Safety factor requirements for fatigue life assessments –

Consideration of input uncertainties and acceptable failure probability

Hydro Power Machines

Erik Isaksson
2025.02.21

Summary of proposal

- Updated section '5.3.6 Safety factors' in ***
  - Keeping as much as possible from previous formulations
  - Aggregated uncertainty in fatigue life considering
    1. Standard value of uncertainty in strength (SN-curve)
    2. Uncertainty in fatigue load calculated from highest and lowest possible load (defined by supplier)
  - Complement section 5.3.6 with a table giving γ_F as function of uncertainty level
  - Total safety factor $\gamma_M \cdot \gamma_F$ will explicitly consider load uncertainty and acceptable failure probability

Tabell 1. *Vänster – nuvarande version, Höger – förslag på uppdatering.*

5.3.6 Safety factors (left)

The corrected fatigue strength shall be divided by two safety factors, γ_F and γ_M. The safety factor, γ_F, reflects uncertainties in internal and external loads and load spectrum, and shall be set to at least 1.1 for nominal operation start-stop cycles and at least 1.2 for other fatigue load cases. The second safety factor, γ_M, considers the uncertainty in fatigue resistance and shall be selected based on consequence of failure according to Table 2.

Table 2. Safety factor γ_M based on consequence of failure.

Consequence of failure	Safety factor γ_M
Loss of function in secondary parts	1.15
Loss of entire structure	1.30
Loss of human life	1.40

5.3.6 Safety factors (right)

The corrected fatigue strength shall be divided by two safety factors, γ_F and γ_M. The safety factor, γ_F, shall be set with reference to the uncertainty level in stress amplitude according to Table 2. Parameter k is calculated as $k = \frac{\sigma_{max}-\sigma_{min}}{2(\sigma_{max}+\sigma_{min})}$, where σ_{max} and σ_{min} are the highest and lowest possible stress amplitudes respectively, when all sources of uncertainties have been considered. The second safety factor, γ_M, shall be selected based on the consequence of failure according to Table 3.

Table 2. Safety factor γ_F based on uncertainty level in stress amplitude

Uncertainty	Safety factor γ_F
$k < 0.10$	1.0
$0.10 < k < 0.20$	1.2
$0.20 < k < 0.30$	1.7
$0.30 < k < 0.40$	2.5
$0.40 < k < 0.50$	3.6

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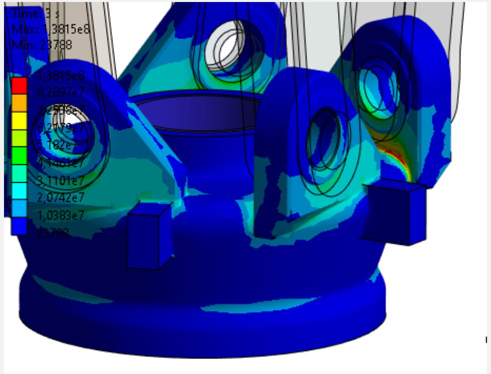
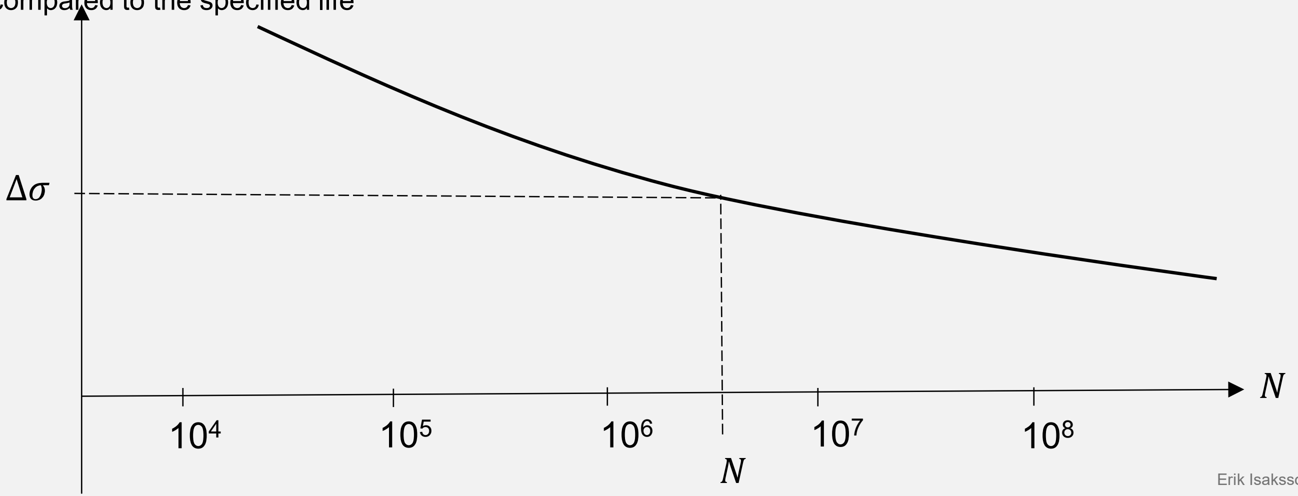
***** PV-2008/0439 REV6, 'MECHANICAL DIMENSIONING OF HYDROPOWER UNITS - TURBINES', valid from 2017-09-15*

Background and idea

- Often, the life of a hydraulic turbine component is governed by fatigue
  - Crack initiation and propagation due to oscillating loading
  - Load level may be far below materials yield limit
- Components fatigue life is verified with stress-based fatigue evaluation
  - Stress oscillation derived from FE-calculations
  - Strength description using Wöhler (SN)-curve (dependent on e.g. material, surface roughness, geometry, environment etc.)
  - The calculated fatigue life N is compared to the specified life





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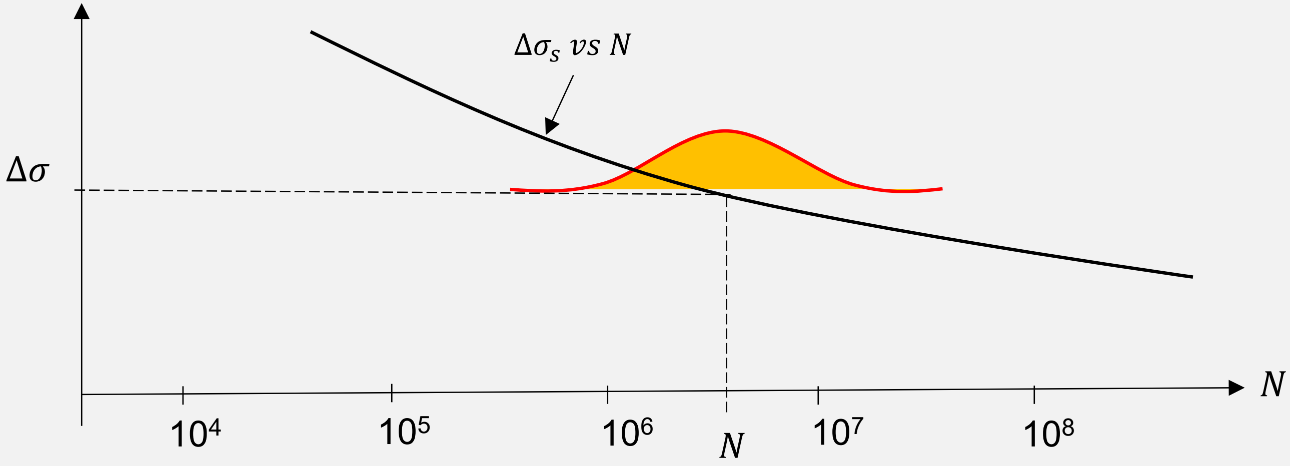
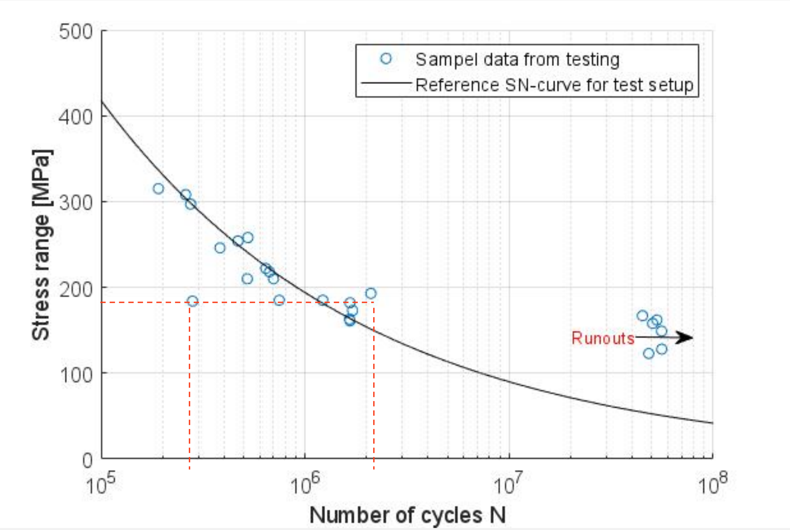
Background and idea

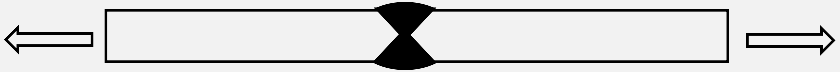
- The evaluated fatigue life is always associated with some degree of uncertainty
  - Fatigue strength description
    - Statistical scatter in laboratory data
    - Correction factors used for extrapolation of laboratory data considering surface roughness, geometry, environment etc.
    - Typical uncertainty in life VC_{N_s} 30 - 60%

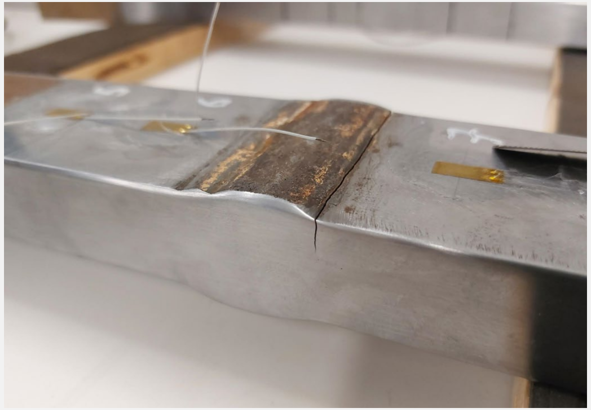


Background and idea

- The evaluated fatigue life is always associated with some degree of uncertainty due to input uncertainties
  - Fatigue strength description
    - Below example from fatigue tests on butt-welded steel samples performed at R&D laboratory in Älvkarleby







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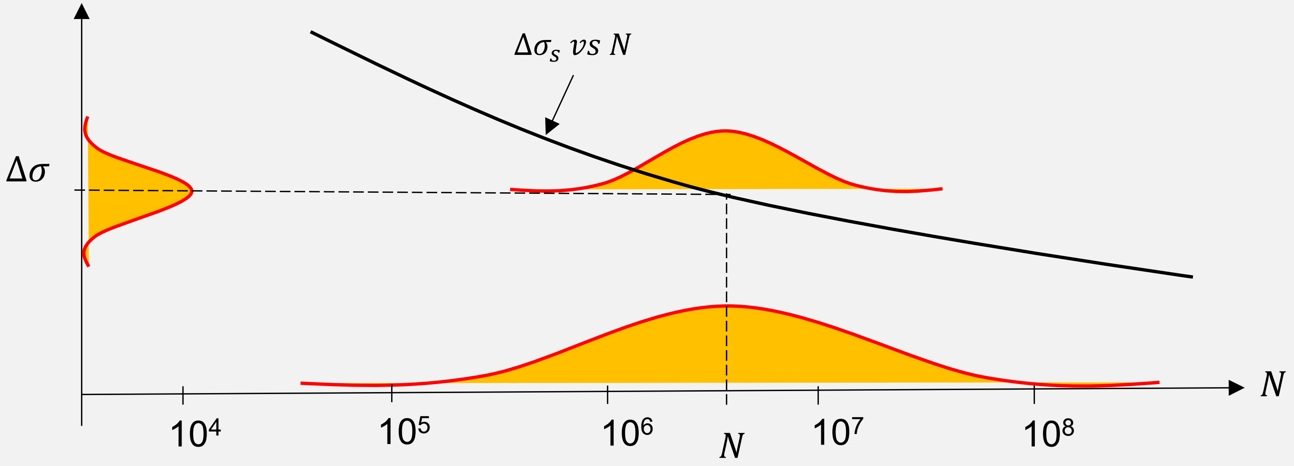
Background and idea

- The evaluated fatigue life is always associated with some degree of uncertainty
  - Fatigue strength description
    - Statistical scatter in laboratory data
    - Correction factors for extrapolation of laboratory data considering surface roughness, geometry, environment etc.
  - Calculated stress oscillation
    - External loads
    - Load application/boundary conditions in FE model
    - Local geometry
    - Capacity of applied method



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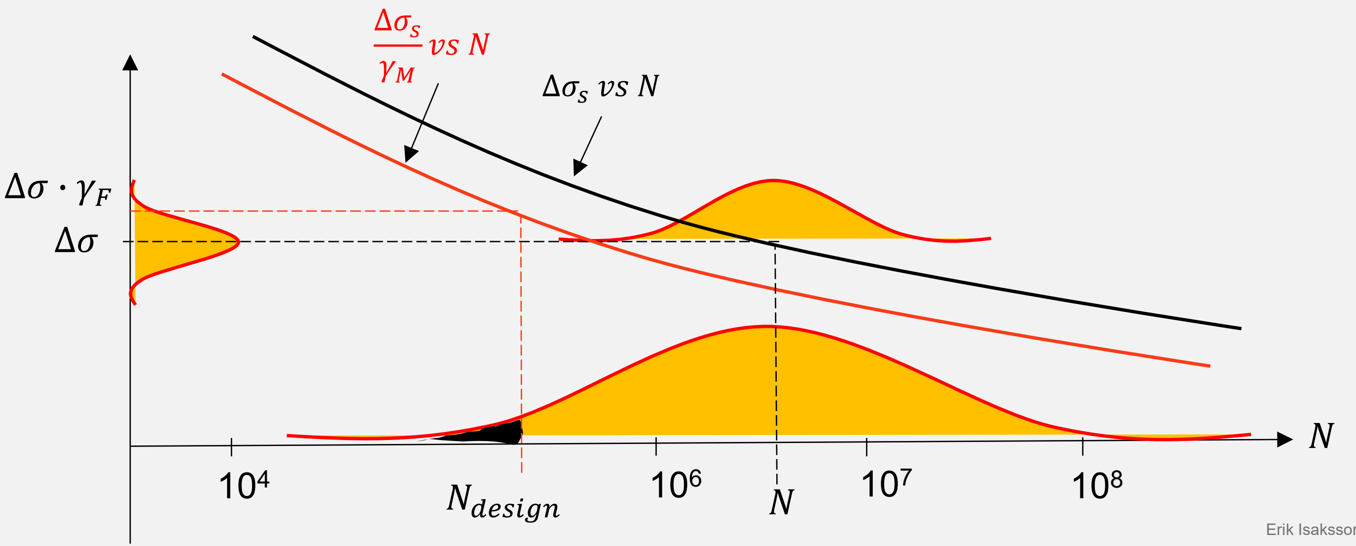
Background and idea

- Robustness of design can be accomplished with application of proper safety factors
  - Limiting the failure probability to an acceptable level over the component's life
  - Acceptable failure probability shall be set with reference to consequence of failure



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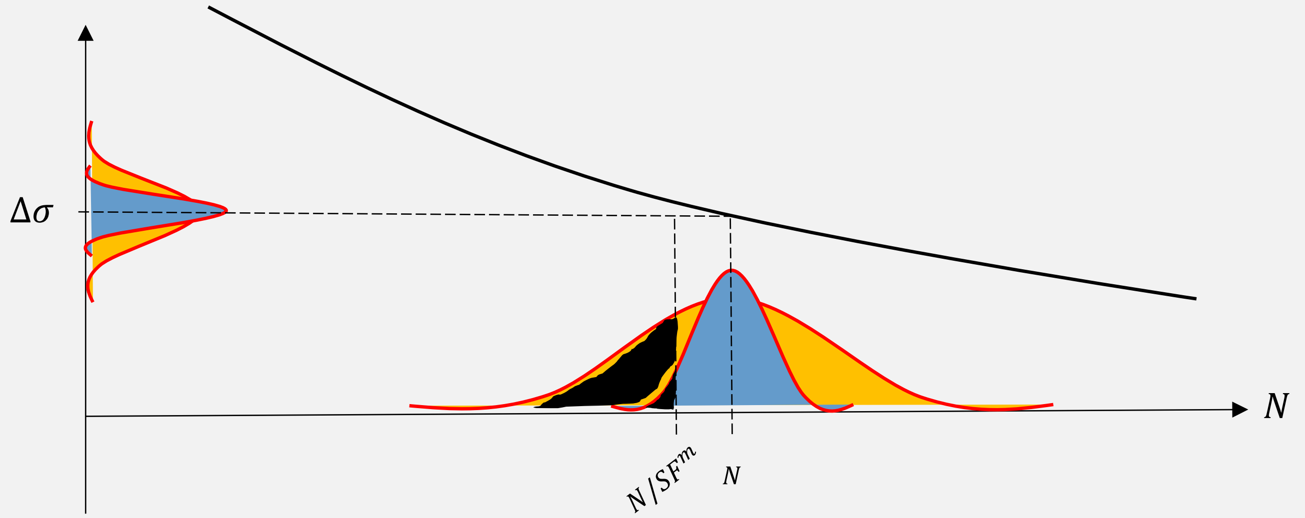
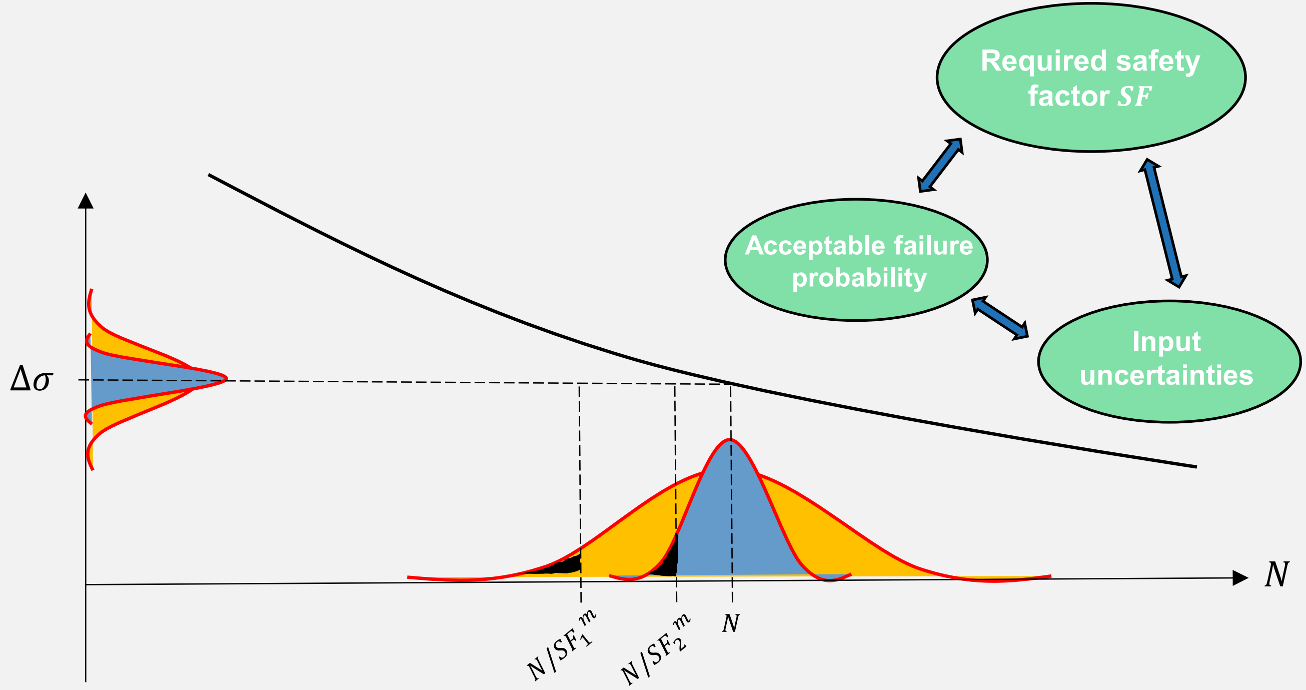
Background and idea

- Given two designs associated with different uncertainty levels in input data
  - Using the same safety factors (SF) will result in different failure probabilities



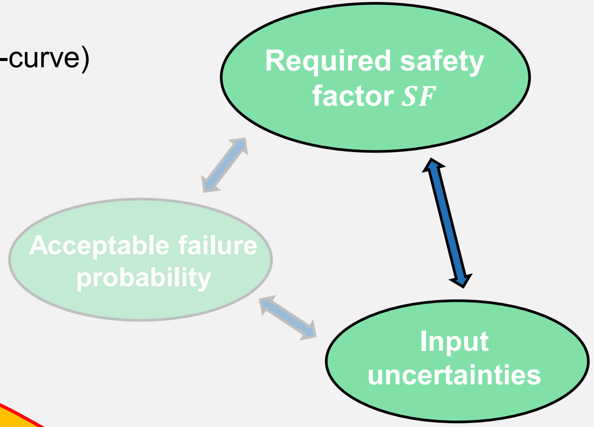
Background and idea

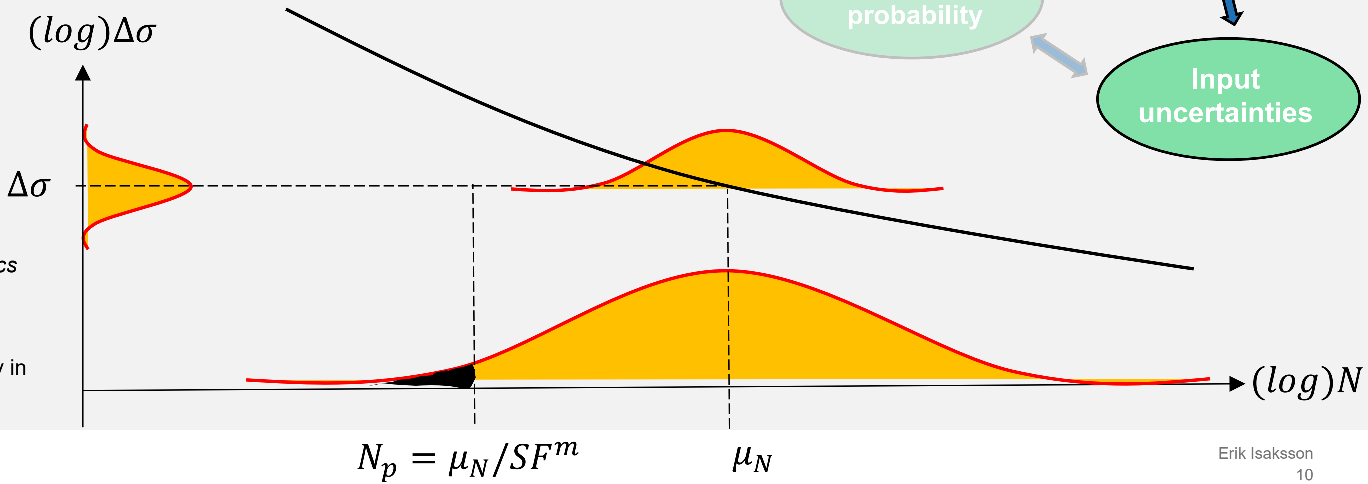
- Given two designs associated with different uncertainty levels in input data
  - Safety factor (SF) must be defined with respect to the input uncertainties and acceptable failure probability



Required SF vs. input uncertainties

- From recognized probabilistic theory (FOSM) described e.g. in */**
  - Strength description according to Basquin equation
  - Fatigue life assumed log-normally distributed
  - Aggregated uncertainty in fatigue life from uncertainties in load ($\Delta\sigma$) and strength (SN-curve)
    - $VC_N = m \cdot \sqrt{{VC_{\Delta\sigma}}^2 + {VC_{\Delta\sigma_{ref}}}^2}$
  - Safety factor (applied on $\Delta\sigma$) that limits the failure probability to p $SF = e^{\left(\frac{\theta_p \cdot VC_N}{m}\right)}$





* Sundararajan, *Probabilistic Structural Mechanics Handbook,* 1995

** Joint Committee for Guides in Metroligy 100:2008, Guide to the expression of uncertainty in measurement data

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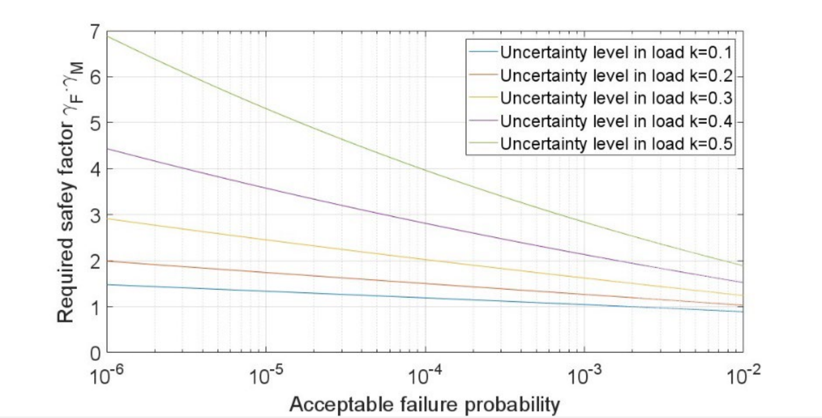
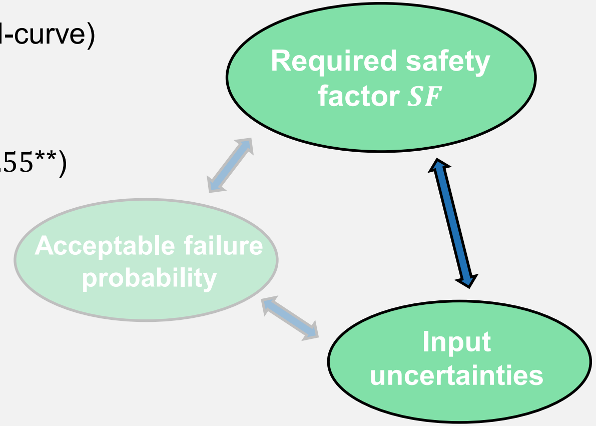
  - Safety factor (applied on $\Delta\sigma$) that limits the failure probability to p $SF = e^{\left(\frac{\theta_p \cdot VC_N}{m}\right)}$
  - Aggregated uncertainty in fatigue life from uncertainties in load ($\Delta\sigma$) and strength (SN-curve)
    - $VC_N = m \cdot \sqrt{VC_{\Delta\sigma}{}^2 + VC_{\Delta\sigma_{ref}}{}^2}$
    - Application of standard value of uncertainty in strength $VC_{\Delta\sigma_{ref}} = 0.18$ ($VC_{N_{ref}} = 0.55$**)
    - $VC_{\Delta\sigma}$ expressed in extreme values as $k = \frac{\Delta\sigma_{max} - \Delta\sigma_{min}}{2(\Delta\sigma_{max} + \Delta\sigma_{min})}$

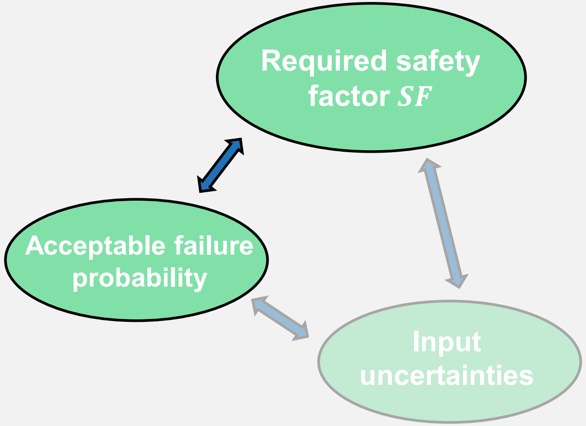




What failure probability can be accepted?

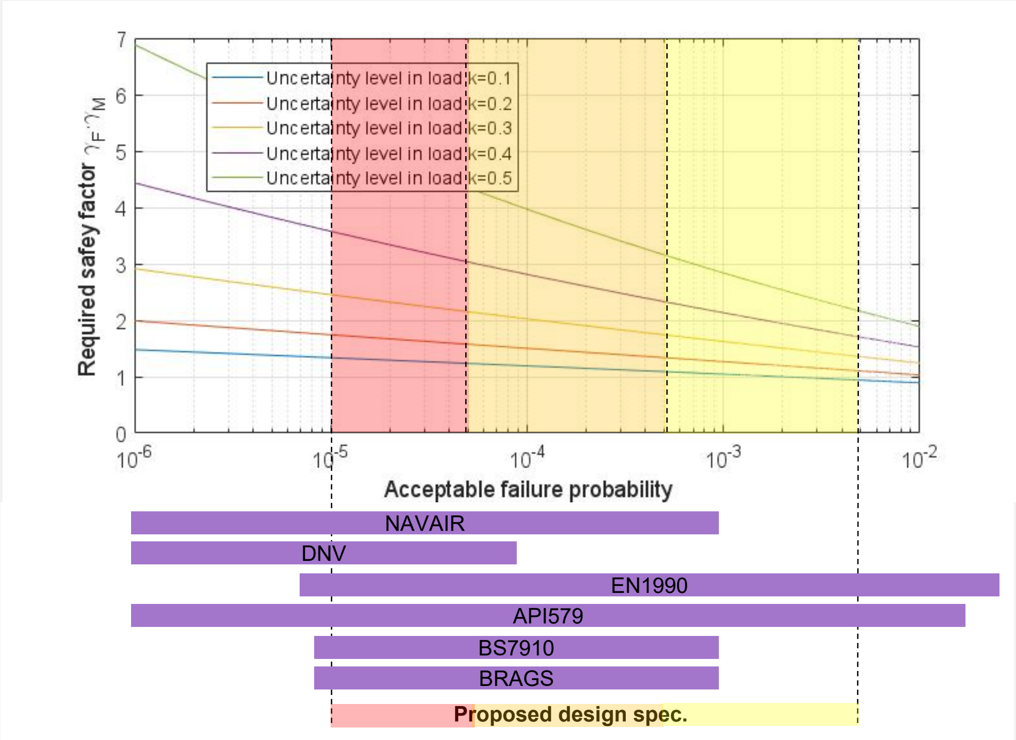
- Acceptable failure probabilities and consequence grading for other applications

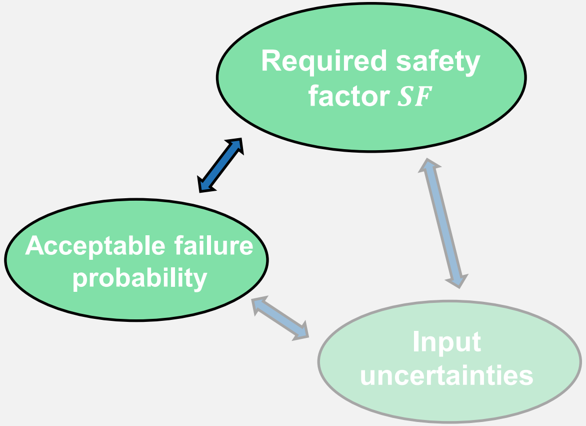
Source and application	Acceptable failure probability	Consequence grading
NAVAIR (Naval Aviation)	$10^{-6} – 10^{-3}$	Cost $1 mill. + possible death - $10000
DNV (Oil platforms)	$10^{-6} – 10^{-4}$	Non-quantified grading high / medium / low
EN1990 (Building and civil engineering)	$7.2x10^{-6}$ / $6.8x10^{-2}$	Collapse / Function
ASME API579 (Pressure vessels and piping)	10^{-6} / 10^{-3} / $2.3x10^{-2}$	Non-quantified grading high / medium / low
BS 7910 (Pressure vessels and piping non-redundant components)	10^{-5} / $7.0x10^{-5}$ / 10^{-3}	Non-quantified grading very severe / severe / moderate
BRAGS (Non-personel elevator (mining))	10^{-4} / 10^{-3}	Collapse / Function
BRAGS (Personel elevator (mining))	10^{-5} / 10^{-4}	Collapse / Function



What failure probability can be accepted?

- Three intervals of acceptable failure probability are defined





Consequence grading	Accepted failure probability
Loss of secondary parts	$5 \cdot 10^{-4} \leq pf < 5 \cdot 10^{-3}$
Loss of entire structure	$5 \cdot 10^{-5} \leq pf < 5 \cdot 10^{-4}$
Loss of human life	$1 \cdot 10^{-5} \leq pf < 5 \cdot 10^{-5}$

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Vänster:

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Thank you for your attention!