AML 883 Properties and selection of engineering materials

LECTURE 12. Toughness: fracture and fatigue

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Cracks in materials

- Machining – surface cracks
- Shrinkage in casting and welding – introduces cracks
- Cracking of inclusions during rolling – introduces cracks
- During service – abrasion, contact stresses, cyclic loading, ...

Rail cracking

Cracks on a rail – Image courtesy: University of Birmingham site

Rail cracking

- Rolling contact produces surface cracks
- Some of these penetrate to regions of the rail that is in tension
- Crack opens, sucks in water
- On closing of the crack due to wheel movement, the compressed water exerts tensile stresses at the tip and hence propagates
- Failure!

The path from crack to fracture

- Most of engineering applications – we do not want cracks
- Even if there be some cracks – we do not want them to propagate
- Or, even if they propagate, we want it to be controlled
- As usual, there might be cases where you do want cracks! (Aircraft engines attached to the wing by shear bolts – desinged to fail and shed the engine if it suddenly seizes)

Toughness

- Resistance of a material to the propagation of crack
- When the crack does propagate, we get fracture
- Fracture: ductile (metal or alloy) and brittle (glass, polymer much below its Tg and ceramics)
- Fatigue fracture: failure under repeated loading (even though the loads themselves might well be within the limits)

Fracture

Ductile and brittle

Stress intensity

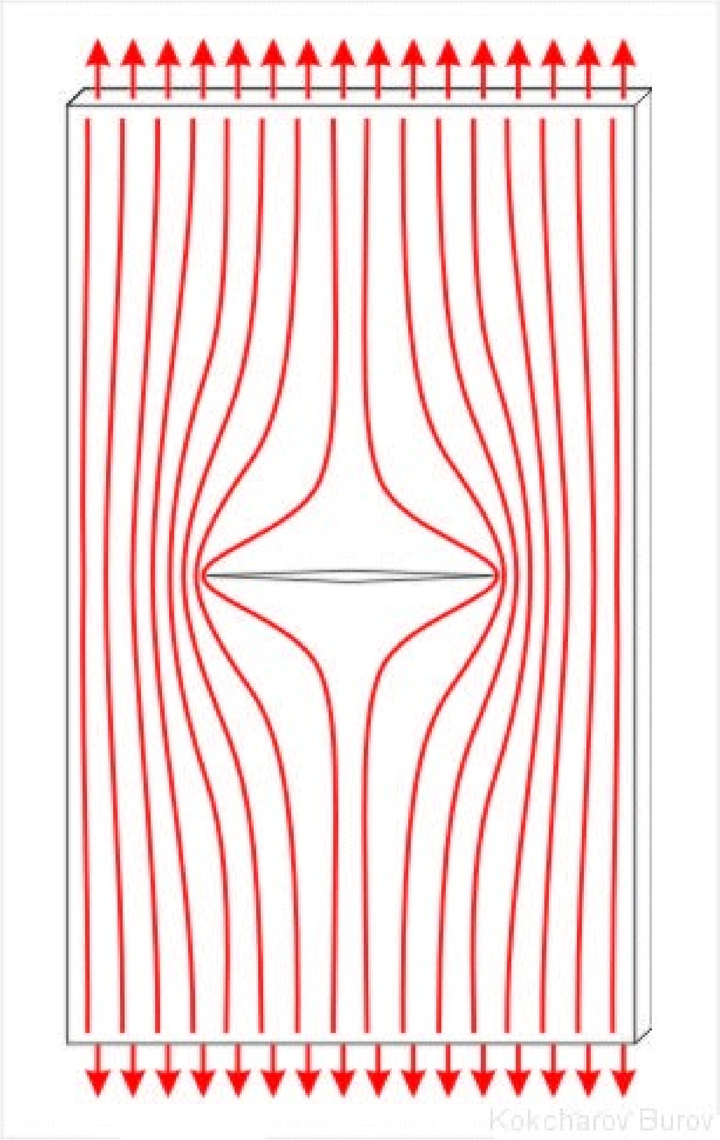
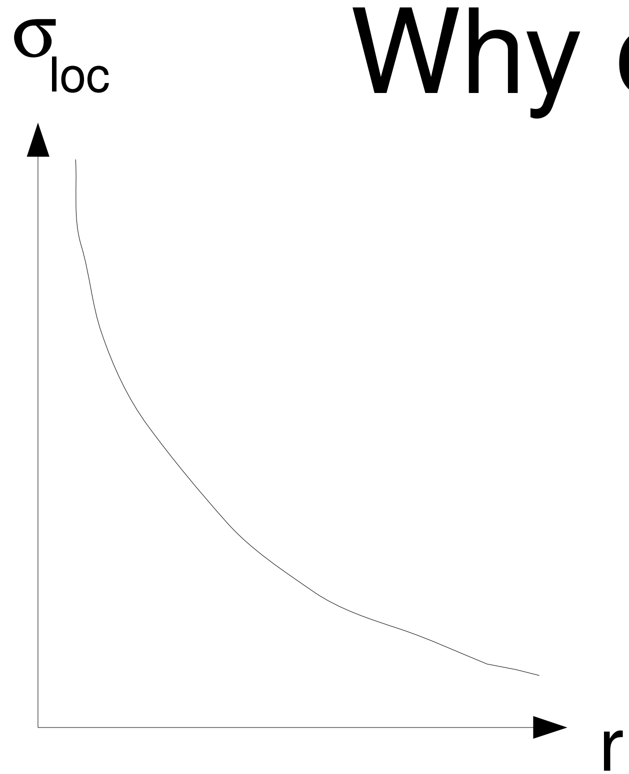


Image courtesy: wiki

Stress intensity

- Cracks concentrate stress
- What happened to our formula (for notches and holes)?
- Does not hold here since the crack tip radius is essentially zero $(\rho = 0)$
- However, a similar formula for the concentration of stress at the tip can be obtained

Why cracks are bad news



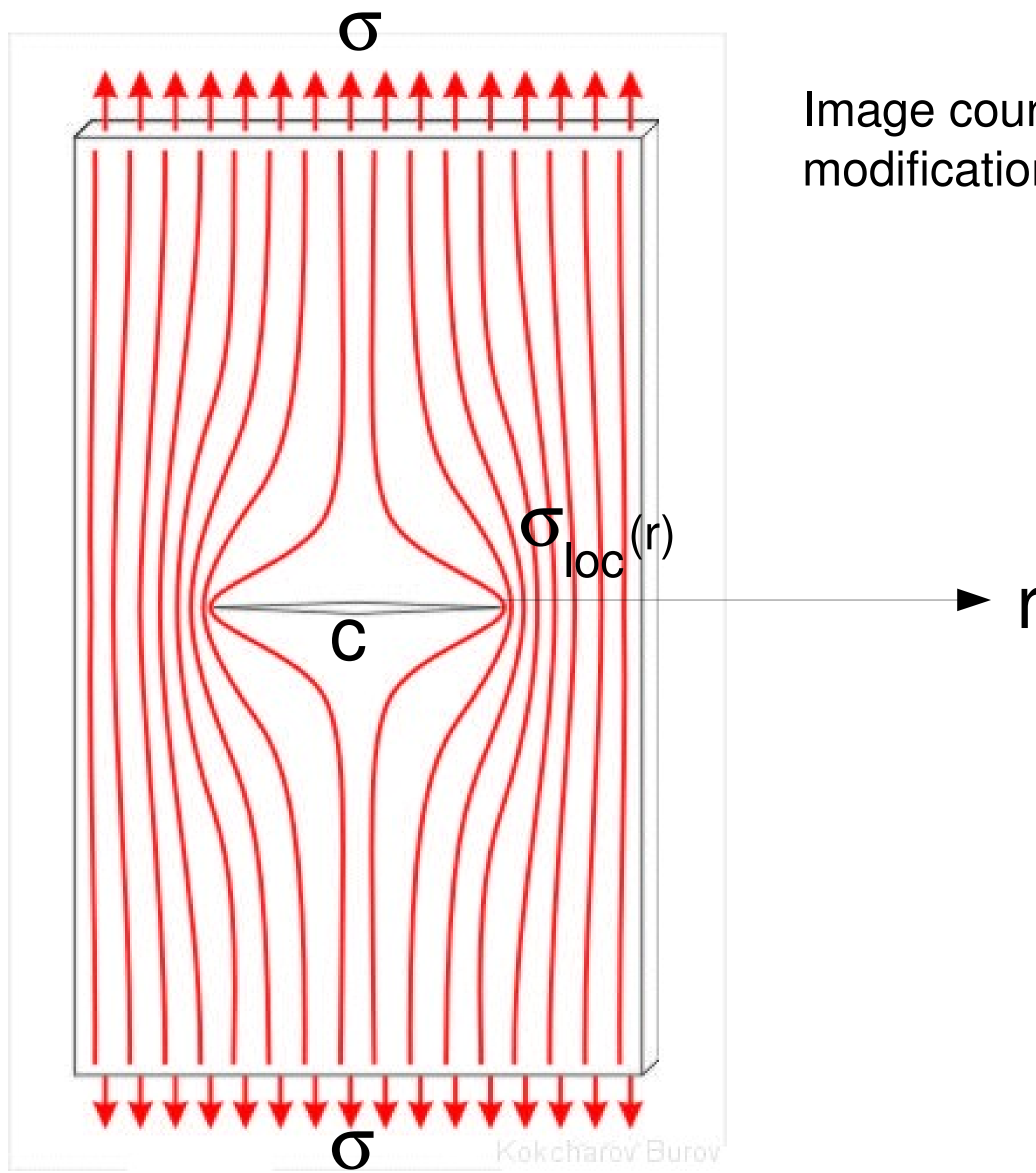


Image courtesy: wiki (with modifications of my own)

$$\sigma_{loc} = \sigma\left[1 + Y\left(\pi c / 2\pi r\right)^{1/2}\right]$$

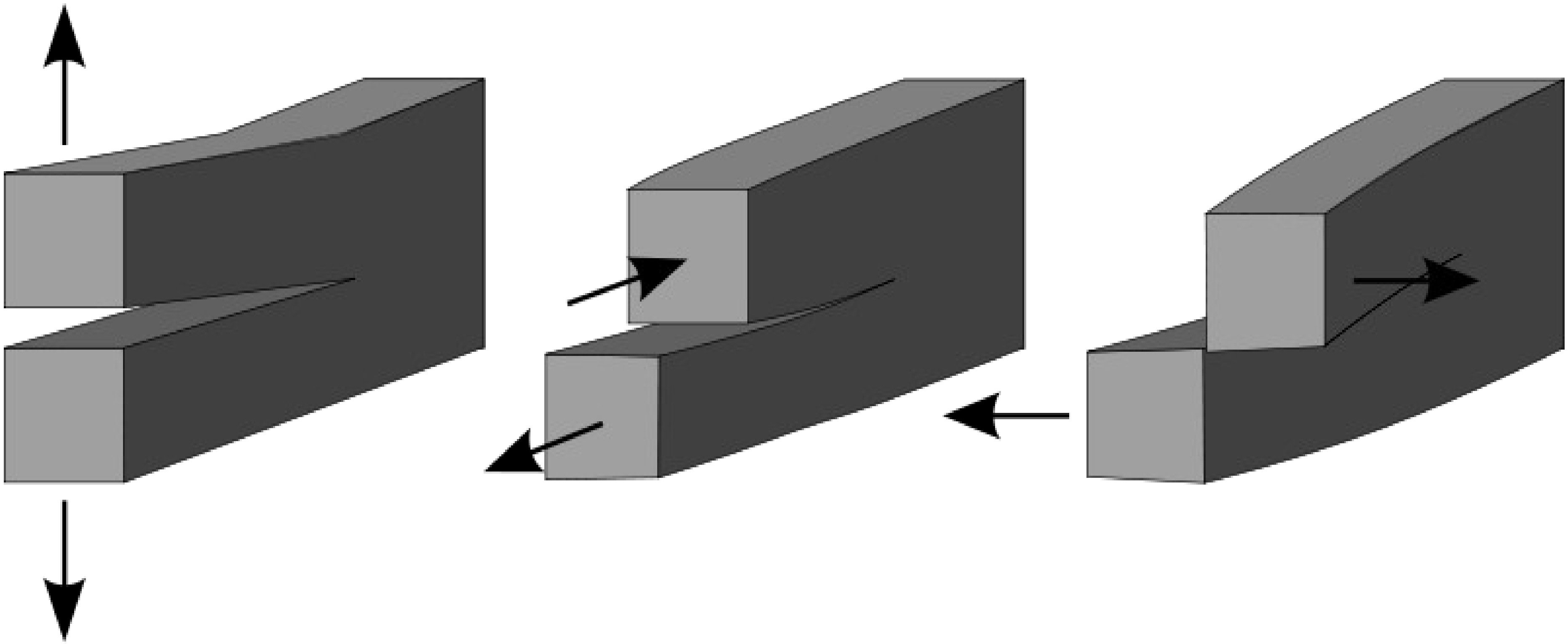
Stress intensity factor

- $\sigma_{loc} = \sigma[1 + Y(\pi c/2\pi r)^{1/2}]$
- Y – a constant of value near unity with weak dependence on geometry
- For r << c, $\sigma_{loc} = Y\sigma(\pi c/2\pi r)^{1/2}$
- Mode 1 stress intensity factor:

$$K_1 = Y\sigma(\pi c)^{1/2}$$

- What is Mode 1: a one slide digression

Modes of fracture



Mode I:
Opening

Mode II:
In-plane shear

Mode III:
Out-of-plane shear

Image courtesy: wiki

Fracture toughness

- Cracks propagate when stress intensity factor exceeds a critical value
- This critical value is called fracture toughness, K_{1c}
- Fracture toughness is a material property: it is independent of the way it is measured; it can be used in design

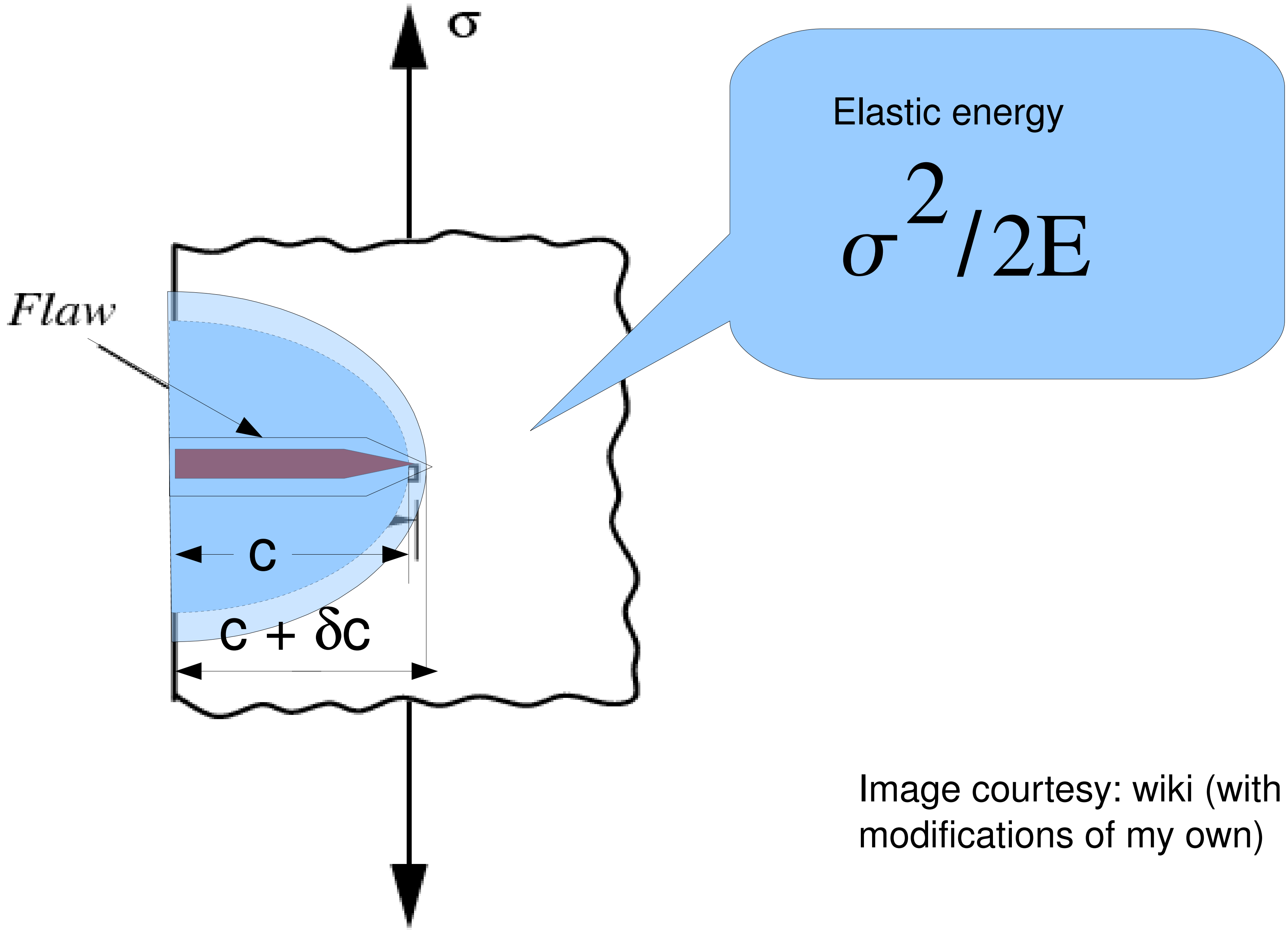
Energy release rate

- Fracture of sample: new surface is created
- Surfaces cost system energy
- Surface energy: γ
- Fracture of a sample of cross-sectional area A costs $2A\gamma$
- If external work done or elastic energy released is equal to or greater than the surface energy, then fracture will happen: $G \geq 2\gamma$
- G: energy release rate (necessary condition)

Energy release rate

- In practice, due to the plastic deformation at the crack tip, much more than 2γ is needed.
- Gc: critical strain energy release rate – a sort of effective surface energy (also called toughness, at times)
- How is Gc related to fracture toughness?

Energy release rate and toughness



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Energy release rate

- Slab of unit thickness carrying stress σ
- Stored elastic energy is $\sigma^2/2\mathrm{E}$ per unit volume
- Put a crack of length c
- Crack relaxes stress in a half-cylinder of radius about c: $\sigma^2 \pi c^2/4\mathrm{E}$
- Suppose the crack now extends by a small length δc

Energy release rate

- The release in elastic energy should pay for the extra surface created
- This cost is $G_c \delta c$
- Differentiating, $\sigma^2 \pi c^2 / 4E$ and equating the result to the cost, we get
- $G_c = \sigma^2 \pi c / 2E$
- $G_c = K_{1c}^2 / 2E$

Energy release rate

- Derivation is approximate
- More rigorous one gets $G_c = K_{1c}^2 / E$
- Or, $K_{1c} = (G_c E)^{1/2}$

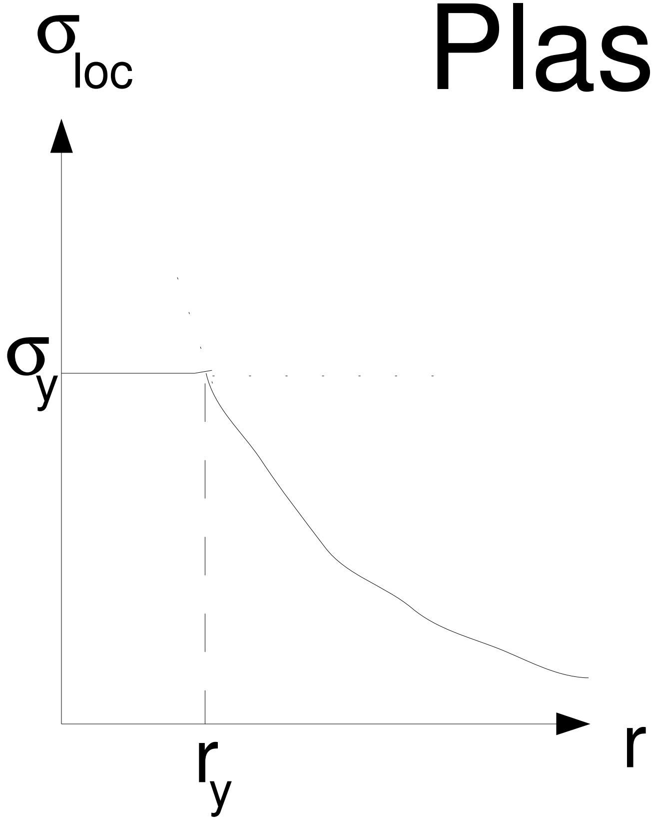
Process zone at the crack tip

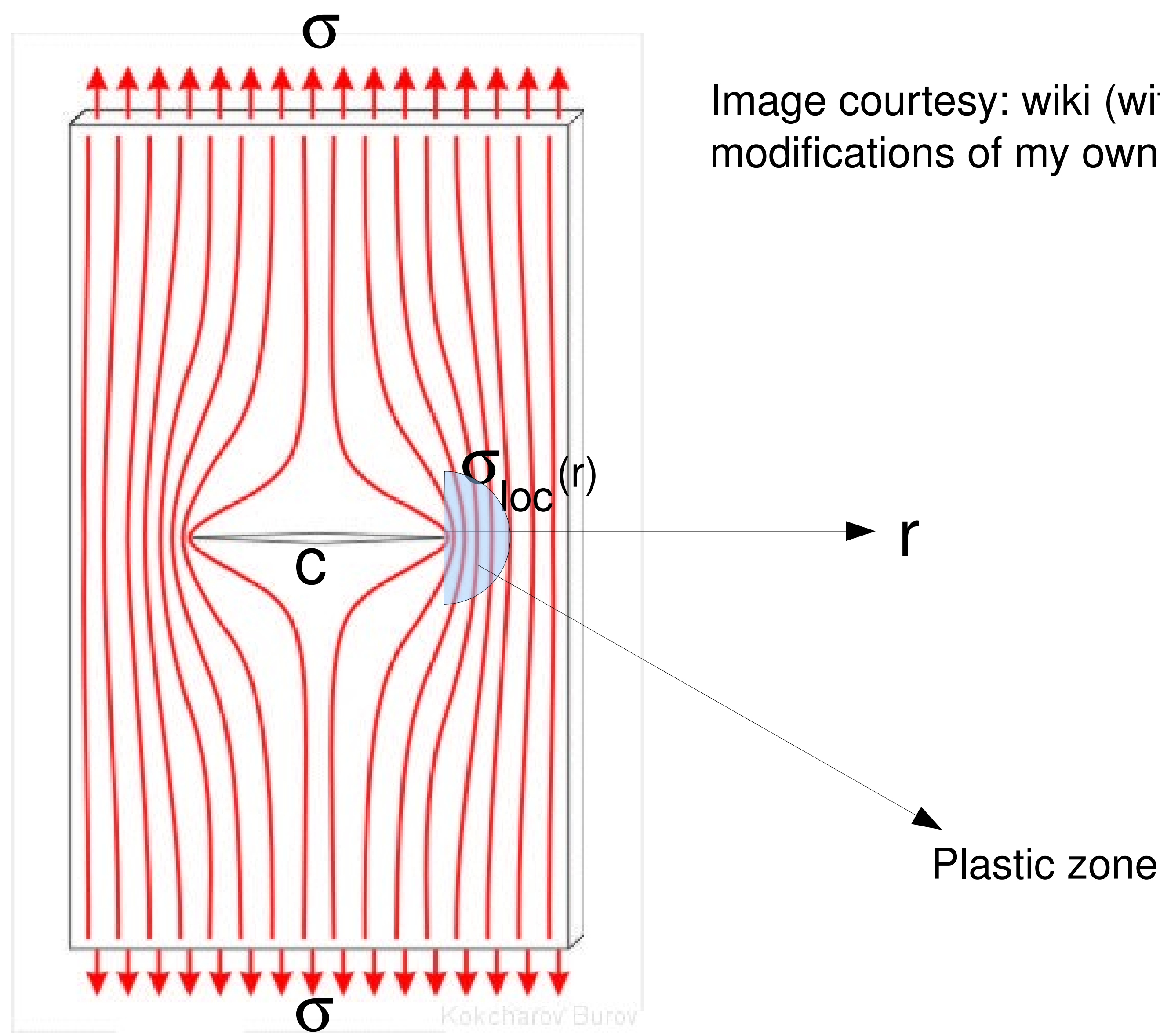
- Stress at crack tip: affects the zone ahead – called process zone
- Ductile solids – plastic zone
- Ceramics – region of micro-cracking
- Composites – region of delamination, debonding and fibre pull-out
- Work done against plastic and/or frictional forces – accounts for the effective surface energy being higher than just surface energy

Estimating the plastic zone size

- For what value of r from the crack tip, does the local stress value reach the yield stress?
- Work hardening – can make this a bit messy
- Plastic zone, however, is larger due to the redistribution of stresses from the truncated part
- $$r_y = K_1^2 / \pi \sigma_y^2$$
- Plastic zone versus yield strength – why soft metals have large plastic zones and ceramics and glasses have almost none at al

Plastic zone at crack tip





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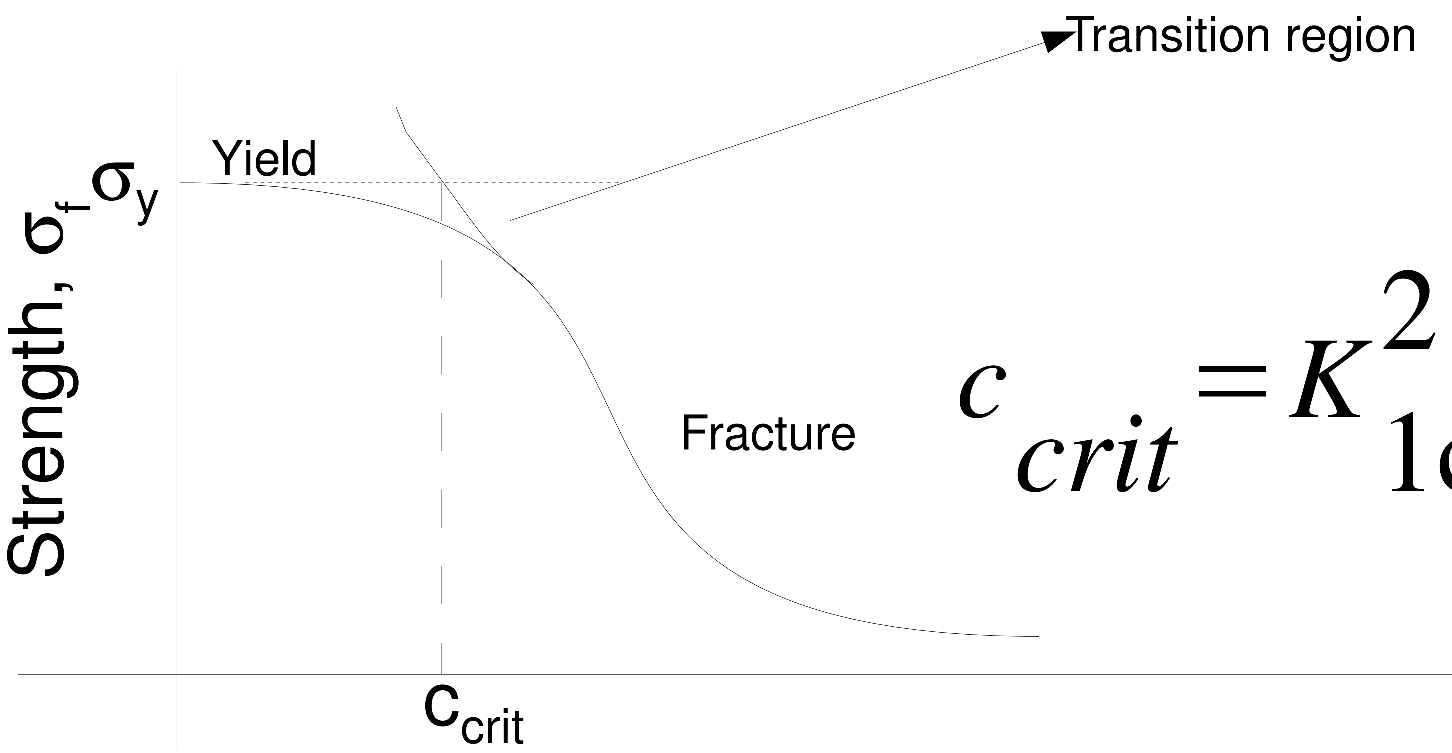
Crack size and fracture/yield

- Brittle materials – fracture toughness is well defined;
- Materials with plastic zone size is small compared to all dimensions of the test sample: fracture toughness is well defined
- Very ductile materials – plastic zone size might exceed the width of the sample – crack doe not propagate but the material yields

Crack size and fracture/yield

- Small cracks – yield before fracture
- Large – fracture before yield
- How small is small enough?



$$c_{crit} = K_{1c}^2 / \pi \sigma_y^2$$

Transition crack lengths

- Metals: 1-1000 mm
- Polymers: 0.1-10 mm
- Ceramics: 0.01 - 0.1 mm
- Composites: 0.1- 10 mm
- Cracks lengths – measure of damage tolerance

Fracture

Fatigue

Cyclic loading

- Vibrating bodies – bells, for example
- Rotation under load– turbine blades, for example
- Repeated loading and unloading -- underside of an aircraft wing during the take-off, cruise, turbulence, and landing cycles for example
- Accumulate damage (since there is some loss of energy); leads to cracks; results in failure
- Fatigue failure

Mechanical loss coefficient

- Damping coefficient
- A measure of the degree to which a material dissipates vibrational energy
- Fraction of stored elastic energy during loading that is not returned during unloading
- Materials for bells – low damping coefficient (bronze and glass)
- Damping – Materials with high damping coefficient: foams, elastomers, polymers, ...

Low cycle fatigue

- Low cycle fatigue: cycling above general yield (but below tensile strength)
- Why would you want to cycle above yield? Where do we use these?

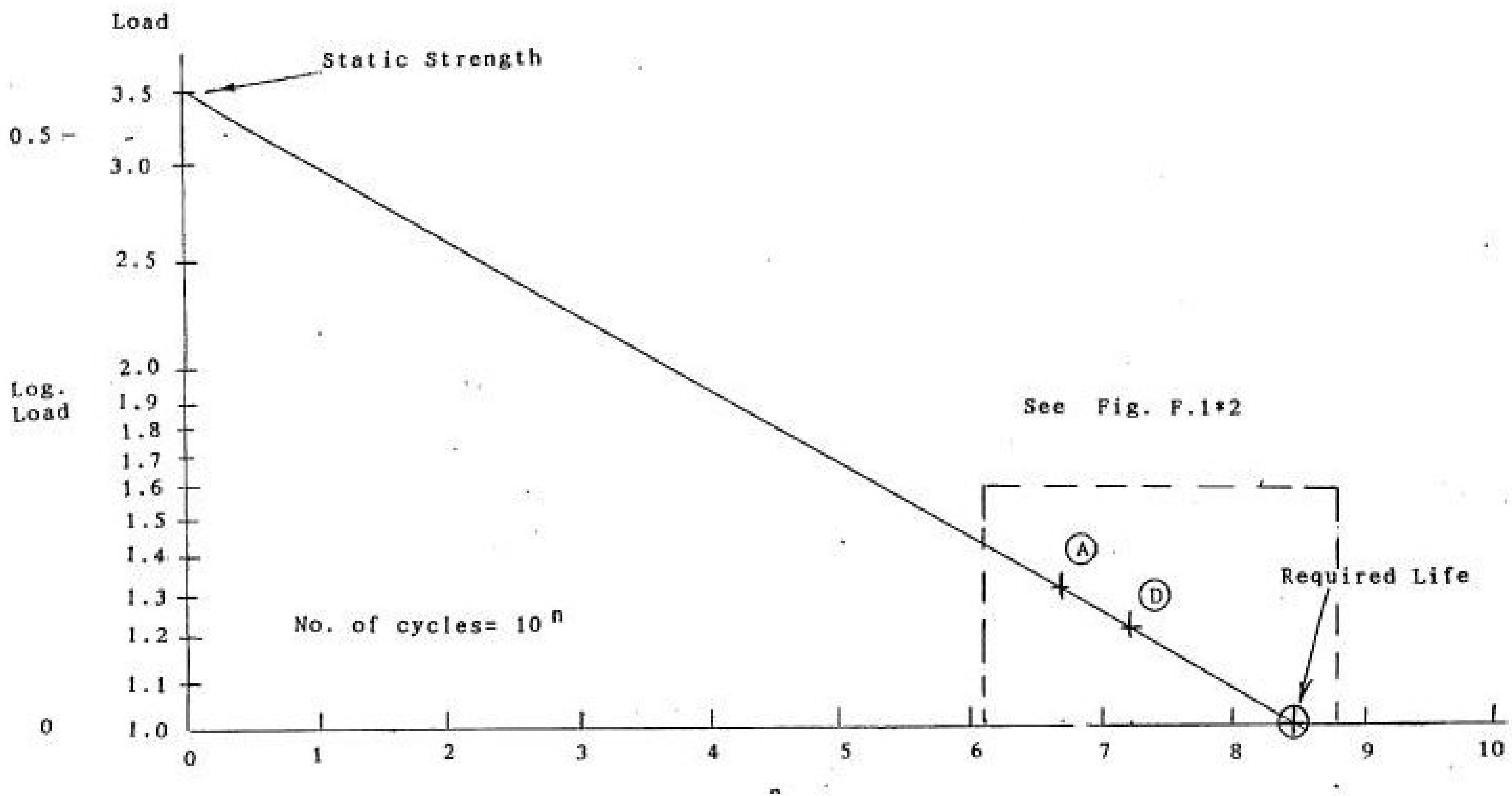
Low cycle fatigue

Image courtesy: wiki

High cycle fatigue

- High cycle fatigue: cycling well below general yield
- Generally elastic stresses, well below the yield stress
- Cracks nonetheless develop and cause failure
- Fan blade -- example

Fatigue tests on fanblades



Fatigue

- Initiation controlled – initial material is crack-free
- Propagation controlled – initial material does contain cracks – but the rate of growth of crack is what matters for failure

- How to measure the fatigue strength of materials?