Introduction to Aerospace Engineering

Lecture slides

Selection of material & structure

Fatigue & durability

Faculty of Aerospace Engineering

23-12-2011

TU Delft Delft University of Technology

Challenge the future

Learning objectives

Student should be able to…

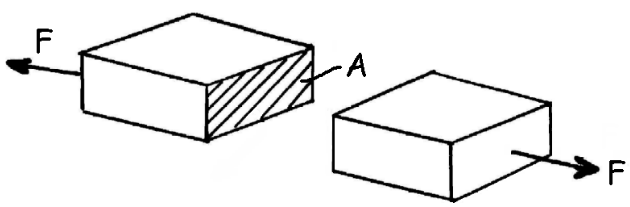
- Explain the meaning of stress & strain concentrations
- Give the definition of fatigue
- Explain & work with S-N curves
- Explain why stress concentration factors can not be applied for cracks

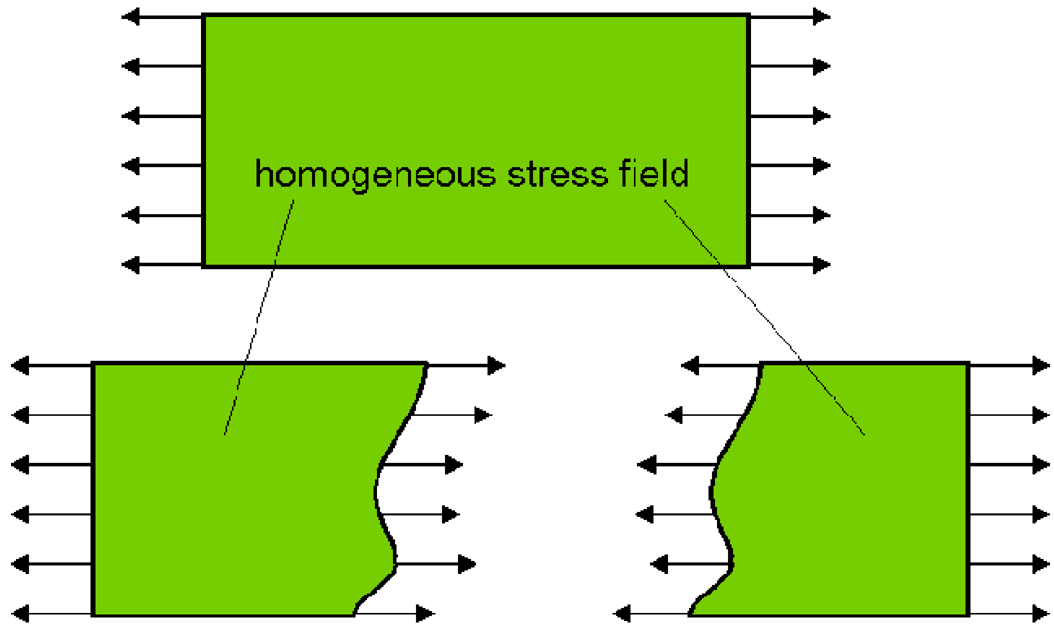
Stress-strain concentrations

Flat panel without notch

- The normal stresses are the same everywhere

$$stress\ \sigma \equiv \frac{force\ F}{area\ A}$$

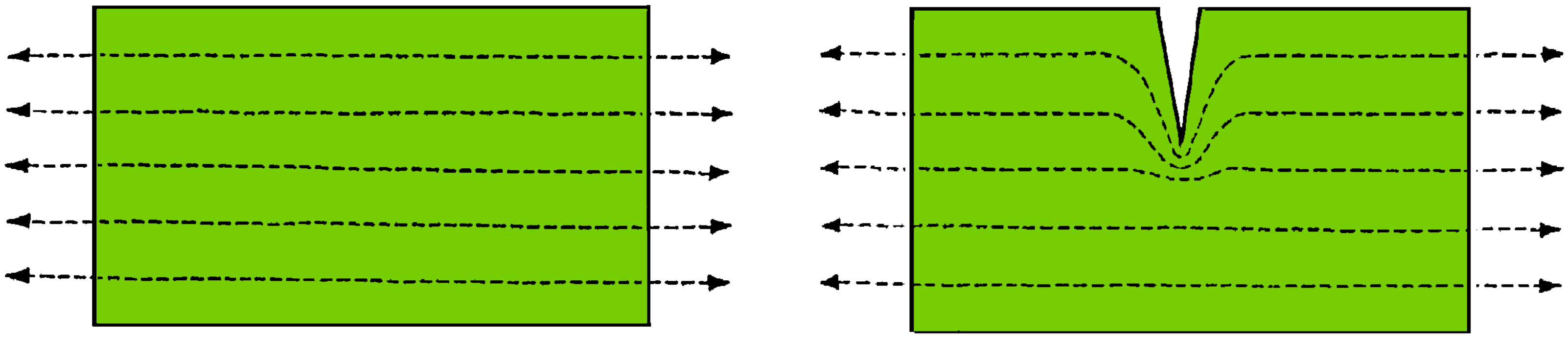




Stress-strain concentrations

Flat panel with notch

- A notch creates a disturbance in the stress flow



Homogeneous stress field Stress field with disturbance

- Notch $\rightarrow$ not only decrease in cross section (increase average σ)
  $\rightarrow$ also concentration of stress (K_t)

Stress-strain concentrations

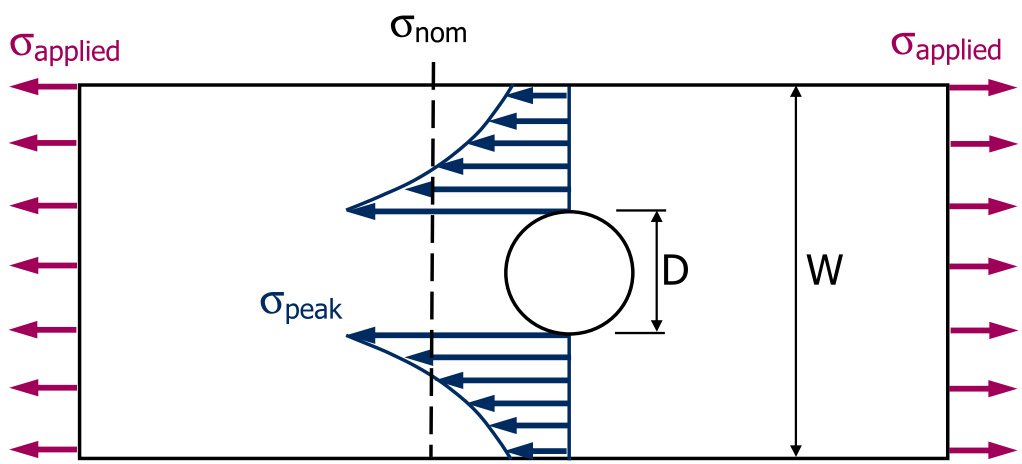
Flat panel with notch

- Definition
  - Nominal stress = average stress in the net-section higher than $\sigma_{applied}$

$$\sigma_{nom} = \frac{W}{W-D}\sigma_{applied}$$

  - Stress concentration factor K_t

$$K_t = \frac{\sigma_{peak}}{\sigma_{nom}}$$

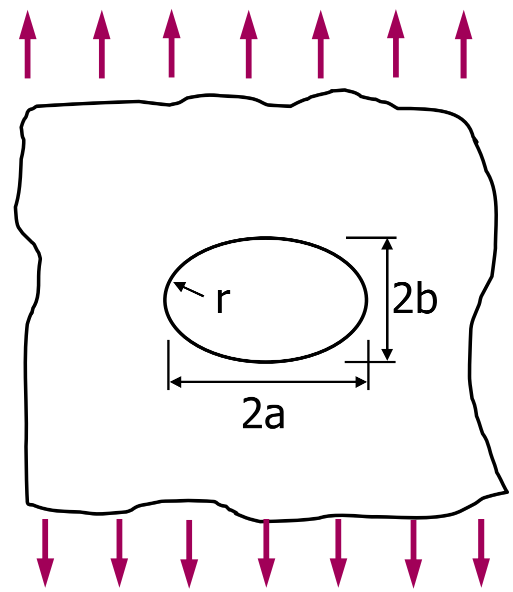


Stress-strain concentrations

Flat panel with notch

- Consider an isotropic infinite sheet with an elliptical hole

$$K_t = \frac{\sigma_{peak}}{\sigma_{nom}} = 1 + 2\frac{a}{b} = 1 + 2\sqrt{\frac{a}{r}}$$



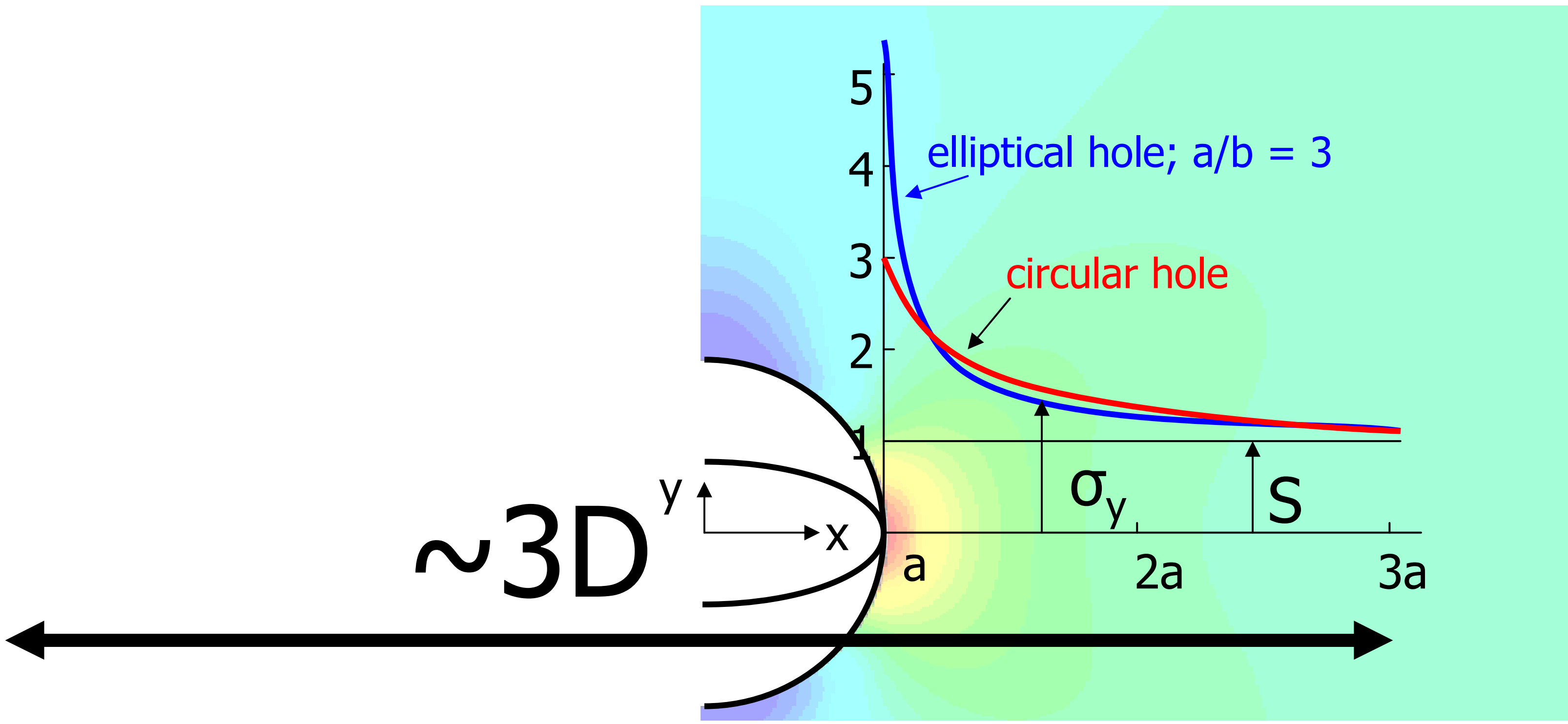
- For a circular hole: K_t = 3, independent of hole dimensions!

- NB: Linear elastic & anisotropic materials (e.g. composites) can be very sensitive for notches

Stress-strain concentrations

Saint Venant's principle

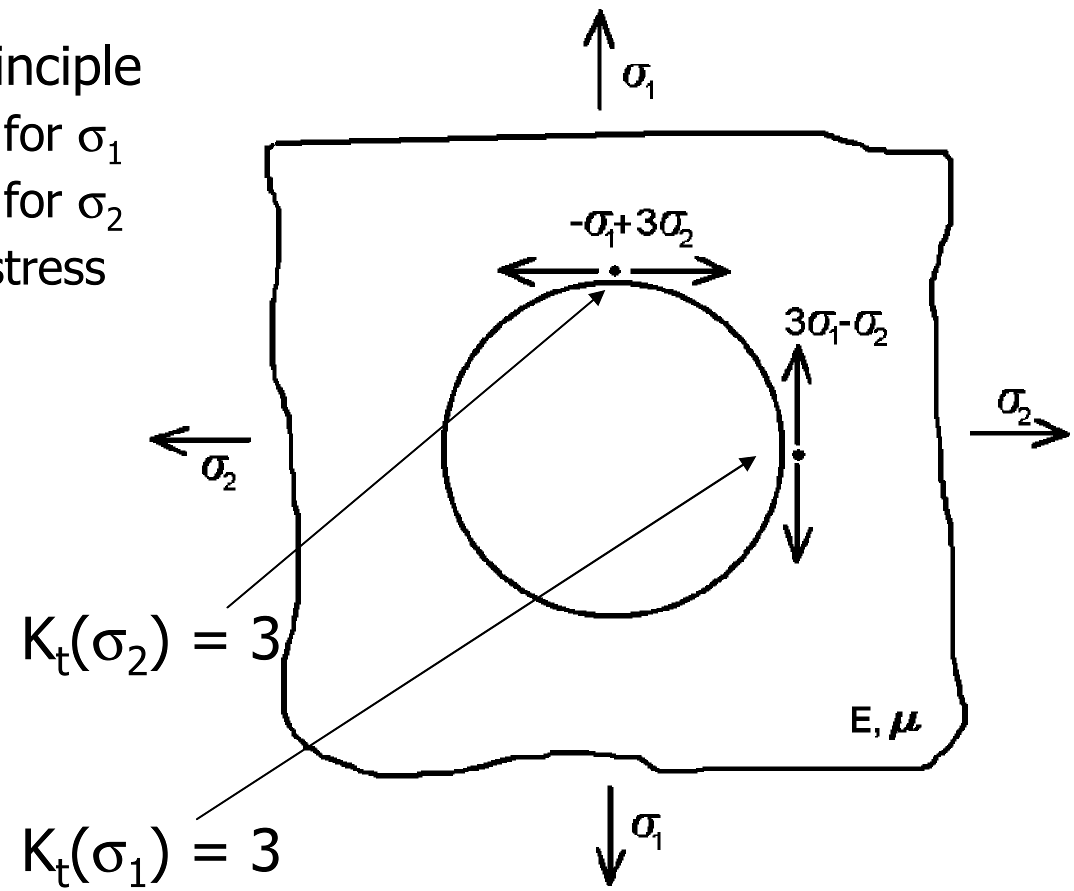
- Disturbance is limited to the direct neighbourhood of the notch causing the disturbance!



Stress-strain concentrations

Plane stress - superposition

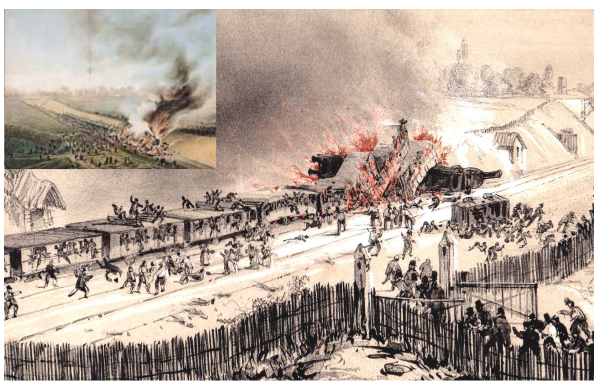
- Use superposition principle
  1. Determine stresses for σ_1
  2. Determine stresses for σ_2
  3. Superimpose both stress systems

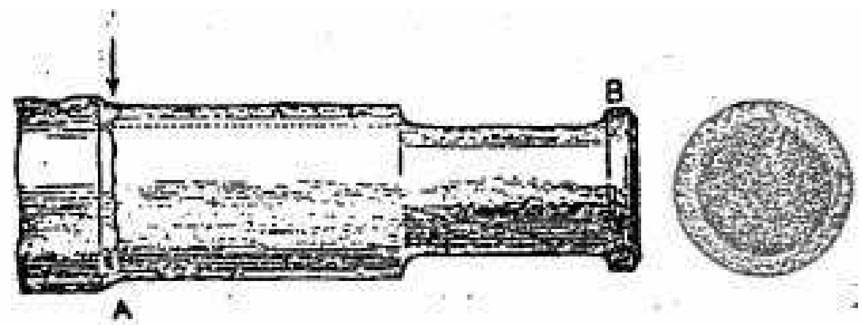


Stress-strain concentrations

Versailles Railway Accident (1842)

- Story
  - Long train: 17 carriages, 3 locomotives, and 1500 passengers.
  - Front axle of first locomotive failed. Second locomotive smashed into first; boiler thrown into air and burst; fire started
  - Approx. 60 fatalities.
- Investigation by W.J.M. Rankine:
  - Fatigue and effect of stress concentrations (stress raisers)

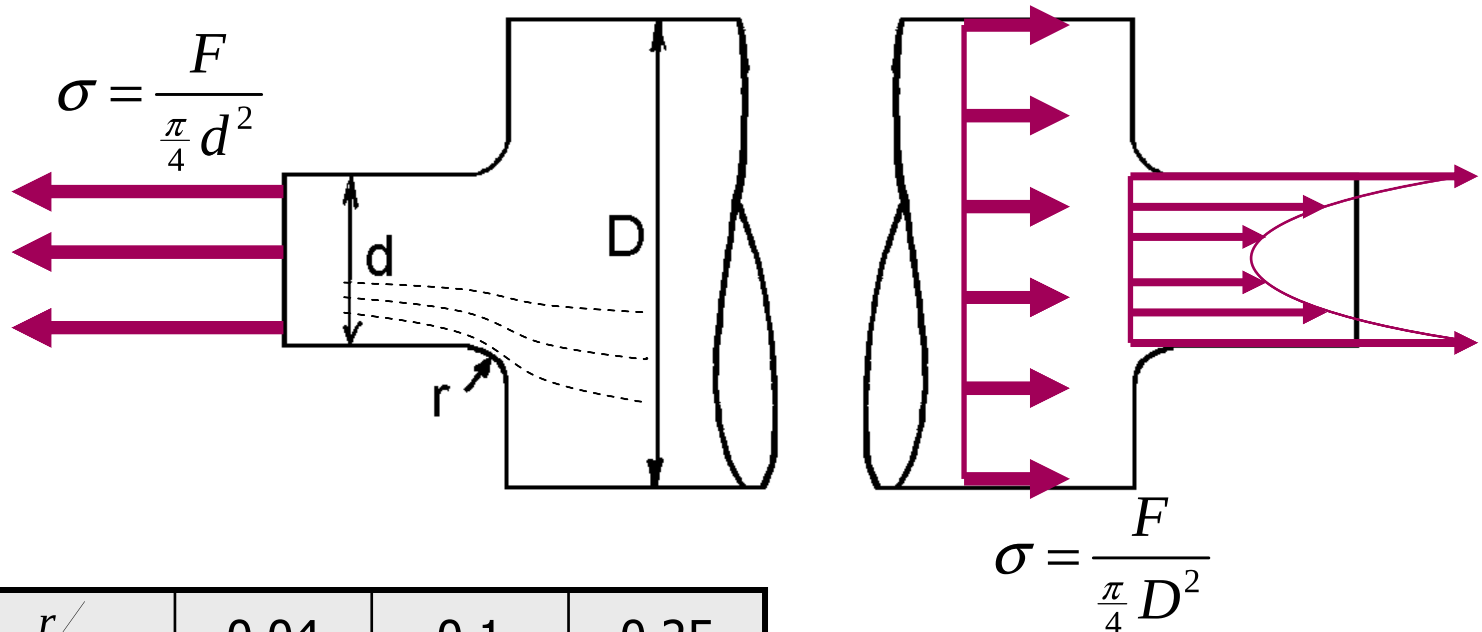




Stress-strain concentrations

Axle with 'reinforcement'

- Thickness increase to strengthen the axle locally implies weakening

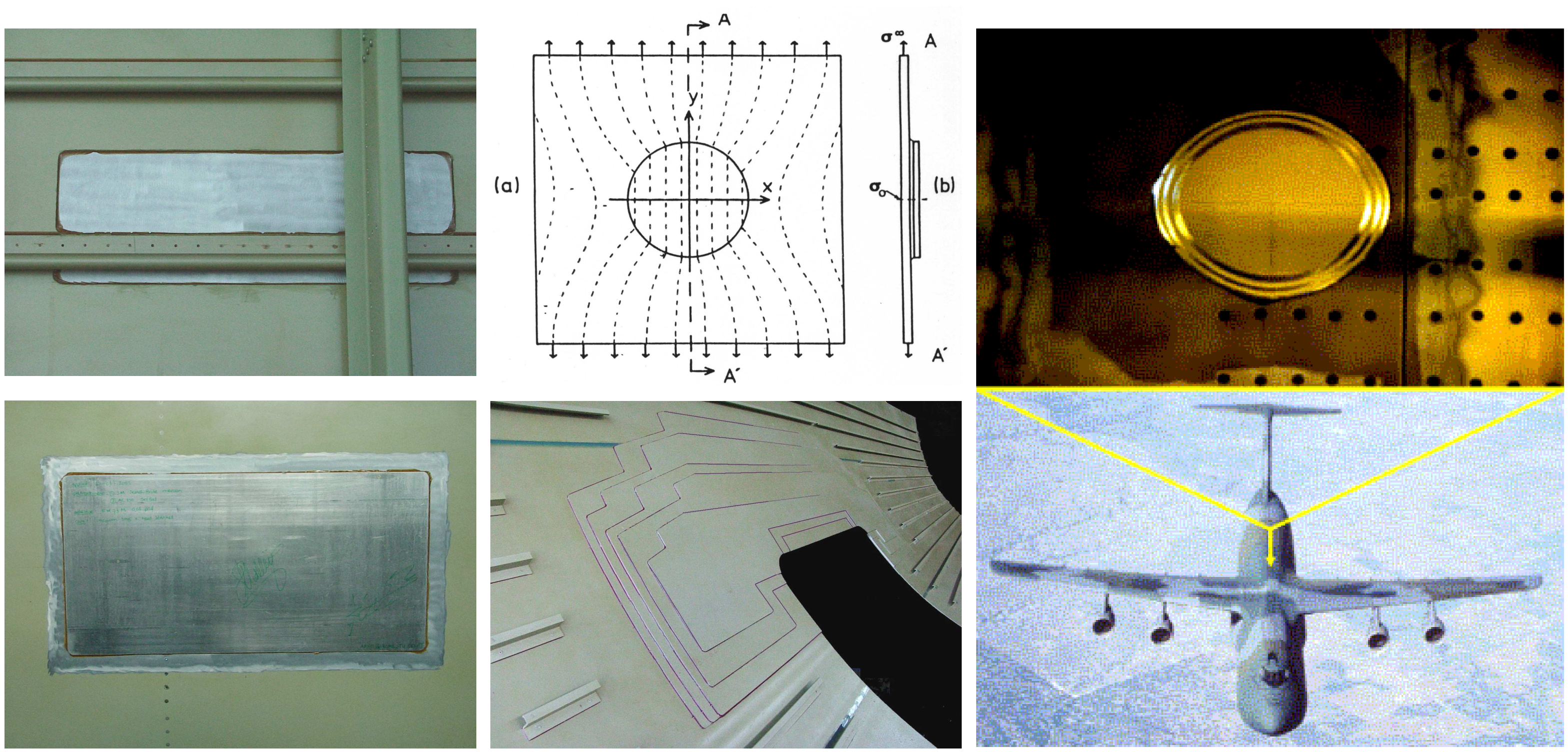


$D/d = 2$	r/D	0.04	0.1	0.25
	K_t	3	2	1.5

Stress-strain concentrations

Adding material to reinforce (repair)

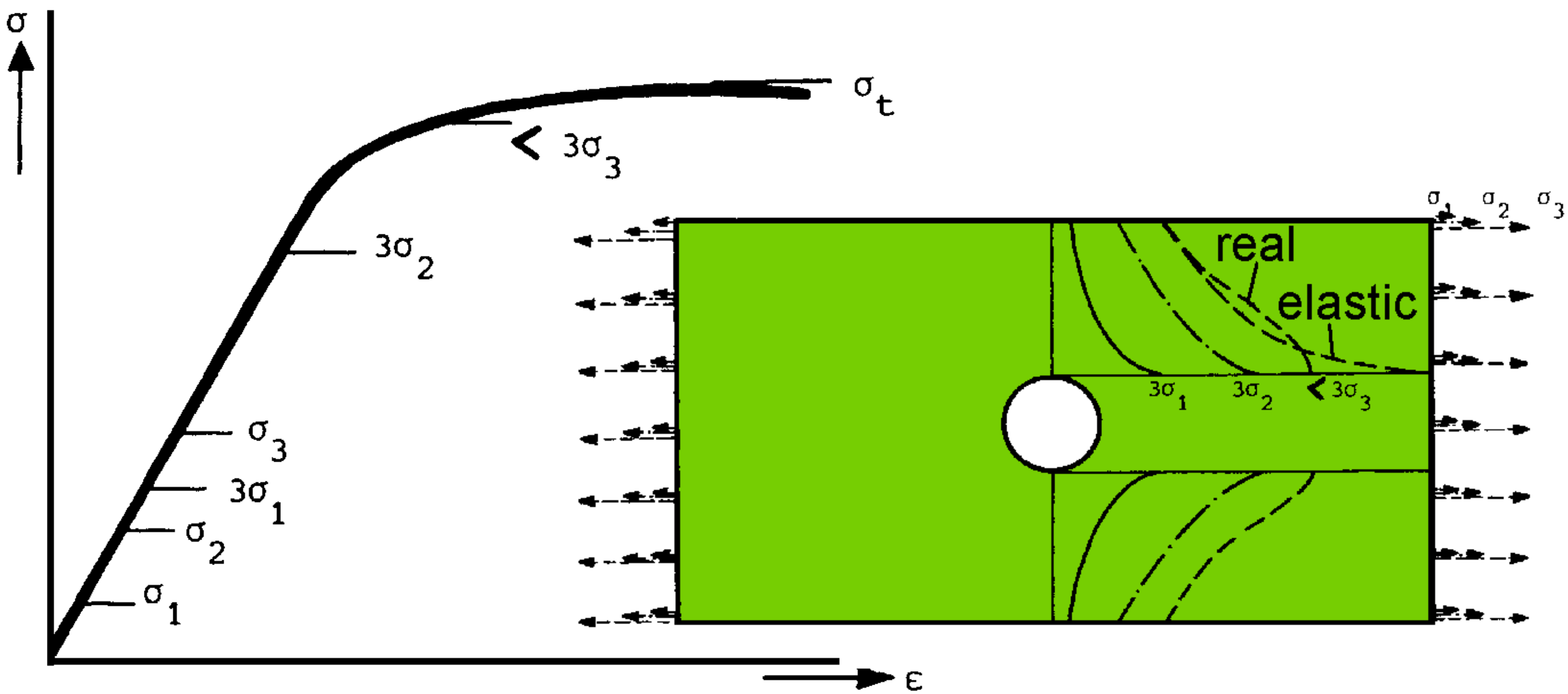
- Repair/reinforcement may ‘attract stress’ because of increased stiffness → Stress concentration



Stress-strain concentrations

Effect of K_t on ultimate strength

- Plasticity at notch reduces peak stress



Stress-strain concentrations

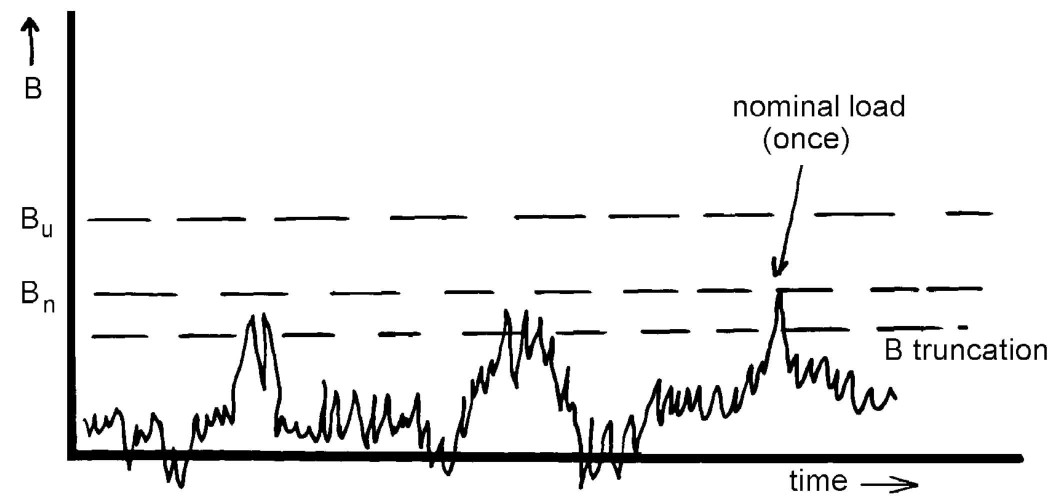
Effect of K_t on ultimate strength

- Concentration of stress & strain
  - A stronger, but more brittle material *can not be loaded as high* as the weaker, more ductile material
- Ductile materials are less notch sensitive under tensile loading
  - Composites do not yield ⇒ peak stresses are not leveled off (notch sensitive)
- The strength of the ductile material can be used much better

Fatigue

Definition

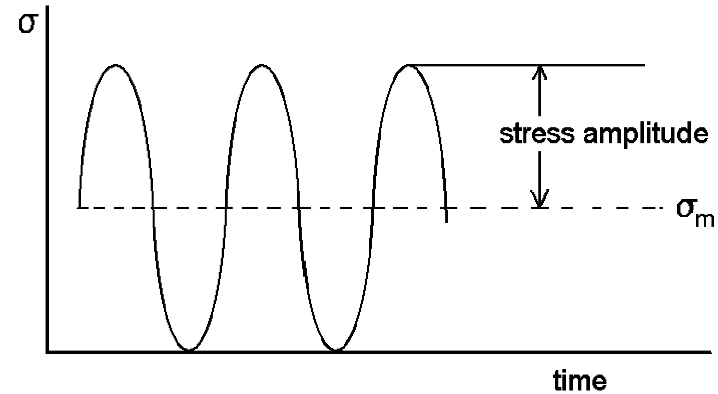
- Damage phenomenon induced by large number of load cycles below ultimate strength resulting in permanent deterioration of material or structure causing a reduction in load bearing capability
  - Load cycles are often related to number of flights, ranging from constant amplitude (fuselage pressurization) to arbitrary spectrum loading (wing loading)

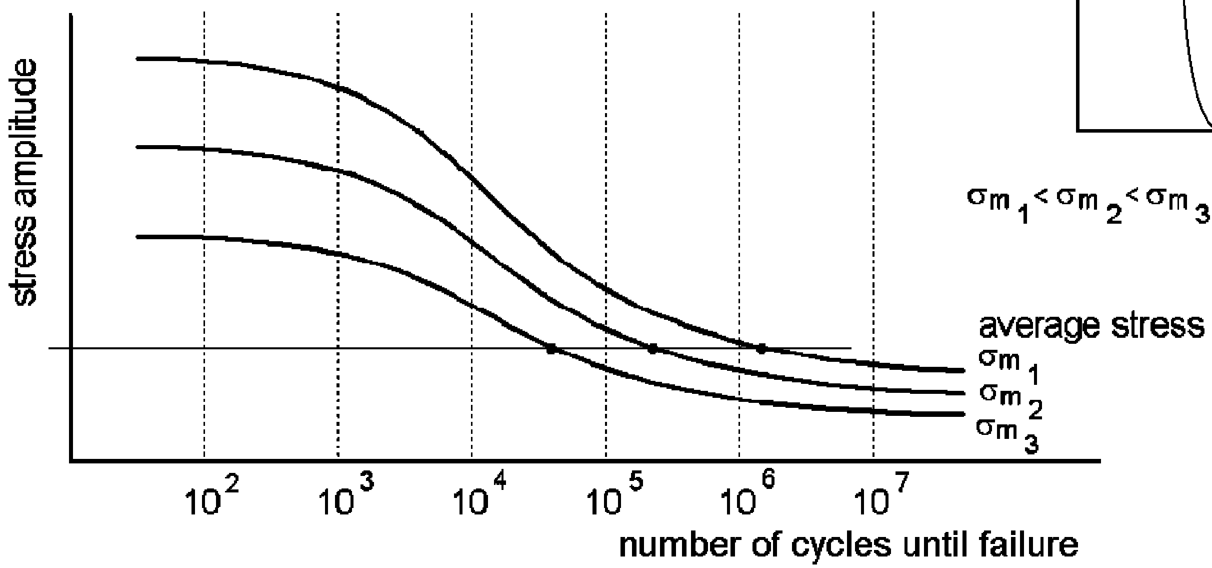


Fatigue

Un-notched panels

- Fatigue life plotted against flights/load cycles
  - Wöhler curve (S-N curve)

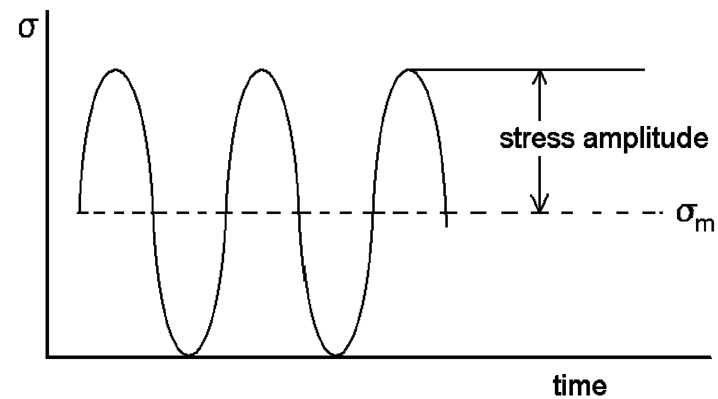


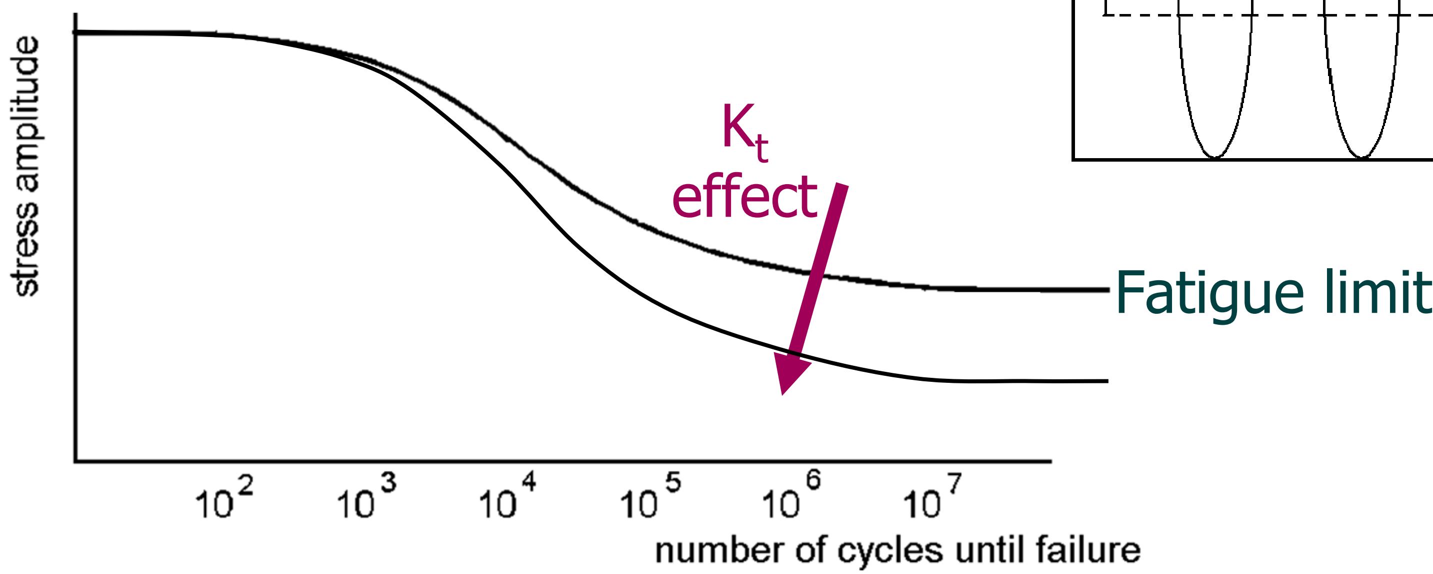


Fatigue

Notched panels

- Fatigue life plotted against flights/load cycles
  - Wöhler curve (S-N curve)
  - Stress concentration reduces fatigue limit





Fatigue

S-N curves

- Initiation & growth of small cracks (<1 mm) = 80-90% of total life
  Remainder of life ≡ fast growth to failure (!)

- Experimental strength justification based on S-N fatigue (*safe life*)
  - Experimental life ≈ 3 - 4 times required life

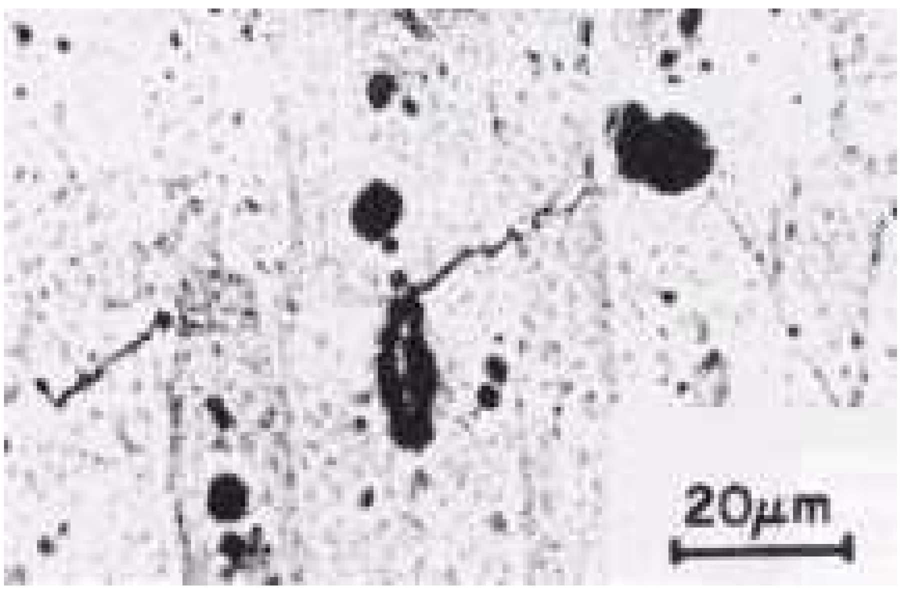
- Thickness of fatigue critical parts is greater than required for static strength

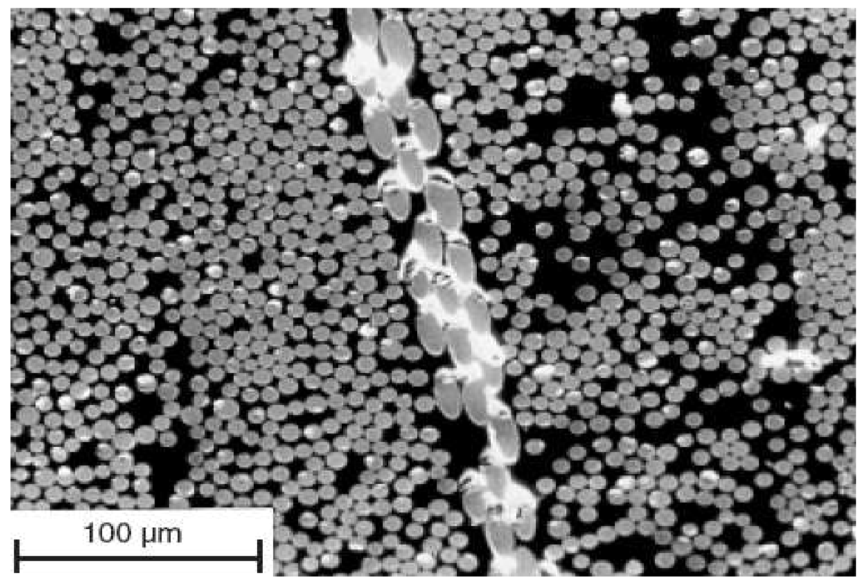
- Means to increase life:
  - Damage tolerance approach (inspection/repair/replacement)
  - Avoid stress concentrations and damage initiators in design
  - Less fatigue sensitive materials

Fatigue

Characteristics features

- Nucleation of micro cracks at inclusions in metals
- Nucleation of micro cracks at interface between fibre and resin

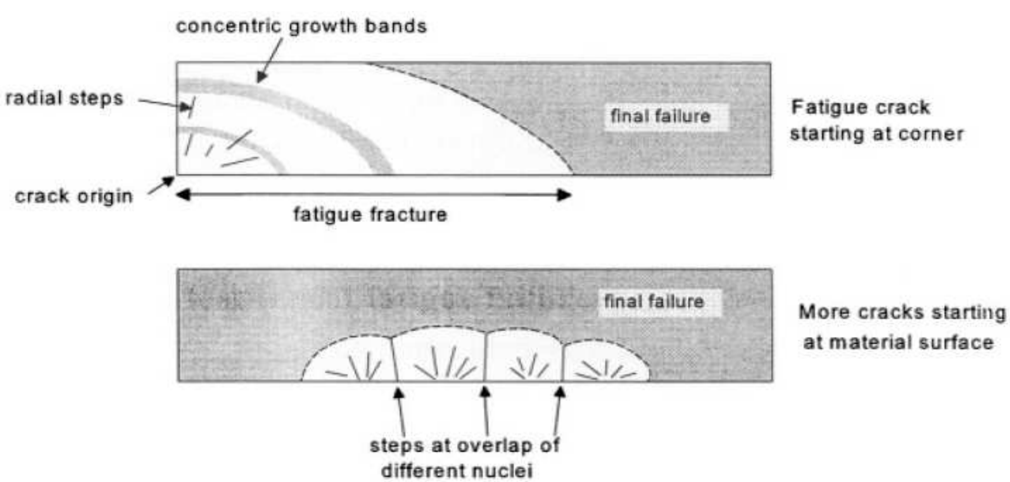


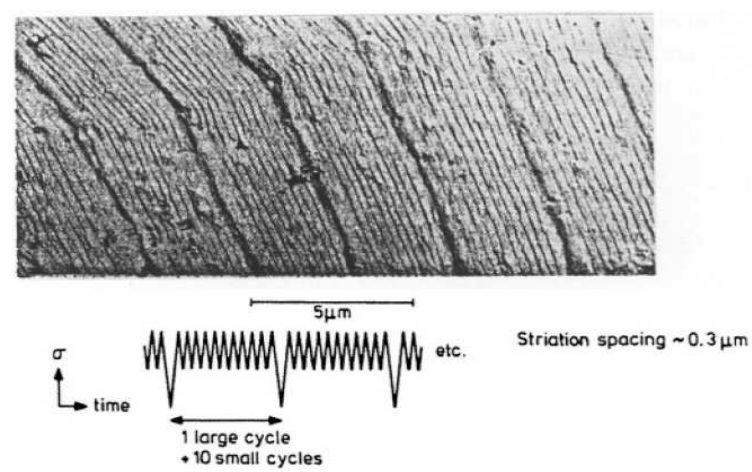


Fatigue

Characteristic features of fatigue failures in metals

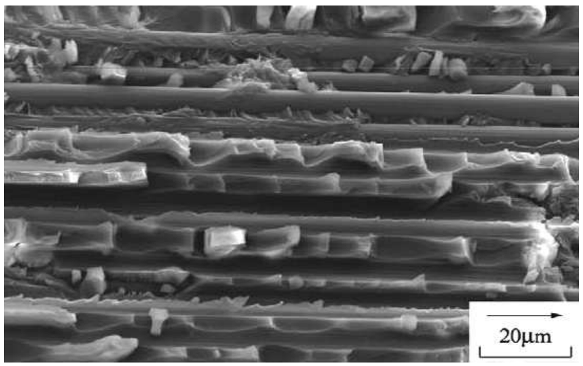
- Macroscopic
  - No macro-plastic deformation
  - Growth bands
  - Growth direction ⊥ main stress
  - Radial steps
  - Number of fatigue nuclei
- Microscopic
  - Striations

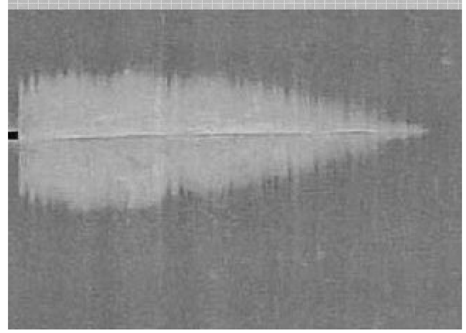




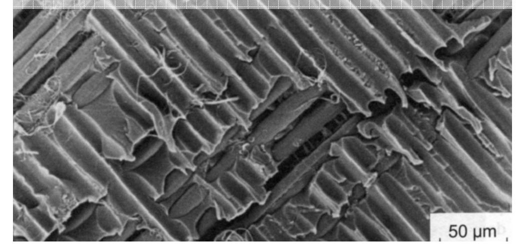
Fatigue

Characteristics features of failure in composites

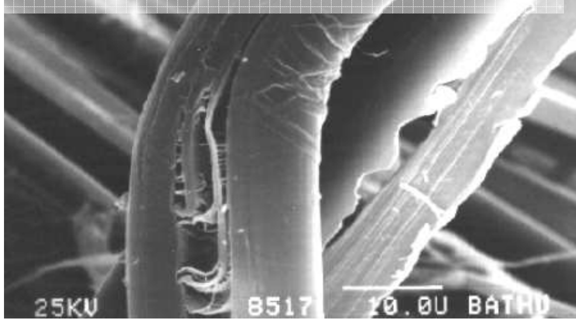




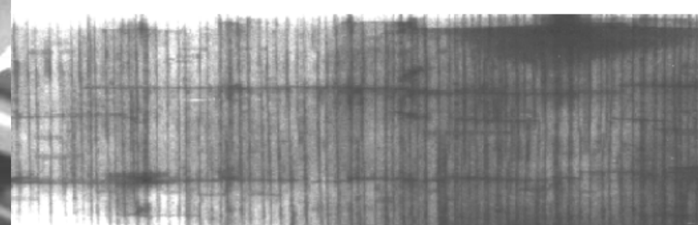
Delamination in FML

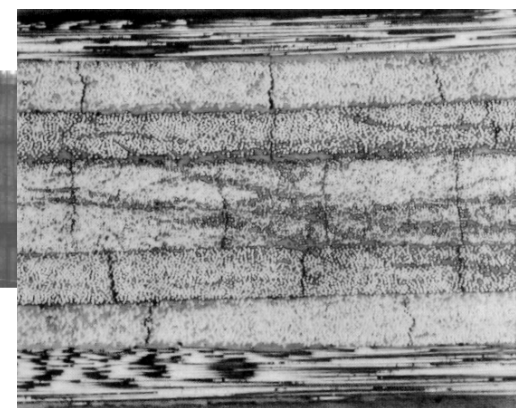


Fibre/matrix delamination



Kevlar fibre failure





Longitudinal and transverse shear cracks

Fatigue

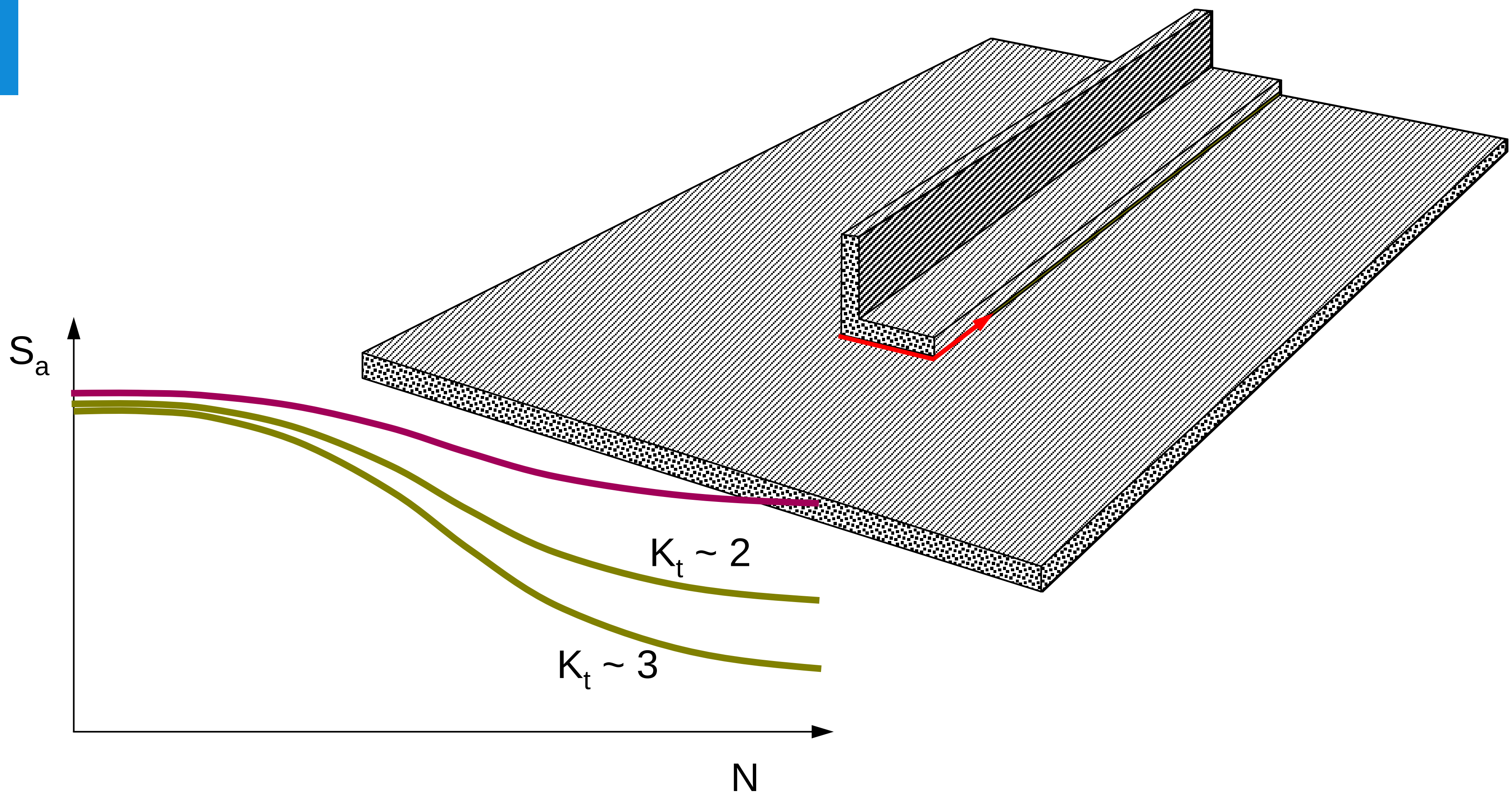
Characteristics features

- Fatigue appears different in metals and composites
  - Metal sensitive to tension-tension fatigue
  - Composites sensitive to compression-tension fatigue

- Static strength requirement for composites (0.35% max strain) often covers fatigue related aspects
  - The fact that fatigue does not show up in most of current applications does not mean that the phenomenon does not exist !
  - (see fatigue studies in composite wind turbine blades)

Fatigue

Fatigue is a structural phenomenon!



Damage tolerance

Residual strength in presence of damage

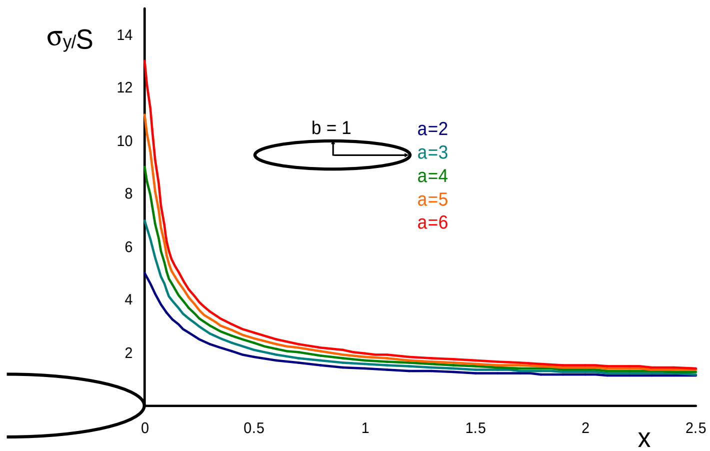
- Once damage has been initiated, how much strength is left?
  - Important aspect in design of damage tolerant structures !

- Stress concentration factor

$$K_t = \frac{\sigma_{peak}}{\sigma_{nom}} = 1 + 2\frac{a}{b} = 1 + 2\sqrt{\frac{a}{r}}$$

- Crack or delamination: $r \to 0 \Rightarrow K_t \to \infty$
  - Concept is meaningless!

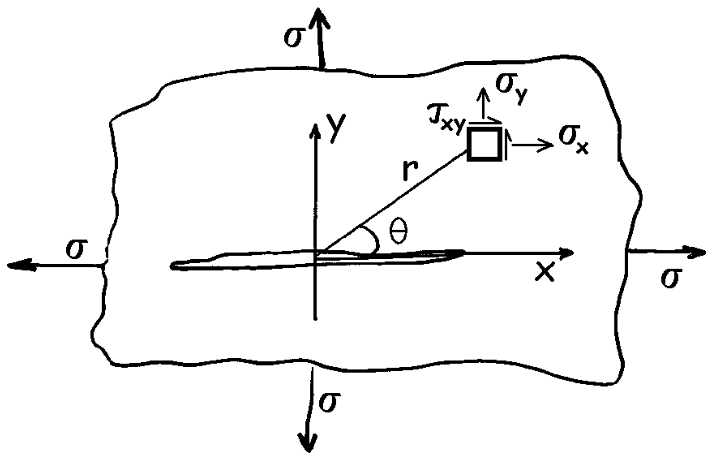
- Introduction of stress intensity factor…



Damage tolerance

Stress Intensity Factor

- Parameter describing the singularity in elastic field at the crack tip



$$\sigma_x = \frac{S\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)-S$$

$$\sigma_y = \frac{S\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\tau_{xy} = \frac{S\sqrt{\pi a}}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\sin\frac{3\theta}{2}$$

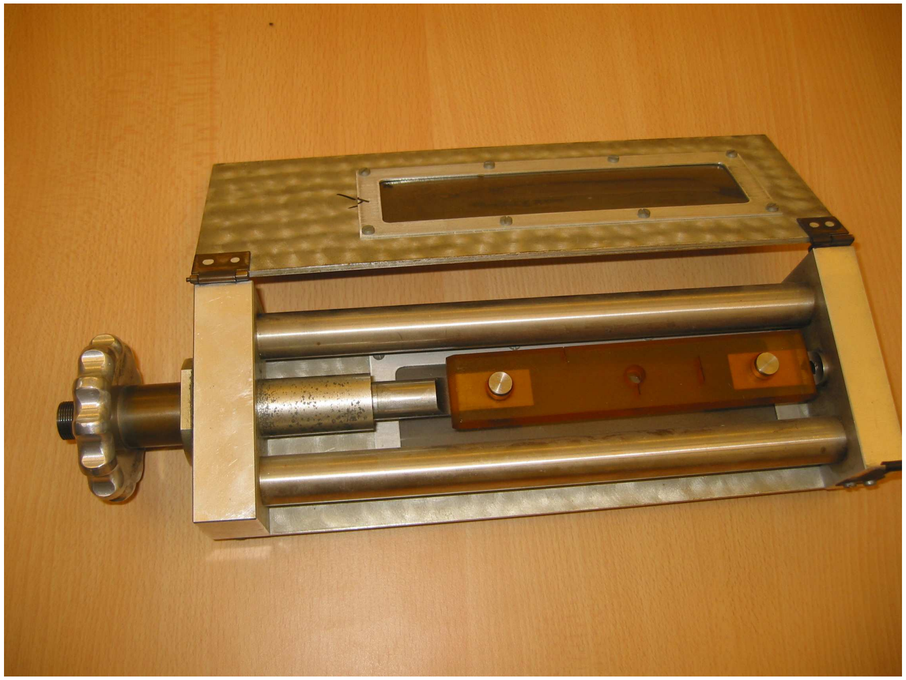
- Rewrite as

$$\sigma_{i,j} = K\ f_{i,j}(r,\theta)$$

$$K = S\sqrt{\pi a}$$

Damage tolerance

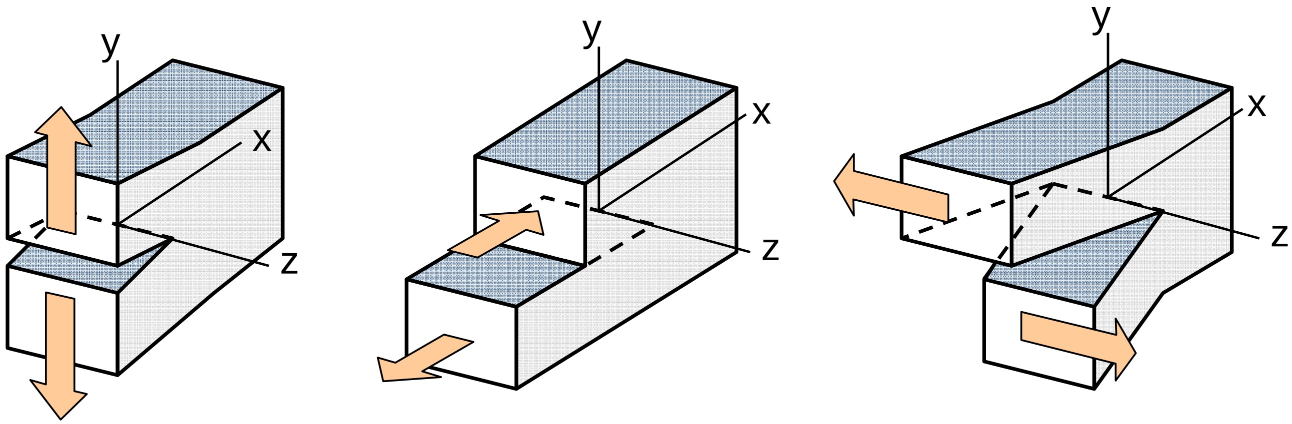
Stress Intensity Factor



Damage tolerance

Stress Intensity Factor

- Three modes to load a crack tip



- Mode I: Tension Mode II: Shear Mode III: transverse shear

- Critical K in mode I is K_{Ic} and is called fracture toughness = material property indicating the sensitivity for cracks under static loading
- (see lecture on material properties)

Damage tolerance

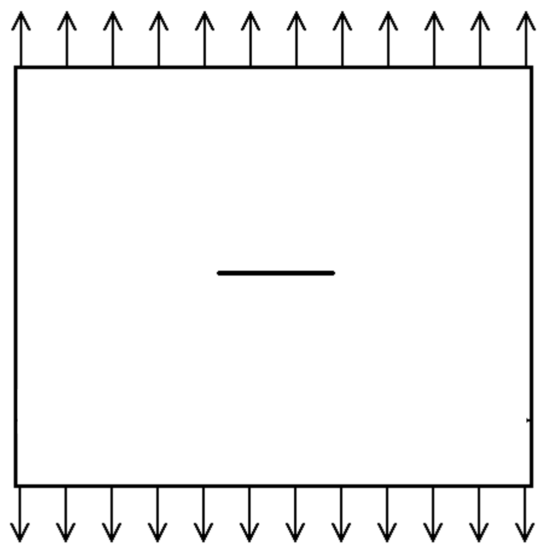
Fracture toughness

- Fracture toughness dependent on material property (ductility!)
- Related critical stress dependent on geometry

$$\sigma_{crit} = \frac{K_{Ic}}{\sqrt{\pi a_{crit}}}$$

- Example: assume $\sigma_{crit} = ½\sigma_{0.2}$

Alloy	$\sigma_{0.2}$ (MPa)	σ_c (MPa)	K_{Ic} (MPa√m)	a_c (mm)
2024-T3	360	180	40	15.7
7075-T6	470	235	27	4.2
Ti-6Al-4V	1020	510	50	3.1
4340 steel	1660	830	58	1.55



Summary

Fatigue & durability

- Stress Concentration Factors K_t
- Fatigue
- Cracks $\Rightarrow$ Stress Intensity Factor K