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Materials safety

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We learn from Failure

Why study failure?

I. Trivialized explanations are not enough to prevent future failures
II. Even full root cause analysis is often limited to specific industry – expensive experience wasted
III. Failures are often unlikely events with serious consequences – it is challenging for experts to communicate risks to non-experts before it's too late

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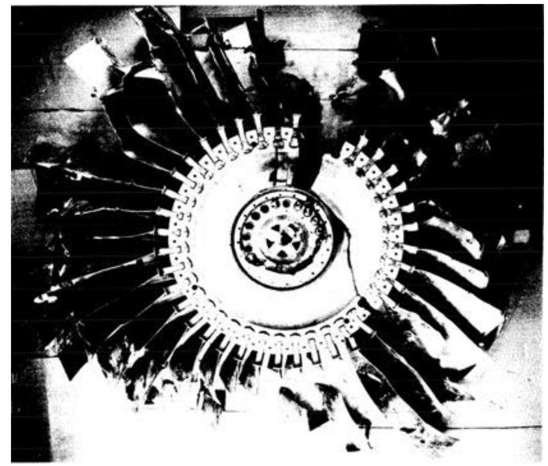
... preferably someone else's Failure

1842, Versailles

Alexander Kielland, 1980

UA232, DC-10, 1989



Eschede, 1998

Failures shape the trends of the industry

I. **High profile events shape**
   I. Engineering culture
   II. Focus technical development
   III. Provide explicit need for new tools for design
II. **Development is non-linear**
   I. Steady development runs out of steam
   II. Culmination and new solution
   III. New solution brings new problems (failure types)
III. **Should be felt more in other industries as well**

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Failure is related to innovation and optimization

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UA 232

Accident

19.7.1989 15:16 DC-10-10 (N1819) United Airlines (232) experienced a massive engine failure during flight

In the airplane, a loud bang was heard. Hydraulics pressure was lost. Airplane became impossible to steer

Emergency landing was attempted to Sioux Gateway-airport

During emergency landing, plane hit the ground, span around and caught fire

Out of 296 people on board, 111 was killed in the crash or in the following fire

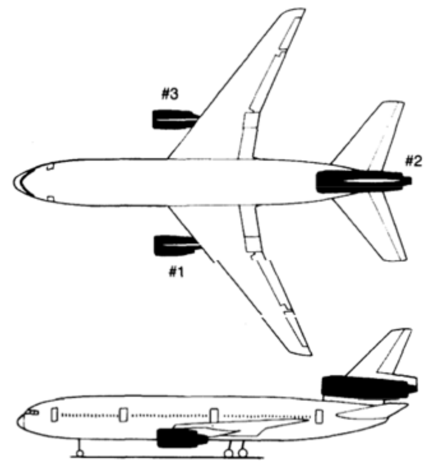
Failure analysis

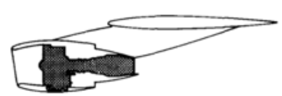
Later investigation revealed, that the engine failure was caused by fracture of the fan disk

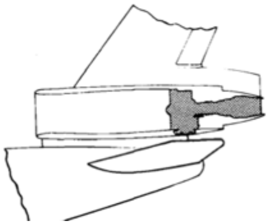
Fracture caused engine fragments to separate and fly to surrounding structures (the energy of disk is too large to be contained by the engine cover)

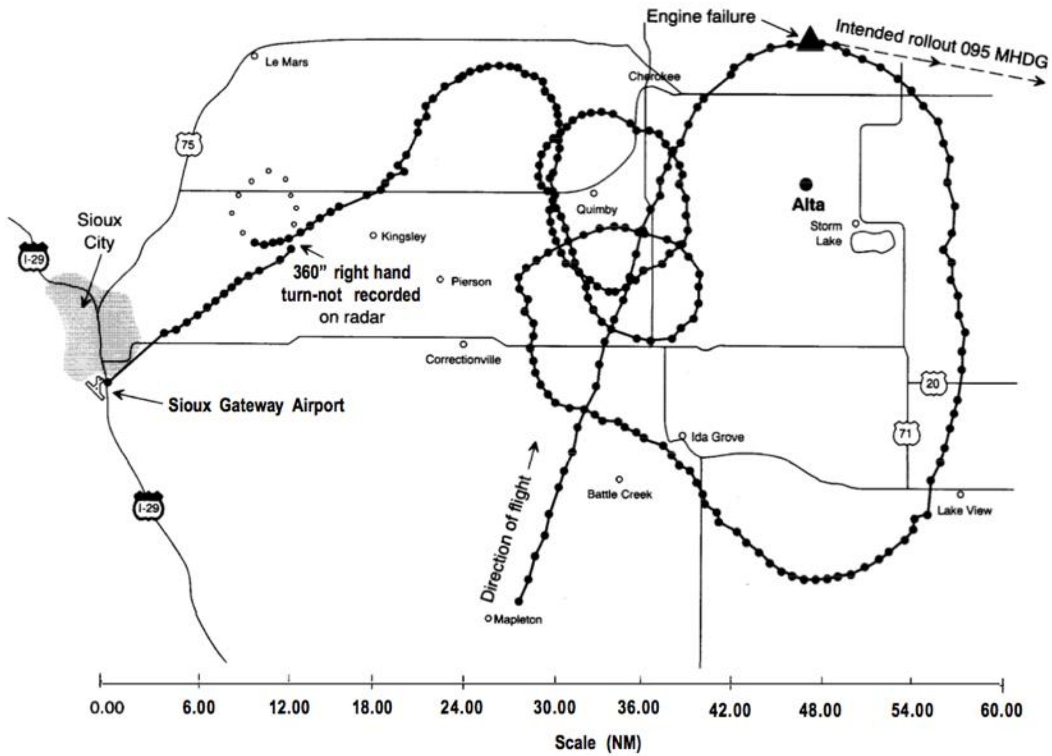
Damage from the fragments caused loss of hydraulic pressure

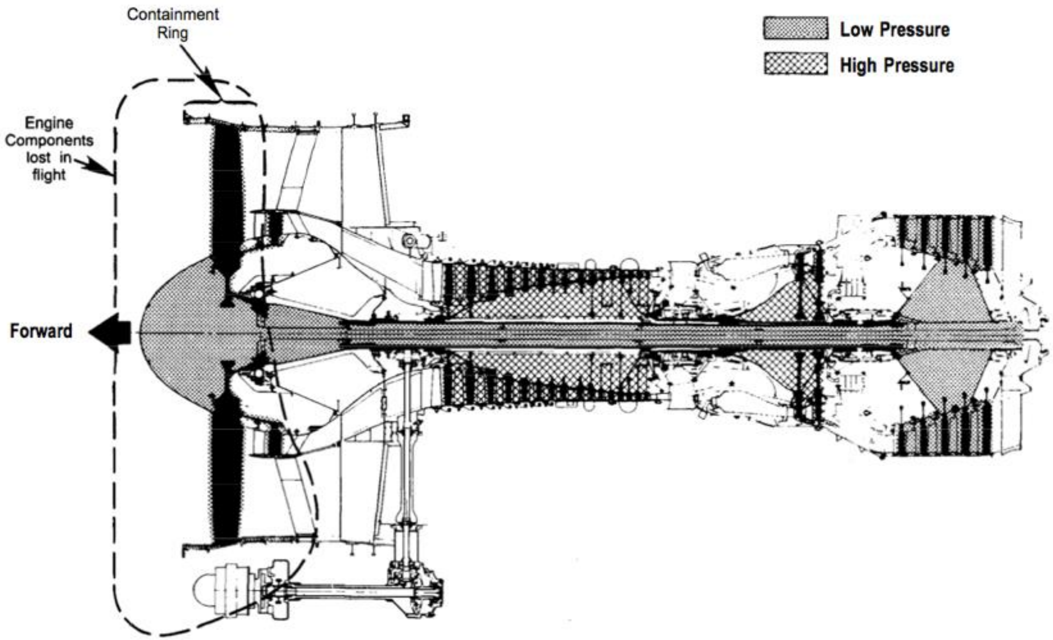
The fan disk was later found from a corn field in Iowa and the origin of the failure could be studied

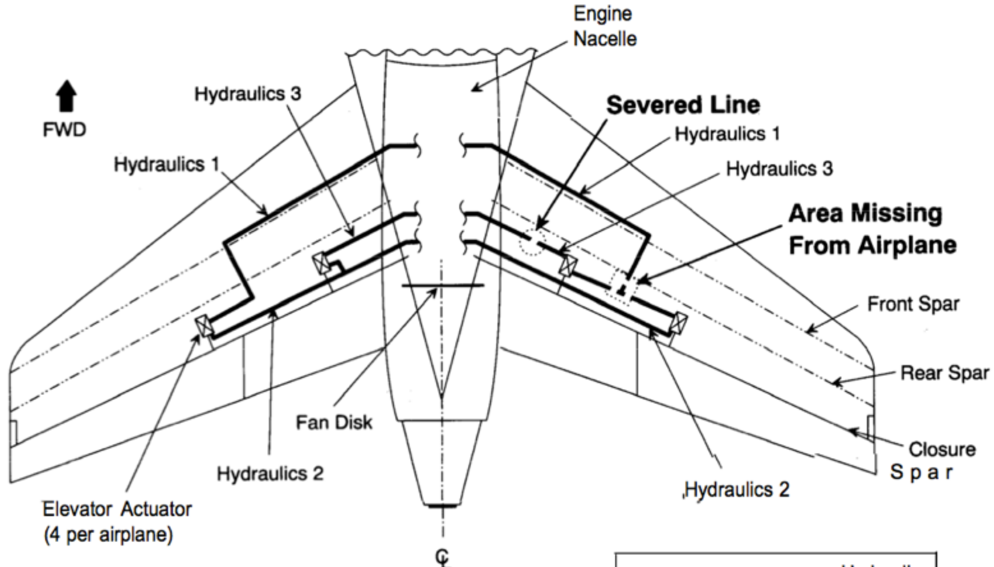

#3
#2
#1


Wing Mounted Engines


Aft Tail
Mounted Engine

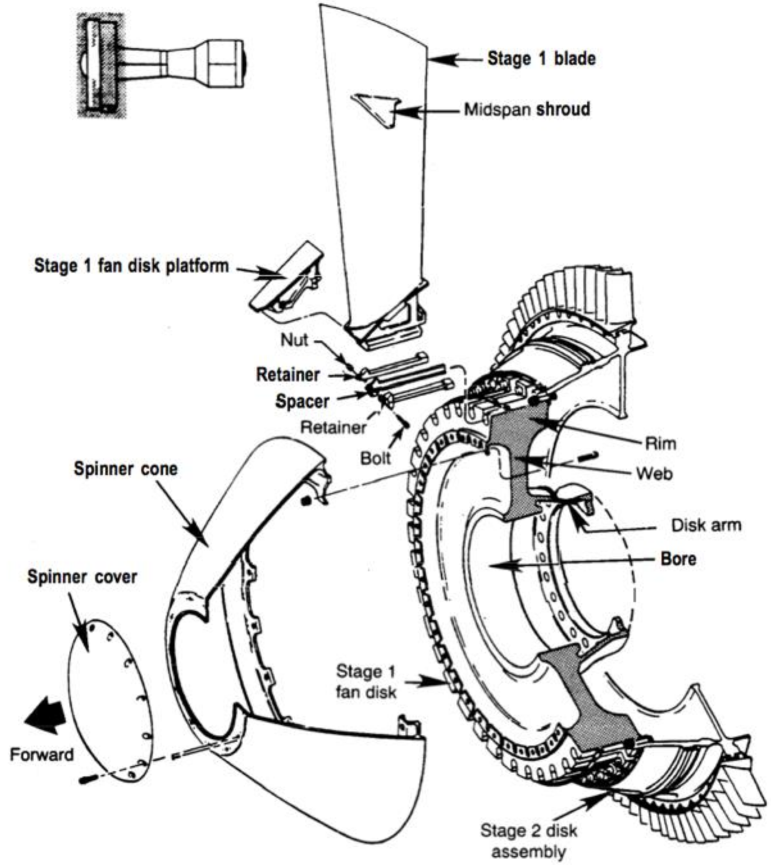

Engine failure
Intended rollout 095 MHDG
Le Mars
Cherokee
75
Sioux City
I-29
Kingsley
Quimby
Alta
Storm Lake
360" right hand turn-not recorded on radar
Pierson
Correctionville
Sioux Gateway Airport
20
71
Ida Grove
Direction of flight
Battle Creek
Lake View
Mapleton
0.00
6.00
12.00
18.00
24.00
30.00
36.00
42.00
48.00
54.00
60.00
Scale (NM)


Containment Ring
Low Pressure
High Pressure
Engine Components lost in flight
Forward



Actuator Position	Hydraulic System
RH Inbd Elev	1 & 3
LH Inbd Elev	2 & 3
RH Outbd Elev	1 & 2
LH Outbd Elev	1 & 2

Not to Scale



Stage 1 blade
Midspan shroud
Stage 1 fan disk platform
Nut
Retainer
Spacer
Retainer
Bolt
Rim
Web
Disk arm
Bore
Spinner cone
Spinner cover
Stage 1
fan disk
Forward
Stage 2 disk
assembly

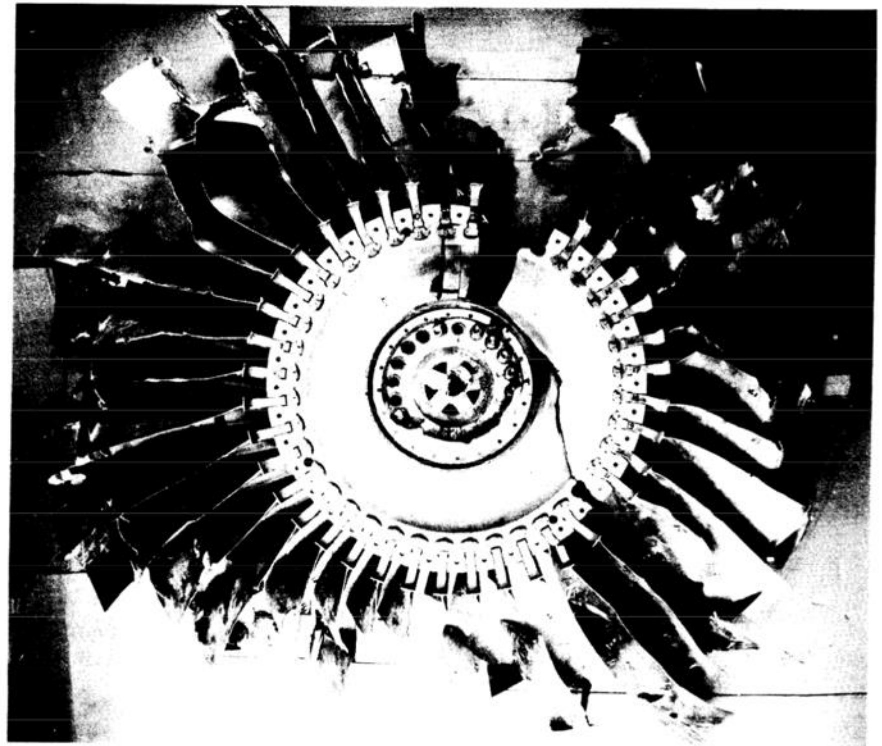


Figure 18.--No. 2engine stage 1 fan disk (reconstructed with blades).

Why did the fan disk break?

... and how can we prevent similar occurences in the future?

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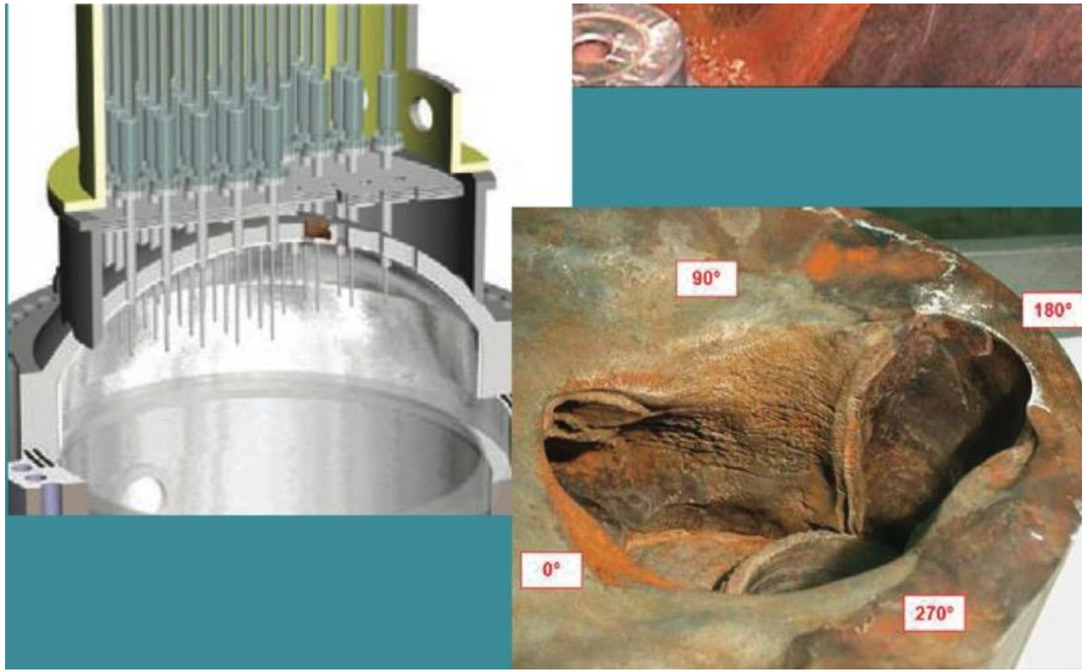
Davis Besse

Davis Besse



http://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation/lessons-learned.html

Background

Cracks found in PWRs in France

- Bugey 1991
- Cracks in pressure vessel head penetrations
- Alloy-600 Nickel alloy susceptible to cracking
- "Primary water stress corrosion"

U.S.A => not an issue on U.S. plants

Cracks in the U.S.A

Similar stress corrosion cracks found in U.S.A.

Oconee 2001 circumferential crack

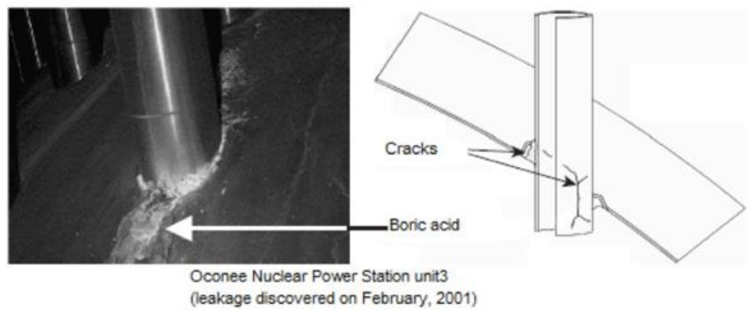


Fig.3 Leakage example in the USA

2001/01 NRC orders additional inspections => "bare metal visual"

Cracks in Davis Besse 2002/02

Bare metal visual inspection was done in connection to fuel loading

Cracks found in three penetrations

Cracks extended through-wall

Decision to repair the cracks in place

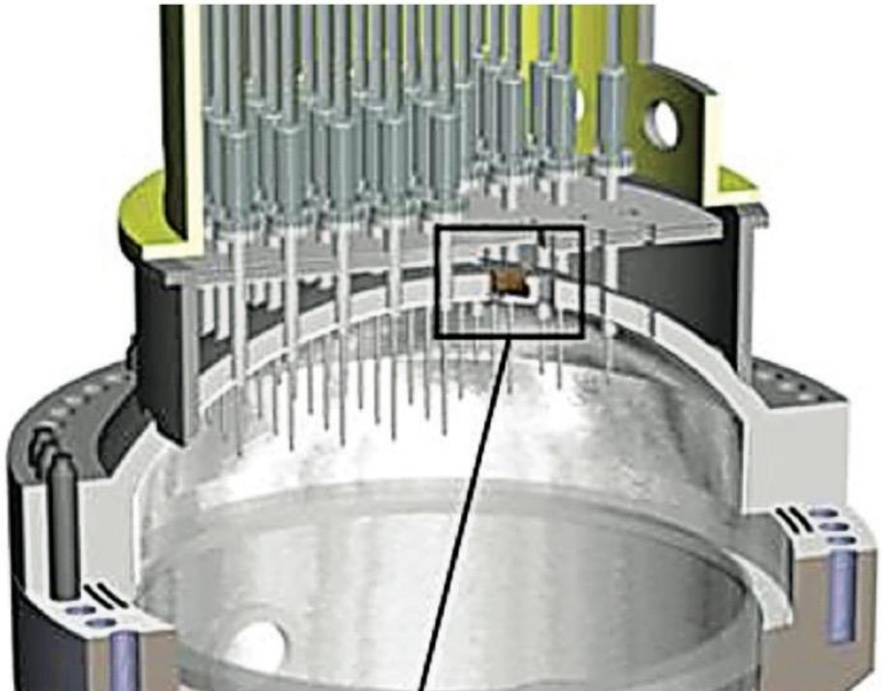
2002/03 repair stopped

Repair equipment behaved "strangely"

Cause of behaviour to be investigated,

Penetration to be removed

Prior to removal, the penetration fell and was left leaning against neighboring penetration



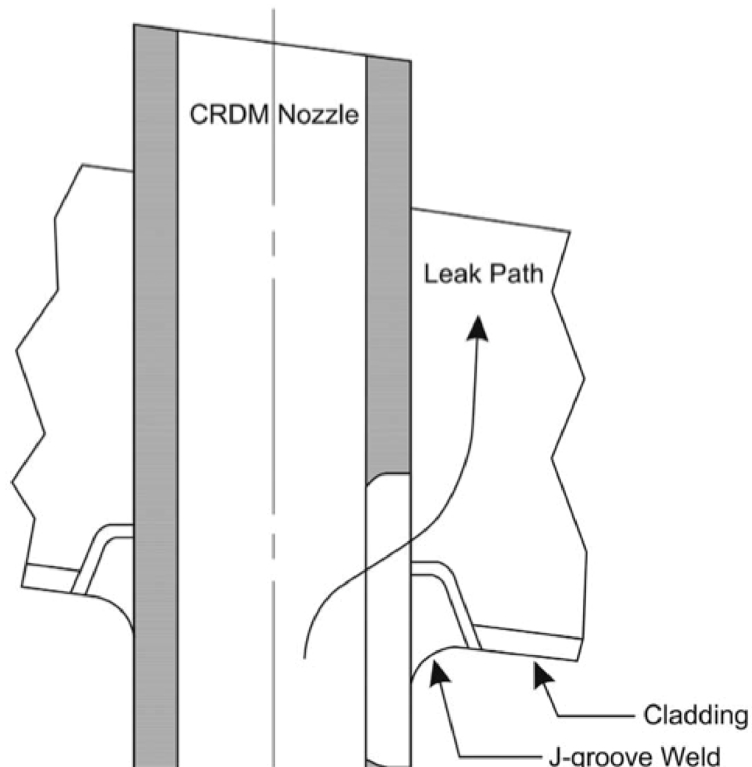


Figure 5. Schematic of the nozzle penetration cross section showing the leak path of the reactor coolant


MADE IN U.S.A.
TEMPERED

Failure

Pressure vessel steel severly corroded

Stainless steel liner still remaining (and held the pressure)

Liner bulged

Liner cracked


(SNIFF) NOBODY TOLD ME THERE WAS A (SOB) PROBLEM AT DAVIS-BESSE (SNIFF) SO I'M THE REAL VICTIM HERE. (CHOKE)
I THINK I'M GOING TO BARF.
PLOP PLOP FIZZ FIZZ
FIRSTENERGY EXECS
The Blade
KIRK

... and then what

Davis Besse inspected throgoughly

Repairs and improvements worth $600 M

Restarted 2004/03

Under NRC's special supervision until 2009

... and THEN what happened

2010-03-12 during fuel loading, ultrasonic inspection was performed

Inspection showed similar cracks to the ones that caused the leak in 2002

Visual inspection showed boric acid deposits (=> leak)

Cracks repaired and plant put back to operation

Why?

... was this not considered to be an isssue in the U.S?

... repairs were delayed?

... failures recurred after repair?

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Fukushima-Daini-1

Fukushima-Daiichi-4

Fukushima 2011

Tōhoku earthquake & tsunami

March 2011

Magnitude 9 earthquake

40 m tsunami

Entire villages destroyed in Japan

Thousands dead due to the tsunami damage

Tsunami hit Fukushima Daiichi nuclear complex

Earthquake launched emergency shutdown (correctly)

Tsunami arrived later and caused station black-out

Station black-out and unfortunate personnel actions prevented emergency cooling from functioning properly

Situation escalated to core melt-down due to insufficient cooling

Related hydrogen production caused hydrogen explosion

Single radiation-related fatality.

Engineering failure?

Tsunami guidelines did not anticipate tsunamis of this magnitude

- Despite previous indication

Cooling systems did not prevent core melt-down

- Operator intervention partly to blame

Station black-out would necessitate external cooling

- This was not available (further made problematic by the disaster surrounding the power plant)

Operator failure?

Operator actions aggravated the situation

- Disaster plans vs. normal operation plans
- Not-doing some of the actions would have worked out better

Decision making too slow?

- High-consequence decisions to be made rapidly and correctly
- How to facilitate in organization

Media failure?

Media concentrated on

- NPP disaster (not the wider catastrophe)
- H-explosion (not the more severe core melt-down situation)
- Conservative safeguard and evacuation limits (not the actual damage)

Political failure?

Nuclear renaissance was cut short

Nuclear phased off in many countries (most notably Germany)

Increased use of coal (especially in the case of Germany)

What could have saved the power plant?

1. Protection against natural hazard

- *Adding safety margin to the results of probabilistic Tsunami hazard analysis*
- *Location of essential safe systems considering Tsunami/Flood 2. Plant capability against SBO and isolation from UHS*
- *Highly reliable assurance of 3 cooling functions (Core, CV, SFP) including enabling systems (power/air/water source) such as backup air supply to SRV*
- *Passive systems*

3. Severe accident guideline (coupled with design provisions)

- *Mobile equipments in onsite/offsite emergency center*
- *Robust SAMG workable under internal events, drills*

4. Enhanced system for aversion of “land contamination”

- *Dependable scrubbing vent*
- *2ndary containment filtration/H2 management system*

Lessons learned around the world

Nuclear power plants here and around the world

- *Increased external cooling facilities (mods in Finland)*
- *Increased emphasis on passive system (newbuilds)*
- *Flooding considerations revisited*
- *Extreme weather and earthquake resistance revisited (higher walls)*
- *More redundant cooling systems and reduction on external dependence (e.g. Loviisa emergency cooling tower)*

Jukka Laaksonen, STUK, 2011

Learning from accidents

In the development of all new technologies, progress has required learning from past mistakes and taking corrective actions to avoid repeating similar mistakes.
Nuclear technology is no exception. Many of the safety principles and approaches can be traced back to specific accidents which have given new insights and have led to enhanced level of safety.

… In spite of very extensive research programs of 1970's, they did not bring many new insights for enhancing nuclear safety and did not contribute much to the regulations. Instead, new accidents were needed for learning lessons. …

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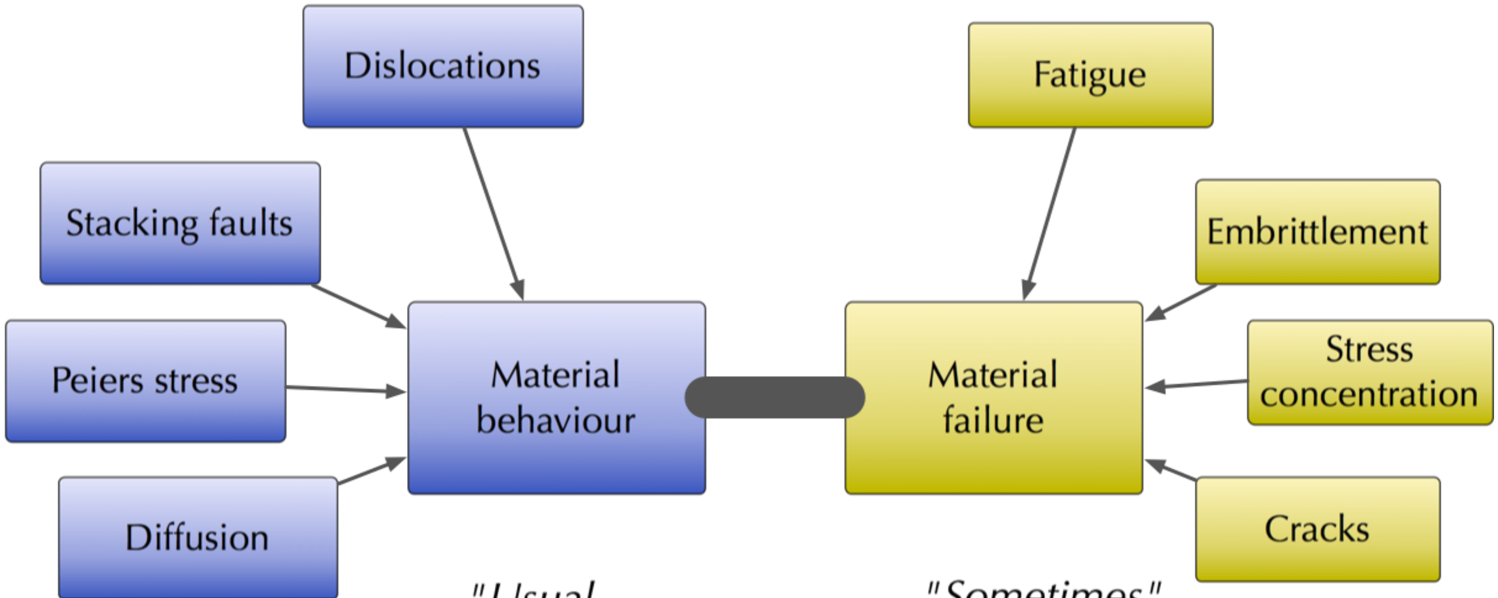
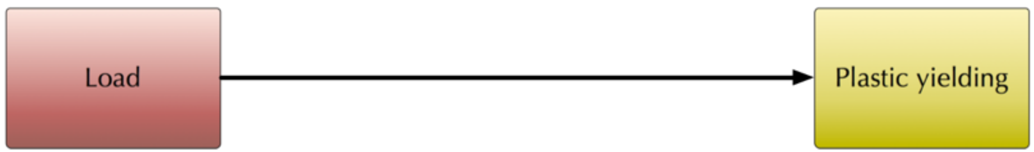
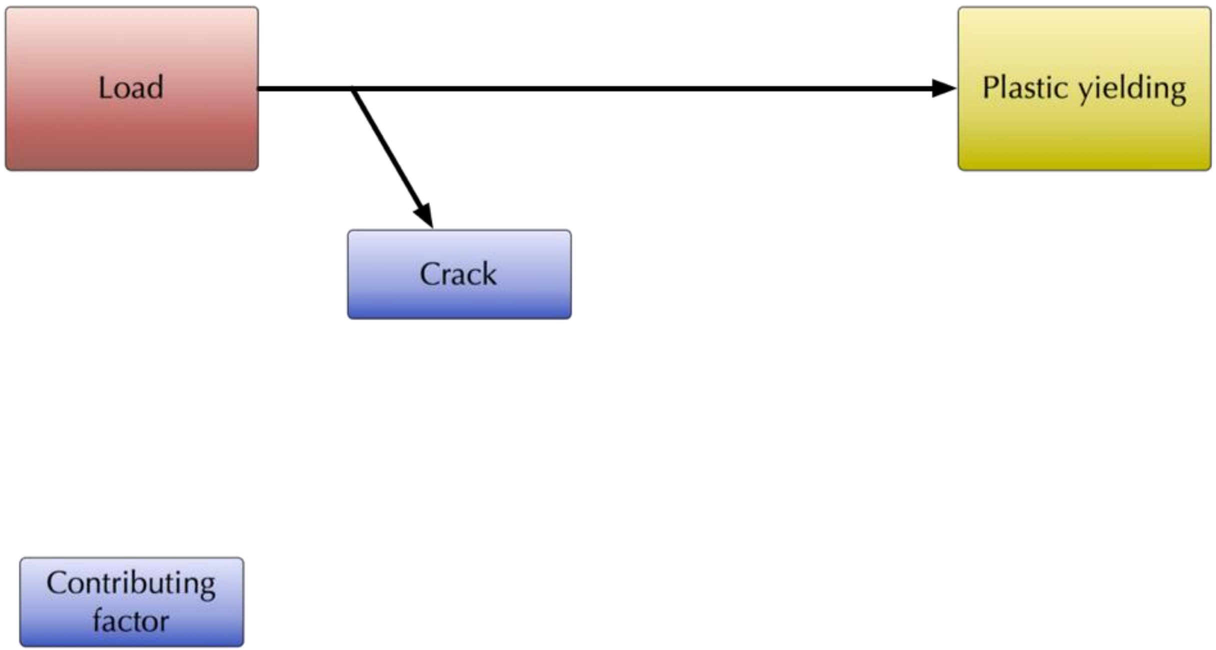
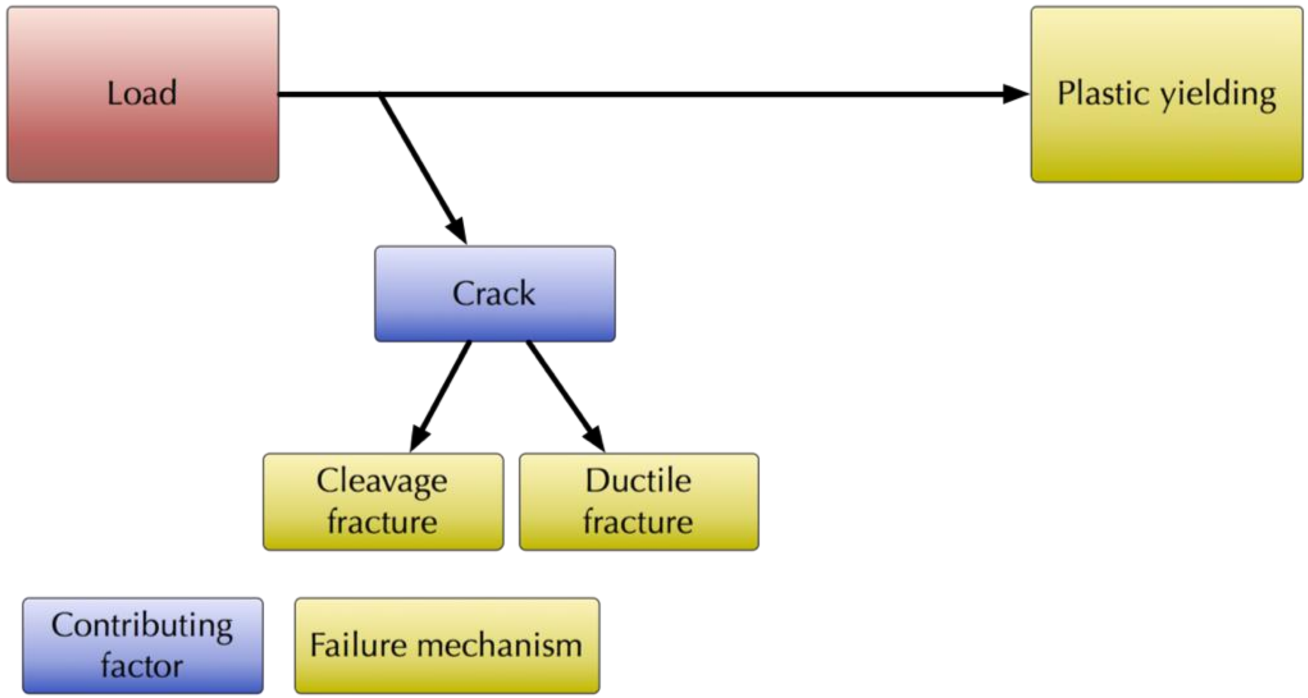
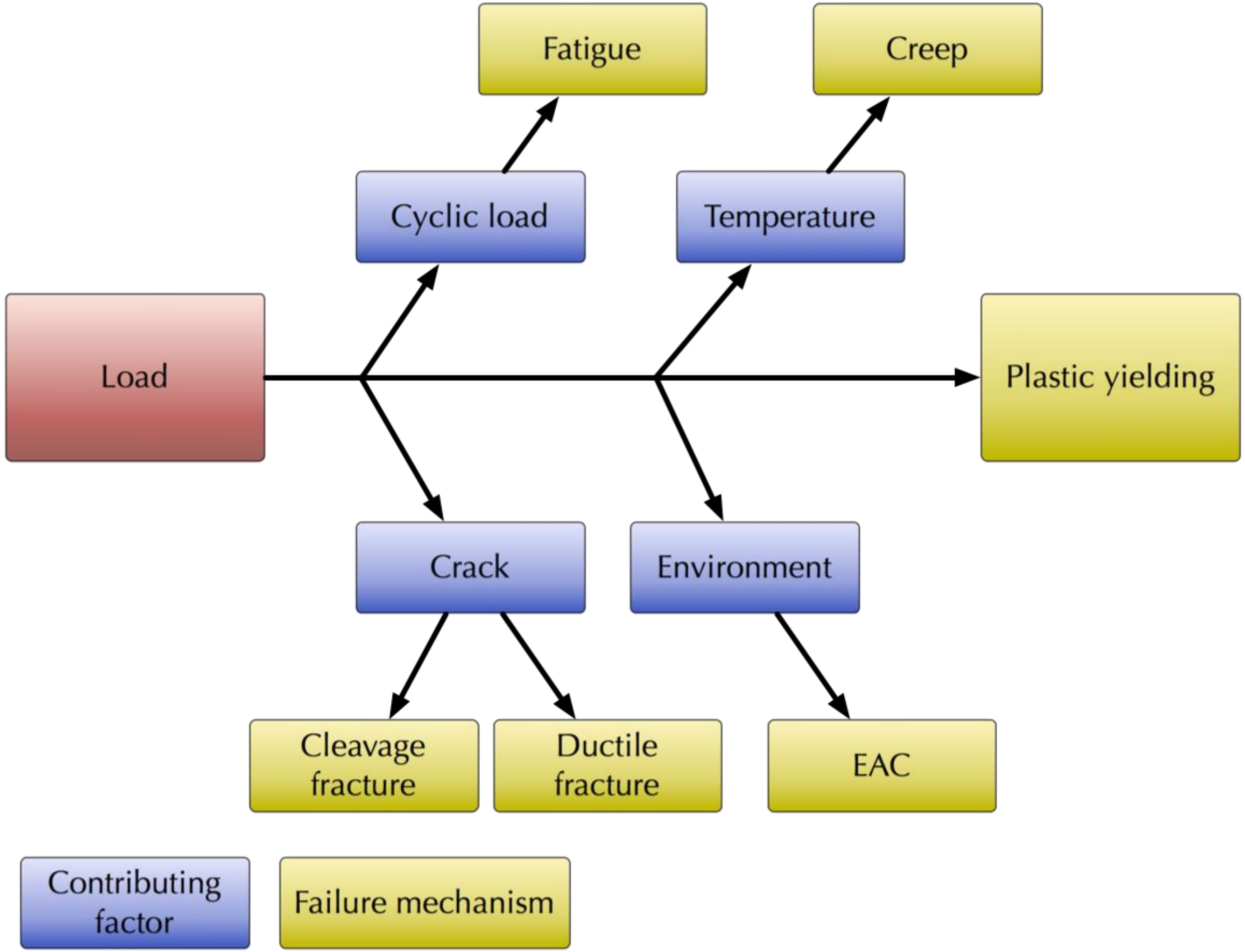


"Usual	*"Sometimes"*
"Global"	*"Locally"*
"Predictable"	*"Suddenly"*


Load
Plastic yielding


Load
Plastic yielding
Crack
Contributing factor


Load
Plastic yielding
Crack
Cleavage fracture
Ductile fracture
Contributing factor
Failure mechanism


Fatigue
Creep
Cyclic load
Temperature
Load
Plastic yielding
Crack
Environment
Cleavage fracture
Ductile fracture
EAC
Contributing factor
Failure mechanism

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Course agenda

In this course:

We'll go deeper into plastic deformation and failure

- Basics are assumed known
- We'll go to gory details and
- investigate inter-relationships between failuremechanisms and
- build the "big picture"

Investigate real failure cases

- beyond immediate appearance
- (popular explanations often overly simplified)
- find alternate ways to avoid failure

Focus

Fracture mechanics

Cleavage fracture

Fatigue

Most serious failures

To be an expert

"The material expert in the company"

"Take advantage of outside experts"

Together

- Go ahead, comment, ask and interrupt
- Bring your own examples and questions

Students learn and teach

Course structure

Tool	**Purpose**
Lecture	Focus and orientation
Book	Details and support
Article analysis	Variation and feedback
Laboratory work	Design of experiment and problem solving by finding evidence
Exam	Dazzle me!

Lecture - morning

"Clear cases"

Learn by listening, following, asking and focus on unclear issues.

Theorethical basis for understanding failures to-be analyzed

"Seems easy" failure analysis

Lecture - afternoon

Student analysis on different and unclear cases

- Student opening presentations from the failure cases
- Discussion

Learn from doing and debating

Learn from each other

Article analysis

New article on Friday (today #1) (e-mail with word template)

Return by next Wednesday 00:00 by email: materials.safety@iikka.fi

All analyses distributed to all students

- Read at least one other analysis from your article AND
- One analysis from an other article

Give points to analysis with the included Excel file and return to materials.safety@iikka.fi by Thursday 12:00

The authors with the most points are asked to give the opening review the next Friday

Lab work

Analyzing others analyses is one thing, gathering data is quite another.

Task to solve and a lab team to support you.

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Sneak peek

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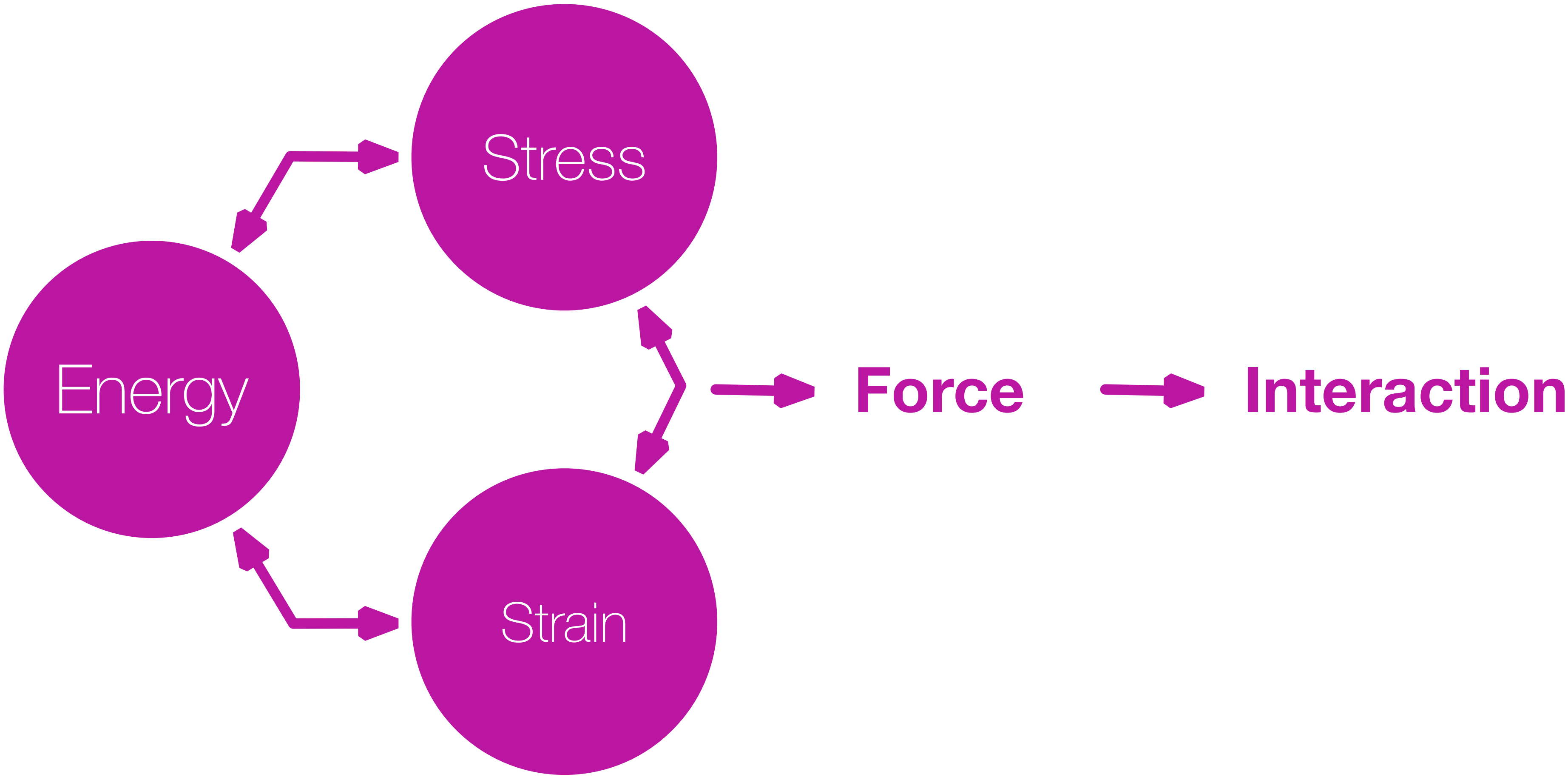
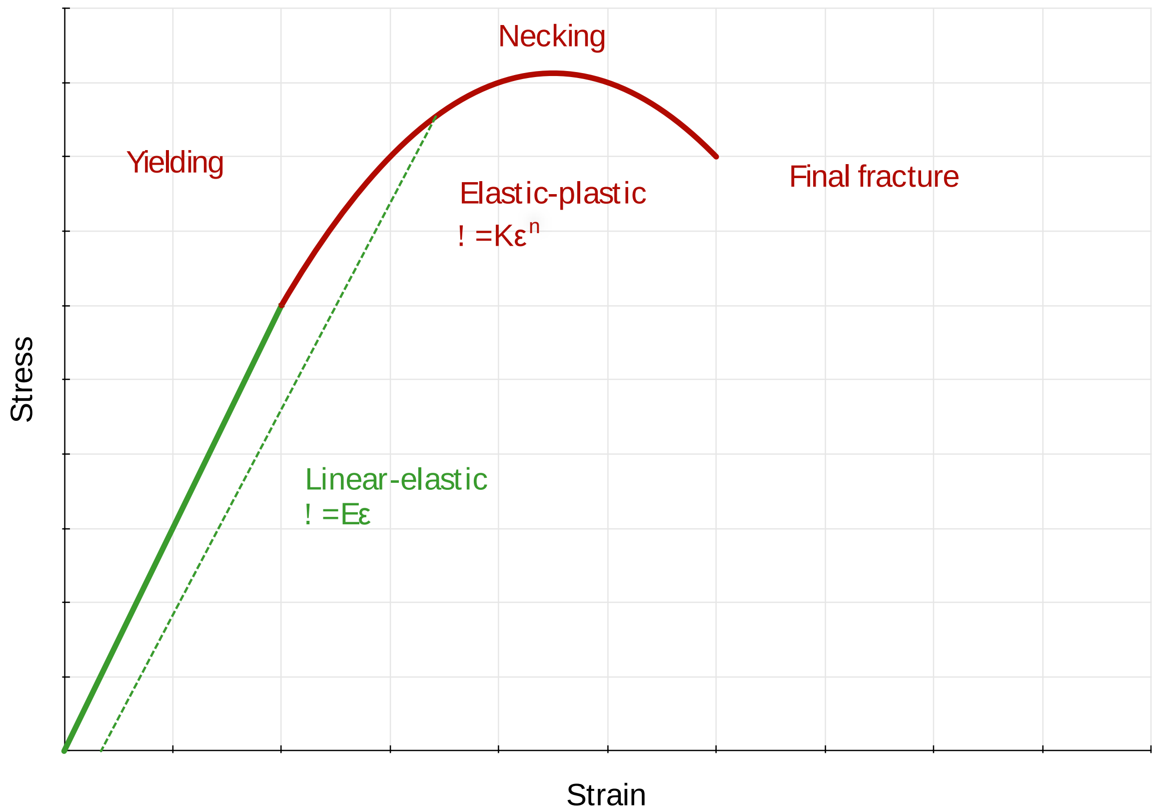
Plastic deformation


Stress
Energy
Strain
Force
Interaction

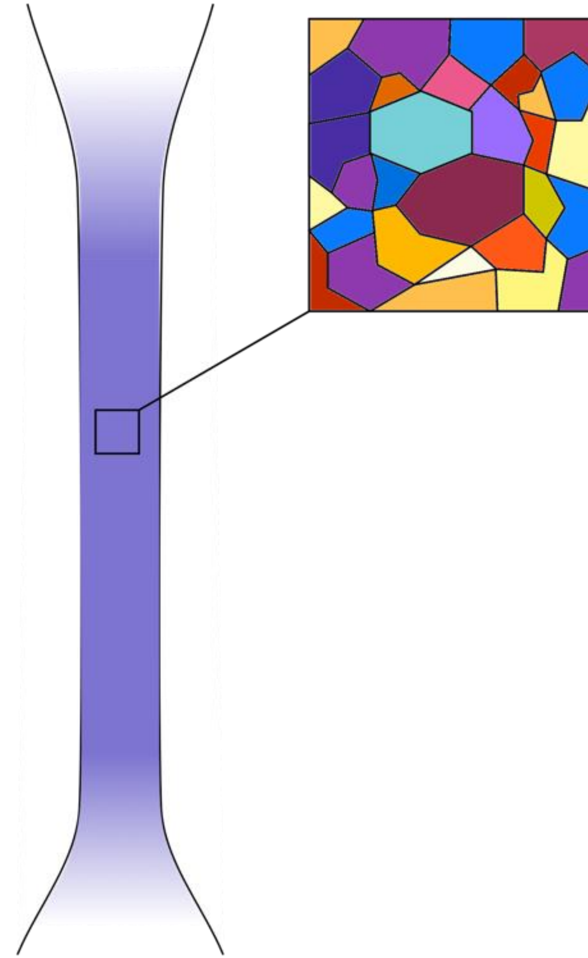
Macroscopic approximation



Micro level

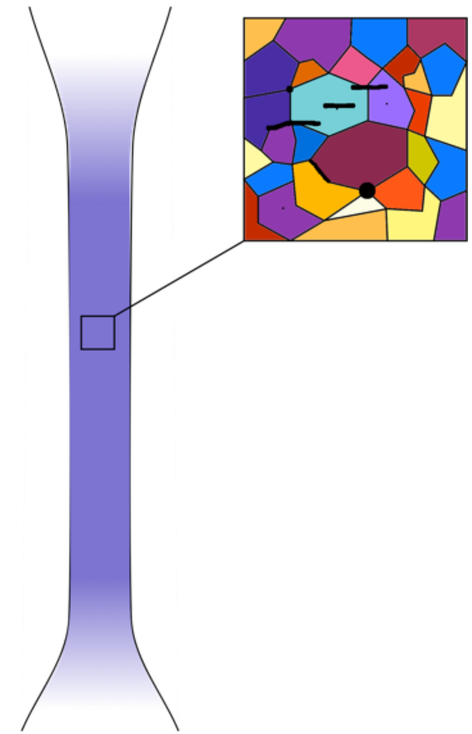
... grain orientation affects the effective stress

... grain geometry caused stress concentrations within grains



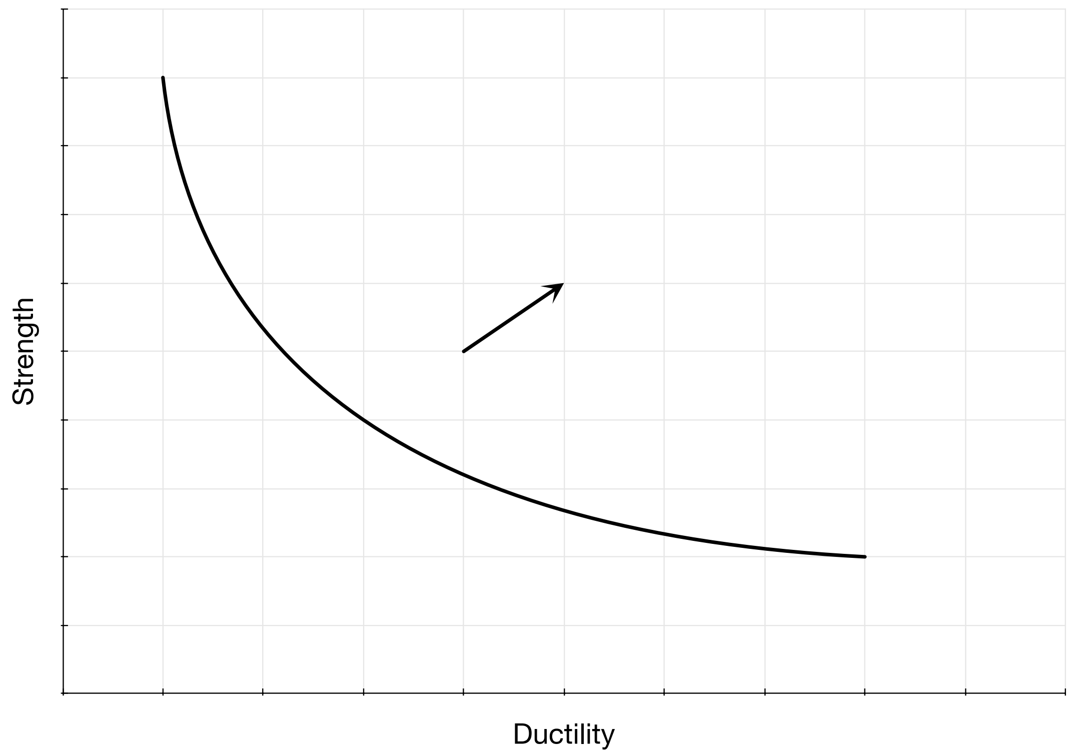
Inhomogenous material

Material has inclusions, precipitates, impurities and lattice defects. These cause stress concentrations in microscopic level.



Strengthening mechanisms

What we win in strength...



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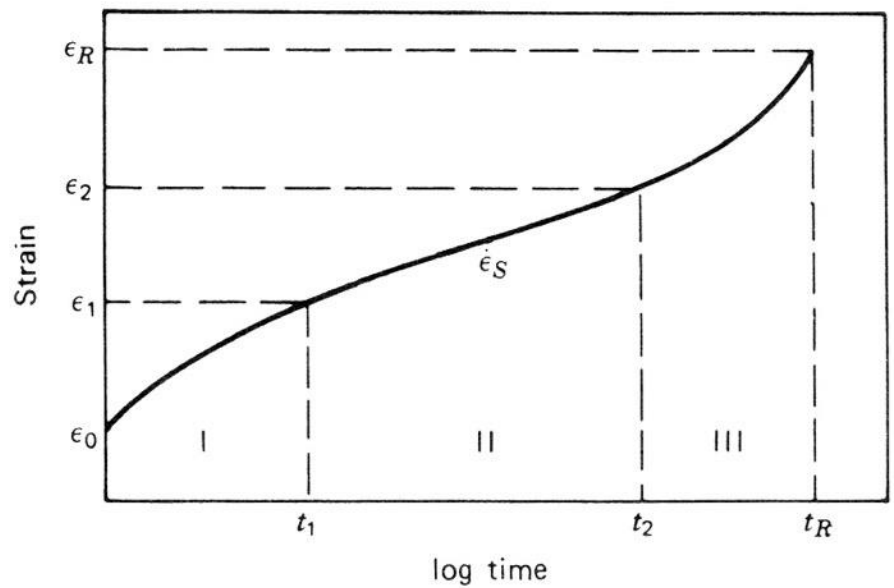
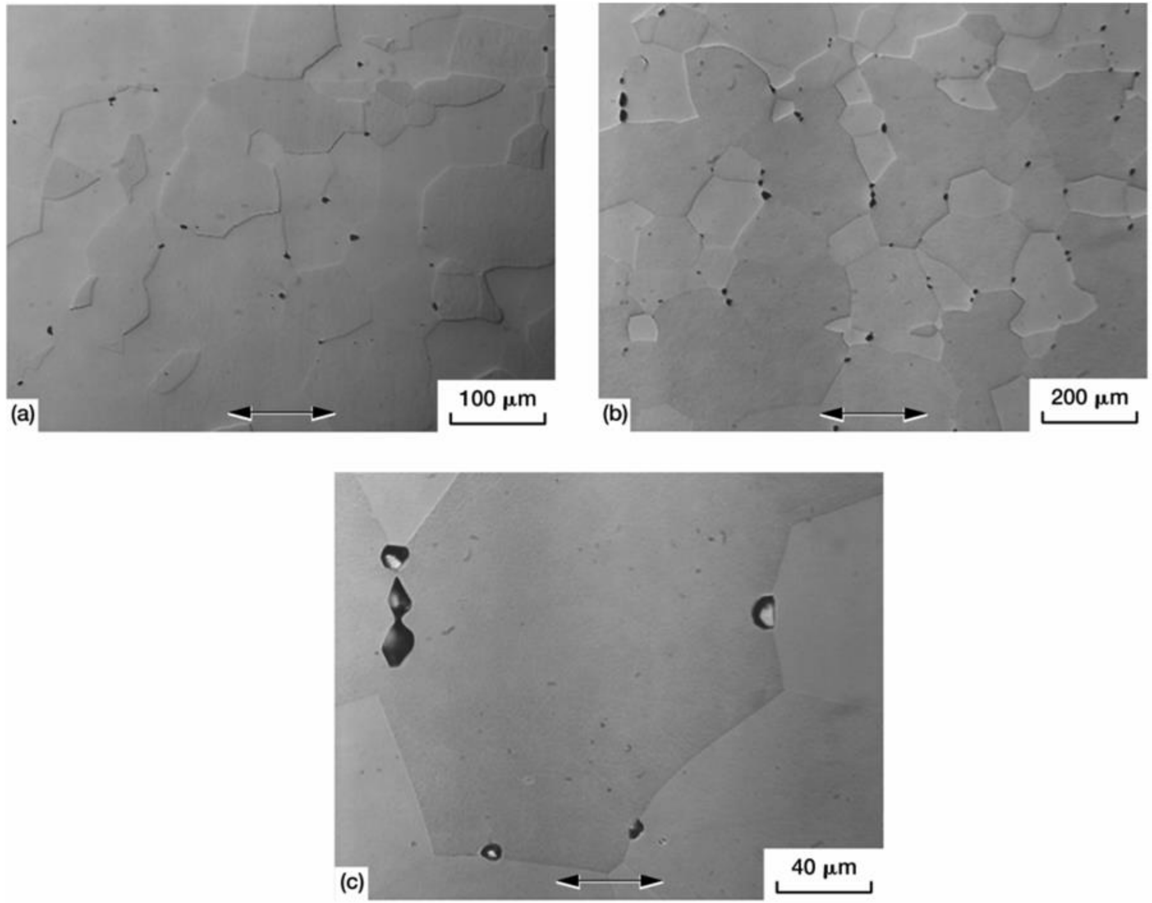
High temperature behaviour of materials

$$\frac{T_{melt}}{2}$$

Creep



ϵ_R
ϵ_2
ϵ_1
ϵ_0
Strain
$\dot{\epsilon}_S$
I
II
III
t_1
t_2
t_R
log time


(a)
100 μm
(b)
200 μm
(c)
40 μm

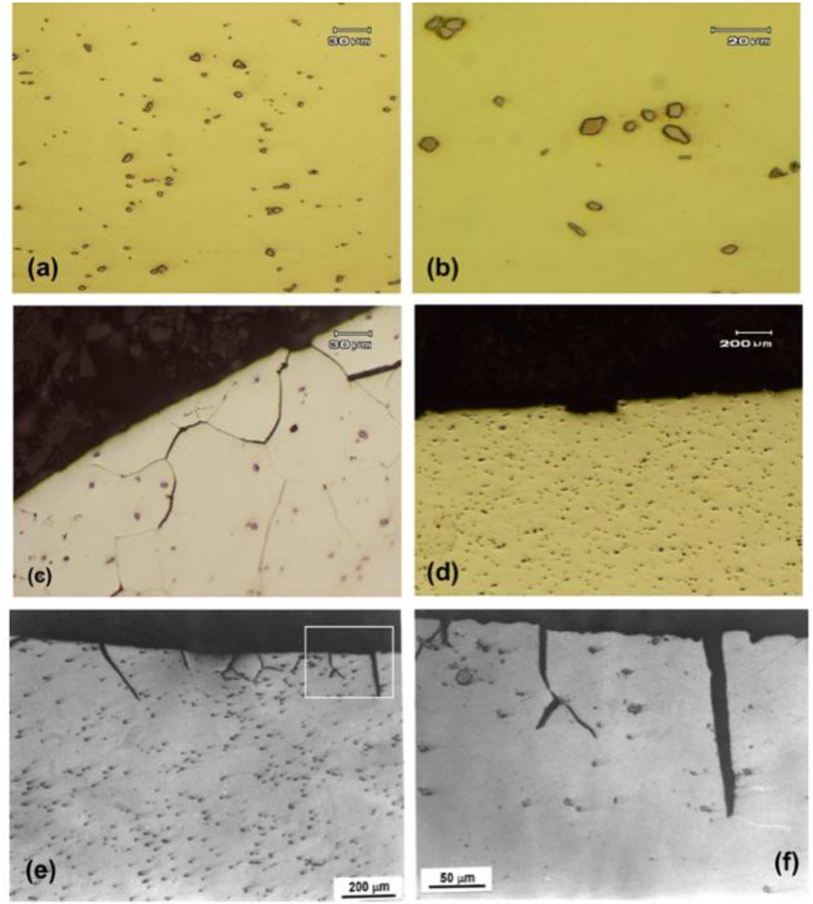


Fig. 3. Polished sample of failed blade, (a) revealing primary carbides, (b) same as (a) at high magnification, (c) cracks at the grain boundaries at region 'C' (see Fig. 2), (d) region 'B', (e and f) neighboring blade at region 'C'.

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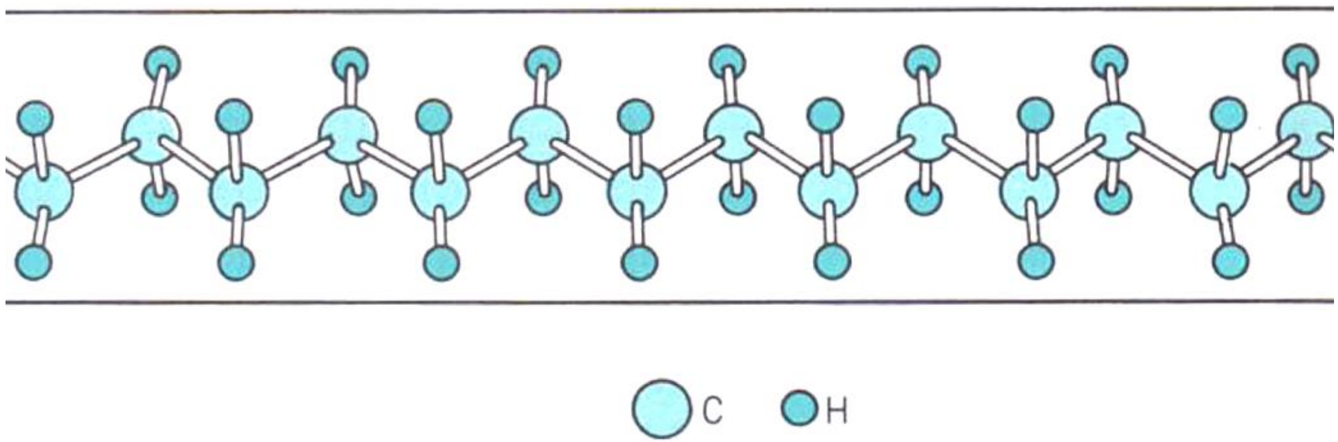
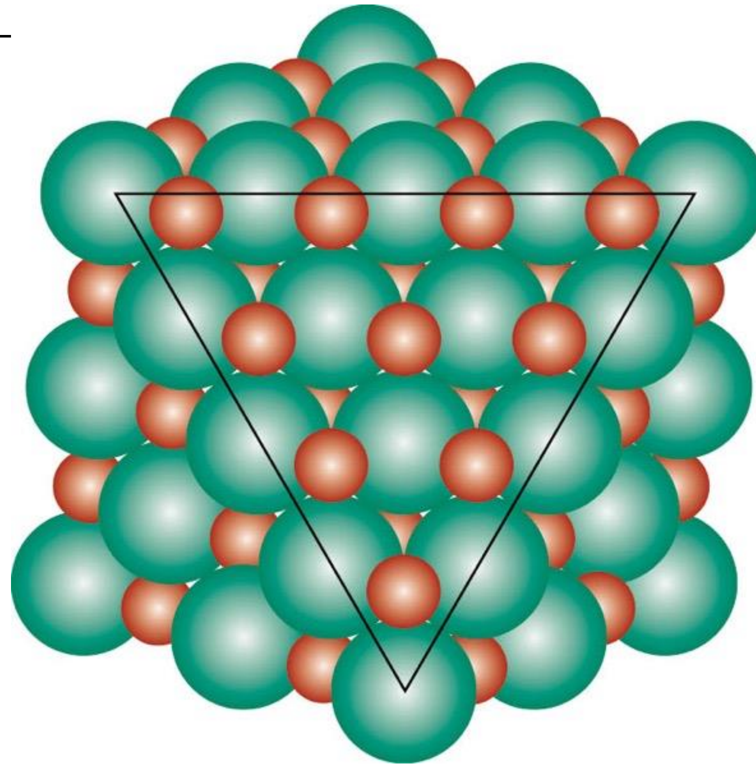
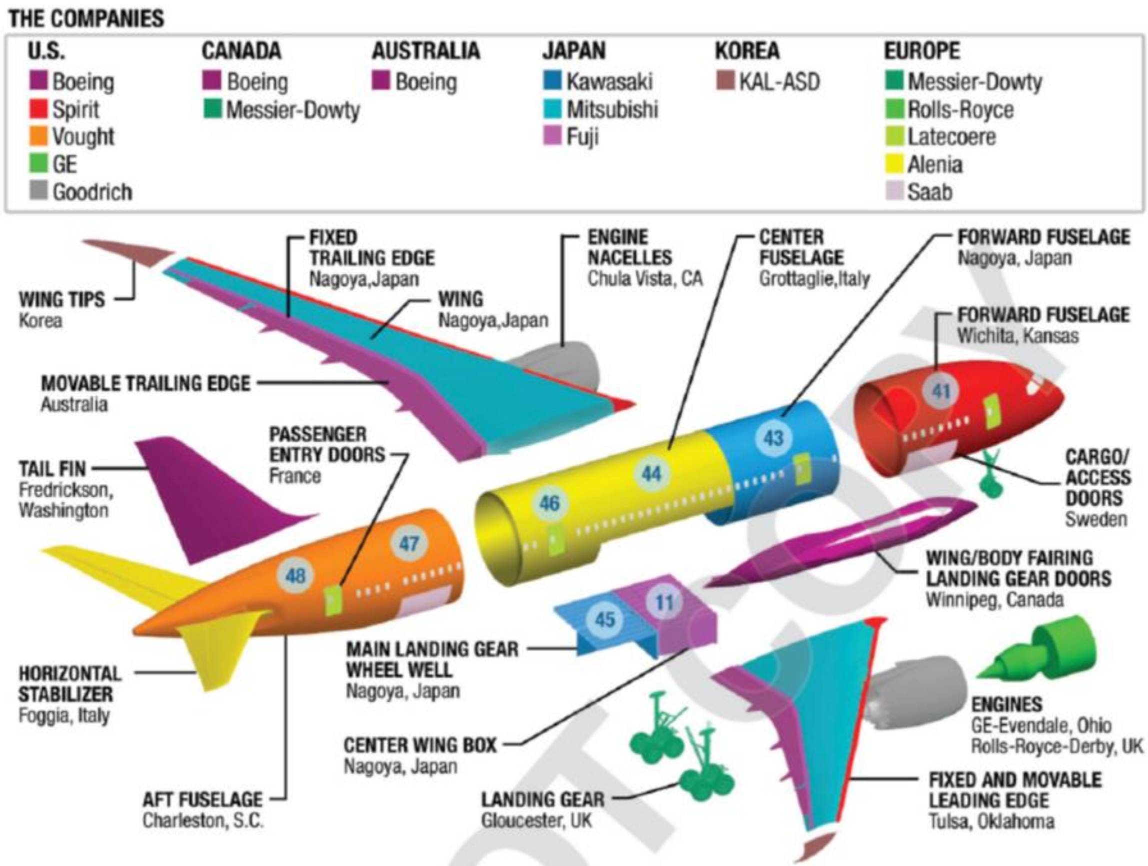
Plastics, ceramics composites


C
H

Kiteinen…




THE COMPANIES
U.S.
Boeing
Spirit
Vought
GE
Goodrich
CANADA
Boeing
Messier-Dowty
AUSTRALIA
Boeing
JAPAN
Kawasaki
Mitsubishi
Fuji
KOREA
KAL-ASD
EUROPE
Messier-Dowty
Rolls-Royce
Latecoere
Alenia
Saab
WING TIPS
Korea
FIXED TRAILING EDGE
Nagoya,Japan
WING
Nagoya,Japan
ENGINE NACELLES
Chula Vista, CA
CENTER FUSELAGE
Grottaglie,Italy
FORWARD FUSELAGE
Nagoya, Japan
FORWARD FUSELAGE
Wichita, Kansas
MOVABLE TRAILING EDGE
Australia
TAIL FIN
Fredrickson, Washington
PASSENGER ENTRY DOORS
France
CARGO/ ACCESS DOORS
Sweden
41
43
44
46
47
48
45
11
WING/BODY FAIRING LANDING GEAR DOORS
Winnipeg, Canada
MAIN LANDING GEAR WHEEL WELL
Nagoya, Japan
HORIZONTAL STABILIZER
Foggia, Italy
CENTER WING BOX
Nagoya, Japan
ENGINES
GE-Evendale, Ohio
Rolls-Royce-Derby, UK
AFT FUSELAGE
Charleston, S.C.
LANDING GEAR
Gloucester, UK
FIXED AND MOVABLE LEADING EDGE
Tulsa, Oklahoma

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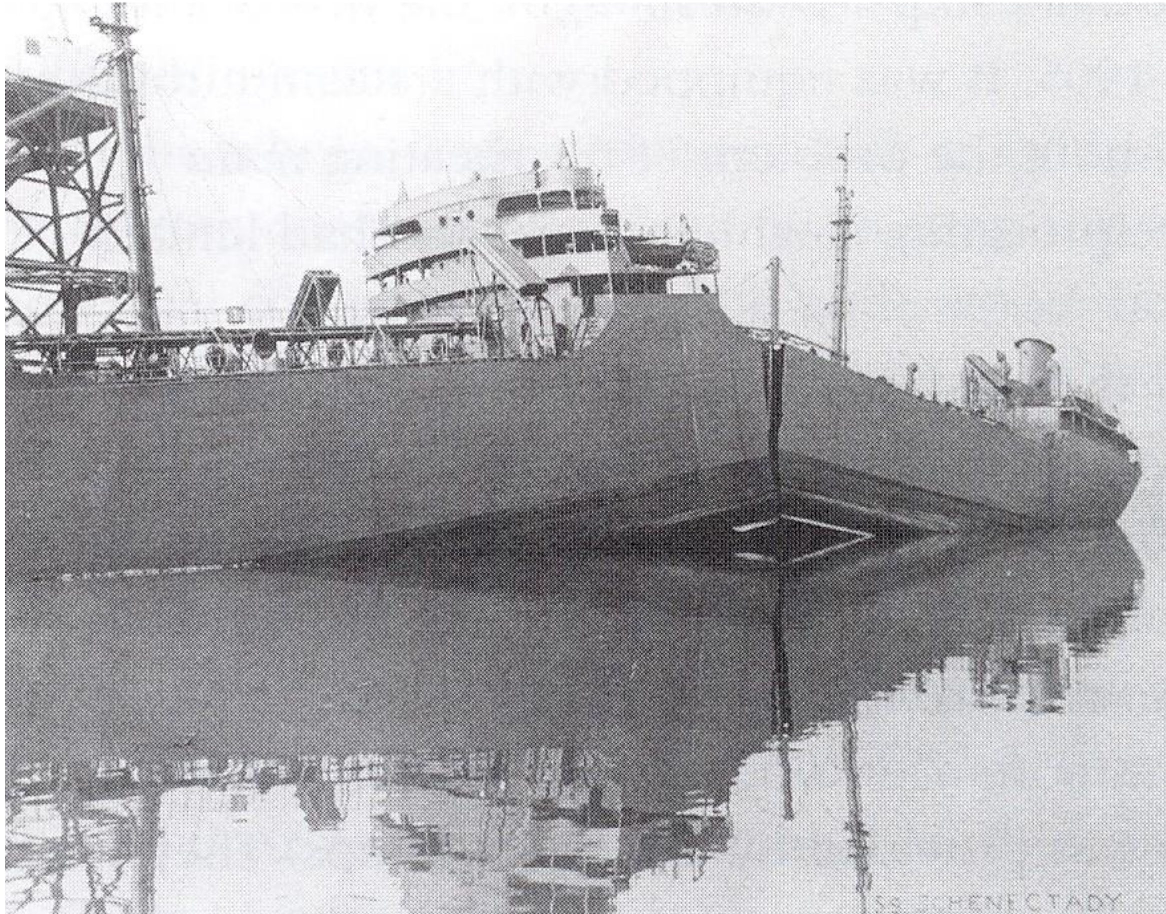
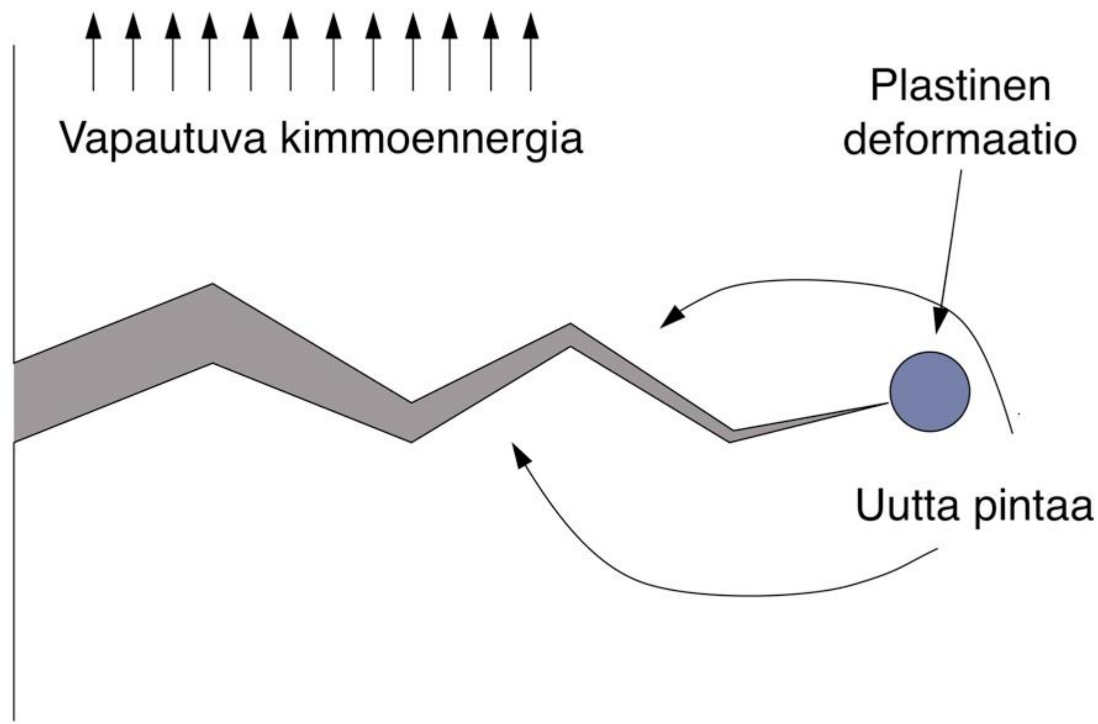
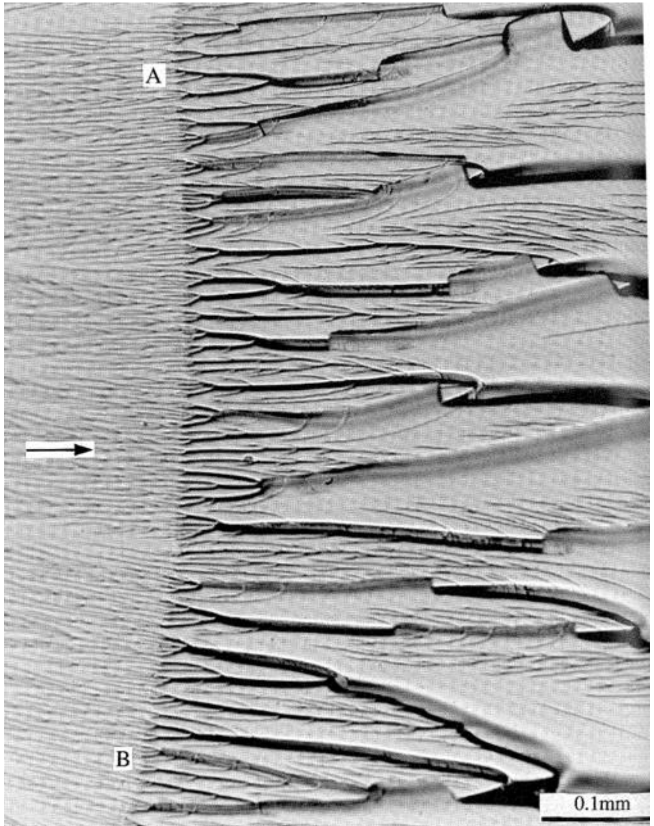
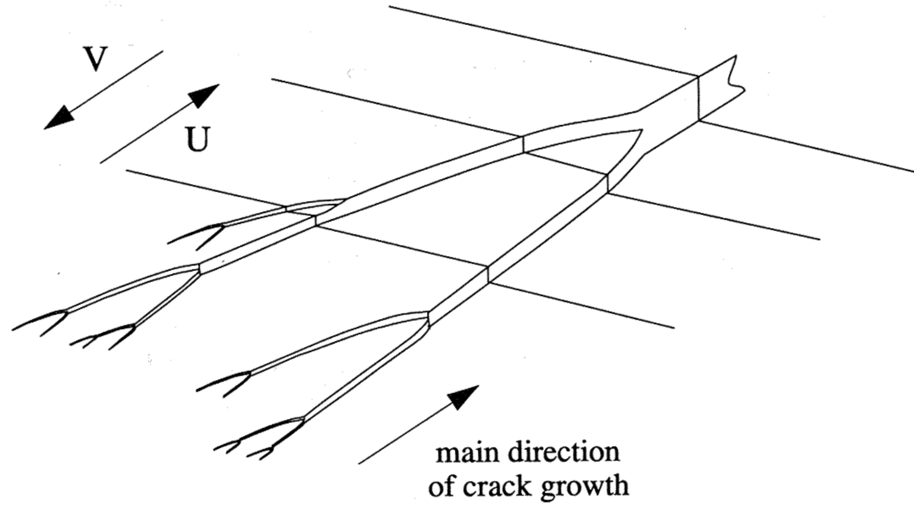
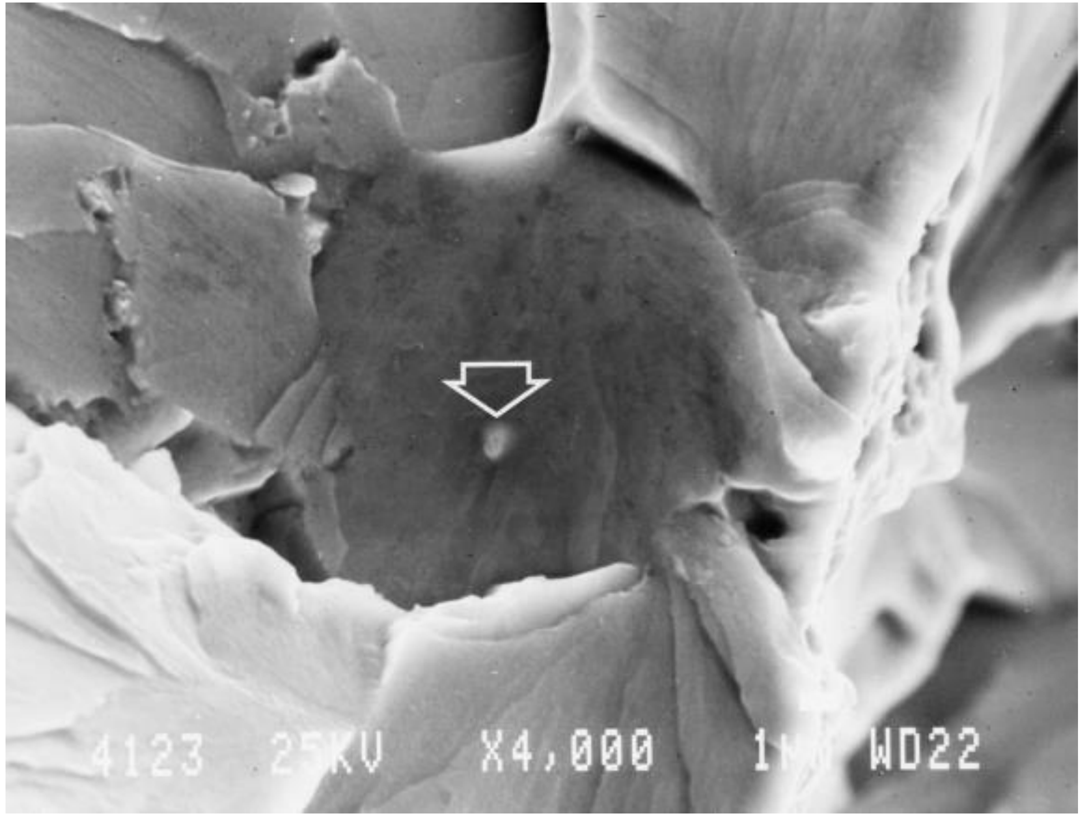
Fracture mechanics

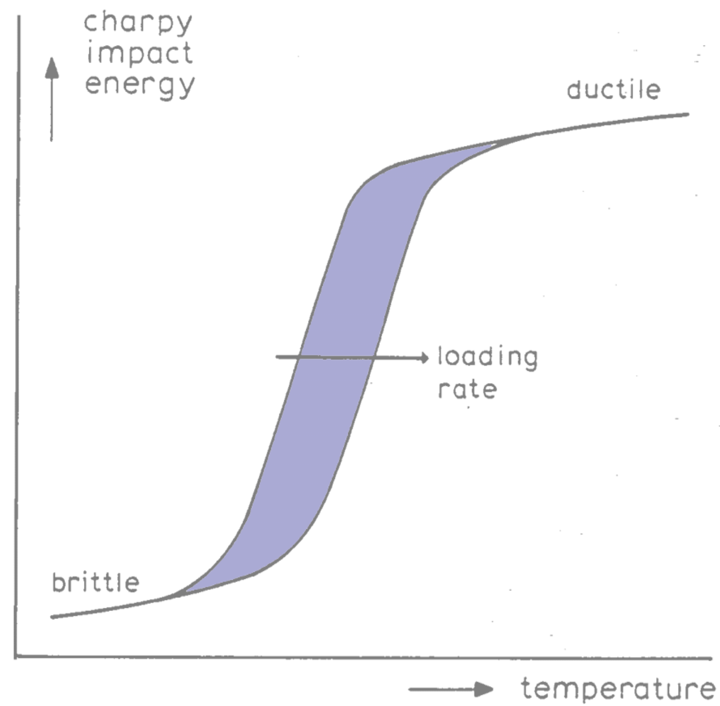

SS SCHENECTADY


Vapautuva kimmoenergia
Plastinen deformaatio
Uutta pintaa

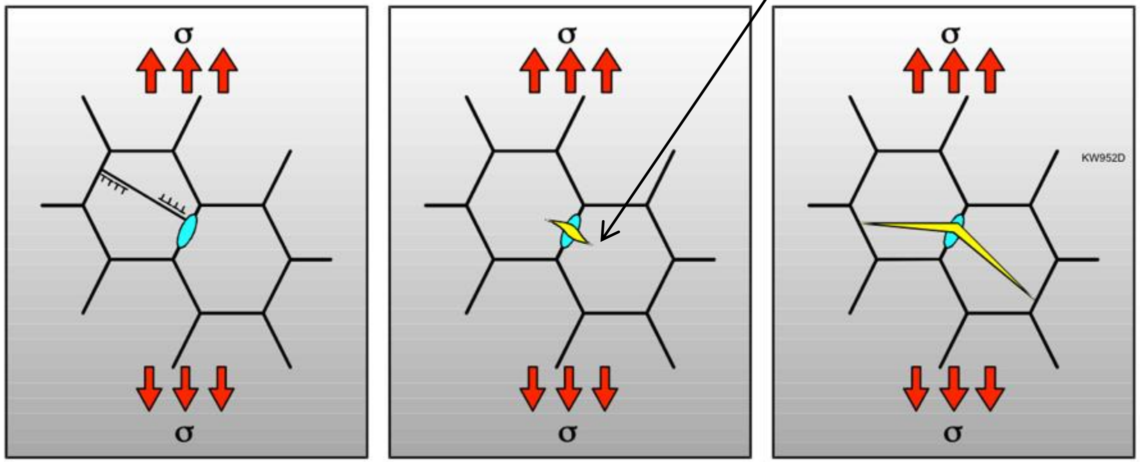

A
B
0.1mm


V
U
main direction
of crack growth

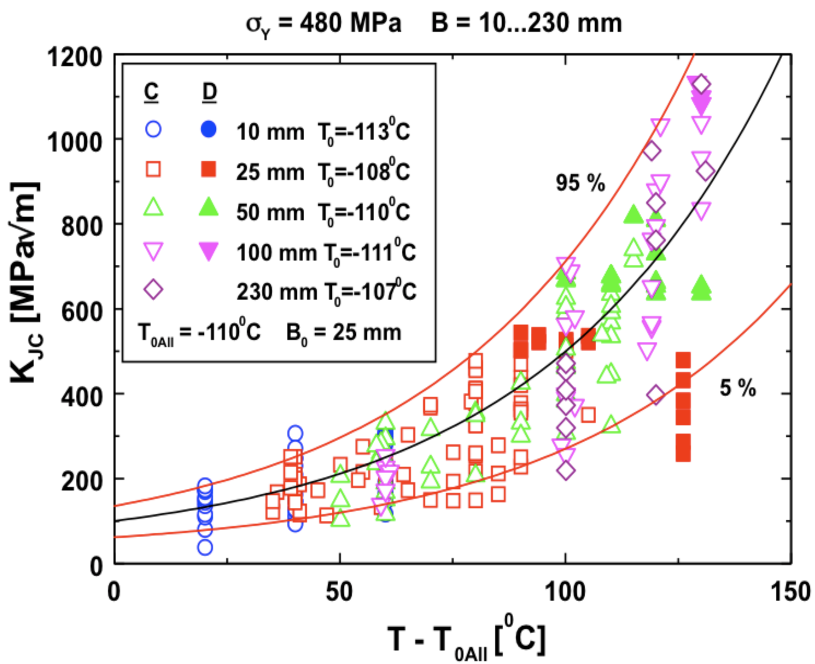

4123 25KV X4,000
WD22

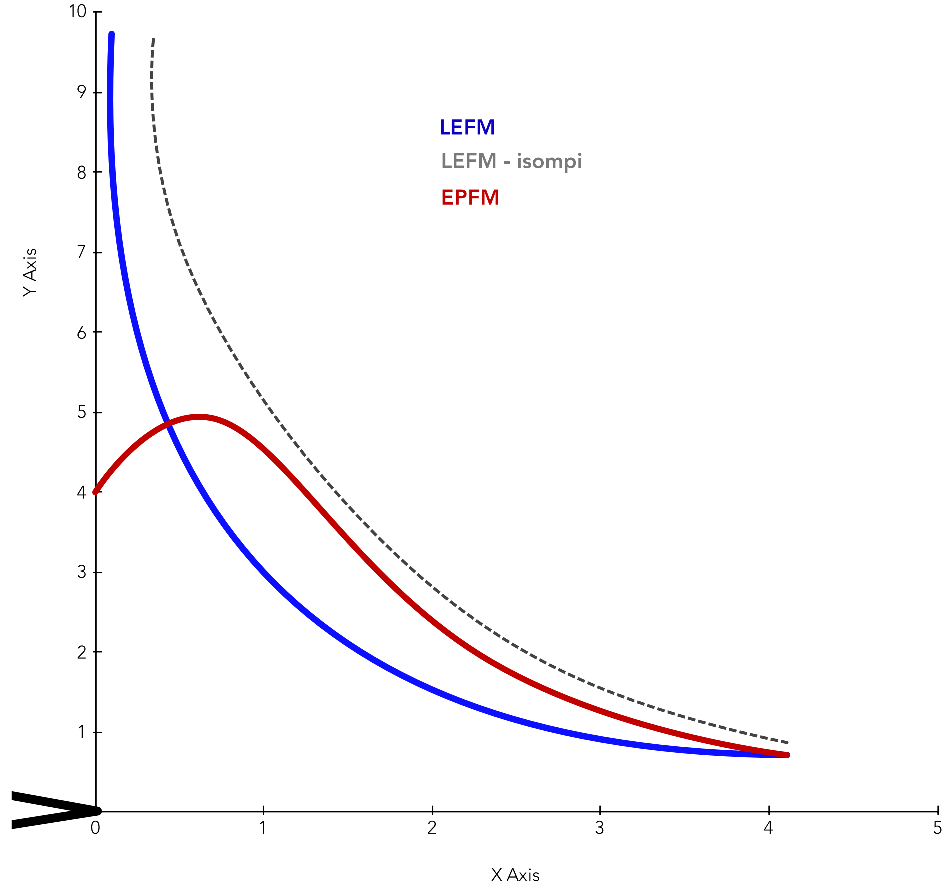

charpy
impact
energy
ductile
loading
rate
brittle
temperature

Haurasmurtuman atomistinen ehto

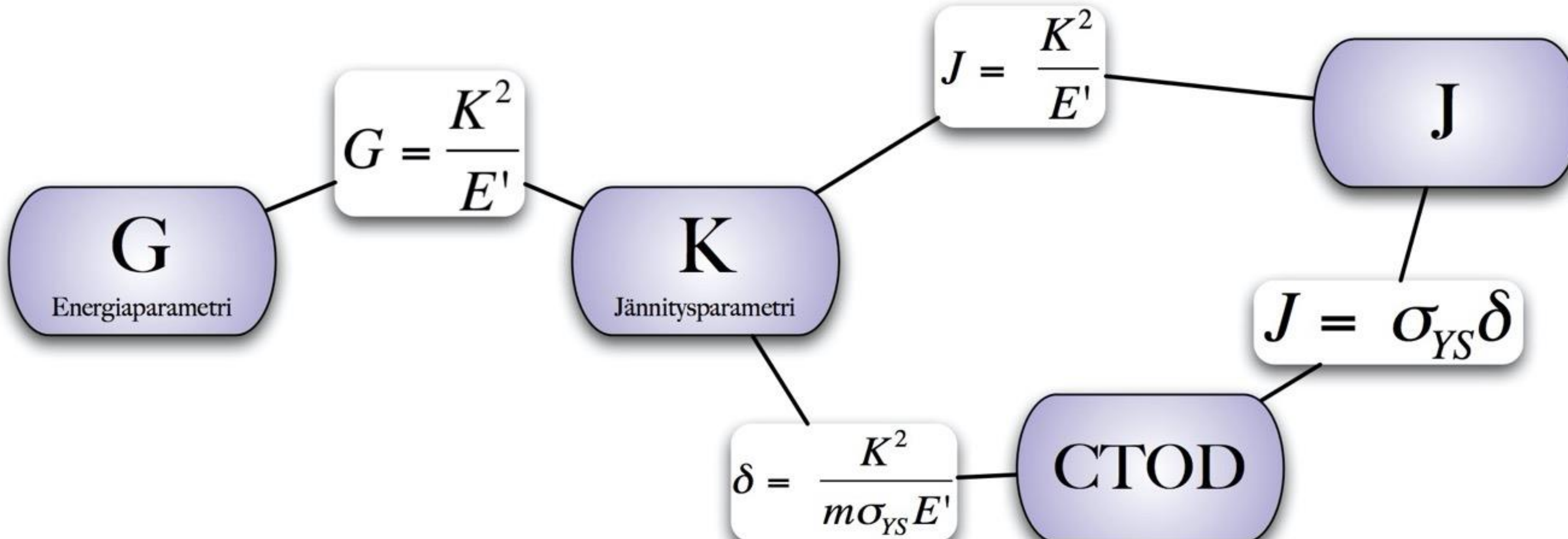


A533B Cl.1 INGHAM & al. (1989)





LEFM
LEFM - isompi
EPFM
Y Axis
X Axis
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5


G
Energiaparametri
$G = \frac{K^2}{E'}$
K
Jännitysparametri
$J = \frac{K^2}{E'}$
J
$J = \sigma_{YS}\delta$
$\delta = \frac{K^2}{m\sigma_{YS}E'}$
CTOD

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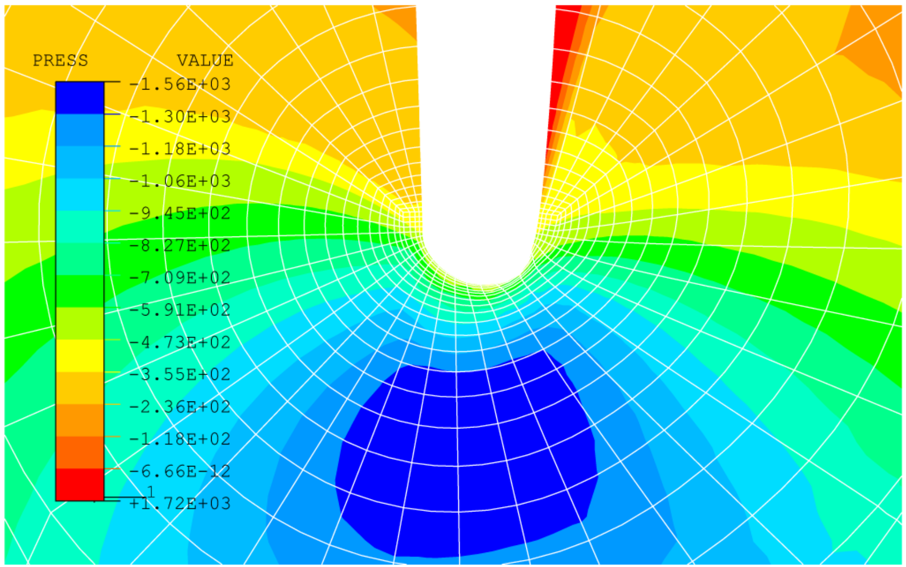
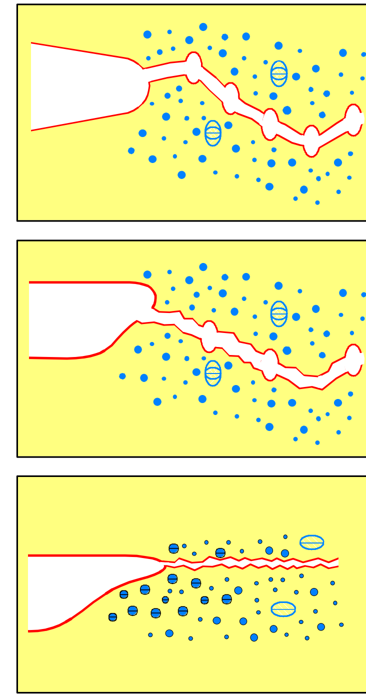
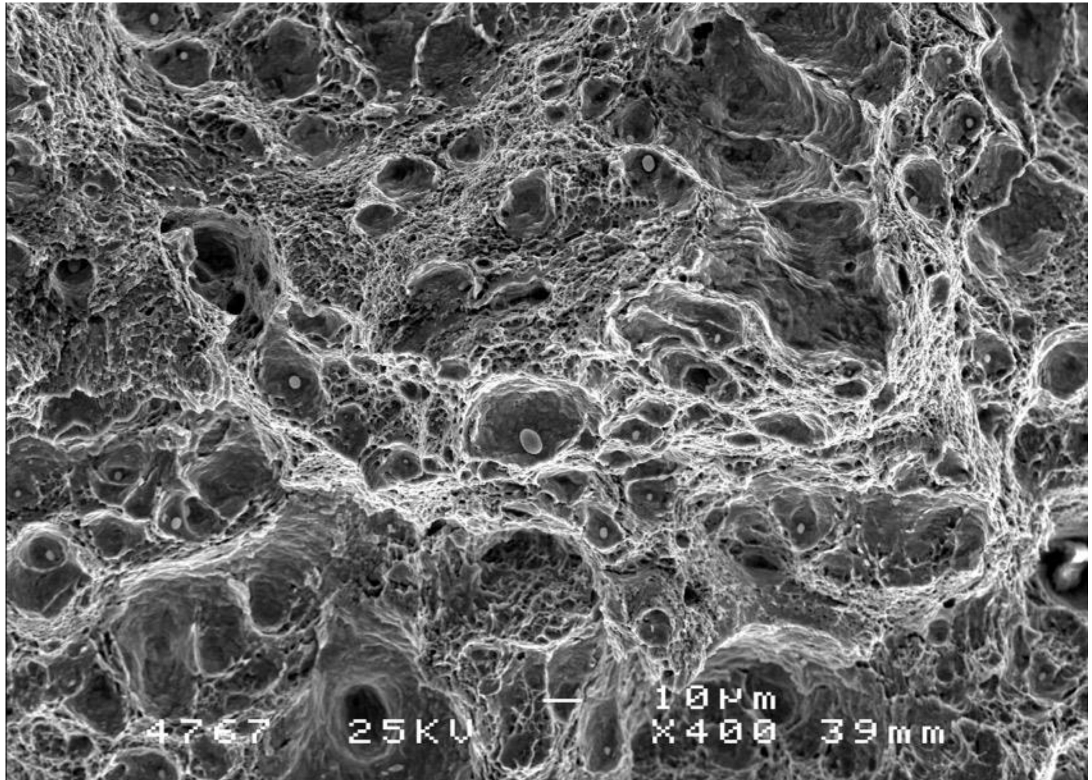
Ductile fracture

Tylpistyminen






10µm
4767 25KV X400 39mm

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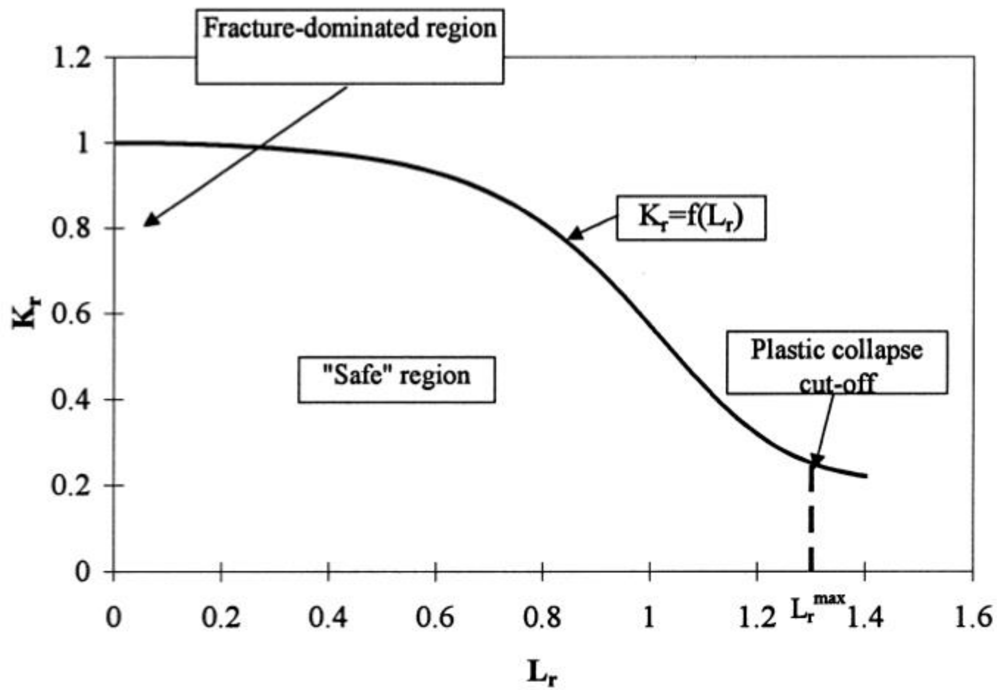
Design codes

Failure assessment diagram – FAD R6



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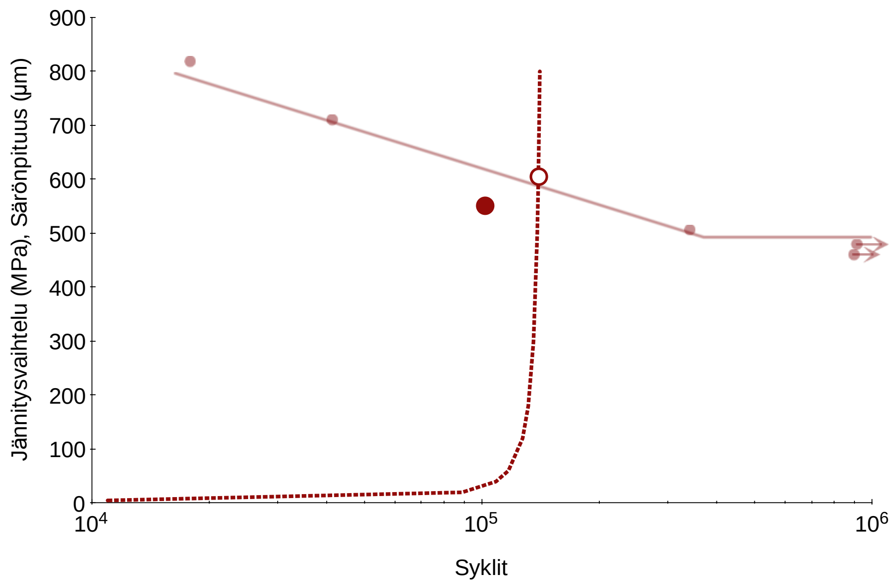
Fatigue

Fatigue crack growth marks

Alexander Kielland, 1980

Nucleation and crack growth



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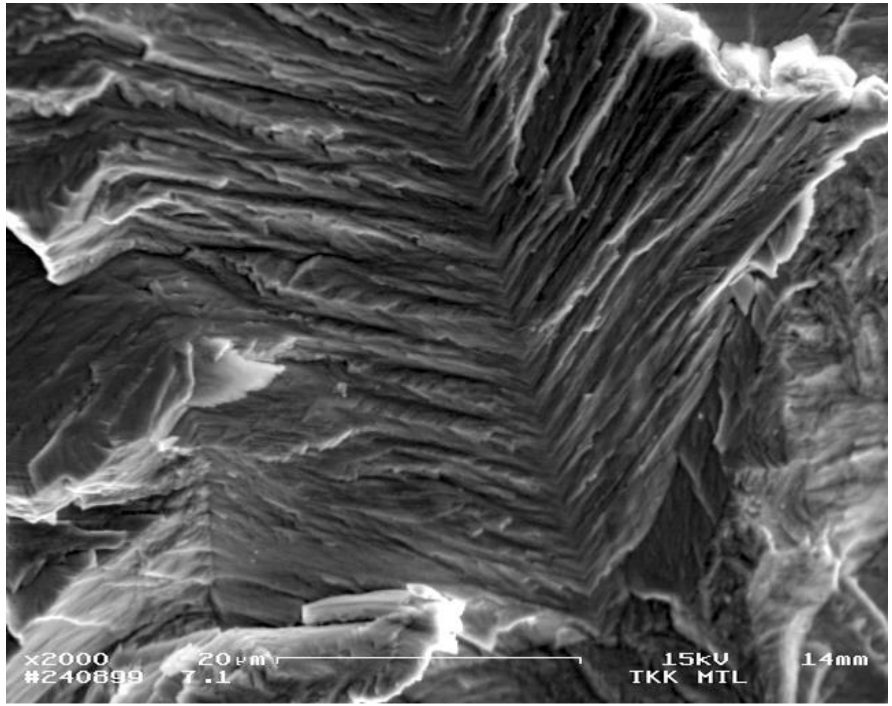
Environmentally assisted cracking

Stress corrosion cracking



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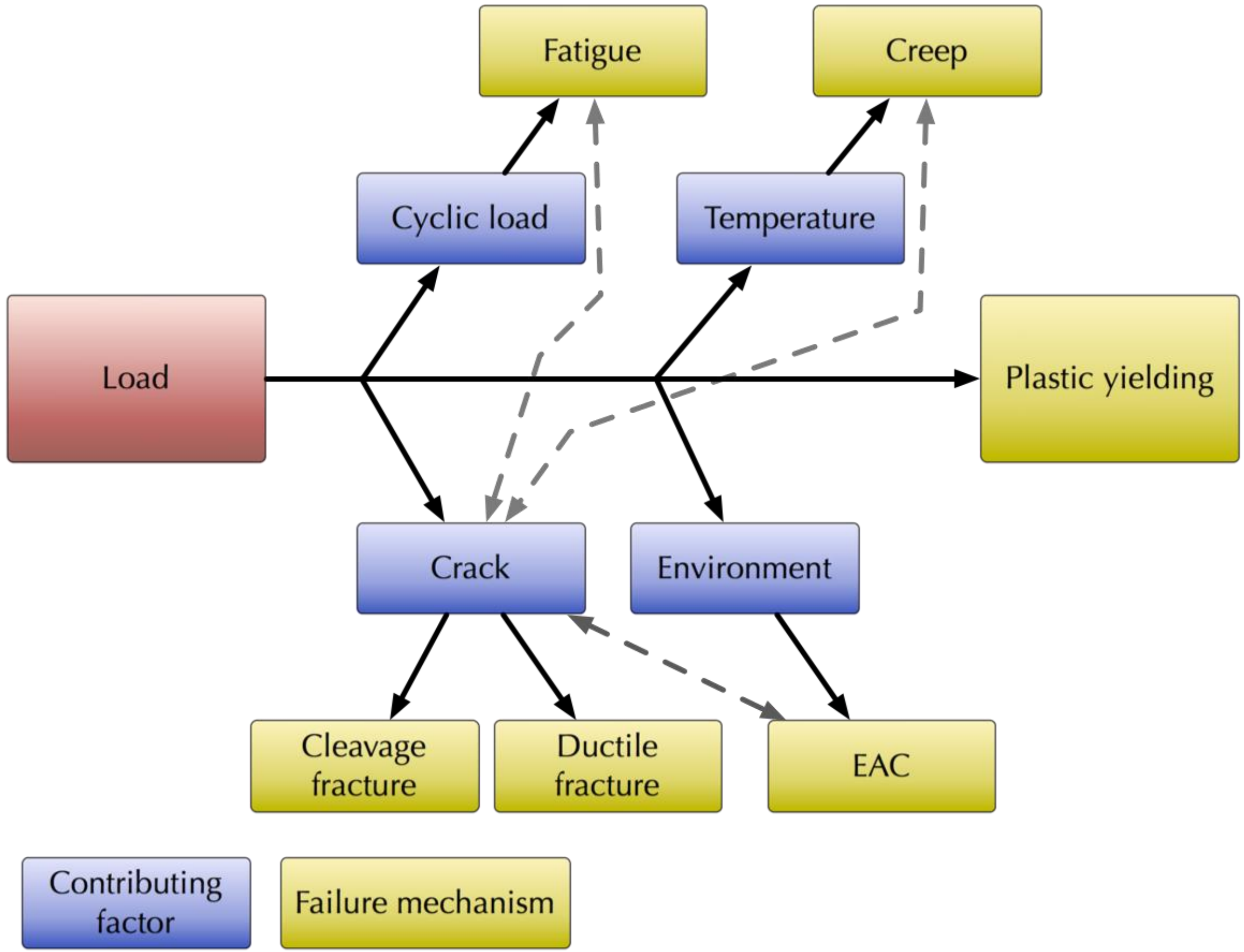
Conclusions


Fatigue
Creep
Cyclic load
Temperature
Load
Plastic yielding
Crack
Environment
Cleavage fracture
Ductile fracture
EAC
Contributing factor
Failure mechanism