Softening the Gap Between Strength and Toughness

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Online Workshop:
"Is fracture toughness applicable as a material property for composites?"

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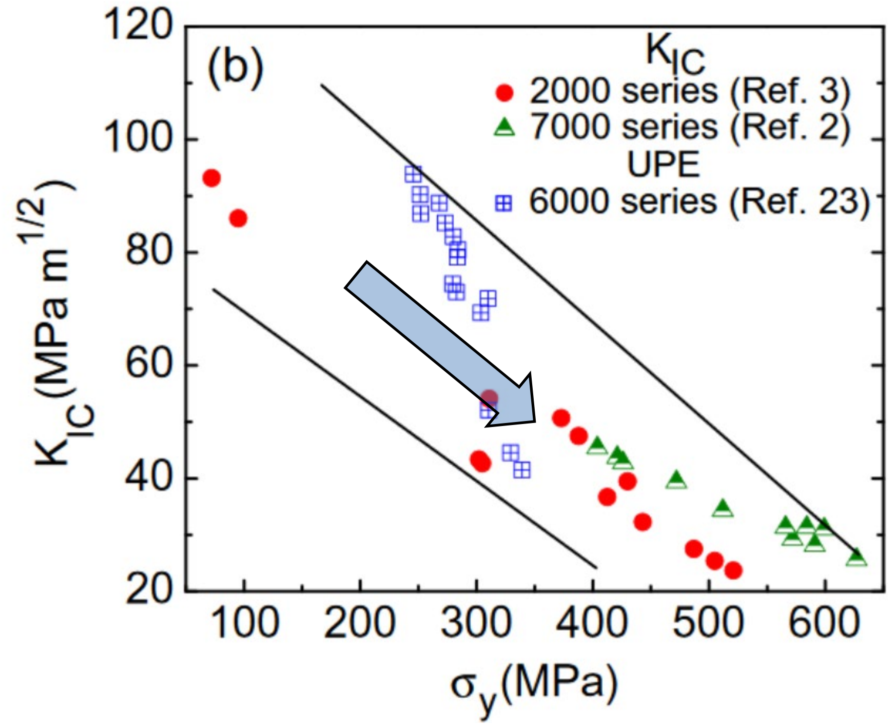
The Conflict Between Strength and Toughness

Metallic alloys



Yuan, S. P., et al. "Effect of precipitate morphology evolution on the strength–toughness relationship in Al–Mg–Si alloys." *Scripta Materialia* 60.12 (2009)

Fibrous composites

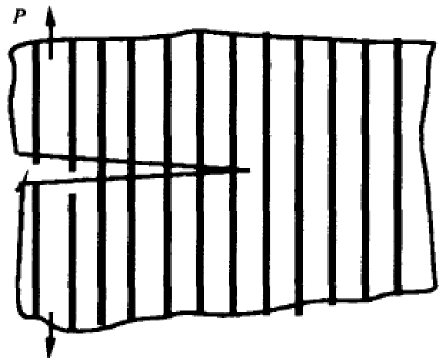


FIG. 2 Fiber pull-out.

Toughness

$$\Gamma \sim \frac{f(1-f)^2 S_b^3 R}{2E\tau}$$

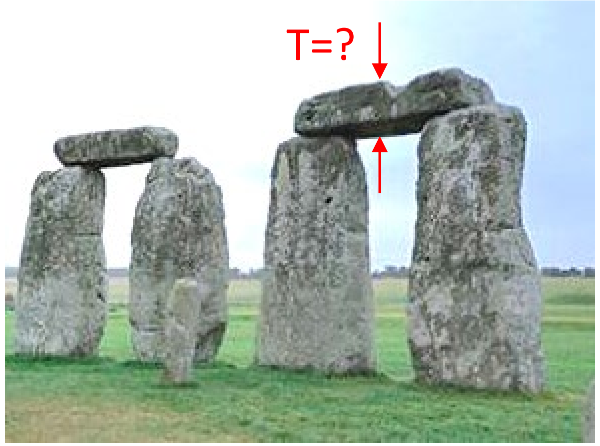
Shear strength

Bao, G., and Zhigang Suo. "Remarks on Crack-Bridging Concepts." Appl Mech Rev 45, no. 8 (1992)

Scaling: the Effect of Size on Strength

Student Assignment: Help a Neolithic tribe design a dolmen.

- Tribe architect wants to know the minimum thickness for the lintels.
- You will test blue and white stones and, from the results, calculate T_{min} for both stones.



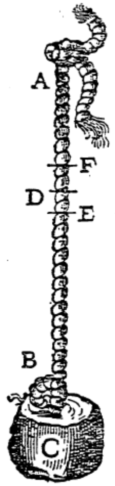
Testing strength of small granite block

→ Strength (σ_c) or Fracture (G_c)?

A Choice of Failure Theory

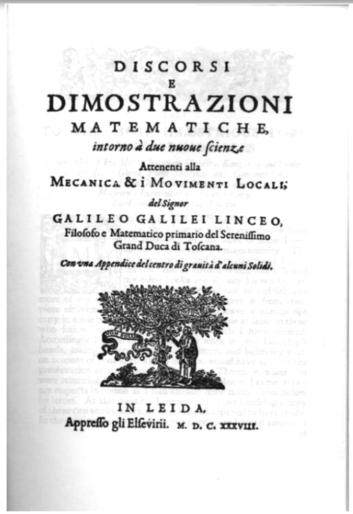
Strength of Materials

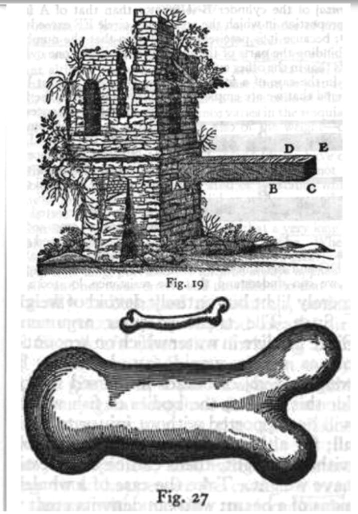
(da Vinci, 1505)



"resistance increases with cross-section"

(Galileo, 1638)


DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & i MOVIMENTI LOCALI;
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con una Appendice del centro di grauità d'alcuni Solidi.
IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

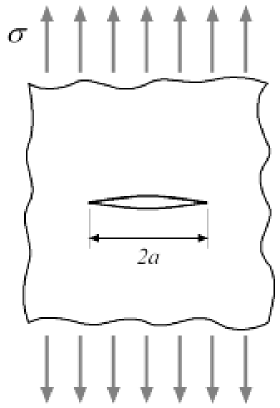


Linear Elastic Fracture Mechanics (LEFM)

(Griffith, 1921)

"weakness is due to the presence of flaws"

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



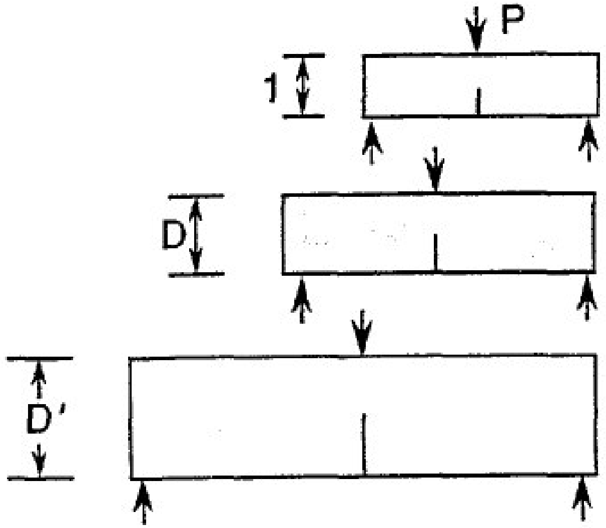
Statistical Theory of Size Effect

(da Vinci, 1505; Mariotte, 1686; Weibull, 1939)

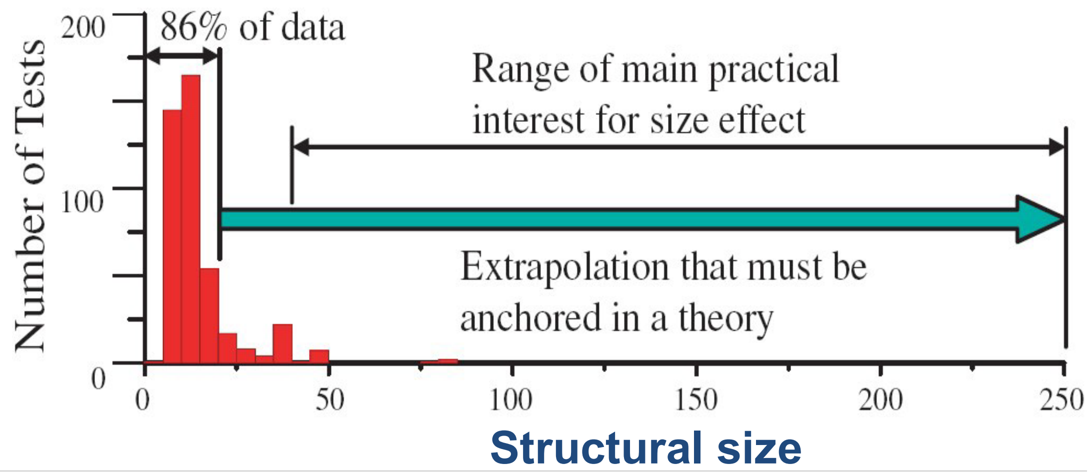
"weakest-link hypothesis"

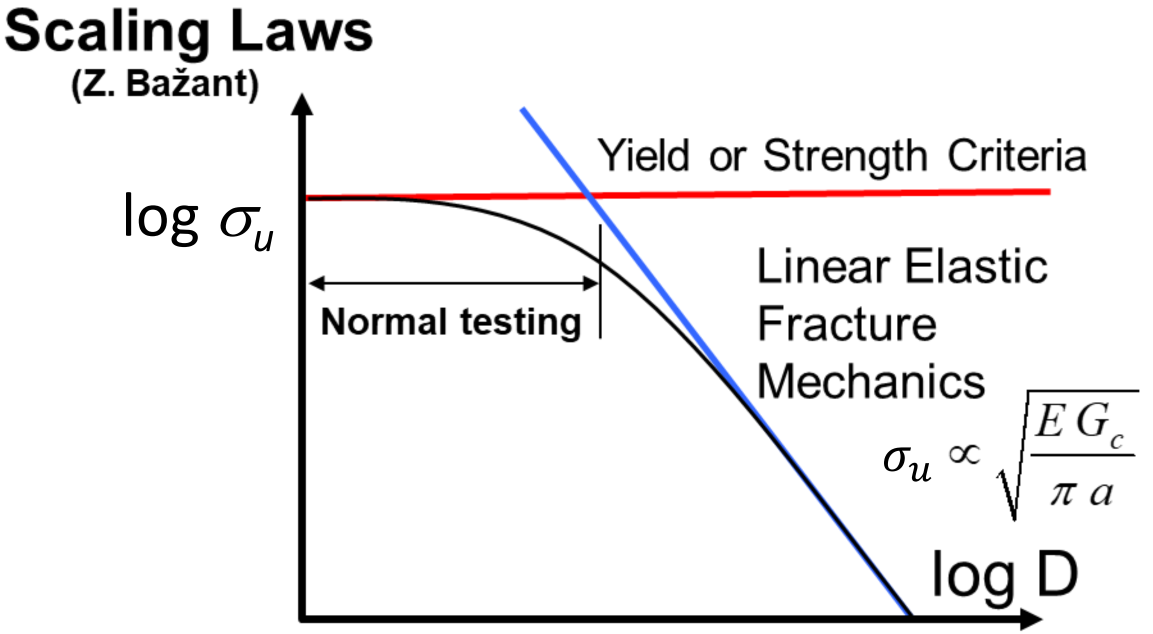
$$\sigma_u \propto L^{-d/m}$$

Scaling: the Effect of Structure Size on Strength

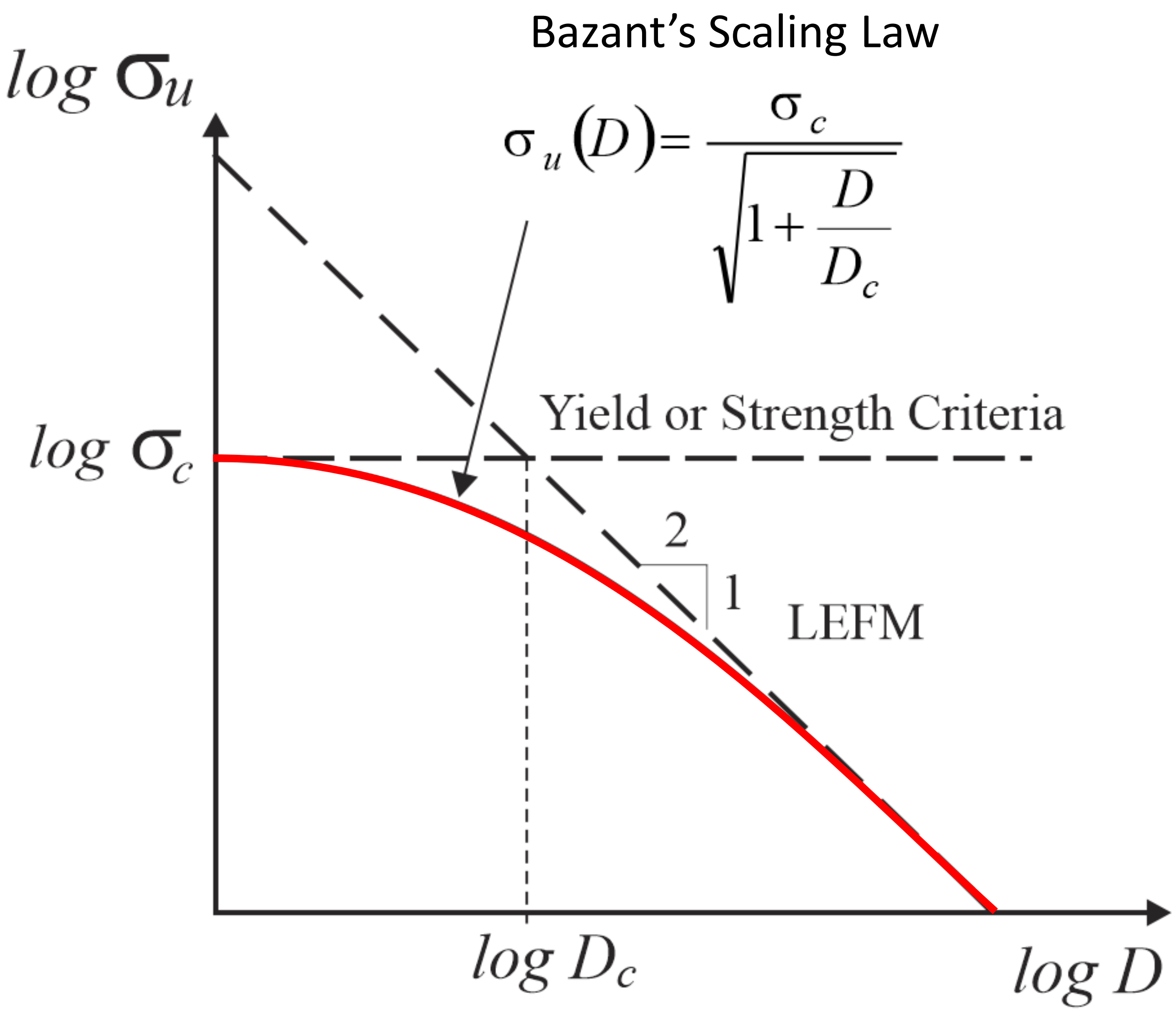


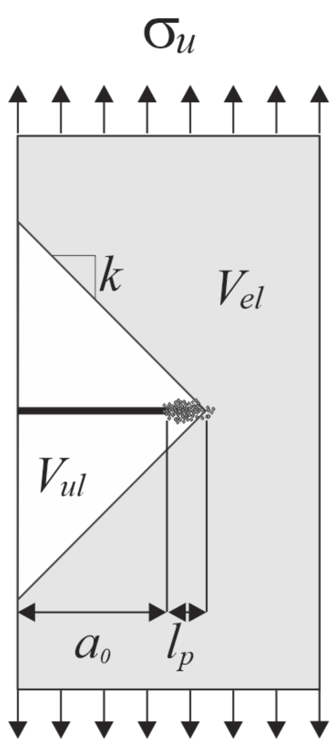
Scaling from test coupon to structure





Scaling: the Effect of Structure Size on Strength

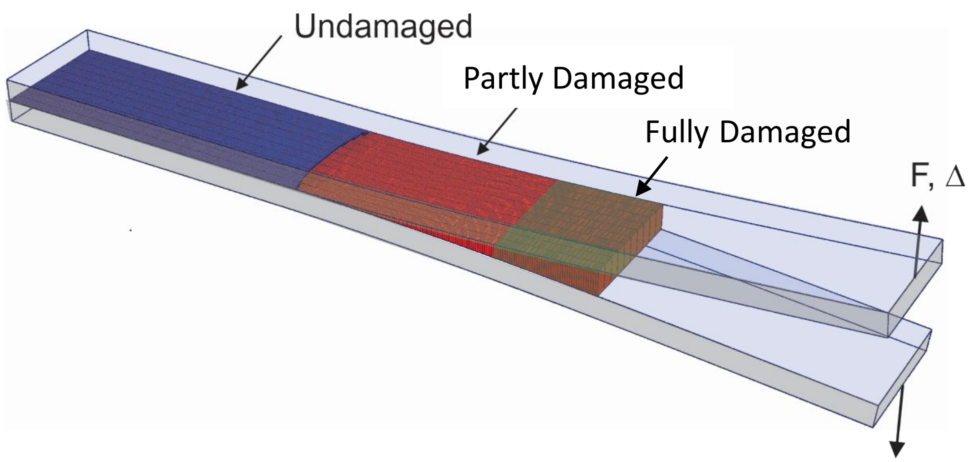




$$\sigma_u = \sqrt{\frac{EG_c}{k(a_0 + l_p)}}$$

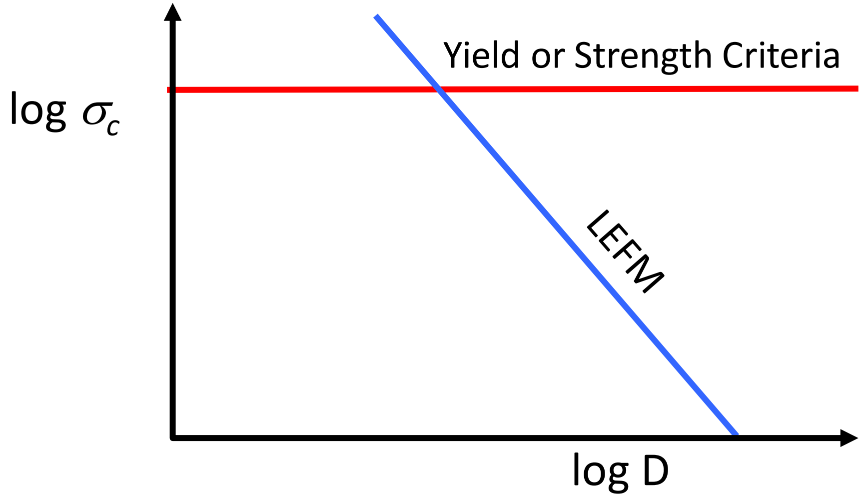
Softening is the bridge between strength scaling theories

Cohesive Laws: Two Criteria in One Softening Law

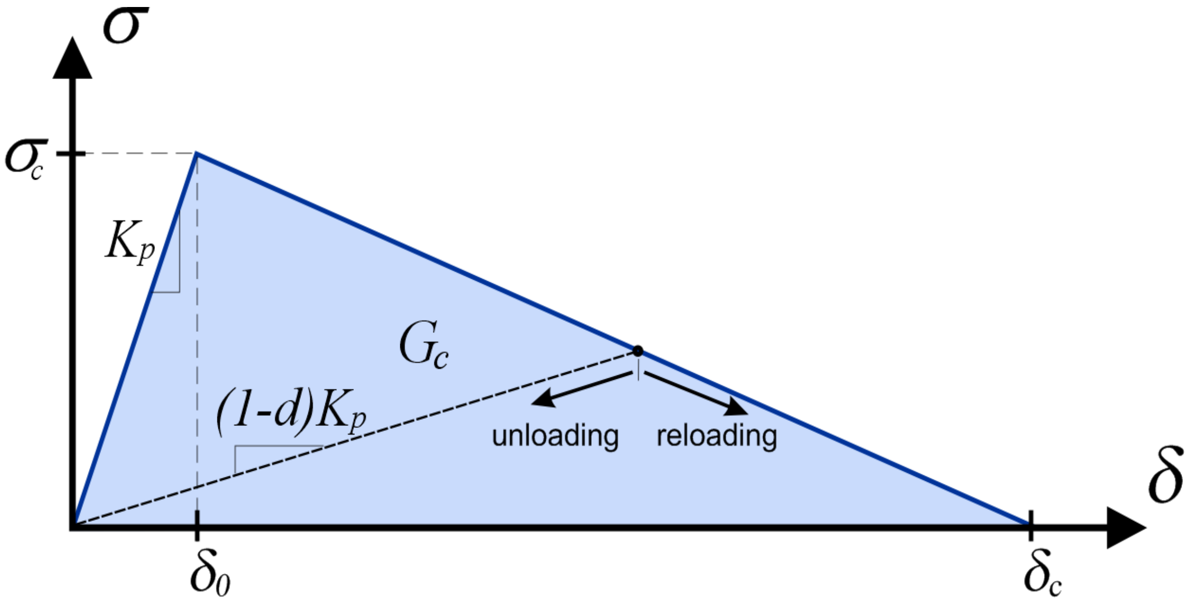


Two material properties:

- G_c Fracture toughness
- σ_c Strength



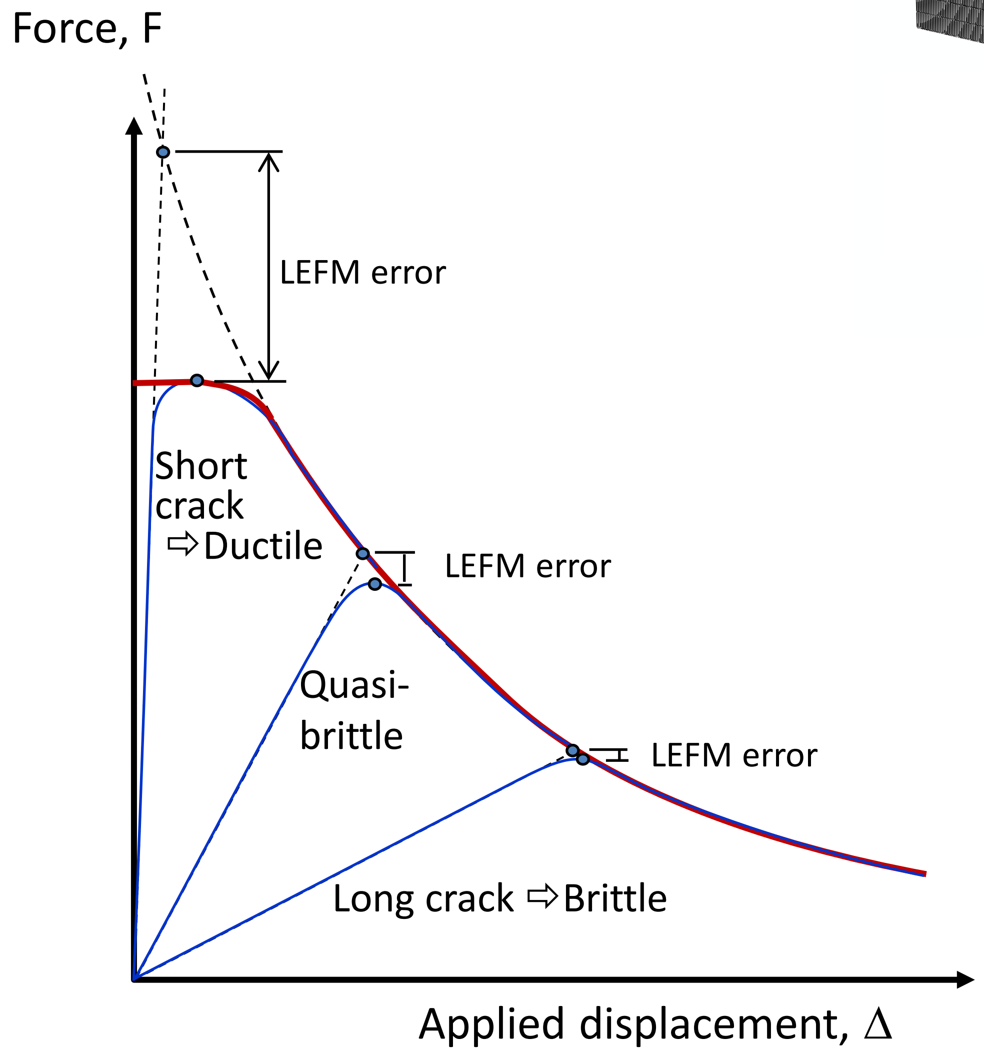
Bilinear Traction-Displacement Law

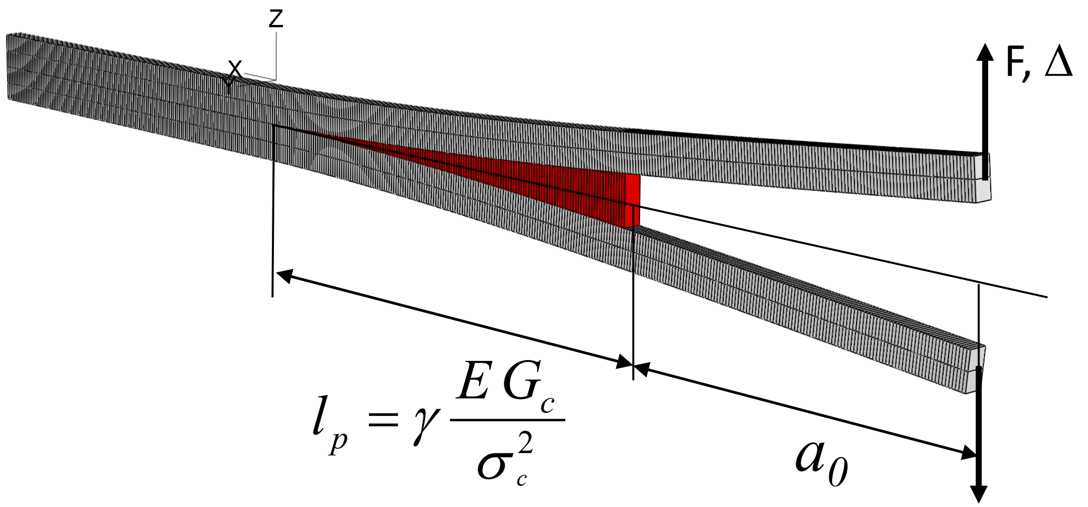


Characteristic Length:

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

Crack Length and Process Zone





Brittle:

$$a_0 > 100\ l_p$$

Quasi-brittle:

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

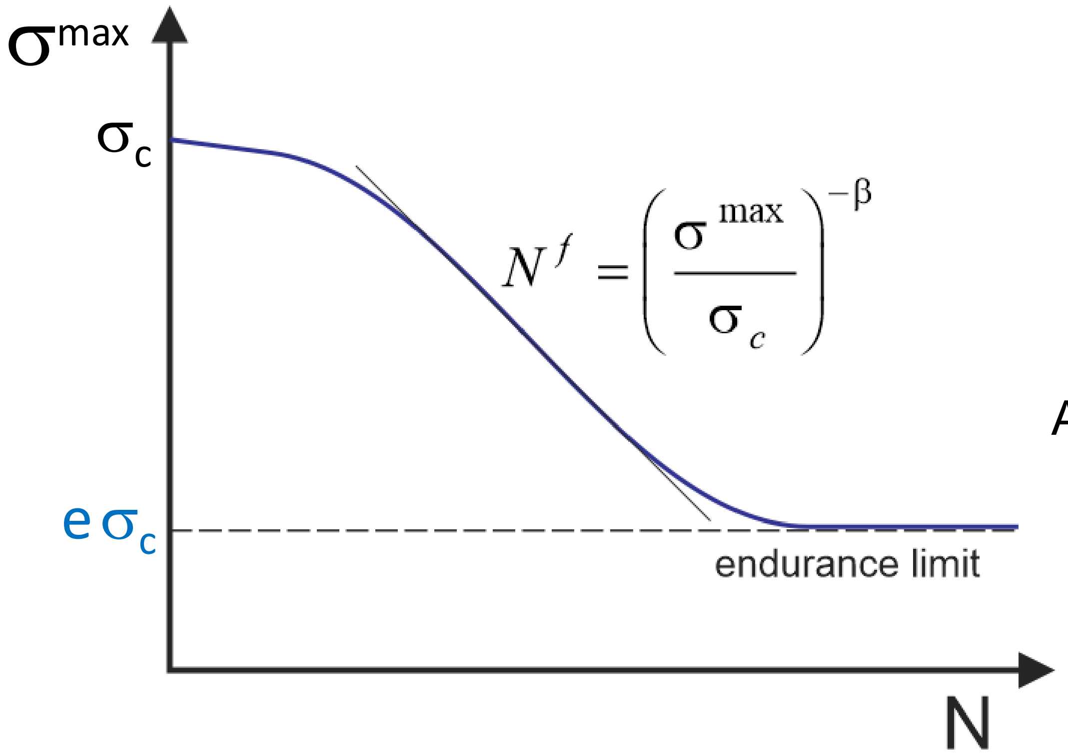
Ductile:

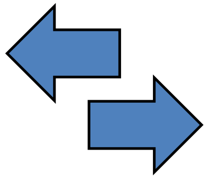
$$5\ l_p > a_0$$

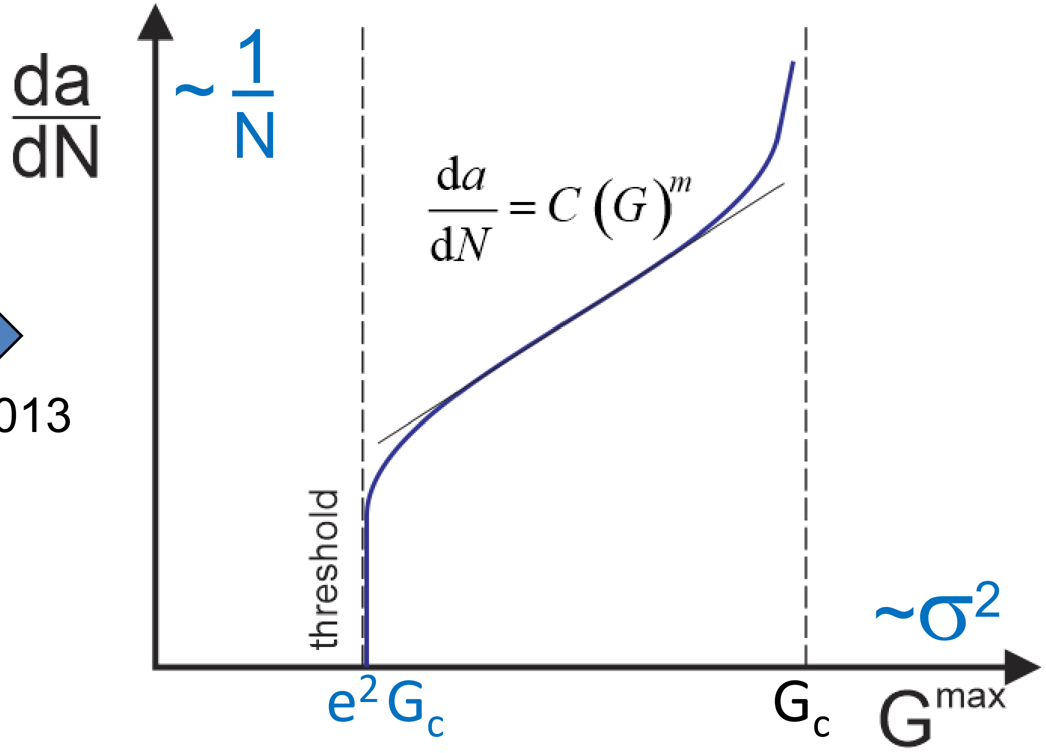
Fatigue: Strength or Toughness?

Strength: S-N Curve

Toughness: Paris Law







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

Remarks

- **Yes, fracture toughness is an important property of composites.**
- **Strength and toughness are complementary aspects of strength scaling.**
- **<u>Softening</u> is a function of strength and toughness that dictates:**
  - **the transition from tough to brittle fracture regimes,**
  - **the structural R-curves.**
- **The effects of strength and toughness are not always fully understood, (e.g. in fatigue).**
- **Stochastic distribution of microstructure induces volumetric effects in homogenized models.**