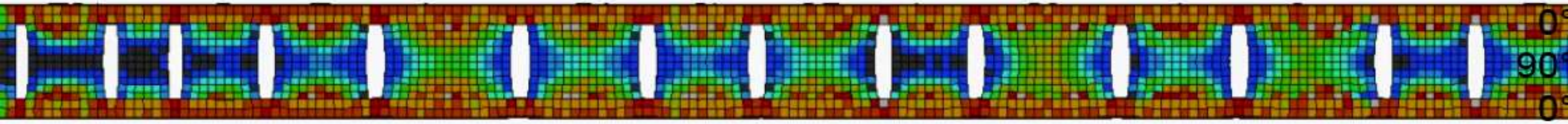
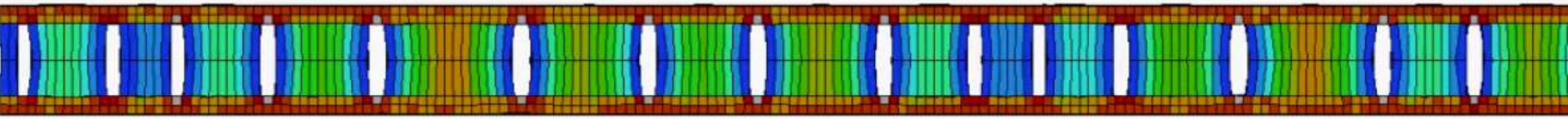


Mesh Convergence Requirements for Composite Damage Models



Carlos G. Dávila

Structural Mechanics and Concepts Branch

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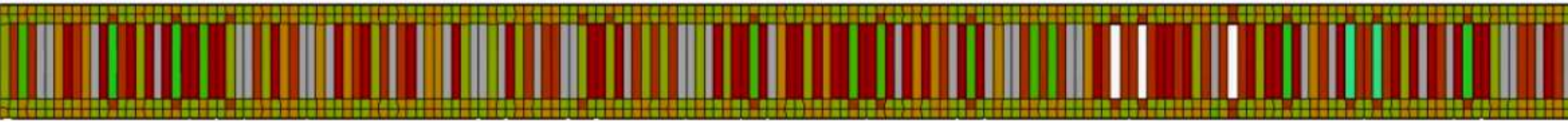
Hampton, VA



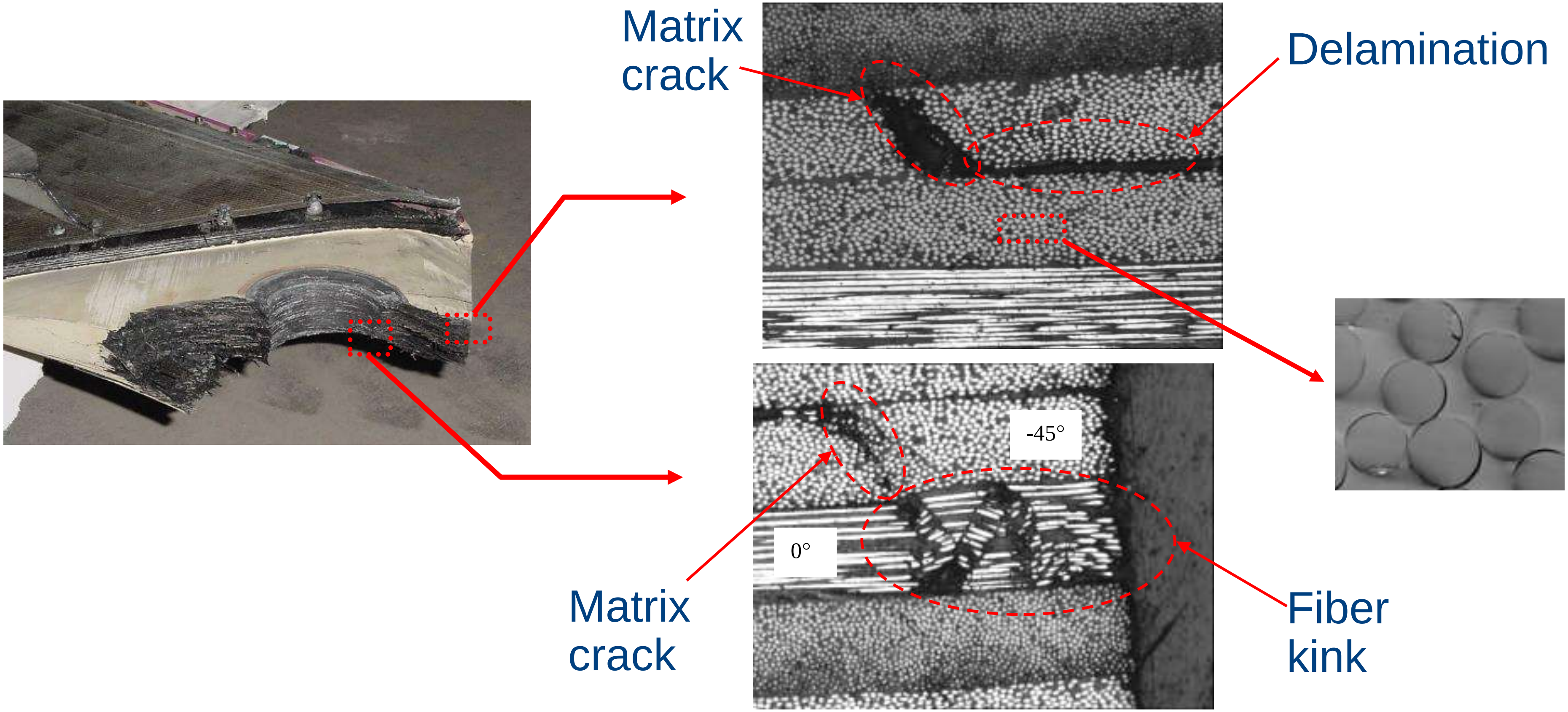
Mechanical Engineering Dept.,
TU Eindhoven, NL
17 March 2016

Outline

- Strength or Toughness?
- Cohesive Laws
- Process Zones and Load Redistribution
- Continuum Damage Models
- Transverse Matrix Cracks
- Summary

Scales of Damage in Composites

Structure → Microstructure

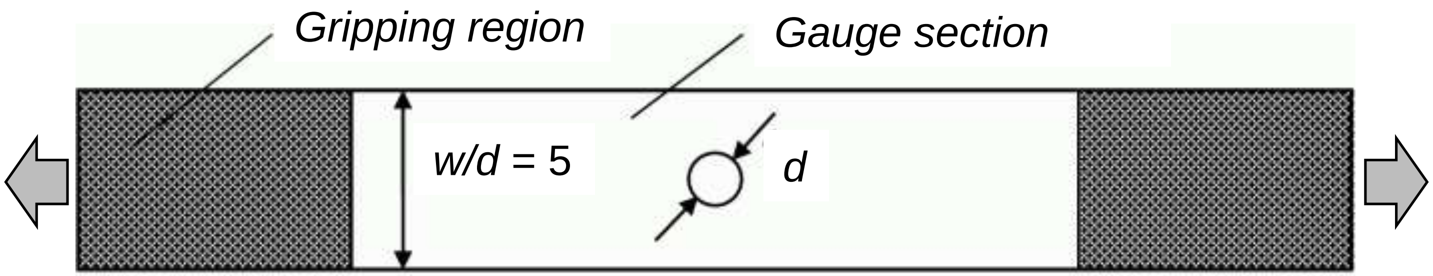


“Physics” of failure:

- At each scale, damage is described by different physical observations

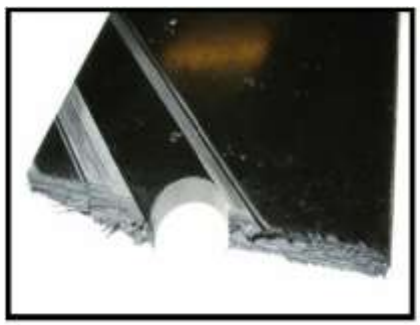
Effect of Material on Structural Response

- Quasi-isotropic laminates, three-dimensional (3-D) scaling
  - $[45_m/90_m/-45_m/0_m]_{ns}$, *m*, *n* = 1, 2, 4, 8
  - *d* = 1/8 in., ¼ in., ½ in.

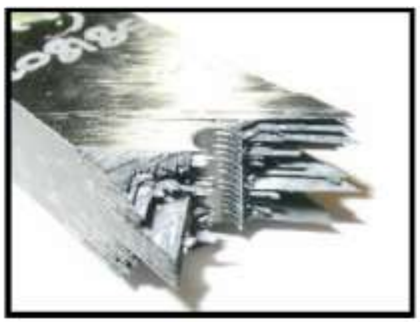


*Green and Wisnom, 2007

Thin plies → Thick plies



Brittle



Pull-out

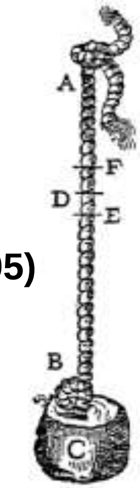
Delamination

Identical material, different modes of failure!

Scaling: the Effect of Structure Size on Strength

Strength of Materials

(da Vinci, 1505)



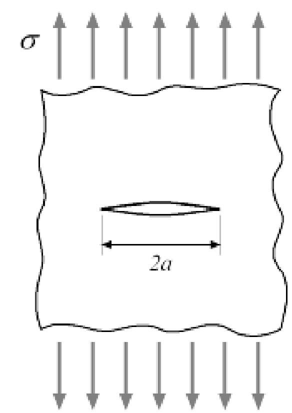
(Galileo, 1638)

Fracture Mechanics

"weakness is due to the presence of flaws"

(Griffith, 1921)

$$\sigma_u = \sqrt{\frac{E\,G_c}{\pi\,a}}$$



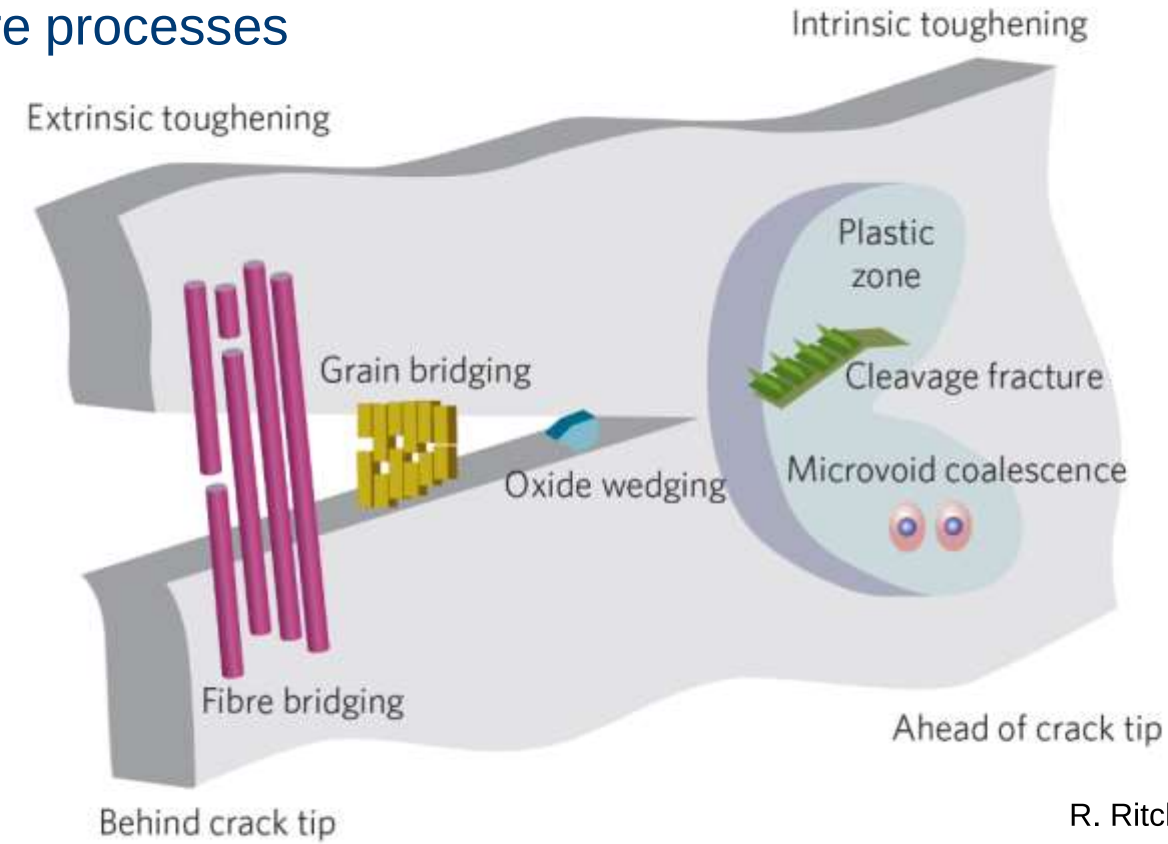
Statistical Theory of Size Effect

(Mariotte, 1686)

(Weibull, 1939)

Damage Length Scales in Structural Materials

Idealization of fracture processes

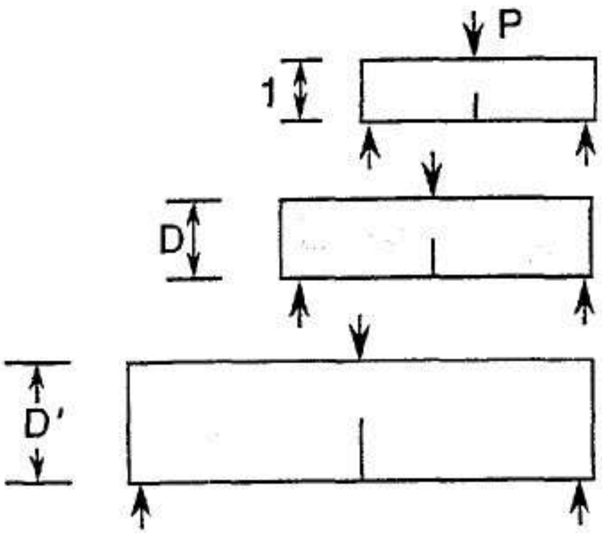


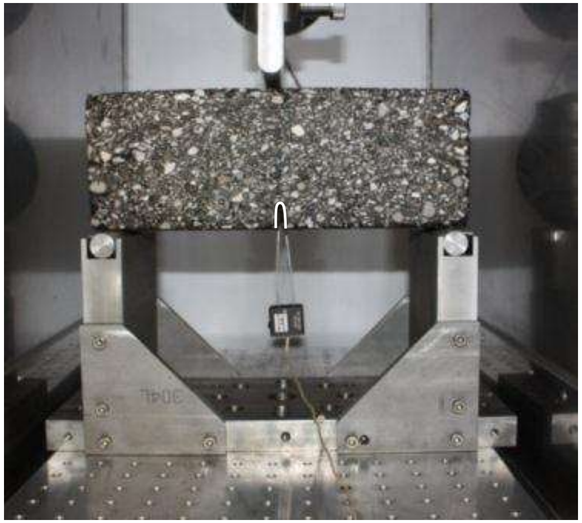
R. Ritchie, 2011

Strength versus toughness:

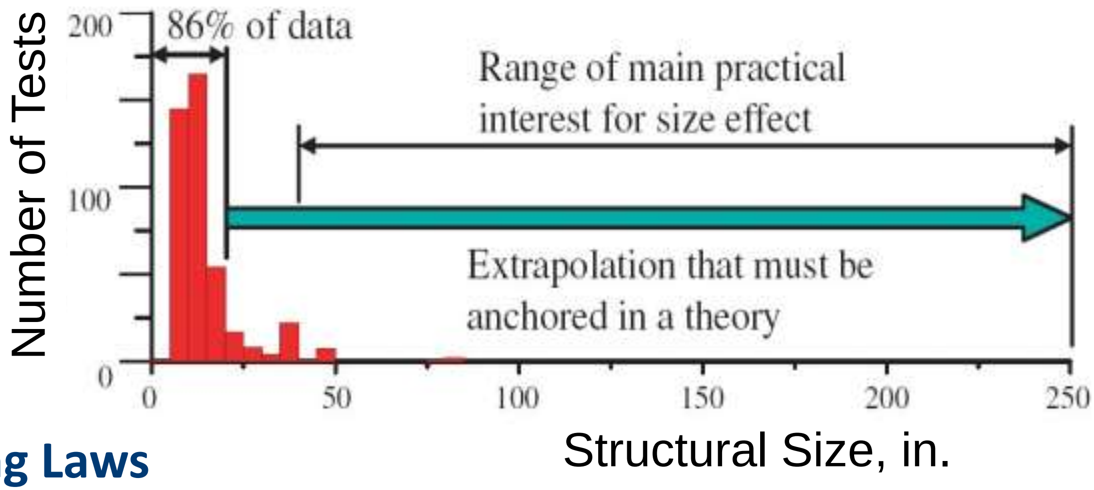
- Strength and toughness is the result of the interplay between a number of individual mechanisms originating at different length scales.
- Some damage mechanisms inhibit crack propagation.

Size Effect - the Issue of Scale



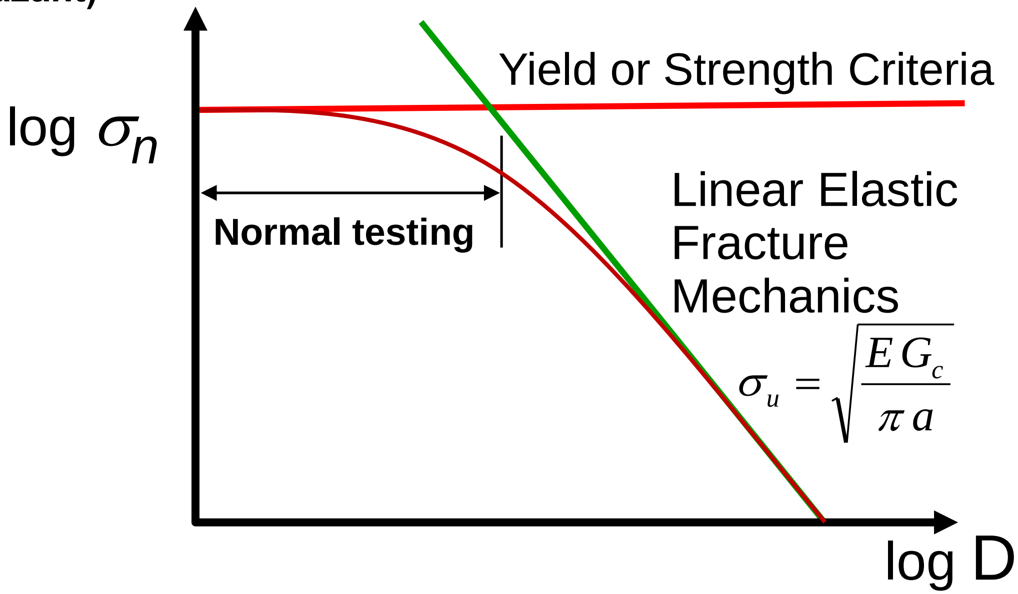


Scaling from test coupon to structure

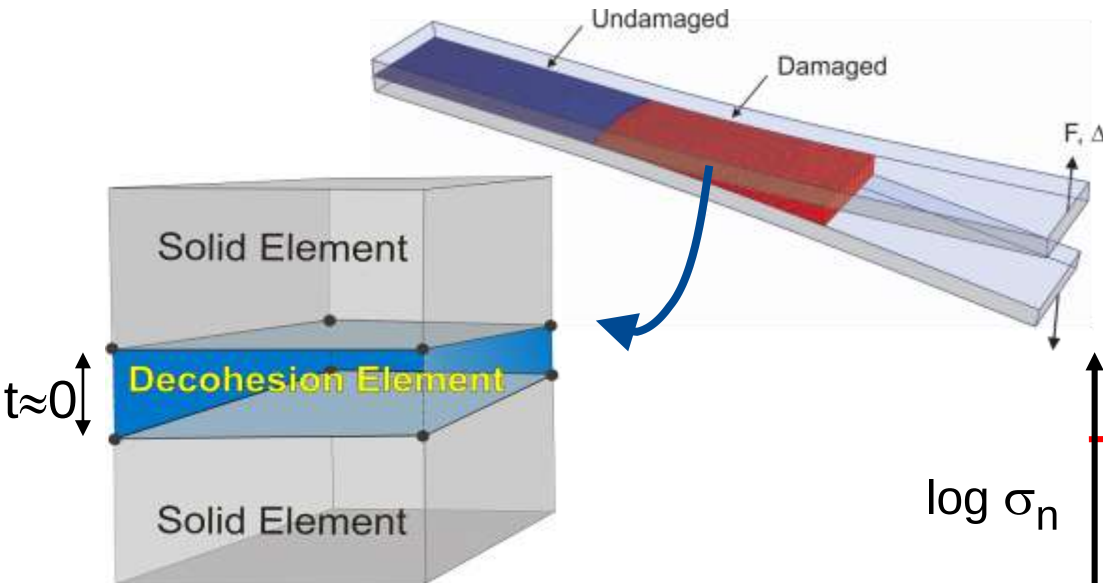


Scaling Laws

(Z. Bažant)

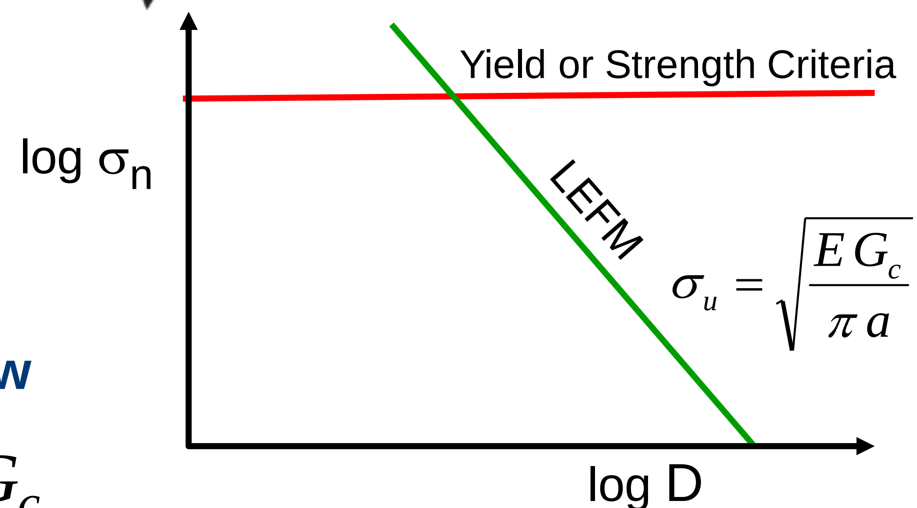


Cohesive Laws



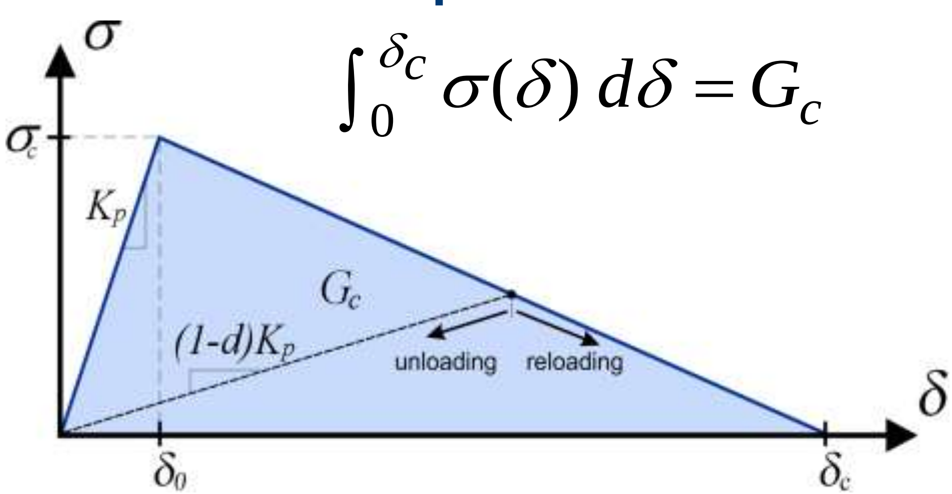
Two material properties:

- G_c Fracture toughness
- σ_c Strength



Bilinear Traction-Displacement Law

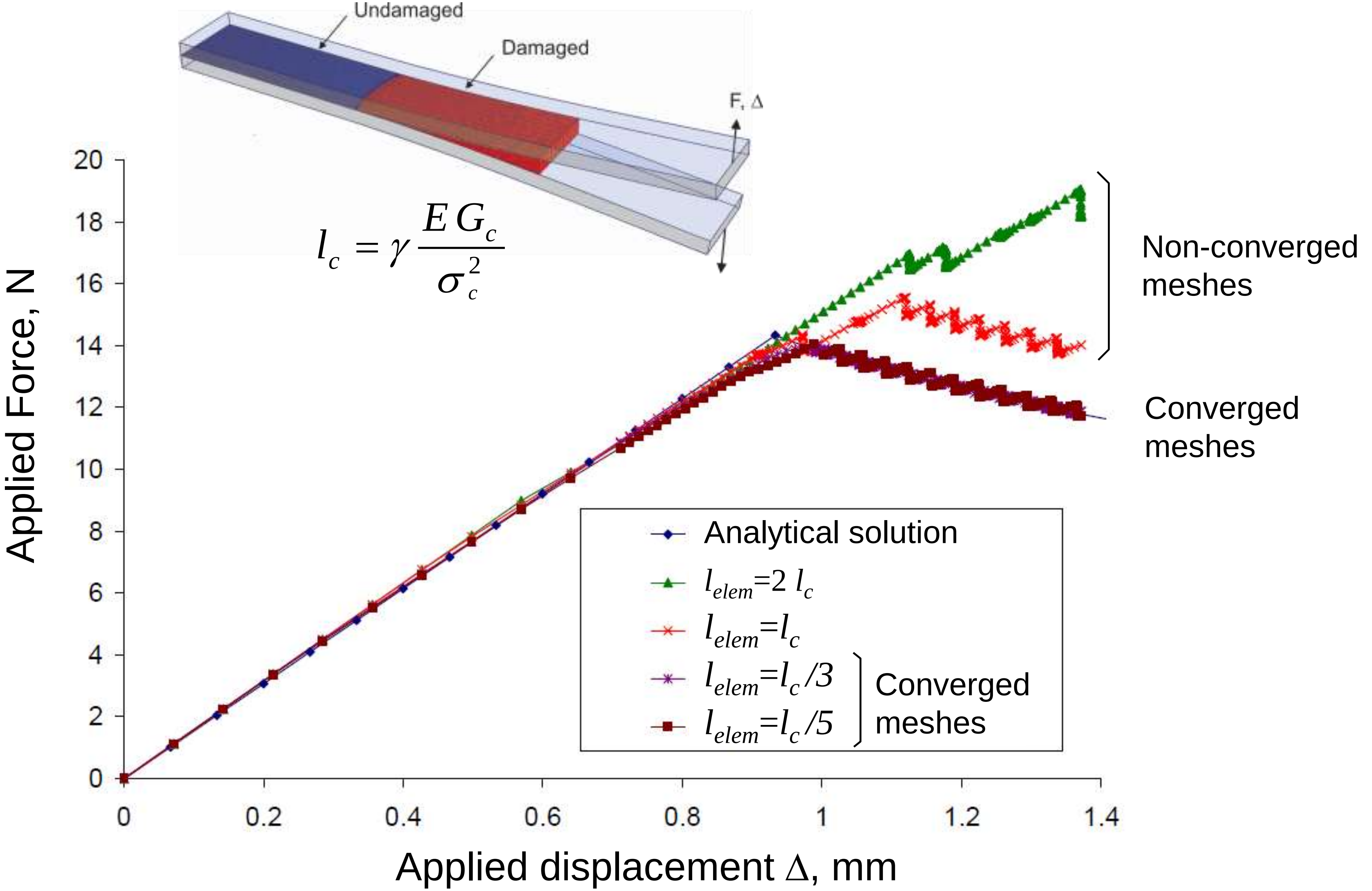
$$\int_0^{\delta_c} \sigma(\delta)\, d\delta = G_c$$



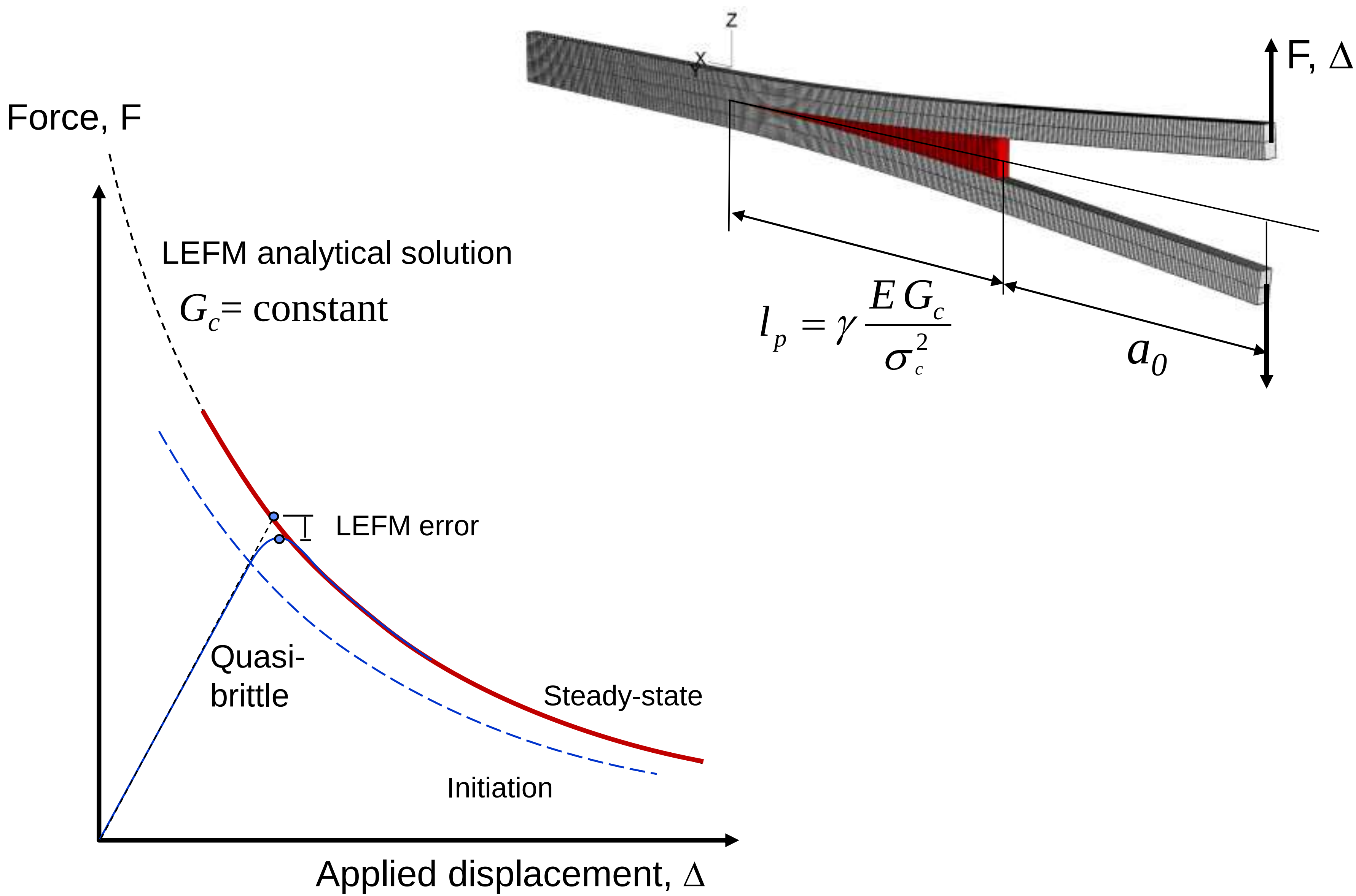
Characteristic Length:

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

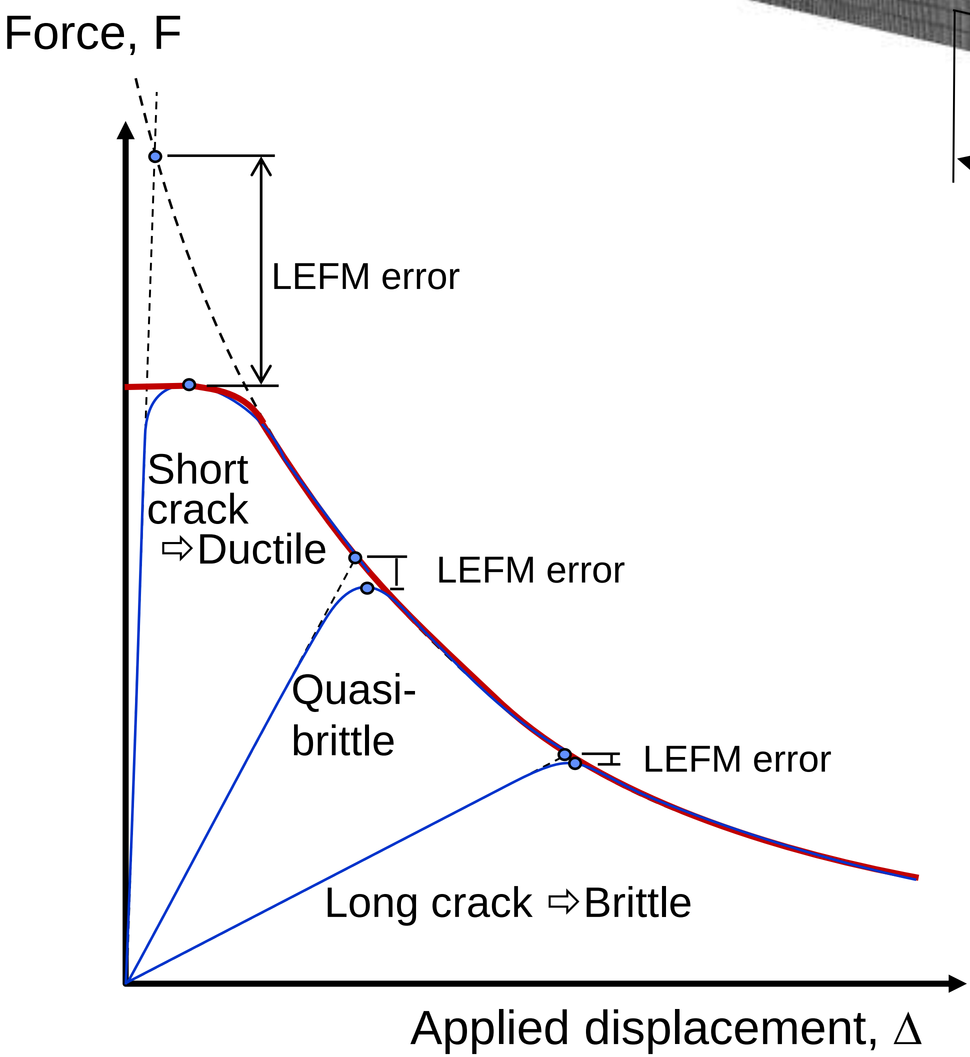
Mesh Convergence Studies

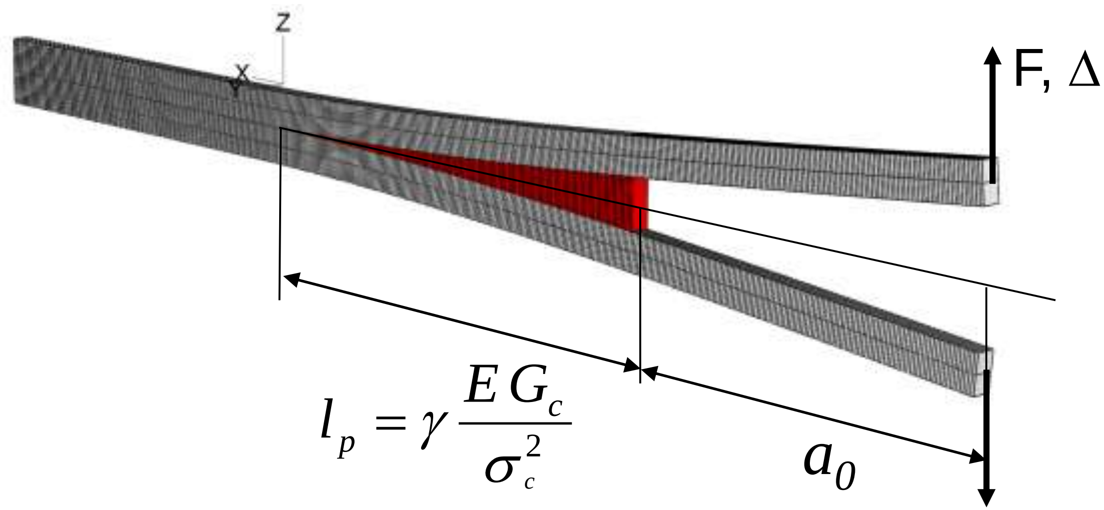


Crack Length and Process Zone



Crack Length and Process Zone





Brittle:

$$a_0 > 100\ l_p$$

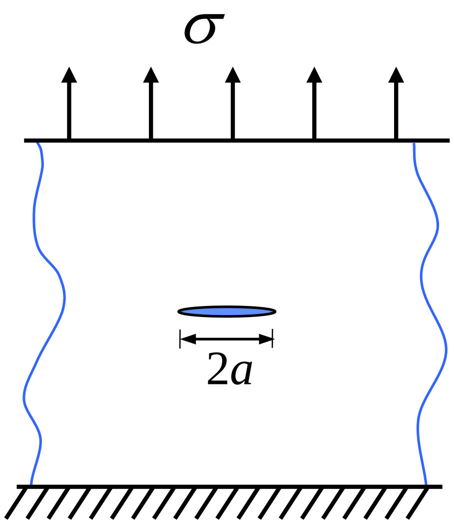
Quasi-brittle:

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

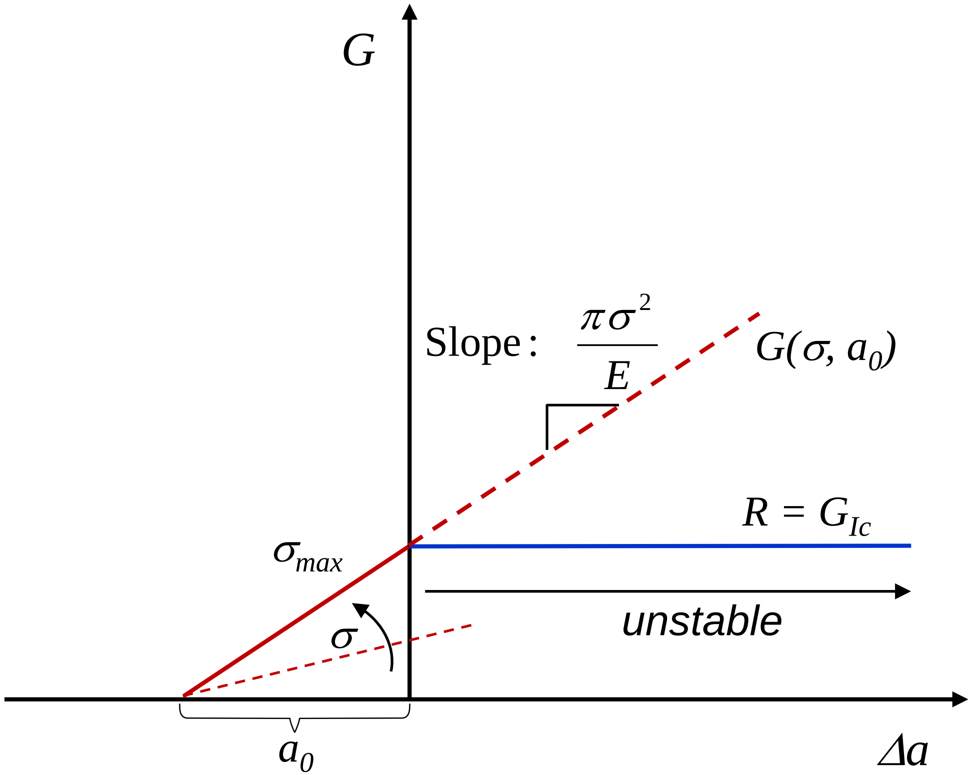
Ductile:

$$5\ l_p > a_0$$

Fracture-Dominated Failure

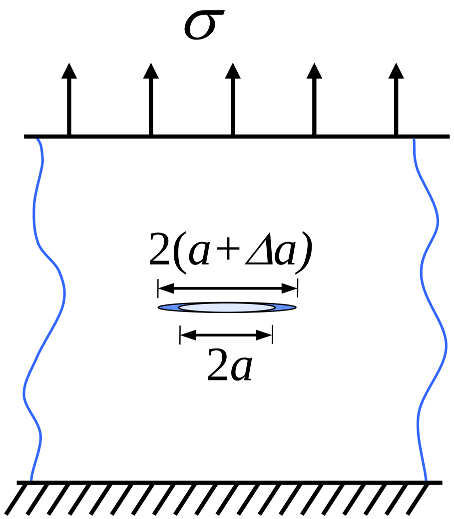


$$G = \frac{\pi \sigma^2 a}{E}$$

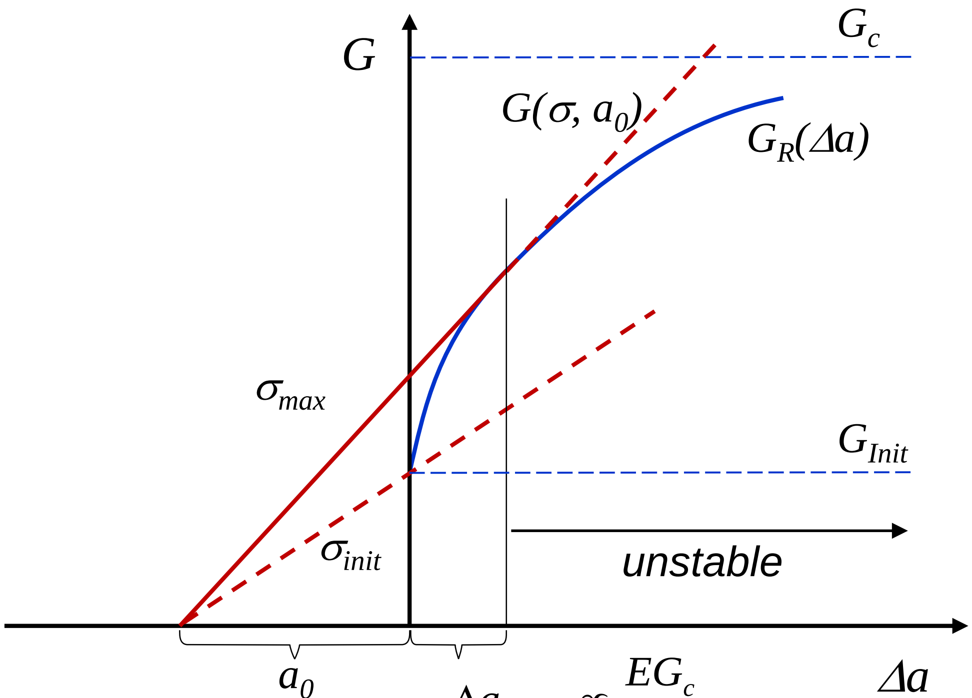


Crack propagates unstably once driving force $G(\sigma, a_0)$ reaches G_{Ic}

Fracture-Dominated Failure: R-Curve



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



$$\Delta a_{stable} \propto \frac{EG_c}{\sigma_c^2}$$

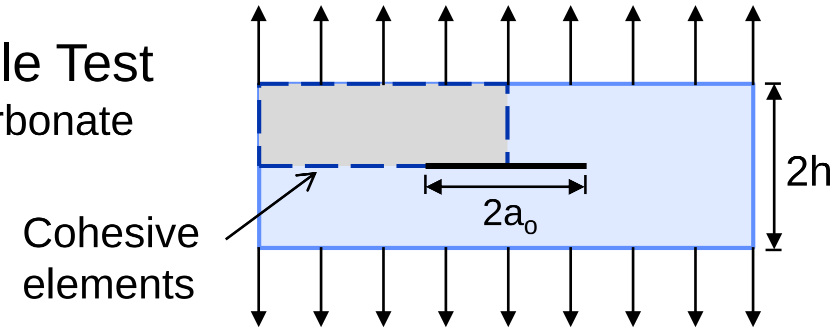
Crack propagates stably when driving force $G(\sigma, a_0) > G_{Init}$

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

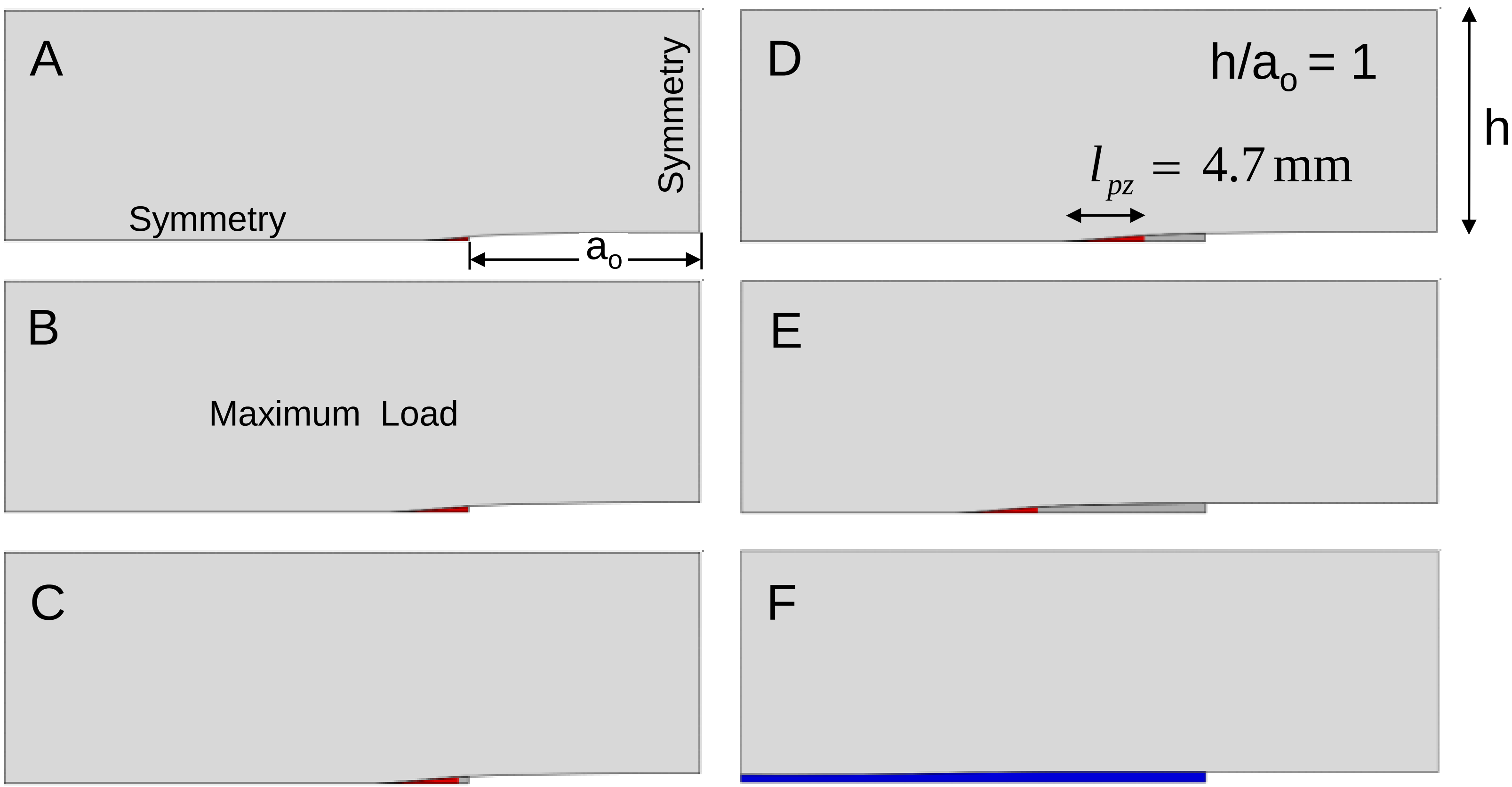
Length of the Process Zone

Short Tensile Test

Lexan Polycarbonate



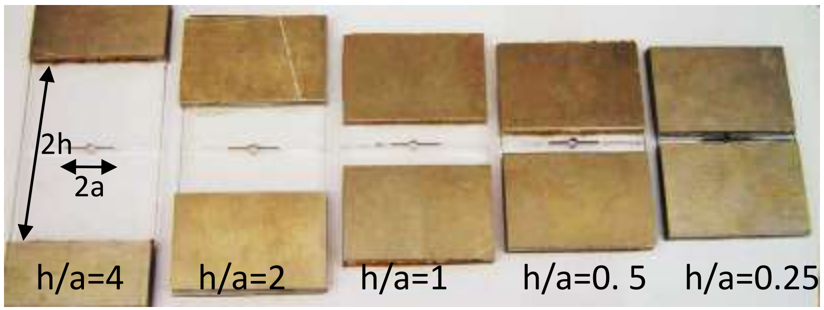
$$l_c \approx 0.6 \frac{E\,G_c}{\sigma_c^2} = 3.4\,\mathrm{mm}$$



Cohesive Laws - Prediction of Scale Effects

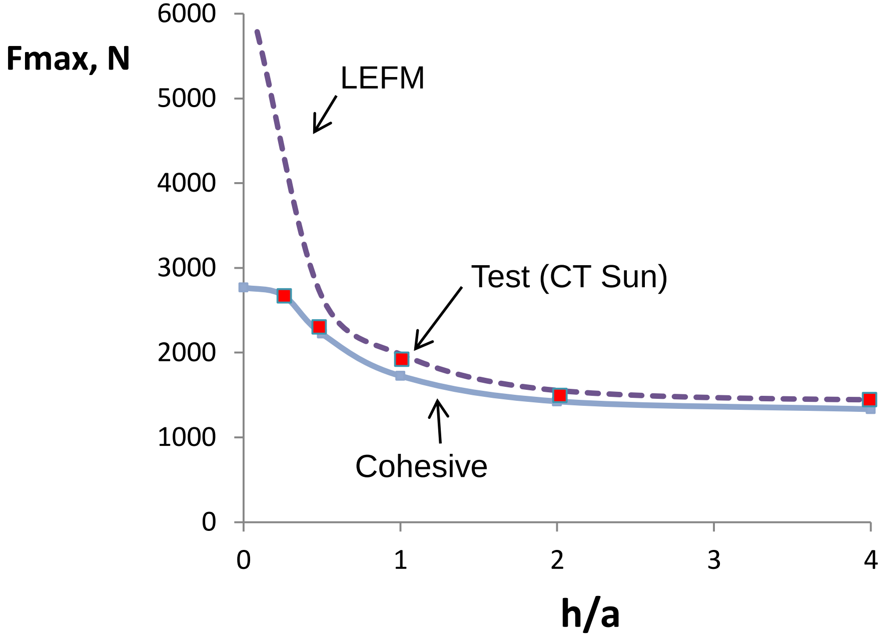
- The use of cohesive laws to predict the fracture in complex stress fields is explored
- The bulk material is modeled as either elastic or elastic-plastic

Lexan Plexiglass tensile specimens (CT Sun)

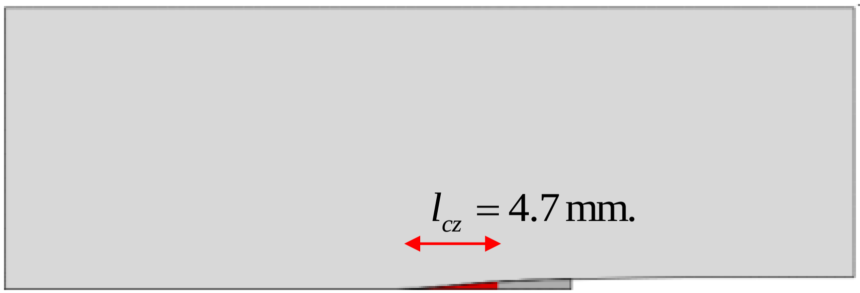


Observations:

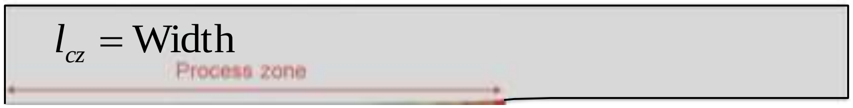
- LEFM overpredicts tests for h/a<1



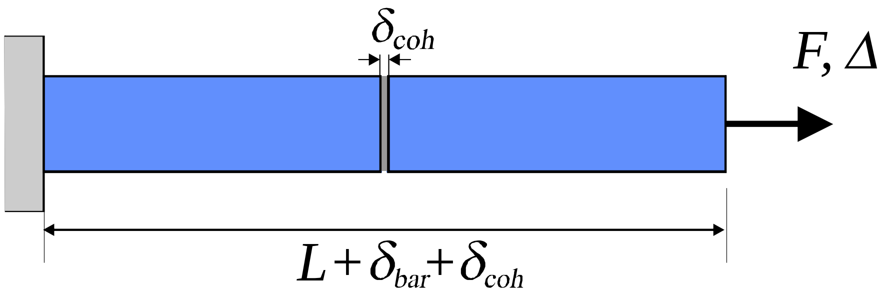
h/a=1 (short process zone)

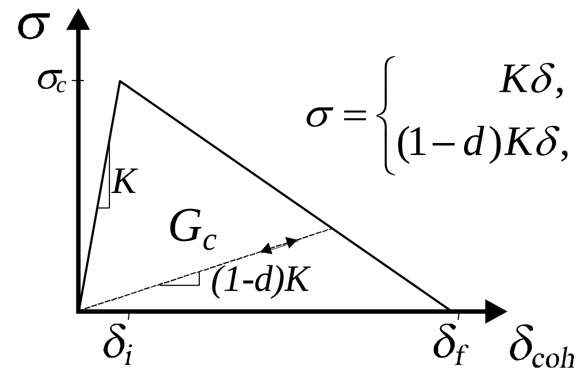


h/a = 0.25 (long process zone)



Quasi-Brittle Response and Fracture





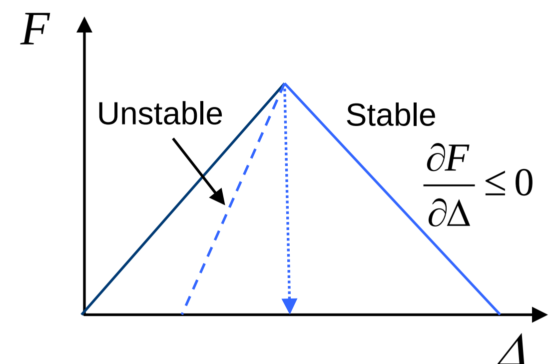
$$\sigma = \begin{cases} K\delta, & \delta < \delta_i \\ (1-d)K\delta, & \delta_i \le \delta < \delta_f \end{cases}$$

Before damage

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

After damage

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



For stable fracture under Δ control: $\frac{\partial F}{\partial \Delta} \le 0 \Rightarrow L \le \frac{2EG_c}{\sigma_c^2}$

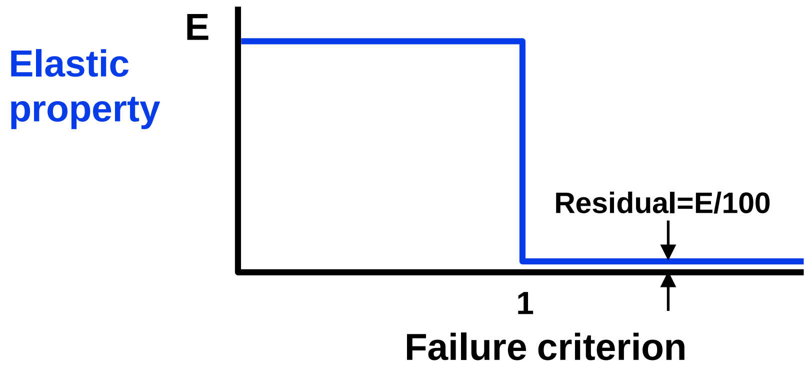
For “long” beams, the response is unstable, dynamic, and independent of Gc

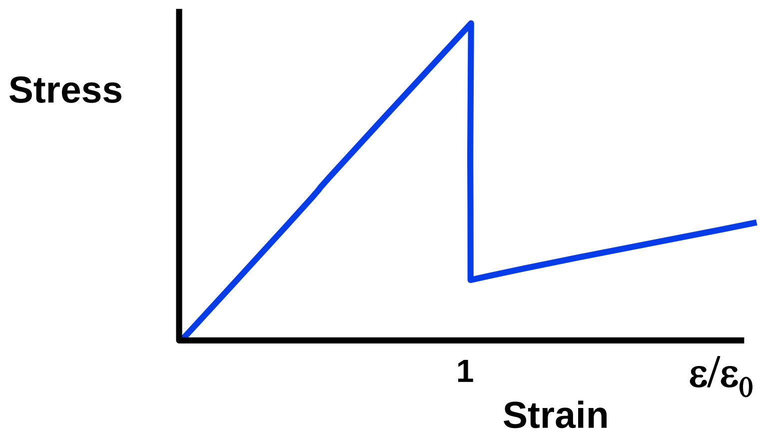
Outline

- Strength or Toughness?
- Cohesive Laws
- Process Zones and Load Redistribution
- **Continuum Damage Models (CDM)**
- Transverse Matrix Cracks
- Summary

Failure Criteria and Material Degradation

Progressive Failure Analysis





Benefits

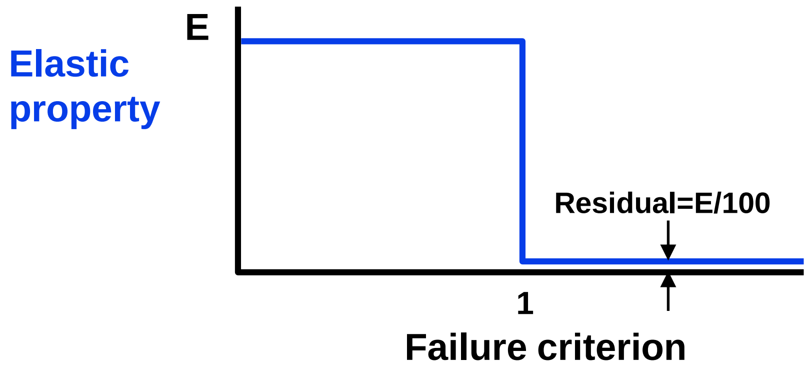
- Simplicity (no programming needed)
- Convergence of equilibrium iterations

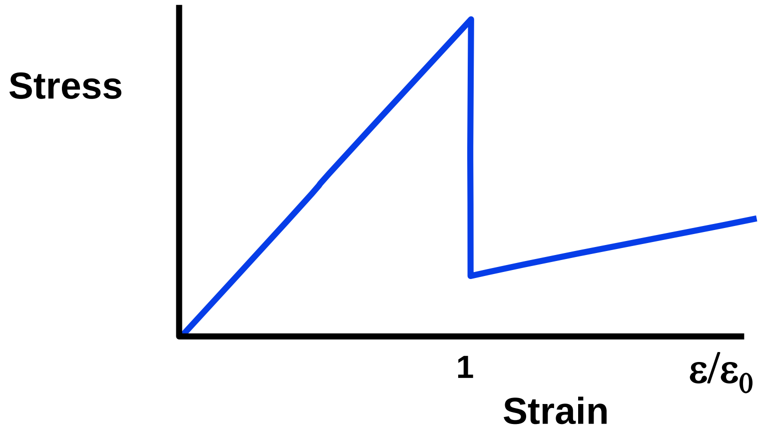
Drawbacks

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

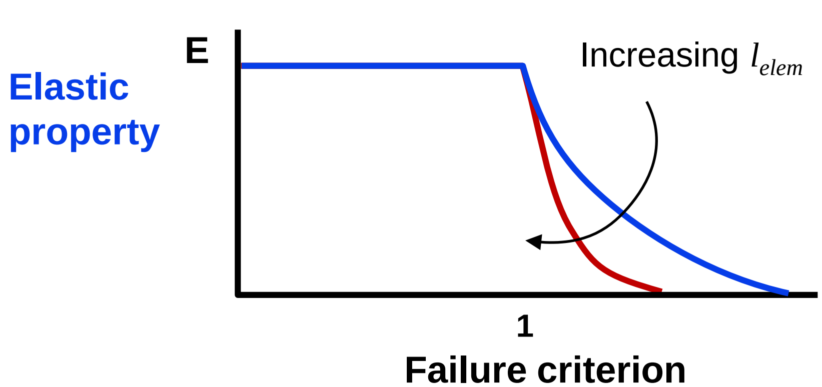
Failure Criteria and Material Degradation

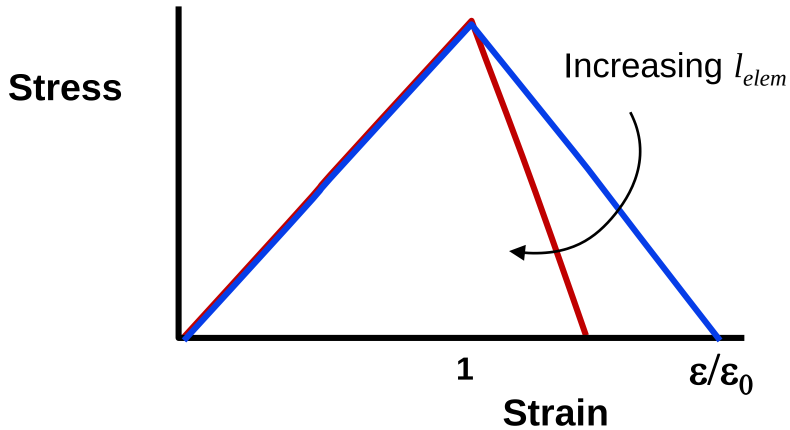
Progressive Failure Analysis



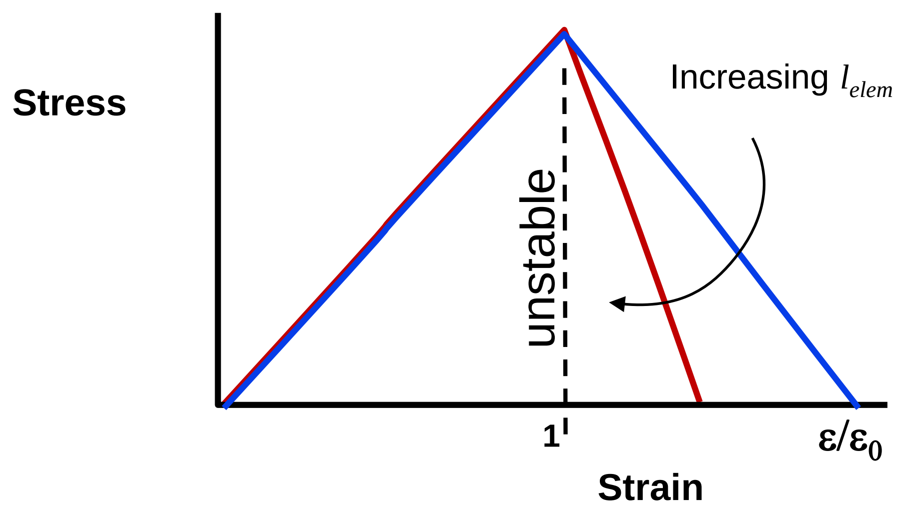


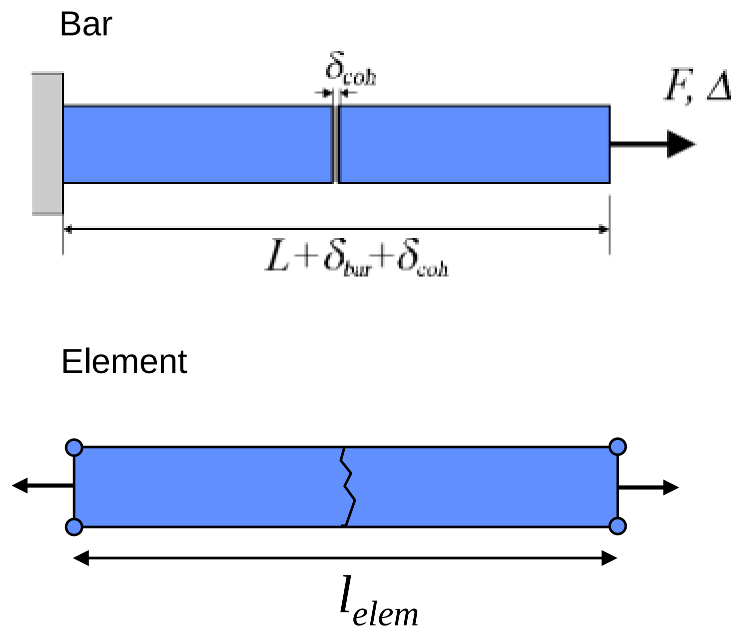
Progressive Damage Analysis – Regularized Softening Laws





Failure Criteria and Material Degradation





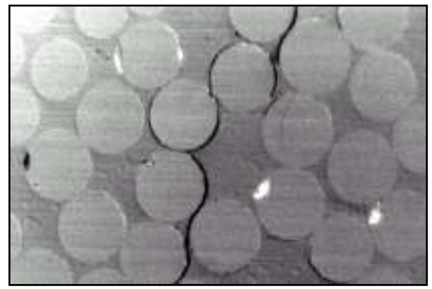
Critical Element size (snap-back):

$$l_{elem} \leq \frac{2EG_c}{\sigma_c^2}$$

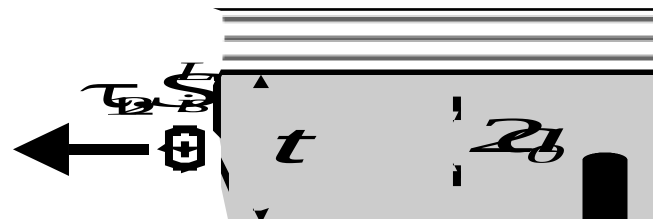
Advanced Failure Criteria for Laminated Composites

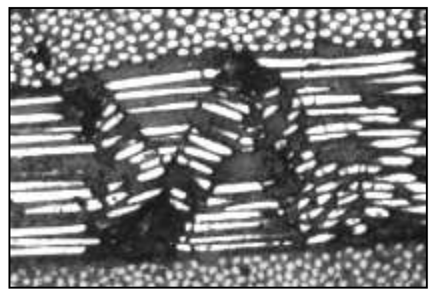
Failure Criteria: equations based on stresses and strengths that represent the initiation of damage mechanisms

LaRC04 Criteria
- In-situ matrix strength prediction
- Advanced fiber kinking criterion
- Prediction of angle of fracture

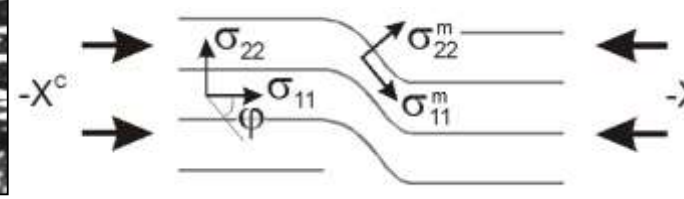


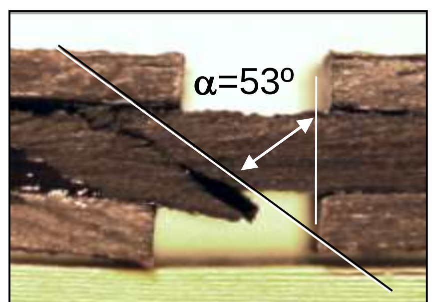
Matrix Tension & Shear



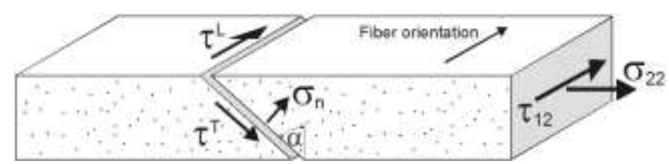


Fiber Compression





Matrix Compression and Shear

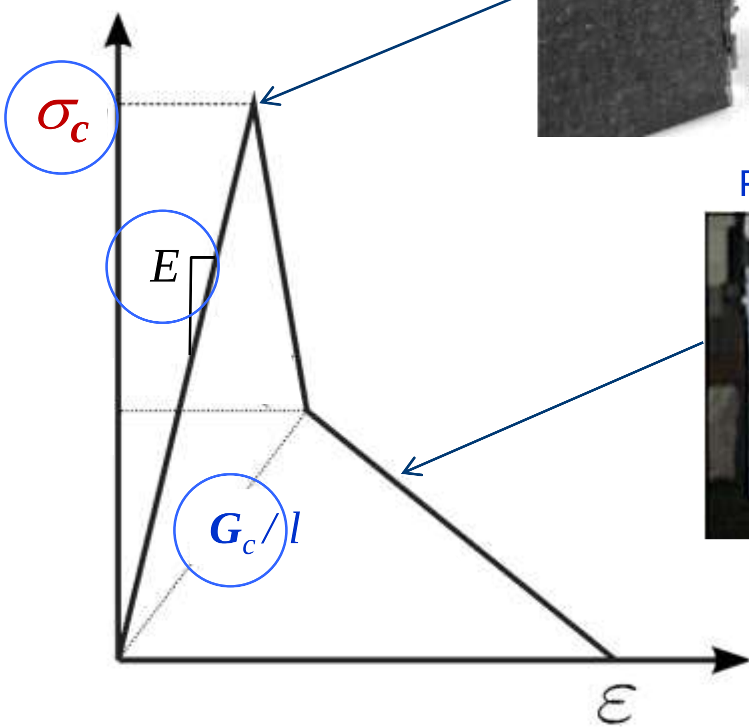


LaRC02 - Dávila, Rose et al., 2003
LaRC04 - Pinho, et al., 2005

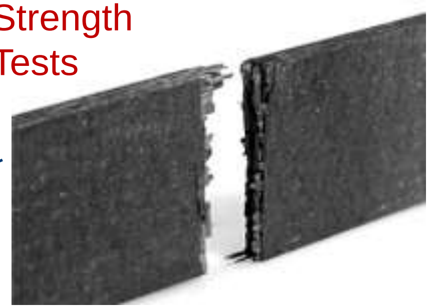
Size Effect and Material Softening Laws

Damage Evolution Laws:

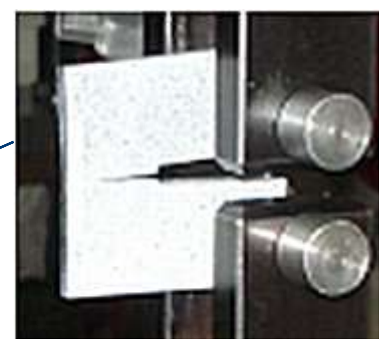
Each damage mode has its own softening response



Strength Tests

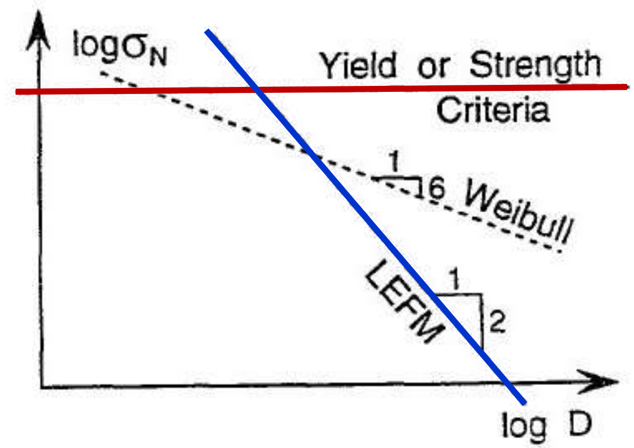


Fracture Tests



Two material properties:

- σ_c Strength
- G_c Fracture toughness

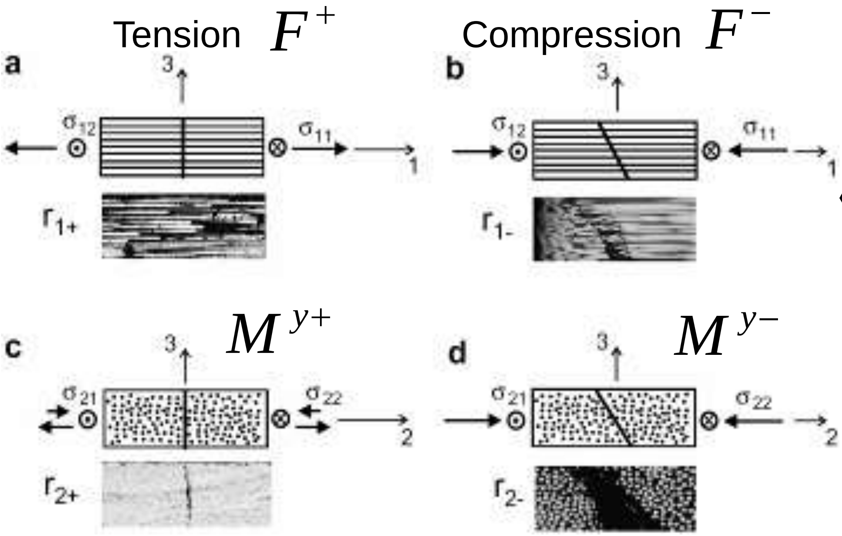


Material length scale

$$l_c \approx 0.6 \frac{E\, G_c}{\sigma_c^2}$$

Continuum Damage Model (CDM) (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 damage mechanics

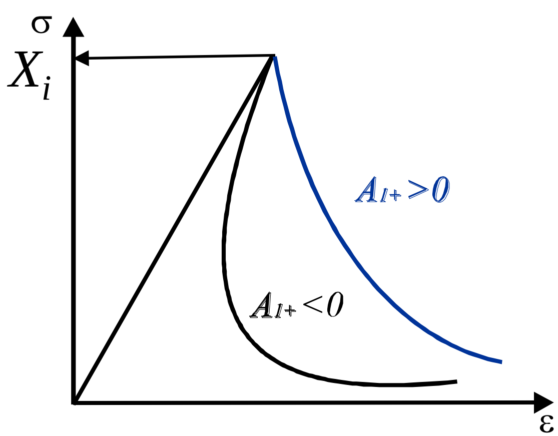
$$d_i = 1 - \frac{1}{f_i}\exp\left(A_i\left(1 - f_i\right)\right)$$

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 CBT:

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

Critical (maximum) finite element size:

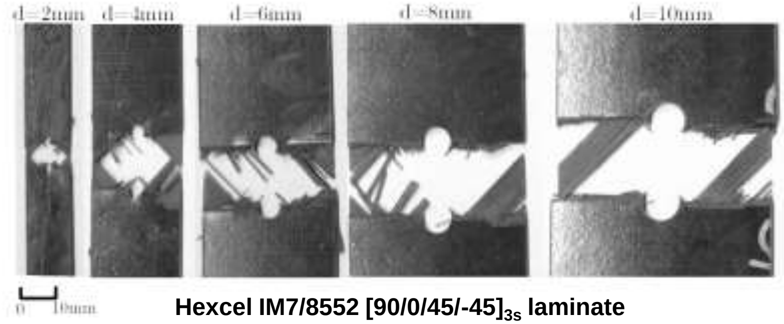
$$l^* \leq \frac{2 E_i G_i}{X_i^2}$$

Scale Effect in Open Hole Tension (OHT)

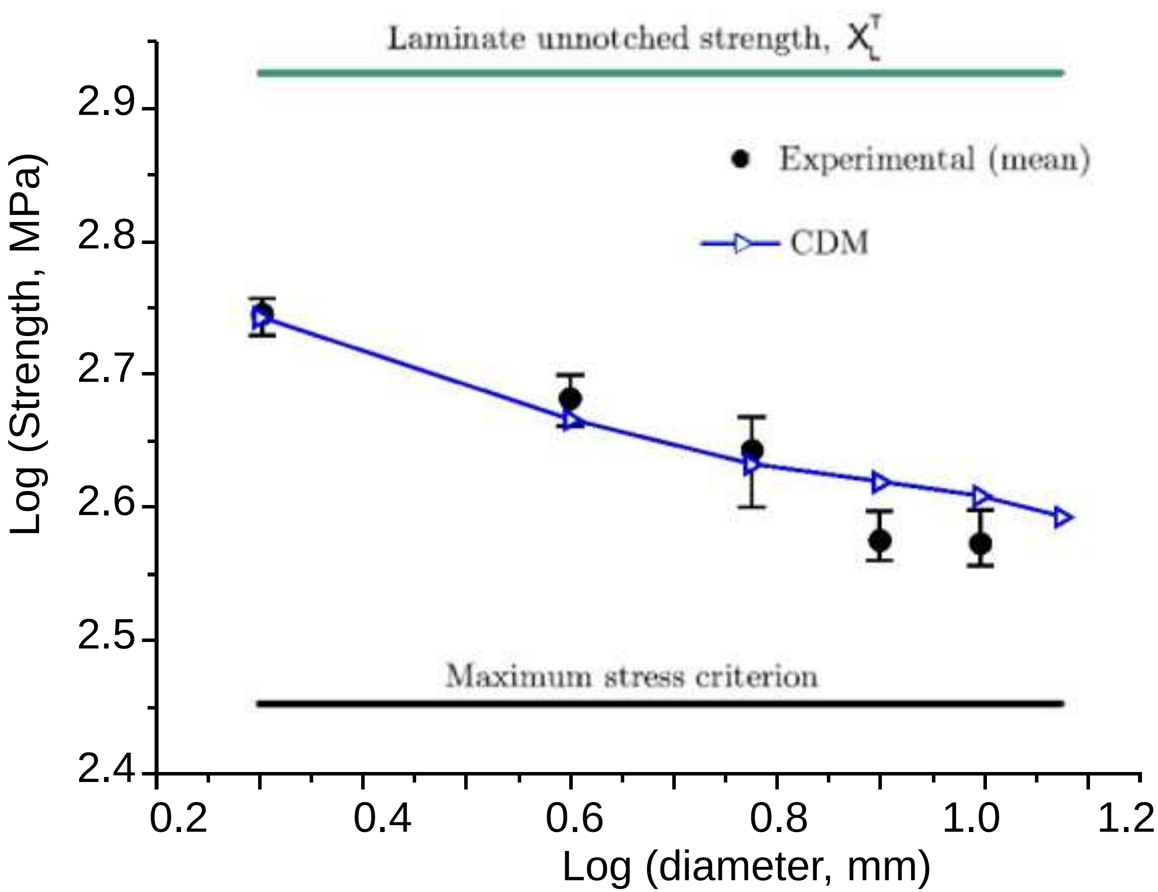
Prediction of size effects in notched composites

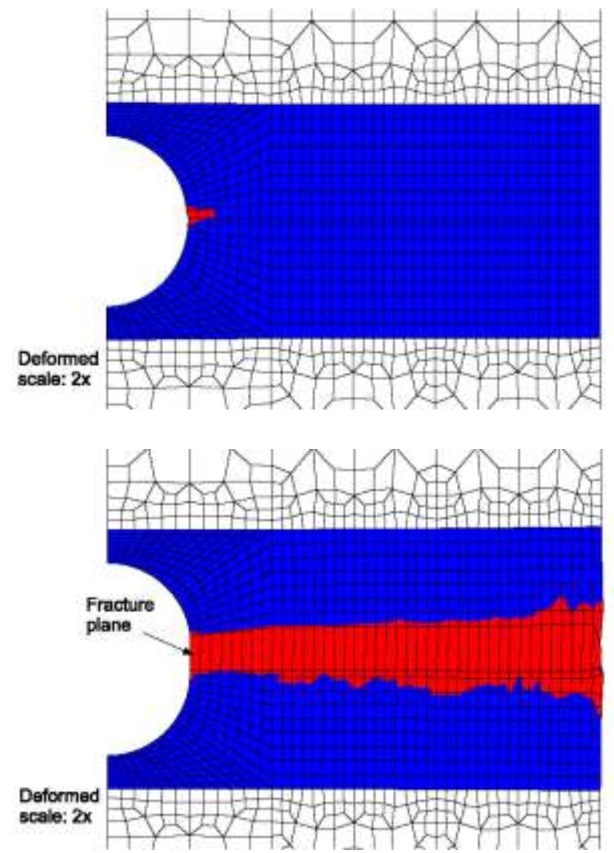
- Stress-based criteria predict no size effect.
- CDM damage model predicts scale effects w/out calibration.

(P. Camanho, 2007)

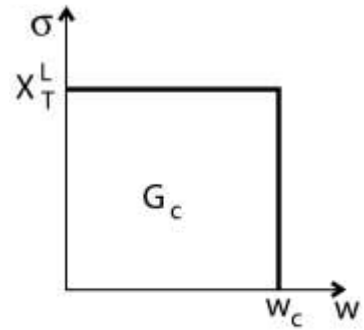


Hexcel IM7/8552 [90/0/45/-45]$_{3s}$ laminate

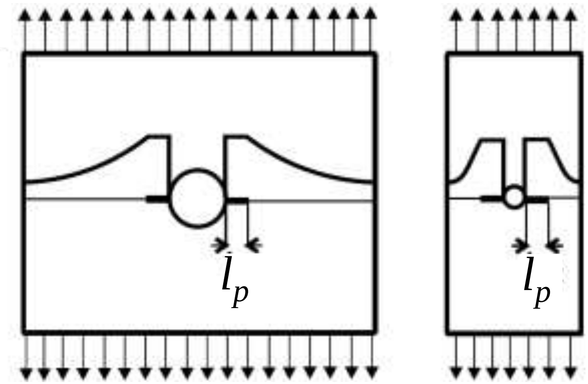




Process Zone and Scale Effect in OHT

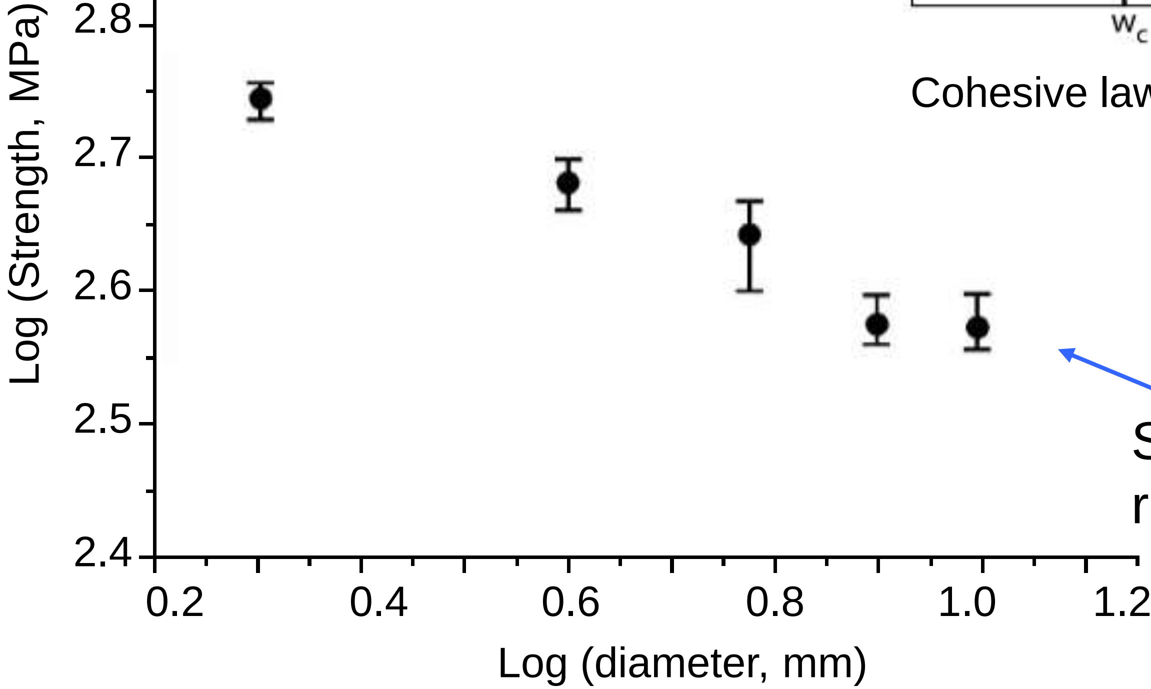


Cohesive law



Stress distribution

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



Scale effect is due to relative size of process zone

"Both energy and stress criteria are necessary conditions for fracture but neither one nor the other are sufficient."

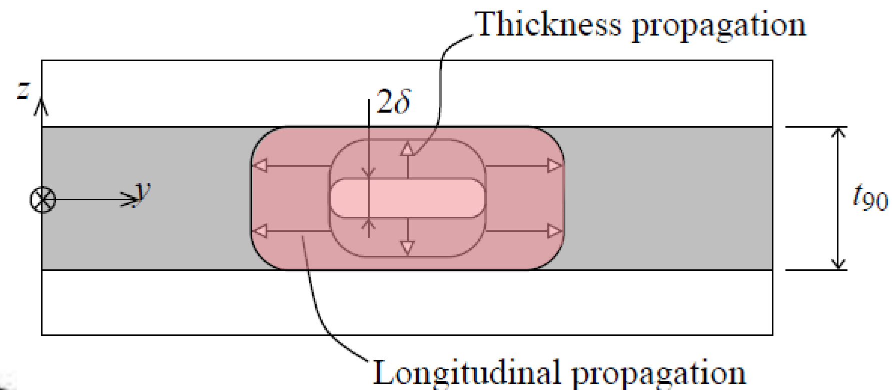
(Leguillon, E J of Mech and Solids, 2001)

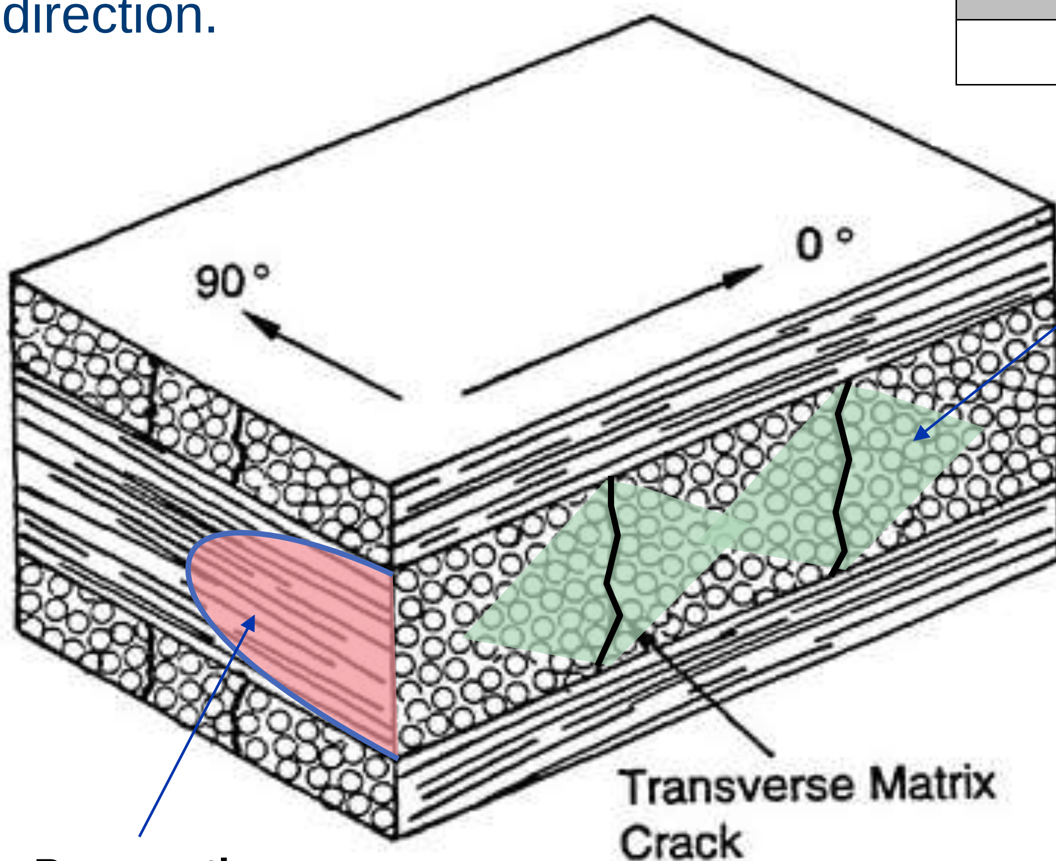
Outline

- Strength or Toughness?
- Cohesive Laws
- Process Zones and Load Redistribution
- Continuum Damage Models
- **Transverse Matrix Cracks**
- Summary

Transverse Matrix Cracks

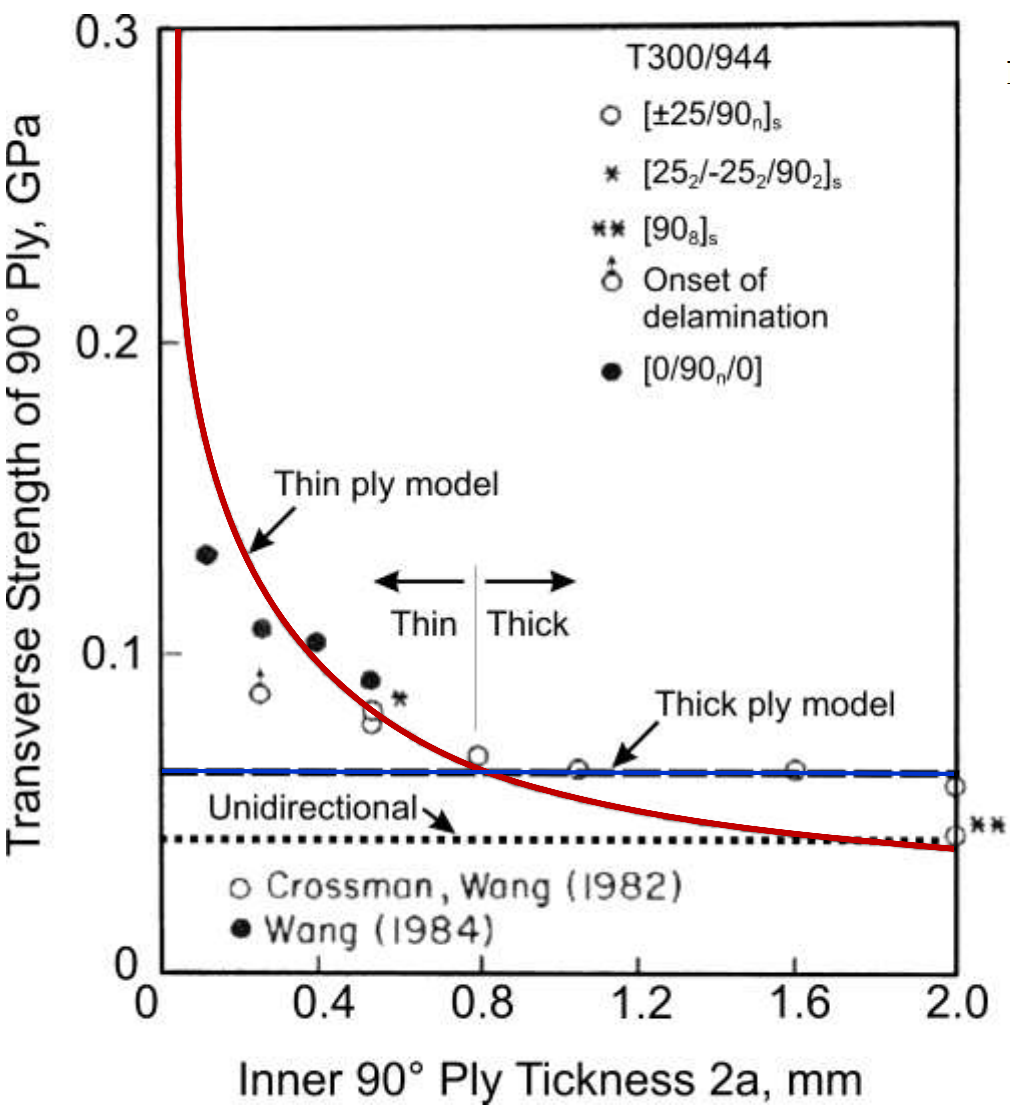
Transverse matrix cracks propagate in thickness direction and in the fiber direction.

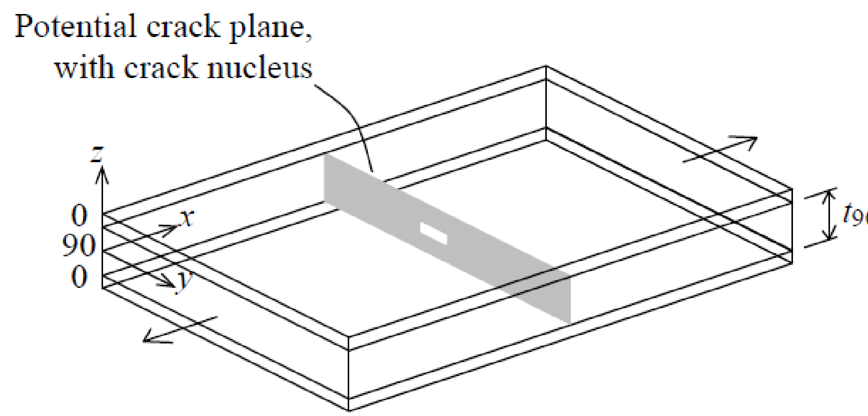


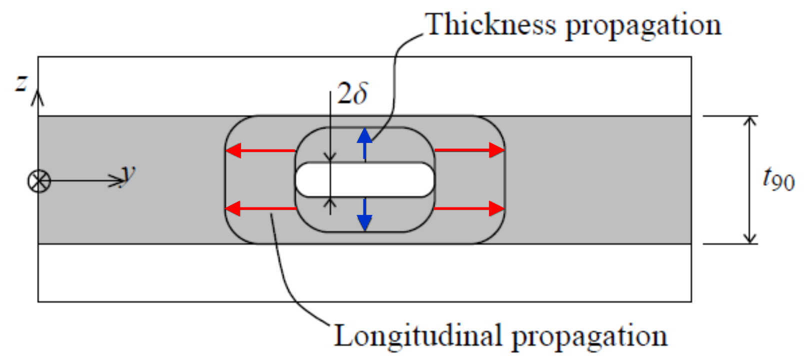


Cracks shield the adjacent material and prevent new cracks.

Matrix Cracking – In Situ Effect

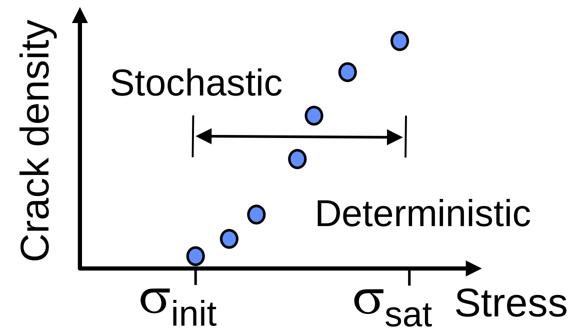




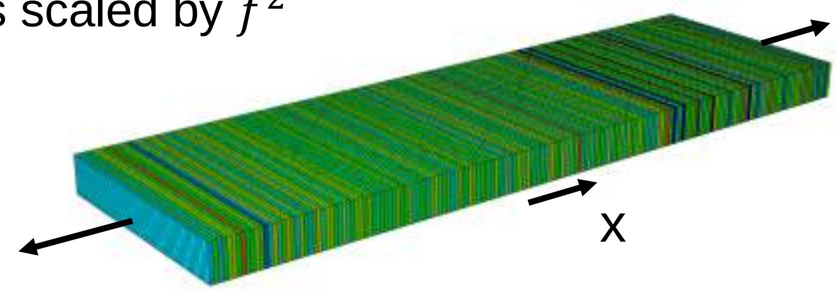


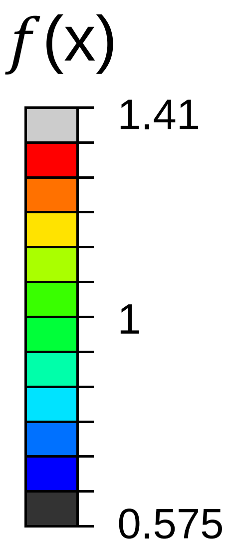
Material Inhomogeneity

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

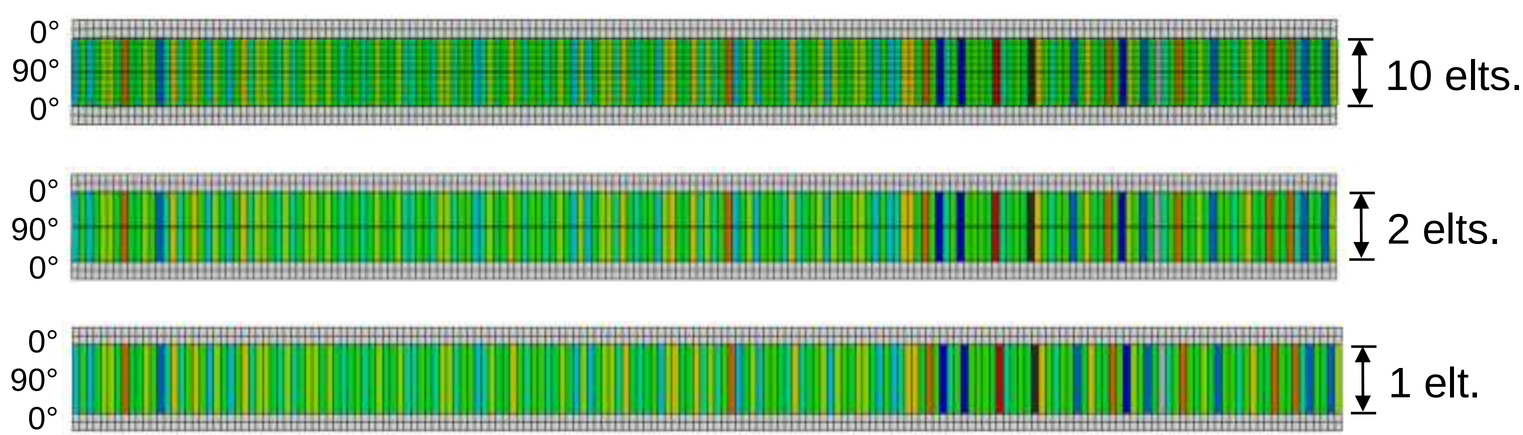


- Strength scaled by f, Fracture toughness scaled by f^2
- Constant f along each crack path





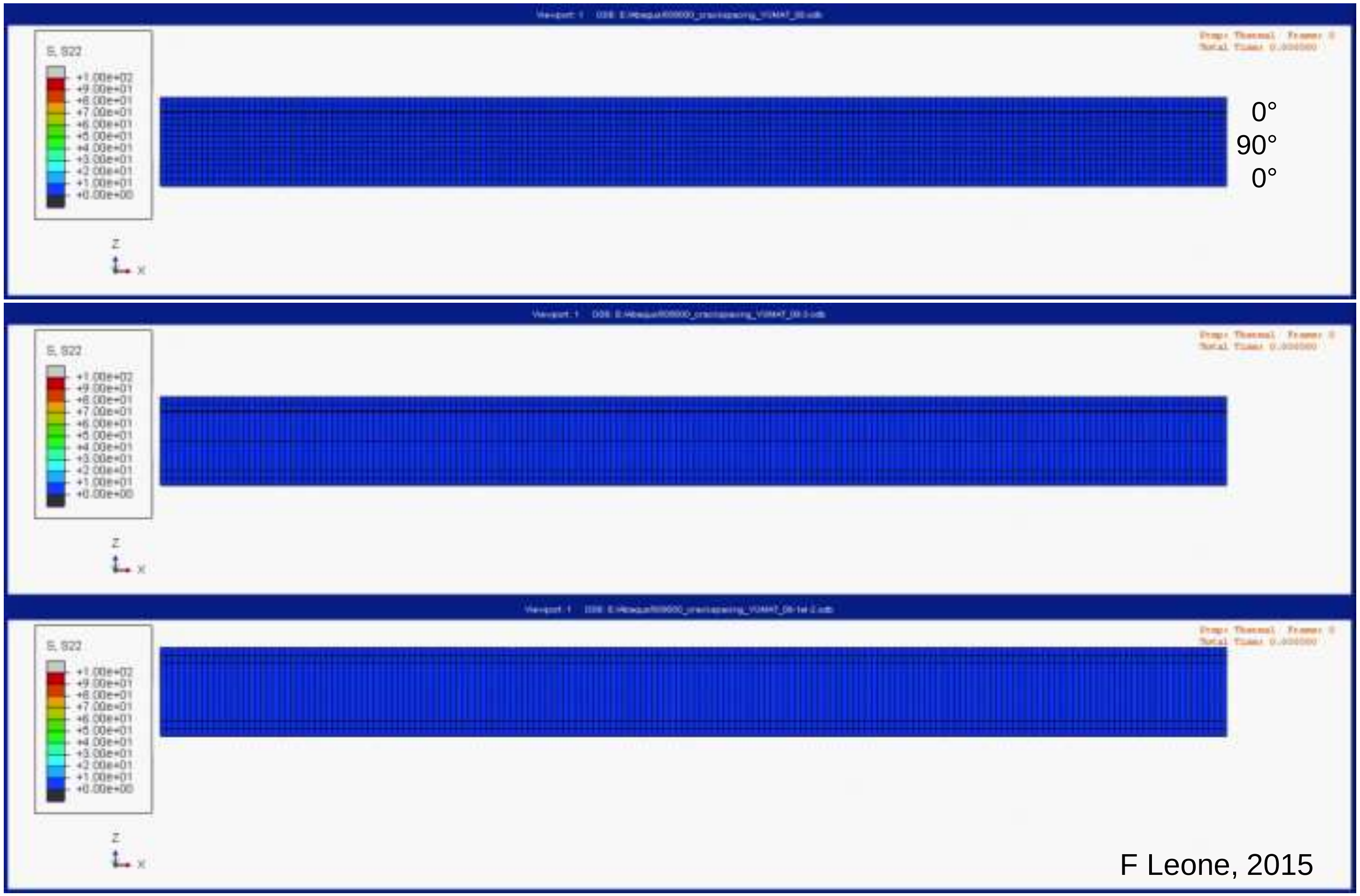
Inhomogeneity applied to 3 levels of mesh refinement



F Leone, 2015

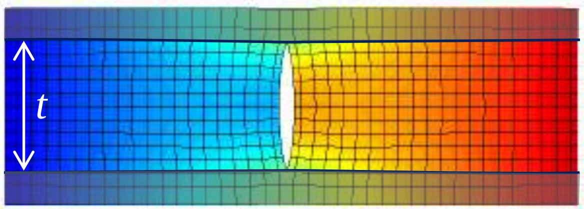
Effect of Transverse Mesh Density on Crack Spacing

Analyses with 3 levels of mesh refinement

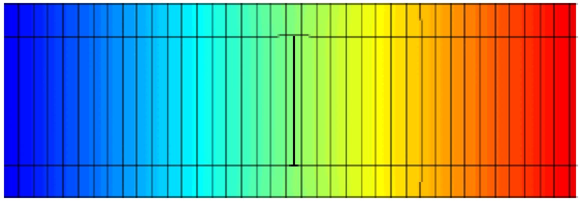


Transverse Matrix Cracks w/ One Element Per Ply

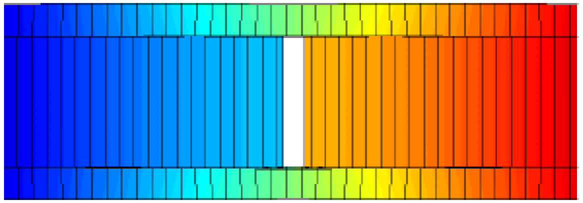
Multi-element model: correct crack evolution



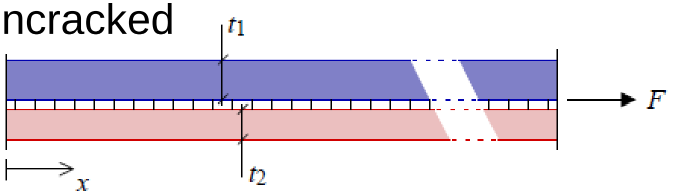
Conventional single-element: no opening w/out delam.



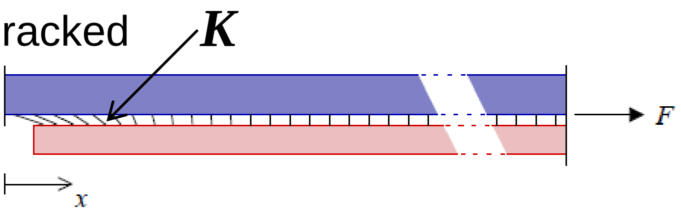
Modified single-element: correct Energy Release Rate



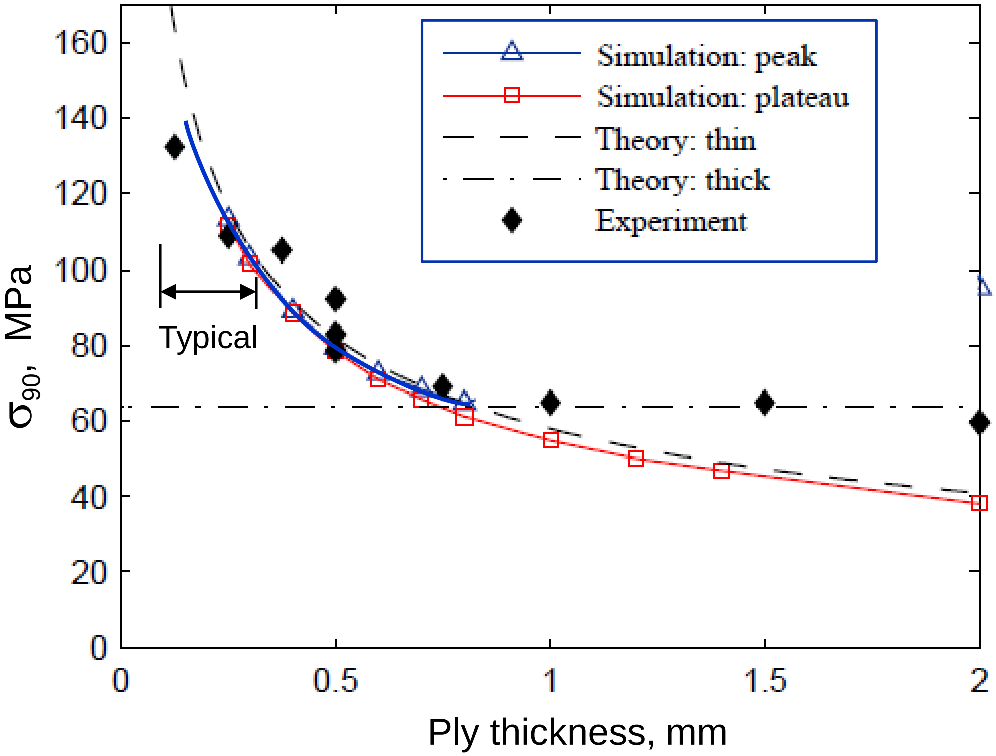
Uncracked



Cracked

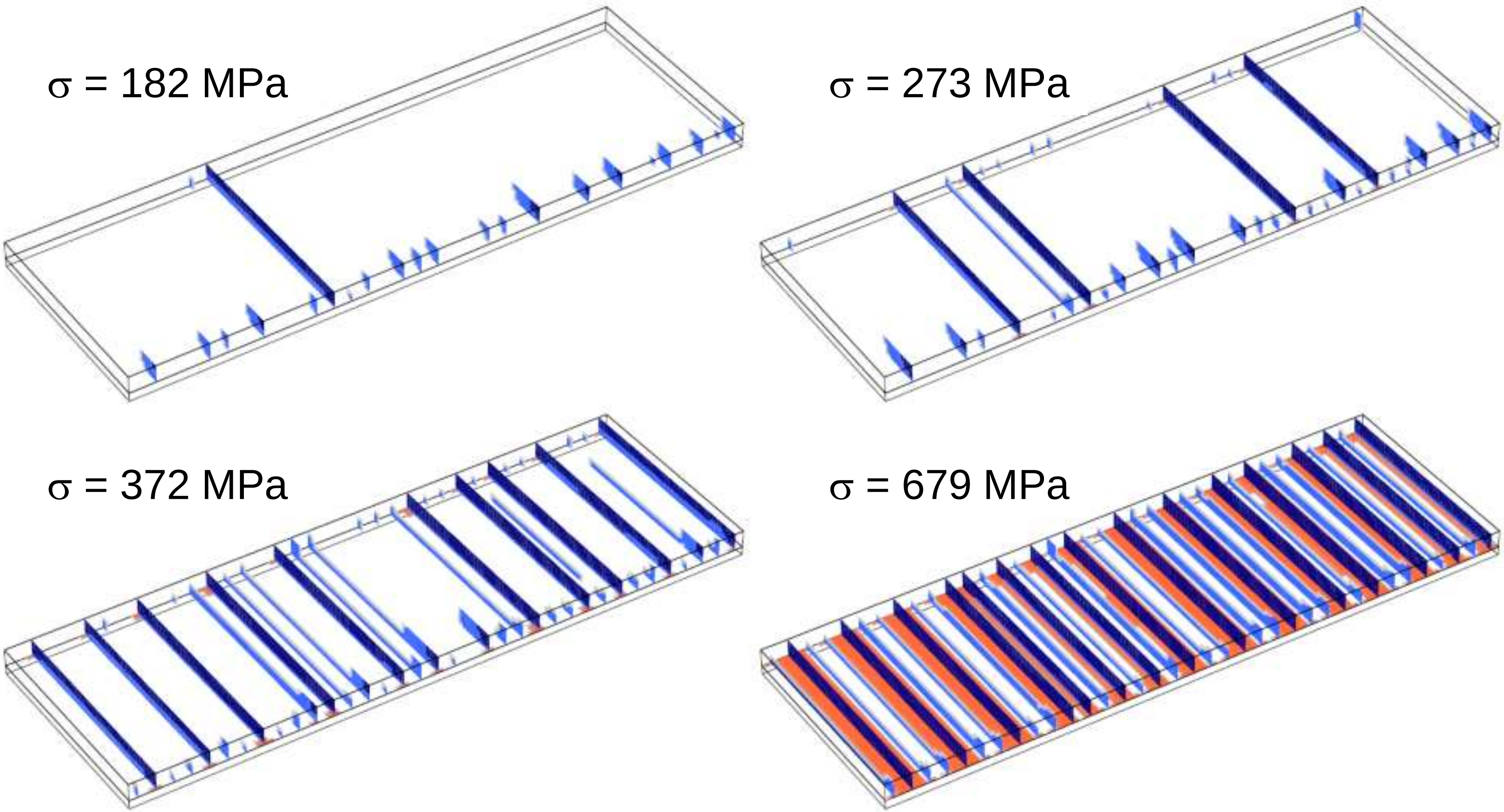


$$K \approx \frac{4E_2}{\pi^2 t}$$



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

Crack Initiation, Densification, and Saturation



Cohesive zone

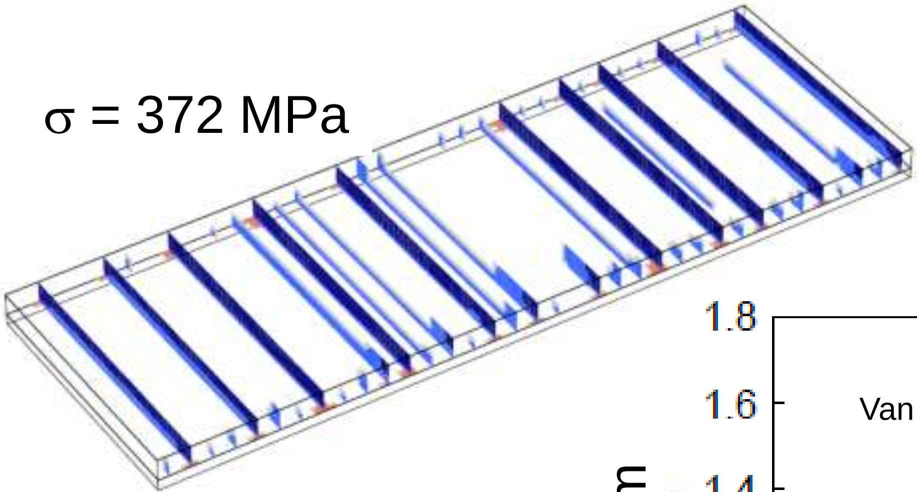
Traction-free cohesive zone

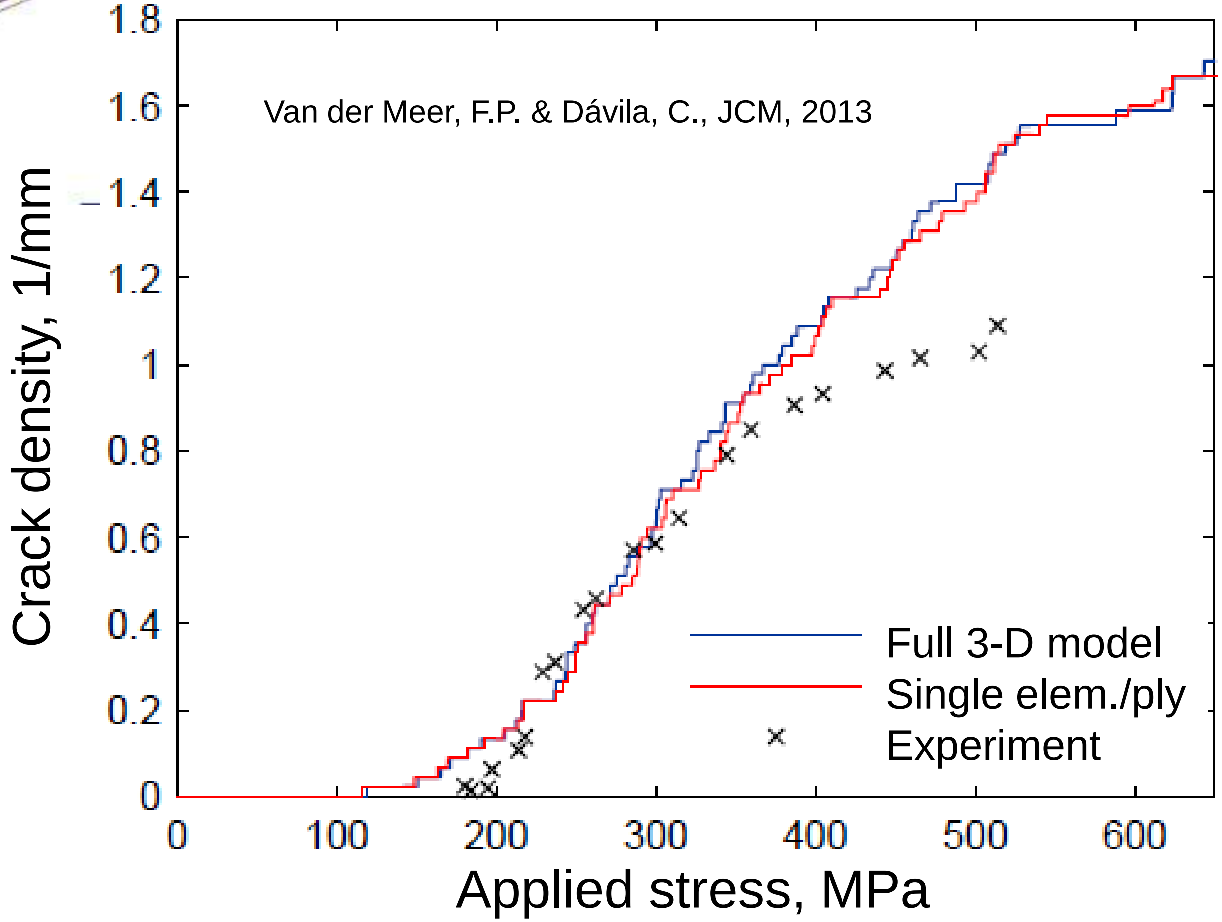
Delamination

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

Comparison of X-FEM Single-Ply Model and Full 3-D

σ = 372 MPa





Summary

- Strength and fracture issues are:
  - Interrelated
  - Subject to size effects
- Cohesive laws:
  - Account for strength and fracture toughness
  - More than 3 elements are required in the process zone
- Continuum damage models
  - Snap-back imposes maximum element size
- Transverse matrix cracks:
  - More than one element per ply is required
- Other mesh issues?

} Mesh Requirements for Damage Models