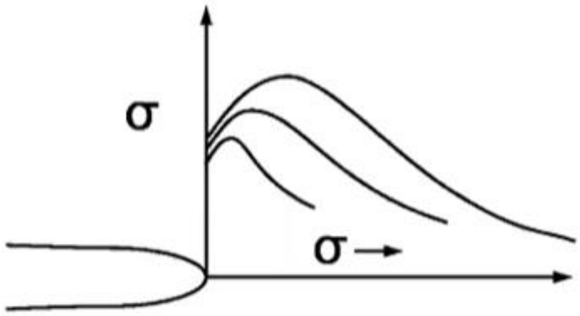
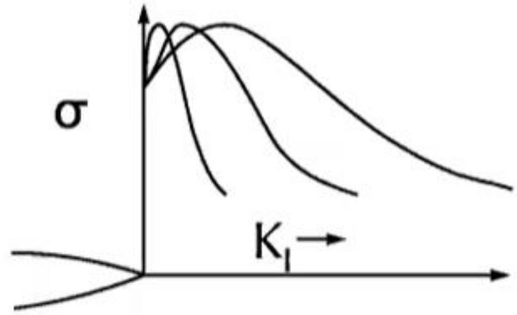
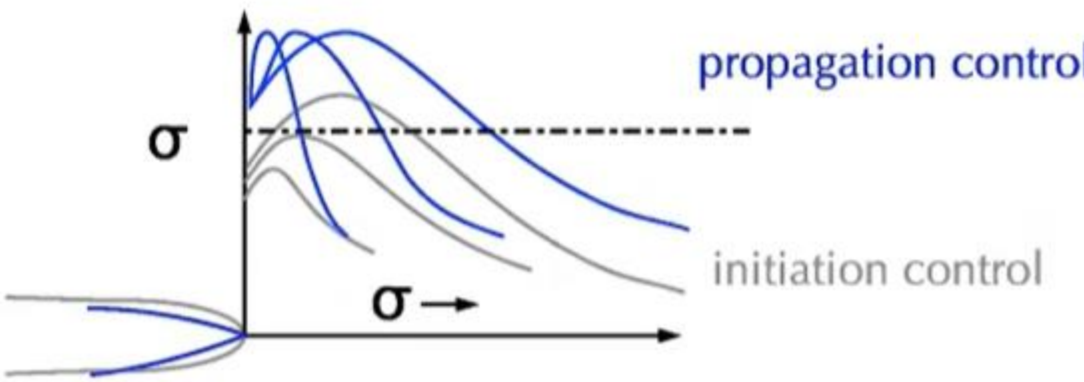






Notched samples show larger variability

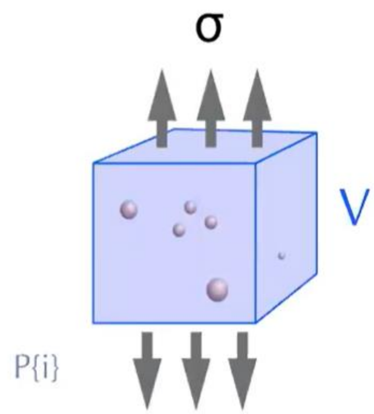
Master curve

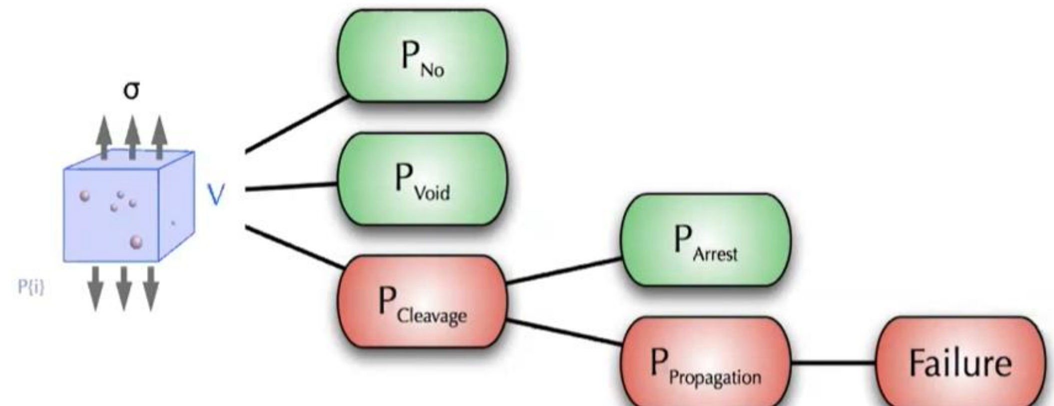
Considers the stochastic nature of the cleavage fracture

Gives quantitative tools for handling cleavage

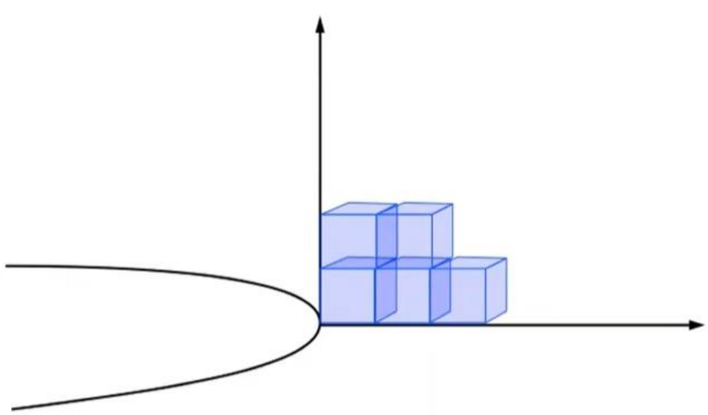
- different experimental data
- temperature dependence

Stochastic nature





$$P_f = 1 - \exp\left\{-\bar{N}_V \cdot V \cdot \Pr\{I\} \cdot \left(1 - \Pr\{V/O\}\right)\right\}$$



Probability of nucleation

$$P_f = 1 - \exp\left\{ -\frac{B}{B_0} \cdot \left(\frac{K_I}{K_0} \right)^4 \right\}$$

Scatter

$$P_f = 1 - \exp\left\{ -\frac{B}{B_0} \cdot \left(\frac{K_I - K_{min}}{K_0 - K_{min}} \right)^4 \right\}$$

Size effect

$$K_{IC_1} = K_{min} + (K_{IC_2} - K_{min}) \cdot \left(\frac{B_2}{B_1}\right)^{1/4}$$

Master - curve

Hajonta

$$P\left[K_{IC} \le K_I\right] = 1 - \exp\left(-\left[\frac{K_I - K_{min}}{K_0 - K_{min}}\right]^4\right)$$

Koon vaikutus

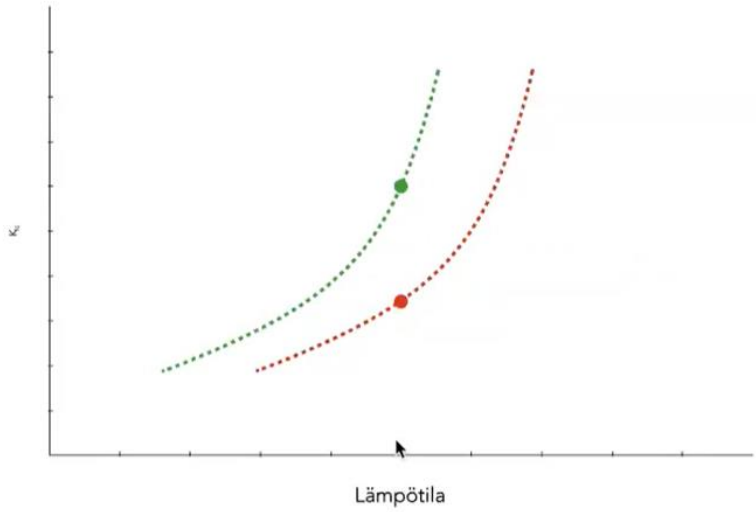
$$K_{B_2} = K_{min} + [K_{B_1} - K_{min}] \cdot \left(\frac{B_1}{B_2}\right)^{1/4}$$

?

Temperature dependence

$$K_0 = 31 + 77 \cdot \exp(0.019 \cdot [T - T_0])$$

Different steels are in different location on the curve



Measurements to determine T_0

Maximum-likelihood estimate on the data

$$\sum_{i=1}^{n} \frac{\delta_i \cdot \exp\{0.019 \cdot [T_i - T_0]\}}{11 + 77 \cdot \exp\{0.019 \cdot [T_i - T_0]\}} - \sum_{i=1}^{n} \frac{(K_{IC_i} - 20)^4 \cdot \exp\{0.019 \cdot [T_i - T_0]\}}{(11 + 77 \cdot \exp\{0.019 \cdot [T_i - T_0]\})^5} = 0$$

Summary

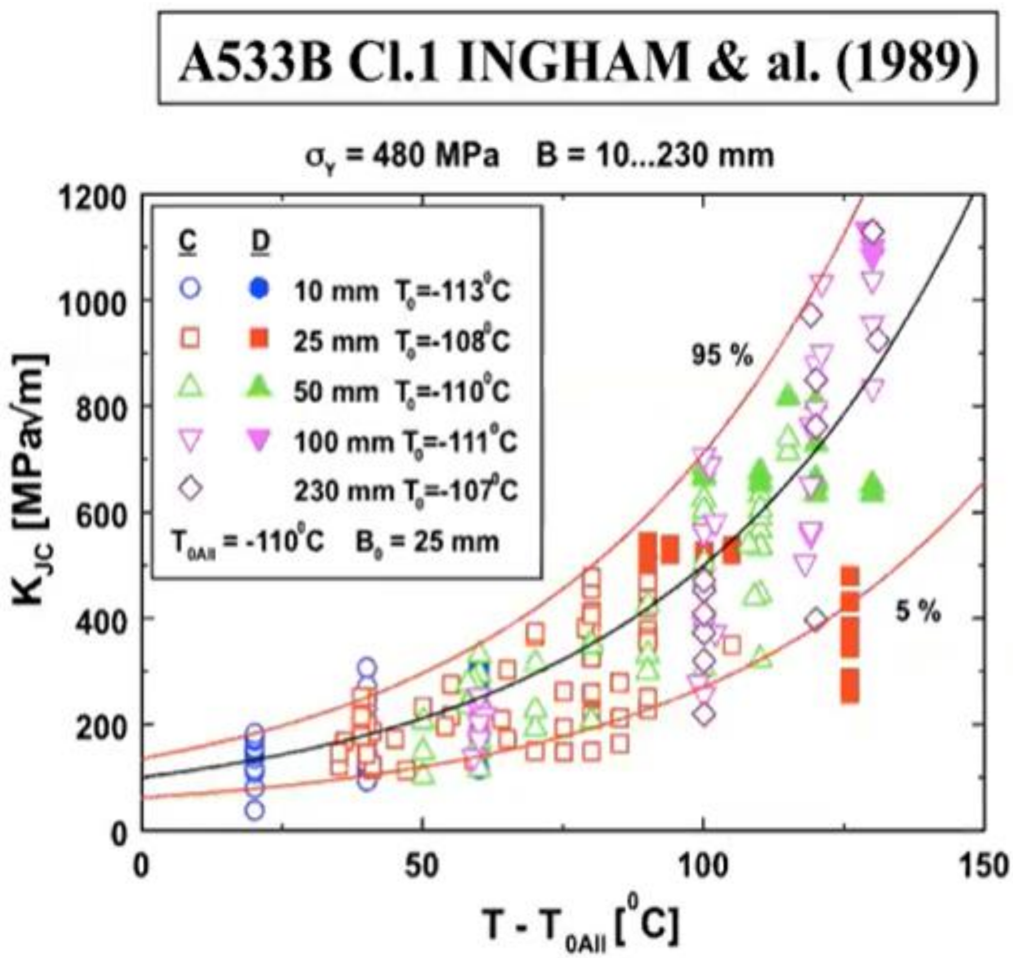
Measure fracture toughness in different temperatures

- K_{IC} tests
- Charpy-tests

Estimate T_0

Determine K_{JC} from the Master curve:

- in different temperatures
- with different failure probabilities



Design guides

Cracked component assessment (efficient use of available data and methods)

Fracture mechanics

K-calculation easy
- ready-made solutions
- linear-elastic models

K –testing expensive

J-computation laborious
- elastic-plastic cracked models

Design guide combines various approach

Use LEFM, when it works

Prevent its use, when it does *not*

Trade work for concervativeness
- Don't pay for performance you don't need

Methods

R6 "*Assessment of the Integrity of Structures Containing Defects*"

SINTAP

BS-PD6493

ETM

etc.

Basic components

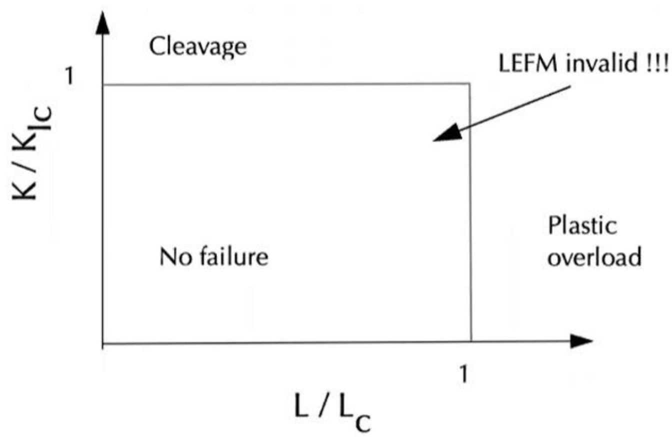
Simplified limit load concept

- FAD
- CDF

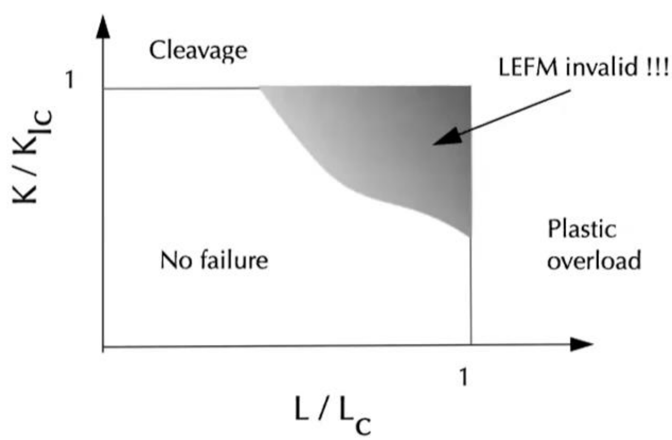
Analysis levels

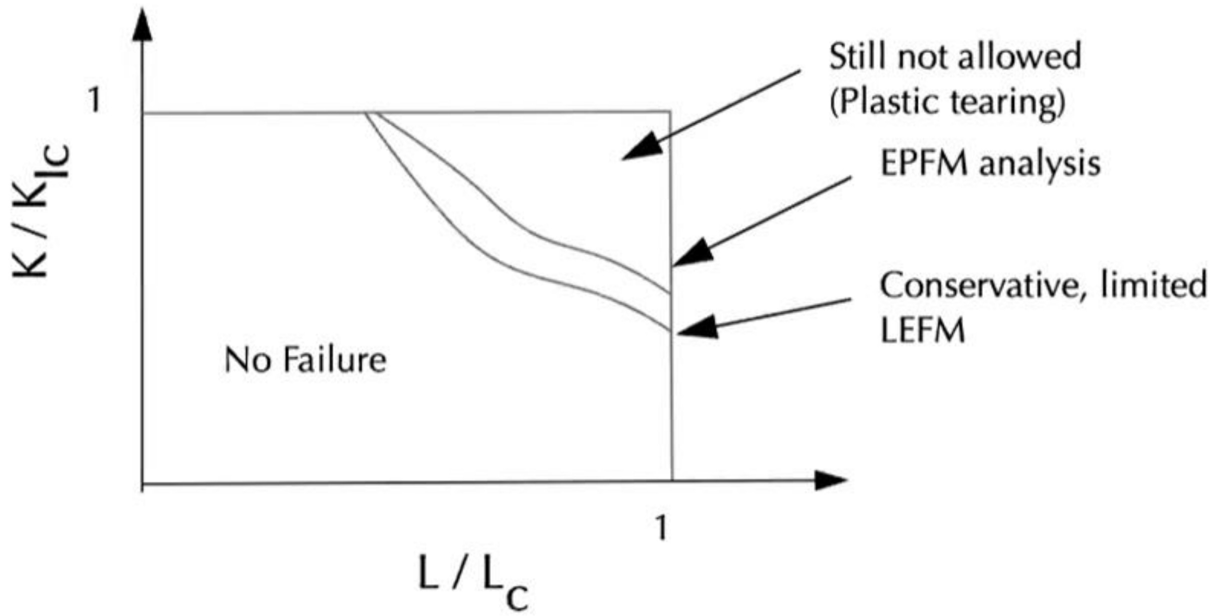
- less concervativeness => more input data and work
- unsatisfactory results guide to next level

Simple model needs alteration

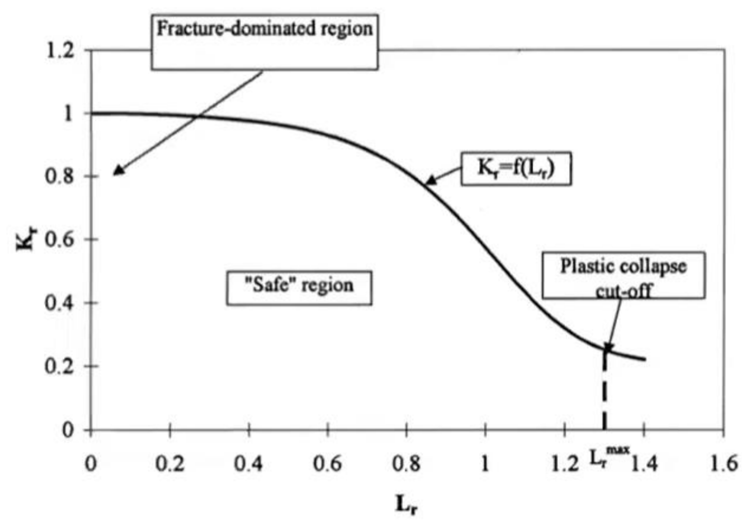


FAD - concept

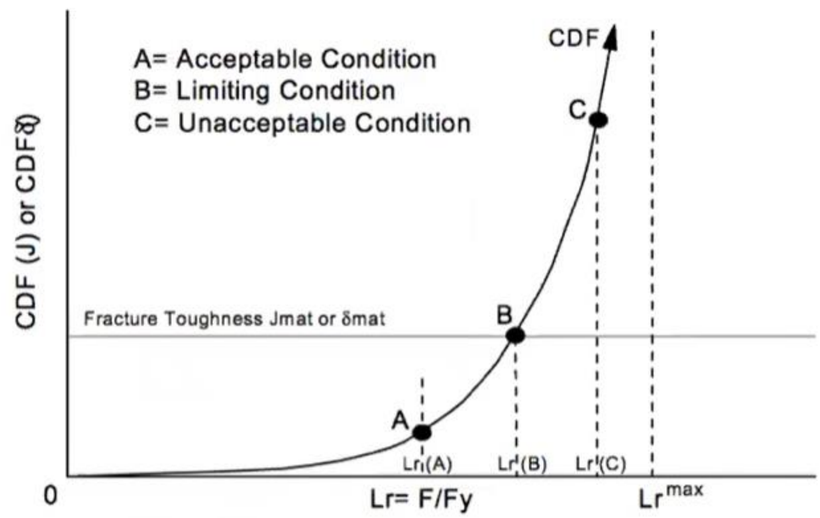




Failure assessment diagram – FAD R6



Crack driving force - CDF



c) CDF Analysis: Fracture Initiation

FAD vs. CDF

Technically equivalent (nowadays)
Choise is yours
Older guides retain FAD for historic reasons
Newer promote simpler (?) CDF

Summary

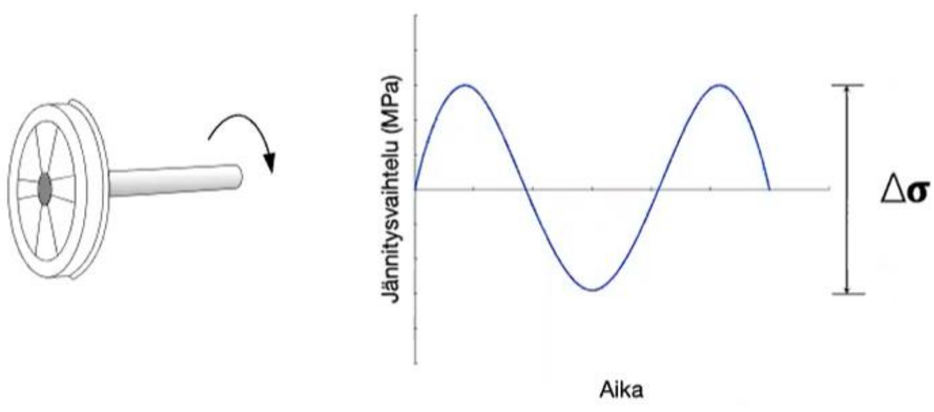
There's number of guides to help you through fracture mechanics design
Mostly outside the scope of this course
If the basics are not understood, the guide will get you nowhere (or worse)

http://www.eurofitnet.org/sintap_Procedure_version_1a.pdf

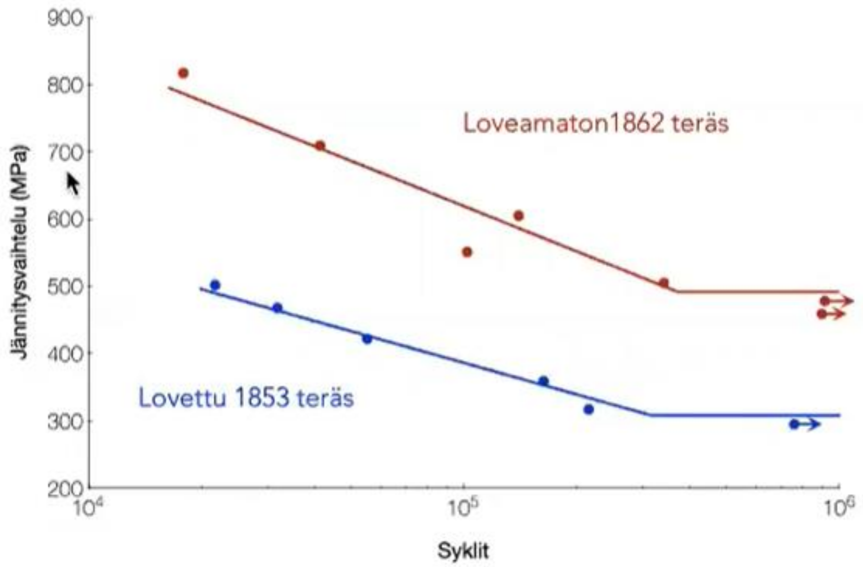
Fatigue

1842, Versailles

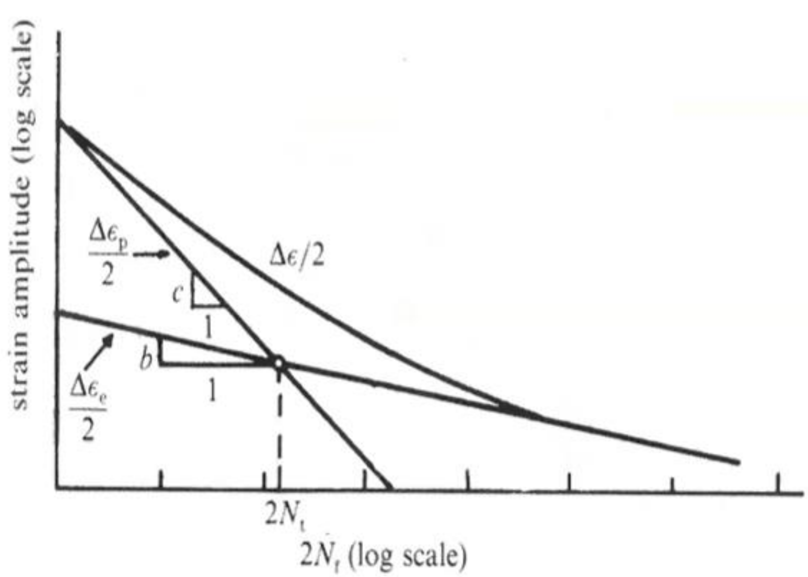
Wöhler

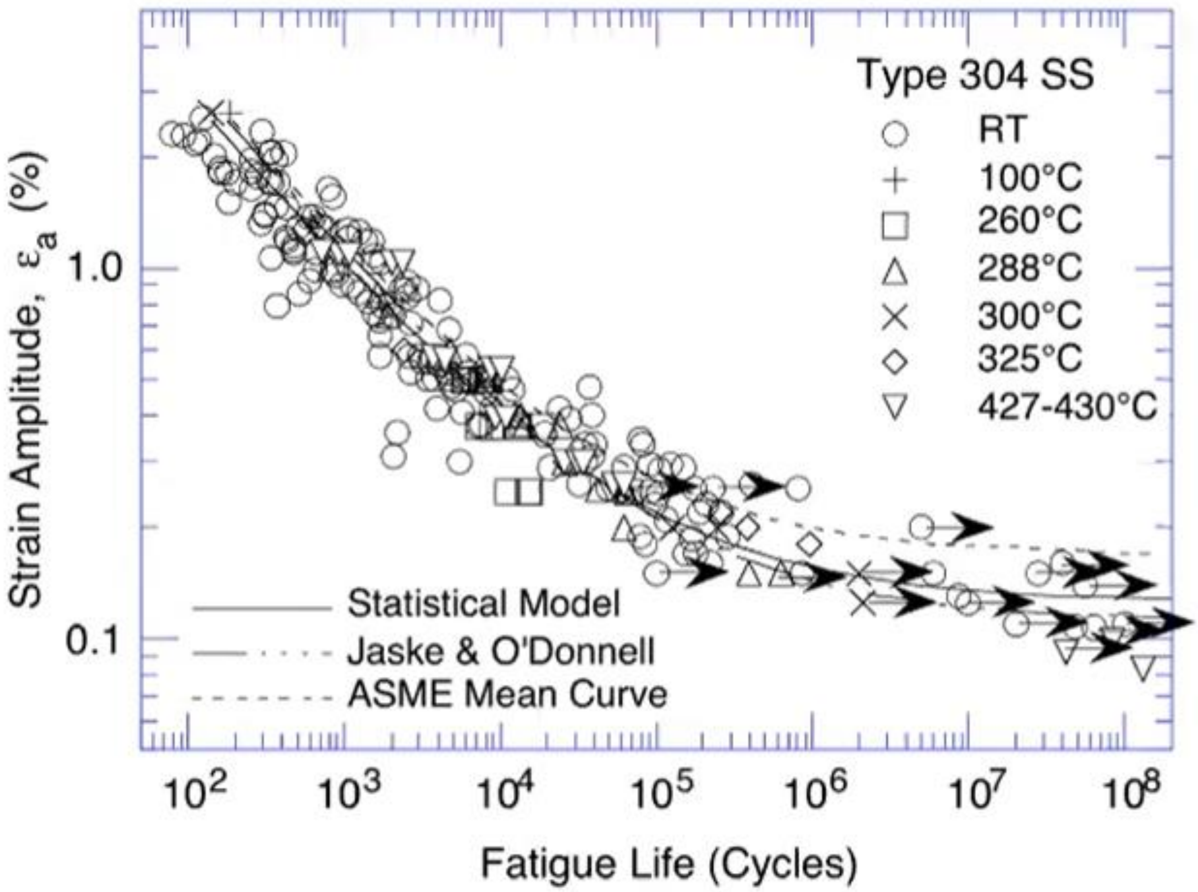


Classic fatigue design

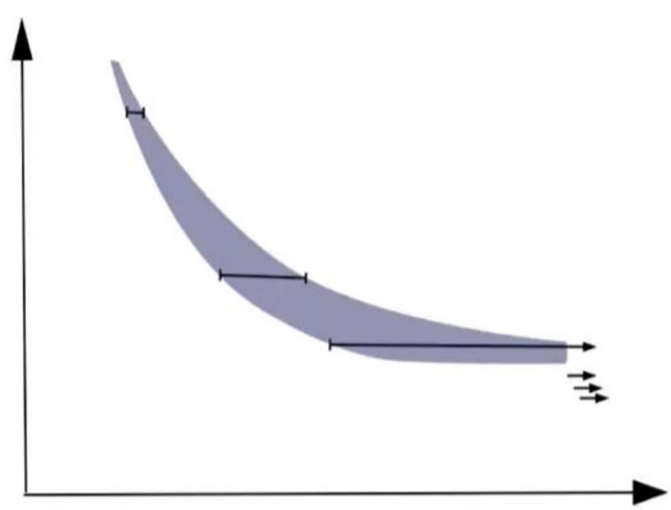


Coffin - Manson

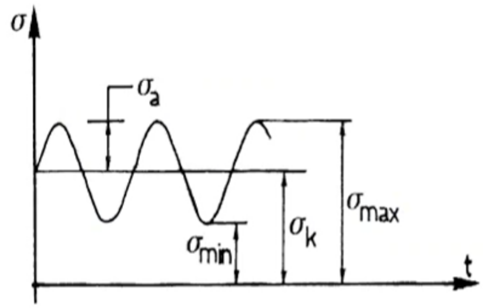




Scatter in S-N curve



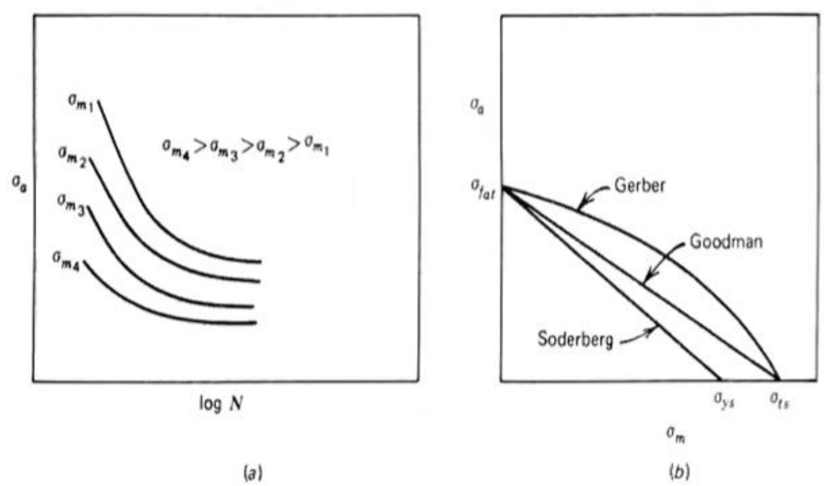
Cyclic loading



$$R = \frac{\sigma_{\max}}{\sigma_{\min}}$$

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$

Average stress has an effect



To account for average stress either...

Test with different average stresses

Estimate fatigue strength based on data from different average stress

Average Stress

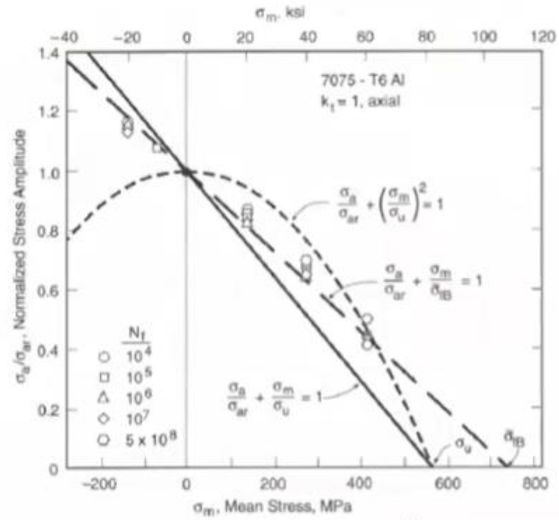
Goodman (1899)

$$\sigma_a = \sigma_{fs}\left\{1 - \frac{\sigma_0}{\sigma_{UTS}}\right\}$$

Gerber (1874)

$$\sigma_a = \sigma_{fs}\left\{1 - \left(\frac{\sigma_0}{\sigma_{UTS}}\right)^2\right\}$$

Average stress effect



Modified Goodman equation

$$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_u} = 1$$

Gerber parabola

$$\frac{\sigma_a}{\sigma_{ar}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1 \quad (\sigma_m \geq 0)$$

$$\sigma_{ar} = \sqrt{\sigma_{\max}\sigma_a} \quad (\sigma_{\max} > 0)$$

$$\sigma_{ar} = \sigma_{\max}\sqrt{\frac{1-R}{2}} \quad (\sigma_{\max} > 0)$$

Smith, Watson, and Topper (SWT) equation

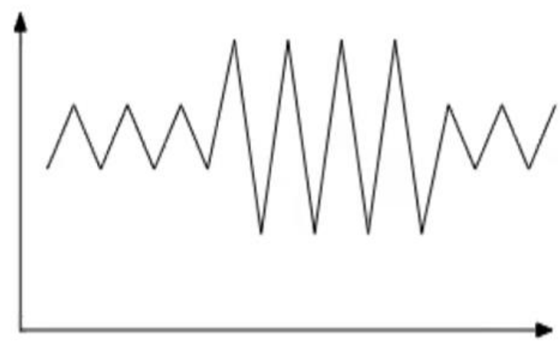
$$\sigma_{ar} = \sigma_{\max}^{1-\gamma}\sigma_a^{\gamma} \quad (\sigma_{\max} > 0)$$

$$\sigma_{ar} = \sigma_{\max}\left(\frac{1-R}{2}\right)^{\gamma} \quad (\sigma_{\max} > 0)$$

Walker equation

Loading with different cycles

Each cycle (load-sequence) takes part of remaining life



Miner

Simple linear sum

Cycle-order assumed insignificant

$$D = \sum_{i=1}^{m} \frac{n_i}{N_{f,i}}$$

... but

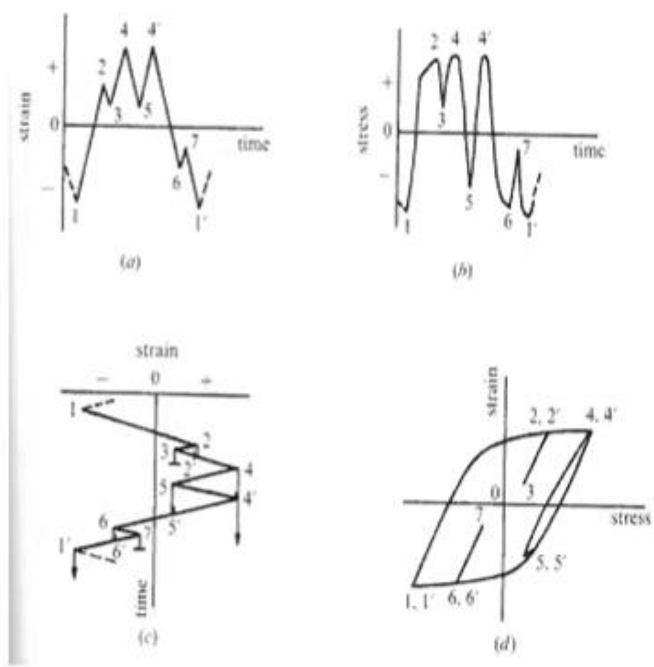
In reality the order does have an effect

- small cycles cause damage, after crack has formed
- intermittent overloads extend life (crack blunting)
- Minerin rule still most used (easy and often good enough)

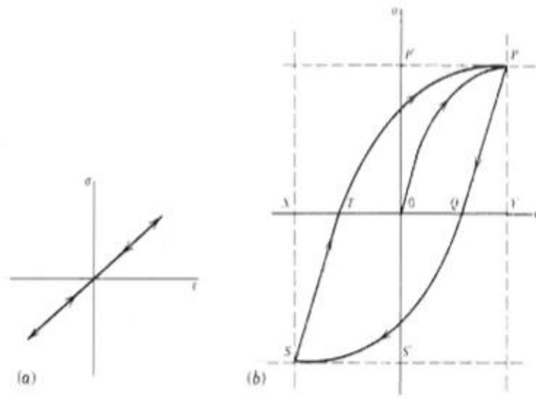
Spectral loading?

What is a cycle?
Many methods
Most used is "rainflow"

Spectral loading



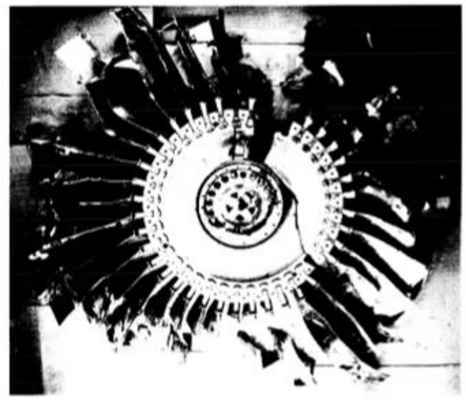
High-cycle vs. Low cycle



Failures, still failures

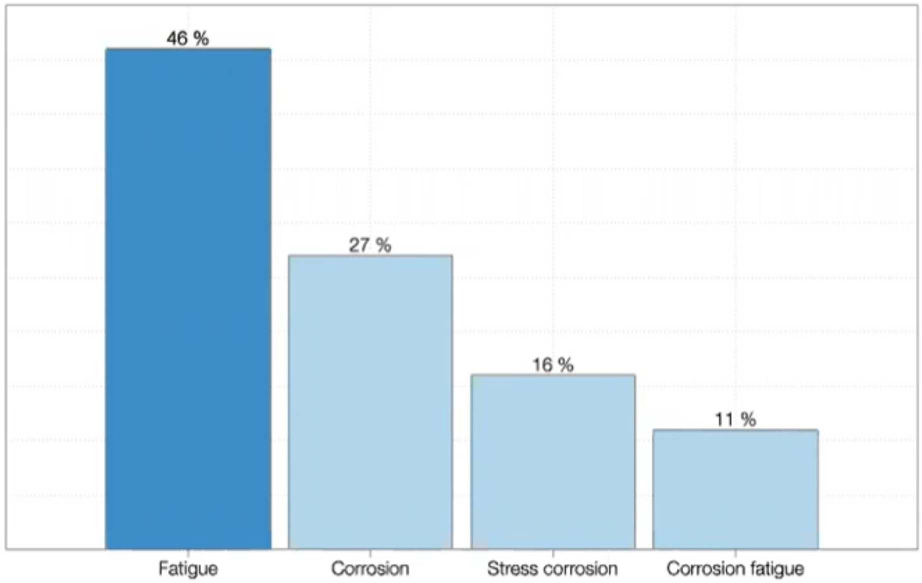
Alexander Kielland, 1980

UA232, DC-10, 1989



Eschede, 1998

Most common failure



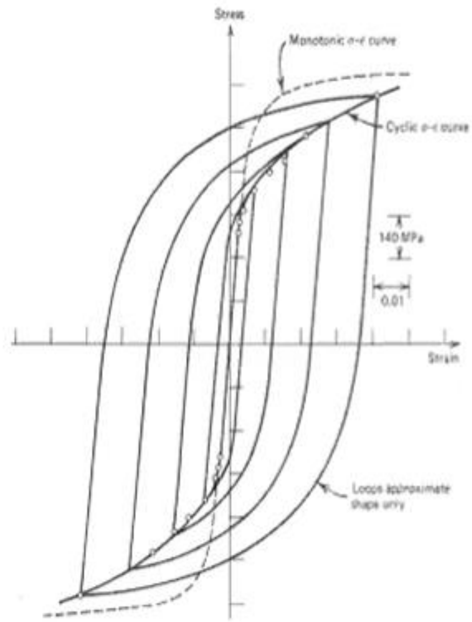
What happens before disaster?

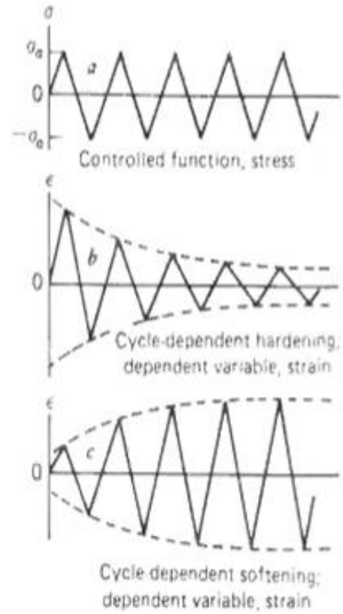
Damage initiation?
Damage accumulation?
What is fatigue?

Material changes during fatigue loading

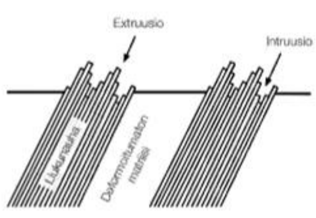
Small
Changes in dislocation structures
High loads cause cyclic strengthening or softening

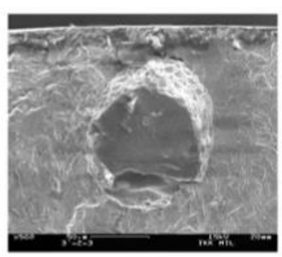
Cyclic stress-strain curves

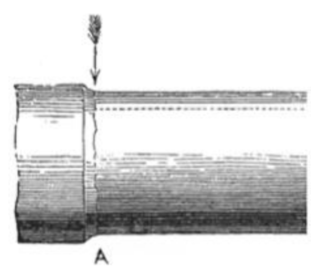




Failure starts with crack initiation





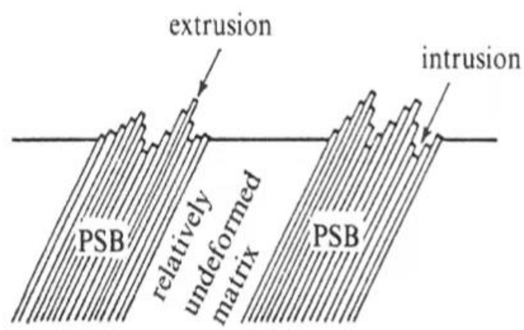


S-N curves

Tested until failure
Time to "engineering crack"

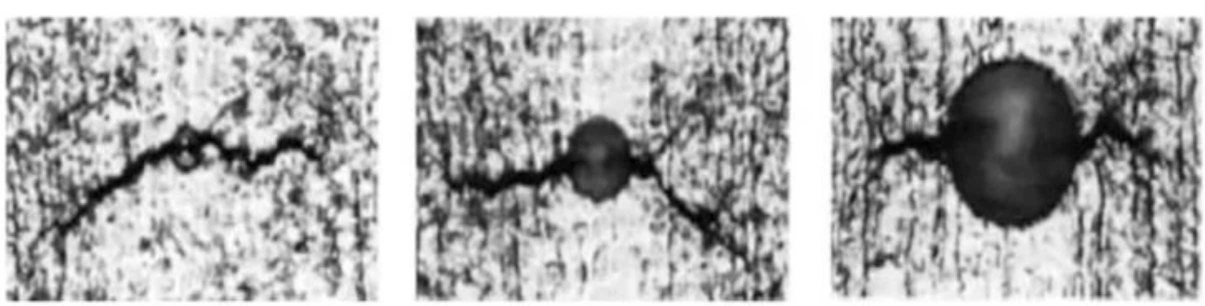
Nucleation

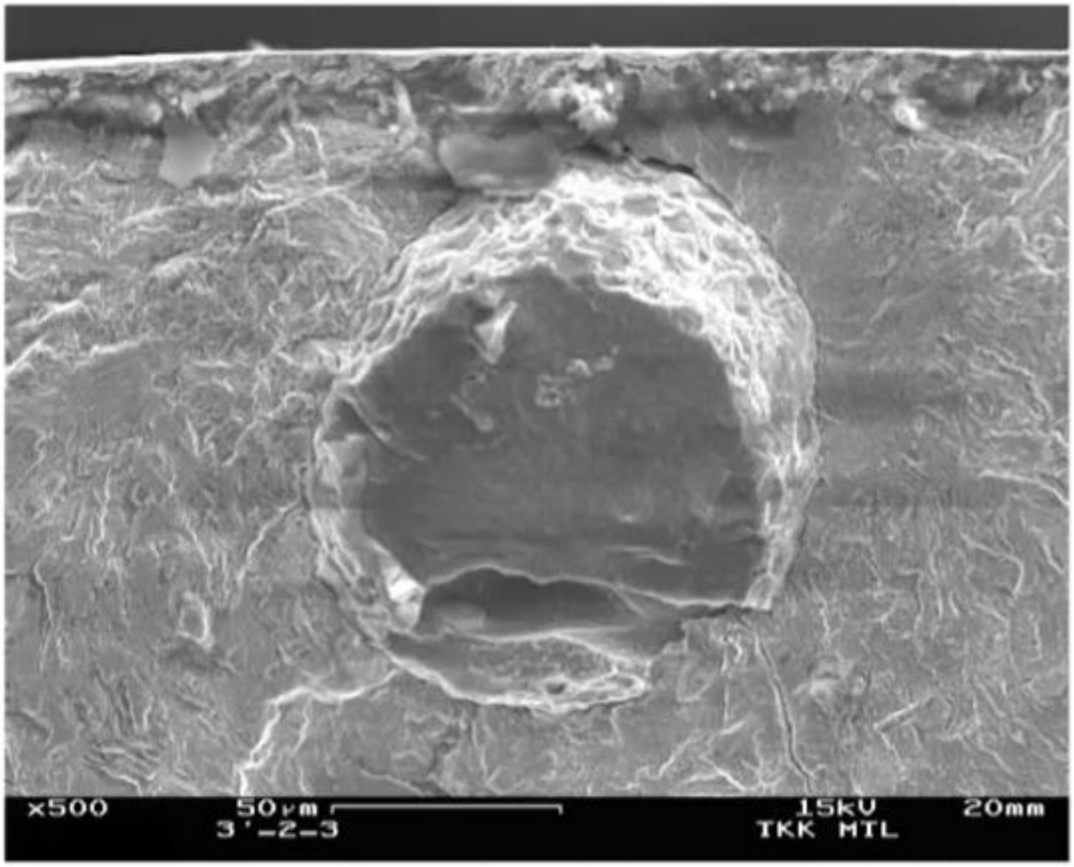
Microscopically irreversible dislocation motion
Slip bands
Deformation localization
Single-grain crack



Nucleation and inclusions

Nucleation happens at local discontinuity (inclusions, notches, corrosion damage, etc.)
=> Large scatter





Inclusion effect

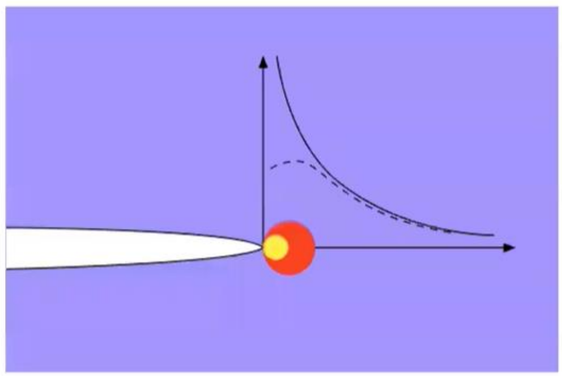
C depends on inclusion location
(C=1.56 below surface and C=1.43 on the surface)

$$\sigma_w = C(HV + 120)/(\sqrt{area})^{1/6}$$

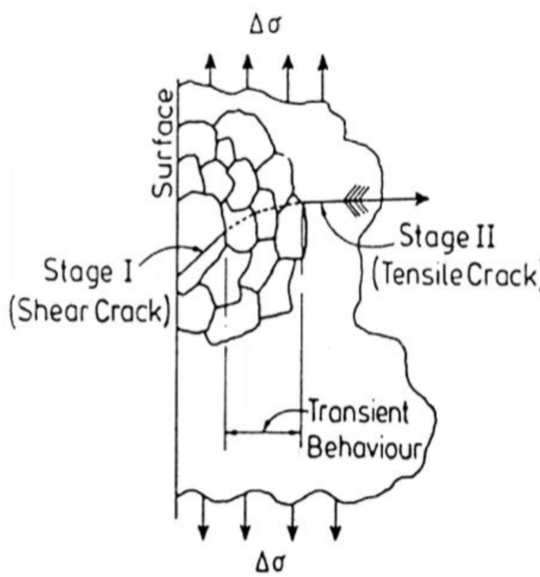
$$\sigma_w = C(HV + 120)/(\sqrt{area})^{1/6} \cdot [(1 - R)/2]^{\alpha_{ME}}$$

Fatigue crack growth

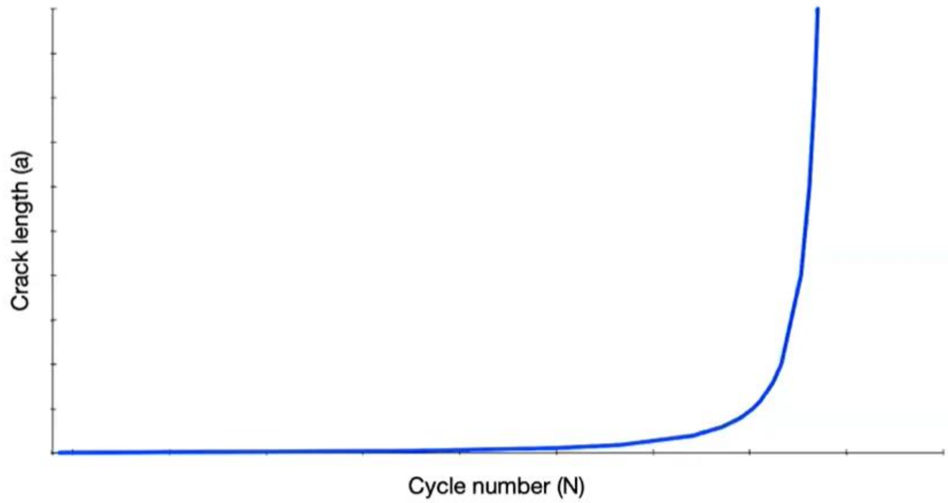
Damage concentrates to crack tip



Stage I – Stage II



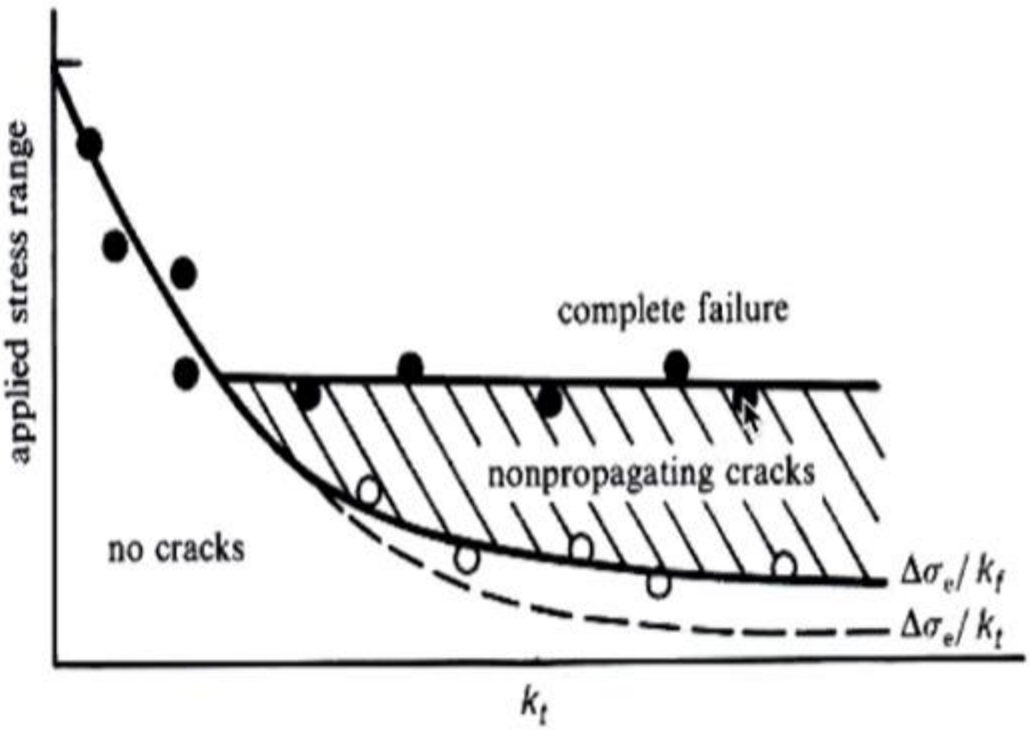
Crack growth accelerates crack growth



What is fatigue limit

No fatigue limit with spectral loading, environmental fatigue, etc.

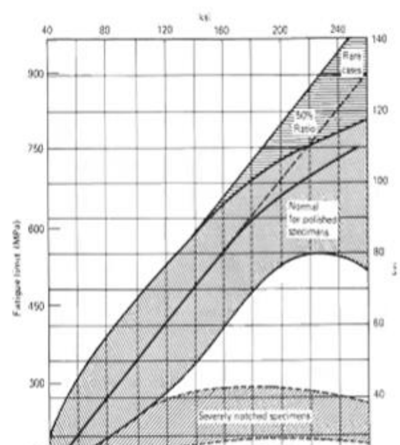
No fatigue limit in all materials



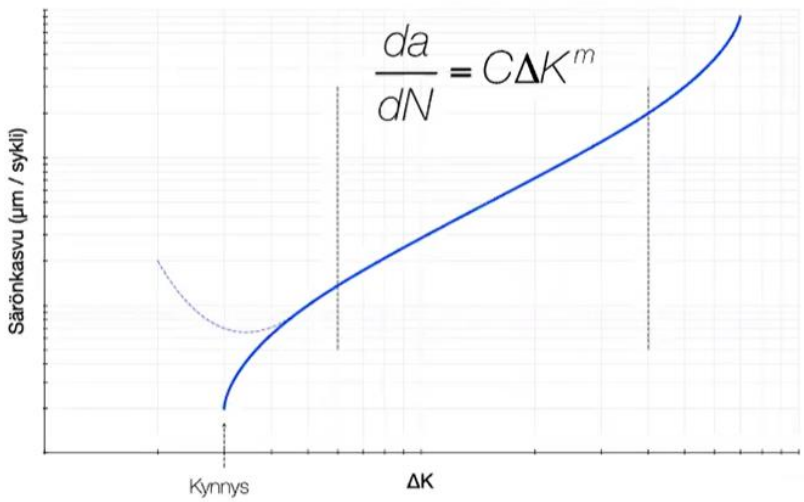
Strength effect

0.5 x UTS

1.6 x HV



Paris: Crack growth can be predicted

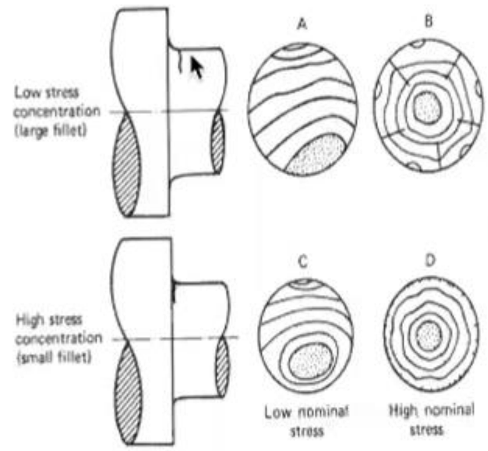


Fracture sufrace shows crack growth

Fracture surface analysis

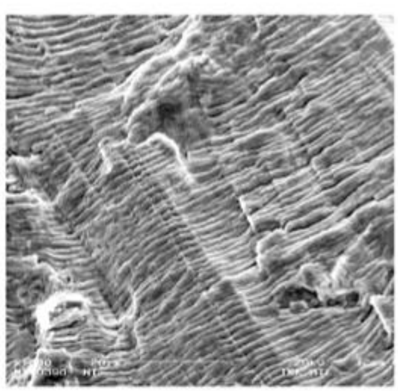
Nucleation

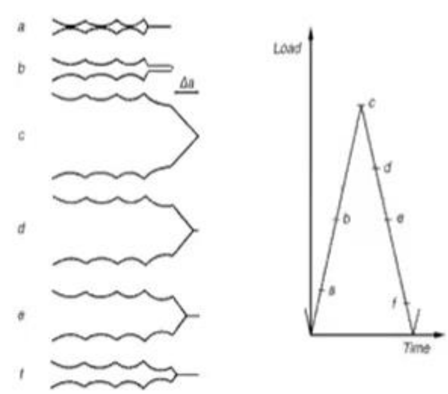
Beach marks



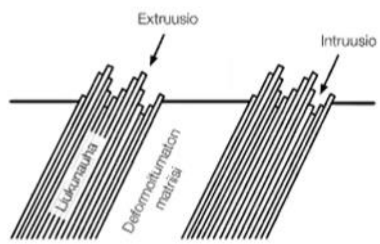
... and under microscope

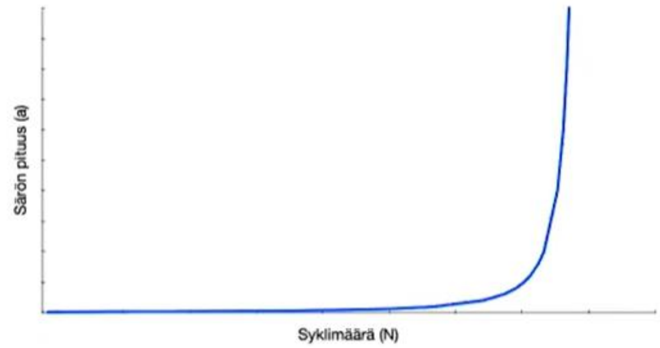
fatigue striations



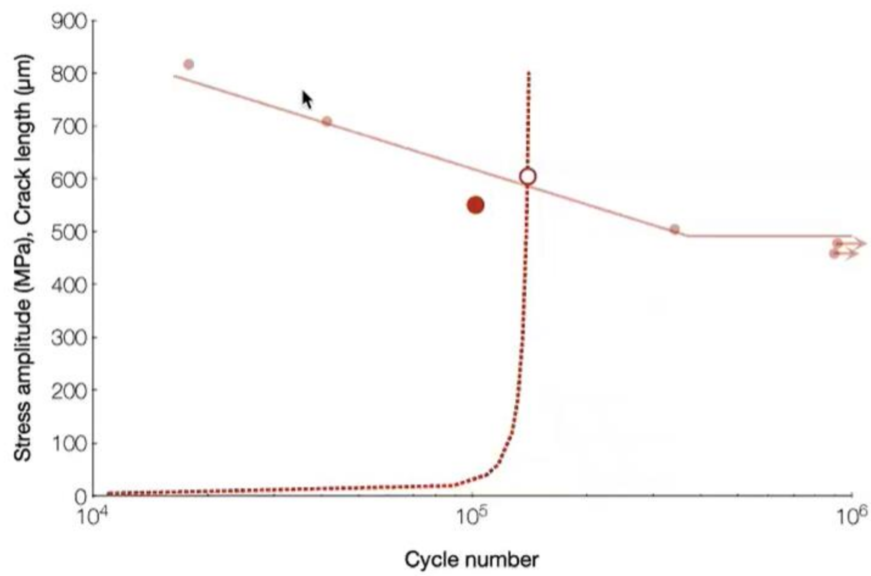


Fatigue= nucleation+ crack growth

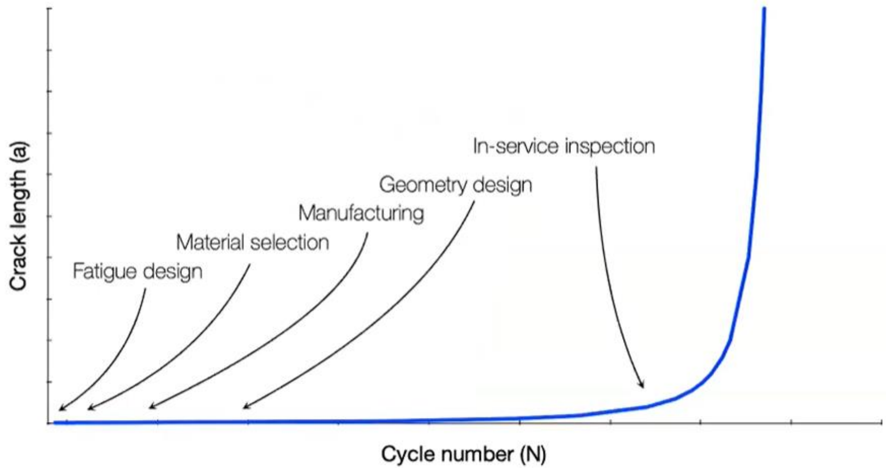




Nucleation portion



Fatigue control



Manufacturing quality control
Improvements on fatigue design
Safety culture

Improved manufacturing inspection
Improved in-service inspection

Improved in-service inspection

Summary

Fatigue is crack growth driven by cyclic loads
Fatigue design encompasses whole life cycle

- Design
- Manufacturing
- In-service inspection