Karlsruher Institut für Technologie

Why everything gets broken or material scientific consideration of damages

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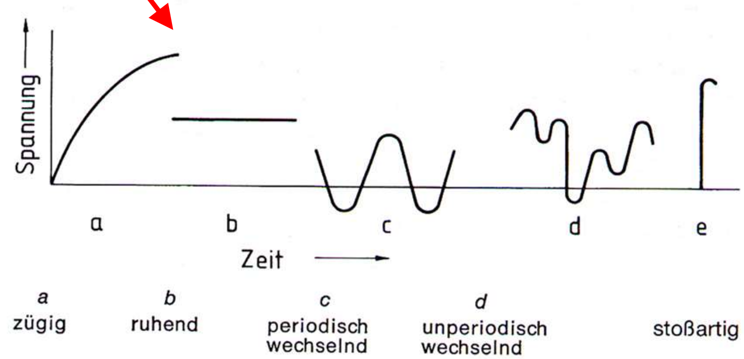
Causes of failure

- Design / calculation / manufacturing or material defects
- Material fatigue
- Fatigue in combination with additional reasons (e.g. corrosion)
- Insufficient maintenance / service
- Improper use / overload
- Human failure

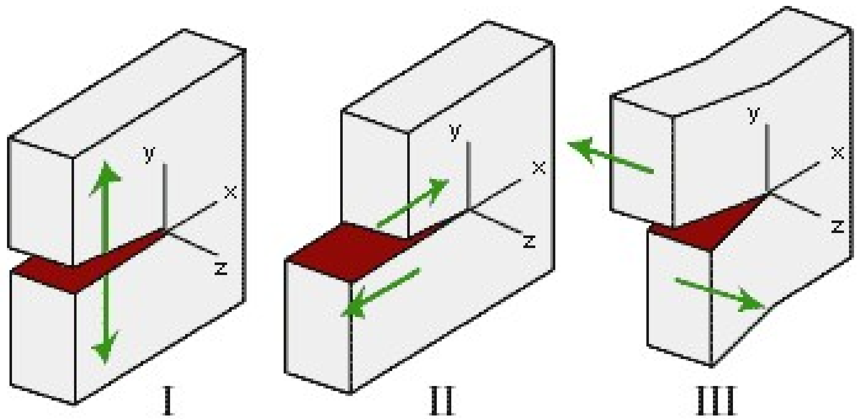


Design-Issues: Collapse of the Tacoma-Narrows-Bridge 07.11.1940

https://www.youtube.com/watch?v=3mclp9QmCGs
(starting at 01:00)

Reasons:
- Terrain profile (coast line formed nozzle)
- Rigidity of the bridge box to low, wrong self frequency calculation (ressonance)
- It is impressive, what materials resist before failure…

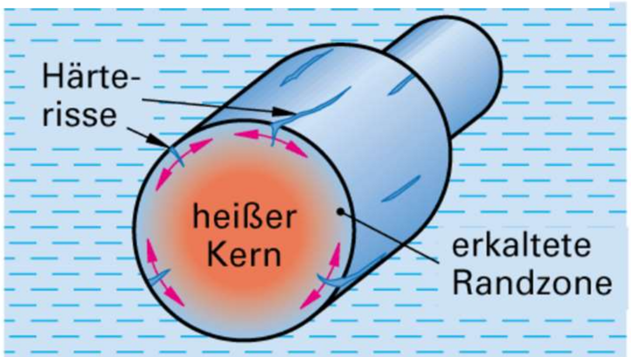
Crack opening modes I-III



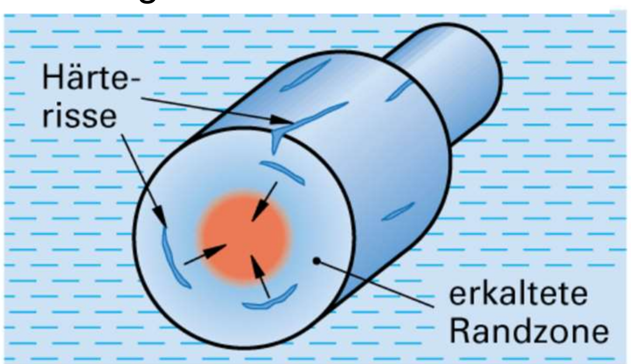
- Mode I: simple crack opening; symmetrical lift-off of the crack edges.
- Mode II: Longitudinal shear; sliding of crack surfaces in the crack plane.
- Mode III: Transverse shear; displacement of the crack surfaces transverse to the direction of the crack

Manufacturing/Processing: Crack initiation

1st phase: Hot core impedes shrinkage of shell



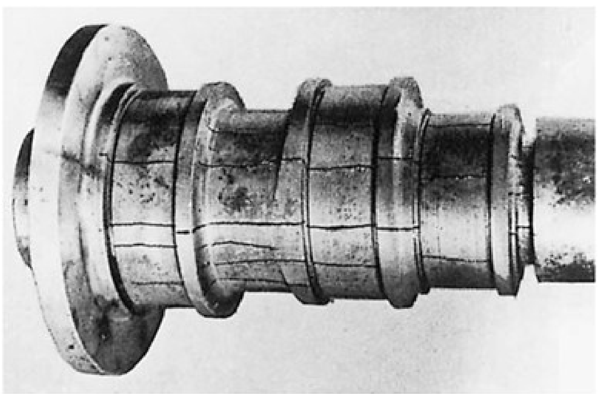
2nd phase: rigid shell impedes shrinkage of core

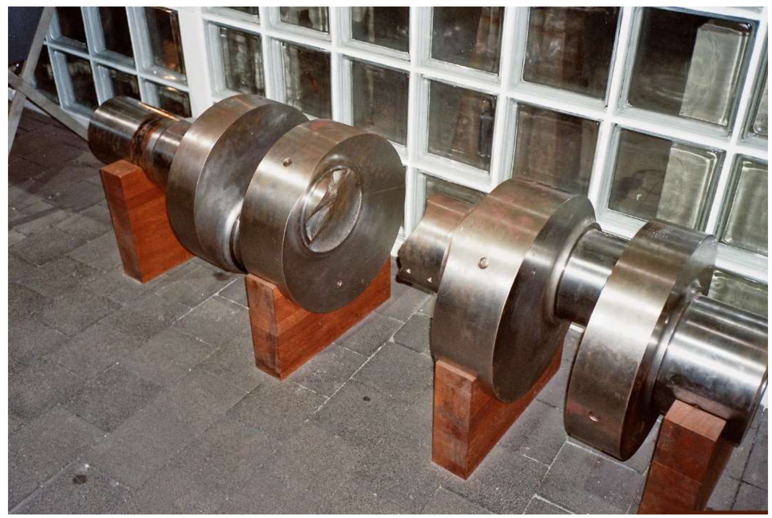


Hardening cracks due to volume change of austenite (fcc) and martensite (tetragonally distorted bcc), superimposition with thermal shrinkage

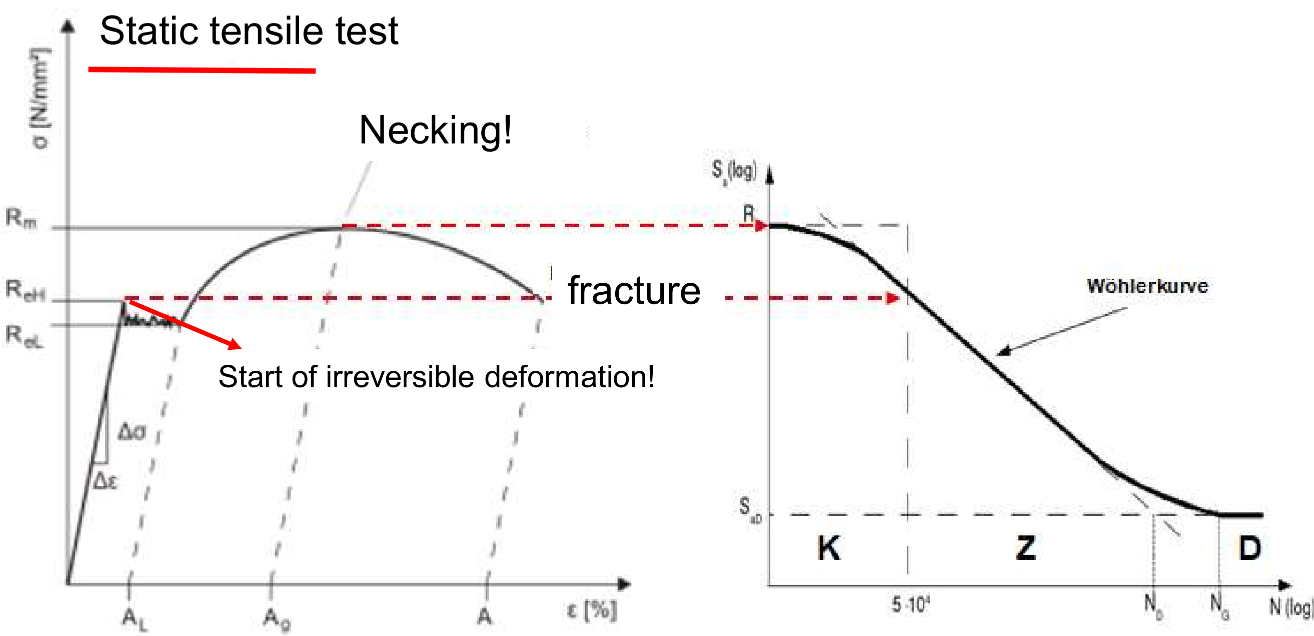
- Dye penetrant test
- Eddy current testing
- Depending on position: possibly not all cracks deteced….

=> Superimposition of residual stress and external stresses (shot peening of surfaces)





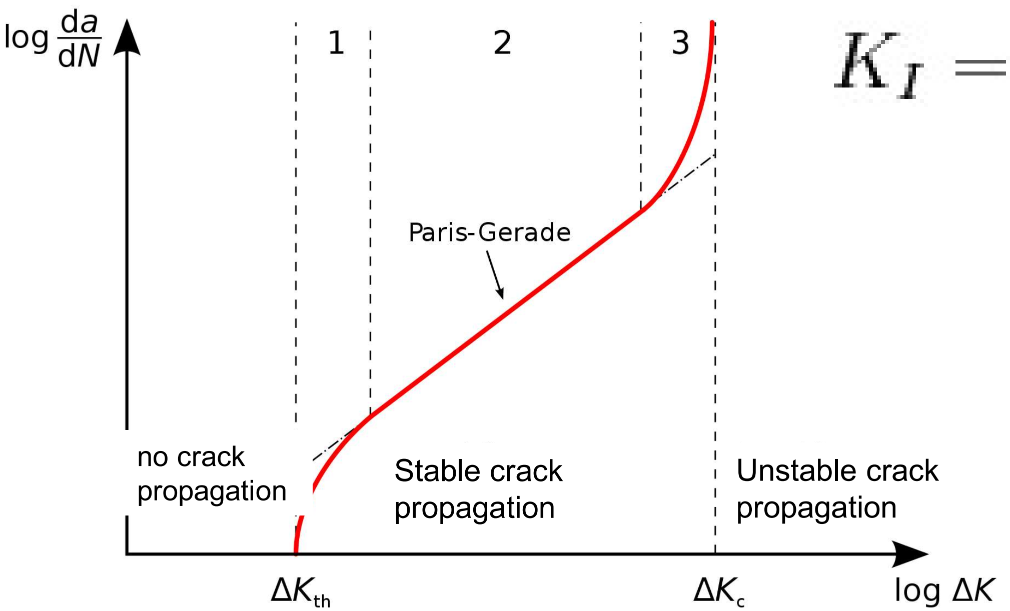
Fatigue resistance (Criterion: Fracture!)



Elongation at fracture

- max. tolerable stress depends on the number of load cycles **n**, (depends on geometry!)
- **Short-term strength** K (100-30.000 load cycles ≈ R_e)
- **Creep strength Z** (max. 2* 10^6 load cycles => often not enough!)
- **Fatigue strength D** ≈ 10^6 Lastspiele
- For n >> 10^6 (10^8-10^9) few experiences, cannot be verified by tests (duration)
- **Engineering:** Mostly creep strength => Monitoring required!
- Crack growth & crack propagation models
- Sometimes: superimposition by unexpected incidents => failure

Why there is only a 5 year warranty against failure on aluminum bicycle frames or: there are no components without any cracks....



K_{1c}: Fracture toughness or critical stress intensity factor

$$K_I = \sigma \cdot \sqrt{\pi \cdot a} \cdot f$$

σ	Stress [MPa]
a	crack length [m]
f	geometric factor
K_{1c}	Fracture toughness [MPa*m$^{1/2}$]

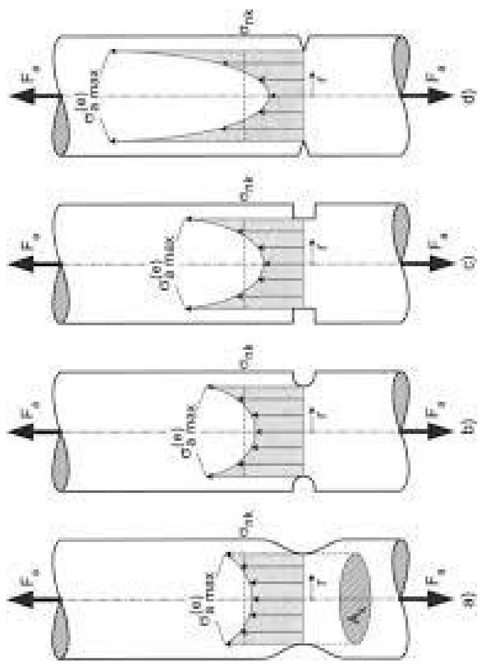
K_{1c} depends on:

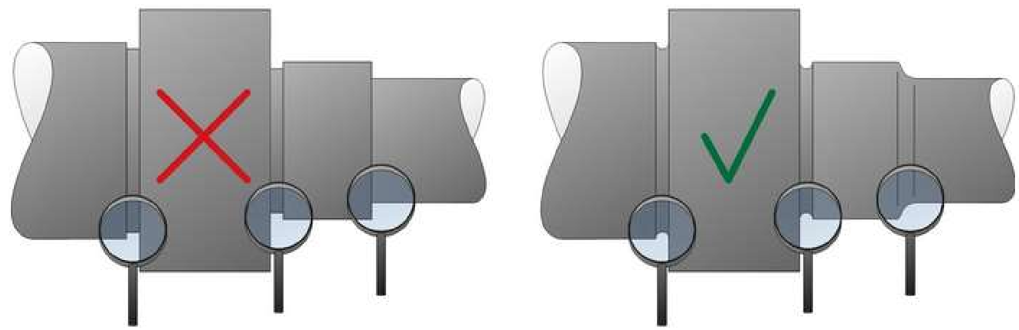
- Material
- **Design**
- **Surface roughness & surface state**

⇒ ceramic materials!

(Shot peening => Compressive residual stresses)

Impact of Design - Load optimized Design





Railway: Historical development of wheelset safety

Jahr	Wellenbrüche in Deutschland	Laufleistung zwischen zwei Wellenbrüchen in Deutschland
1880	80	100 Mio. km/Wellenbruch
1900	94	256 Mio. km/Wellenbruch
1930	88	414 Mio. km/Wellenbruch
1940	277	380 Mio. km/Wellenbruch
1955	225	117 Mio. km/Wellenbruch
1960	57	465 Mio. km/Wellenbruch
1970	35	826 Mio. km/Wellenbruch
1980	7	3.972 Mio. km/Wellenbruch
1990	7	3.866 Mio. km/Wellenbruch
2006	9	4.383 Mio. km/Wellenbruch
2007	4	10.099 Mio. km/Wellenbruch
2008	9	4.513 Mio. km/Wellenbruch
2009	1	39.040 Mio. km/Wellenbruch

Durchschnitt Deutschland 2006 – 2009 **6.953 Mio. km/Wellenbruch**

Durchschnitt EU-Bahnen 2006 – 2009 **1.983 Mio. km/Wellenbruch**

Quelle: Auswertung der statistischen Jahrbücher und ERA-Report durch BVV

=> Mileage between two damages at an all-time high!

ICE-Disaster Eschede 03.06.1998 - A sequence of unfortunate events

- *Composite wheel: Fracture of wheel rim due to material fatigue.*
- *Wheel rim made of rolled and tempered carbon steel, joined to the wheel disc via rubber sleeve.*
- *At the wheel contact point, the wheel rim is bent inward => tensile bending stresses in the circumferential direction at inner side.*
- *Per revolution: change of stress tension ⇔ compression.*
- *Amplitude increased by wear and runout.*
- *Fatigue failure after1.8x10^6 km (**6,2x10^8 load cycles**).*
- *Broken wheel wedged into the wheel control arm. Fracture pushed wheels out of rails.*
- *Intact wheel hits a switch that had just been passed and changes it. The following wagons derailed. A bridge pier is broken down. The collapsing bridge buries one wagon. The remaining wagons are pushed by the heavy rear powerhead.*
- *101 dead , more than 100 people injured.*
- ***Runout was noticed at last maintenance but considered still uncritical => crack growth faster than expected.***
- **Consequence: Reduction of maintenance intervals of wheelsets from 300,000 => 60,000 => 30,000 km (capacity problem for maintenance)**

Different Railroad Wheels

Composite wheels consist of a wheel body and a wheel rim (different steel alloys). Wheel rims are shrunk => tensile stresses.

Full wheel : forged from one piece

- By heat treatment, surface is harened (if worn out, the entire wheel must be replaced).
- Full wheel is pressed onto the wheel shaft. =>
- Design of tolerances based on **operating experience**.

Quality: Random samples destructively tested; 100% NDT.
=> Highest stresses occur in tight curves and switches at low speed; never at high speed when driving straight !!!

=> Most of damages with "fatigue fractures" is due to corrosion (mixed loading; failure hardly predictable).

Wheelset shaft fracture at ICE 3 on 09.07.2008 in Köln

Broken axle shortly before Cologne main station; train derails on departure (!)

Reason: Manufacturing-related material inclusions in the wheelset shaft.

Only fortunate circumstances prevent an accident; cruising speed shortly before 330km/h!

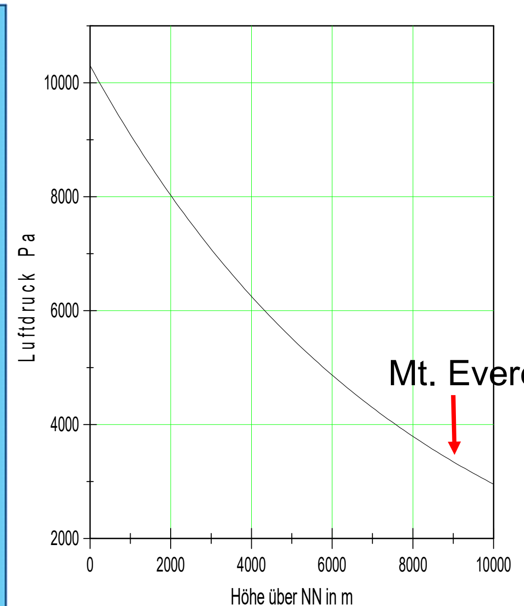
Consequence: Reduction of maintenance intervals of wheelsets from 300,000 => 60,000 => 30,000 km (capacity problem for maintenance)

Conflict between Technology ⇔ Society

- German railroads: Operating experience for mileages from 2.5 million km to 10 million km without crack detection.
- Load cycles of approx. $9*10^8$ or. $4*10^9$ (similar to crankshafts and generator shafts).
- No noticeable accumulation of damage at high mileages.
- Predominant number of damages with "fatigue fractures" due to corrosion.Gesellschaft erwartet technische Höchstleistungen ohne jegliches Risiko („Vollkasko-Gesellschaft“)

1. There is no such thing as operation without any failure!
2. There is always a certain probability of occurrence for failure
3. The maintenance is designed accornding it. **Question:** Are the assumptions o.k.?
4. Consideration & social acceptance of the residual risk

Barometric Elevation Formula



Mt. Everest: 8848m

Barometrische Höhenformel:

$$p(h) = p_0 \cdot e^{-\frac{\rho_0}{p_0} \cdot g \cdot h}$$

Aloha-Airlines-Flight 243, (Boing 737-200, 28.4.88)

Reason:

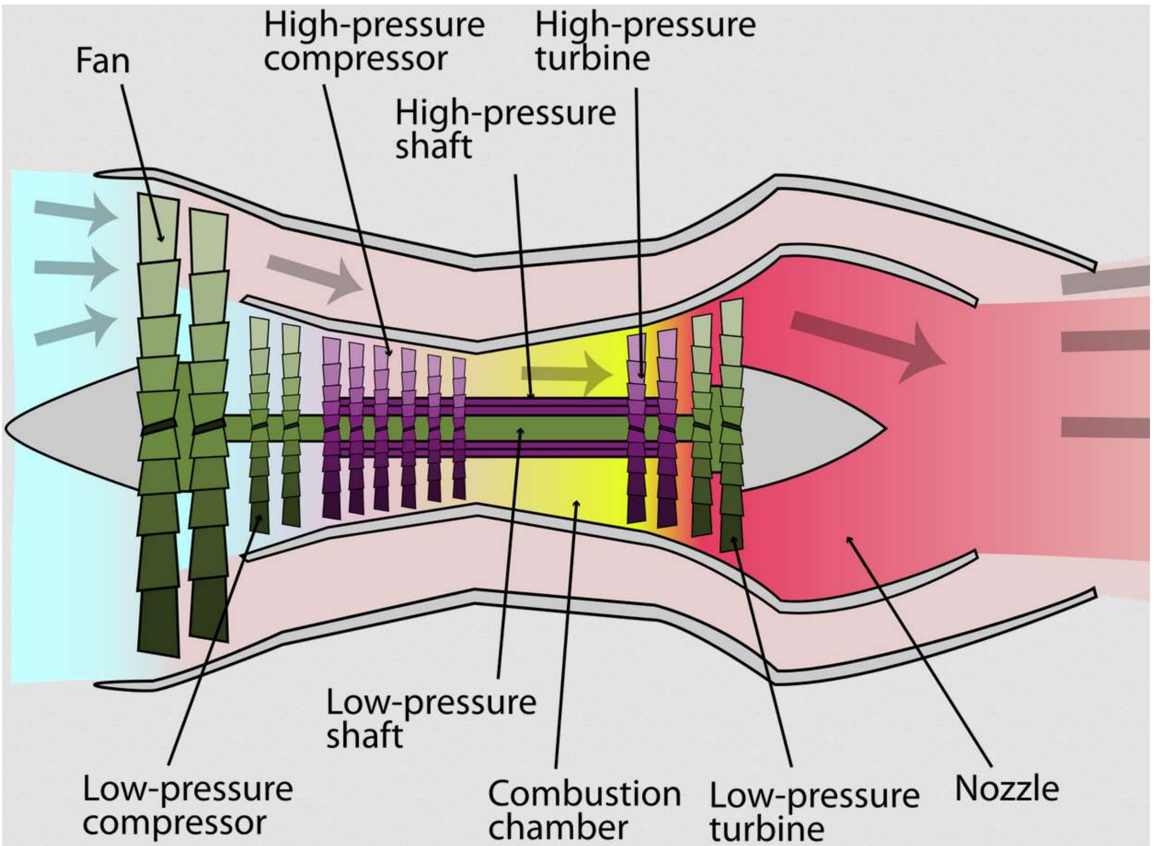
- Island-hopping (short range)
- after 90.000 cycles (designed for 50.000 only *)
- corrosion (salt spraying) +
- fatigue (∆p)
- Crack propagation between rivet holes in the hull @ 7300 m

Consequences:

- 1 flight attendant sucked off (✝)
- 65 people injured, 7 of it severe

*) D. Rataj, „Ermüdungsfestigkeit“, Springer, ISBN 978-3-662-07108-3, S.3

Turbofan



- Very efficient & quiet (housing)
- Almost all commercial aircraft
- By-pass ratio up to 1:12
- GE9X: 597 kN thrust, Fan-Ø=3,4 m

Flight QF32 (A 380, 4.11.10) and United-Flight UA328 (Boing 777, 20.2.21 and some more….)

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A few years ago, engine explosion was a case-1 accident, resulting in a total loss of the aircraft
Today, the most frequent reason of crashes is operator failure

QF 32:

- Fatigue fracture of an oil rail in the RR Trent-900 engine
- Turbine disk detached from drive shaft due to oil fire.
- Engine casing, left wing, 2 tanks & hydraulic lines penetrated.

UA328

- two fan blades broken

Composite Materials: Crash of AA 587 (Airbus A300, 4.11.01)


- Generally: Problems with NDT, no ultrasonic testing possible.
- Airbus A300 flew through wake vortices of a previously launched Boeing 747 after takeoff in N. Y.
- Copilot reacted with full deflections of the rudder in both directions (hydraulically operated, no haptic feedback!).
- Load limits were exceeded, rudder broken.

Coal-fired Power Station

Steam temperature: up to 600°C,
pressure: 80-300 bar (8-30 MPa),
Steam throughput: up to 350 t/h
Efficency: up to 47% (Nordjyland 3, Danmark, 411 MW)

Boiler house of power station Staudinger (Großkotzenburg, 12.05.2004) after „steam leakage“

Conclusions

- Often technical equipment is operated in the range of creep rupture strength
- Engineering monitoring and maintenance plans are necessary and
- Underlying assumptions of load cases & failure mechanisms must be appropriate
- Otherwise, catastrophic failure is possible
- Usually engineering designs behave well and endure more than what they were designed for
- There is no technology without residual risks….
- Nowadays, safety is at a level never reached before
- However, due to global reporting, accidents are becoming more prominent in the public's mind.