Fatigue of aluminium structures EN 1999-1-3

Eurocode 9: Design of aluminium structures

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Contents

Fatigue

Crack initiation and propagation due to repeated loading

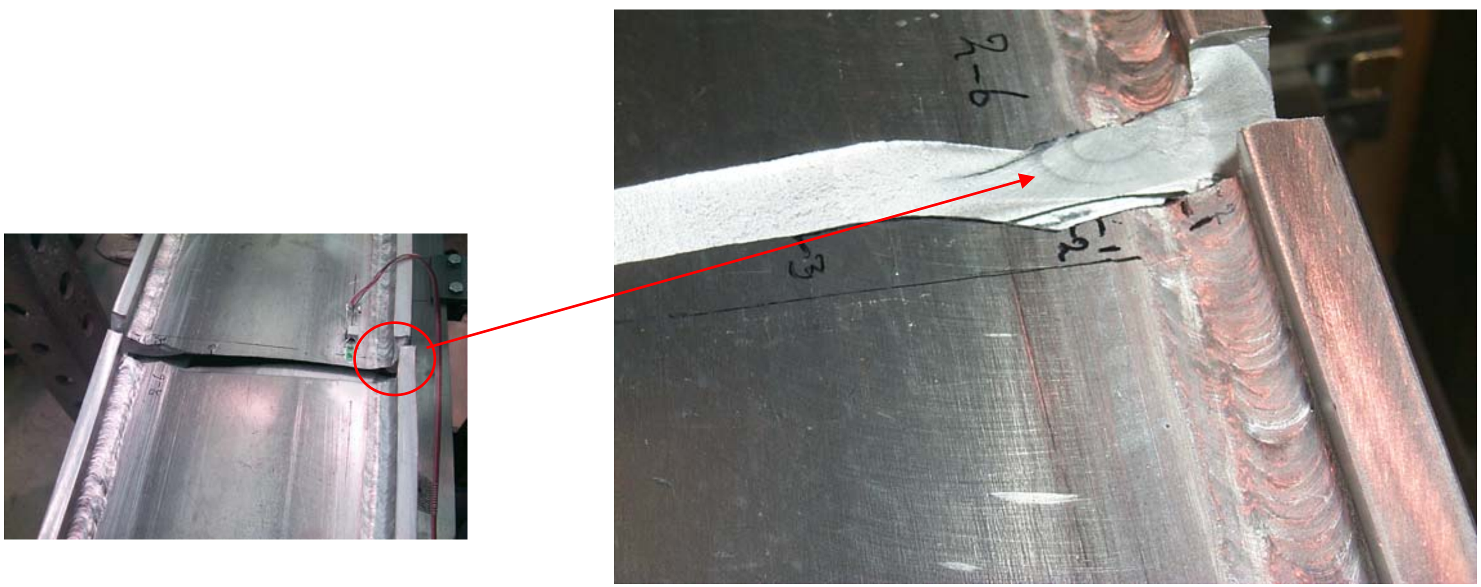
Examples of repeated loading:

- Traffic loads
- Wave loads
- Wind loads

Fatigue and aluminium

Important for aluminium structures, due to generally high ratio between life load and dead load

Example of fatigue crack:

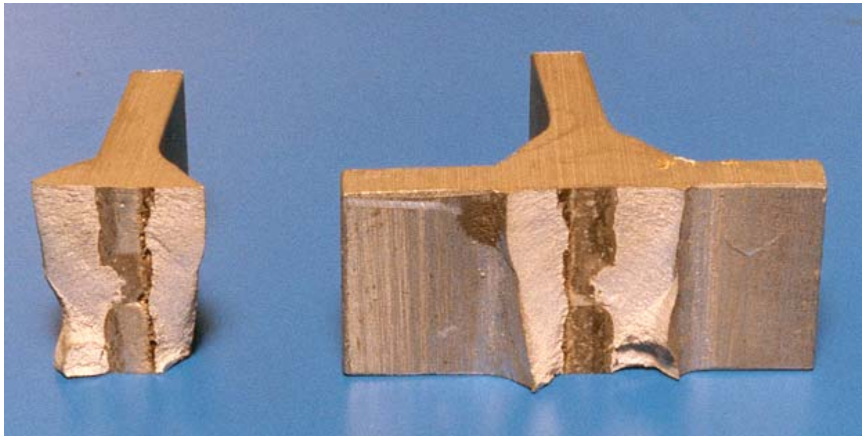


Eurocodes

Loads	Design	Execution / Inspection
Eurocode 1 EN 1991	Eurocode 9 EN 1999 → 1-1: General structural rules → 1-2: Fire design → **1-3: Fatigue design** → 1-4: Cold-formed sheets → 1-5: Shells	EN 1090-3 Execution Quality / Quality control Inspection / Supervision

Background to EN 1999-1-3

- **General format of code for steel structures, but with specific issues for aluminium**
- **Based on a comprehensive and reliable data bank**
  - Small-size component tests (shown here)
  - Full-size component tests
- **Refined statistical evaluation of test results**



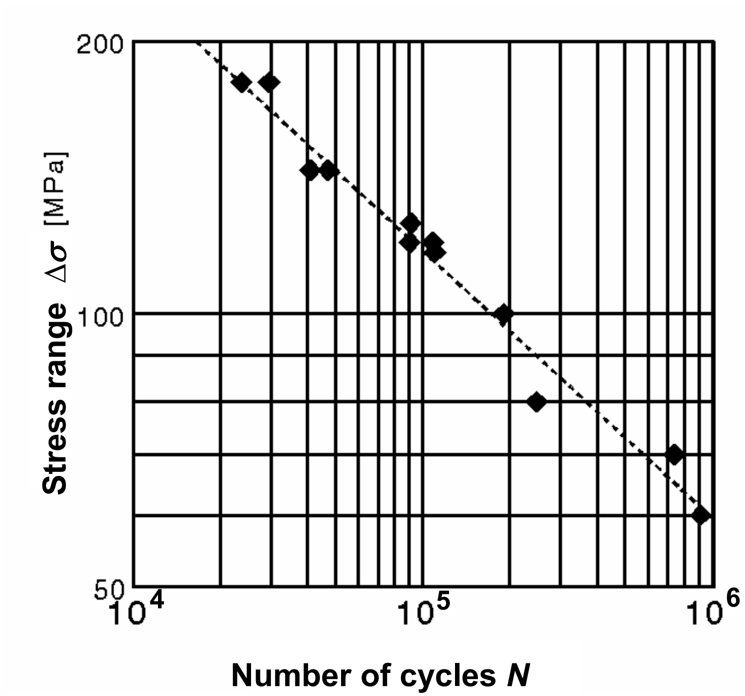
Fatigue design procedures

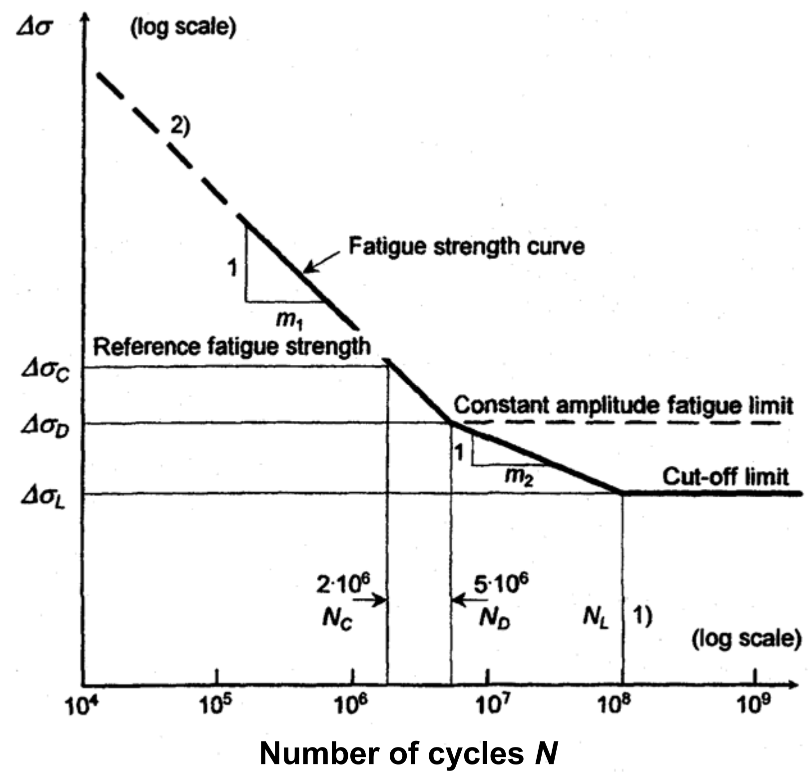
Three methods in EN 1999-1-3

- **Safe life design – S-N curve approach**
- **Damage tolerant design – Fracture mechanics approach**
- **Design assisted by testing**

S-N curves

- **S-N curve: Log-based relation between stress range and number of cycles:**



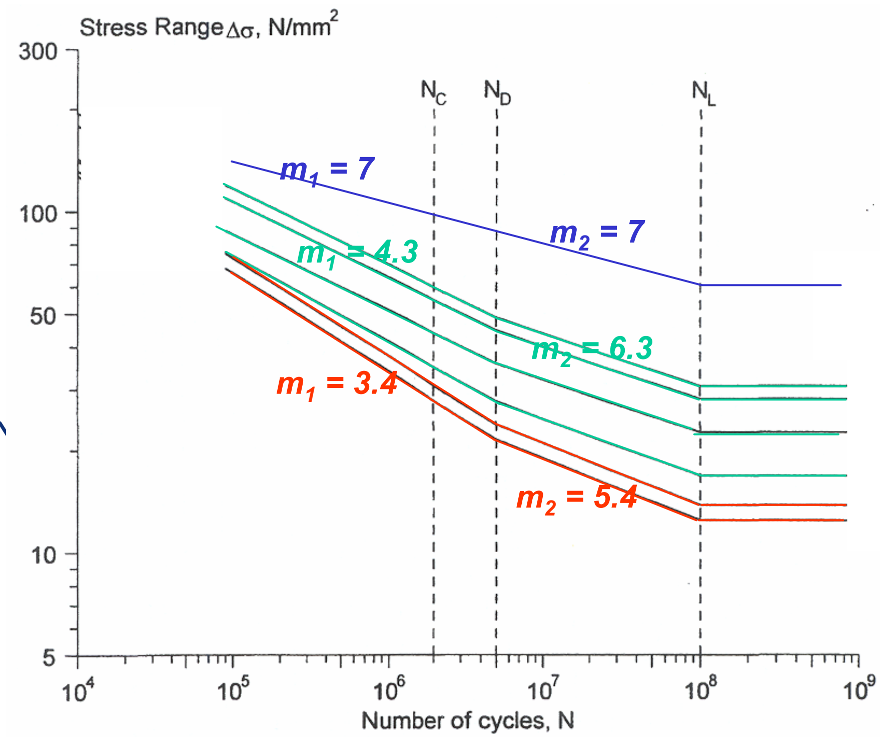


S-N curves for aluminium

- **Characteristic values depending on detail**
- **3 slopes in range N = 10^5 to $5 \cdot 10^6$:**
  - m_1 = 7 for base metal
  - m_1 = 4.3 or 3.4 for welded details
- **Influence of alloy on S-N curve: Base material**
  - Same S-N curve for all 5xxx and 6xxx alloys listed EN1999-1-1
  - Different (more favourable) curve for alloy 7020 Influence of alloy on S-

Welds

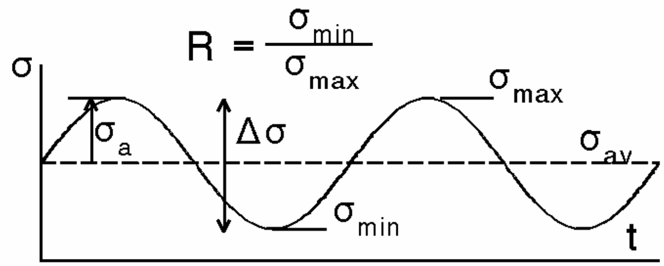
- Same S-N curve for all alloys

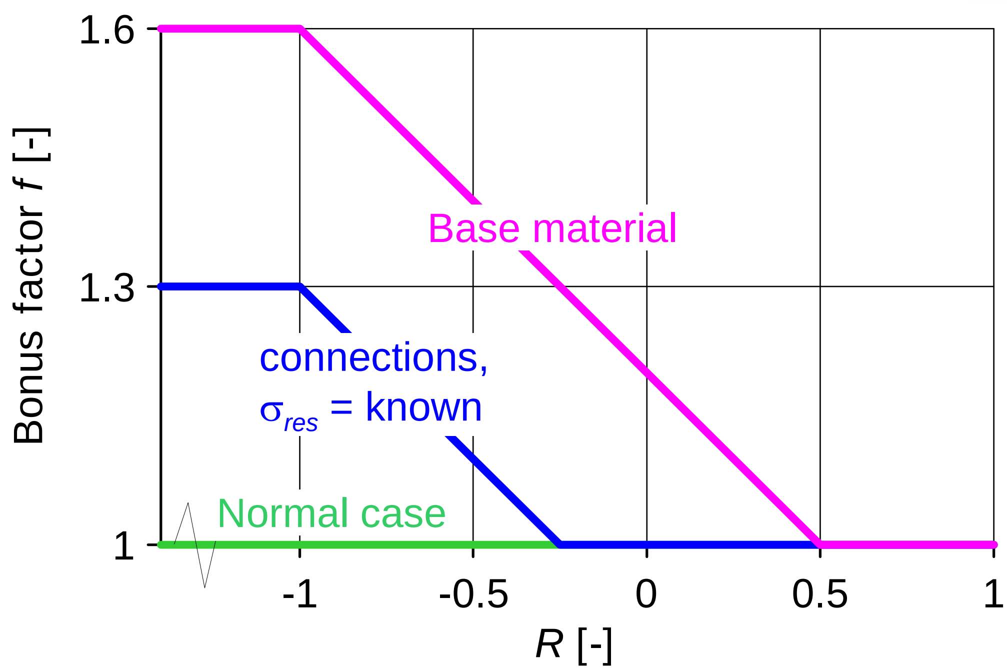


Mean stress effect

- **Taken into account by bonus factor**

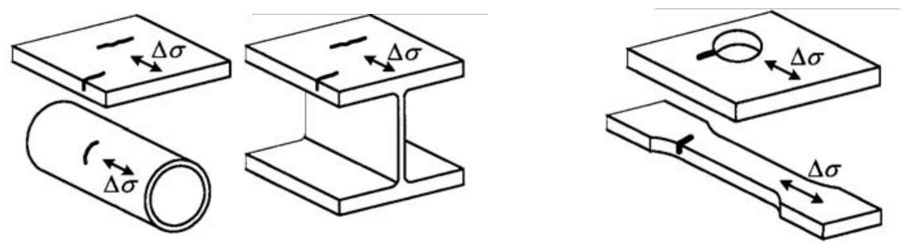
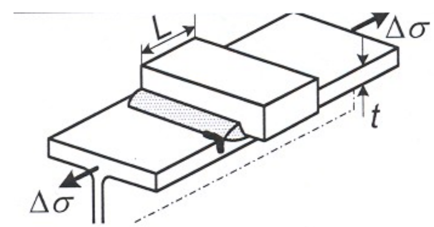
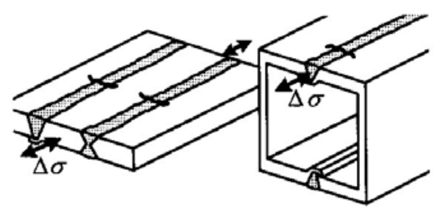
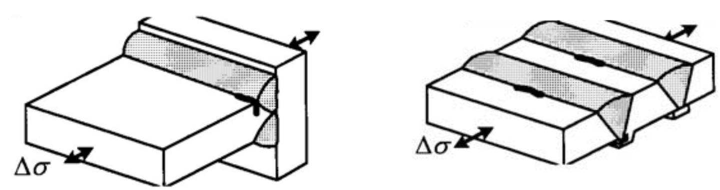
$$\Delta\sigma_{C(R)} = f\,\Delta\sigma_C$$





$$R_{eff} = \frac{2\sigma_{res} - \Delta\sigma}{2\sigma_{res} + \Delta\sigma}$$

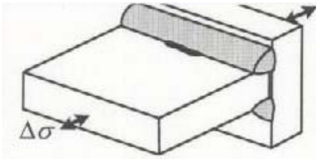
Types of details distinguished (1)

		$\Delta\sigma_c$
• Parent metal		70-100
• Welded attachments		18-36
• Longitudinal welds		28-63
• Butt welds		18-56

Types of details distinguished (2)

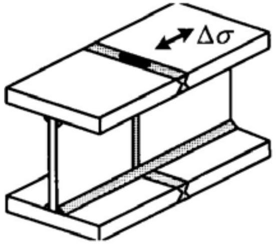
$\Delta\sigma_c$

- Fillet welds



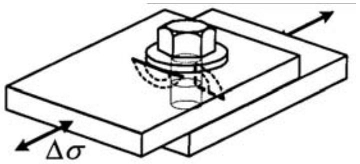
12-28

- Crossing welds in built-up beams



18-40

- Bolted joints



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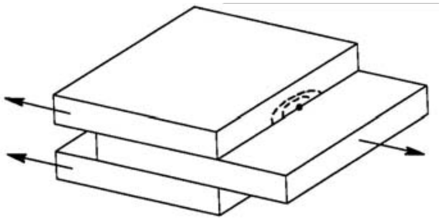
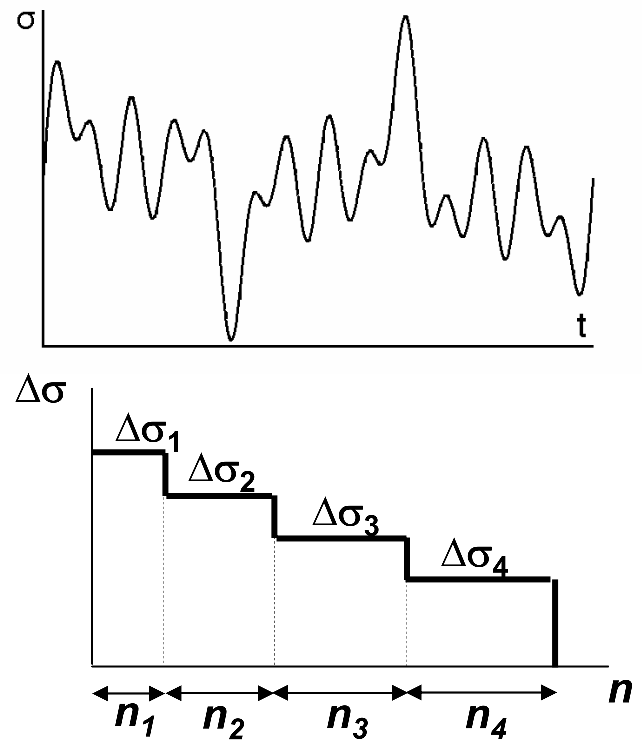
- Adhesive bonded joints



Variable amplitude load

- **Rainflow-counting method**
- **Spectrum**
- **Palmgren-Miner damage accumulation:**



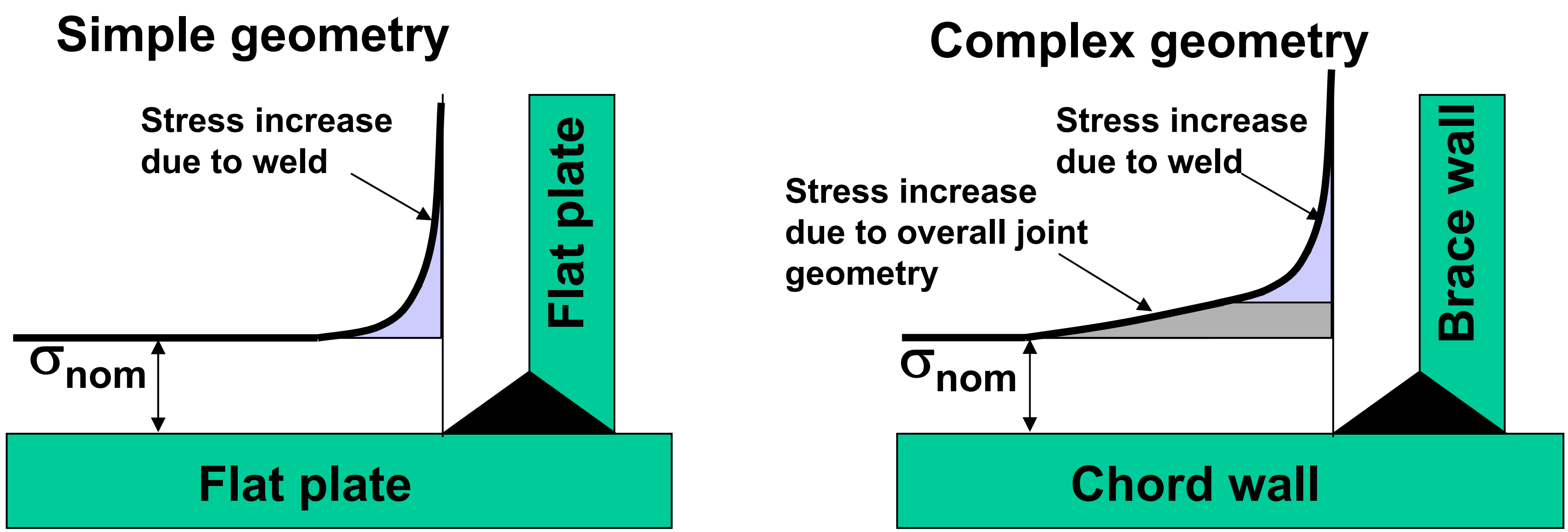
$$D = \Sigma_i \frac{n_i}{N_i}$$

n_i **Number of cycles in spectrum with range $\Delta\sigma_i$ (load)**
N_i **Number of cycles according to S-N curve with range $\Delta\sigma_i$ (resistance)**

D **Accumulative damage (shall be ≤ 1.0)**

Geometric stress analysis

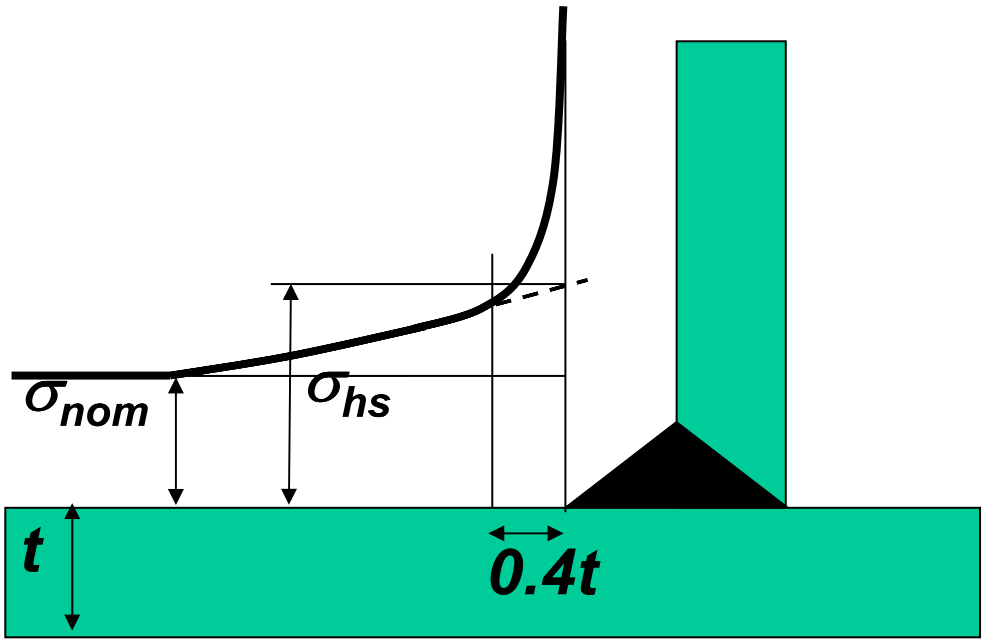
- Local stress concentration factor (due to weld geometry) in classification of detail
- Global stress concentration factor (due to overall joint geometry) depends on geometry:



Hot spot stress method

Not applicable according to EN 1999-1-3, because:

- **Variable stress-strain relationship in HAZ**
- **Finite element results depend on mesh density, type of modelling and type of elements**



Reference detail procedure

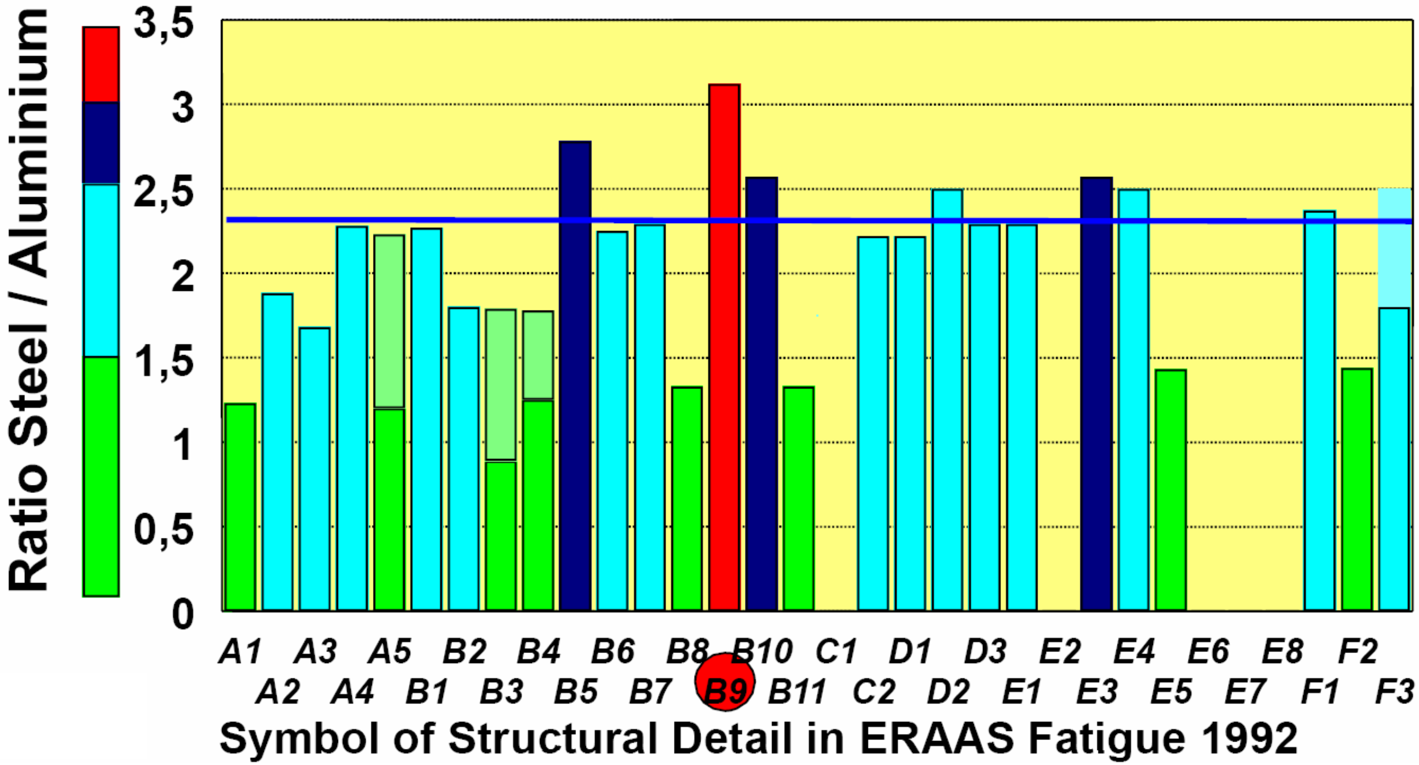
Method in EN 1993-1-1 to take into account the joint geometry:

- **Select similar detail (reference detail) and its S-N curve from EN 1999-1-2**
- **Identify type for stress of reference and assessed details**
- **Establish same FEM on both reference and assessed details**
- **Load both details with stress identified above**
- **Determine hot spot stress ranges (HS) for both details**
- **Assume for assessed detail the same slopes m1 and m2 as in reference detail**
- **Estimate fatigue strength for assessed detail at 2 x 10^6 cycles:**

$$\Delta\sigma_{C,assess} = \frac{\sigma_{HS,ref}}{\sigma_{HS,assess}} \Delta\sigma_{C,ref}$$

Steel versus aluminium (1)

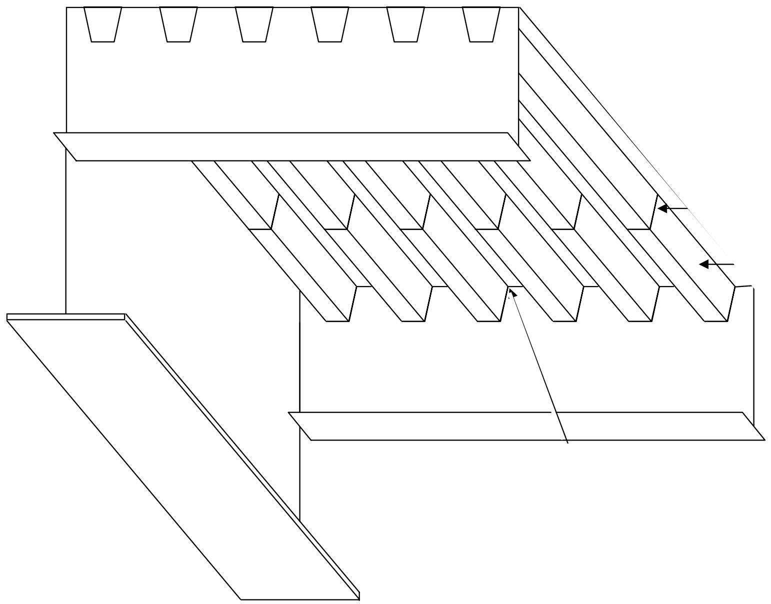
Fatigue design values at $2 \cdot 10^6$ cycles for various details



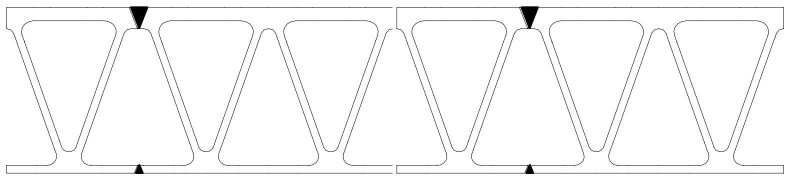
Steel versus aluminium (2)

Different designs

Steel bridge deck
Welded



Aluminium bridge deck
Extruded



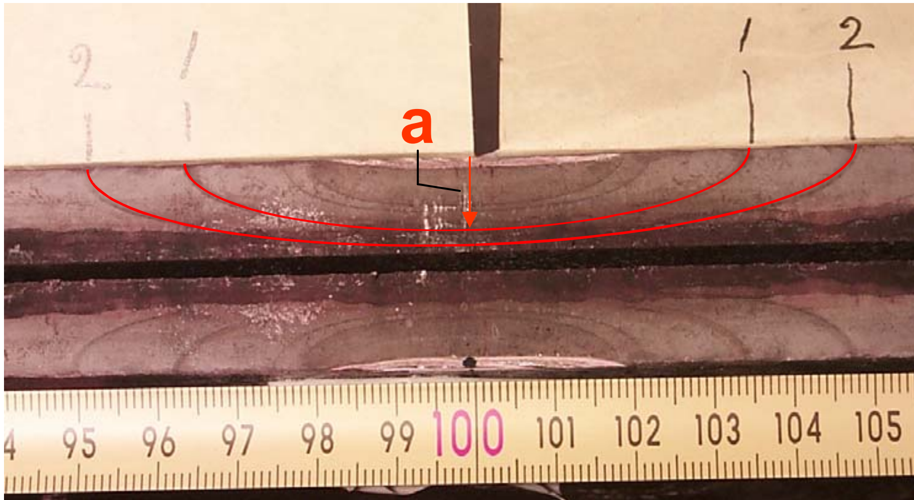
Damage tolerant design

Explanation damage tolerant design (1)

- Analytical background
- Starts with an initial defect
- Predicts crack growth

Crack growth due to one stress cycle related to joint geometry:

da / dN ←→ ΔK

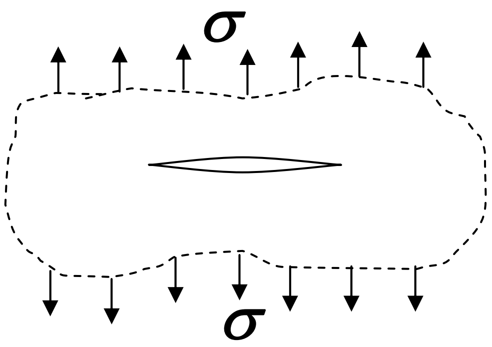


Explanation damage tolerant design (2)

da / dN ←→ ΔK

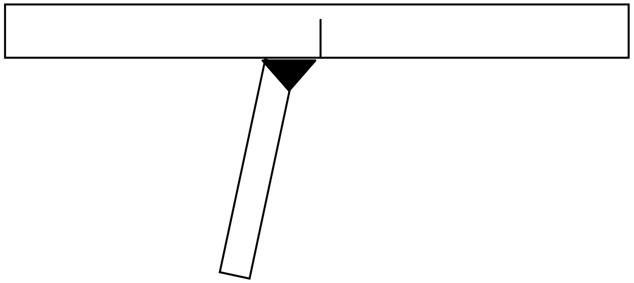
- **Central through-crack in infinitely large plate:**

$$K = \sigma \sqrt{\pi a}$$



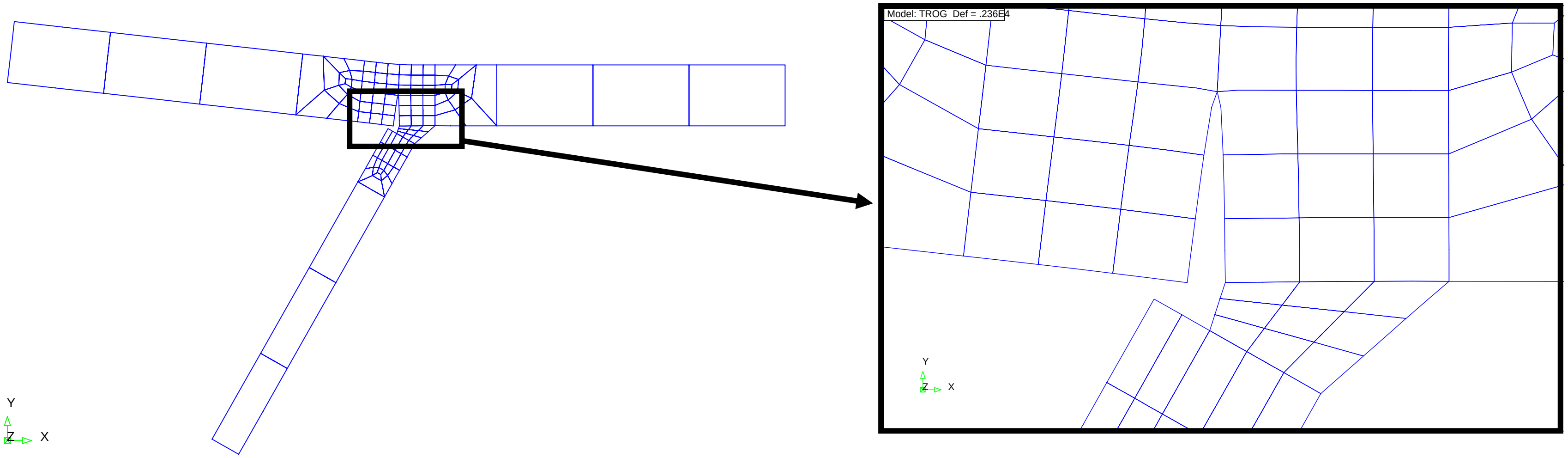
- **Other geometries:**

$$K = Y\sigma \sqrt{\pi a}$$



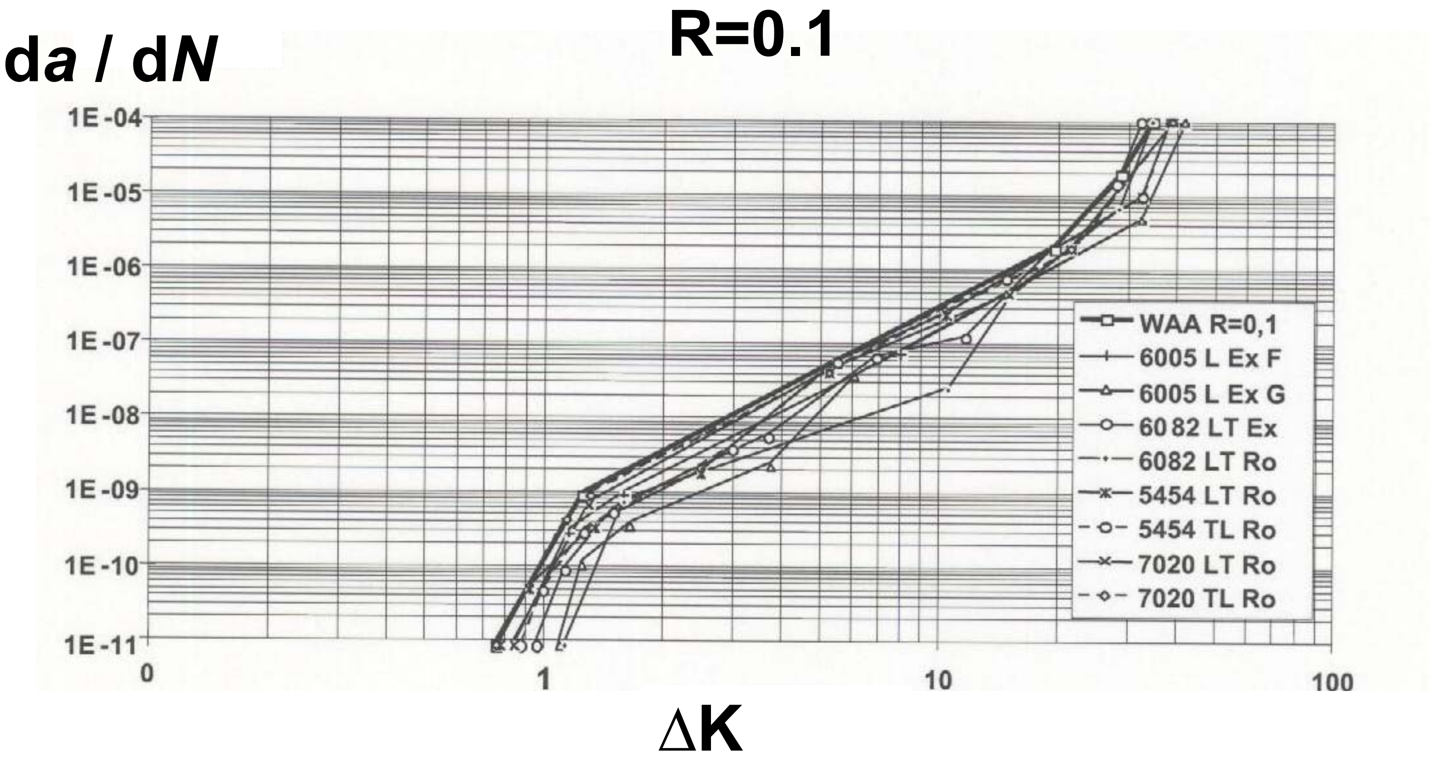
Determination of *Y*

Y = geometry factor, to be determined with FEM



Crack propagation data

Available for parent metal, HAZ and weld metal for (welded) aluminium alloys



Design by testing

Testing for fatigue design

Required in case:

- **Applied load spectrum is not available**
- **Geometry of structure is too complex for practical calculations**
- **Different materials, dimensional details, or manufacturing methods than those given in detail category tables**
- **Crack growth data are needed for damage tolerant design**

Acceptance

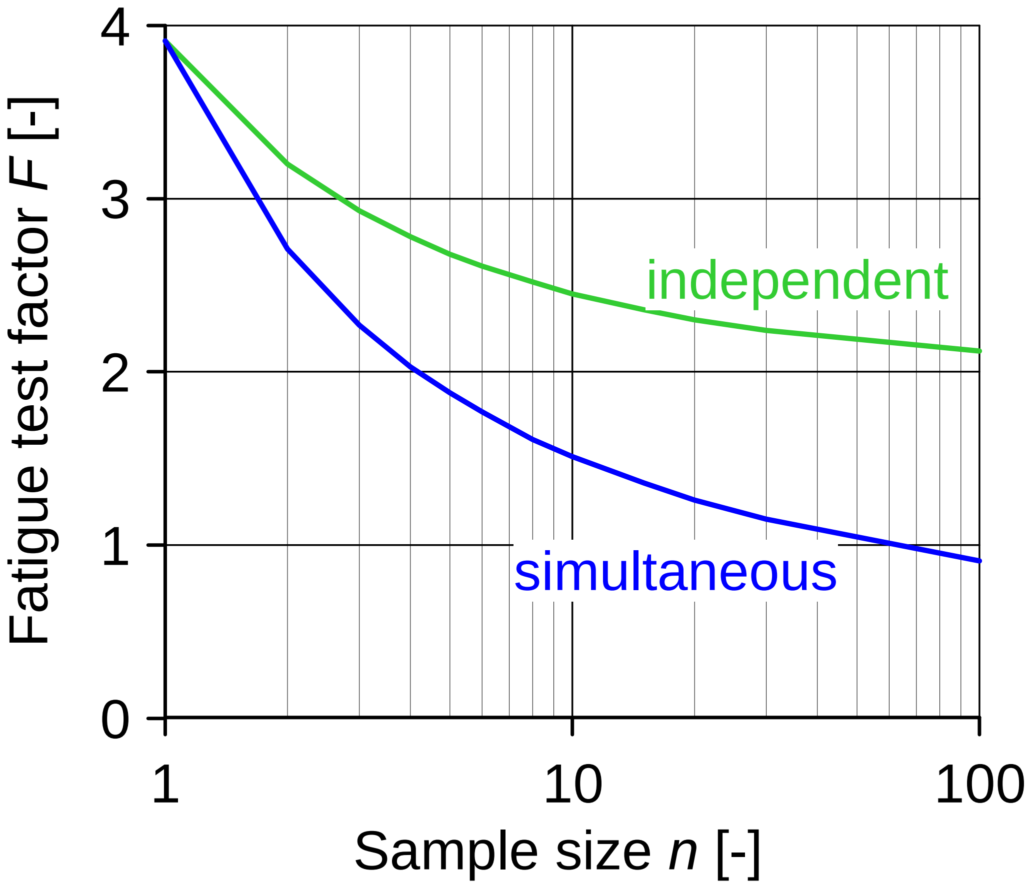
For safe life design:

$$T_L = \frac{T_m}{F}$$

T_L = Design life (in cycles)
T_m = Mean life to failure determined by tests (in cycles)
F = Fatigue test factor, depending on number of tests

Fatigue test factor

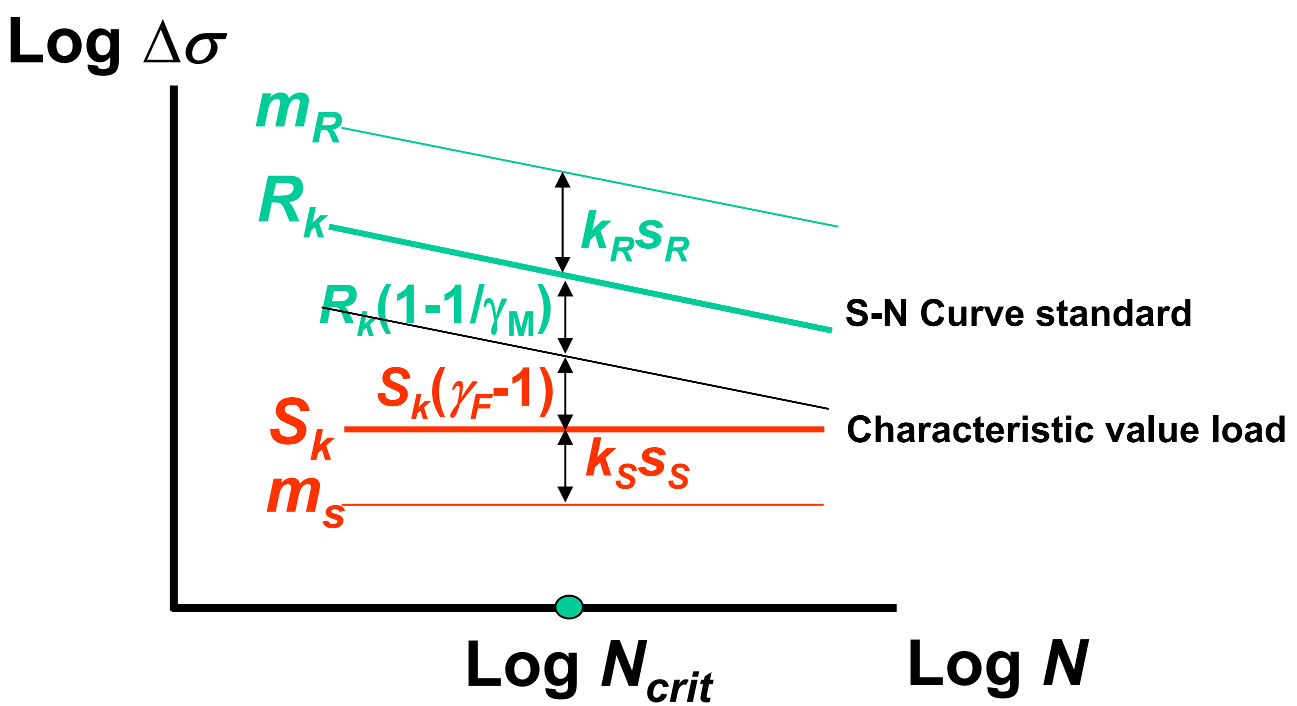
In agreement with EN 1990:



Safety factors and reliability

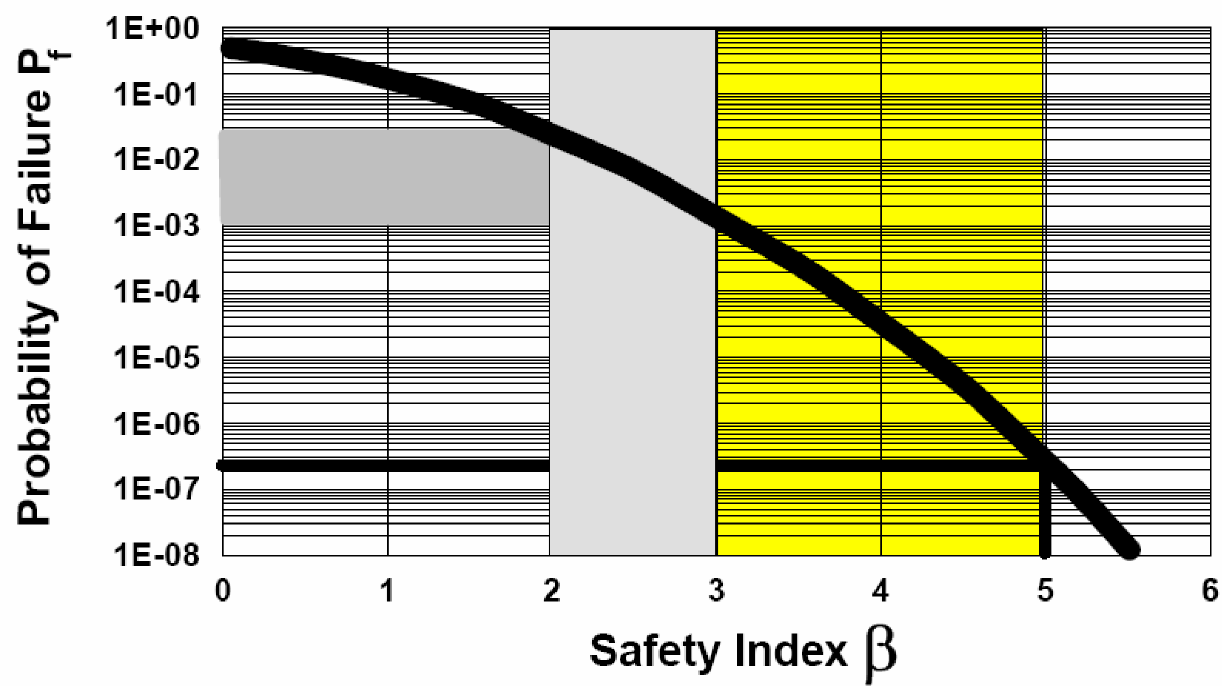
Partial safety factors

- Partial safety factor on loading γ_{Ff} = between 1.0 and 1.5
- Partial safety factor for fatigue strength γ_{Mf} = 1.0 (excluding adhesive bonded joints)



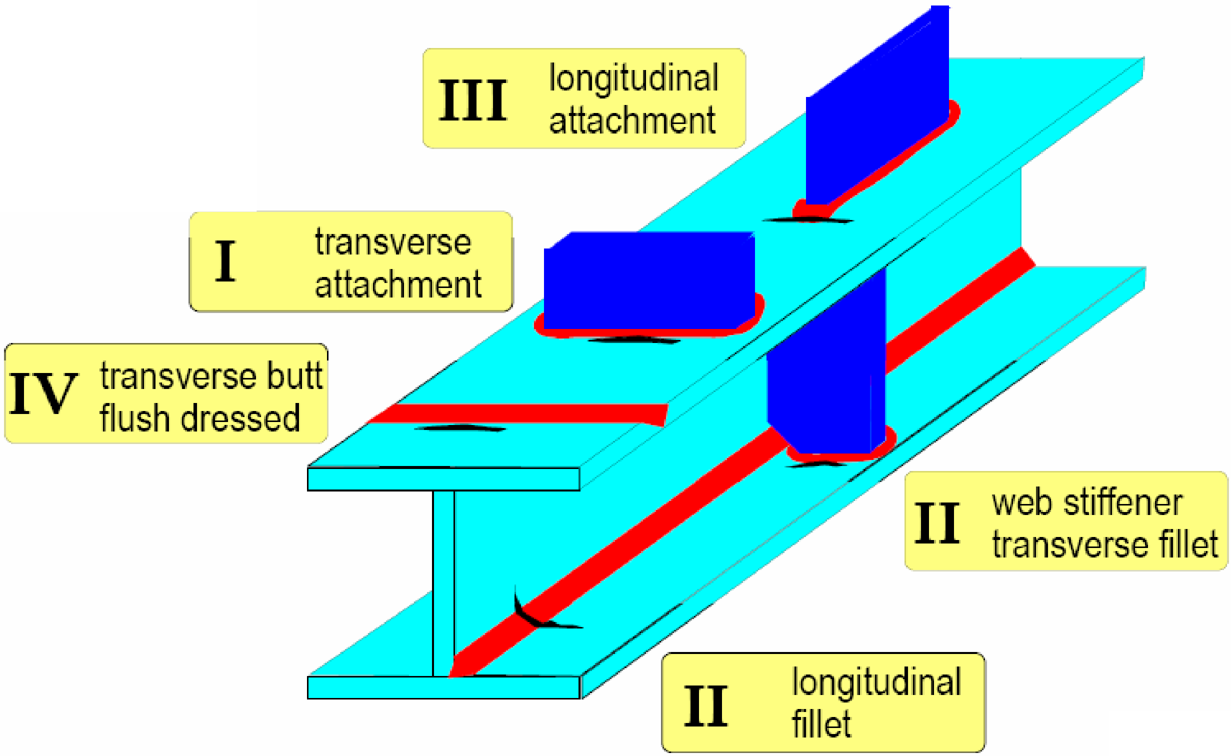
Reliability index

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 - \sigma_S^2}}$$



Example of reliability EN 1999-1-3

By Prof. Kosteas



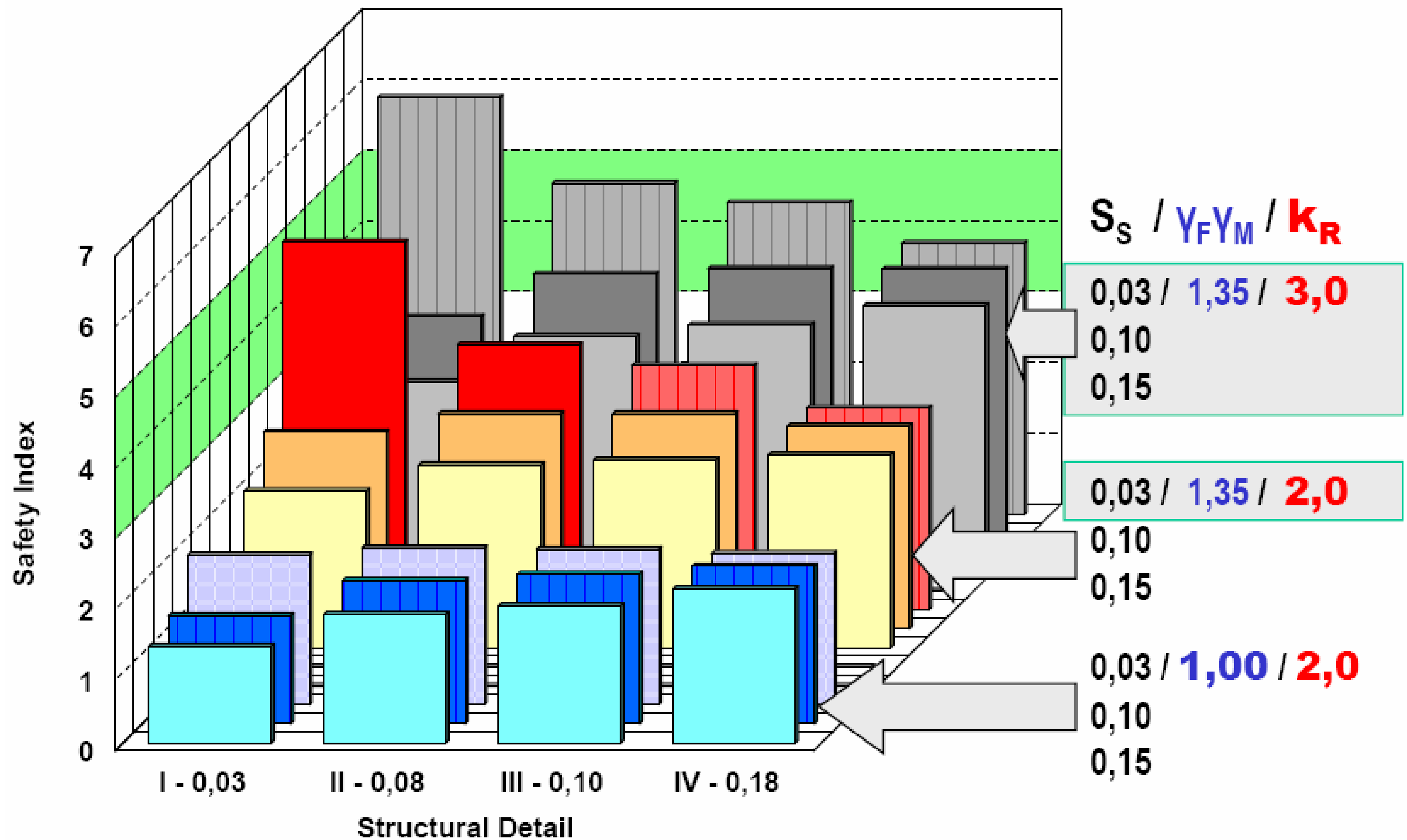
$k_R = 2.0$

$k_S = 1.0$

$s_r = 0.03\text{-}0.18$

$s_s = 0.03\text{-}0.15$

Example of reliability EN 1999-1-3

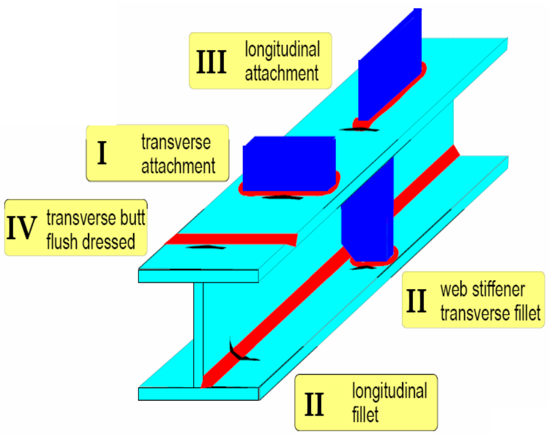


Example of reliability EN 1999-1-3

- $\gamma_M \ \gamma_F = 1.0 \rightarrow \beta \approx 2.2$
- $\gamma_M \ \gamma_F > 1.35 \rightarrow \beta \approx 3.5$

- Recommended value: $\beta \approx 3.8$

- This issue needs further elaboration



Fatigue design and execution

Relation Eurocodes

Consequence class CC (3) EN 1990

Execution class EXC (4) EN 1999-1-1

↕

Execution requirements EN 1090-3

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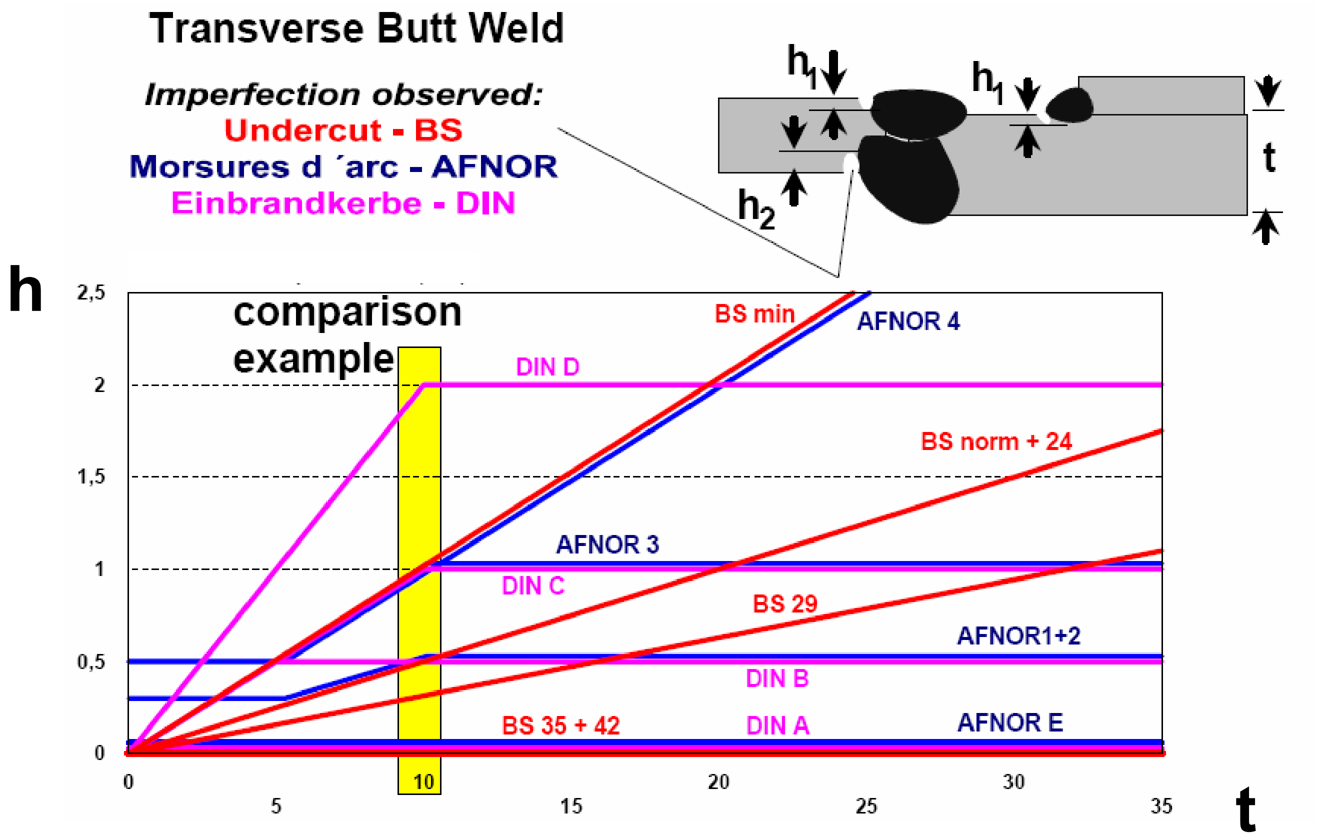
Acceptance criteria for welds in EN ISO 10042

Execution classes

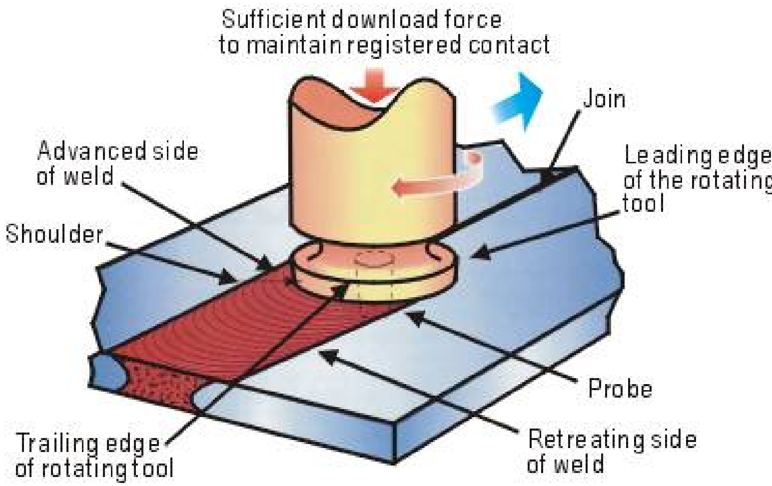
Conseq. class	CC1		CC2		CC3	
Service category	Quasi static	Fatigue	Quasi static	Fatigue	Quasi static	Fatigue
Non-welded	1	1	2	3	3	3
Welded	1	2	2	3	3	4

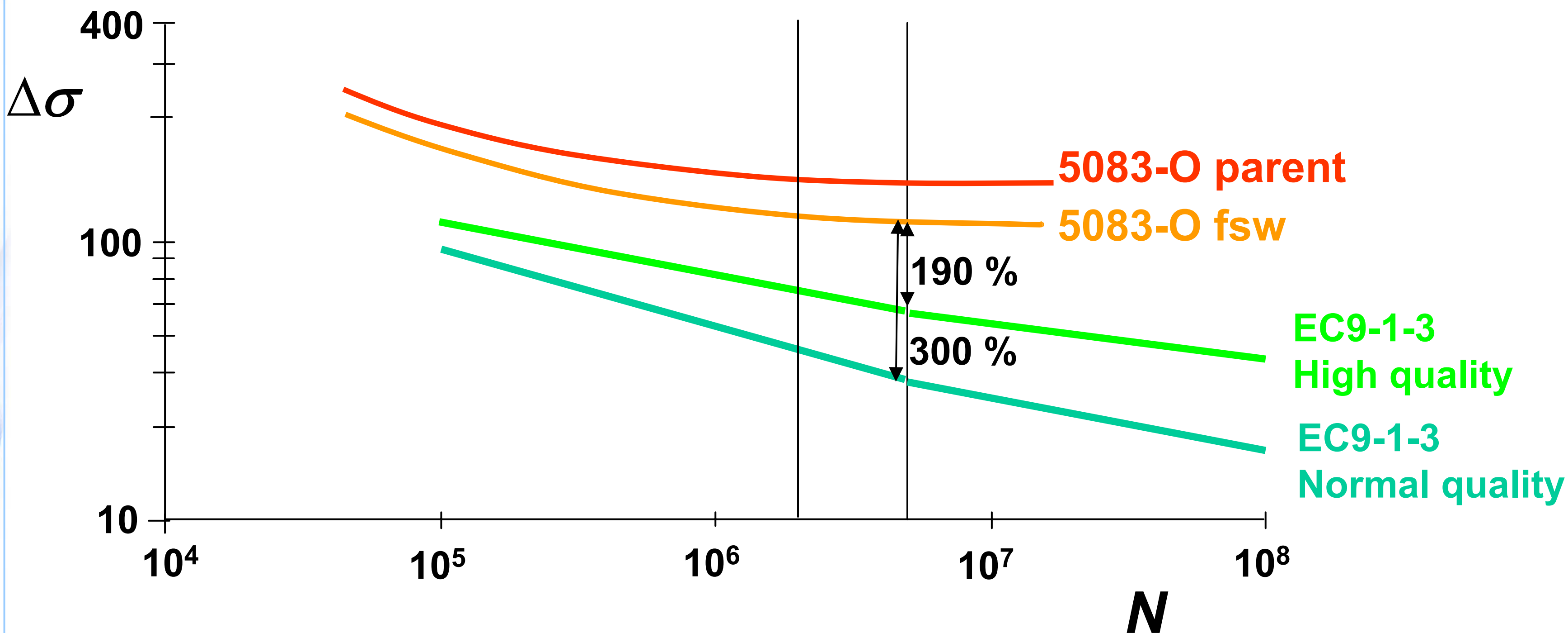
Further developments

Harmonisation of imperfections / classification



Friction stir welding





Conclusions & recommendations

- **EN 1999-1-3 is powerful fatigue design tool. It enhances:**
  - Safe life design (S-N curves)
  - Damage tolerant design (fracture mechanics)
  - Design by testing
- **Evaluation and simplification of requirements for inspection and acceptance**
- **Further work**
  - Friction stir welding
  - Damage tolerant design