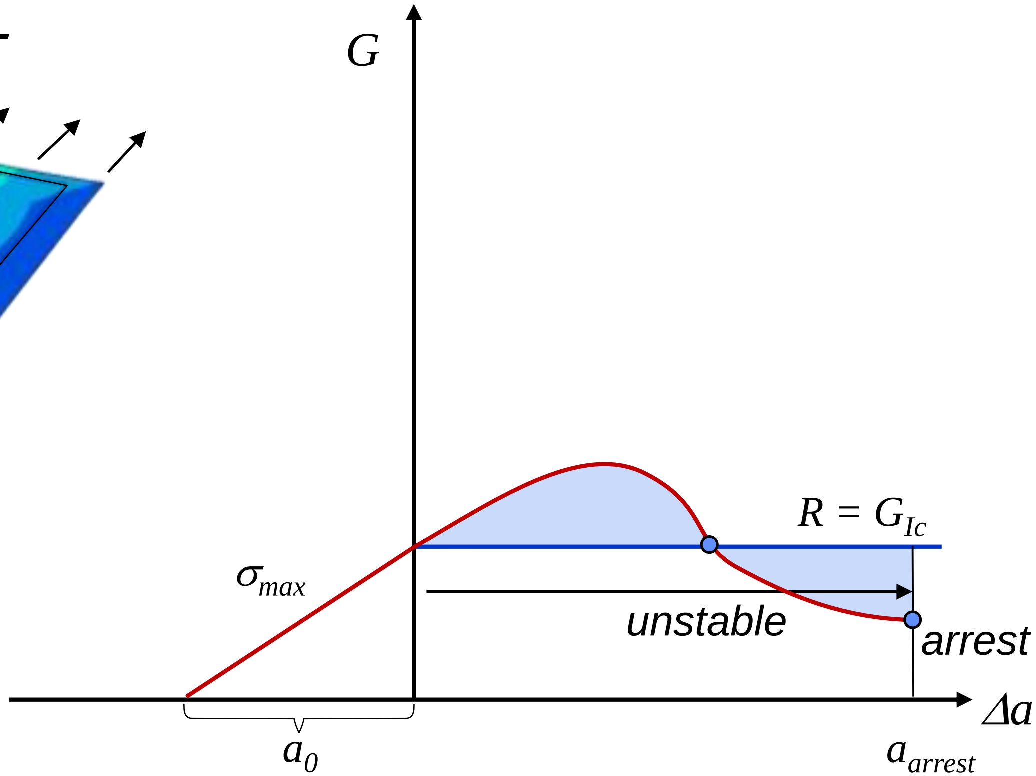


Crack propagates stably when driving force $G(\sigma, a_0) > G_{Init}$

Unstable propagation initiates at $G_{Init} < G \leq G_c$

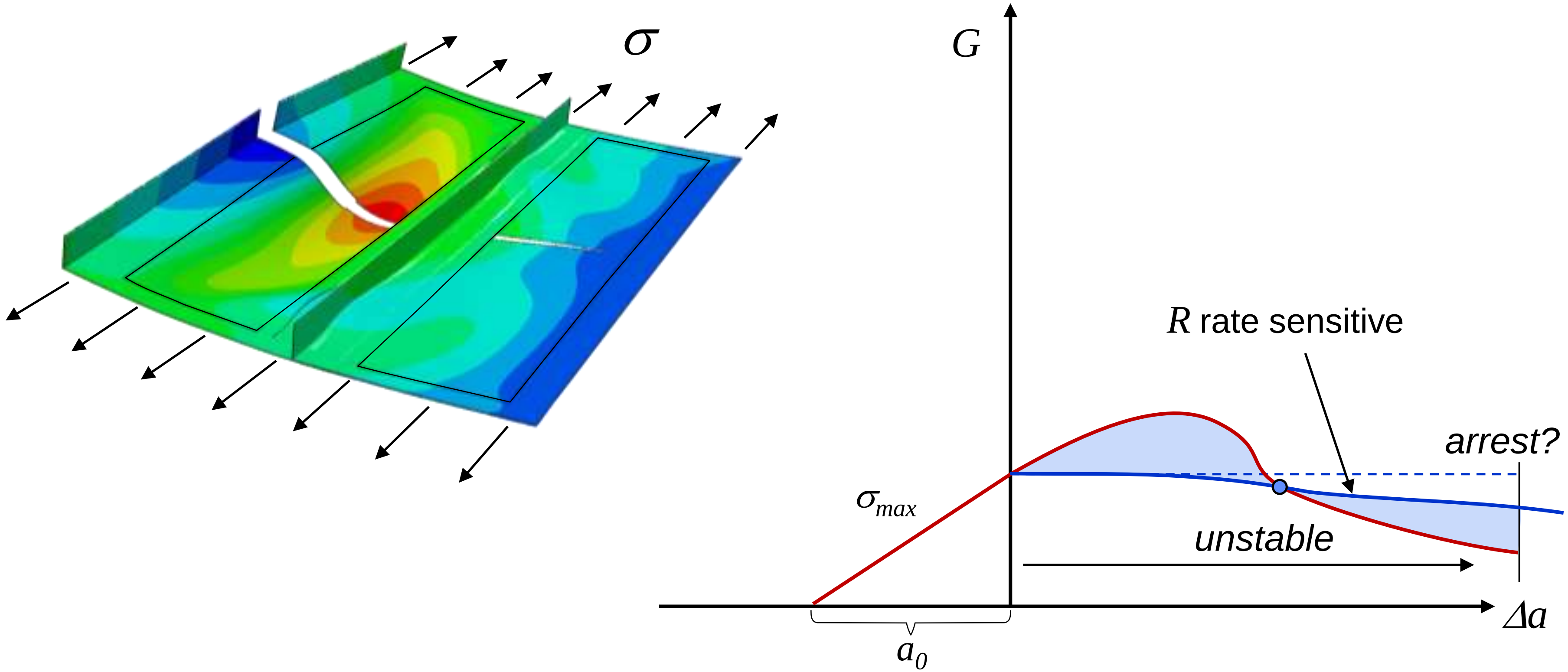
Mechanics of Crack Arrest





Crack arrest due to decreasing *G*

Mechanics of Crack Arrest



Large strain rates often result in lower fracture toughness and delayed arrest

Griffith Criterion and Stability

Griffith growth criterion

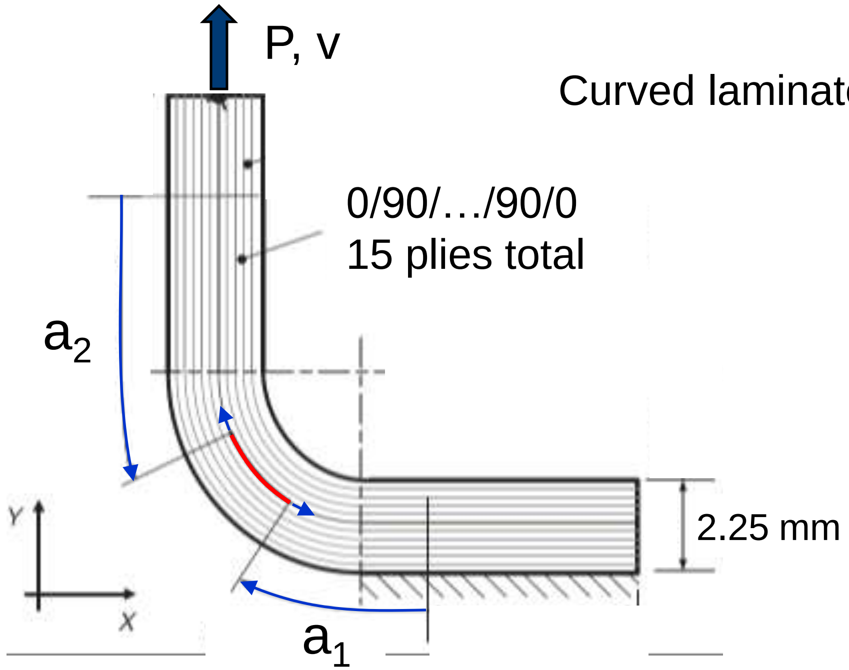
$$\frac{\partial \Pi_{\text{total}}}{\partial a_i} = \frac{\partial(\Pi_{\text{int}} + \Pi_{\text{ext}})}{\partial a_i} + G_{c,i} = \begin{cases} > 0 & \text{no growth} \\ 0 & \text{equilibrium growth} \\ < 0 & \text{dynamic growth} \end{cases}$$

Stability of equilibrium propagation

$$\frac{\partial^2 \Pi_{\text{total}}}{\partial {a_i}^2} = \begin{cases} > 0 & \text{stable} \\ < 0 & \text{unstable} \end{cases}$$

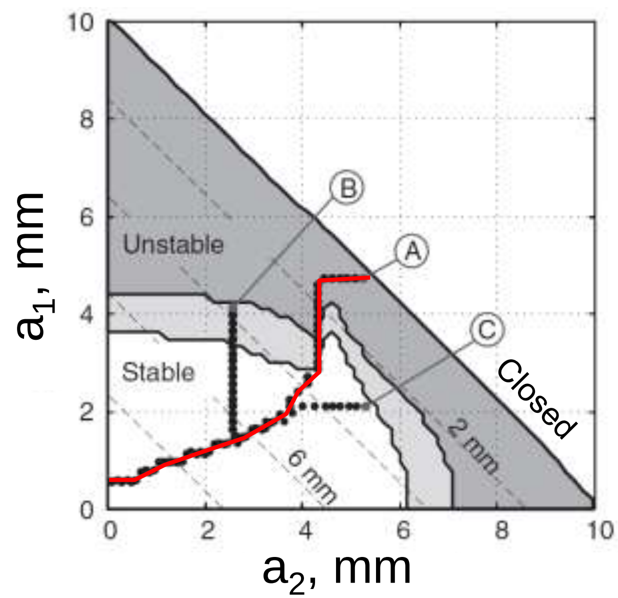
Wimmer & Pettermann
J of Comp. Mater, 2009

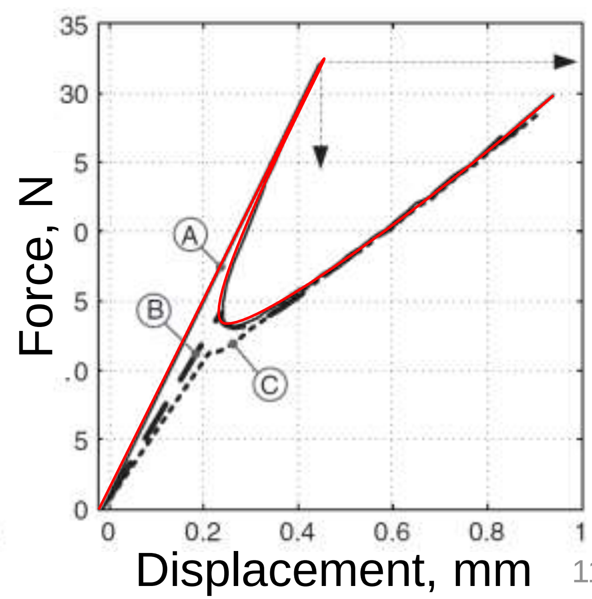
Stability of Propagation with Multiple Crack Tips



Curved laminate with through-the-width delamination

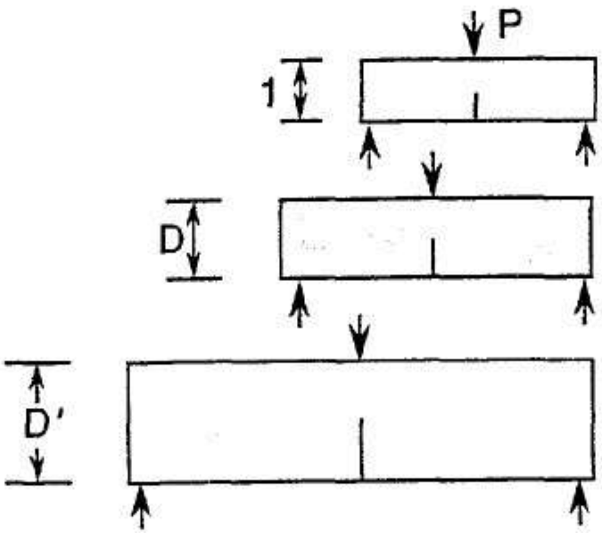
$$\frac{\partial^2 \Pi_{\text{total}}}{\partial a_i^2} = \begin{cases} > 0 & \text{stable} \\ < 0 & \text{unstable} \end{cases}$$



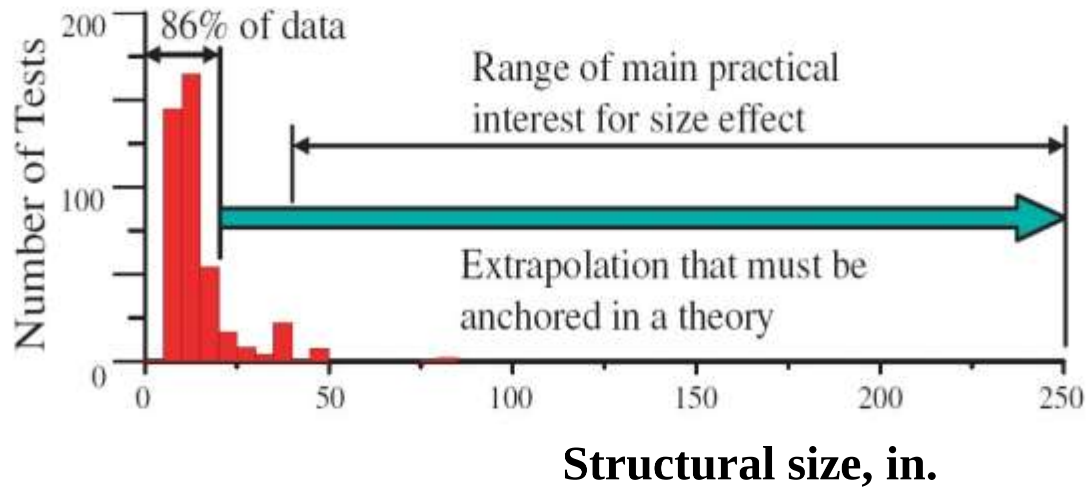


Wimmer & Pettermann
J of Comp. Mater, 2009

Scaling: The Effect of Structure Size on Strength

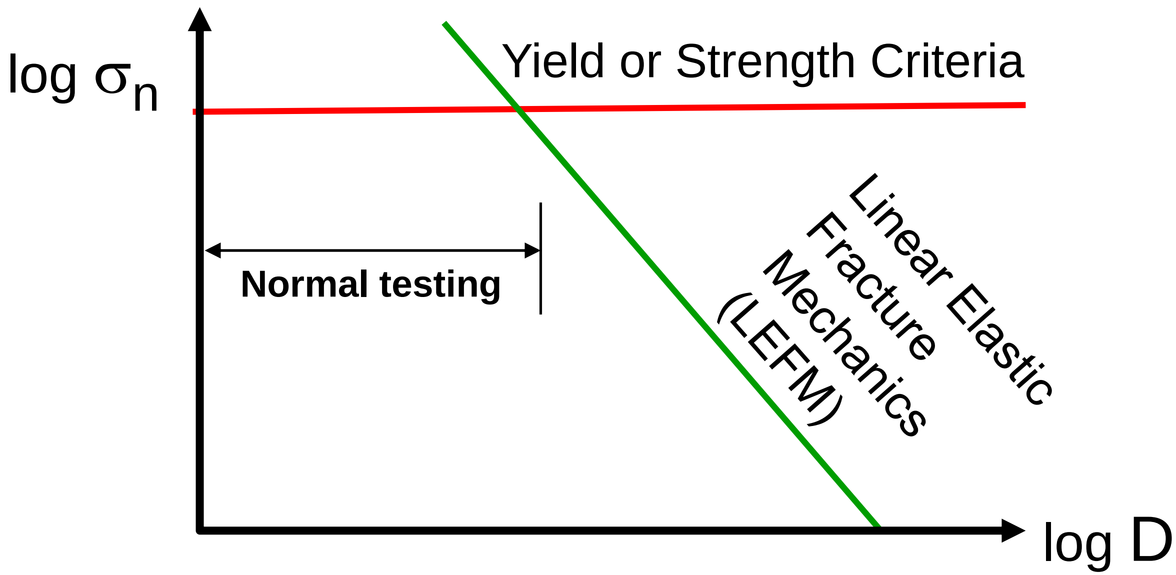


Scaling from test coupon to structure

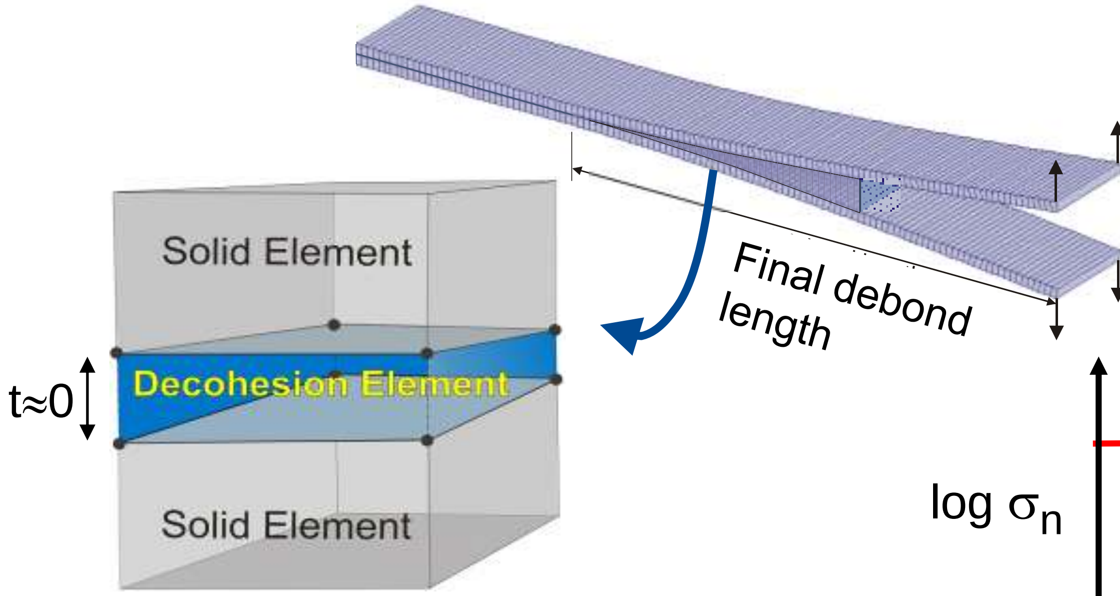


Scaling Laws

(Z. Bažant)

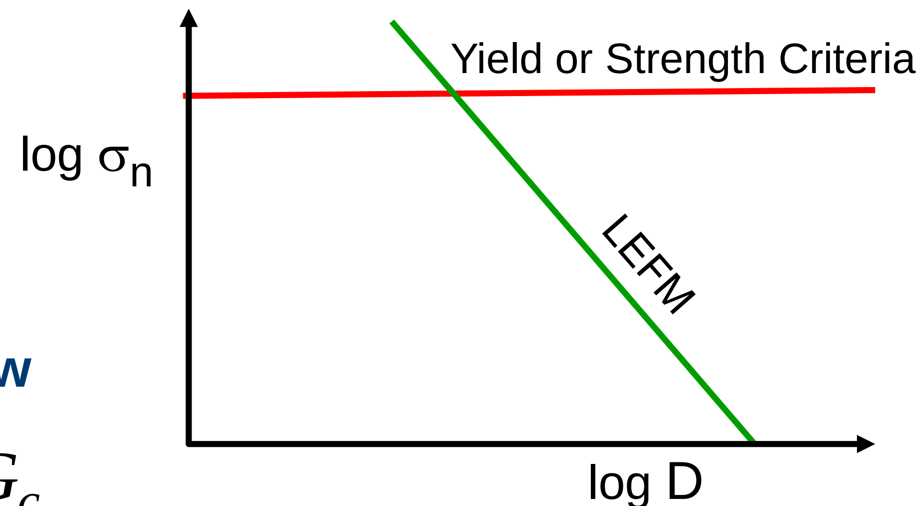


Cohesive Laws



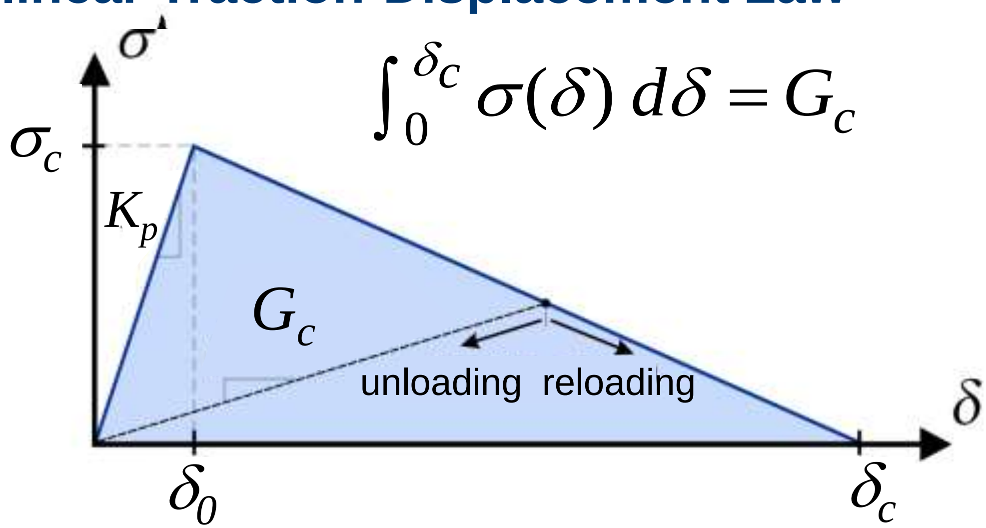
Two material properties:

- G_c Fracture toughness
- σ_c Strength



Bilinear Traction-Displacement Law

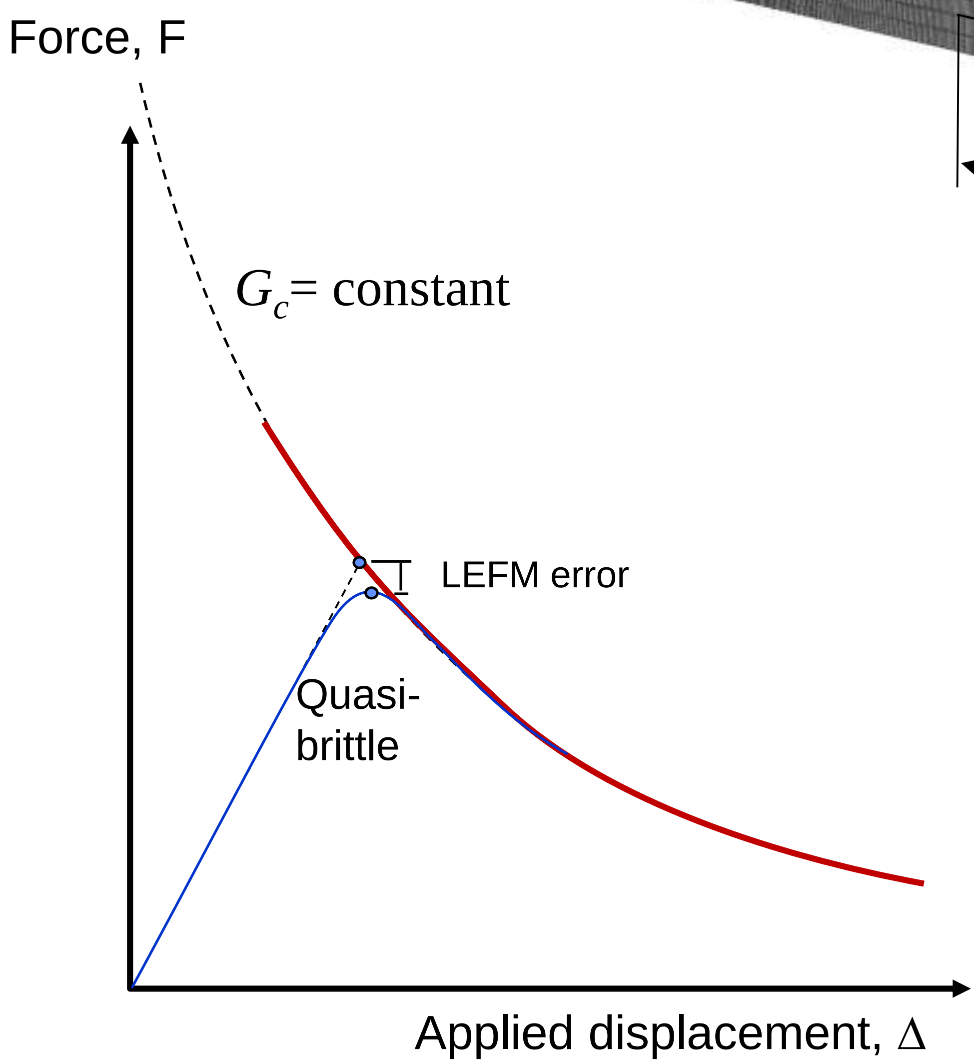
$$\int_0^{\delta_c} \sigma(\delta)\, d\delta = G_c$$

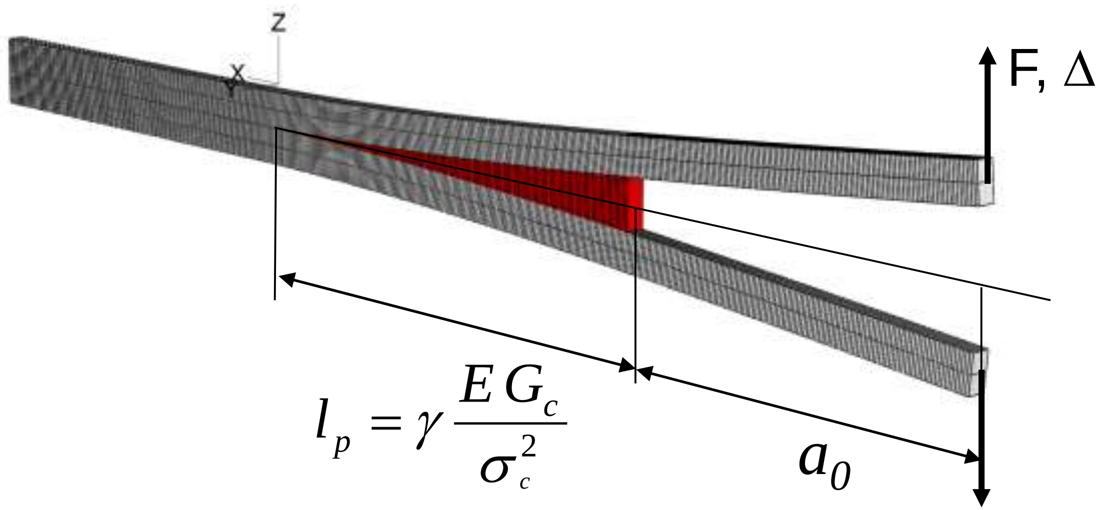


Characteristic Length:

$$l_p = \gamma \frac{E\, G_c}{\sigma_c^2}$$

Crack Length and Process Zone





Brittle:

$$a_0 > 100\ l_p$$

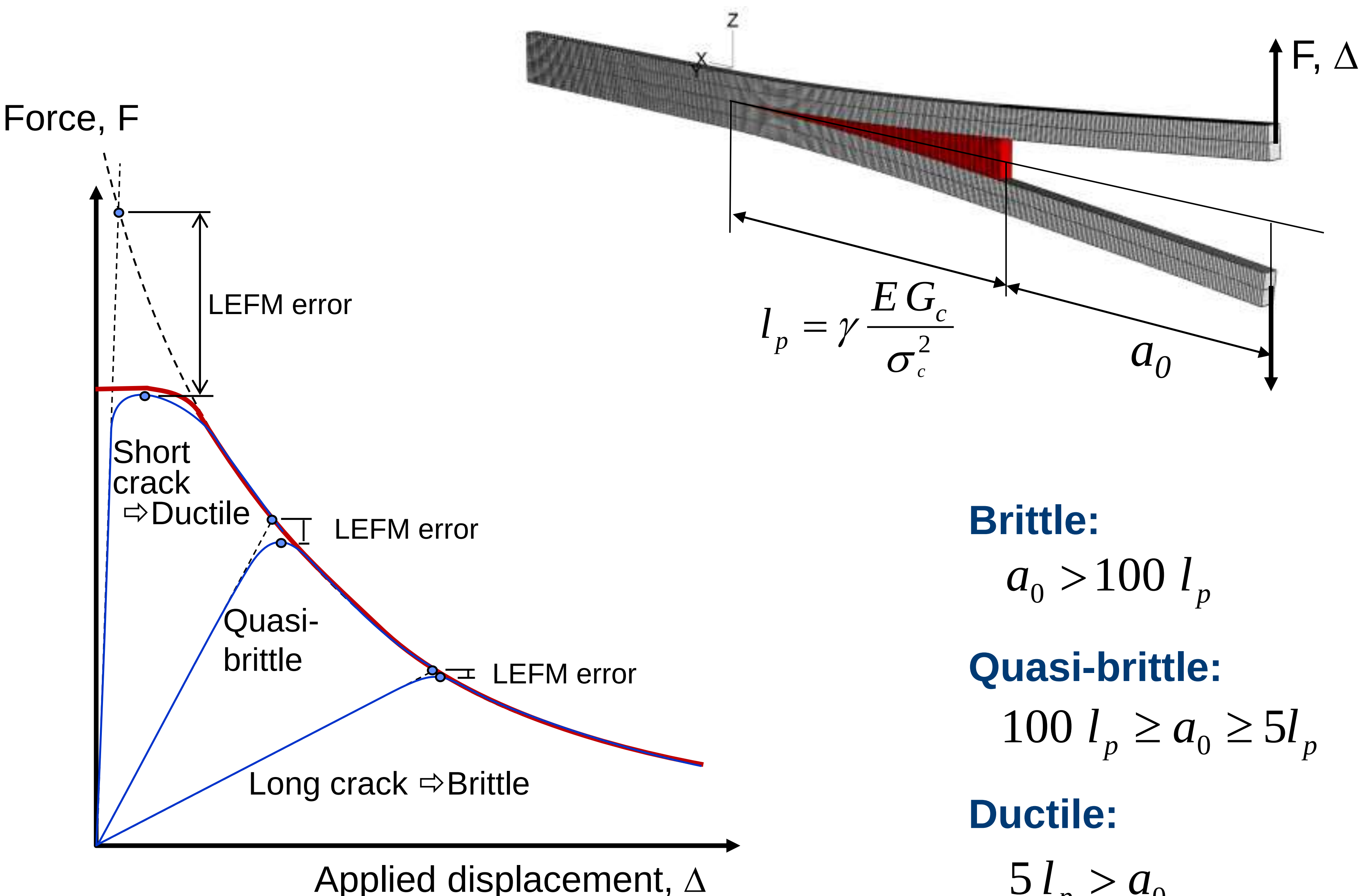
Quasi-brittle:

$$100\ l_p \geq a_0 \geq 5 l_p$$

Ductile:

$$5\ l_p > a_0$$

Crack Length and Process Zone



Brittle:

$$a_0 > 100\ l_p$$

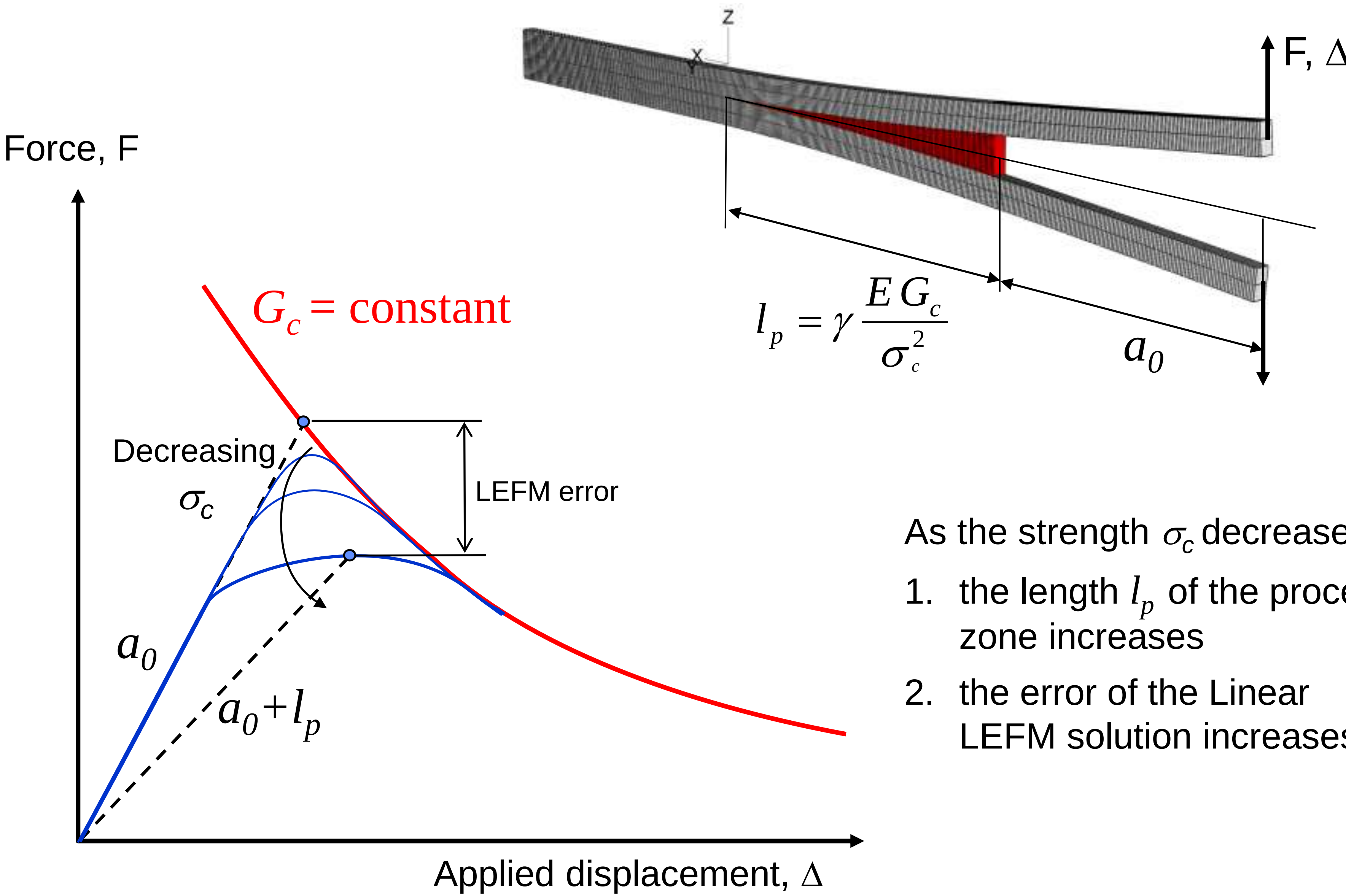
Quasi-brittle:

$$100\ l_p \ge a_0 \ge 5 l_p$$

Ductile:

$$5\ l_p > a_0$$

Strength and Process Zone



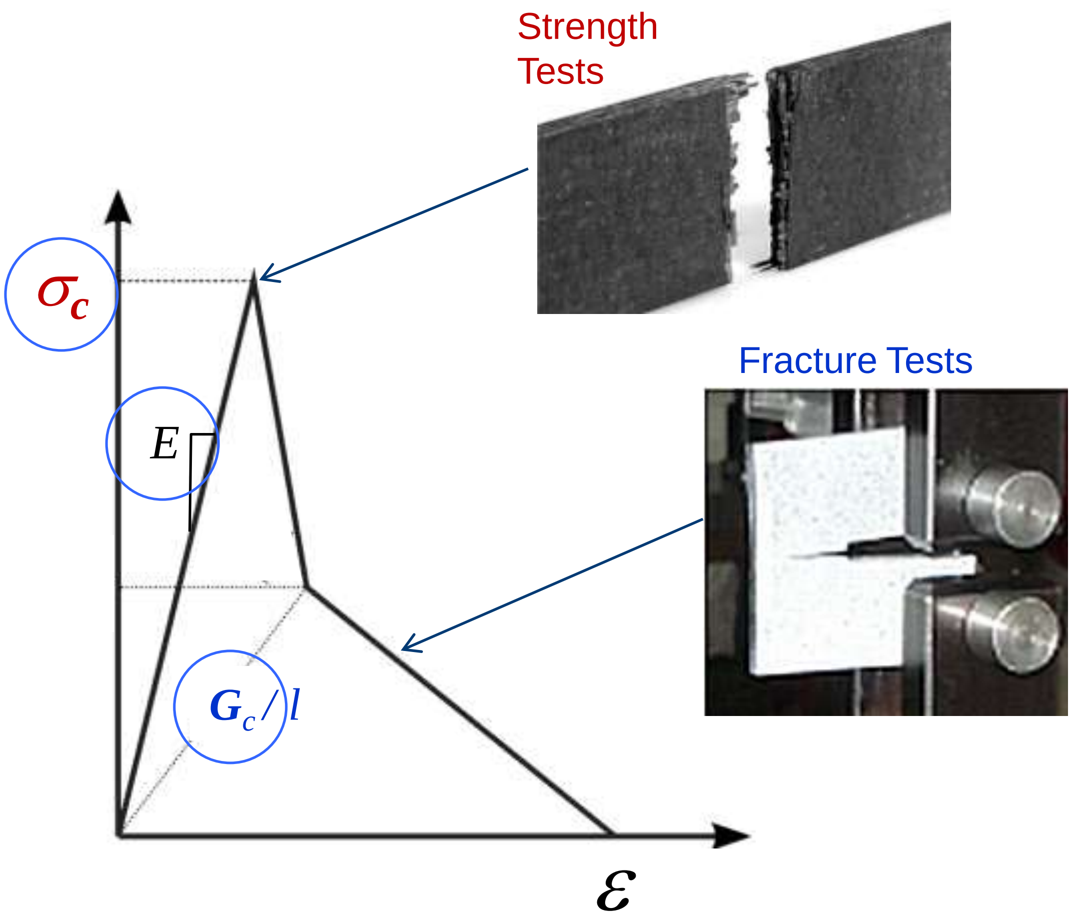
As the strength σ_c decreases,

1. the length l_p of the process zone increases
2. the error of the Linear LEFM solution increases

Size Effect and Material Softening Laws

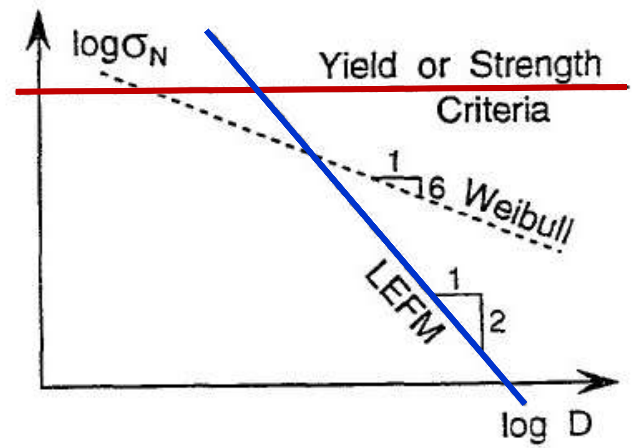
Damage Evolution Laws:

Each damage mode has its own softening response



Two material properties:

- σ_c Strength
- G_c Fracture toughness

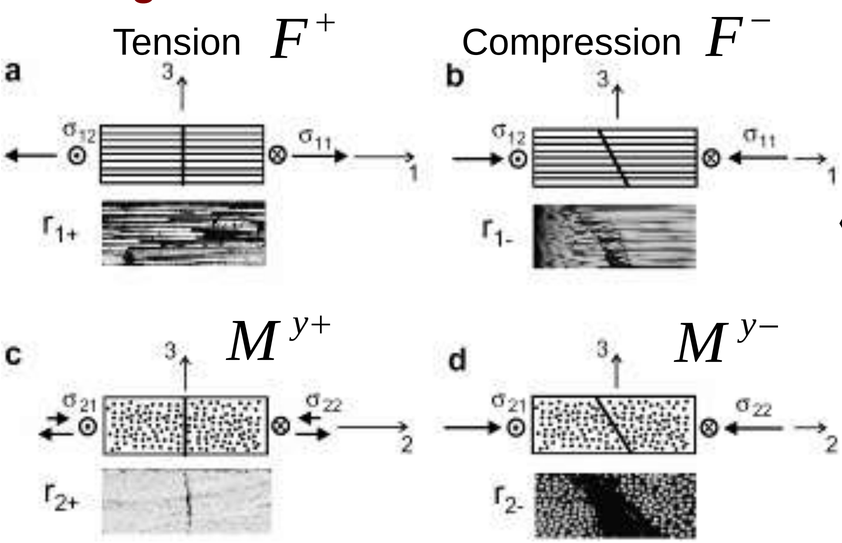


Material length scale

$$l_c \approx \gamma \frac{E\, G_c}{\sigma_c^2}$$

Progressive Damage Analysis (Maimí/Camanho 2007)

Damage Modes:



LaRC04 Criteria

- In-situ matrix strength prediction
- Advanced fiber kinking criterion
- Prediction of angle of fracture (compression)
- Criteria used as activation functions within framework of continuum damage mechanics (CDM)

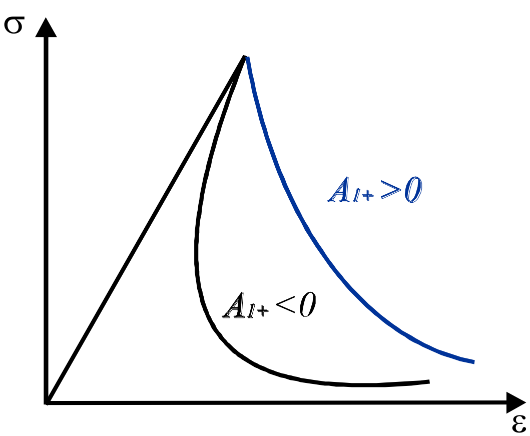
$$d_i = 1 - \frac{1}{f_i}\exp\left(A_i\left(1 - f_i\right)\right)$$

f_i: LaRC04 failure criteria as activation functions

$$i = F^+; F^-; M^{y+}; M^{y-}; M^s$$

Damage Evolution:

Thermodynamically-consistent material degradation takes into account energy release rate and element size for each mode



Bazant Crack Band Theory:

$$A_i = \frac{2l^* X_i^2}{2E_i G_i - l^* X_i^2}$$

Critical (maximum) finite element size:

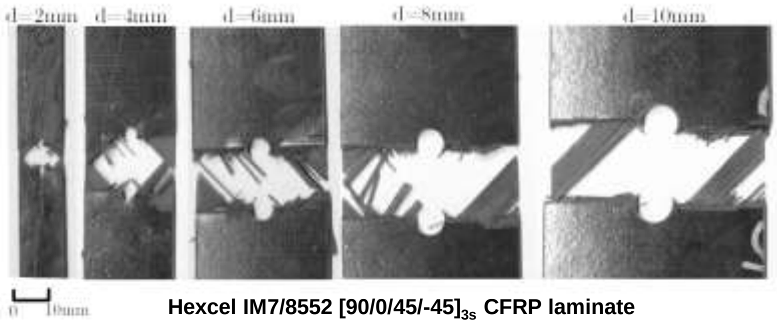
$$l^* \leq \frac{2E_i G_i}{X_i^2}$$

Predicting Scale Effects with Continuum Damage Models

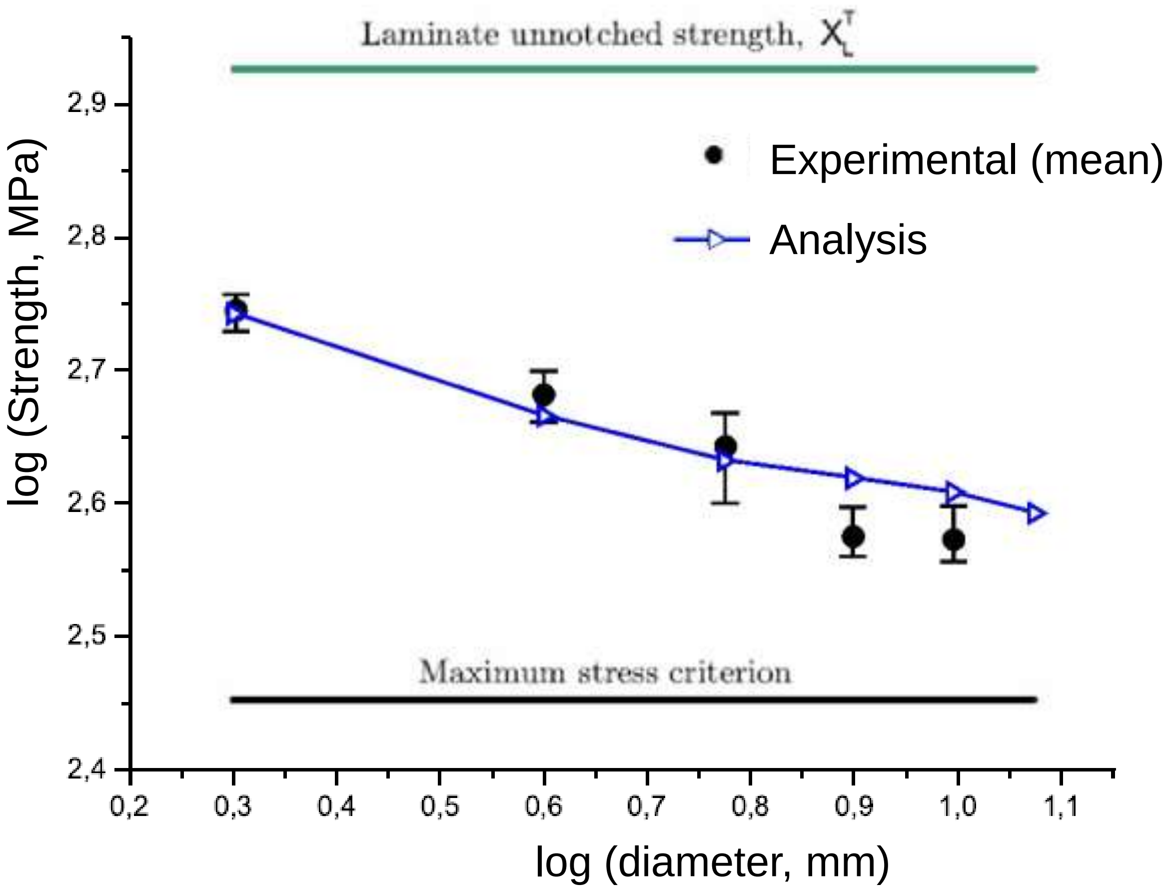
Prediction of size effects in notched composites

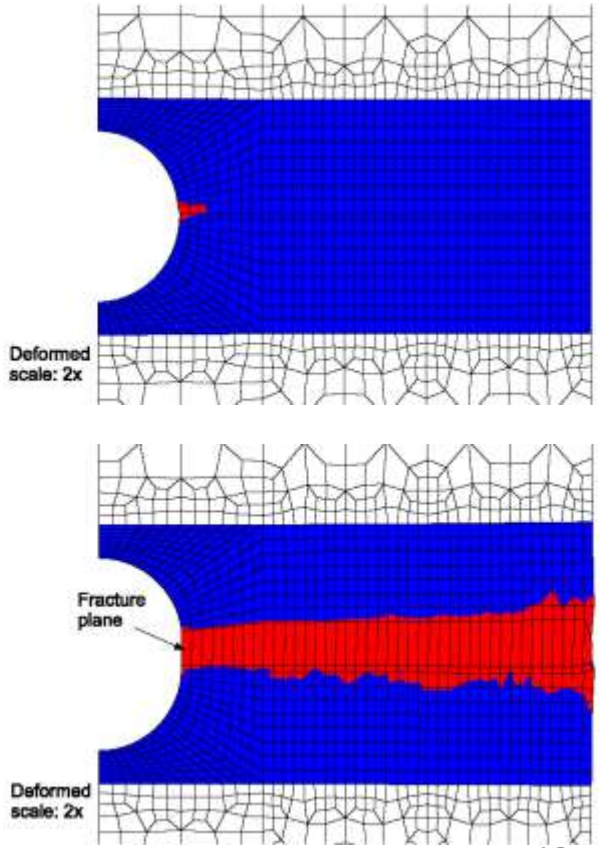
- Stress-based criteria predict no size effect
- CDM damage model predicts scale effects w/out calibration

(P. Camanho, 2007)

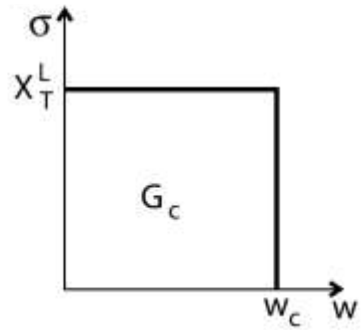


Hexcel IM7/8552 $[90/0/45/-45]_{3s}$ CFRP laminate

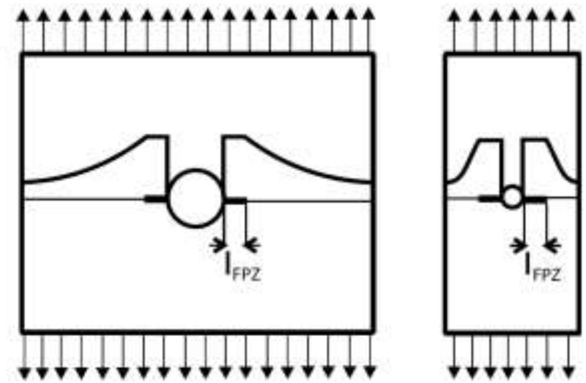




Process Zone and Scale Effect in Open Hole Tension

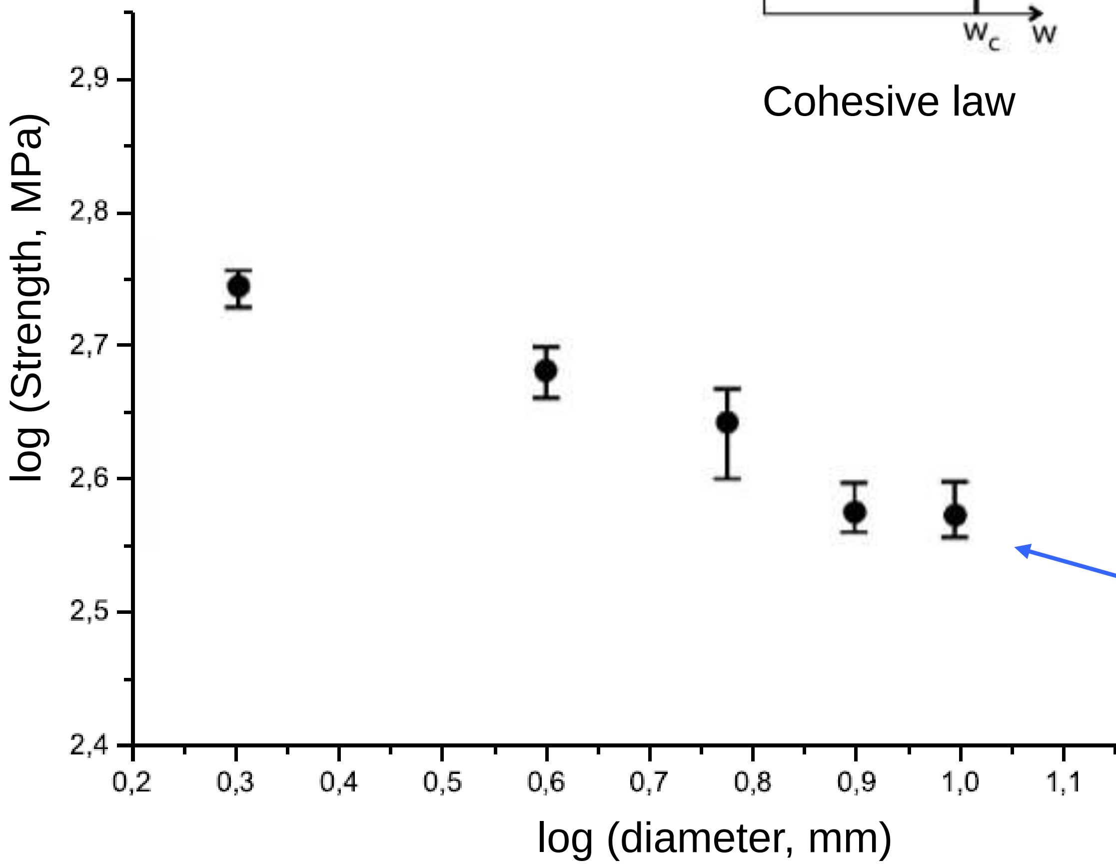


Cohesive law



Stress distribution

(P. Camanho, 2007)

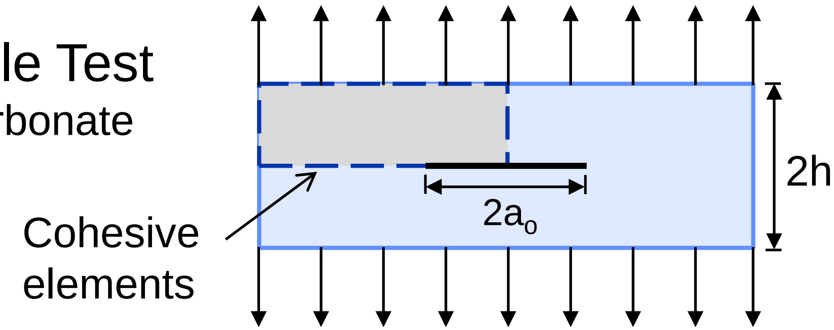


Scale effect is due to relative size of process zone

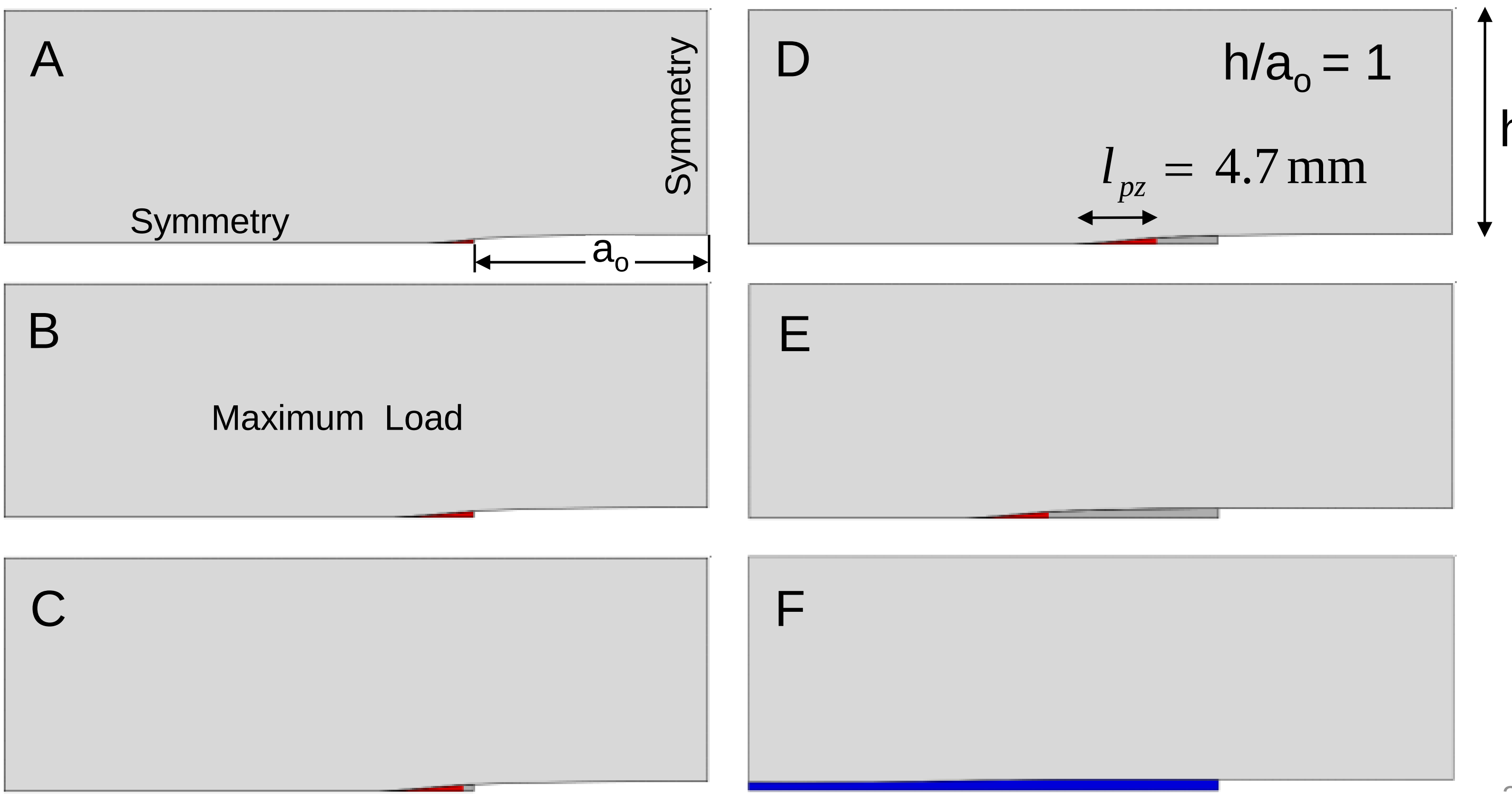
Length of the Process Zone (Elastic Bulk Material)

Short Tensile Test

Lexan Polycarbonate



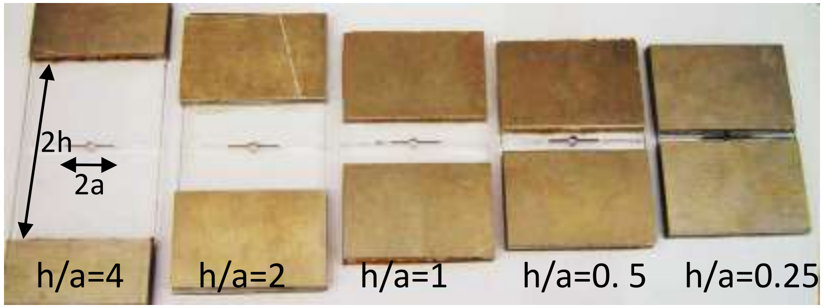
$$l_c \approx 0.6 \frac{E\, G_c}{\sigma_c^2} = 3.4\,\text{mm}$$



Cohesive Laws - Prediction of Scale Effects

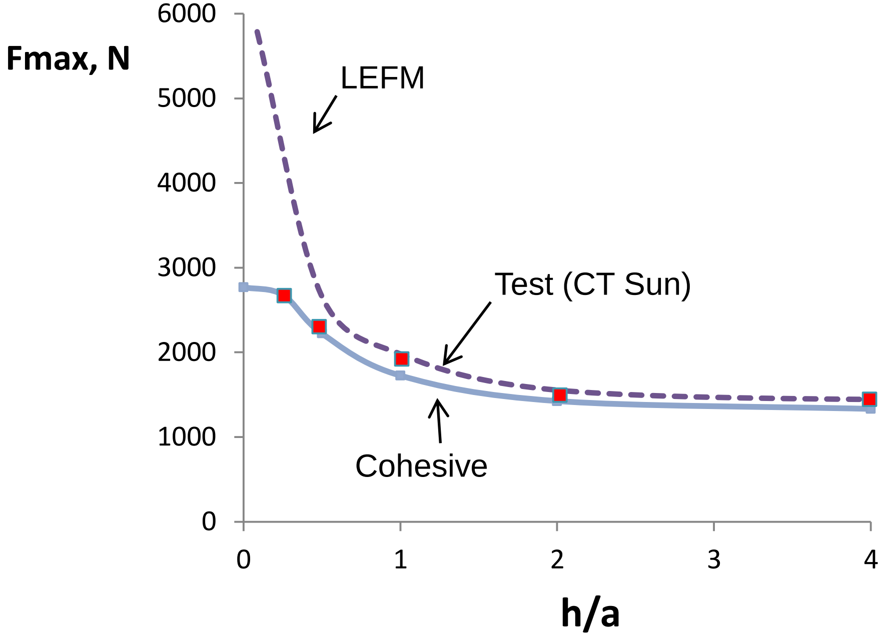
- The use of cohesive laws to predict the fracture in complex stress fields is explored
- The bulk material is modeled as either elastic or elastic-plastic

Lexan Plexiglass tensile specimens (CT Sun)

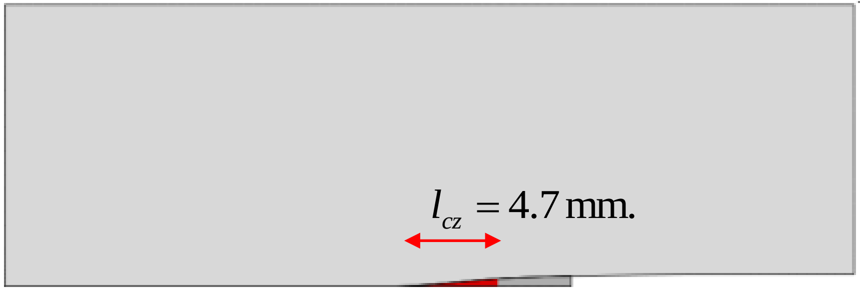


Observations:

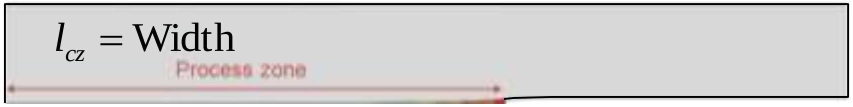
- LEFM overpredicts tests for h/a<1



h/a=1 (short process zone)

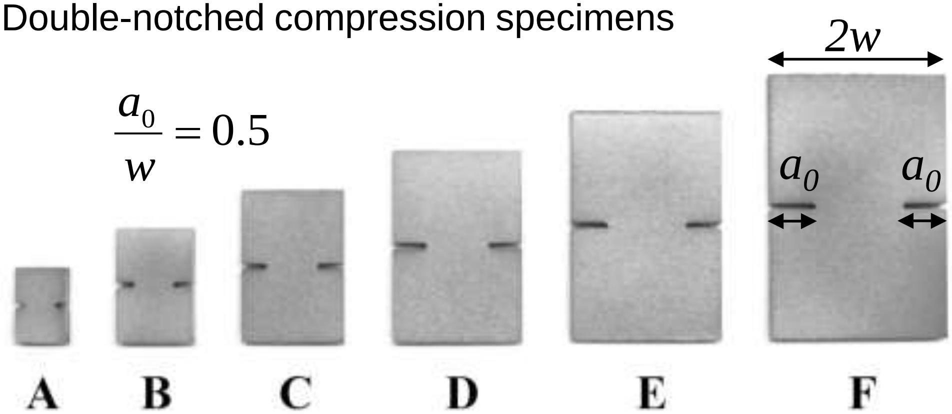


h/a = 0.25 (long process zone)



Study of size effect: measuring the R-curve

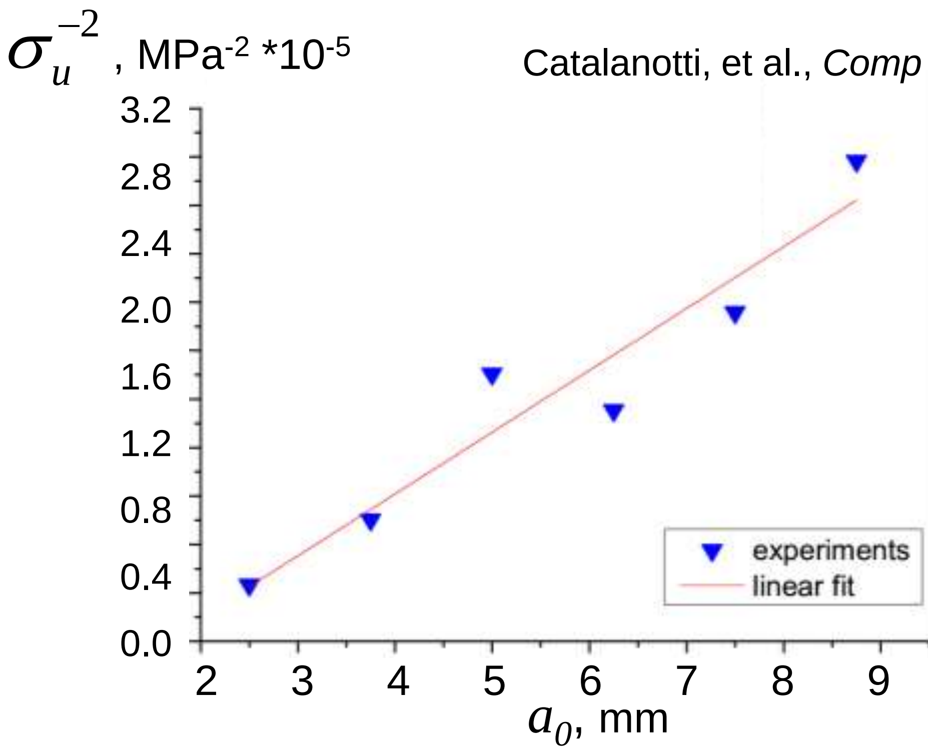
Double-notched compression specimens

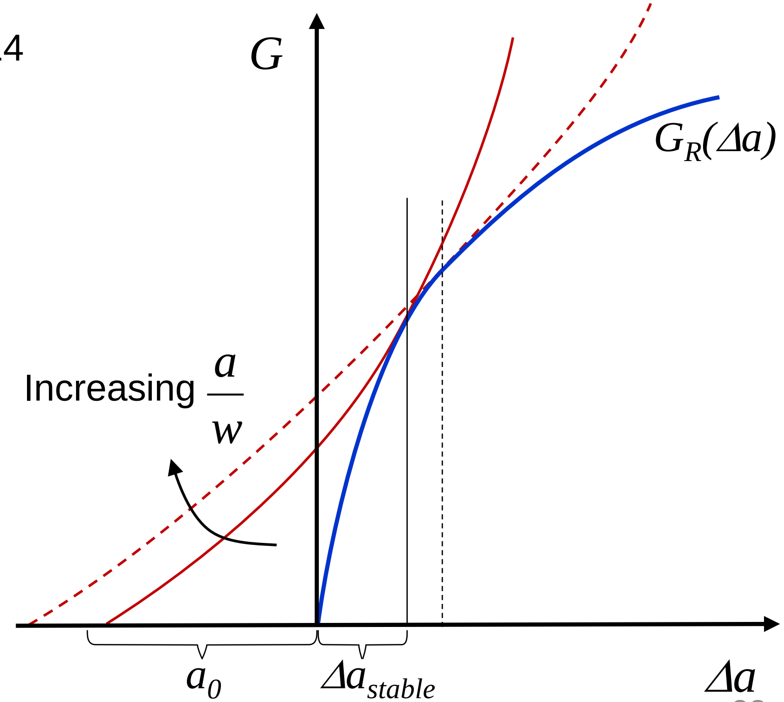


$$G = \overbrace{\phi\left(\frac{a}{w}\right)}^{\text{By FEM analysis}} \frac{\overbrace{\sigma_u^2}^{\text{From test}}\, a}{E^{eff}}$$

(Similar to $G = \frac{\pi \sigma^2 a}{E}$)

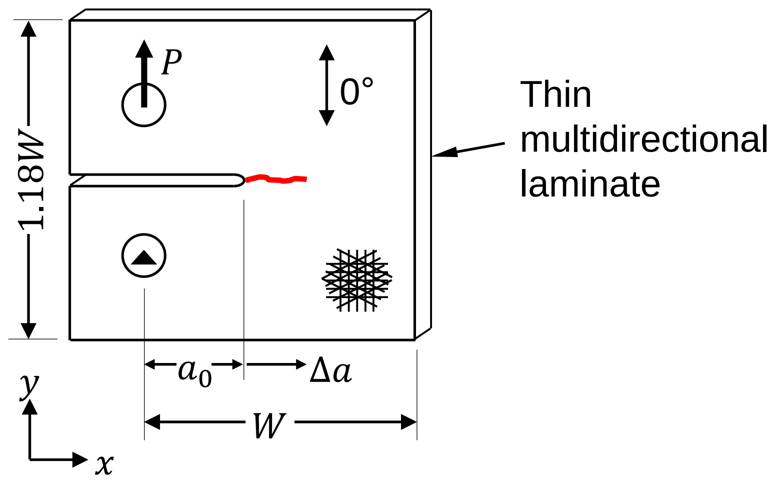
Catalanotti, et al., *Comp A*, 2014





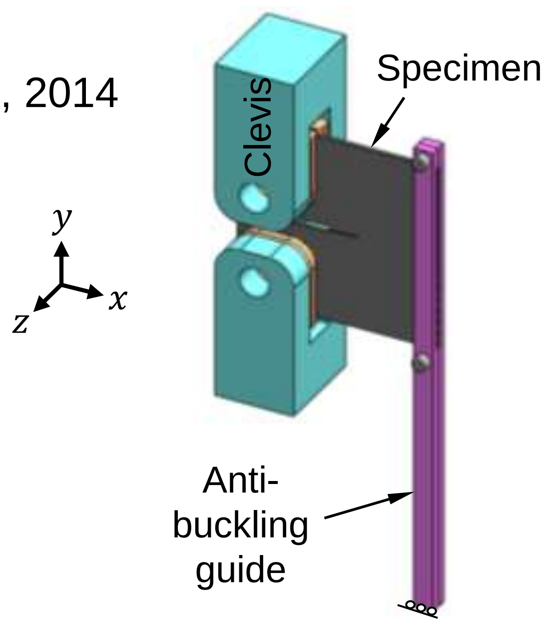
Characterization of Through-Crack Cohesive Law

Compact Tension (CT) Specimen



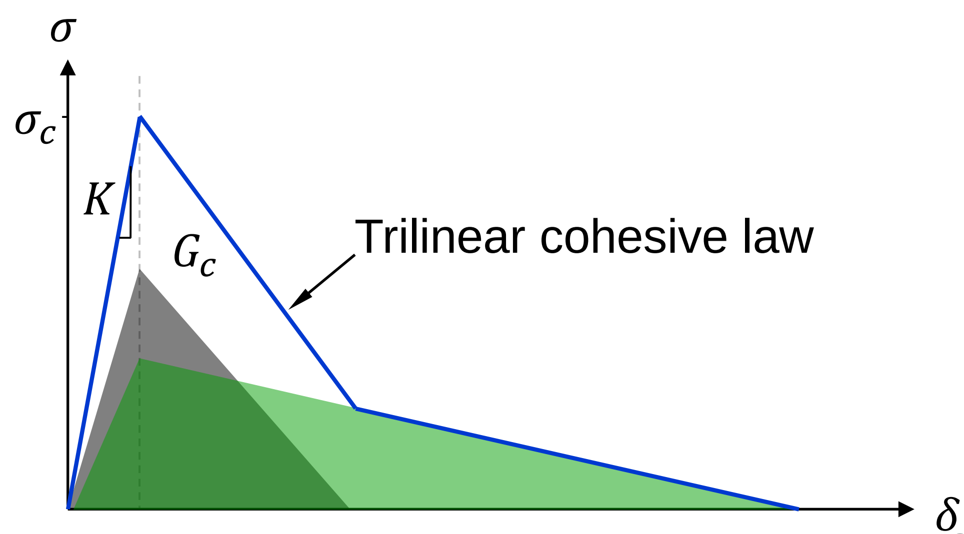
Experimental setup

Bergan, 2014

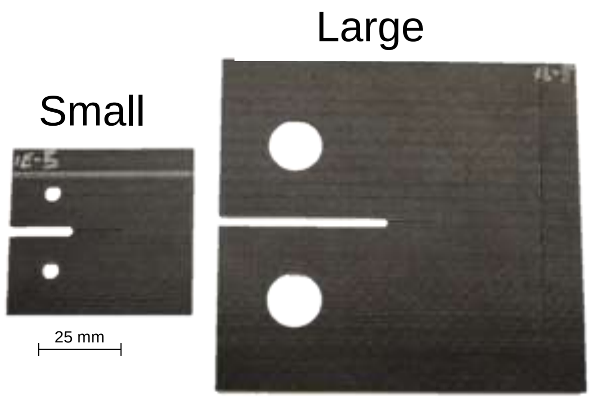


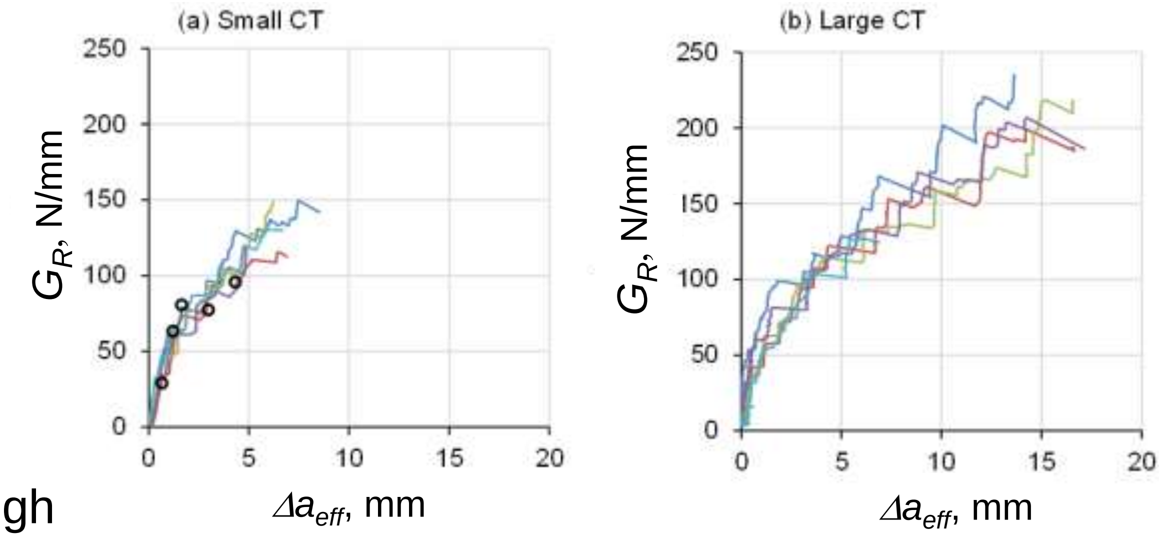
Characterization Procedure:

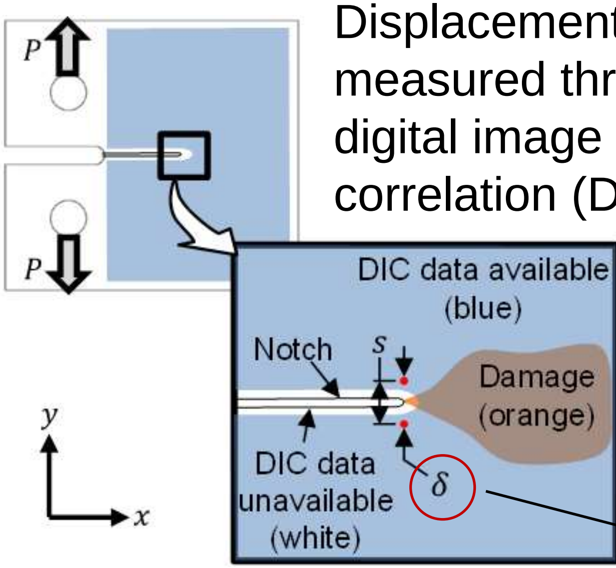
1. Measure R-curve from CT test $$G_R = \frac{P^2}{2t}\frac{\partial C}{\partial a}$$
2. Assuming a trilinear cohesive law, fit analytical R-curve to the measured R-curve $$\eta = \sum_{i}^{n_s} \left| J_{\text{fit}}^i - G_R^i \right|$$
3. Obtain the cohesive law by differentiating the analytical R-curve $$\sigma(\delta) = \frac{\partial J_{\text{fit}}}{\partial \delta}$$



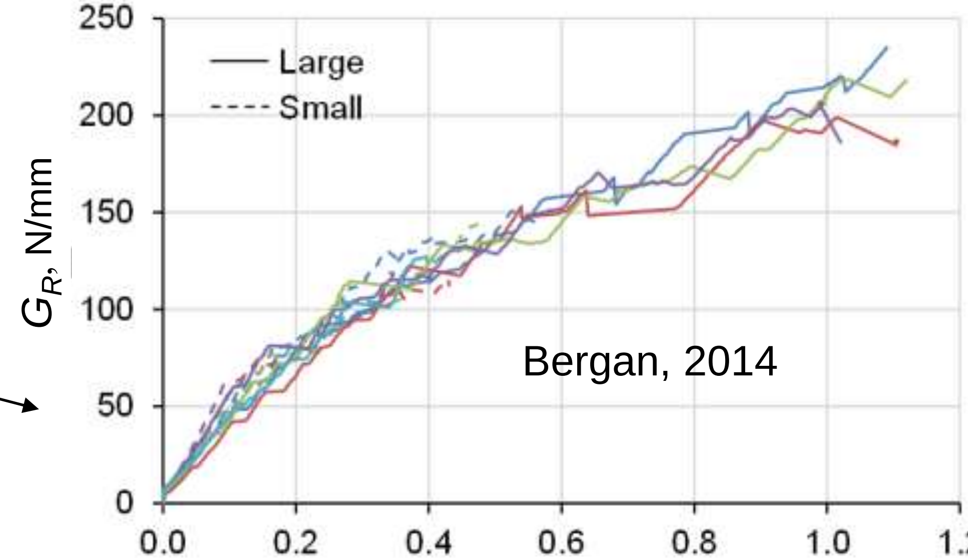
Size-Dependence of R-Curve





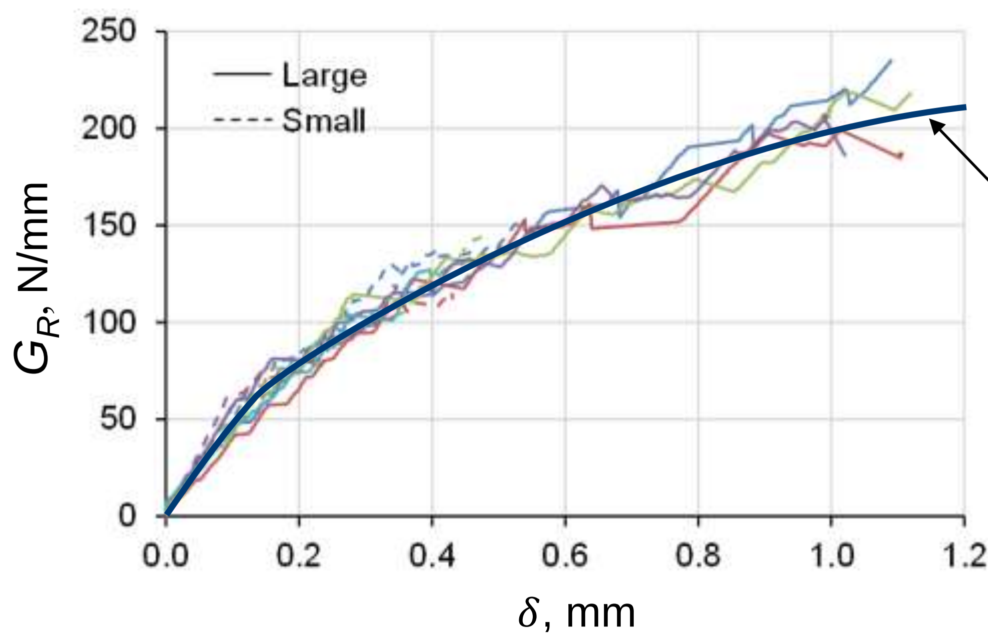


Displacements measured through digital image correlation (DIC)



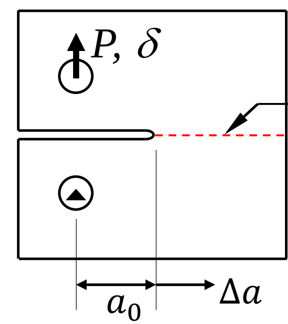
Plotting the R-curve as a function of the notch displacement removes the size-dependency

R-Curve Effect in Fiber Fracture

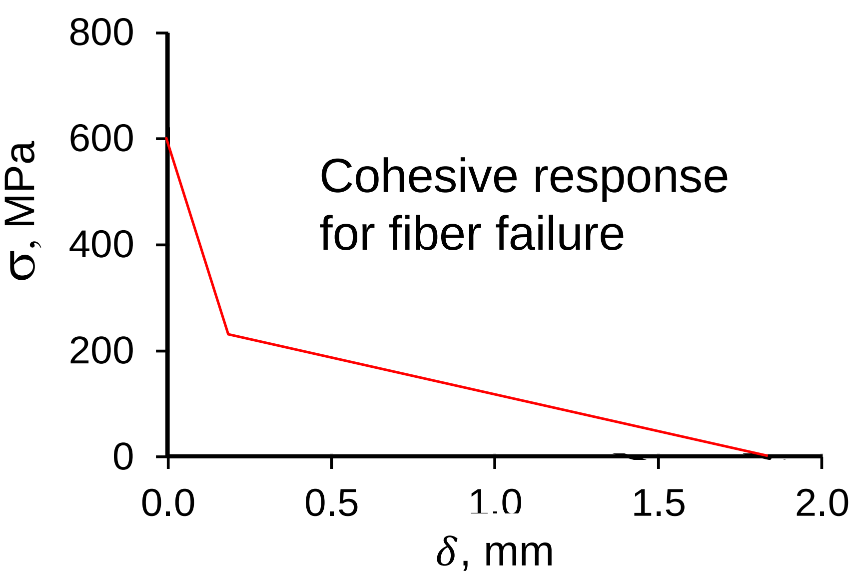


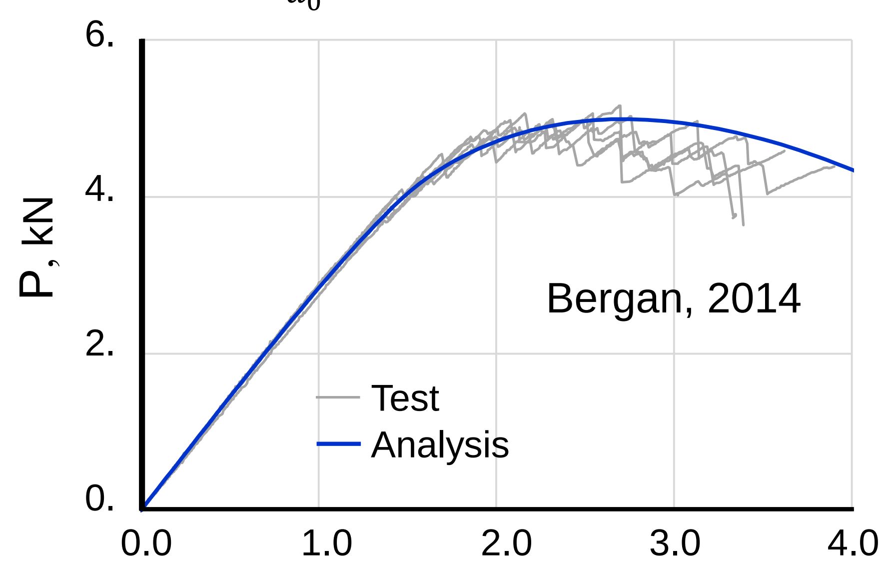
$$J_R = \int_0^{\delta_c} \sigma(\delta)\,d\delta$$

Curve fit assuming bilinear $\sigma(\delta)$

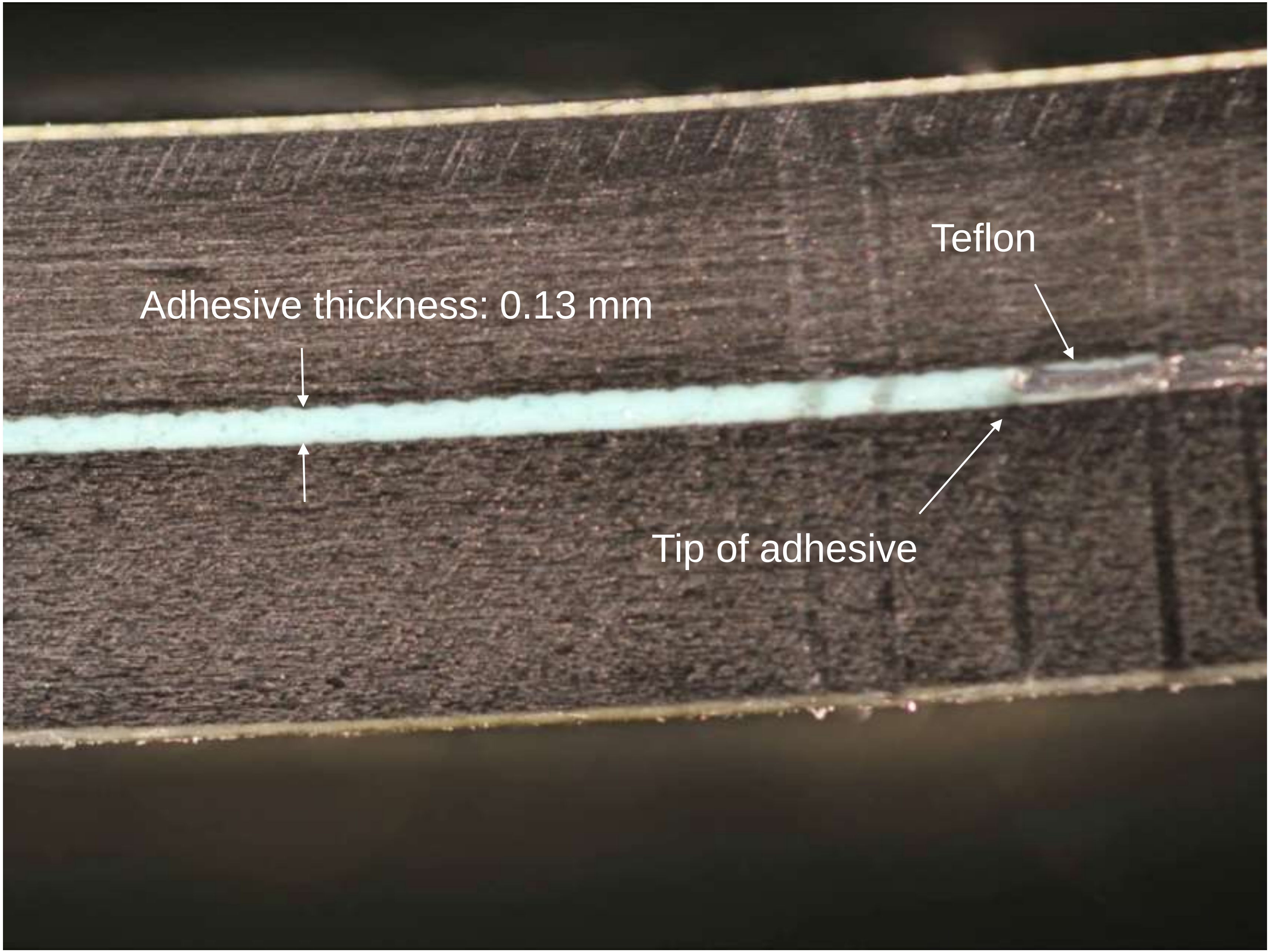


Cohesive elements w/ characterized cohesive law

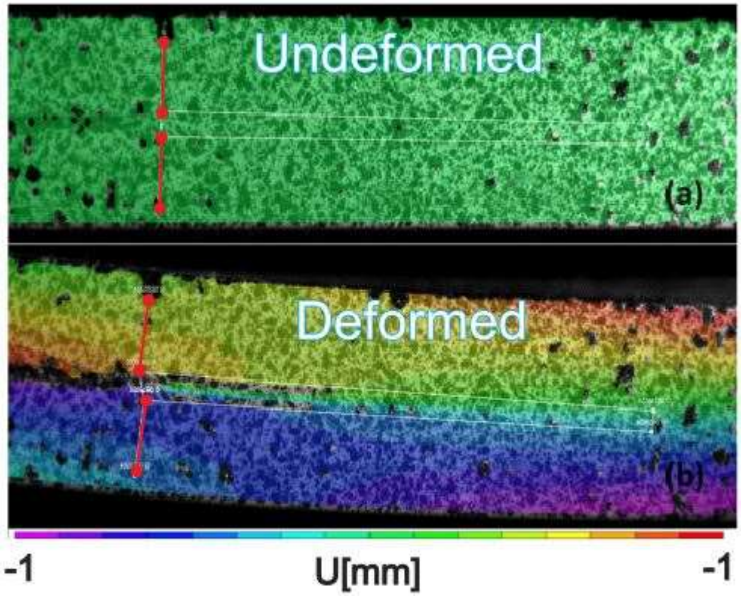


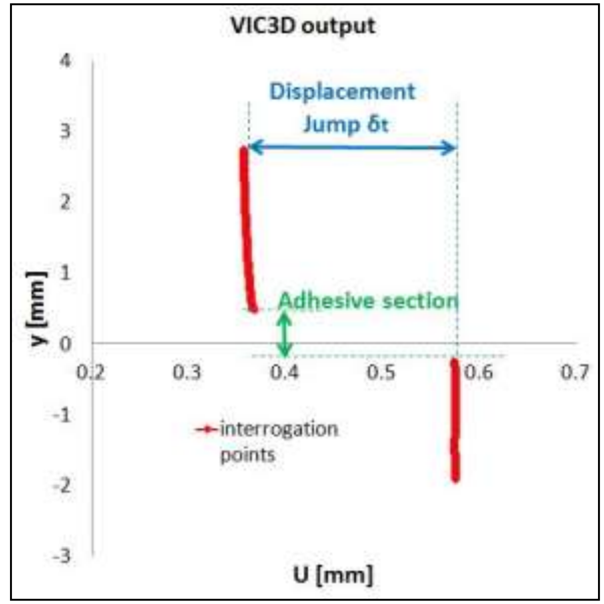


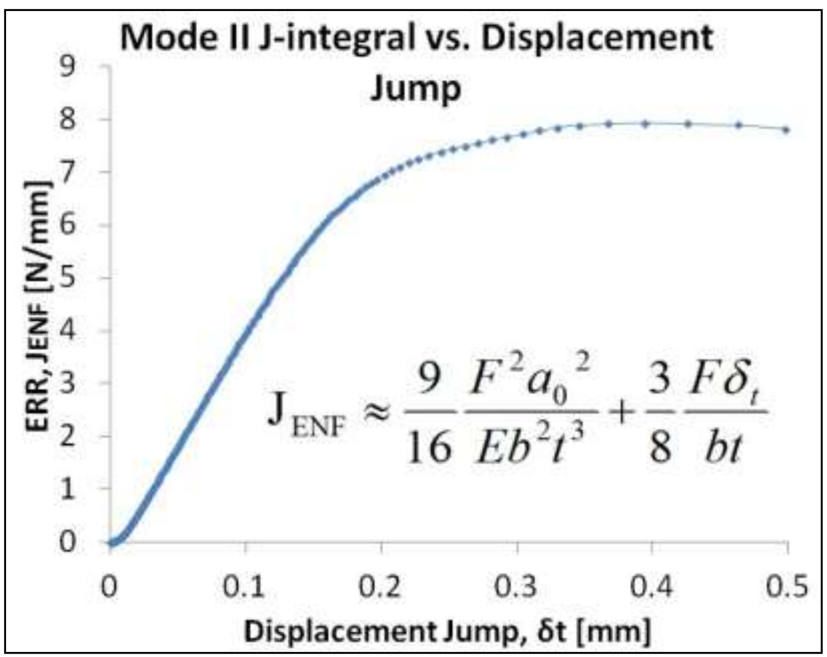
Mode II-Dominated Adhesive Fracture

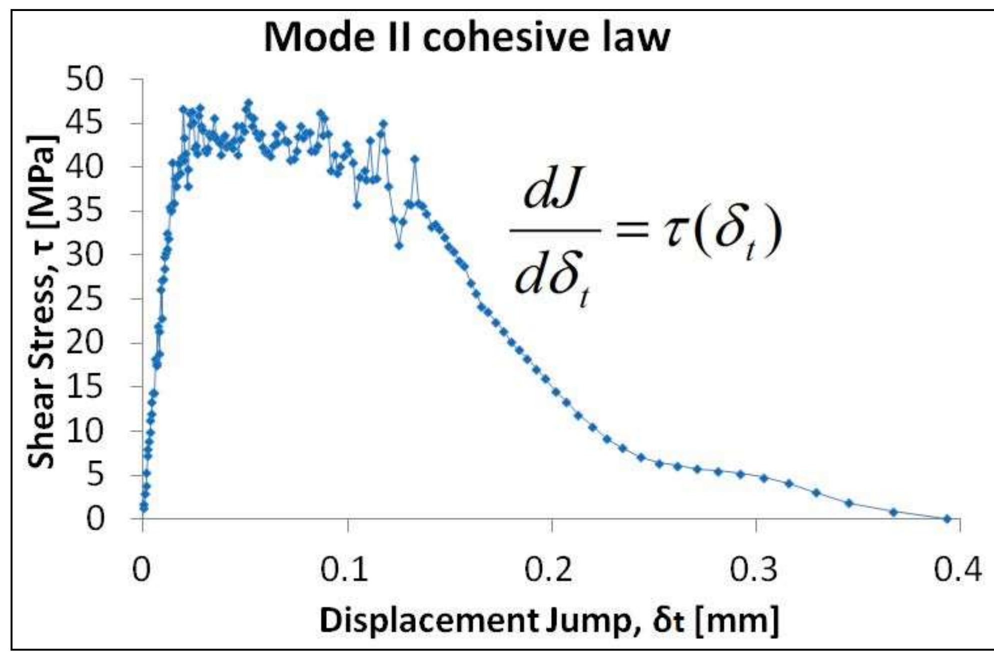


ENF J-Integral from DIC



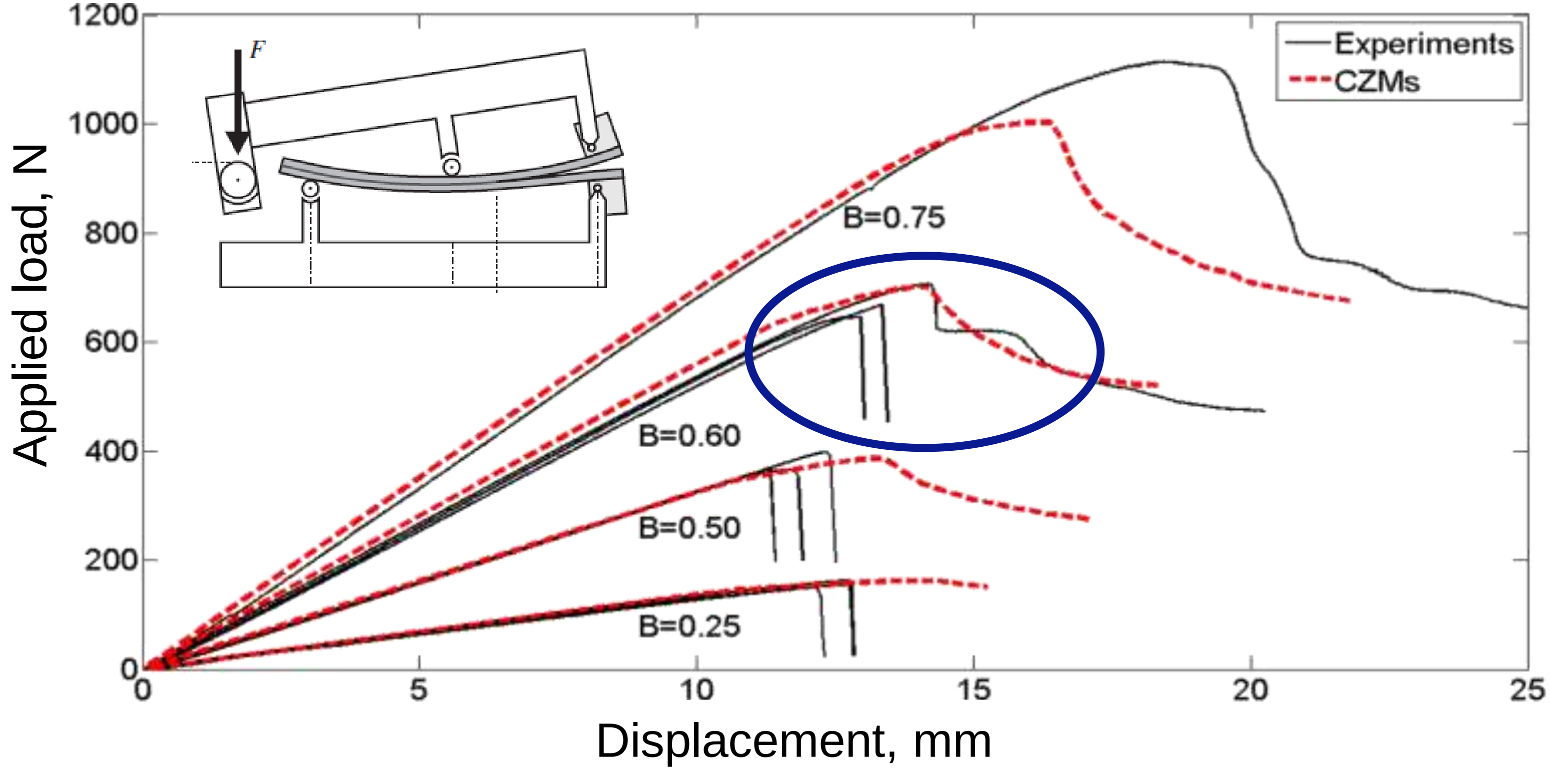






MMB Test - Analysis Results

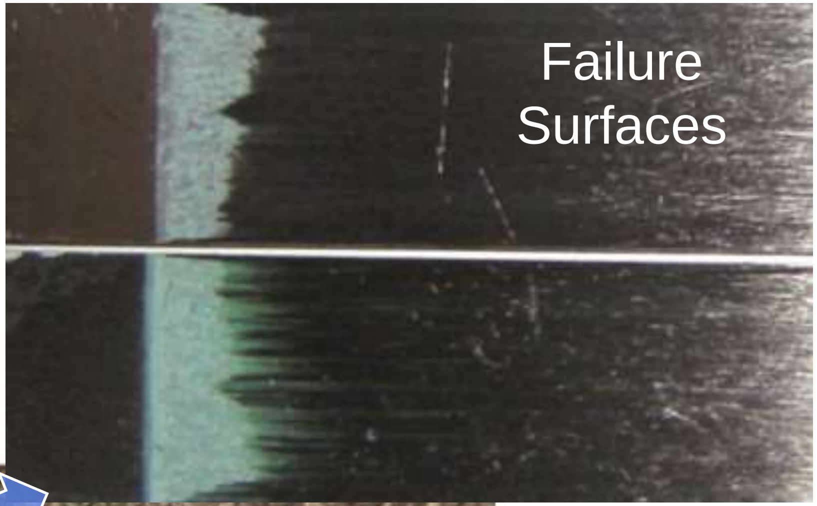
Mixed mode bending (MMB) test fixture

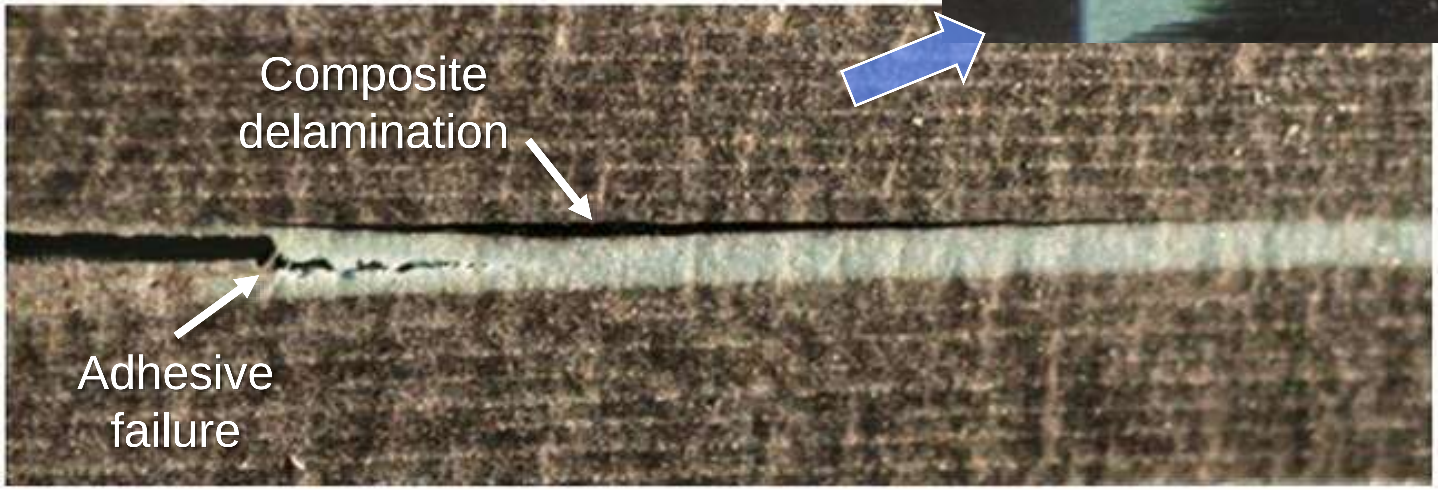


Nominally identical bonded MMB specimens sometimes fail in quasi-static mode and others dynamically. Why?

Double Delamination in MMB Tests

- Unexpected failure mechanism
- Two delamination fronts run in parallel: one in the adhesive, the other in the composite





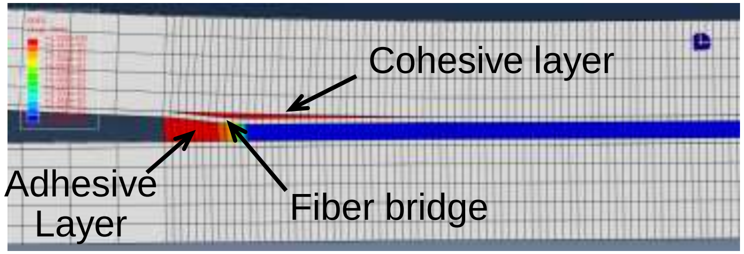
- When the fiber bridge breaks, the crack grows unstably in the composite causing the drop in the load-displacement curve

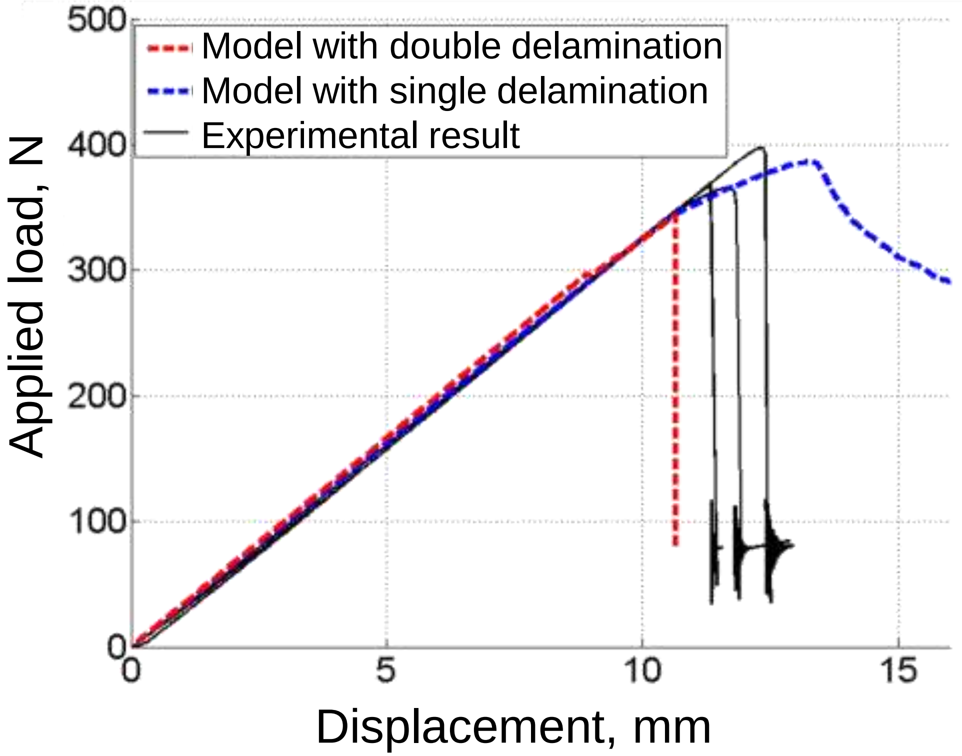
Modeling the Double Delamination

- A model was developed to evaluate the observed double delamination phenomenon
- The model contains two additional cohesive layers within the composite arms

MMB test specimen

Model of MMB specimen with double delamination





- This failure mechanism is often observed in bonded joints

Representative Volume Element and Micromechanics

Why Micromechanics?

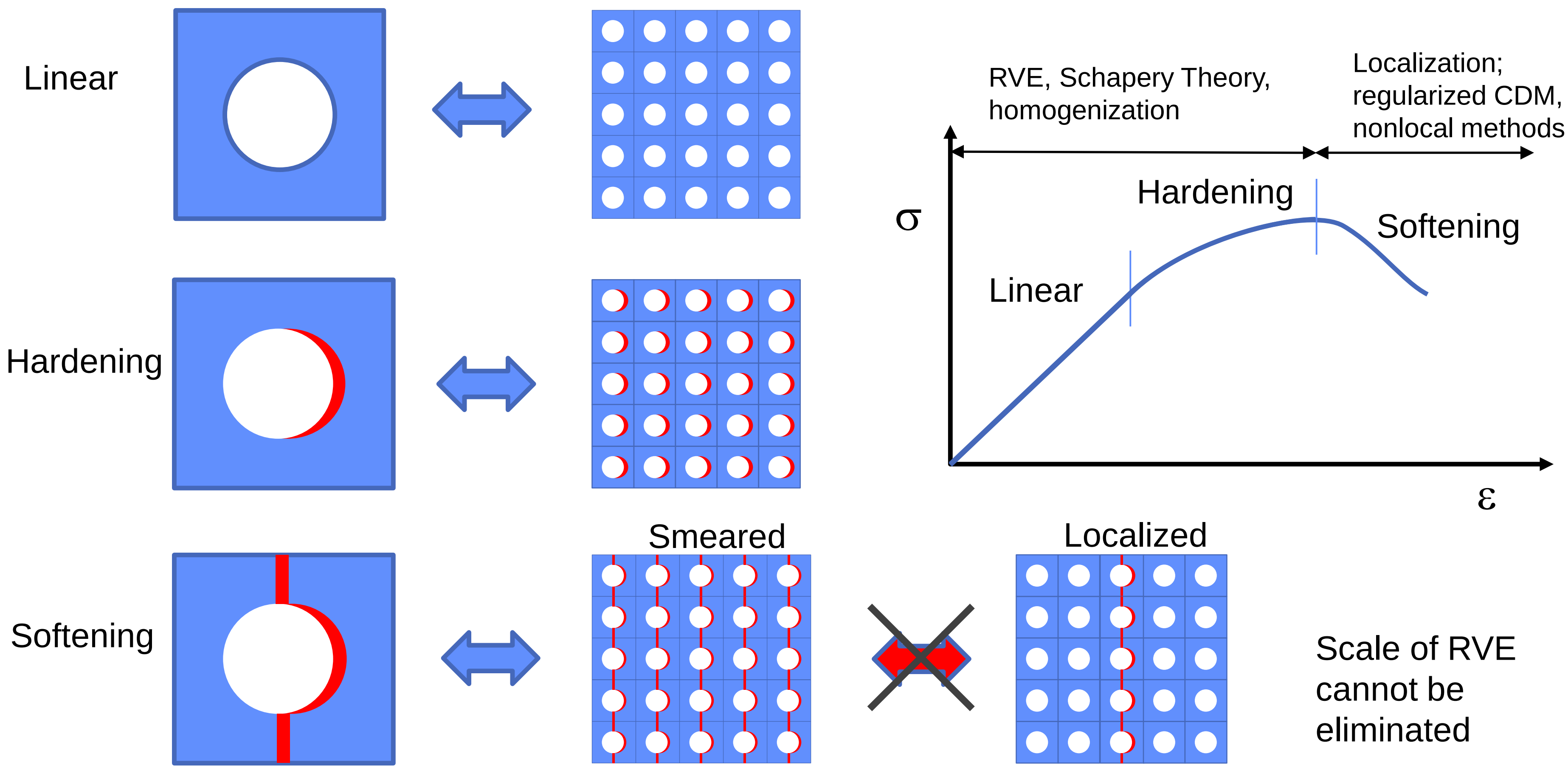
Assumption:

*“Micromechanics has **more built-in physics** because it is closer to the scale at which fracture occurs”*

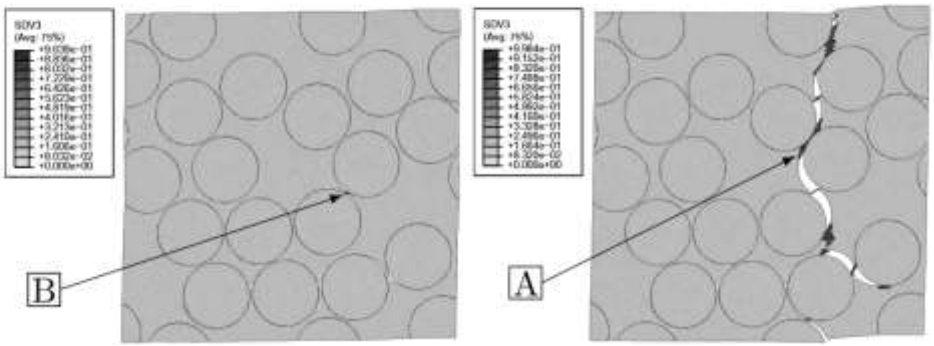
Why NOT Micromechanics? (Representative Volume Element [RVE])

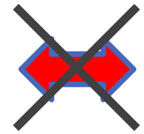
- Problem of localization
- Randomness of unit cell configurations
- Lengthscales missing
- Characterization of material properties, especially the interface
- Computational expense

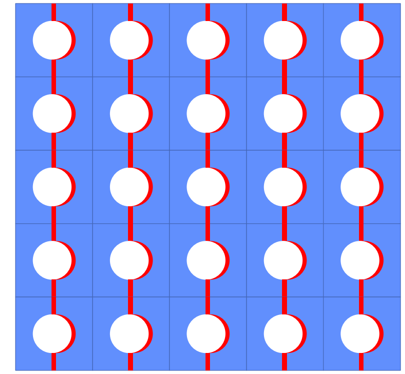
RVE: 1) Problem of Localization



RVE: 2) Randomness of Unit Cell Configurations

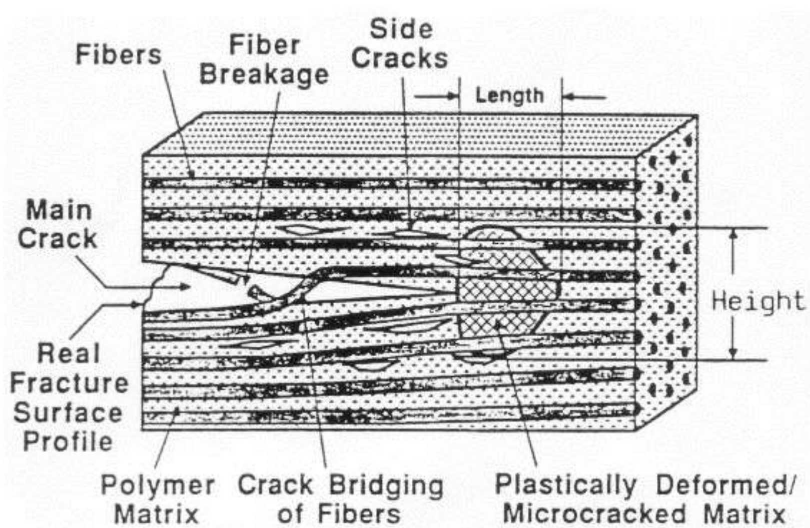






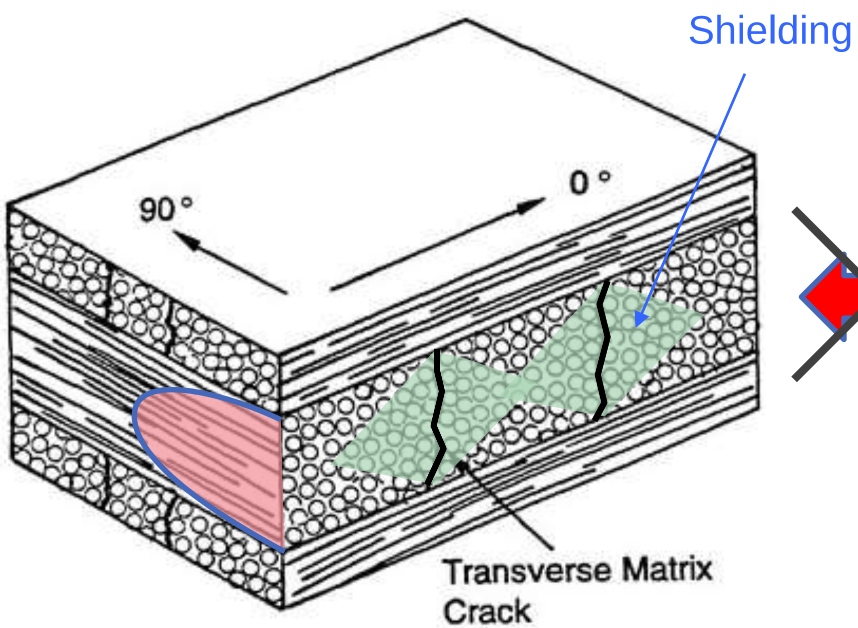
Melro et al. *IJSS, 2013.*

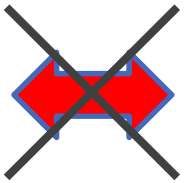
Fracture is a combination of interacting discrete and diffuse damage mechanisms

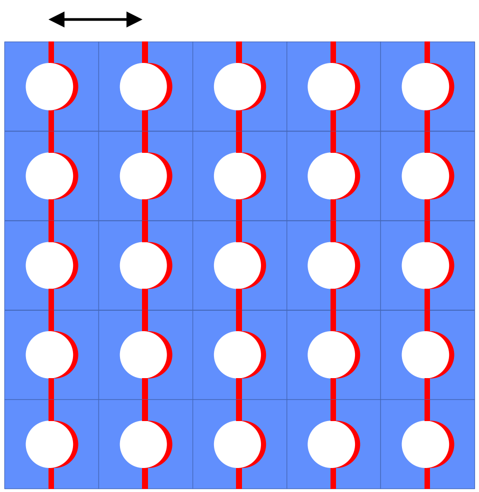


Bloodworth, V., PhD Dissertation, Imperial College, UK, 2008.

RVE: 3) Issue of Length Scales



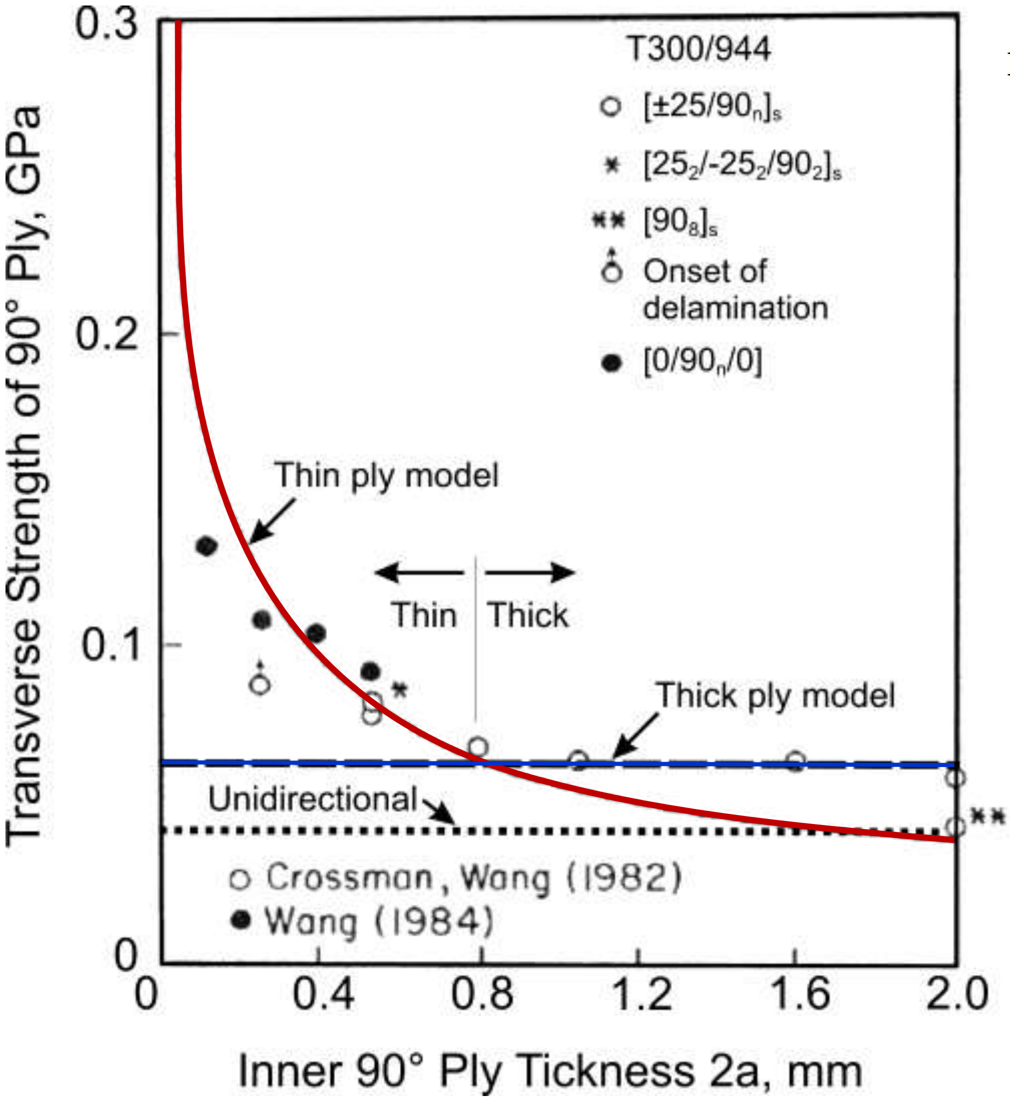


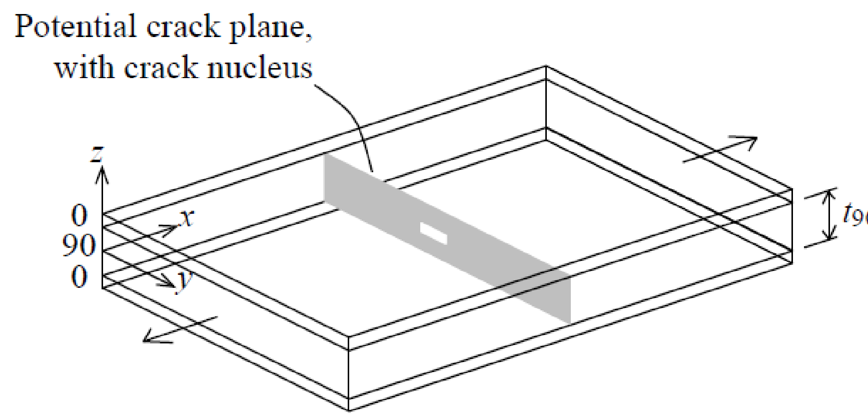


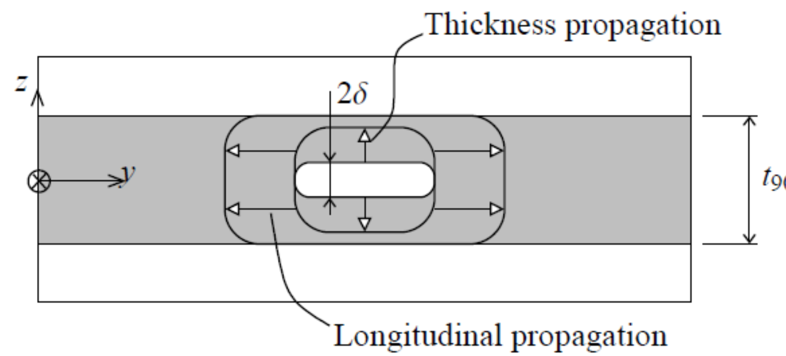
RVE may not account for:

- Ply thickness
- Longitudinal crack length
- Crack spacing

Matrix Cracking – In Situ Effect

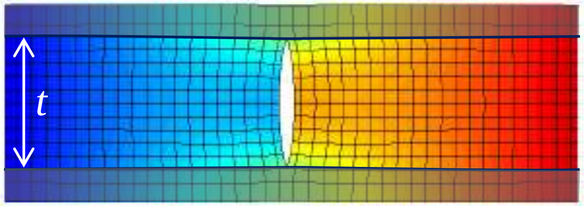




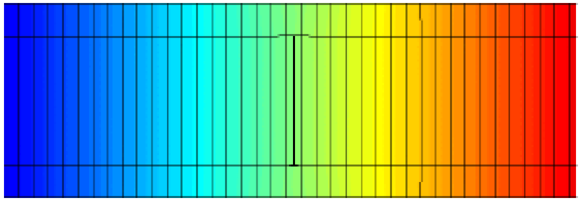


Transverse Matrix Cracks w/ One Element Per Ply

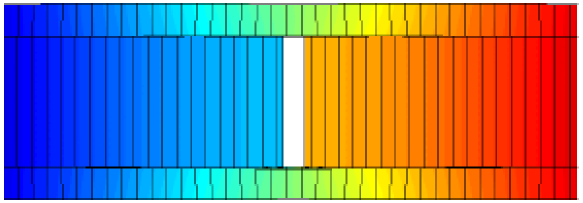
Multi-element model: correct crack evolution

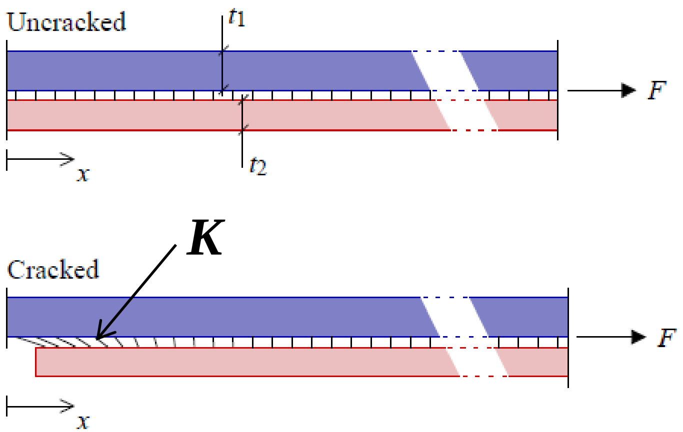


Conventional single-element: no opening w/out delam.

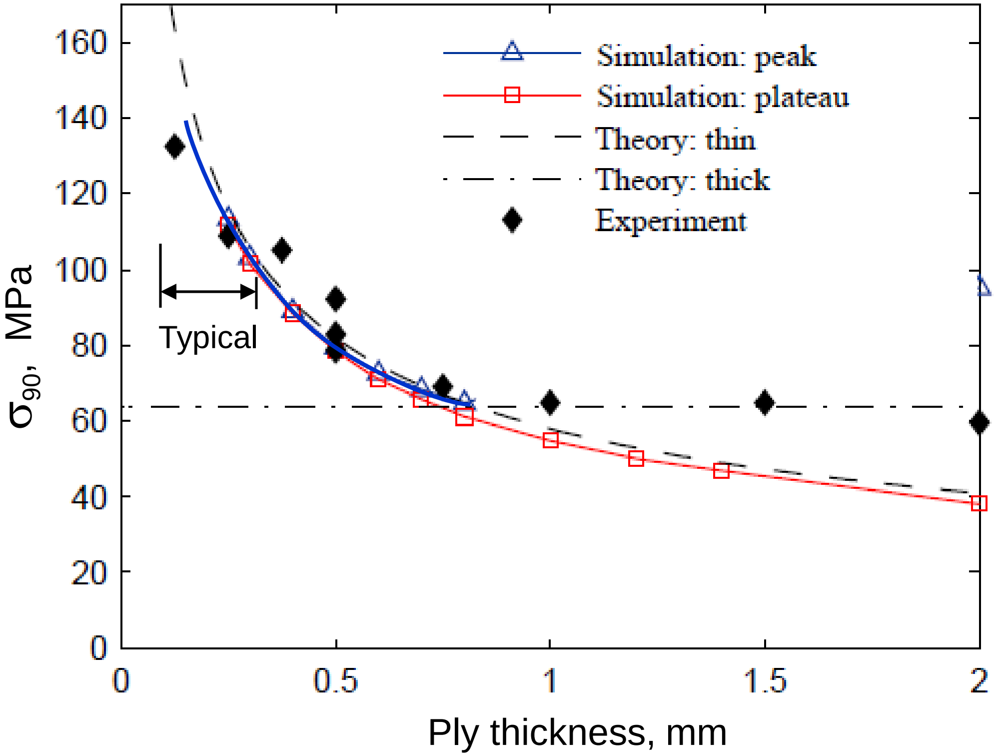


Modified single-element: correct Energy Release Rate



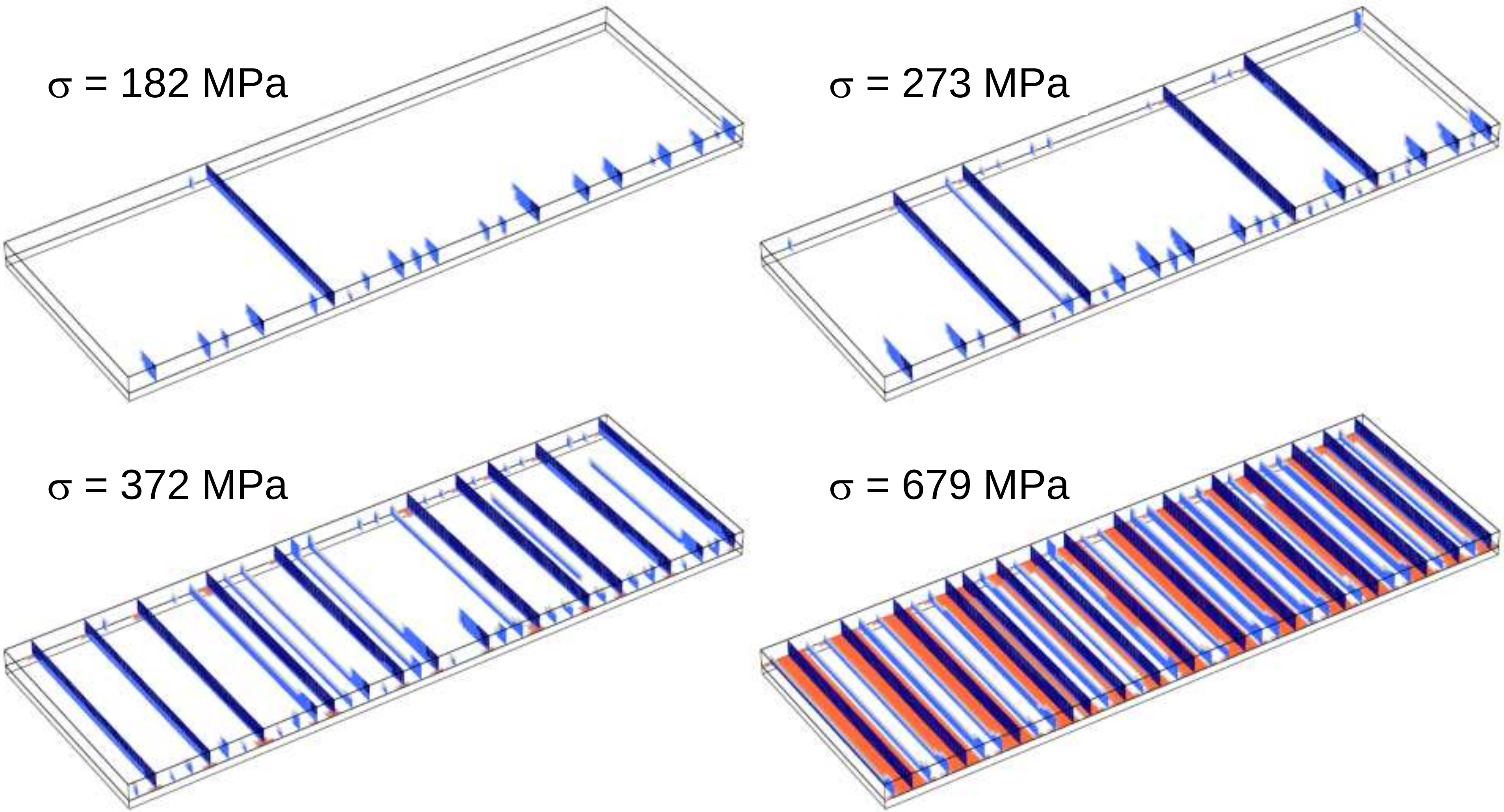


$$K \approx \frac{4E_2}{\pi^2 t}$$



Van der Meer, F.P. & Dávila, C., JCM, 2013

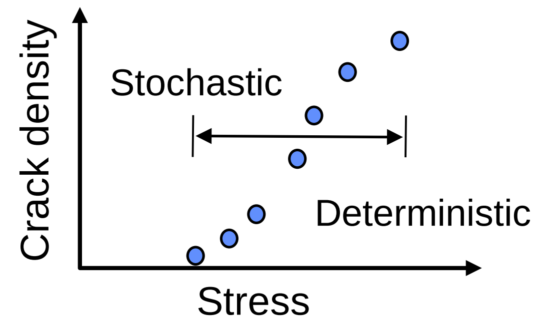
Crack Initiation, Densification, and Saturation



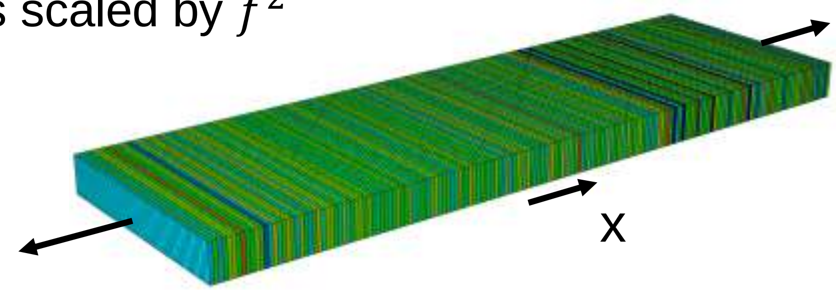
Van der Meer, F.P. & Dávila, C., JCM, 2013

Material Inhomogeneity

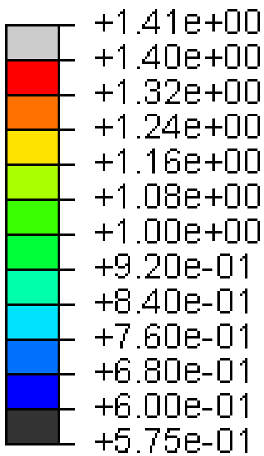
Initial crack density in a uniformly stressed laminate is strictly a function of material inhomogeneity



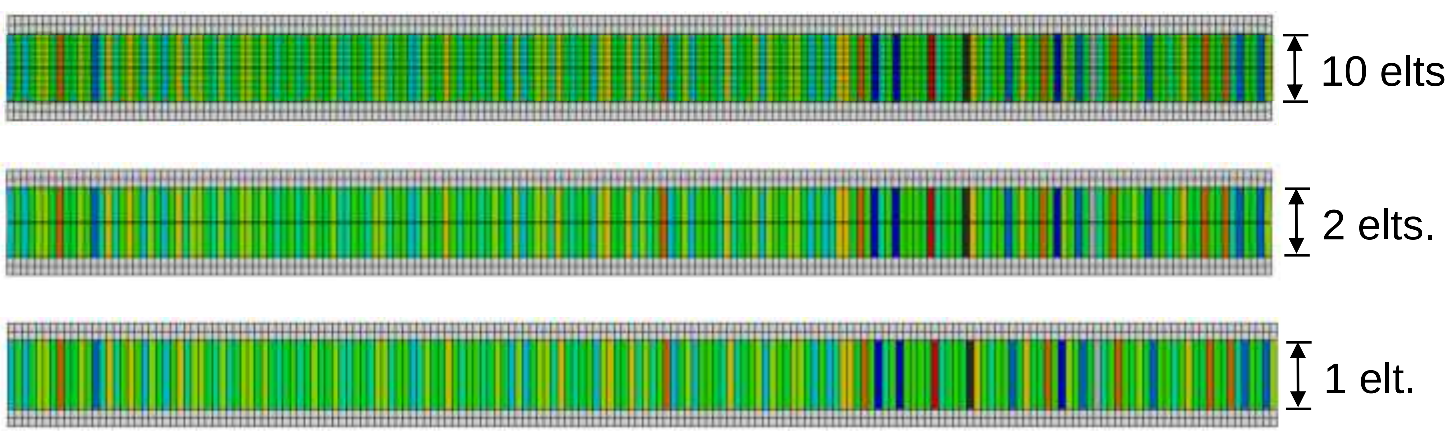
- Strength scaled by f, Fracture toughness scaled by f^2
- Constant f along each crack path



f(x)



Inhomogeneity applied to 3 levels of mesh refinement



F Leone, 2015

Effect of Transverse Mesh Density on Crack Spacing

F Leone, 2015

What Happened to Quadratic Convergence!!??

Commercial finite element vendors and developers are providing more and more tools for progressive damage analysis.

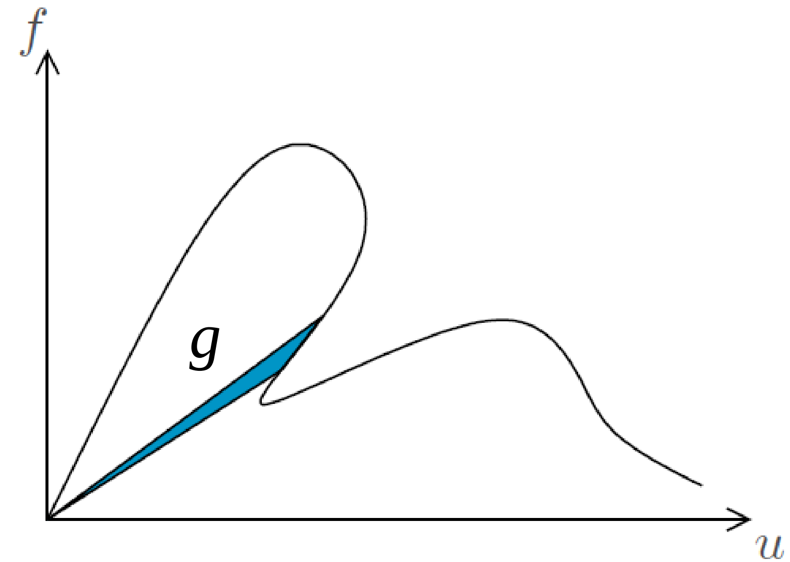
But, if the load incrementation procedures do not converge…

… more analysis tools
=
more rope!

Techniques for Achieving Solution Convergence

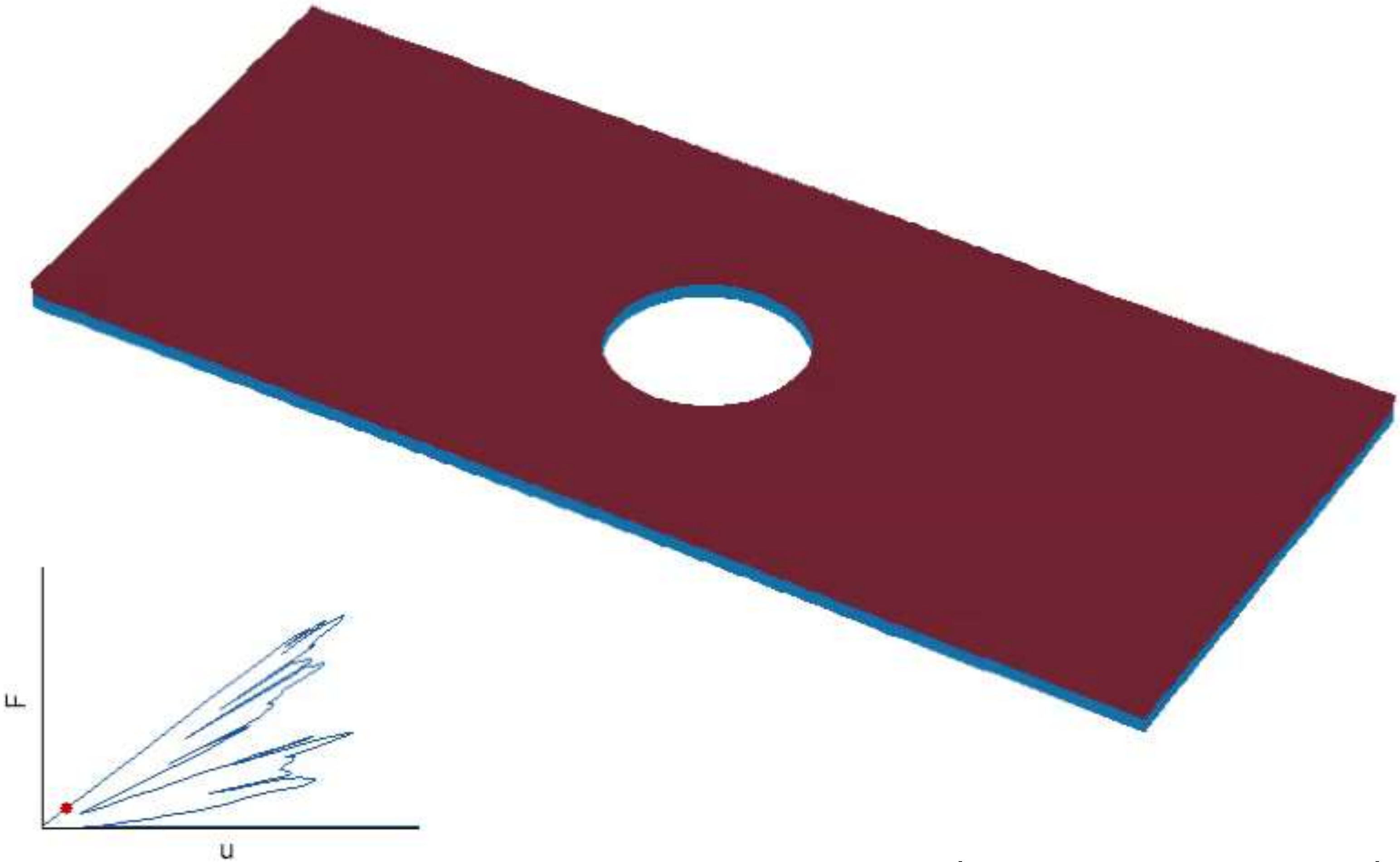
- Viscoelastic Stabilization
  - Delayed damage evolution
- Implicit dynamics or Explicit solution
- Arc-length techniques
  - Dissipation-based arc-length

Constant energy dissipation in each load increment



Gutiérrez, *Comm Numer Meth Eng (2004)*
Verhoosel et al. *Int J Numer Meth Eng (2009)*

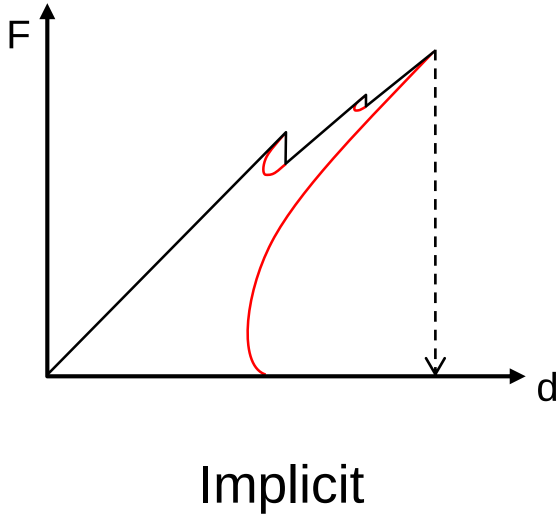
QS Solution of Unstable OHT Fracture

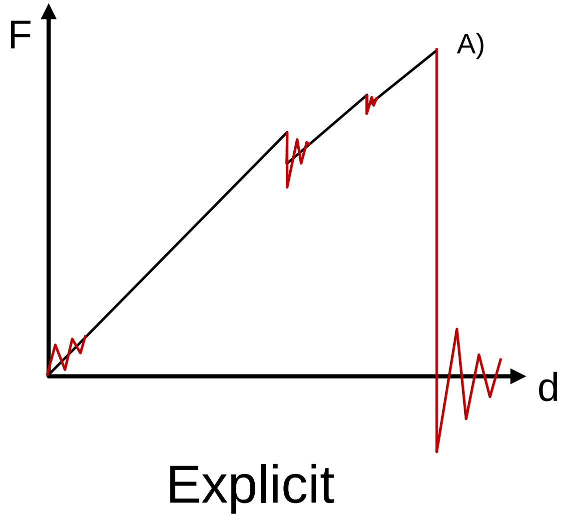


Van der Meer, *Eng Fract Mech, 2010*

Open Questions

- Is the QS solution physical?
- Are the dynamic effects necessary?
- Which solution provides more insight into failure modes?





Concluding Remarks

- A typical structural tests usually consist of three stages:
  1. QS elastic response without damage
  2. QS response with damage accumulation
  3. Dynamic collapse/rupture
- Most structural failures exhibit size effects that depend on load redistribution that occurs during the QS phases
  - Correct softening laws based on strength and toughness considerations are required
- Dynamic collapse/rupture is a result of the interaction between damage propagation and structural response
  - A stable equilibrium state often does not exist after failure under either load or displacement control
  - Onset of instability (failure) occurs when more elastic strain energy can be released by the structure than is necessary for damage propagation
  - Simulation of unstable rupture is often needed to ascertain mode of failure and to compare to test results