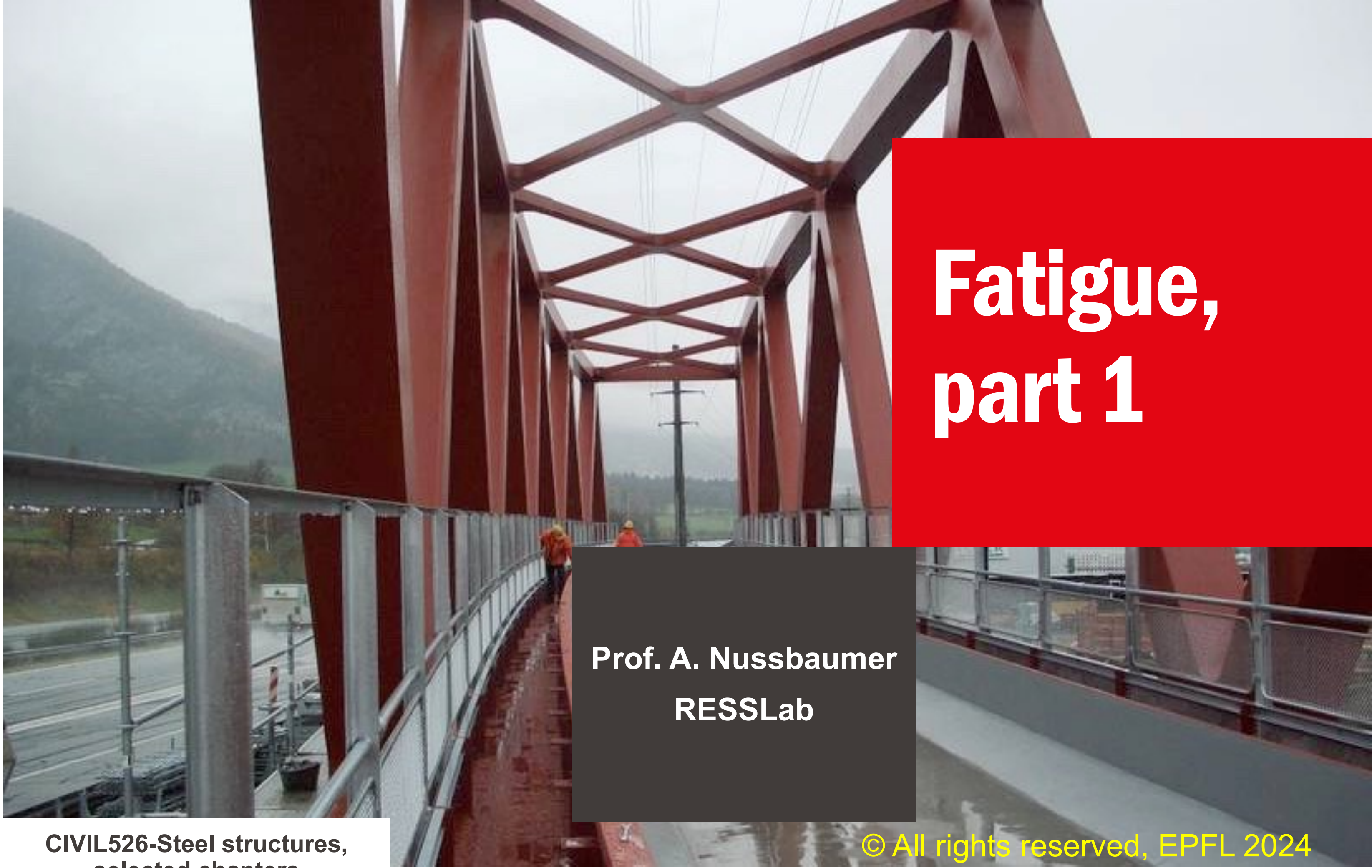


Fatigue, part 1

Prof. A. Nussbaumer
RESSLab

CIVIL526-Steel structures, selected chapters

Fall 2024

Content

- Introduction, motivation, examples
- Fatigue and fracture mechanics
- Material: initiation and propagation
- Structure: important parameters
- Fatigue curves and verification format

Fatigue

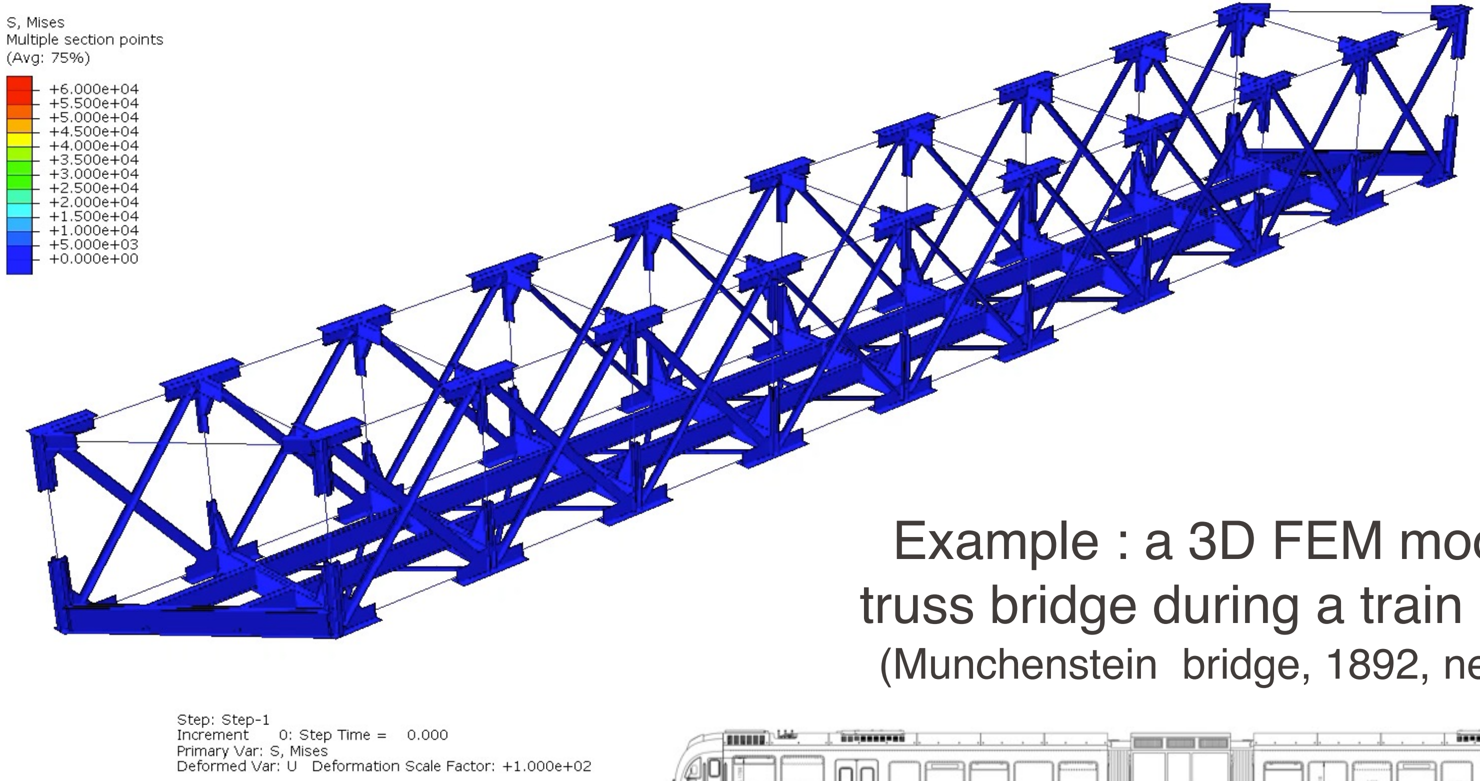
- **Definition**: Study of cracks, how they form and grow under the action of cyclic stresses.

$$\text{Total service life} = \frac{\text{Cycles to initiate a mechanically relevant crack} + \text{Cycles to make it propagate until failure}}{\text{Safety factor}}$$

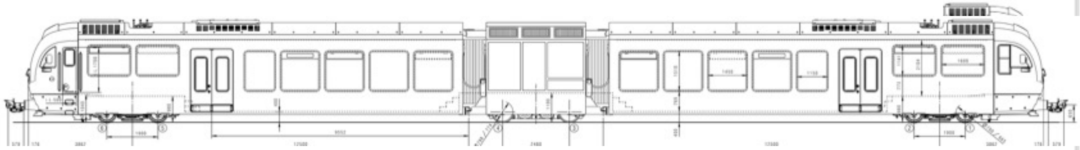
Fatigue: challenges in determining the effects of actions and resistance

(Munchenstein bridge, 1892, near Basel)

Fatigue: challenges in determining traffic action effects and resistance

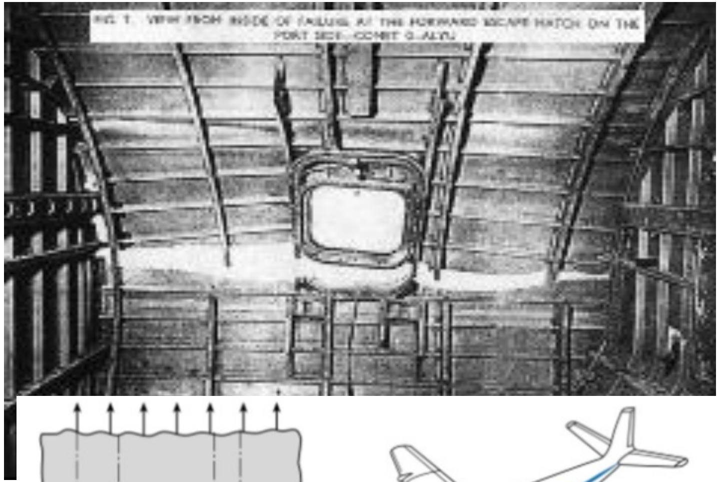


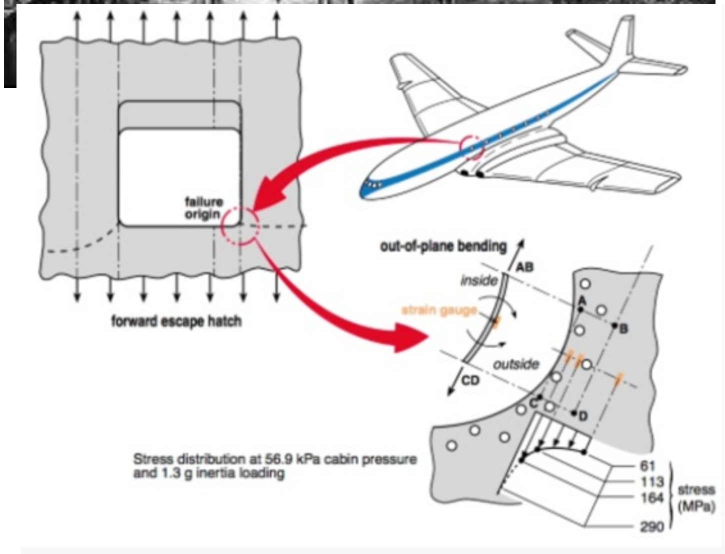
Example : a 3D FEM model of a truss bridge during a train passage
(Munchenstein bridge, 1892, near Basel)



Source: E. Ghafoori *et al.*, 'Finite Element Analysis for Fatigue Damage Reduction in Metallic Riveted Bridges Using Pre-Stressed CFRP Plates', *Polymers*, vol. 6, no. 4, pp. 1096–1118, Apr. 2014, doi: 10.3390/polym6041096.

Fatigue affects all types of structures: aircrafts

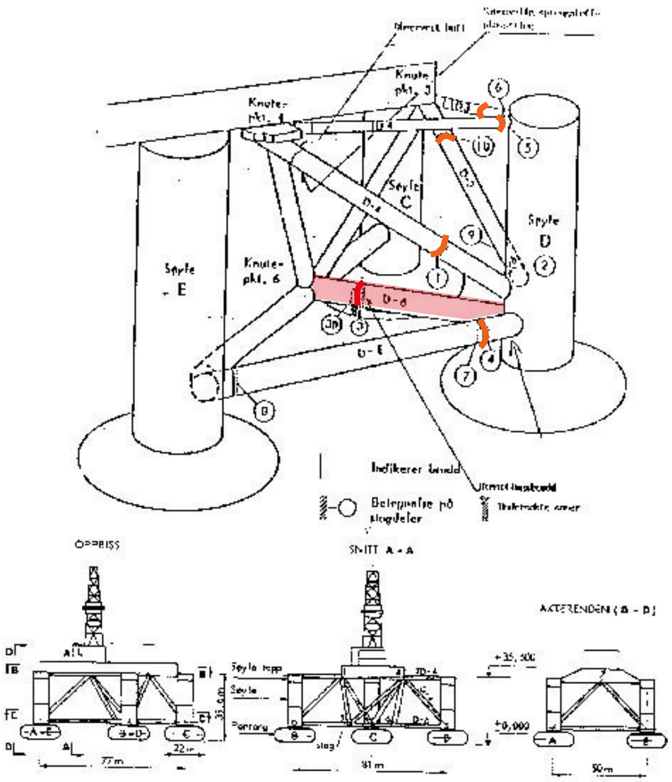


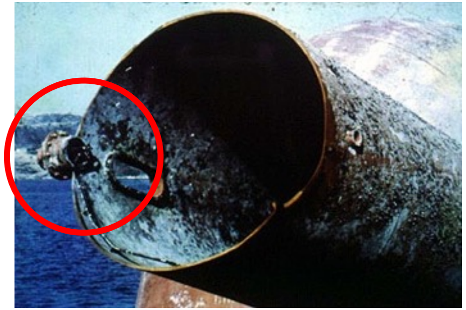


Sources: - Withey, P.A., 1996. Fatigue failure of the De Havilland Comet I, School of Metallurgy and Materials, Univ. of Birmingham, UK.
http://aerospaceengineeringblog.com/dehavilland-comet-crash/

Fatigue affects all types of structures: offshore

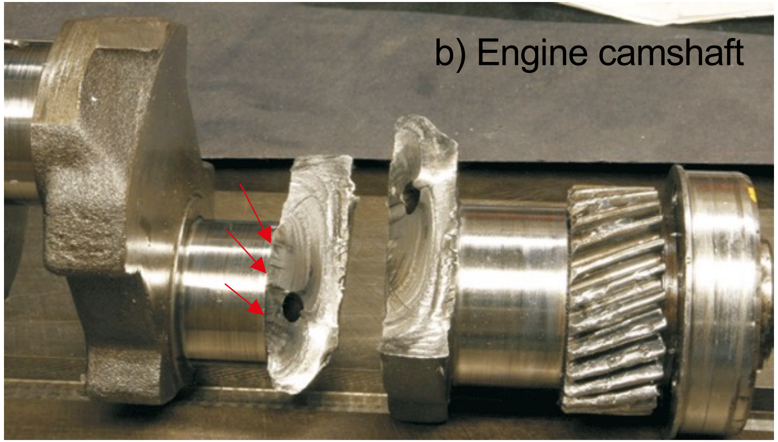
Example: Alexander Kielland offshore platform (1980)





A crack developed around a hydrophone hole. After failure of the first brace, the remaining five braces attached to the leg failed in quick succession causing the leg to break off. The rig almost immediately listed to one side at an angle of 35 degrees and sunk. It killed 123 people, only 89 of those on board survived.

Fatigue affects all types of structures



Main difference between a), b) and c) a bone ?

Fatigue affects all types of structures: windturbine tower

Installed 2001. 2013 failure of one. 4/6 other wind turbine towers also had cracks

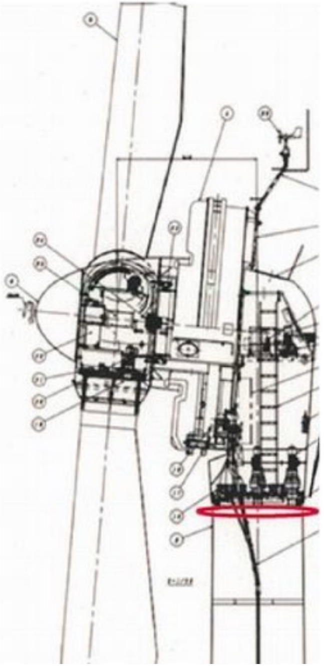


Fig. 1: Failure section

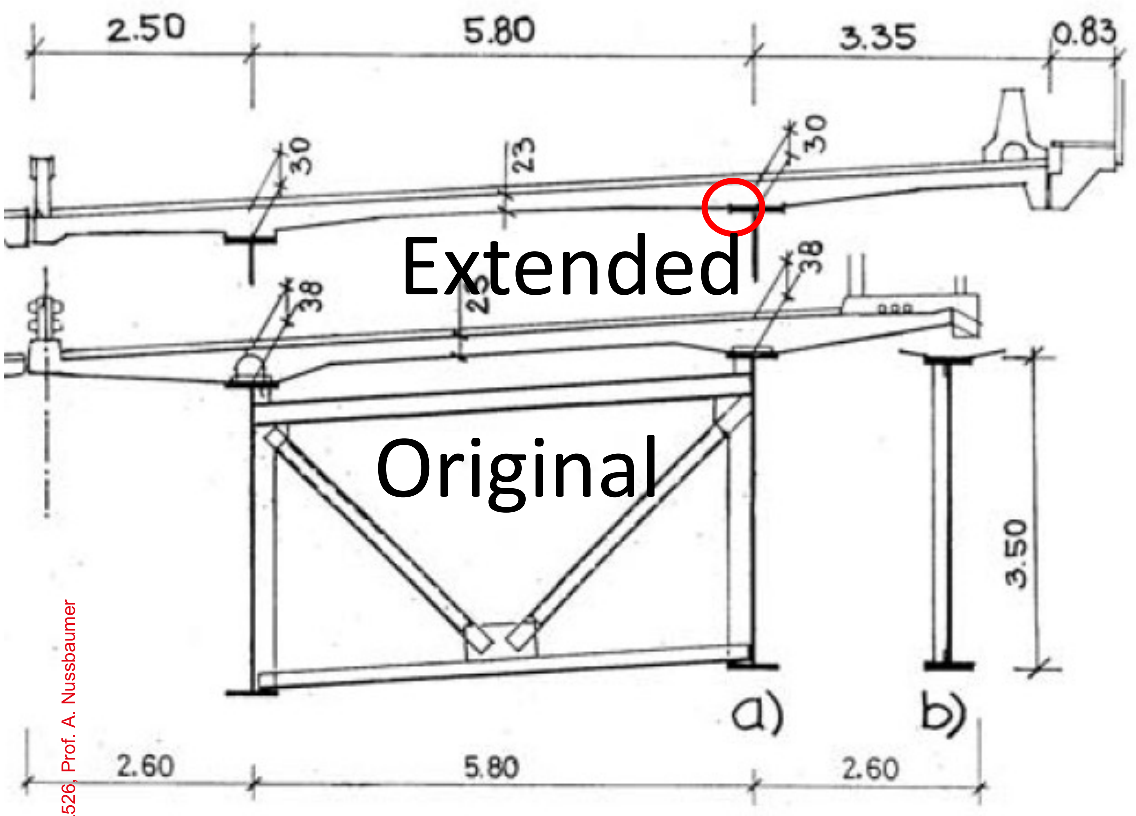
Fig. 2: Turbine part on the ground

Fig. 3: Images of both sides of the failure (nacelle and shaft)

Source: *Yin LIU, Takeshi Ishihara "Fatigue Failure Accident of windturbine tower in Taikoyama Wind Power Plant, EWEA conf., Paris, 2015*

Fatigue affects all types of structures

Example: Motorway bridge (Austria), built 1974, damage 2008



Cantilever increased during refurbishment after 20 years of operation. Vertical stiffeners subjected to bending moments imposed by rotation of concrete slab, initiated cracks at many stiffeners.

Source: Greiner, R., Taras, A., ECCS_TC6_24.2.2010, Damage cases

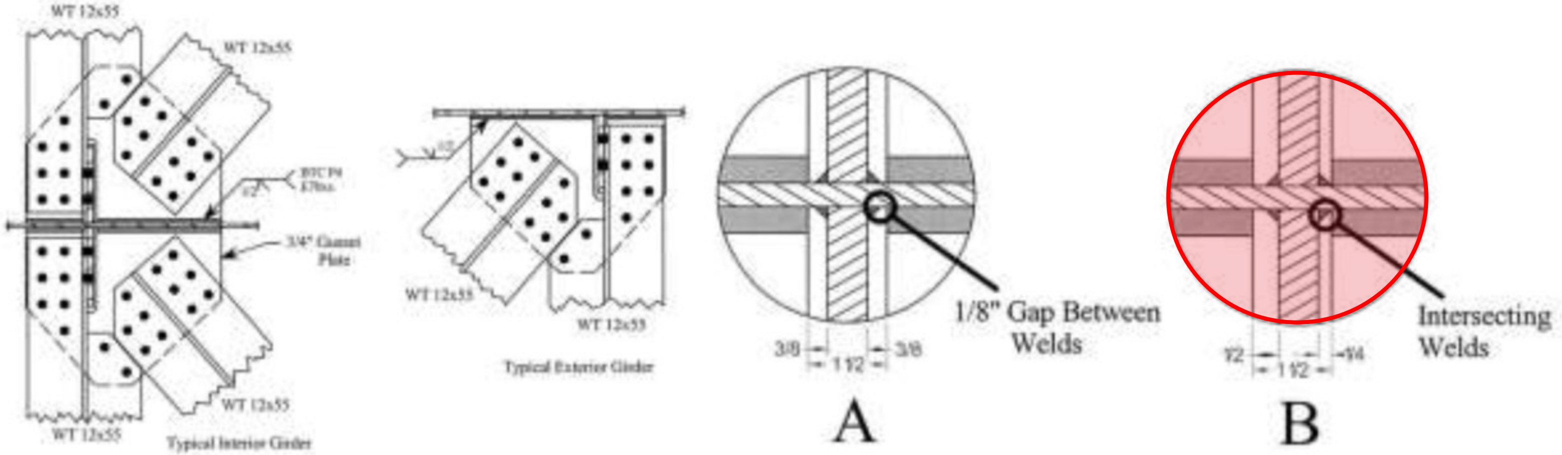
Counter-example: Hoan Bridge (USA), built 1972, failure 2000

Brittle fracture due to low temperature and strong clamping (triaxiality)

Source: HOAN BRIDGE FORENSIC INVESTIGATION: FAILURE ANALYSIS FINAL REPORT, By John W. Fisher et al, June 2001

Counter-example: Hoan Bridge (USA), built 1972, failure 2000

- 3 Crossing welds
- Tolerance problems
- Strong clamping of the last weld



Origin of fractures in various fields of structural engineering

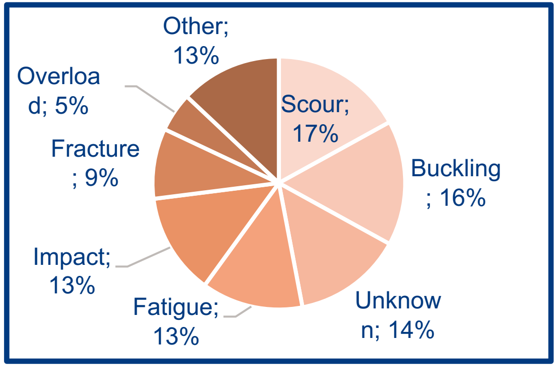
Damage cause (Multiple denomination possible)	Totality		Buildings		Bridges		Conveyors	
	No	%	No	%	No	%	No	%
Static strength	161	29.7	102	33.6	19	14.8	40	36.0
Stability (local or global)	87	16.0	62	20.4	11	8.6	14	12.6
Fatigue	92	16.9	8	2.6	49	38.3	35	31.5
Rigid body movement	44	8.1	25	8.2	2	1.6	17	15.3
Elastic deformation	15	2.8	14	4.6	1	0.8	0	0
Brittle fracture	15	2.8	9	3.0	5	3.9	1	0.9
Environment	101	18.6	59	19.4	41	32.0	1	0.9
Thermal loads	23	4.2	23	7.6	0	0	0	0
Others	5	0.9	2	0.7	0	0	3	2.7
Sum	543	100	304	100	128	100	111	100

Tiré de P. Oehme, for steel structures only

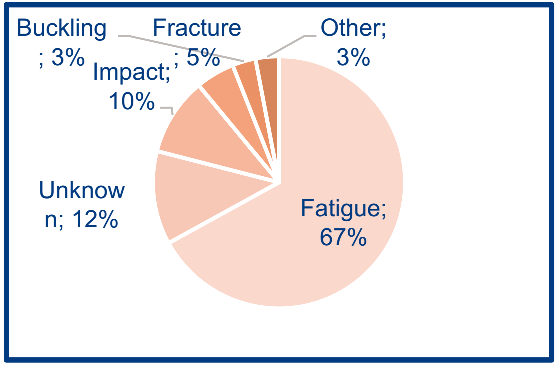
Note: https://en.wikipedia.org/wiki/List_of_bridge_failures (2020) refers to only 4 fatigue failures and one brittle failure out of 257 cases.

Main causes of metallic bridge failures [Imam & Chryssanthopolus, 2010]

- 164 cases: 87 (collapsed), 73 (non-collapsed, lost of serviceability), 4 (unknown)



Collapsed structures



Non-Collapsed structures

- In total, 60 cases of fatigue failure (49 cases of non-collapse failure, **81%**)
- Doe not account for all non-reported cases where fatigue damage was detected by inspection before any failure and repaired

Motivation to study fatigue

- Main causes of damage to metal components:
  - Corrosion
  - Wear and tear
  - Fatigue
- Need to inspect, to fix intervals
- Note: In mechanical parts, up to 90% of fatigue failures (expected or not)!

In short, fatigue:

- Occurs in structural elements subjected to repeated <u>variable stresses</u>, well below static strength
- Manifest itself by the development of cracks, progressive damage, at specific locations
- Occurs under low overall stresses but high local stresses (stress concentrations and/or imperfections)
- Will result in non-collapse failure (often) but can result in more catastrophic ones ⬄ Periodic inspections

Source: A. Nussbaumer, rail fixture near Morges

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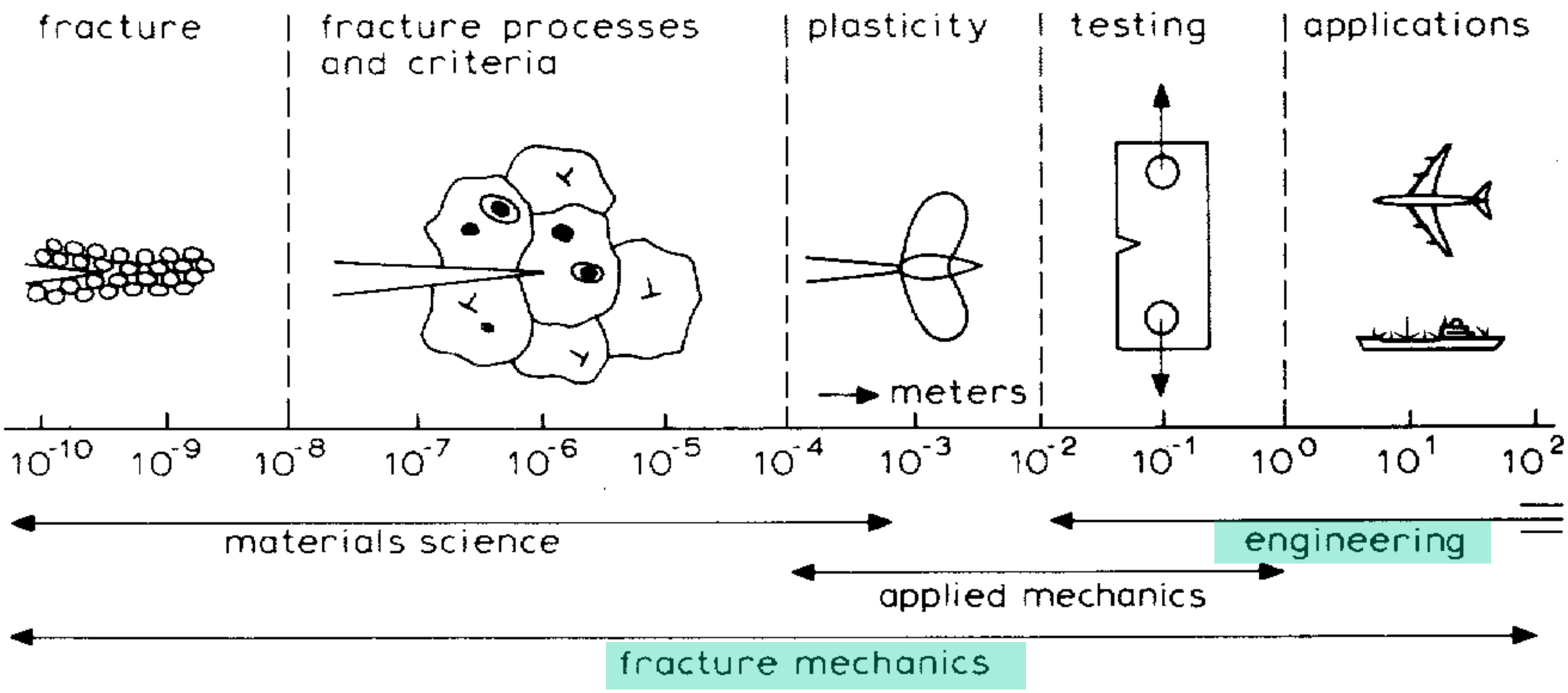
Overlap between disciplines



Use of these disciplines

Fatigue:

- For dimensioning structures subject to variable loads

  → Aircraft, pressure vessels, bridges, cranes, chimneys, etc.

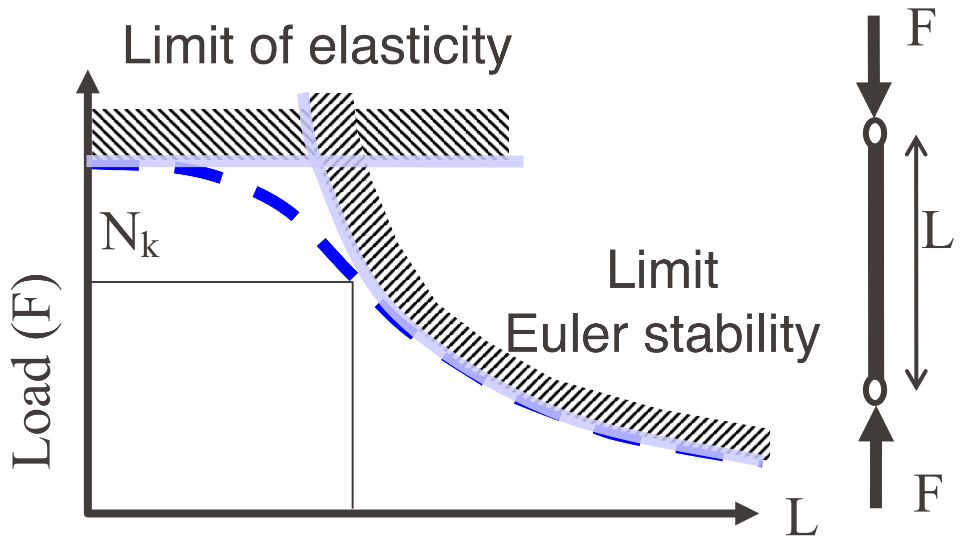
Fracture mechanics:

1. to prevent fatigue, fracture

   → Aircraft, pressure vessels, bridges, glass façades, dams and rocky massifs, etc.

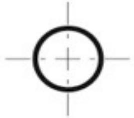
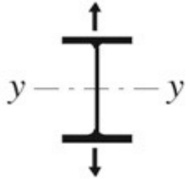
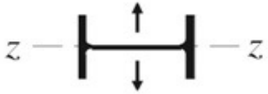
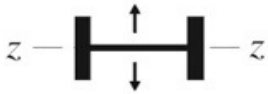
2. to cause a fracture, rupture

Solution to the buckling problem

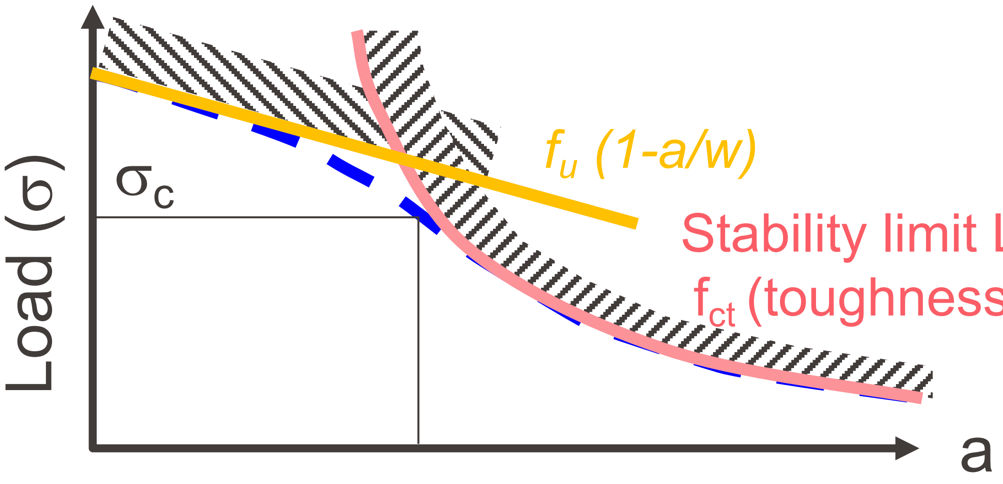


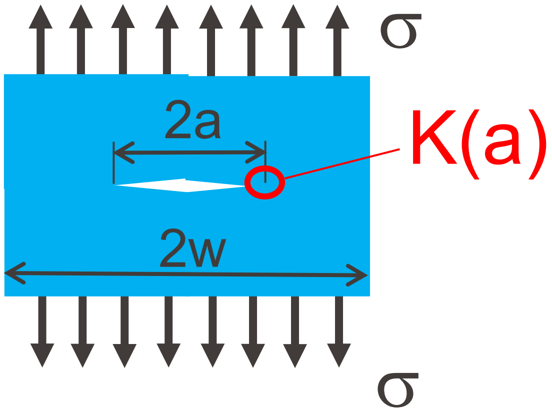
Parameters:

- Slenderness
- Geometric imperfections, dimensions
- Residual stress

Buckling curve	Examples
a	
b	
c	
d	

Reminder: solution to the problem of crack instability



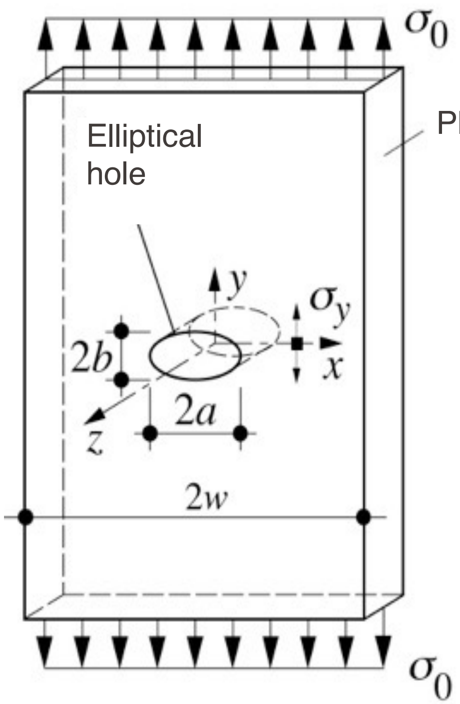


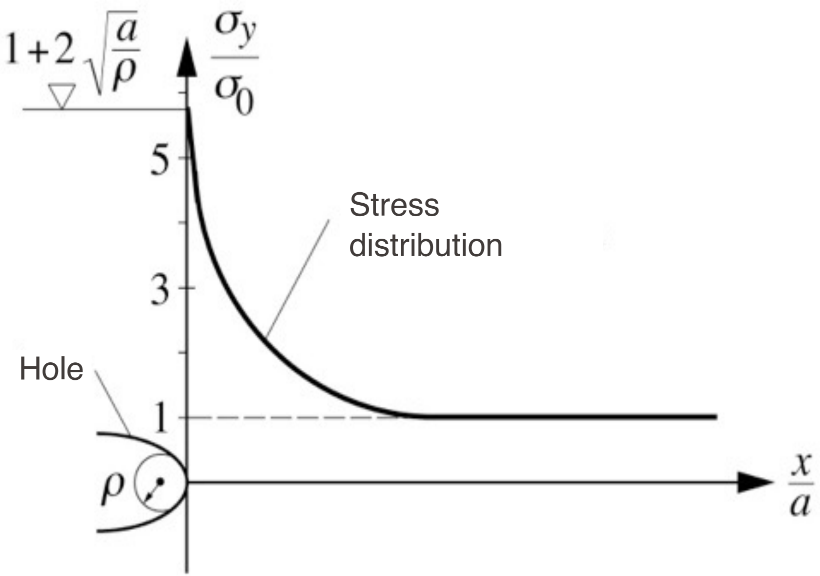
Parameters:

- Imperfections, concentration σ
- Effects of scale and triaxiality
- Residual stress

Limit case between continuous and non-continuous mechanics (fracture mechanics)

$$\sigma_{y,max} = \sigma_0 \cdot k_t = \sigma_0\left(1 + 2\frac{a}{b}\right) = \sigma_0\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$





TGC 10, chap. 13

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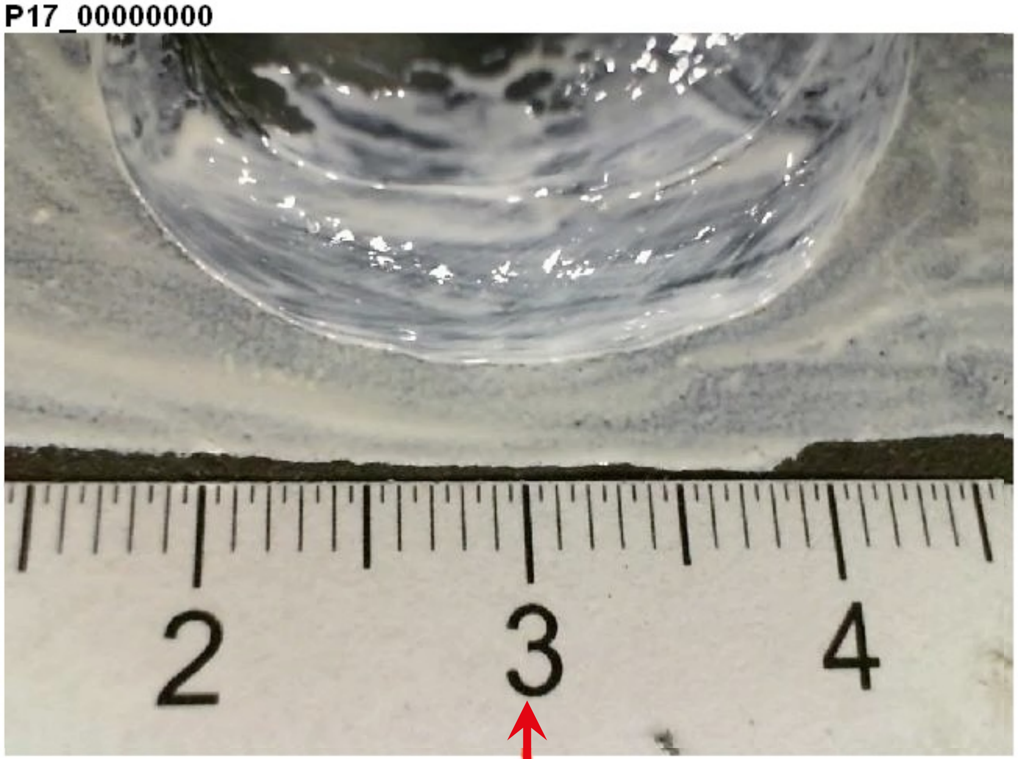
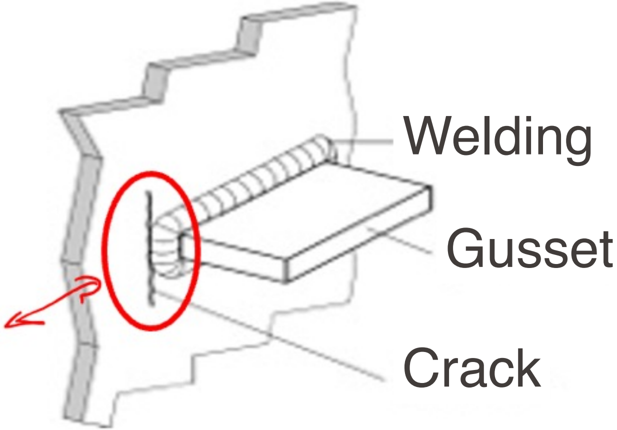
Fatigue crack development video

No. of cycles



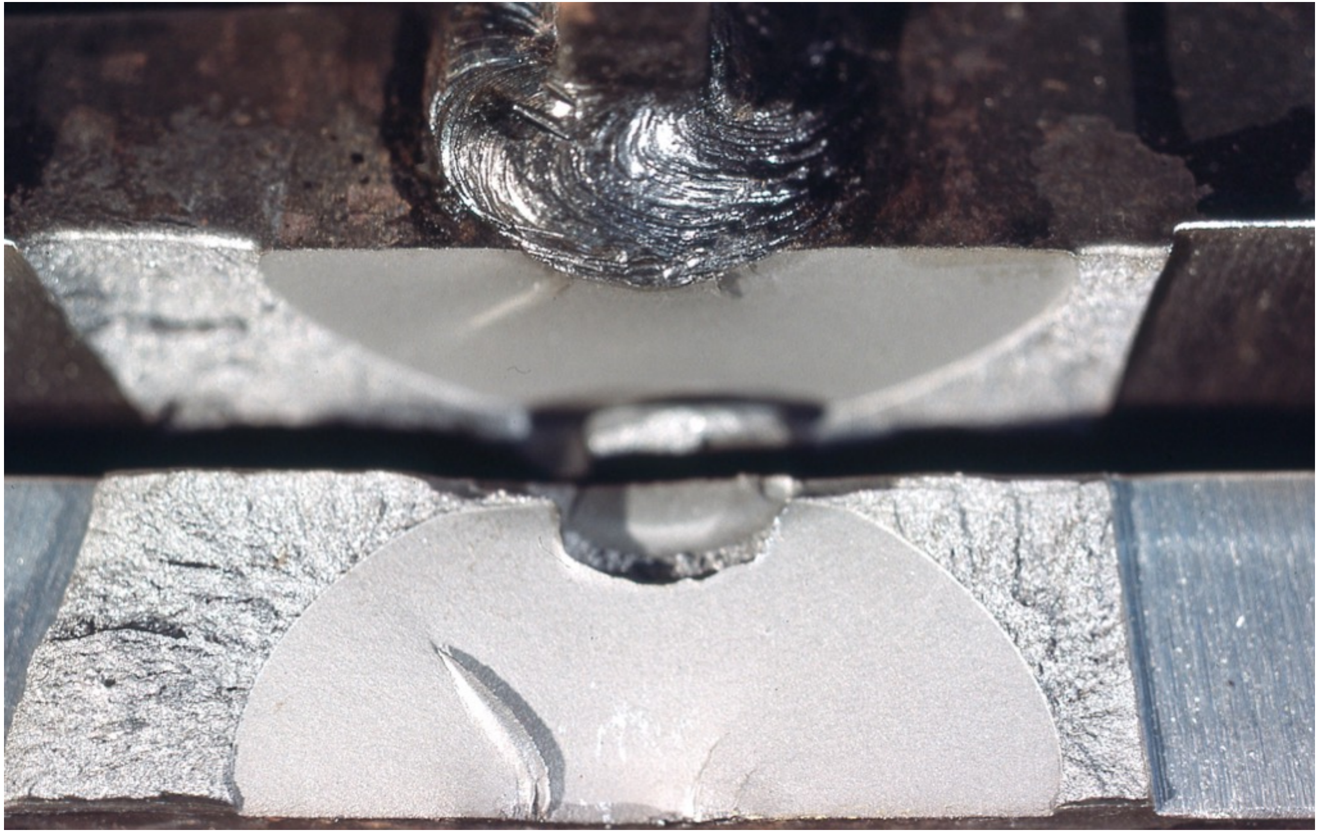
Cyclic loading

Detail of a longitudinal gusset



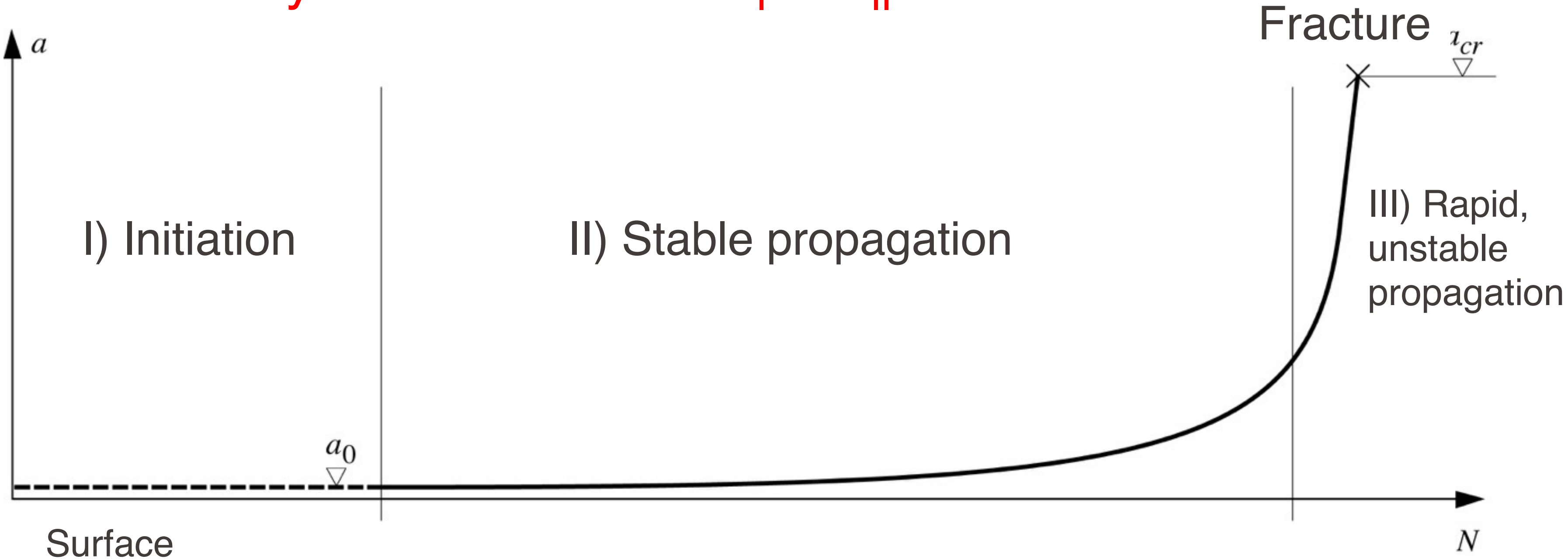
Courtesy from: Fraunhofer LBF

Opening of a crack at end of longitudinal attachment



Stages of crack development

No. of cycles to failure $\cong N_I + N_{II}$



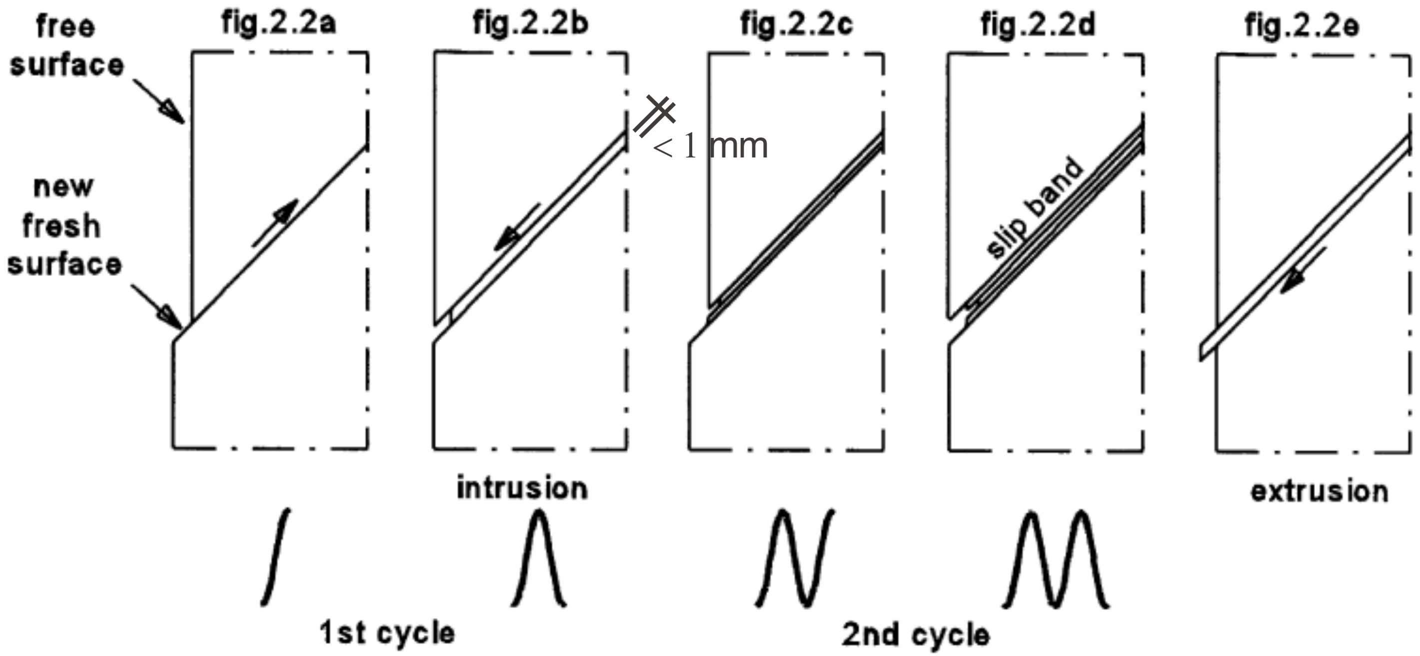
Surface phenomena and plastic deformation in shear

Phenomenon in the volume, crack orientation function of loading direction

Depends on toughness, temperature and loading rate

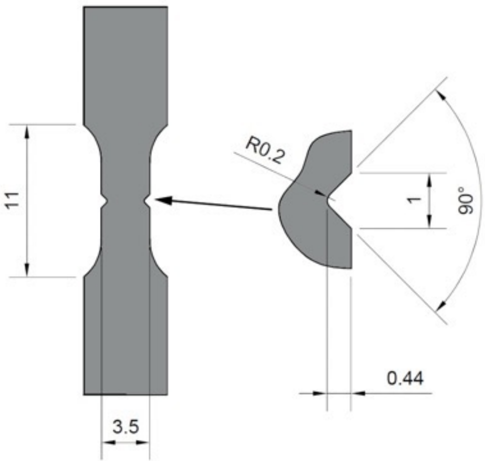
Material fatigue INITIATION

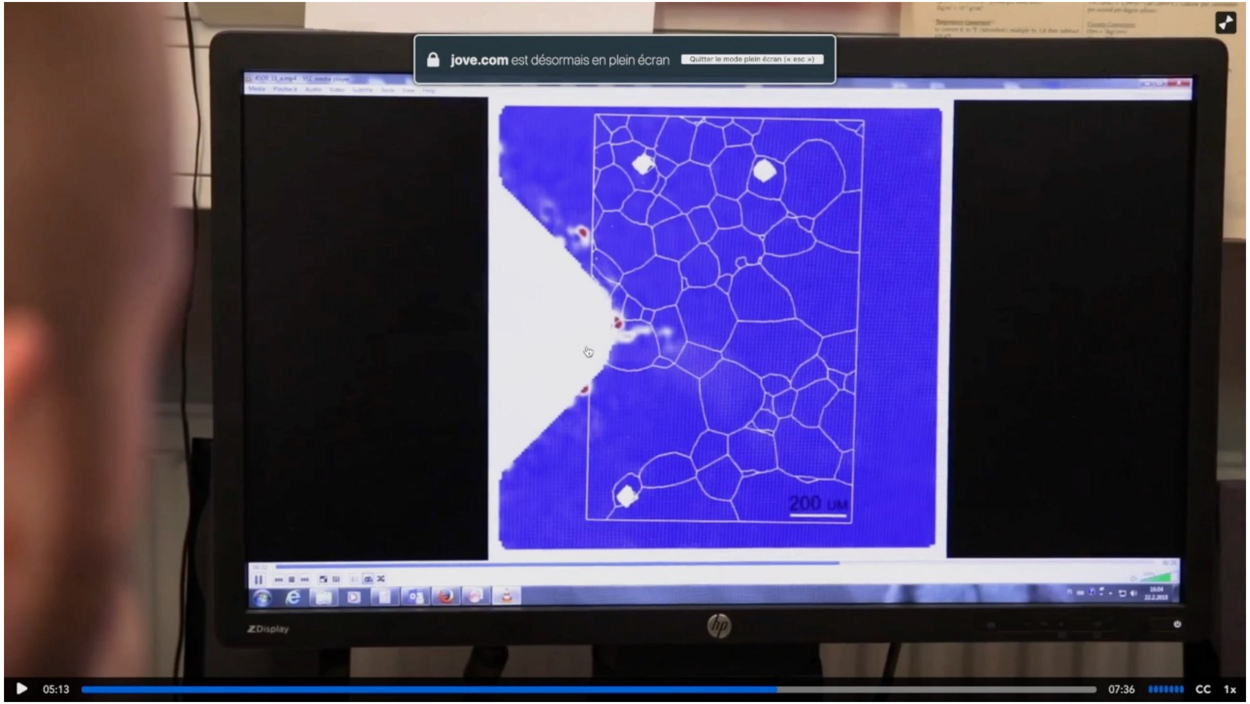
Cyclic slip irreversibilities leads to the nucleation of a micro-crack



Source: Schijve 2001

Material fatigue INITIATION





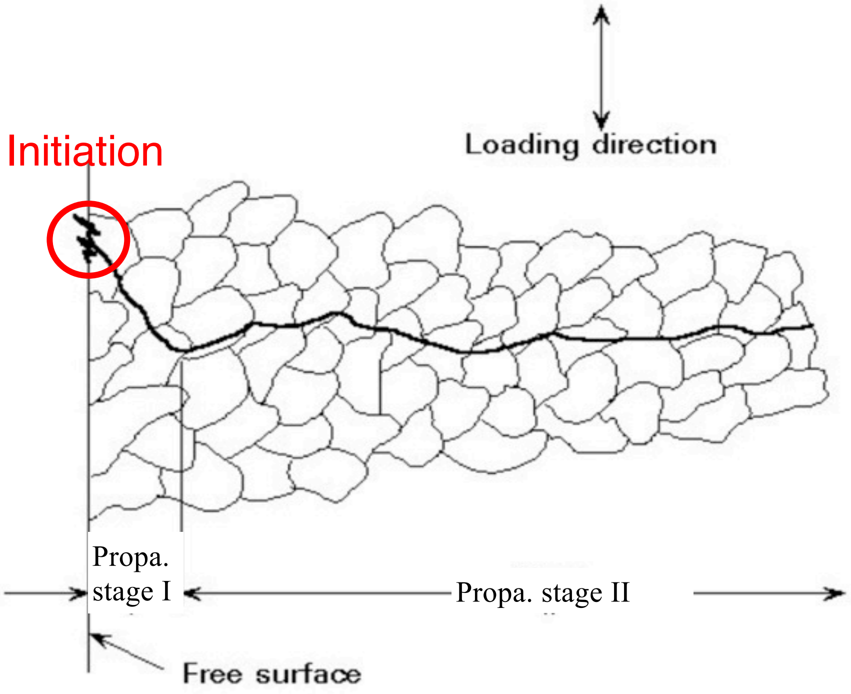
Source: complete video https://www.jove.com/video/59134

Evgenii Malitckii, Heikki Remes, Pauli Lehto, Sven Bossuyt, Full-field Strain Measurements for Microstructurally Small Fatigue CrackPropagation Using Digital Image Correlation Method, J. Vis. Exp. (143), e59134, doi:10.3791/59134 (2019).

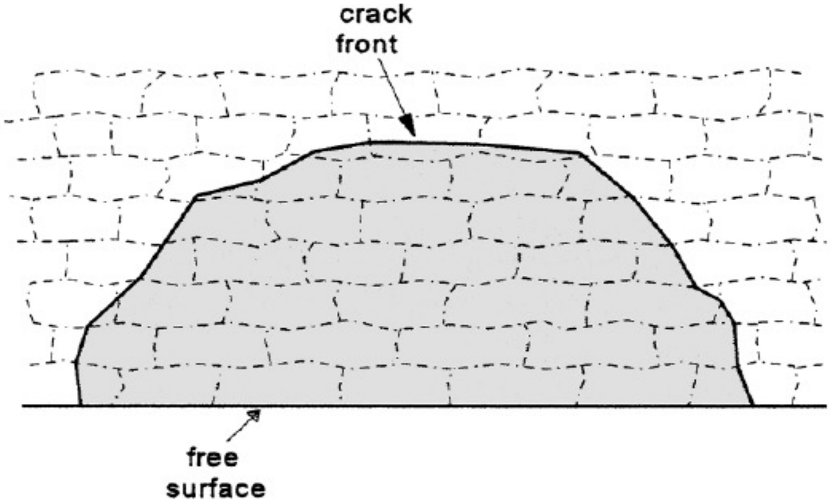
Material fatigue INITIATION

- During the initiation period, fatigue is a material surface and a plastic shear deformation phenomena
- Fatigue behaviour therefore depends on:
  - surface finish
  - the environment
  - crystallography: crystal system, grain size
  - material properties: anisotropy, modulus of elasticity, tensile strength, ductility, strain hardening, etc.
  - the average stress (or stress ratio)

Material fatigue PROPAGATION



Cross-section of a crack



Top view of crack front

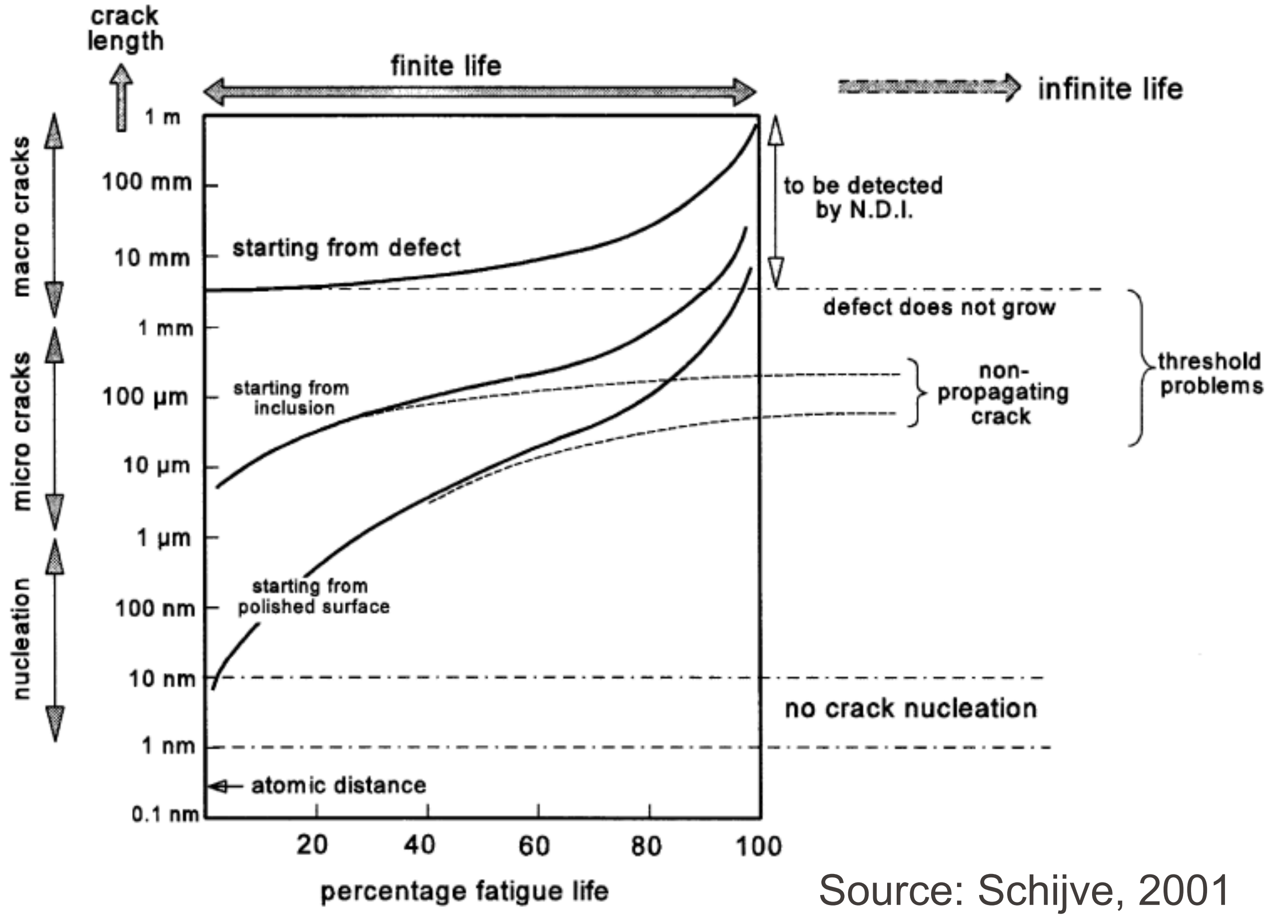
Material fatigue PROPAGATION

- After the initiation period, fatigue is a phenomenon in the volume of material, no longer a surface phenomenon. Direction of crack depends on loading, and generates its own plastic zone
- Fatigue behaviour therefore depends on:
  - the environment
  - certain material properties: modulus of elasticity, tensile strength, toughness, etc.
  - the average stress (or stress ratio)

AMORCAGE + PROPAGATION scenarios

2 very different cases of fatigue lifetimes:

- Finite lifetime
- Infinite lifetime (practically)



Source: Schijve, 2001

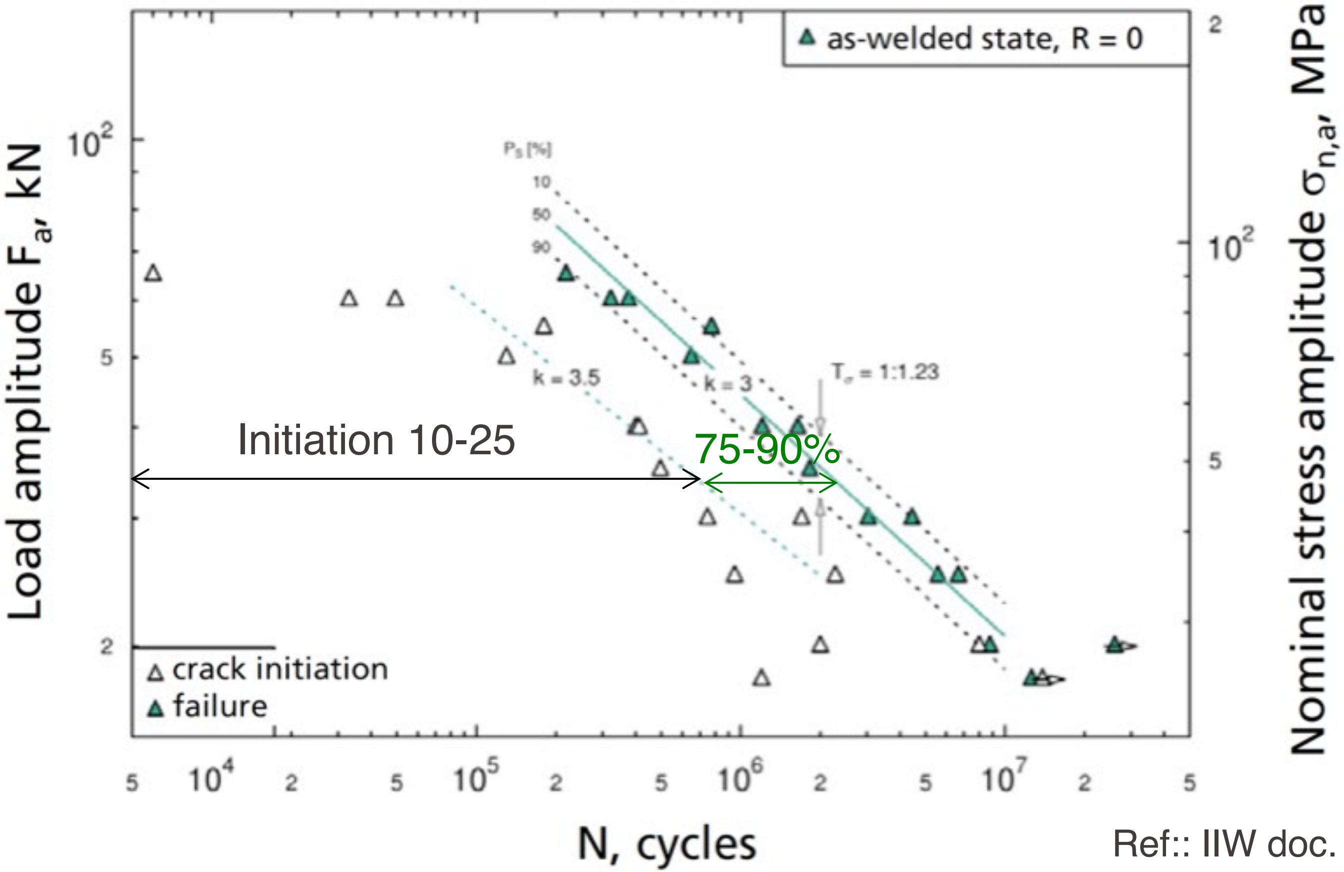
Distribution between stages (finite lifetimes)

$$\text{Total service life} = \frac{\text{Cycles to initiate a mechanically relevant crack} + \text{Cycles to make it propagate until failure}}{\text{Safety factor}}$$

	Cycles to initiate a mechanically relevant crack	Cycles to make it propagate until failure
Mechanical parts	> 75%	< 25%
Drilled holes	60%	40%
Welded joints (standard)	< 25%	> 75
Welded joints (high quality, or post treated)	50%	50%

Example: fatigue tests on longitudinal attachments

- Initiation accounts for 10 to 25% of finite lifetime



Ref:: IIW doc. XIII-2489-13

Fatigue modelling

- Fatigue crack initiation and propagation are not the result of a single mechanism
- Microstructure and applied loading play an important role in the damage process
- Consequently, it is not possible to apply a single damage model to all materials, components, assemblies, connections, types of loading, etc.

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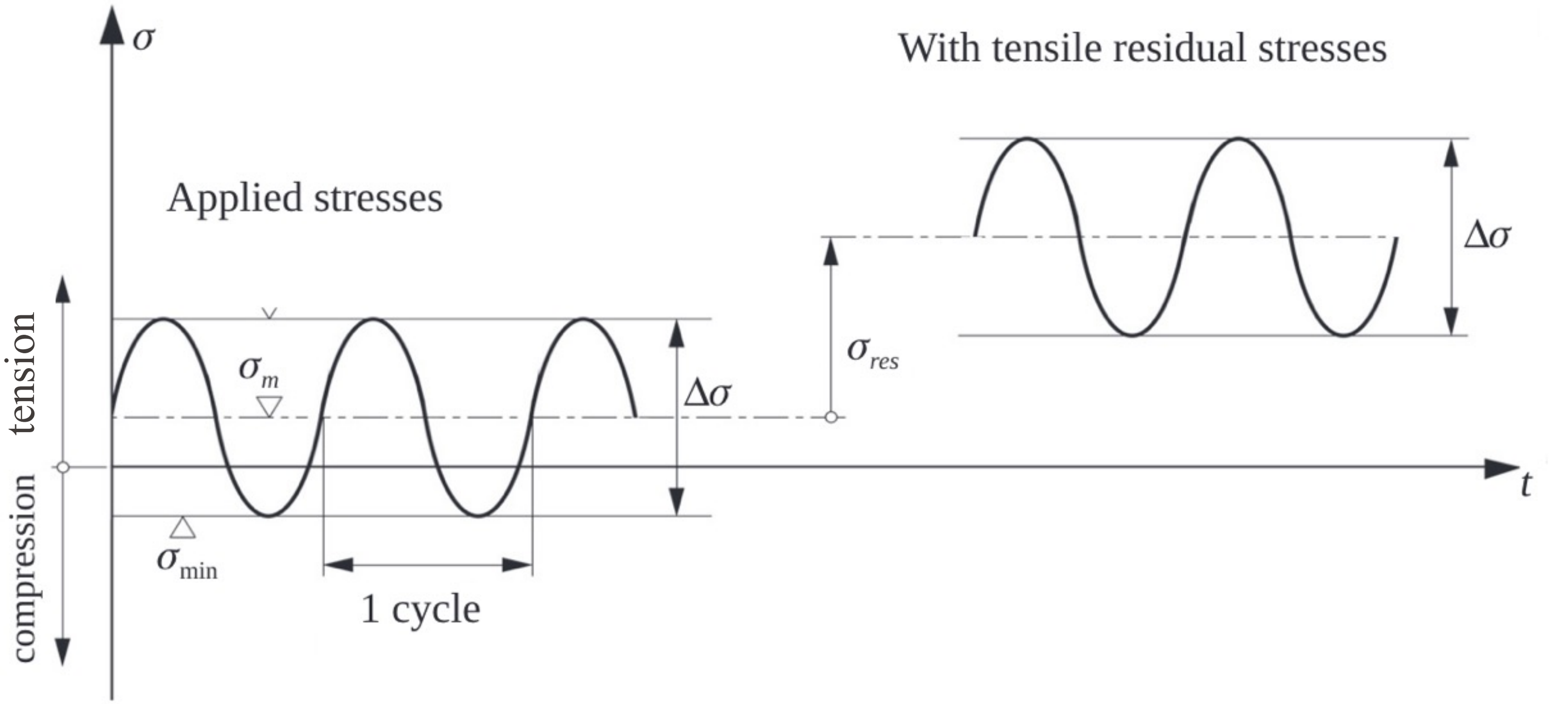
Fatigue at level of the STRUCTURE
Fatigue damage, service life

4 important parameters:

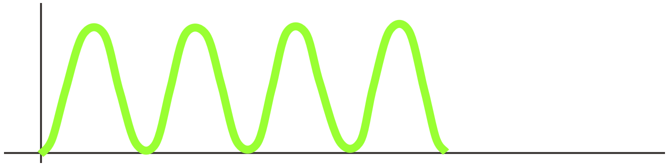
- Stress difference (stress range)
- Global and local geometry
- Material characteristics
- Environment

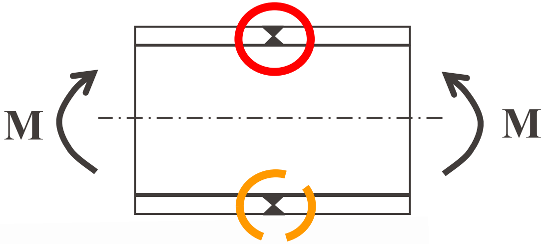
Stress difference and average stress



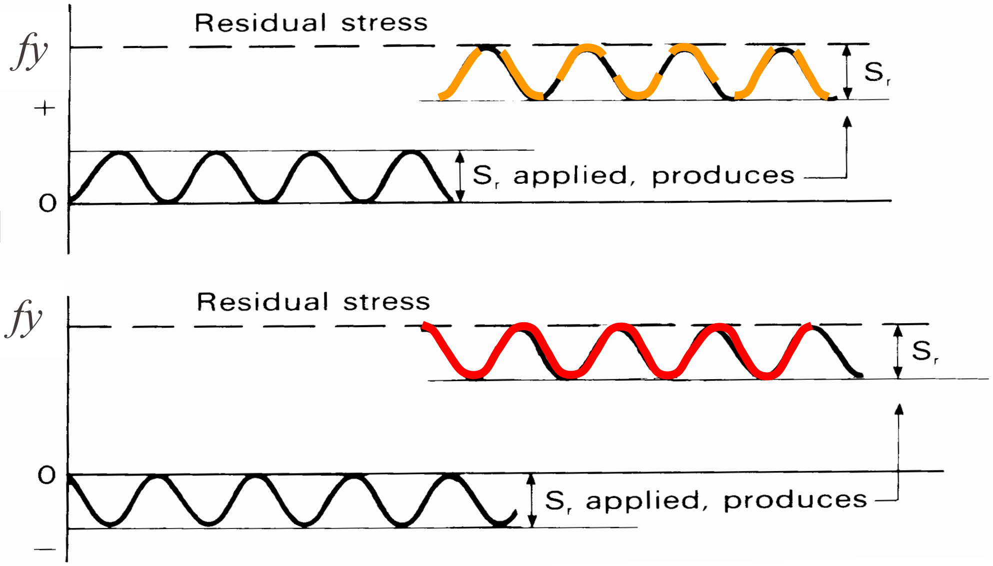
Stress difference and average stress - Welded joint

Applied loads

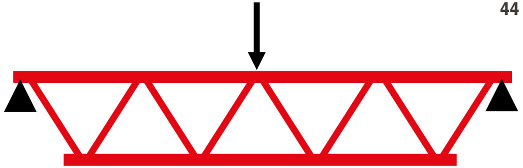




Welded joint



Example: Lattice girder test



Composed of CHS K-joints

In S355 steel

Length: 8.6 m

Height: 1.8 m

In quasi-inert environ.

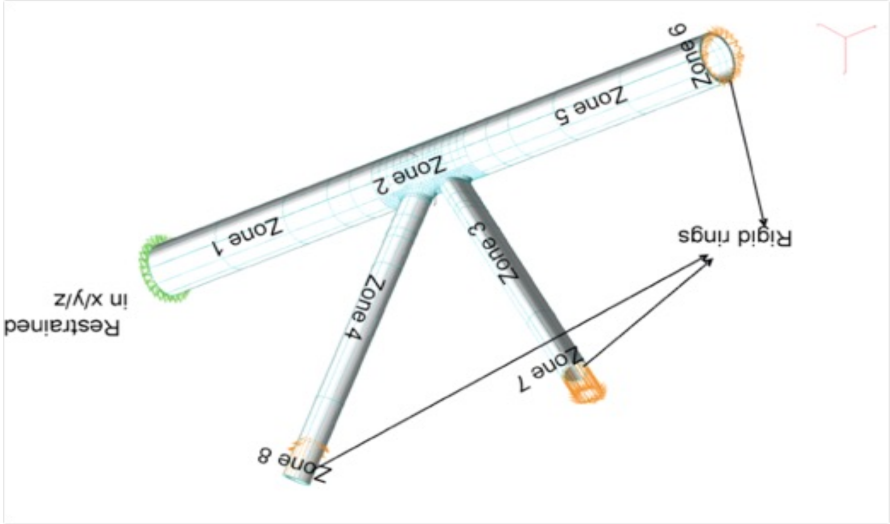
f = 0.7 hz

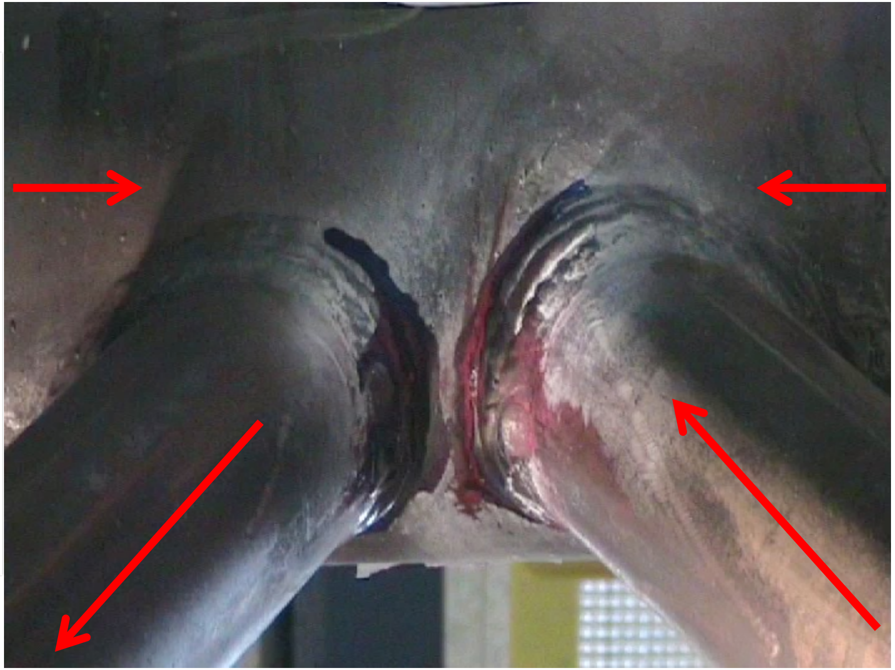
Q_{min} = 60 kN

Qmax = 610 kN

Example: Lattice girder test

What if we look at a compression chord joint ?





Inert fatigue propagation (microscope)

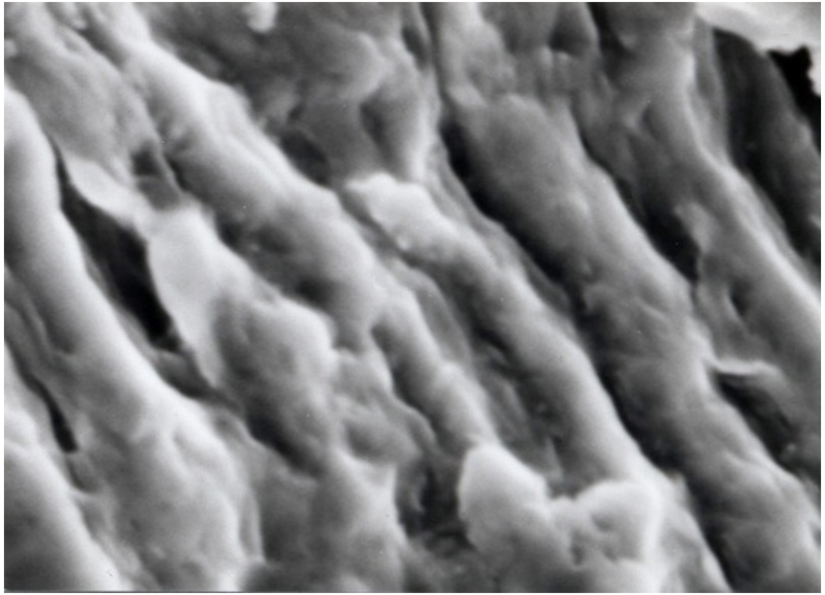
HSLA 80 (equivalent to S560)

In lab conditions

Stress difference

= 170 MPa

Propagation rate:
$\cong 1\ \mu m/cycle$



1 µm

Source: A. Nussbaumer, 1993

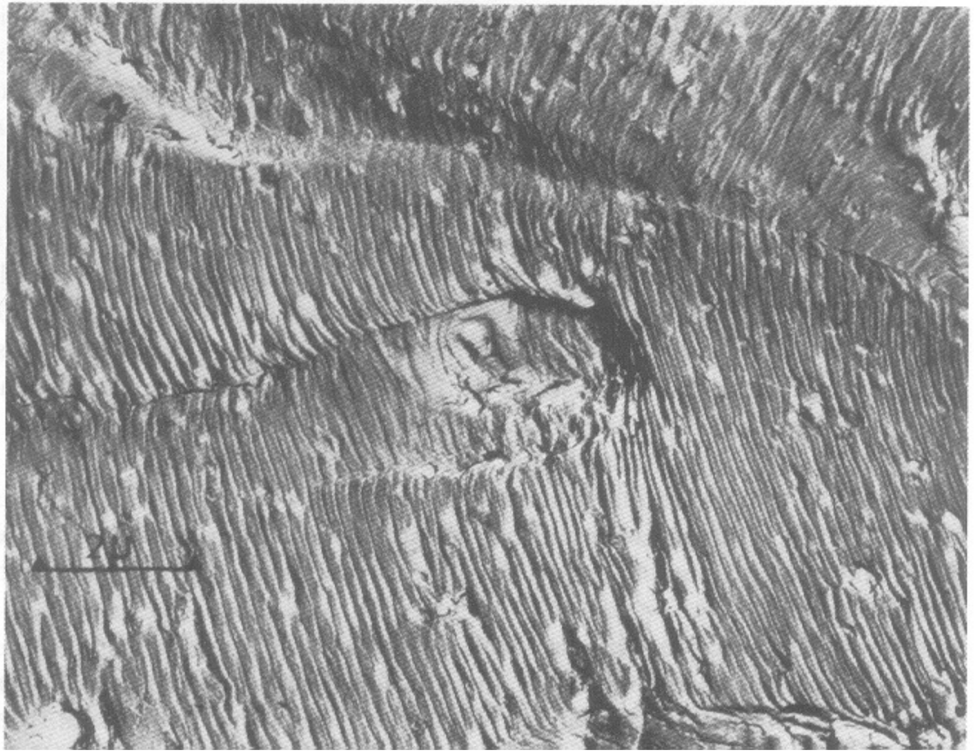
Inert fatigue propagation (microscope)

Aluminium alloy

2024 T3

(AlCu4Mg1)

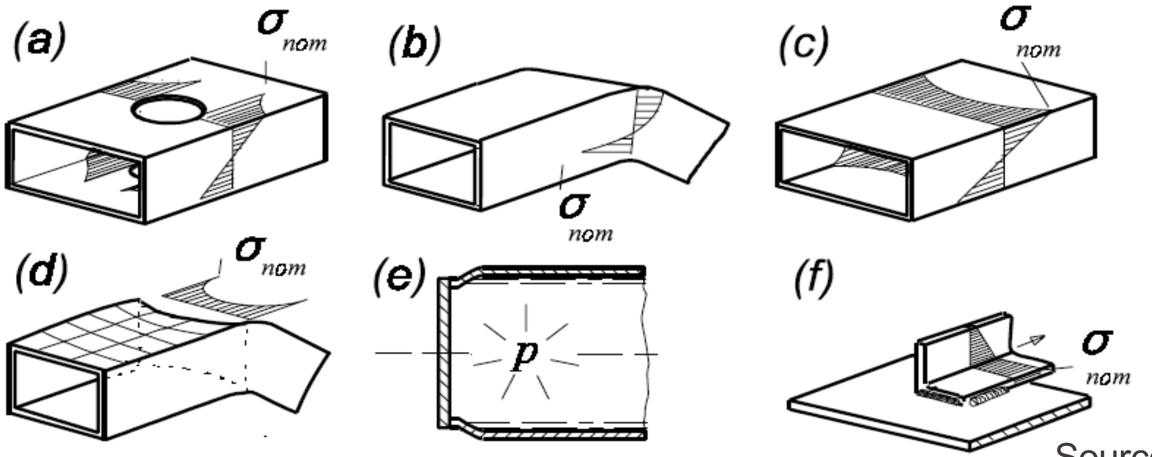
In lab conditions



Source: D. Broek, 1990

Global and local geometry of elements

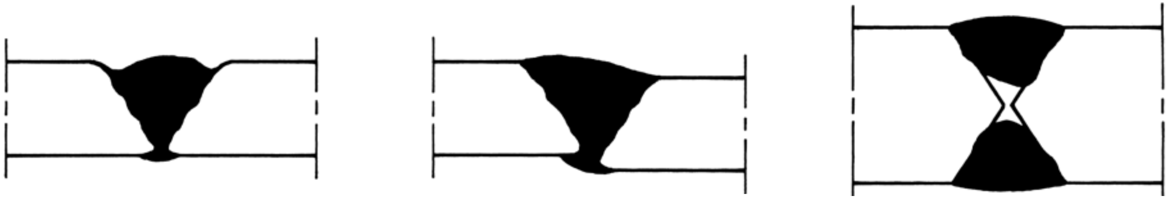
Examples of the influence of global geometry



Stress concentrations (SCF)

Source: IIW recommendations, 2016

Examples of local imperfections or 'defects' that have an influence

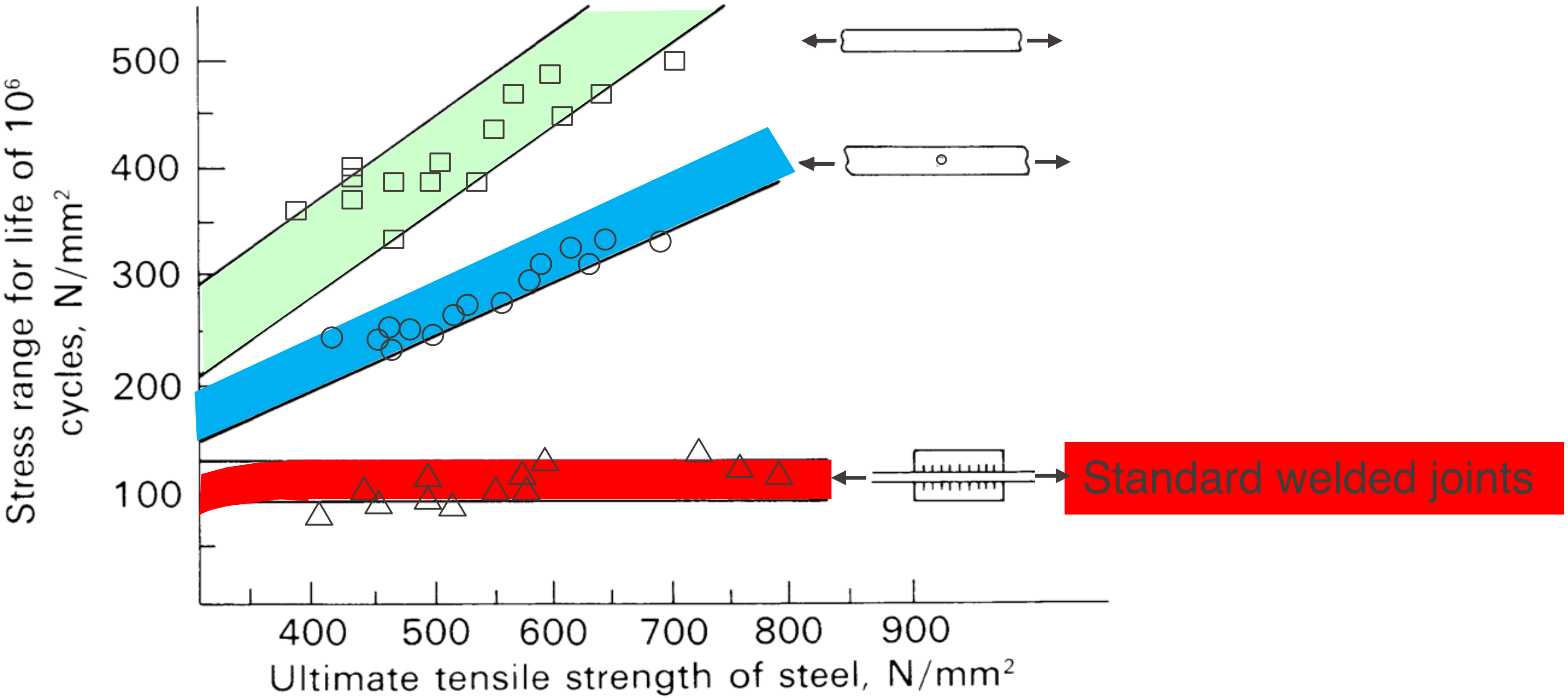


Undercuts caniveaux	Plates misalignment Décalage des bords	Lack of penetration Manque de pénétration

Notch effect (SCF)

Source: TGC 10, 2015

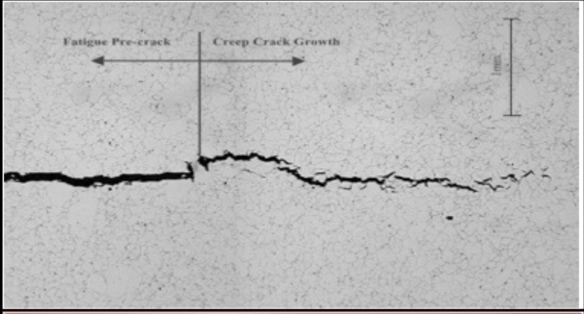
Influence of the steel ultimate strength



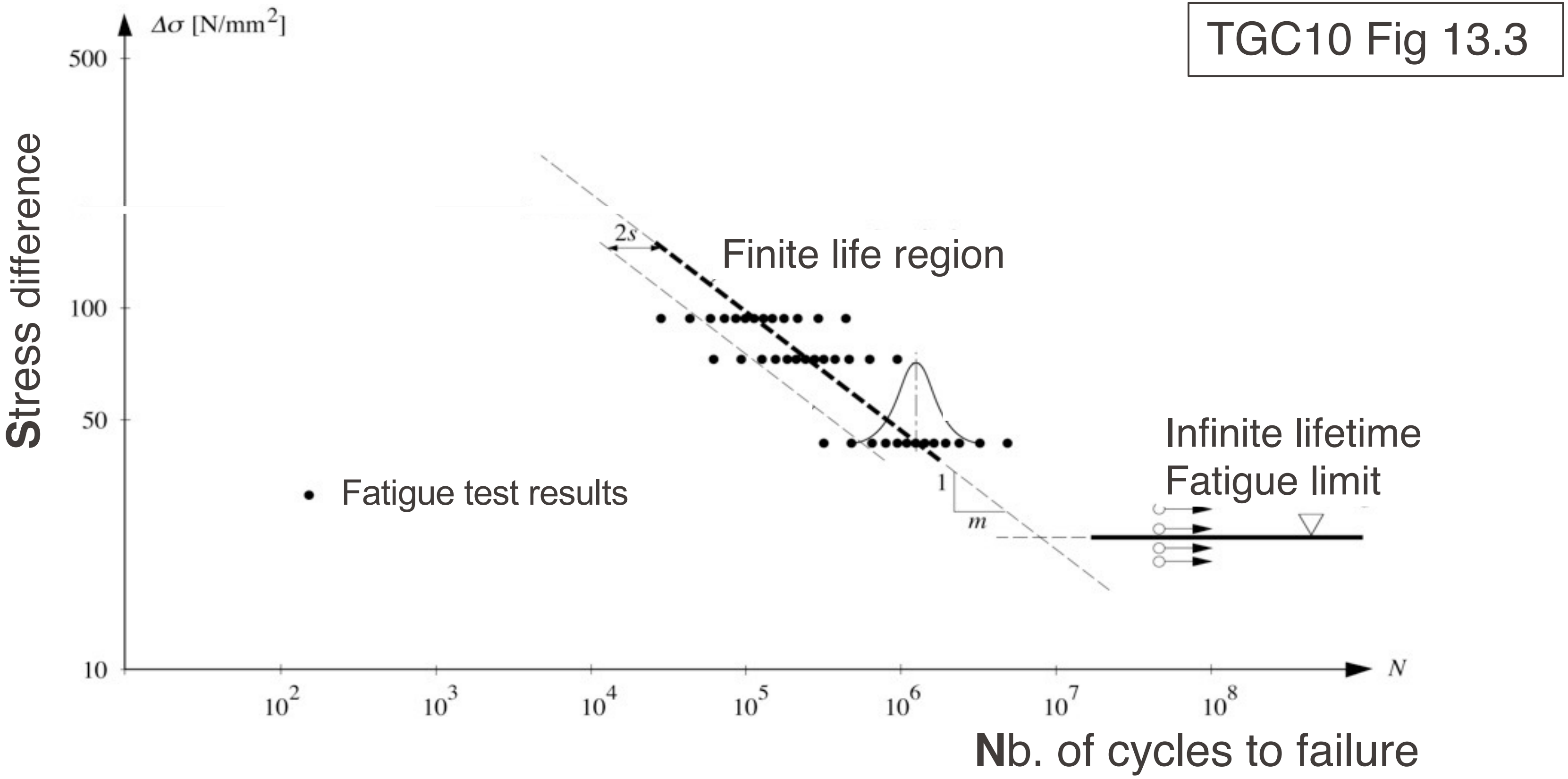
Influence of the environment on propagation

LOADING	ENVIRONMENT	
	Inert	Aggressive
Static (constant load)	Creep crack growth (propagation liée au fluage)	Stress corrosion cracking, SCC (corrosion sous contrainte)
Cyclic or fatigue	Inert fatigue (fatigue «pure»)	Corrosion fatigue (fatigue-corrosion)

Influence of the environment on propagation

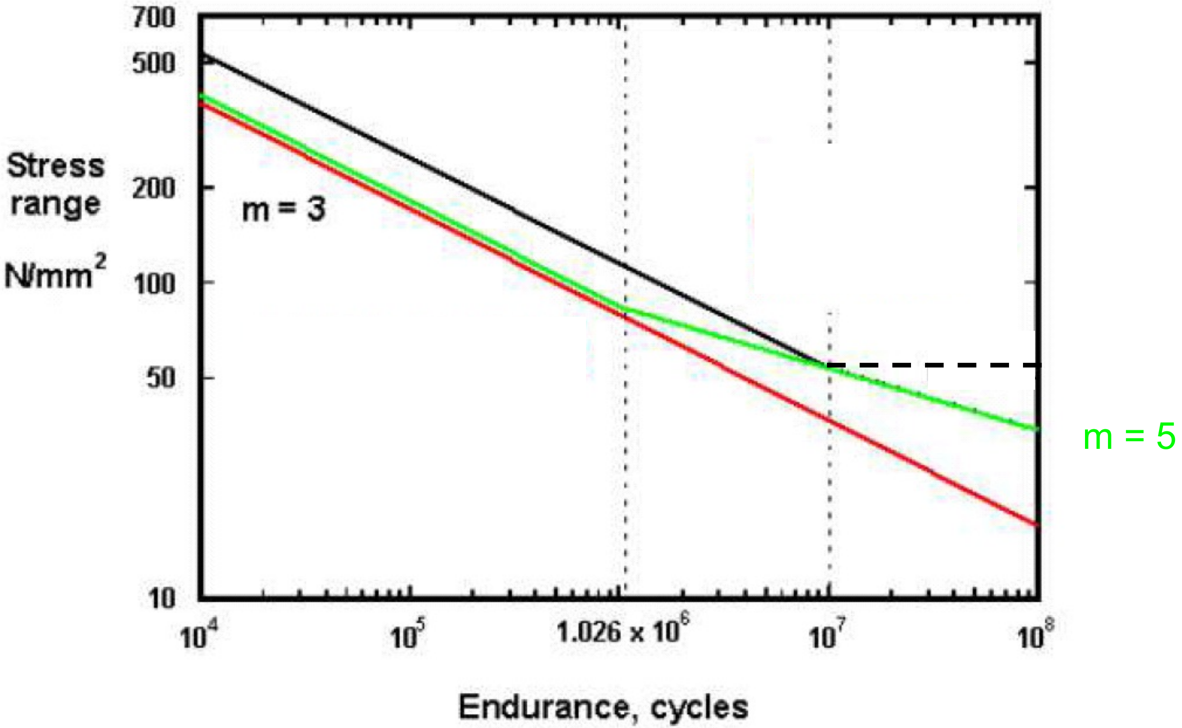
LOADING	ENVIRONMENT	
	Inert	Aggressive
Static (constant load)		
Cyclic or fatigue		

Let's introduce the fatigue S-N curve (or Wöhler* curve)



* August Wöhler (1819-1914): Alsace-Lorraine railroad director/engineer. Demonstrated that many railway accidents were not caused by defective components, but by fatigue failure of axles. At the time, it was not known that the cyclic failure load of a material is lower than its static failure load. Developed the test and curve to express fatigue resistance

Influence of the environment: S-N curves



Which is which ?

- In air
- In see-water
- In sea-water with cathodic protection

Difference in both:

- Finite life region
- The fatigue limit

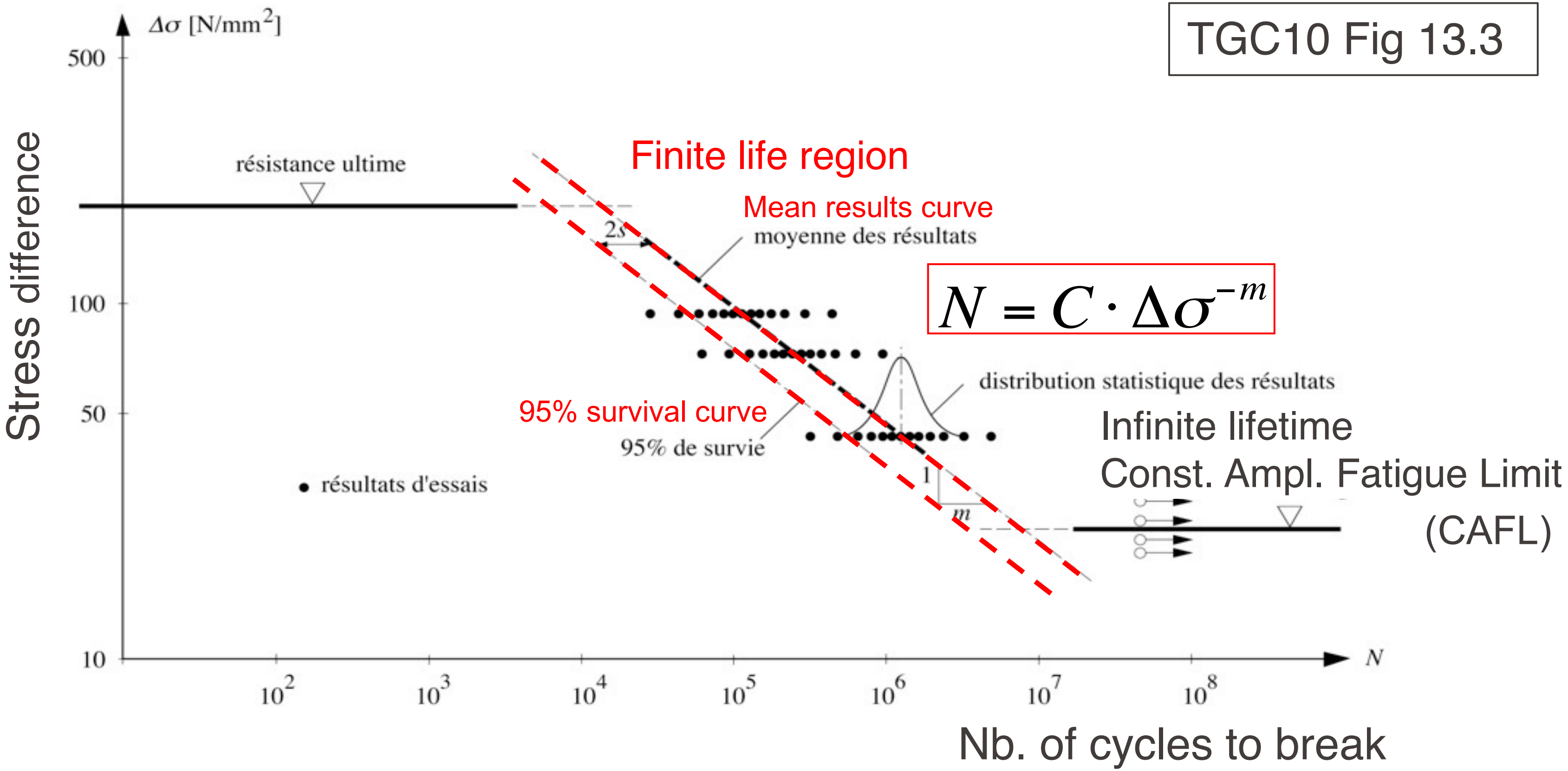
Ref : DNVGL-RP-C203:2011, Fatigue design of offshore steel structures

Content

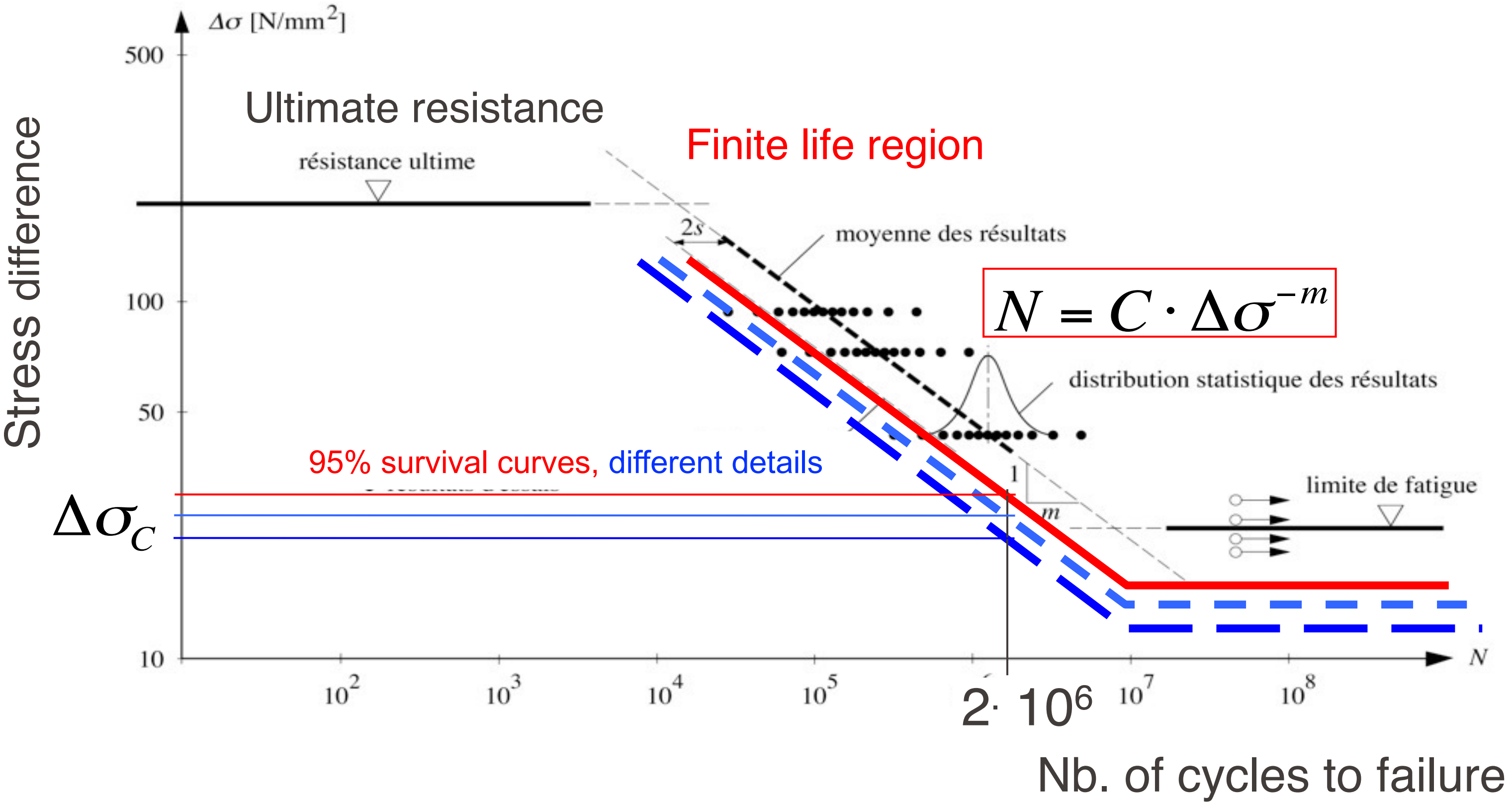
- Introduction, motivation, examples
- Fatigue and fracture mechanics
- Material: initiation and propagation
- Structure: Important parameters
- **Fatigue curves and verification format**

Test results and fatigue curve regions

TGC10 Fig 13.3



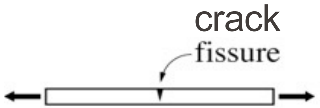
Different curves depending on geometry (or detail)



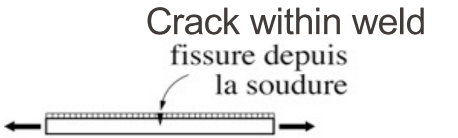
Fatigue resistance categories (detail categories)

TGC 10 Tab. 13.30

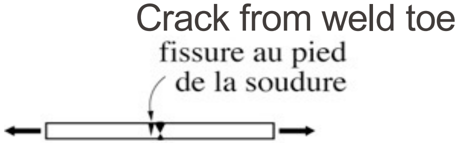
FAT 160-125



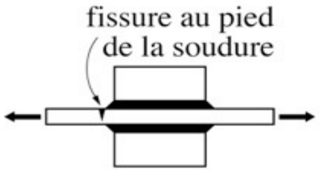
FAT 125-100



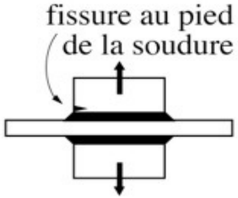
FAT 100-80



FAT 63-50



FAT 71-36



Fatigue verification format (constant amplitude)

$$E_D \leq R_D \qquad \gamma_{Ff}\Delta\sigma_{E2} \leq \Delta\sigma_C/\gamma_{Mf}$$

- Basis of comparison 2 million cycles (FAT)
- Action load effects adjusted to 2 million cycles

$$\Delta\sigma_{E2} = \left(\frac{N}{2 \cdot 10^6}\right)^{1/m} \cdot \Delta\sigma_N$$

- Fatigue load factor, $\gamma_{Ff} = 1.0$ (by default)
- Fatigue resistance factor, $\gamma_{Mf} \geq 1.0$

Fatigue exercise series

- FAT 1: S-N curves questions & failure case (TO TURN IN, same groups as before)
- FAT 2: Crack positions and detail categories
- FAT 3: Determination of stress at fracture of component with different defects
- FAT 4: Calculation of cumulative damage
- FAT 5: Simplified verification, "lambda factors" method

Thank you

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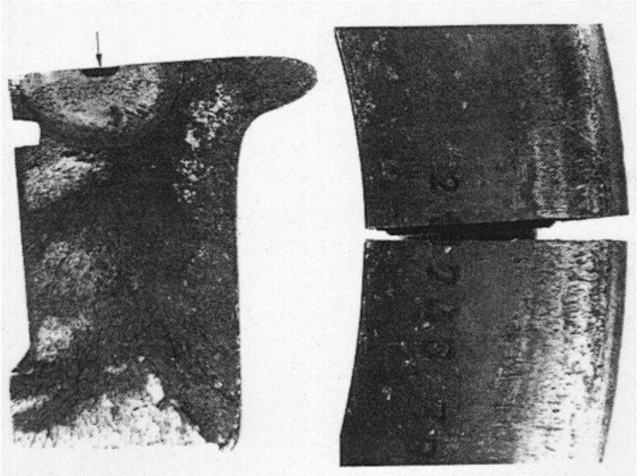
RESSLab

APPENDICES

Railway breakdowns: history repeats itself

1. 1871: Wöhler, studies on wagon wheel axle fractures
2. 20$^{\text{ème}}$ century: Crack beginning at 1 of the production number

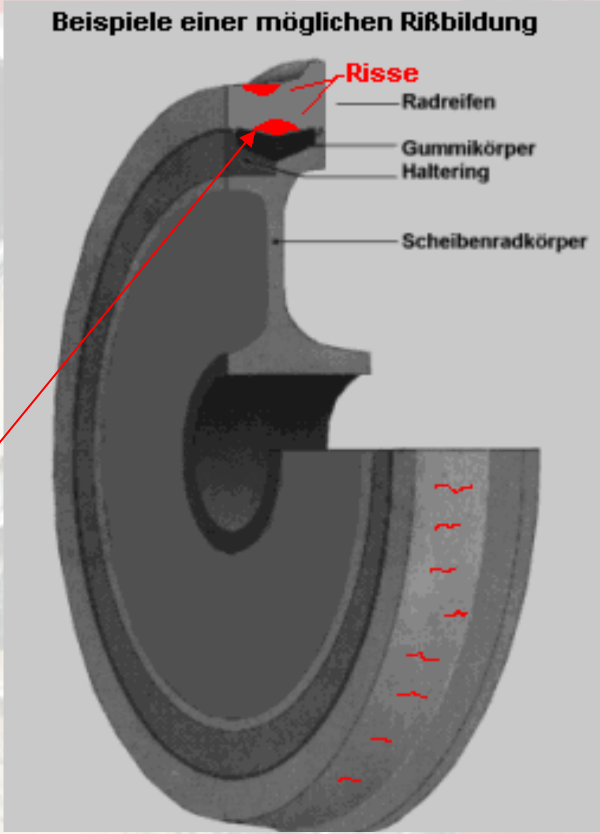


3. 1998: Eschede, wheel flange failure
4. 2023: Gotthard tunnel, wheel flange failure

Cases of railway breakdowns: the Eschede disaster

- Derailment of an ICE following a wheel steel tire failure (rupture boudin de roue)
- The train hit a bridge pier which collapsed on top of the train
- 102 casualties

Undetected crack

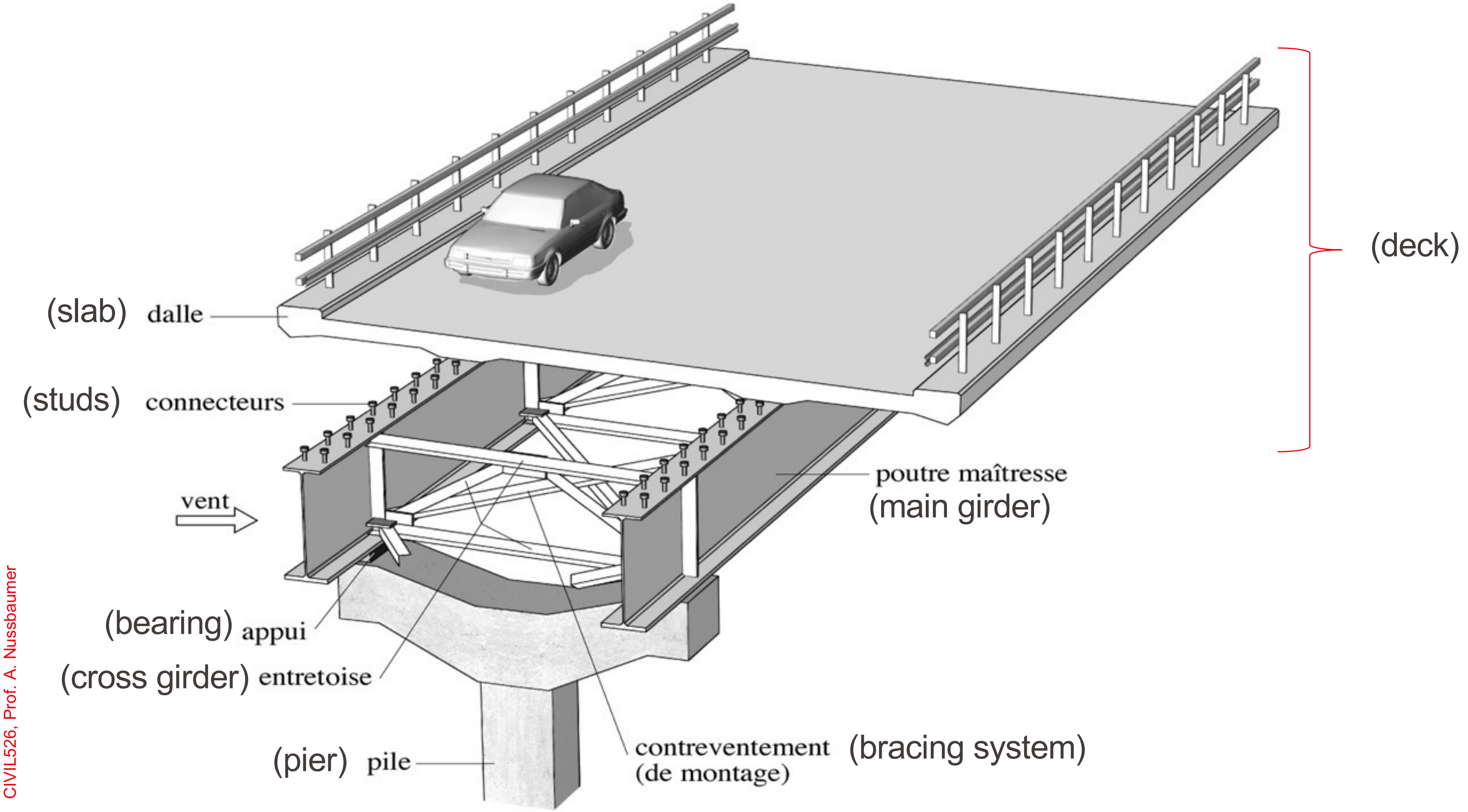


Source: Esslinger et al, the railway accident of Eschede - technical background, Eng. Failure Analysis, 8/2004

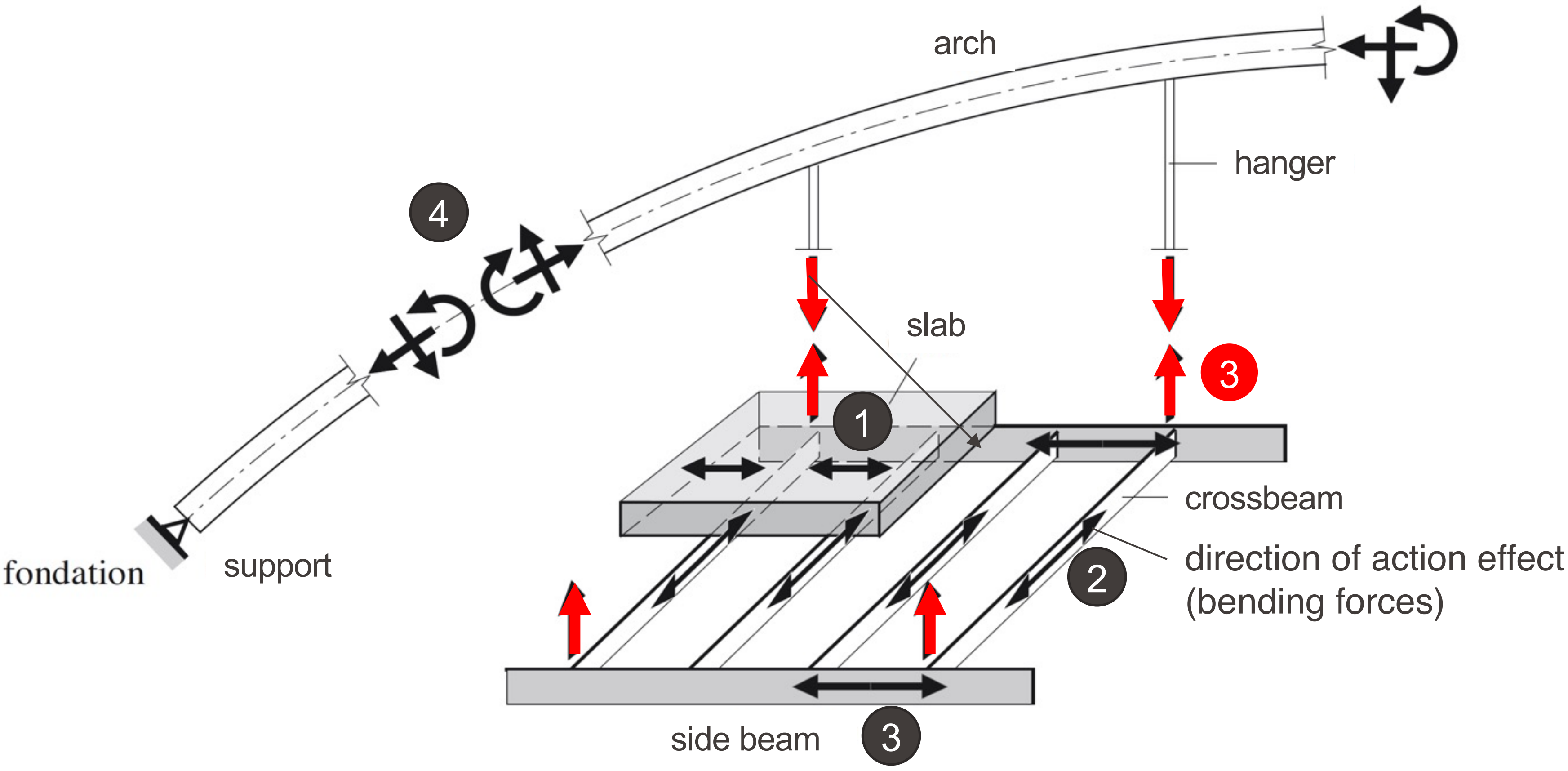
Bridges: longitudinal load-bearing systems

1. Beam bridges (double-beam or multi-beam)
   - Laminated beams/welded components
   - Lattice
   - In a box
2. Arch bridges
   - With 3 joints
   - Bi-recessed
   - With 2 joints (upper, lower, bow and bowstring)
3. Crane bridges
4. Cable-supported bridges
   - Suspension bridges
   - Cable-stayed bridges
   - Stretched ribbons

Bridges: Load-bearing components

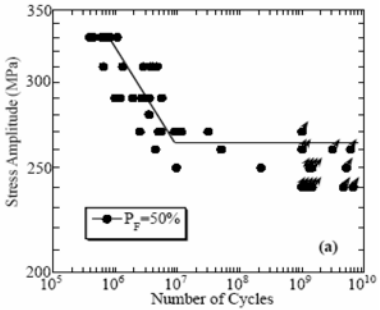


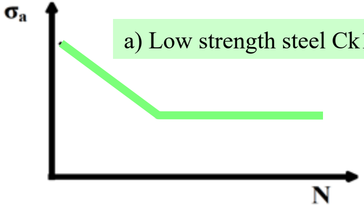
Example of vertical load route to foundation (arch bridge)



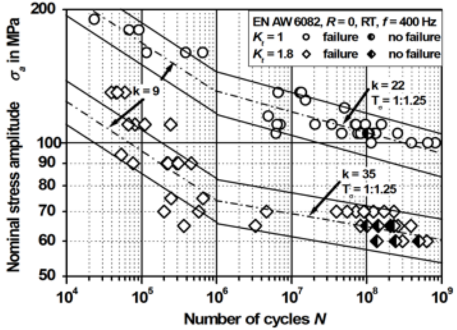
Fatigue in steel: 4 possible behaviours

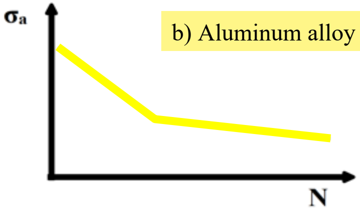
(C. Berger, LBF Darmstadt)



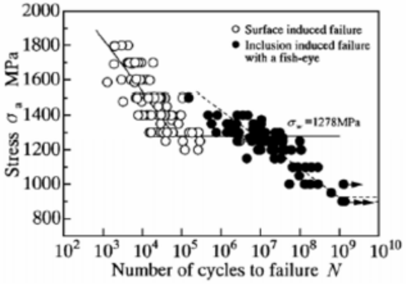


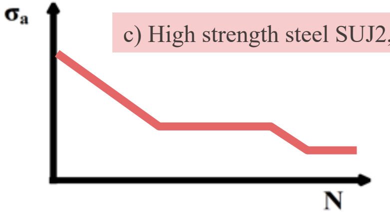
a) Low strength steel Ck15, R=-1



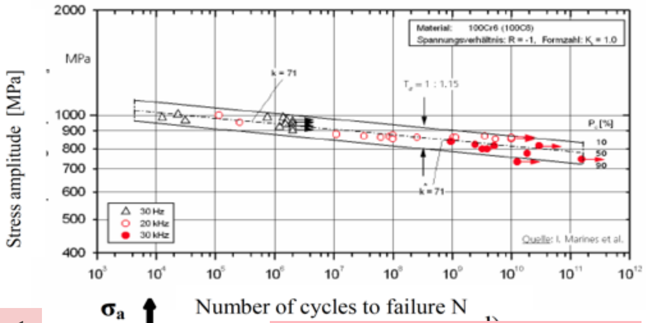


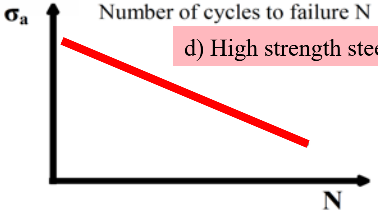
b) Aluminum alloy EN AW 6082





c) High strength steel SUJ2, R=-1

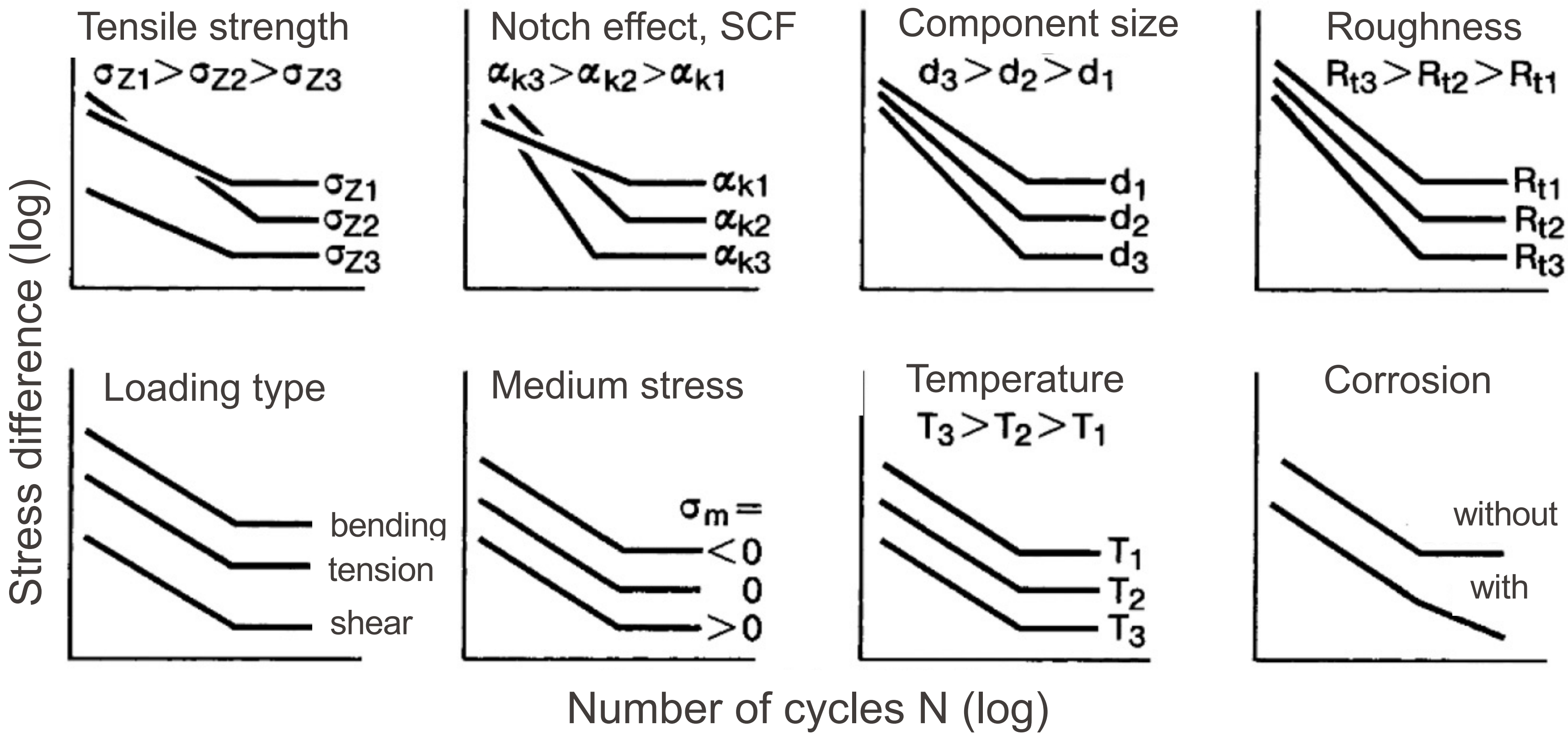




d) High strength steel 100Cr6, R=-1

EPFL

Summary of influences on resistance curves



Source: Gudehus, H.; Zenner, H, Leitfaden für eine Betriebsfestigkeitsrechnung, Verlag Stahleisen, Düsseldorf, 1999