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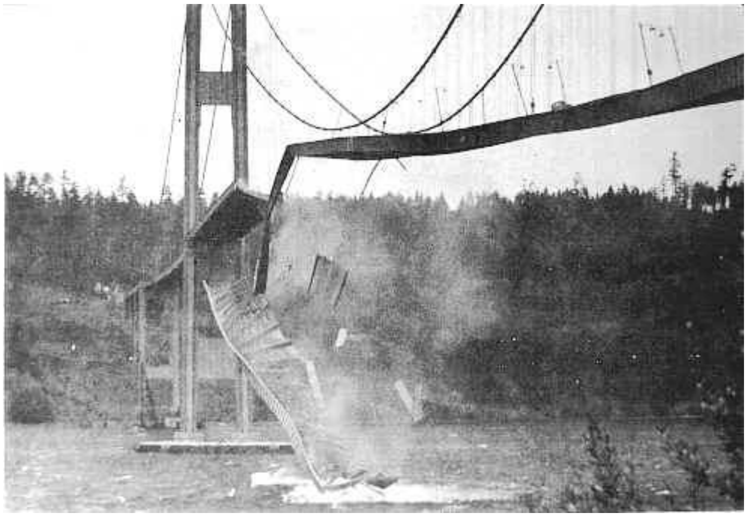

Physical phenomena
Loads & Failure Mechanisms

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Outline

- **Background and introduction**
- **Load vs. Capacity**
- **Load types**
- **Failure mechanisms**

- **Applications**
  - Preventive maintenance and prognostics
  - RAMS analysis → Relevant Failure Parameter
  - Condition monitoring
  - Root cause analysis

Objective

- **Demonstrate benefit of understanding failures**
  - Enables quantification of maintenance
  - Provides structured way of problem solving

- **Give a flavour of loads & failure mechanisms**
  - Not complete overview
  - Simple examples
    - not representative for your practical problems
    - illustrate principles
    - demonstrate quantification – some equations !

- **Provide directions for application**
  - Not complete overview
  - Not in-depth treatment of one case

Background

Defence organization:
- Technologically sophisticated systems
- Largely variable and demanding operating conditions
- High requirements for availability and reliability
- Constant pressure to reduce costs

Maintenance important

***Predictability* of maintenance desired**

Introduction

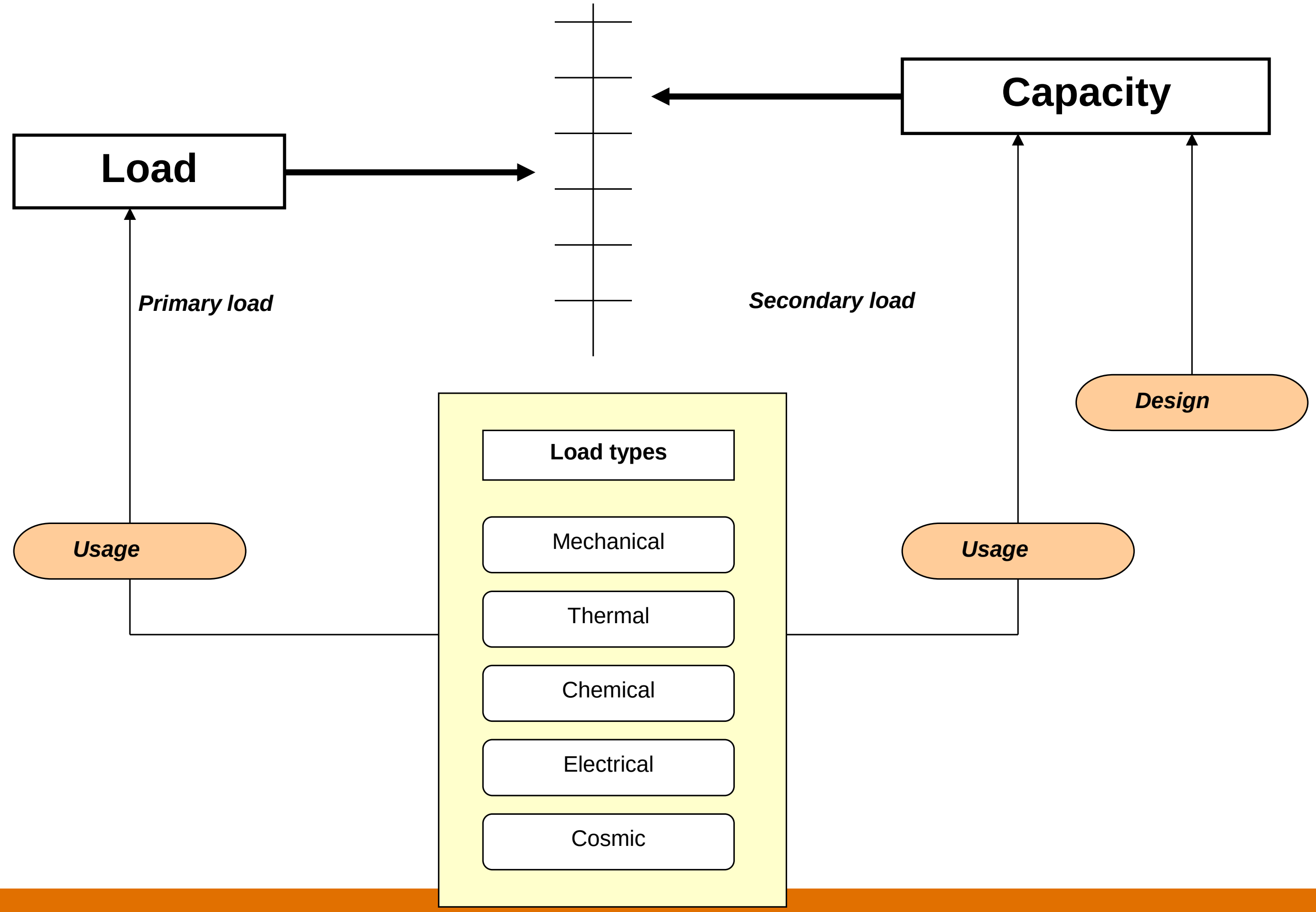
- **Preventive maintenance → length of intervals**
- **Balance between**
  - low costs → efficient
  - high availability → effective
- **Two approaches to find optimum**
  - Experience based approach
    - predict failures based on historic data
    - Reliability Engineering / RAMS analyses
    - requires large datasets / inaccurate for changing conditions
  - Model based approach
    - predict failures with physical failure models and monitored (or prescribed) variation in usage
    - quantitative relation between usage and degradation
    - enables *dynamic maintenance*

Failure

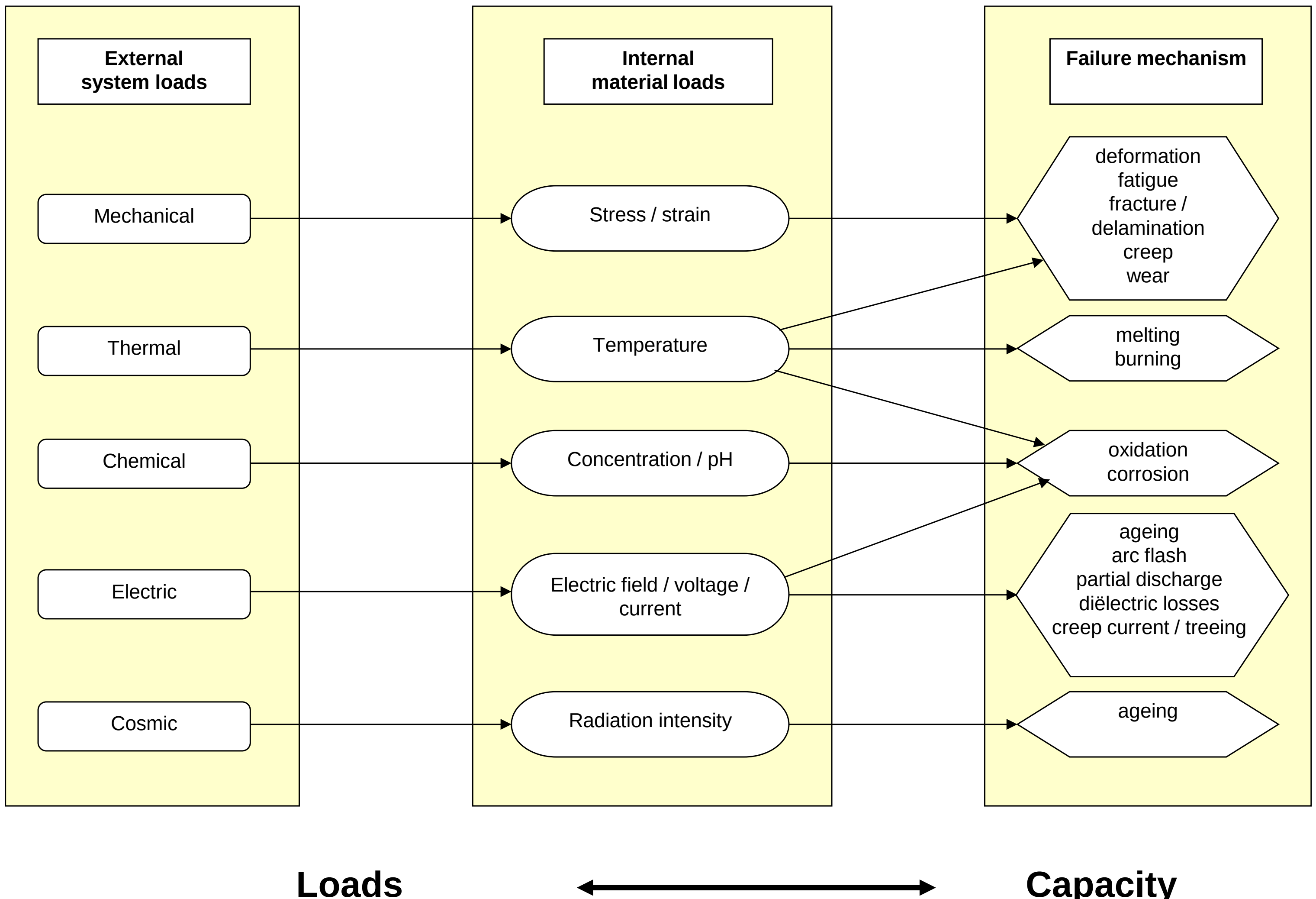
- **Requires understanding of failure behaviour**
  - How ? Why ? When ?
- **Failure: “reaching such a state that the intended function can no longer be fulfilled”**
  - depends on function
  - not always physical failure
- **Failure mode**
  - Manner in which a system functionally fails
  - Detected by decreased performance or inspection
  - Several hierarchical levels
  - Also non-physical causes: human errors / contamination
- **Failure mechanism**
  - Physical or chemical process yielding degradation and leading to failure
  - Limited number !

Balance

- **Load versus load-carrying capacity**



Load types and failure mechanisms



Problem 1

Determine for the failures mentioned below

- the failure mechanism
- the governing load
- the load-carrying capacity
- a preventive solution

- **Fractured window hit by football**
- **Broken bicycle chain**

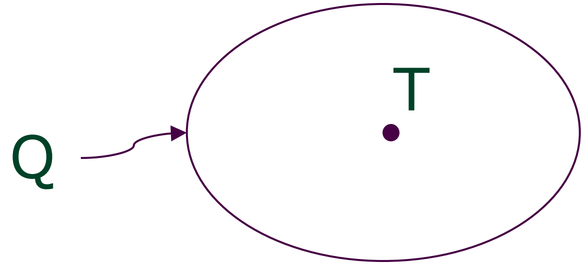
LOADS

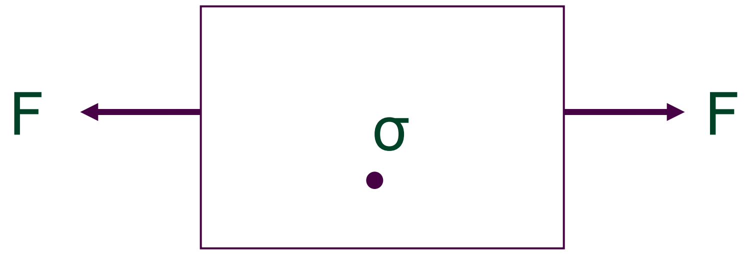
Loads

- **External loads vs internal loads**
- **Different load types**
  - Mechanical
  - Thermal
  - Electric
  - Chemical
  - Radiative
- **Relation with usage**

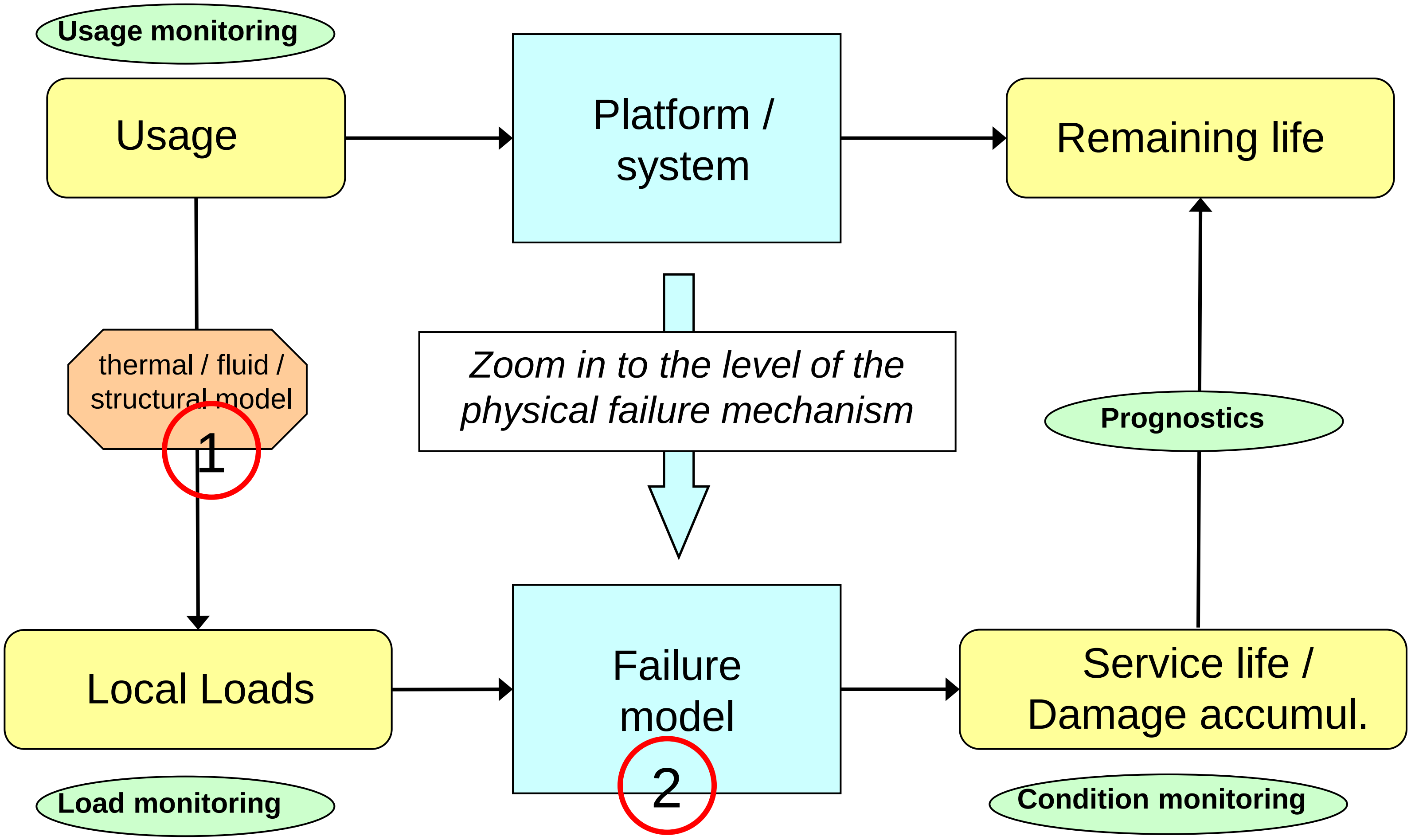
External and internal loads

- **Failure occurs on (microscopic) material level**
  - mechanical fracture = release of atom bonds
  - breakdown of electric insulator = release of electrons
- **Failure is governed by local *internal* load**
  - local stress, strain, electric field, temperature
- **Operator determines *external* loads**
  - Force, moment, charge distribution, heat input



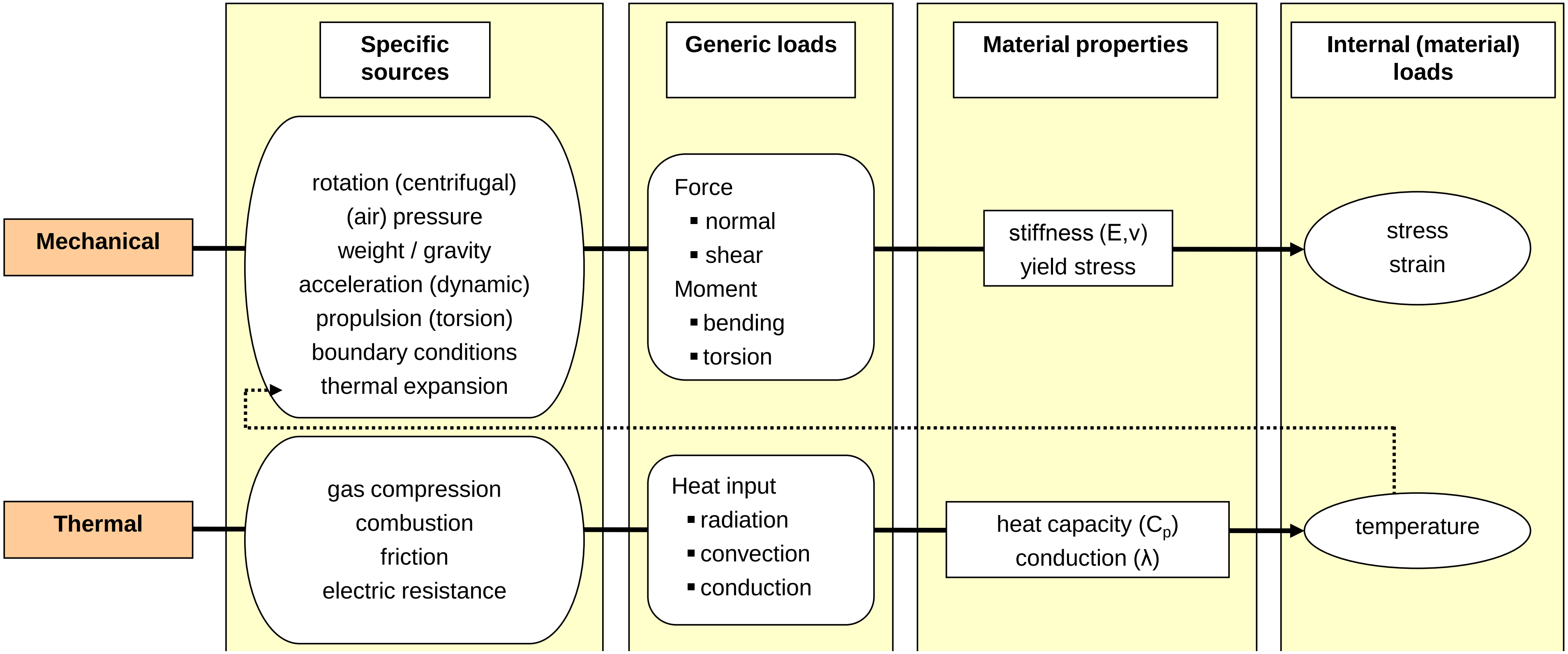


Relating usage to service life



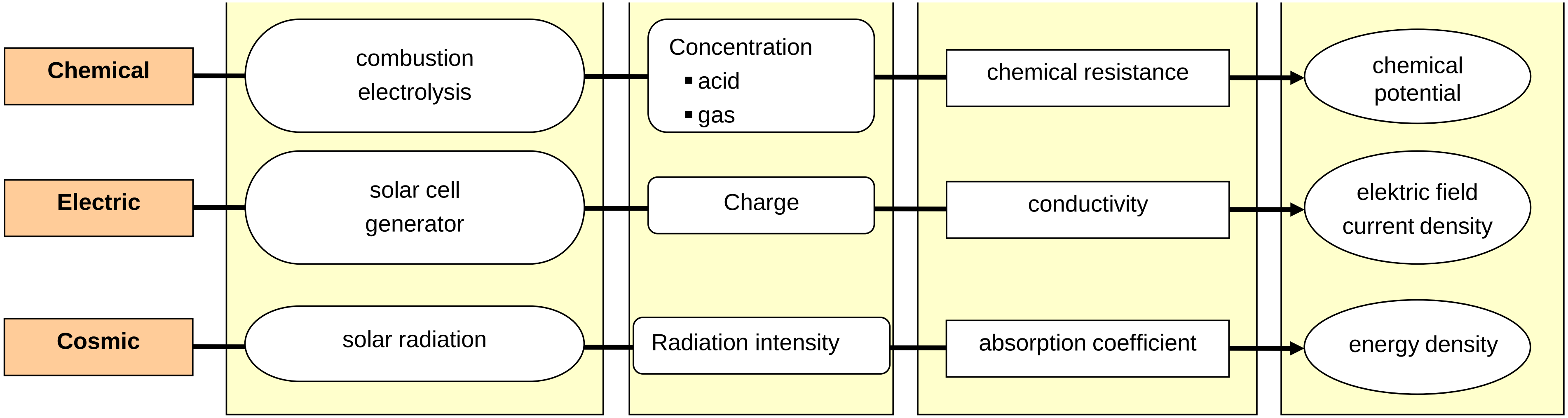
Load types

- **Mechanical:** Forces/moments caused by various sources



- **Thermal:** Heat flow caused by several sources

Load types (2)


Chemical
Electric
Cosmic
combustion
electrolysis
solar cell
generator
solar radiation
Concentration
▪ acid
▪ gas
Charge
Radiation intensity
chemical resistance
conductivity
absorption coefficient
chemical
potential
elektric field
current density
energy density

Examples of sources mechanical loads

- **Pressure**
  - distributed load exerted by environment of body:
    - water pressure (hull of ship, submarine)
    - air / gas pressure (gas pressure vessel, aircraft wing)
  - total force determined by distributed load (f in N/m^2) and surface (A):

$$F = \int_A f dA$$

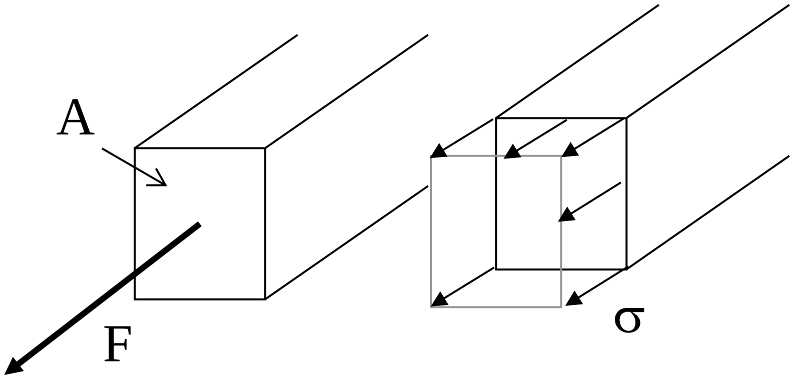
- **Acceleration:**
  - acceleration (a) requires force (Newton's law) proportional to mass (m) and a: $F = m\ a$
  - Rotation is acceleration → centrifugal force acts on rotating body (angular velocity ω and radius r):

$$F_{cf} = m\omega^2 r$$

Internal mechanical loads: stress

- **Local load parameter**
- **Relating external load (force / moment) to the properties of cross section**
- **Normal force**
  - uniform normal stress σ

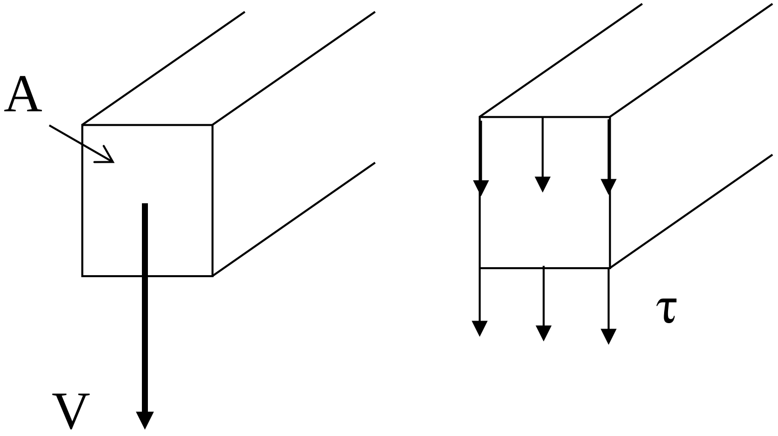
$$\sigma = \frac{F}{A}$$



Internal mechanical loads: stress (2)

- **Similar for shear, bending and torsion**

$$\tau = \frac{V}{A}$$

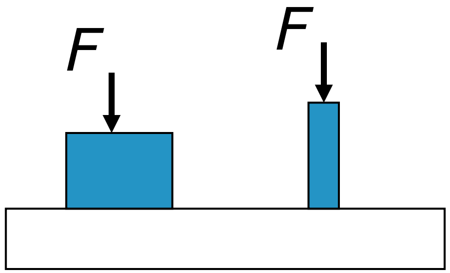


$$\sigma = \frac{Md}{I_x} \qquad I_x = \frac{1}{12} b h^3$$

$$\tau(r) = \frac{Tr}{I_p} \qquad I_p = \frac{\pi}{32} \; D^4 - d^4$$

Thermal loads

- **Heat input per unit time and unit area: *q* [W/m²]**
- **internal heat generation**
  - friction $$Q = F_w v = \mu F_n v$$
  - electric resistance $$Q = \frac{V^2}{R} = I^2 R$$



- **external heat generation**
  - compression $$\frac{pV}{T} = \text{constant}$$
  - combustion
- **causes increase or decrease of temperature: *T* [ºC of K]**

Internal load: temperature

- **temperature is state variable: always a value**
- **only changes when (nett) amount of heat is added / removed**
- **temperature increase depends on amount of heat *Q* [J], mass and material:**

$$\Delta T = \frac{Q}{m c_p}$$

- **Typical values c_p**
  - metal: 100 – 500 J/kgK
  - water: 4000 J/kgK

Summary

- **External loads**
  - Type and magnitude determined by usage of system

- **Internal loads**
  - Depend on magnitude external load + properties / dimensions
  - Directly responsible for failure

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- **Usage + poperties determine loads**

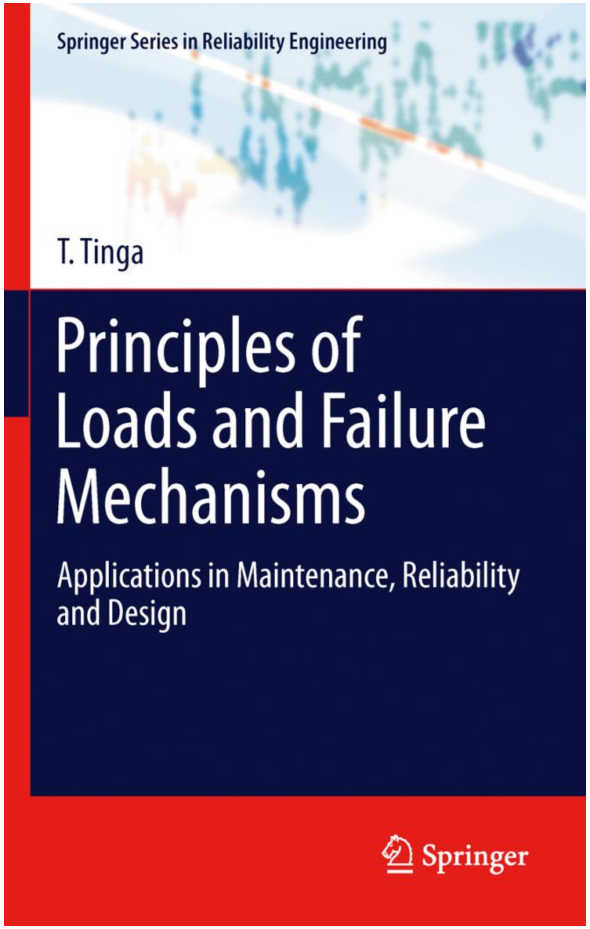
- **Compare with capacity → failure mechanisms**

FAILURE MECHANISMS

Failure mechanisms

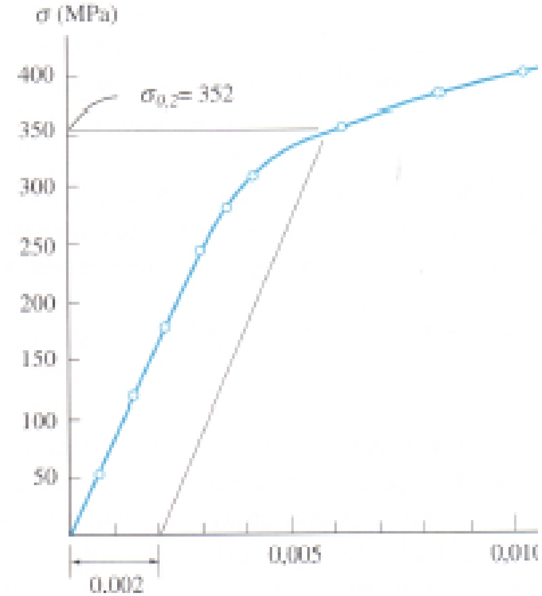
- ***Static overload***
- **Deformation**
- ***Fatigue***
- **Creep**
- ***Wear***
- **Melting**
- **Thermal degradation**
- **Electric failures**
- **Corrosion**
- **Radiative failures**

- **Complete overview:**

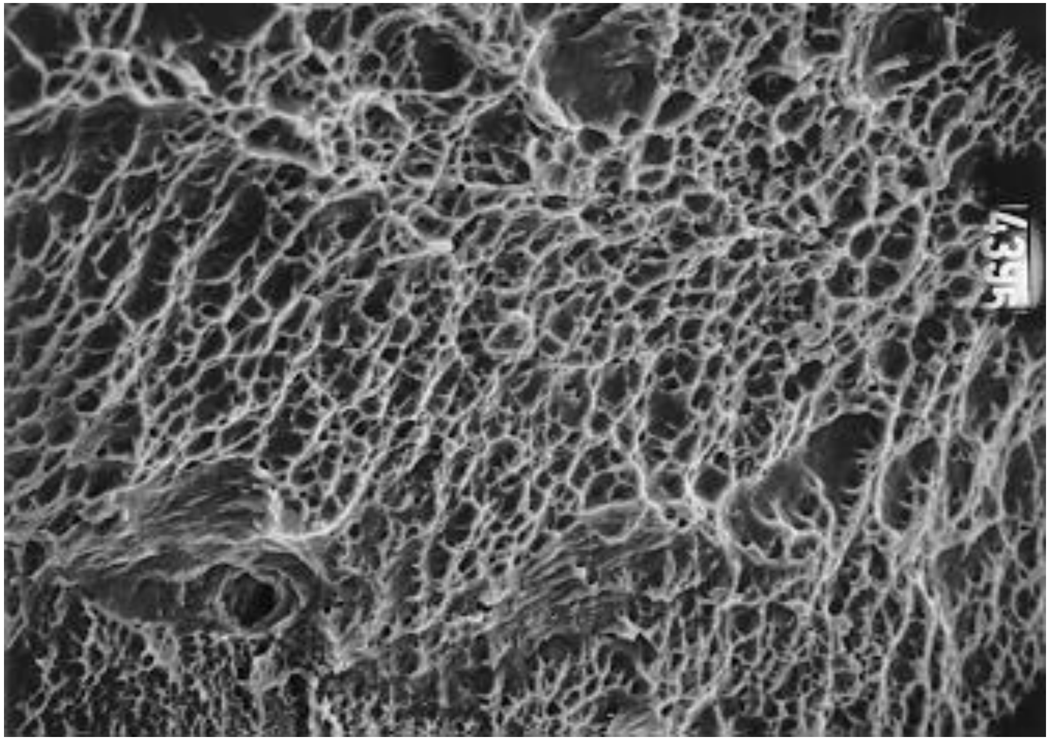


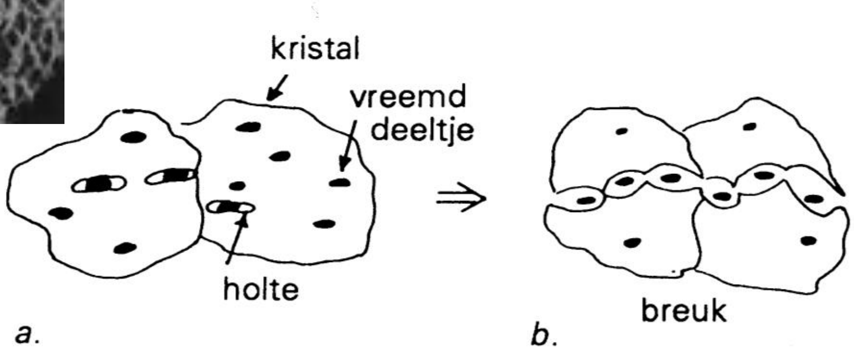
Static overload

- **when stress > strength**
  - *load* = stress
  - *capacity* = material strength
- **tensile strength determined by tensile test**
- **tensile strength temperature dependent**
  - T ⬆ σ_t ⬇
- **design: expected load < strength**
  - effect temperature
  - safety factors
- **Failure analysis**
  - fracture surface → 'dimples'



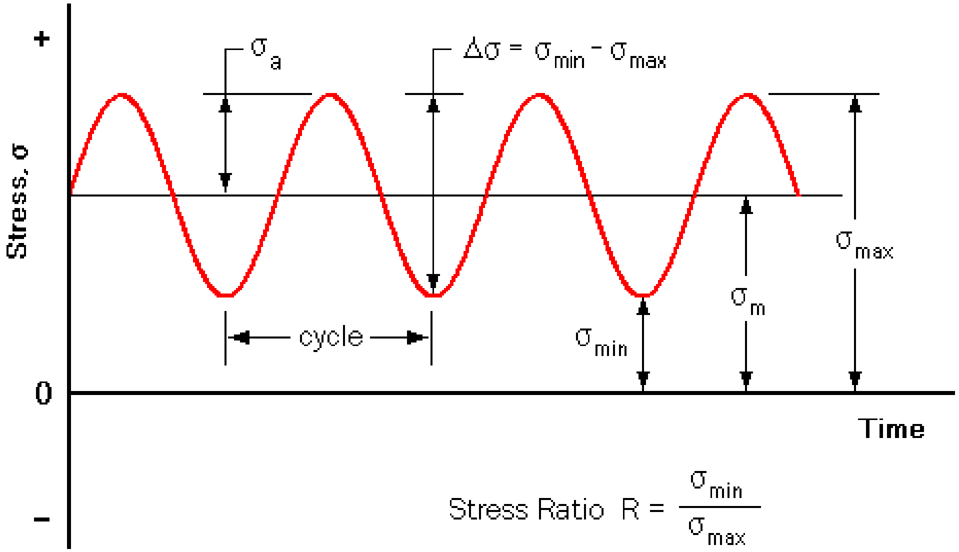
Fracture surface static overload





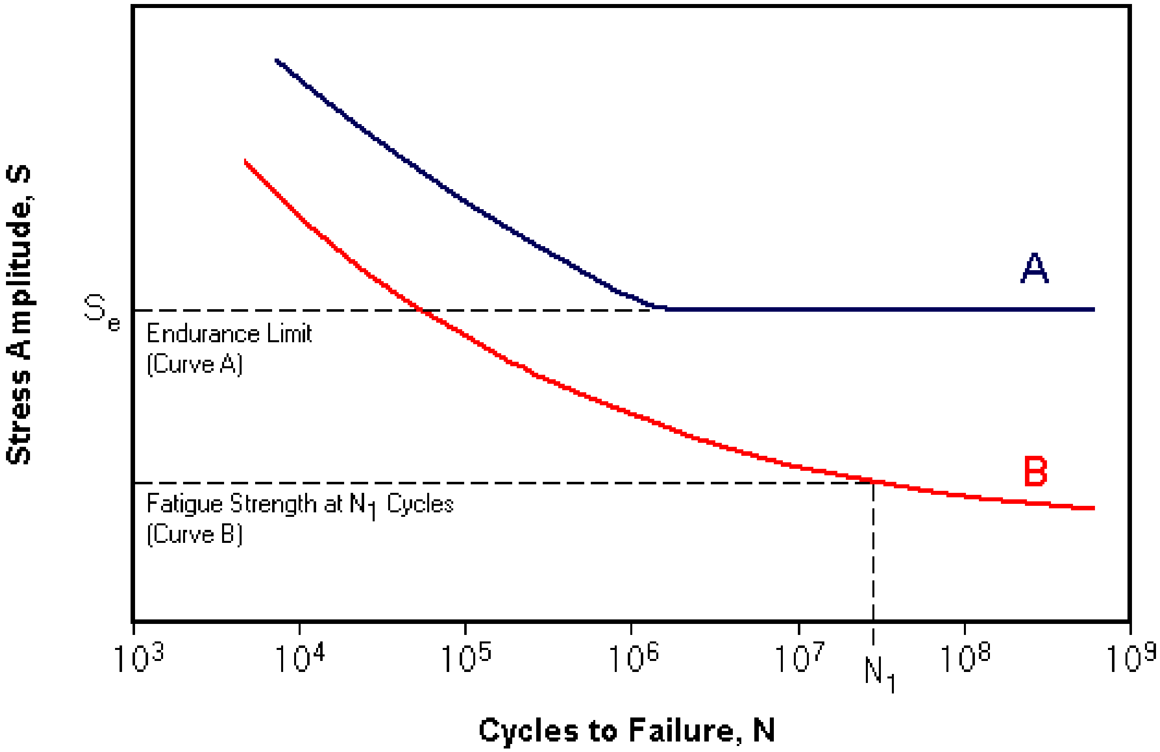
Fatigue

- **caused by cyclic load**
- **stress level below tensile strength**
- **failure occurs after large number of cycles (10^4 – 10^7)**
- ***load* = strain or stress cycle ($\Delta\varepsilon$ of $\Delta\sigma$)**

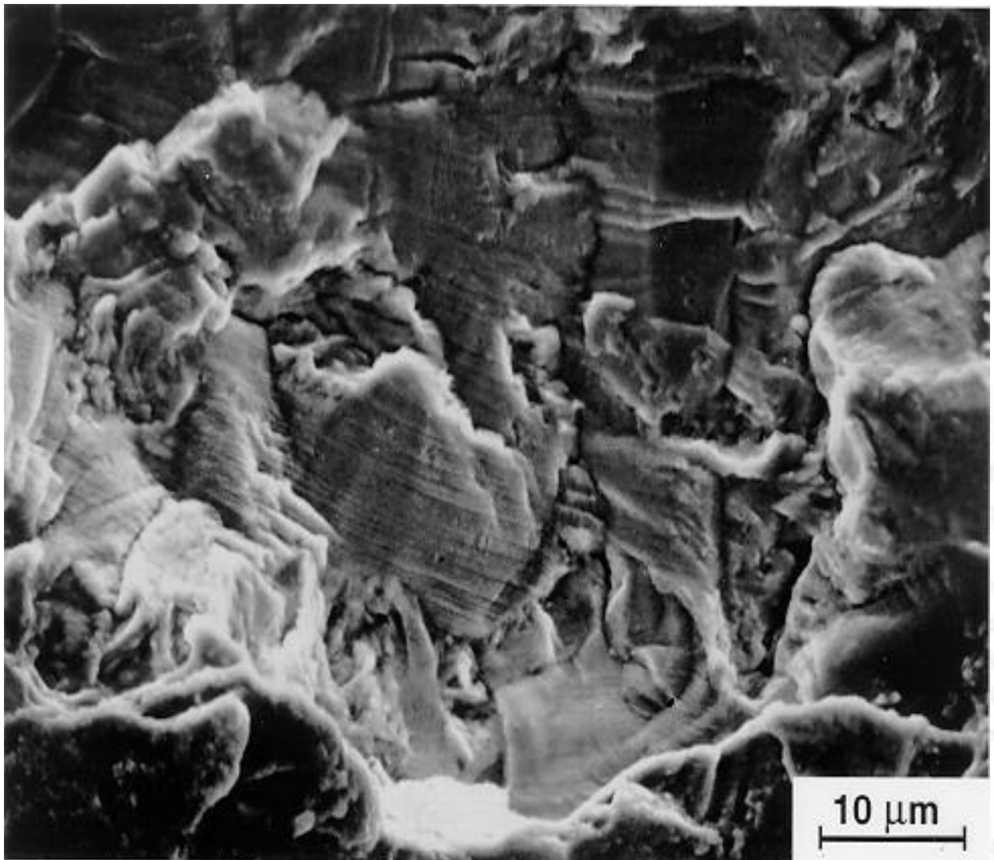


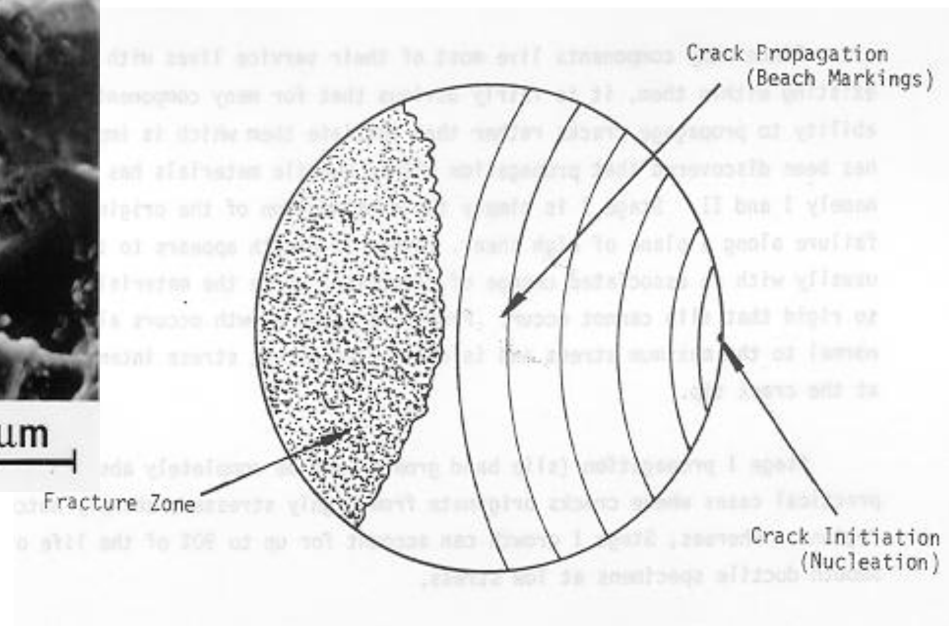
Fatigue (2)

- ***Capacity* = fatigue resistance**
  - *S*-*N* diagram or Wöhler-curve



Failure analysis





Life assessment

- **Constant amplitude: from *S-N* or Smith diagram**
- **Variable amplitude: Miner damage rule**
  - *n* cycles at load with life *N* yields damage *D*

$$D = \frac{n}{N}$$

  - $0 < D < 1$: percentage of life consumed
  - *p* blocks of n_i cycles with life N_i yields damage

$$D = \sum_{i=1}^{p} D_i = \sum_{i=1}^{p} \frac{n_i}{N_i}$$

  - no sequence effects

Problem 2

For a gas turbine blade it has been derived:

- $\sigma = 3.95\ N^2$

A start/stop cycle is defined as:

- start/stop: N from 0 to 14.000 rpm and back to 0

- **Calculate the number of start/stops before the blade fails due to fatigue**

In addittion to the start/stop cycle two more cycles exist:

- manoeuvre: N from 8.000 to 14.000 rpm and back to 8.000 rpm
- correction: N from 10.000 to 12.000 and back to 10.000 rpm

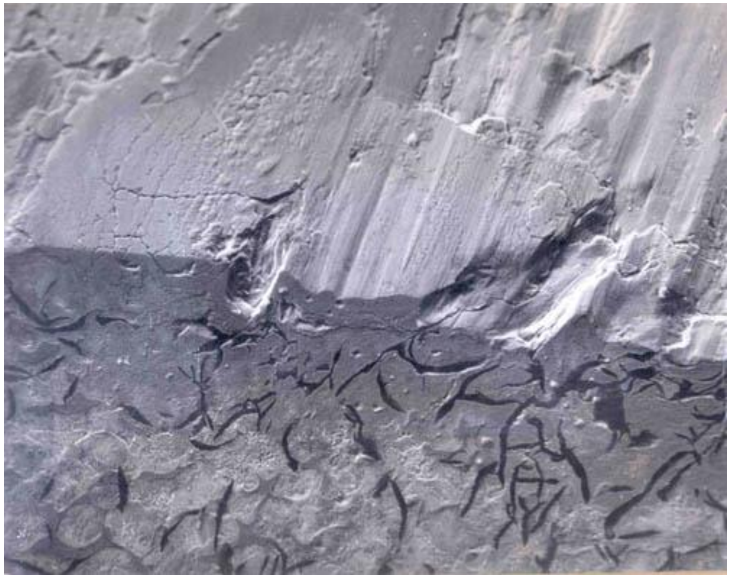
The usage profiel of the engine is: per flight 1 start/stop, 3 manoeuvres and 10 corrections.

- **Calculate the number of flights to failure**

Wear

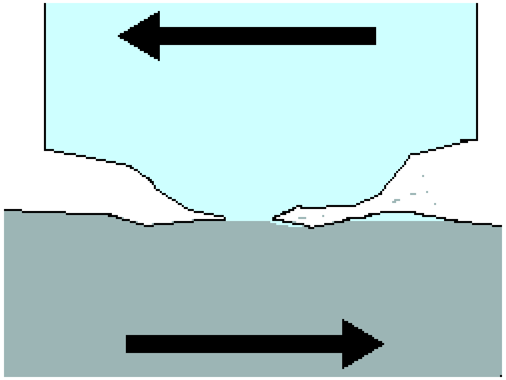
- **occurs when parts move relative to each other or along liquid / gas**
- **two types**
  - two-body wear mechanisms
    - » on contact between two parts
  - single-body wear mechanisms
    - » on surface due to flowing medium
- **resulting in**
  - bad fitting
  - vibrations (e.g. bearings)
  - cracks – fracture

Wear mechanisms



Two-body wear

- **abrasive wear**
- **corrosive wear**
- **surface wear**
- **adhesive wear**
  - strong bonding between peaks of surface roughness
  - high friction → high temperature
  - improve by lowering friction:
    - » materials
    - » lubrication

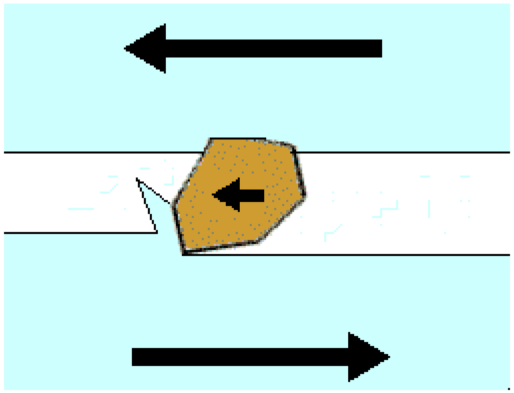


Single body wear

- **Erosion**

Wear mechanisms (2)

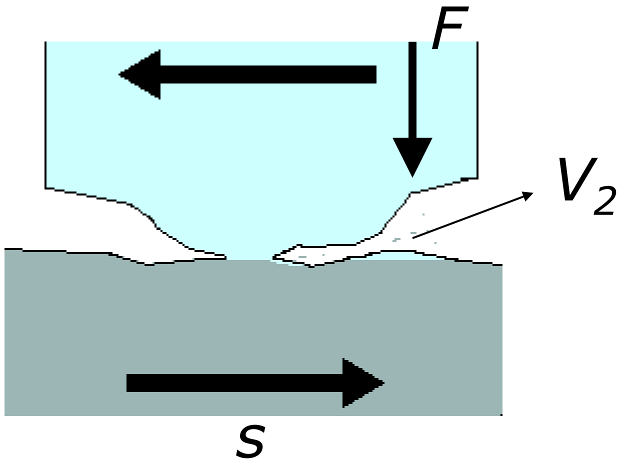
- **abrasive wear**
  - when considerable differences in hardness (> 20%)
  - presence of hard particles
    - » as additional body (three-body): sand
    - » fractured particles (debris)



Wear rate

- **Archard's law**

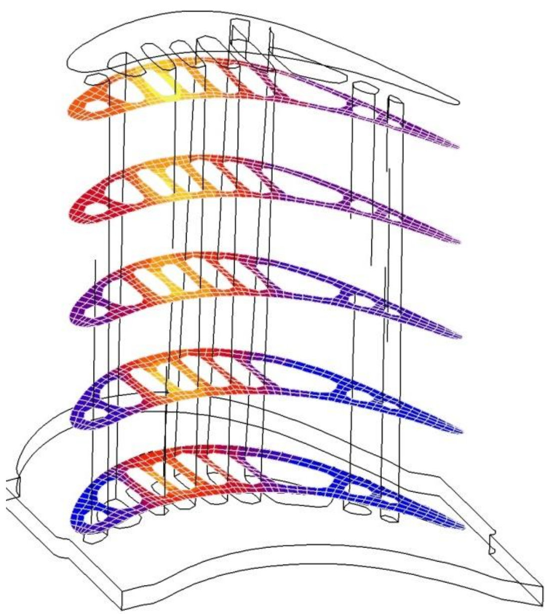
$$V_i = k_i F s$$

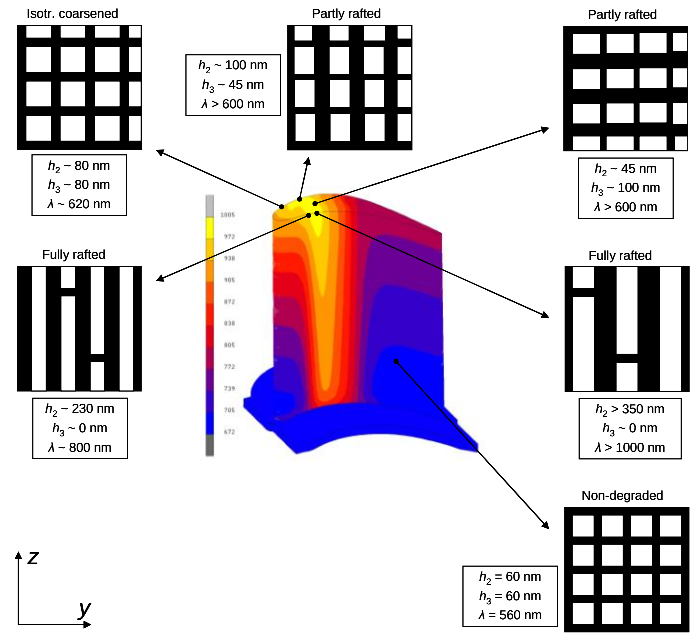


  - *k* [mm³/Nm] is specific wear rate (different for two bodies)
  - *k* depends on
    - » material combination
    - » surface roughness
    - » contact temperature
    - » hardness
    - » lubrication

More advanced methods

- **Calculate loads with FE / CFD models**
- **Complex (multi-scale) damage models**





- **Find balance between effort and benefits !**

Summary

- **Loads – capacity balance**
- **Load types**
- **Failure mechanisms**

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- **Application in maintenance**
  - Preventive maintenance and prognostics
  - RAMS analysis → Relevant Failure Parameter
  - Condition monitoring
  - Root cause analysis

APPLICATIONS

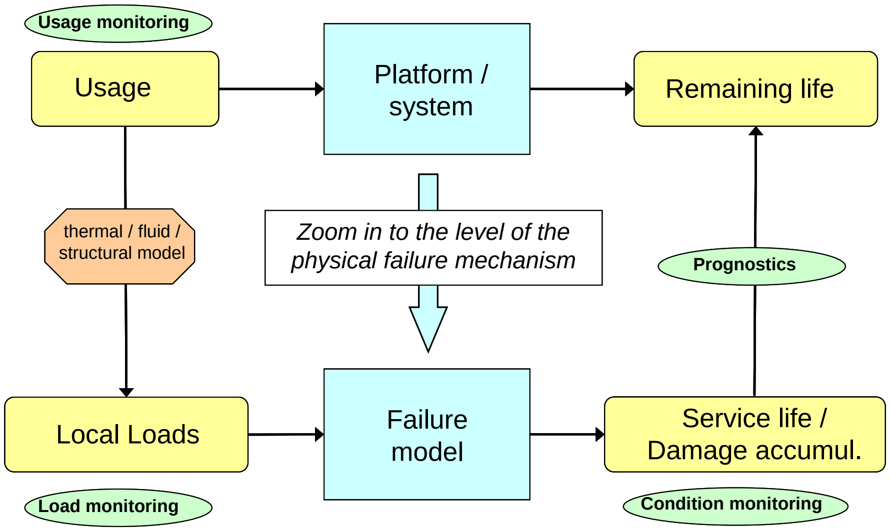
Application in maintenance

Knowledge on failure (mechanisms) can be used …

- **before failures occur**
  - Identify critical components → FMECA
  - Predict time to failure → determine optimal maintenance intervals
  - Develop efficient condition monitoring systems
- **after failure has occurred**
  - Why did component fail ?
  - How can future failures be prevented ?
  - Root Cause Analysis
- **when a fraction of a (larger) population has failed**
  - Quantify failure behaviour
  - Find Relevant Failure Parameter (RFP)

1. Preventive maintenance & prognostics

- **Procedure**
  - Monitor actual usage of the system
  - Derive internal loads from the usage
  - Develop physical models for critical failure mechanism(s)
  - Calculate service life consumption and remaining life
  - See *Tinga, Reliability Engineering and System Safety 2010*
- **Applied to several military systems**
  - Chinook helicopter
  - NH-90 helicopter
  - CV-90 combat vehicle
  - LC frigate

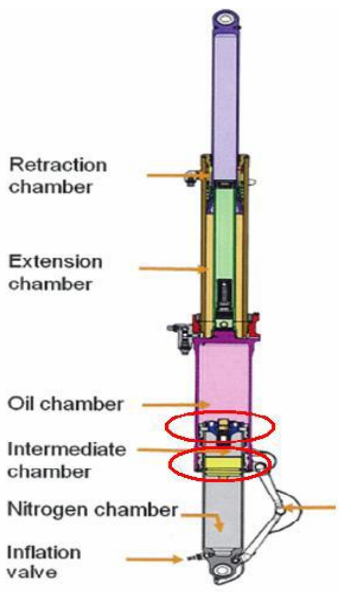


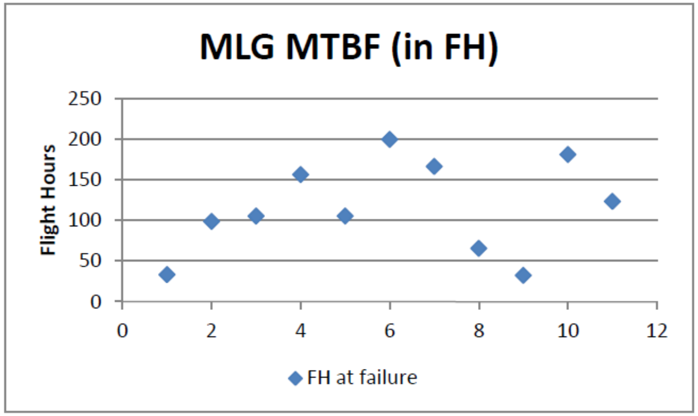
NH-90 helicopter prognostics

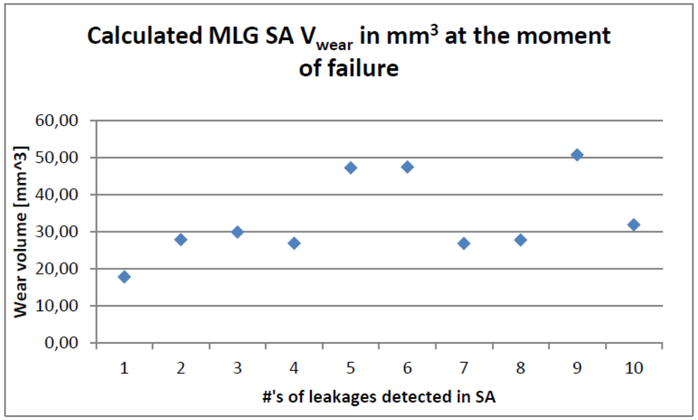
- **Identified critical components**
  - Cost drivers
  - Availability killers
- **Determined failure mechanism + governing loads**
- **HUMS system available for monitoring**
  - Usage → flight hours, landings, conditions, etc.
  - Health → mainly vibrations
- **Maintenance primarely related to flight hours**

NH-90 helicopter prognostics (2)

- **For some components better parameters**
  - Landing gear shock absorber
    - Mechanism: wear of seal
    - Usage parameter: travelled distance → # landings + weight
  - Blade folding system locking mechanism
    - Mechanism: corrosion
    - Usage parameter: *saline* flight hours
  - See *Heerink, TU Delft 2012*







2. Relevant Failure Parameter

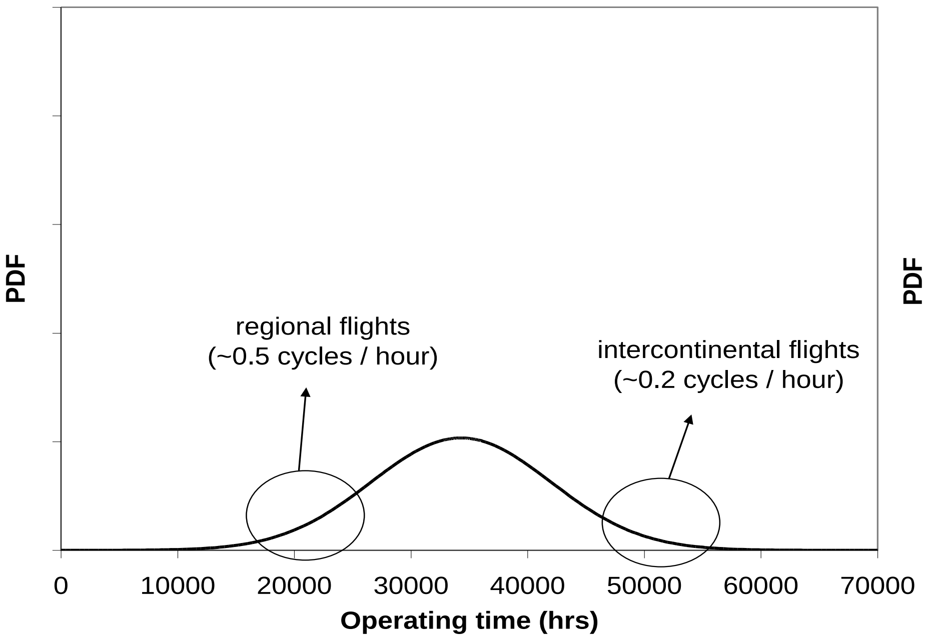
- **RAMS / data analyses → typical approach**
  - Collect failure data - *ttf* in calendar / operating time
  - Analyze data
    - Mean Time Between Failures (MTBF)
    - Parameters of distribution function (Weibull, exponential)
  - Adapt maintenance policy to obtained values

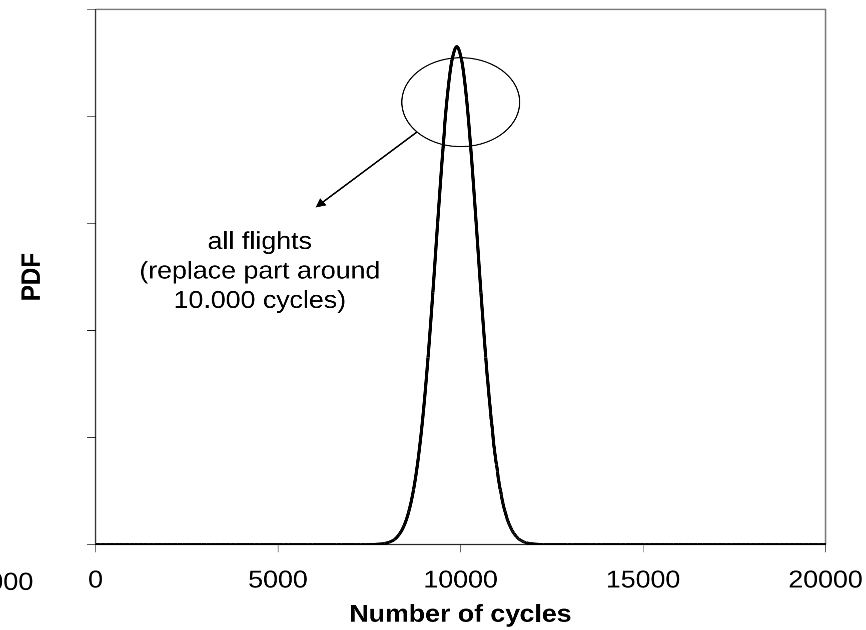
- **Problem: uncertainty / variation**
  - Variation in usage / conditions causes variation in MTBF
  - Ineffective or inefficient maintenance

- **Solution**
  - Determine more relevant failure parameter
    - Operating hours, starts, cycles, … in stead of hours / days

Relevant Failure Parameter - example

- Airliner with fleet of aircraft
- Part fails due to fatigue (~ 10.000 cycles)





Problem 3 - RFP

- **A car is maintained every 15.000 km / 1 year**
  - Many parts replaced or inspected
  - Usage parameter: km or calendar time

- **What would be the most relevant failure parameter for:**
  1. brake discs
  2. tires
  3. structure
  4. engine lubrication oil
  5. hydraulic oil in the brake system
- **Is usage based maintenance the most appropriate policy ?**

3. Condition monitoring

- **Sensoring and data acquisition now well developed**
- **Remaining challenges**
  1. Translation of data into maintenance information
     → only when condition is not directly monitored
       – performance
       – usage
  2. Add prognosis to diagnosis
  3. Selection of proper measurements and location

Condition Monitoring → Condition Based Maintenance

Diagnosis vs. Prognosis

- **Condition monitoring → assess the present condition**
- **Need for *prediction* of future maintenance**
    - › less risk / better planning
- **Two options:**
    - wait for indication of failure / degradation (*diagnostic*)
        - » often based on certain threshold value with safety factor
    - predict remaining life (*prognostic*)
        - » from every state prediction of expected maintenance
        - » prediction improves when reaching end of life
        - » based on assumed usage
- **Prognostic approaches**
    - raw data / statistics → trending
    - physical processes

Development of new CM / CBM systems

- **Selecting appropriate quantities for CM**
  - which parameters should be measured ?
  - at what location ?
  - how can measured quantities be translated into condition information ?
- **Criteria**
  - representative (knowledge on failure mechanisms)
  - measurable (sensors, accesibility)

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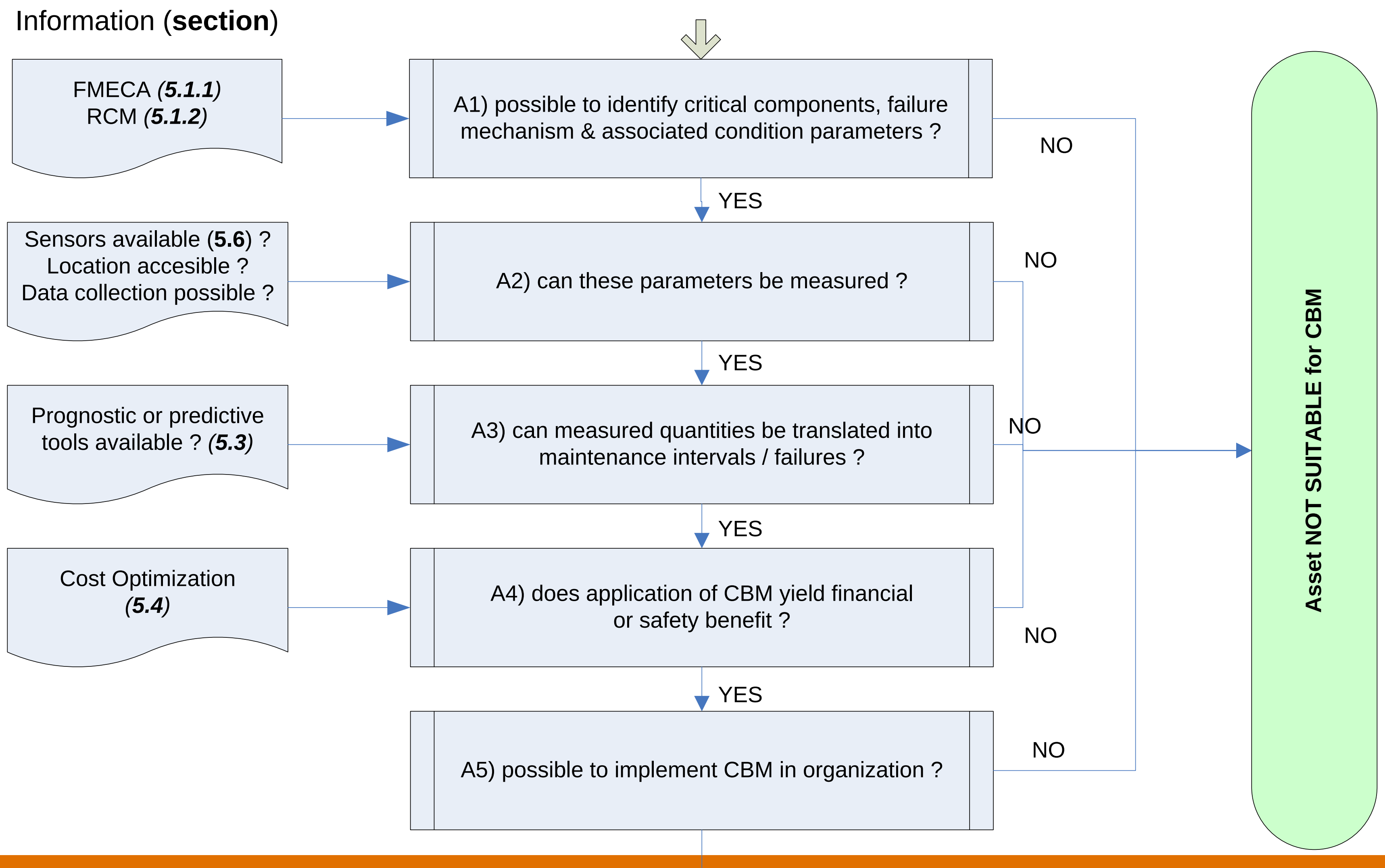
Condition Monitoring → Condition Based Maintenance

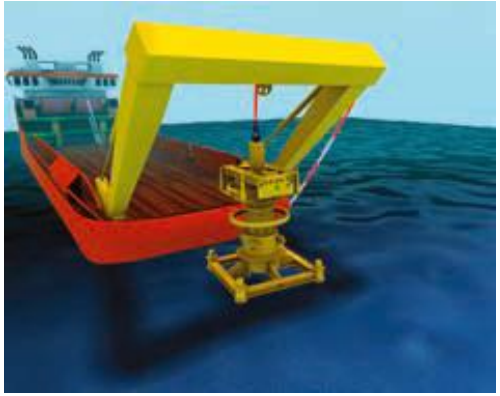
Decision scheme Condition Based Maintenance



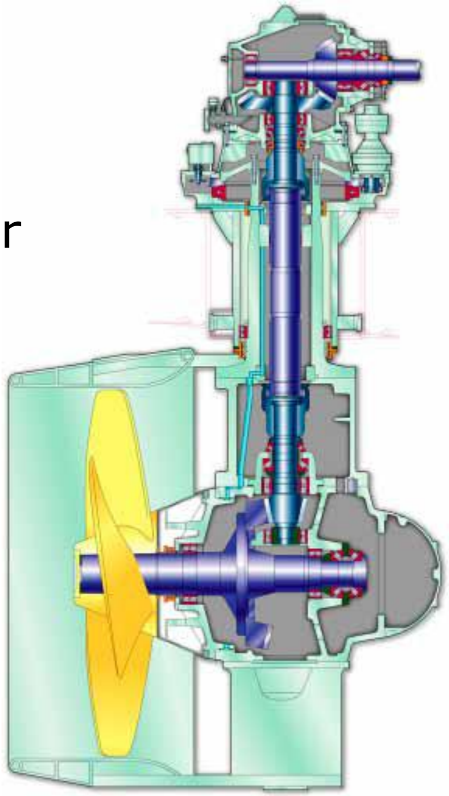
4. Root Cause Analysis (RCA)

- **Structured method to find the cause of a failure in a system**
- **Solving problems is often only solving the symptoms**
  - Failures keep returning
  - Low availaility / high costs
- **RCA should be executed to a sufficiently deep level → failure mechanism + loads !**
- **Solution is often rather simple**
  - Reduce loads on the system
  - Increase capacity of the system

Case studies in WCM-IP



- **Bosch Rexroth**
  - hydraulic cylinder for off-shore
- **Wärtsilä**
  - Bearing in thruster

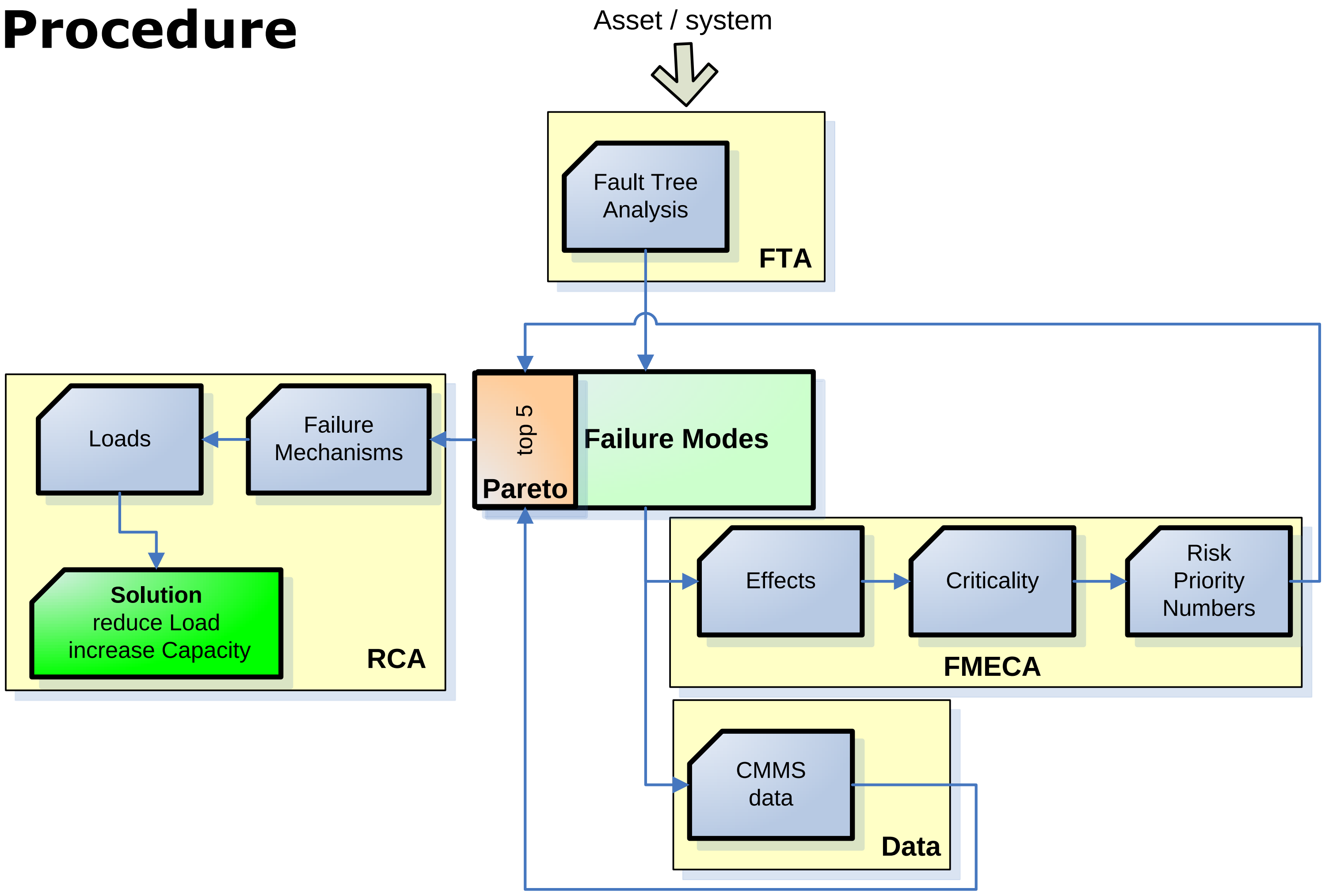


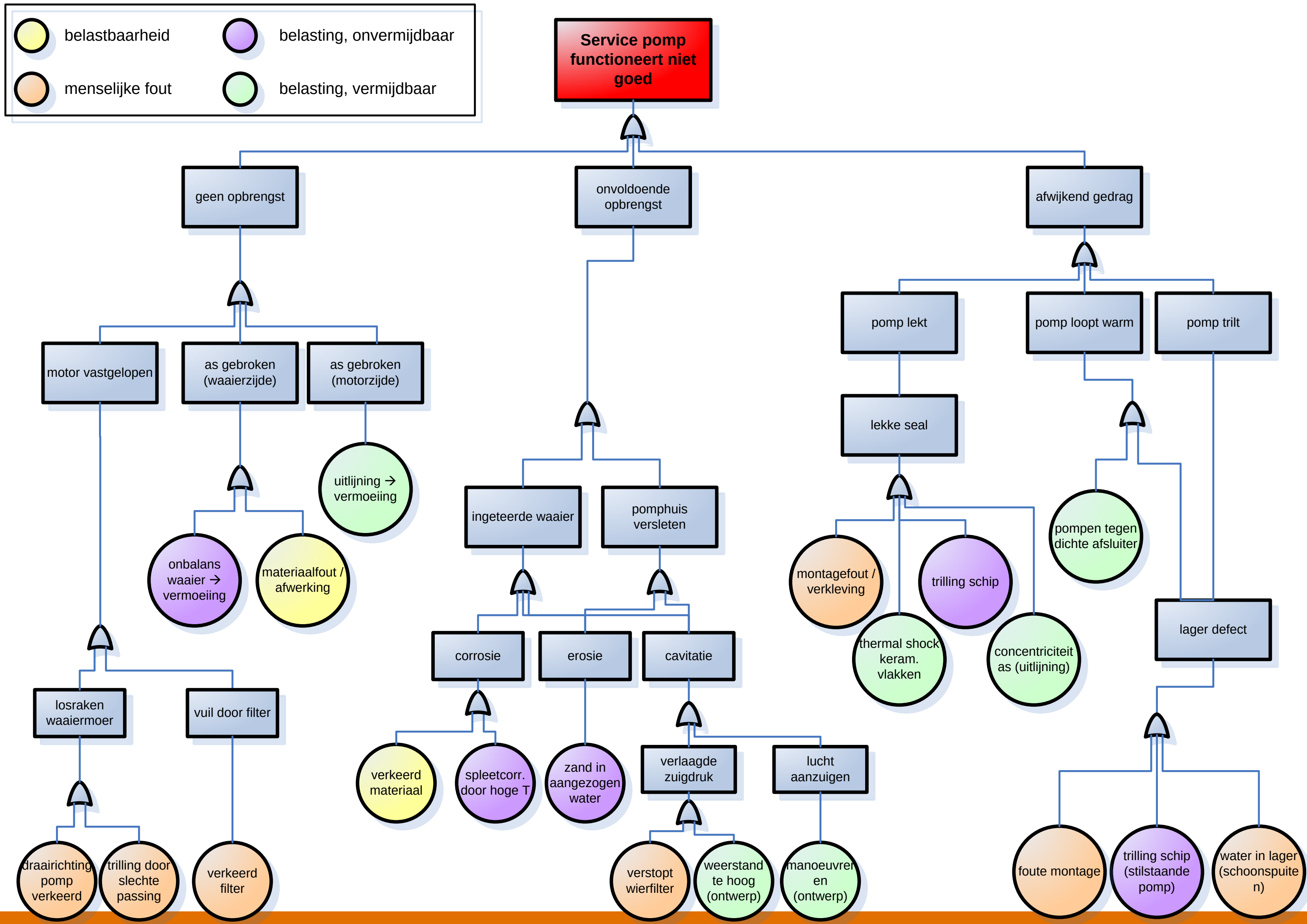
Case studies in WCM-IP

- **Gasunie → valves in gas network**
- **Koninklijke Marine → fire extinguishing pump**

Mechanism based Failure Analysis

- **Procedure**




belastbaarheid
belasting, onvermijdbaar
menselijke fout
belasting, vermijdbaar
Service pomp functioneert niet goed
geen opbrengst
onvoldoende opbrengst
afwijkend gedrag
motor vastgelopen
as gebroken (waaierzijde)
as gebroken (motorzijde)
uitlijning → vermoeiing
onbalans waaier → vermoeiing
materiaalfout / afwerking
losraken waaiermoer
vuil door filter
draairichting pomp verkeerd
trilling door slechte passing
verkeerd filter
ingeteerde waaier
pomphuis versleten
corrosie
erosie
cavitatie
verkeerd materiaal
spleetcorr. door hoge T
zand in aangezogen water
verlaagde zuigdruk
lucht aanzuigen
verstopt wierfilter
weerstand te hoog (ontwerp)
manoeuvreren (ontwerp)
pomp lekt
pomp loopt warm
pomp trilt
lekke seal
montagefout / verkleving
trilling schip
thermal shock keram. vlakken
concentriciteit as (uitlijning)
pompen tegen dichte afsluiter
lager defect
foute montage
trilling schip (stilstaande pomp)
water in lager (schoonspuiten)

4 types of causes

1. **Capacity too low → quality control**
    - e.g. wrong impeller material → corrosion
2. **Human error → (obeying) regulations**
    - e.g. wrong rotation direction
3. **Load** ***avoidably*** **too high** (misuse)
    - e.g. shaft fracture due to misalignment, operating with closed valve
4. **Load** ***unavoidably*** **too high**
    - e.g. failure of non-rotating bearing due to vibrations

Mechanisms & Solutions

- **Seal leakage**
  - Mechanisms
    - wear (no water in pump during operation)
    - thermal shock (cooling of heated seals causes fracture)
    - damage due to vibration overload (cavitation, misalignment)
  - Solution
    - mainly caused by operating the pump incorrectly
    - prevented by better instruction and training of the operators
- **Insufficient yield**
  - Mechanisms: damaged impeller due to
    - Corrosion, erosion by sand (shallow water), fatigue (cavit.)
  - Solution
    - most impeller failures unavoidable → due to regular usage
    - Prediction may be possible → monitor operating hours in shallow water

Conclusion

- **Understanding the failure behaviour enables more efficient maintenance strategies**
- **(in)balance between load and capacity is key to failures**
- **Effect of variations in usage is often neglected**

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- **Model-based approach good addition to traditional experience-based approach**