INVESTMECH

Fatigue design according to standards BS EN 1993-1-9, SANS 10162-1 and IIW Bulletin 520

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Compulsory study material

1. EN 1993-1-9. CCYY. Eurocode 3: Design of steel structures – Part 1-9: Fatigue. *European Standard*
2. IIW Bulletin 520
3. BS 7608:2014

- Investmech course:
  - Investmech will issue a legitimate copy to every delegate
- University course:
  - The student shall obtain a legitimate copy for the purpose of this course
  - No notes or extractions from these documents will be made available to delegates
    - ❑ The copy made available to delegates will reference tables and figures

Scope of BS EN 1993-1-9: Eurocode 3 Part 9: Fatigue

- Gives methods for assessment of fatigue resistance of members, connections and joints subject to variable amplitude loading
  - Derived from fatigue tests with large scale specimens
  - Include effects of geometrical & structural imperfections from material production & execution
    - E.g. tolerances & residual stress from welding
- Execution shall conform with EN 1090
  - BS EN 1090-2:2008+A1:2011. Execution of steel structures and aluminium structures. Technical requirements for steel structures
    - Define products: steels, welding consumables, mechanical fasteners
    - Preparation, welding, testing, erection of structural systems
    - Inspection & correction to ensure maximum levels of quality control

- Applicable to all grades of:
  - Structural steels
  - Stainless steels
  - Unprotected weathering steels

  Steel must conform to toughness requirement of BS EN 1993-1-10
- Fatigue assessment **methods not covered**:
  - Fracture mechanics
  - Notch strain
- Improvement techniques:
  - Covered: Stress relieving
  - Not covered: Toe dressing, burring, peening, etc

See IIW Bulletin 520 & BS 7608 for comprehensive coverage of these methods

- Environment covered:
  - Structures operating under normal atmospheric conditions
  - Sufficient corrosion protection
  - Regular maintenance
- Environment not covered:
  - Effect of seawater corrosion
  - Microstructural damage from high temperature $> 150\ ^\circ C$

  See IIW Bulletin 520 & BS 7608 for coverage of these

- Other standards referred to
- BS EN 1090. Execution of steel structures – Technical requirements
- BS EN 1990. Basis of structural design
- BS EN 1991. Actions on structures
- BS EN 1993. Design of steel structures
- BS EN 1993-2. Design of composite steel and concrete structures: Part2: Bridges
- BS EN 1999. Aluminium

See the terms and conditions in the notes issued in class

Basics

- Structural members:
  - Design for fatigue such that there is an acceptable level of probability that their performance will be satisfactorily through their design life
    - Use fatigue actions from BS EN 1991
    - Use fatigue resistance curves from BS EN 1993-1-9
    - Use BS EN 1993-1-9 Annex A for specific loading model if:
      - No fatigue load model is available in BS EN 1991
      - A more realistic fatigue model is required
- Fatigue tests to:
  - Determine fatigue strength for details not included in this part
  - Determine fatigue life of prototypes for:
    - Actual fatigue loads
    - Damage equivalent fatigue loads
  - Take BS EN 1990 into account for structural inputs
- Methods for fatigue assessment in BS EN 1993-1-9:
  - Principle of design verification comparing action effects & fatigue strengths
    - Only possible when fatigue actions are determined with parameters of fatigue strengths prescribed
- Fatigue actions:
  - Determined according to requirements of fatigue assessment
  - Are different from actions for ultimate limit state & serviceability limit state verifications
- Crack initiation
  - Do not necessarily mean the end of service life
    - Could be repaired with particular care to **avoid introducing more severe notch** conditions

Fatigue assessment methods

Damage Tolerant Method

- Provide acceptable reliability that structure will perform satisfactorily for its design life provided that:
  - Prescribed inspection and maintenance regime for detecting and correcting fatigue damage is implemented throughout the design life
- Apply in the event where fatigue damage occurring, a load distribution between components of structural elements can occur
- Structures assessed to BS EN 1993-1-9 & material according to BS EN 1993-1-10 subjected to regular maintenance = damage tolerant

Safe Life Method

- Provide acceptable level of reliability that structure will perform satisfactorily for design life without need for regular in-service inspection for fatigue damage
- Apply in cases where local formation of cracks in one component could rapidly lead to failure of the structural element or structure
- Implies that the structure will resist the ultimate limit state load at the end of its design life

Partial factor for fatigue strength

- Use partial factor for fatigue strength γ_{Mf} taking into account
  - Consequences of failure
  - Design assessment used

Assessment method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1.00	1.15
Safe life	1.15	1.35
Source: BS EN 1993-1-9, 2005:11		

This leads to a reduced fatigue strength: $\Delta\sigma_{C,red} = \frac{\Delta\sigma_C}{\gamma_{Mf}}$

- Fatigue strengths
  - Are determined considering:
    - ❑ Structural detail
    - ❑ Metallurgical and geometric notch effects
    - ❑ Probable site of crack initiation
  - Standard details applicable to nominal stresses
    - ❑ Cross-section dimensions that has an effect on the nominal stress
  - Reference weld configurations applicable to geometric stresses
    - ❑ Stress concentrations due to the geometry can result at weld detail that must be included
- Achieving reliability: Damage Tolerant Method
  - Selecting details, materials, stress levels so that in the event of crack initiation
    - ❑ low rate of crack propagation result
    - ❑ long critical crack length can result
  - Provision of multiple load path
  - Provision of crack-arresting detail
  - Provision of readily inspectable details during regular inspections
- Achieving reliability: Safe-life method
  - Selecting details and stress levels resulting in a fatigue life sufficient to achieve the β values equal to those for ultimate limit state verifications at the end of the design life

Stresses from fatigue actions

- Nominal stresses take into account:
  - All actions
  - Distortional effects
  - Linear elastic analysis for members and connections
- Latticed girders made of hollow sections:
  - Model may be based on simplified truss model with pinned connections
    - ❑ Stresses due to external loading applied to members between joints must be taken into account
    - ❑ The effects from secondary moments due to the stiffness of the connection can be allowed for by k_1 factors
- When hot-spot stress is calculated at weld toe using shell/solid elements, no factors are used because the FEA calculates all stresses

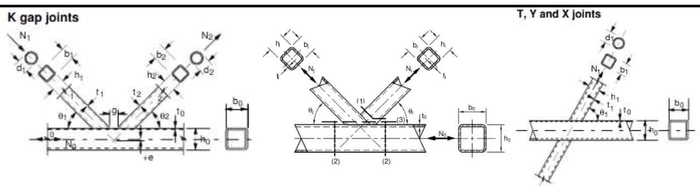


Table 4.1: k_1-factors for circular hollow sections under in-plane loading

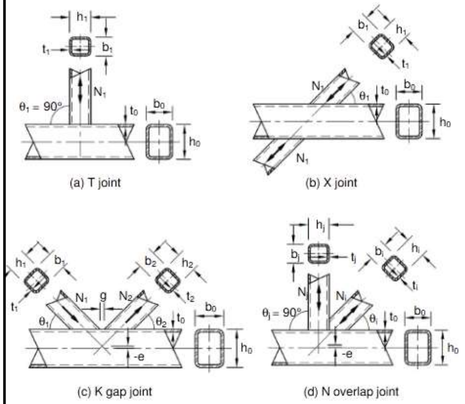
Type of joint		Chords	Verticals	Diagonals
Gap joints	K type	1,5	1,0	1,3
	N type / KT type	1,5	1,8	1,4
Overlap joints	K type	1,5	1,0	1,2
	N type / KT type	1,5	1,65	1,25

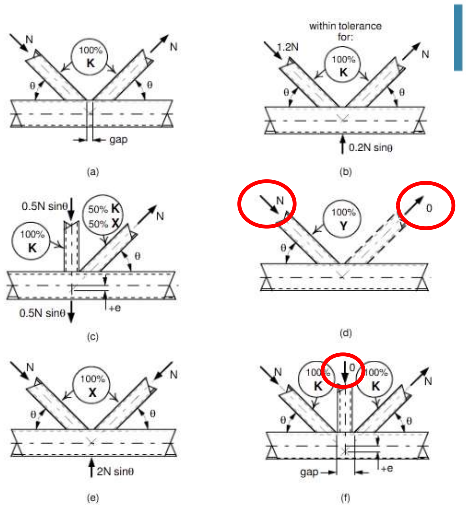
Reference: BS EN 1993-1-9, 2005:11

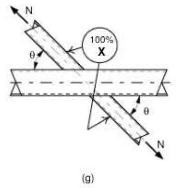
Table 4.2: k_1-factors for rectangular hollow sections under in-plane loading

Type of joint		Chords	Verticals	Diagonals
Gap joints	K type	1,5	1,0	1,5
	N type / KT type	1,5	2,2	1,6
Overlap joints	K type	1,5	1,0	1,3
	N type / KT type	1,5	2,0	1,4

Reference: BS EN 1993-1-9, 2005:12







http://www.scribd.com/doc/37761724/25/Joint-resistance-equations-for-T-Y-X-and-K-gap-joints Page 29 and 30
PACKER, J.A., WARDENIER, J., ZHAO, X.L., VAN DER VEGTE, A. & KUROBANE, Y. 2009. Design guide for rectangular hollow section (RHS) under predominantly static loading. Cidect.

The loads on the joint effects the joint classification!

Calculation of stresses

- Calculate at the serviceability limit state
- Class 4 cross-sections
  - According to BS EN 1993-1-5
    - See BS EN 1993-2 to BS EN 1993-6
- Calculate nominal stress at site of potential fatigue initiation
  - Account for stress concentrations at detail other than those in Table 8.1 to Table 8.10 by using stress concentration factor according to 6.3 to give *modified nominal stress*
- For geometrical (hot spot) stress approach as per Table B.1 calculate stress as per Section 6.5

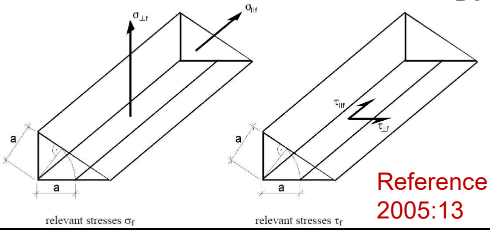
- Relevant stresses:
  - Nominal direct stress: σ
  - Nominal shear stress: τ
  - Use combined effect where applicable
- Relevant stresses - equations:
  - Normal stresses transverse to the axis of the weld:

$$\sigma_{wf} = \sqrt{\sigma_{\perp f}^2 + \tau_{\perp f}^2}$$

  - Shear stresses longitudinal to the axis of the weld:

$$\tau_{wf} = \tau_{\parallel f}$$

  - Do TWO separate checks



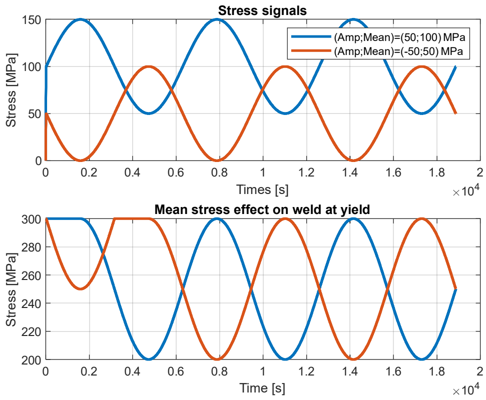
Reference: BS EN 1993-1-9, 2005:13

Stress range on weld fatigue curves

- The fatigue curves are given for 2 x amplitude (range = 2 x amplitude)
- Residual stress, etc. are treated based on empirical data
  - Non-heat-treated welds have a residual stress in the order of 0.7 x yield strength after welding and cooling
  - Results showed that large scale manufactured components can be modelled for fatigue using the stress ranges
  - After stress relieving, a reduced stress range (range = tensile - 60% x compressive) can be used in some cases to model fatigue
- Machined parts are modelled where mean stress correction is done and the completely reversed stress amplitude used as ordinate in the fatigue curve (we did this in the first few lectures)
- The important thing is:
  - Fatigue curves can be presented as stress range or stress amplitude
  - Stress range is normally used where the effect of mean stress is not modelled to the extent that it is done on analysis based on fatigue curves constructed with completely reversed stress amplitude as ordinate, and in which case mean stress effects need to be modelled

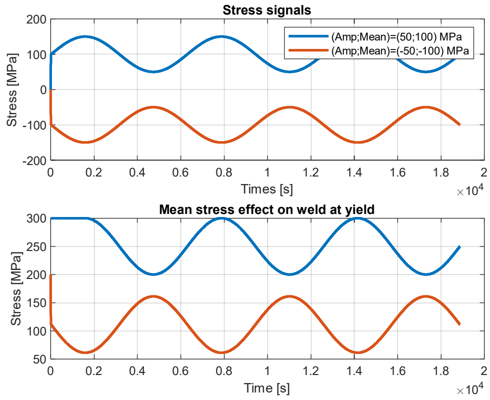
Effect of mean stress on stresses in the weld

- If the residual stress is taken as yield strength
- Applying a stress signal with different tensile mean stress will have the same response in the weld (because of yielding under tensile loading)



What about a tensile and compressive mean stress

- Standard suggest the use of 60% x compressive mean stress in SOME detail to model its benefit



Stress ranges

- Use:
  - Nominal stress ranges for details in Tables 8.1 to 8.10
  - Modified nominal stress ranges where:
    - Abrupt changes of a section close to initiation site not included in Tables 8.1 to 8.10
  - Geometric (hot spot) stress ranges:
    - Where high stress gradients occur close to weld toe in joints covered by Table B.1
- Design value of stress range to be used:

$$\Delta\sigma_{Design} = \gamma_{Ff}\Delta\sigma_{E,2}$$

Where $\boldsymbol{\Delta\sigma_{E,2}}$ **corresponds to** $\boldsymbol{N_C = 2 \times 10^6}$ cycles on the relevant

$\Delta\sigma_R - N$ curve and is: $\Delta\sigma_{E,2} = \frac{\Delta\sigma_{Design}}{\gamma_{Ff}}$

$\Delta\sigma_{E,2}$ is the equivalent constant amplitude stress range related to 2×10^6 cycles [MPa]

γ_{Ff} is the partial factor for equivalent constant amplitude stress ranges $\Delta\sigma_E$ & $\Delta\tau_E$ and is in most cases $\boldsymbol{\gamma_{Ff} = 1.0}$ because the exact loads are used

- Design value of **nominal stress ranges**:

$$\gamma_{Ff}\Delta\sigma_{E,2} = \gamma_1\gamma_2\gamma_i \dots \gamma_n \times \Delta\sigma(\gamma_{Ff}Q_k)$$
$$\gamma_{Ff}\Delta\tau_{E,2} = \gamma_1\gamma_2\gamma_i \dots \gamma_n \times \Delta\tau(\gamma_{Ff}Q_k)$$

Where

$\Delta\sigma(\gamma_{Ff}Q_k), \Delta\tau(\gamma_{Ff}Q_k)$ is the stress range caused by the fatigue loads specified in EN 1991
γ_i are damage equivalent factors depending on the spectra as specified in EN 1993
Use Annex A where no appropriate data is available for γ_i

- Design value of **modified nominal stress range**:

$$\gamma_{Ff}\Delta\sigma_{E,2} = k_f\gamma_1\gamma_2\gamma_i \dots \gamma_n \times \Delta\sigma(\gamma_{Ff}Q_k)$$
$$\gamma_{Ff}\Delta\tau_{E,2} = k_f\gamma_1\gamma_2\gamma_i \dots \gamma_n \times \Delta\tau(\gamma_{Ff}Q_k)$$

Where:

k_f is the stress concentration factor to take account of local stress magnification in relation to detail geometry not included in the reference $\Delta\sigma_R - N$ curve

Use handbooks or FEA to determine

- Design value of stress range for **geometrical (hot spot) stress**:

$$\gamma_{Ff}\Delta\sigma_{E,2} = k_f(\gamma_{Ff}\Delta\sigma^*_{E,2})$$

Where:

k_f is stress concentration factor

- Design value of stress range for welded joints of **hollow sections**:

$$\gamma_{Ff}\Delta\sigma_{E,2} = k_1(\gamma_{Ff}\Delta\sigma^*_{E,2})$$

Where:

$\gamma_{Ff}\Delta\sigma^*_{E,2}$ is the design value of stress range calculated with simplified truss model with pinned joints

k_1 is the magnification factor according to Table 4.1 or Table 4.2 to make provision for the secondary stresses due to the joint stiffness

Table 4.1: k_1-factors for circular hollow sections under in-plane loading

Type of joint		Chords	Verticals	Diagonals
Gap joints	K type	1,5	1,0	1,3
	N type / KT type	1,5	1,8	1,4
Overlap joints	K type	1,5	1,0	1,2
	N type / KT type	1,5	1,65	1,25

Reference: BS EN 1993-1-9, 2005:11

Table 4.2: k_1-factors for rectangular hollow sections under in-plane loading

Type of joint		Chords	Verticals	Diagonals
Gap joints	K type	1,5	1,0	1,5
	N type / KT type	1,5	2,2	1,6
Overlap joints	K type	1,5	1,0	1,3
	N type / KT type	1,5	2,0	1,4

Reference: BS EN 1993-1-9, 2005:12

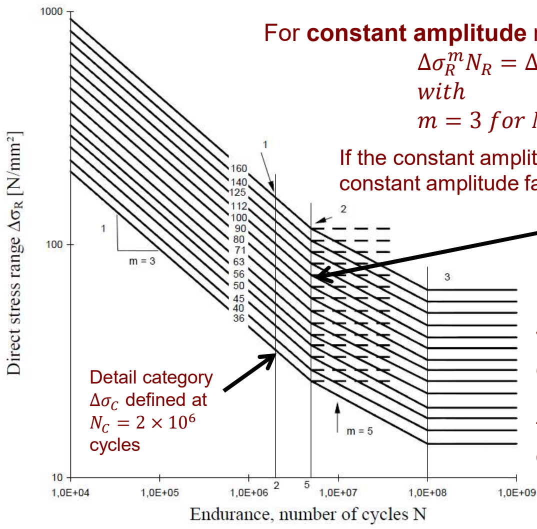
Typical values for γ_{Ff}

- Include typical values for γ_{Ff} See BS EN 1001-2:2003 Annex D 2(2)
  - For bridges: EN 1993-2 9.3(1)
    - The partial load factor is $\gamma_{Ff} = 1.0$
    - That is, the exact loads are used for fatigue calculations in bridges
- Imposed loads: EN 1991-1-1 and EN 1990, 1.5.3 and 4.1.1.
- Use section on bridges to demonstrate. There is a good example.
  - EN 1994-2-2:2005

Damage fatigue factors for bridges

- $\lambda = \lambda_1 \lambda_2 \lambda_3 \lambda_4 \leq \lambda_{max}$
- λ_1:
  - Takes damage effect of traffic into account
  - Depends on critical length of the influence line or area
- λ_2:
  - Takes spectrum of traffic frequency and weights into account
  - Fairly crude factor
- $\lambda_3 = \left(\frac{t_{Ld}}{100}\right)^{\frac{1}{5}}$:
  - Takes into account the design life of the bridge where t_{Ld} is the design life in years
- λ_4:
  - Takes into account traffic on other lanes
  - Due to the ability of most bridges to transmit load transversely, detail will usually attract fatigue stress from vehicles passing in lanes remote from those directly above them

Fatigue strength: Constant amplitude stress



For **constant amplitude** nominal fatigue strengths:

$$\Delta\sigma_R^m N_R = \Delta\sigma_C^m 2 \times 10^6$$
$$with$$
$$m = 3 \; for \; N \leq 5 \times 10^6$$

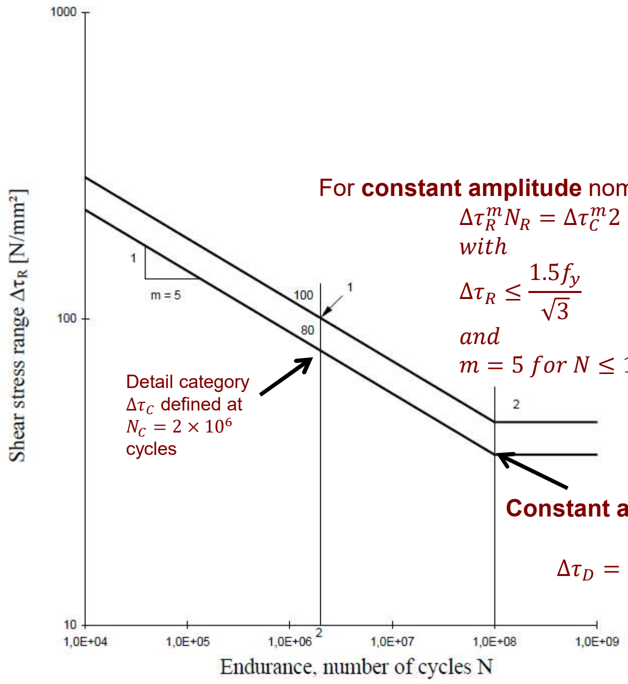
If the constant amplitude stress range is less than the constant amplitude fatigue limit → infinite fatigue life

Constant amplitude fatigue limit:

$$\Delta\sigma_D = \left[\frac{2}{5}\right]^{\frac{1}{3}} \Delta\sigma_C = 0.737\Delta\sigma_C$$

Detail category $\Delta\sigma_C$ defined at $N_C = 2 \times 10^6$ cycles

The curves are for a 75% confidence level of 95% probability of survival for log(N), taking into account the standard deviation and sample size and residual stress effects



For **constant amplitude** nominal fatigue strengths:

$$\Delta\tau_R^m N_R = \Delta\tau_C^m 2 \times 10^6$$

with

$$\Delta\tau_R \leq \frac{1.5 f_y}{\sqrt{3}}$$

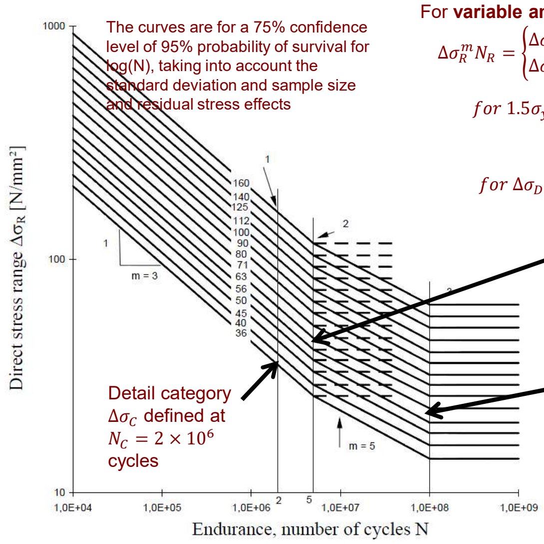
and

$$m = 5 \; for \; N \leq 100 \times 10^6$$

Constant amplitude cut off limit:

$$\Delta\tau_D = \left[\frac{2}{100}\right]^{\frac{1}{5}} \Delta\tau_C = 0.457\Delta\tau_C$$

Fatigue strength: Variable amplitude loading



For **variable amplitude** nominal fatigue strengths:

$$\Delta\sigma_R^m N_R = \begin{cases} \Delta\sigma_C^m 2 \times 10^6 & , m = 3 \; for \; N \leq 5 \times 10^6 \\ \Delta\sigma_D^m 5 \times 10^6 & , m = 5 \; for \; 5 \times 10^6 \leq N \leq 10^8 \end{cases}$$

$$for \; 1.5\sigma_y > \Delta\sigma_R \geq \Delta\sigma_D: \; N_R = \frac{\Delta\sigma_C^{m_1} N_C}{\Delta\sigma_R^{m_1}}, m_1 = 3$$

$$for \; \Delta\sigma_D > \Delta\sigma_R \geq \Delta\sigma_L: \; N_R = \frac{\Delta\sigma_D^{m_2} N_D}{\Delta\sigma_R^{m_2}}, m_2 = 5$$

Constant amplitude fatigue limit:

$$\Delta\sigma_D = \left[\frac{2}{5}\right]^{\frac{1}{3}} \Delta\sigma_C = 0.737\Delta\sigma_C$$

Cut off limit:

$$\Delta\sigma_L = \left[\frac{5}{100}\right]^{\frac{1}{5}} \Delta\sigma_D = 0.549\Delta\sigma_D$$

$$= 0.405\Delta\sigma_C$$

If no stress range exceeds the constant amplitude fatigue limit → infinite life. If one $\Delta\sigma_R$ exceeds $\Delta\sigma_D$ → finite fatigue life and use section of the curve below the knee-point.

Manipulation of $\Delta\sigma_R - N_R$ curves

For **variable amplitude** nominal fatigue strengths:

$$\Delta\sigma_R^m N_R = \begin{cases} \Delta\sigma_C^{m_1} \cdot 2 \times 10^6 & for\ N_R \leq 5 \times 10^6 \\ \Delta\sigma_D^{m_2} \cdot 5 \times 10^6 & for\ 5 \times 10^6 \leq N_R \leq 10^8 \end{cases}$$

Normally we have the stress range $\Delta\sigma_R$ and want to calculate the endurance, N_R,:

$$N_R = \begin{cases} \left(\frac{\Delta\sigma_C}{\Delta\sigma_R}\right)^{m_1} N_C \quad m_1 = 3 & for\ 1.5f_y > \Delta\sigma_R \geq \Delta\sigma_D \\ \left(\frac{\Delta\sigma_D}{\Delta\sigma_R}\right)^{m_2} N_D \quad m_2 = 5 & for\ \Delta\sigma_D > \Delta\sigma_R \geq \Delta\sigma_L \\ \infty & for\ \Delta\sigma_R < \Delta\sigma_L \end{cases}$$

$m_2 = m_1 + 2$

If we have the endurance, N_R, and want to calculation the stress range $\Delta\sigma_R$:

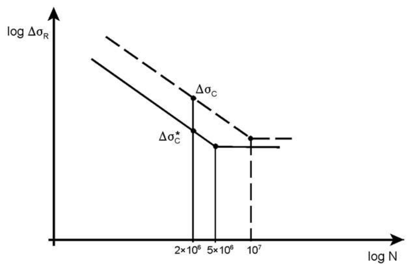
$$\Delta\sigma_R = \begin{cases} \Delta\sigma_C \left(\frac{N_C}{N_R}\right)^{\frac{1}{m_1}} & for\ N_R \leq N_D \\ \Delta\sigma_D \left(\frac{N_D}{N_R}\right)^{\frac{1}{m_2}} & for\ N_D < N_R \leq N_L \\ \Delta\sigma_L & for\ N_R > N_L \end{cases}$$

Test data for some details do not exactly fit the fatigue curves

These are marked with * to avoid non-conservative conditions, and are located **one detail category lower** than their fatigue strength at 2×10^6 cycles would require

An alternative assessment may **increase the classification of these * details by one category provided that the constant amplitude fatigue limit $\Delta\sigma_D$ is defined as the fatigue strength at 10^7 cycles and $m = 3$**

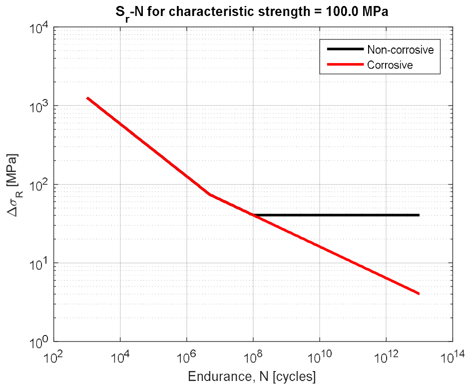
EN 19



Reduction factors from IIW Bulletin 520

Effect of corrosion

- Can reduce the fatigue class and reduce the position of the knee point
- For steel, except stainless steel, in marine environment:
  - For fatigue:
    - Reduce the S-N to 70% - that's just more than one detail category
    - Not fatigue limit applies, that is, the knee point disappears
  - For Fracture Mechanics:
    - Increase the crack growth constant by 3 ($3 \times C_o$)
    - No threshold value applies



Effect of temperature

Application of the effect of temperature on the BS EN 1993-1-9 curves implies:

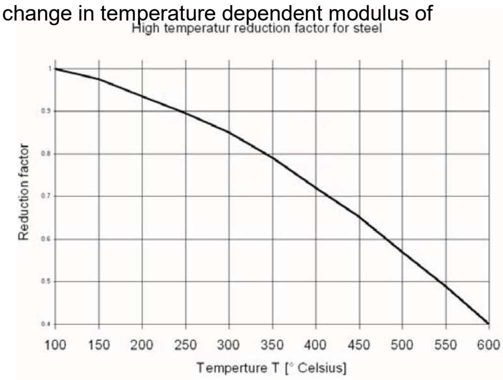
$$\Delta_{C,HT} = \Delta\sigma_C \frac{E_{HT}}{E_{20°C}}$$

$$C_T = \frac{E_{HT}}{E_{20°C}}$$

$$= \begin{cases} \min\begin{cases} 1.0 \\ -1.386 \times 10^{-6}T^2 - 2.547 \times 10^{-4}T + 1.046 \end{cases} & 0\,°C \le T \le 600\,°C \\ 0.0 & T > 600\,°C \end{cases}$$

That is, the fatigue curve is scaled by the change in temperature dependent modulus of elasticity

See notes for 2nd order polynomial trendline



Benefits due to post weld improvement according to IIW Bulletin 520

General
- May raise the fatigue resistance
- How:
  - Improve weld profile and reduce stress concentration
    - Machining or grinding of weld seam flush to surface
    - Machining or grinding the weld transition at the toe
    - Remelting the weld toe by TIG-, plasma or laser dressing
  - Control residual stresses
    - Peening (hammer-, needle-, shot-, brush-peening or ultrasonic treatment)
    - Overstressing (proof testing)
    - Stress relieving thermal treatments
  - Improve environmental conditions
    - Painting
    - Resin coating
- Improvement techniques may be used to:
  - Increase the fatigue strength of new structures
  - Ensure sufficient life during repair or upgrading of existing structures

- Applicability
  - All arc welded steel or aluminium components subjected to fluctuating/cyclic stress
  - Structural steel for $f_y \leq 900\ MPa$
  - Weldable structural aluminium alloys commonly used in welded structures
  - Apply to welded joints in:
    - Plates
    - Sections built up of plates
    - Similar rolled or extruded shapes
    - Hollow sections
  - Thicknesses:
    - Steel: 5 to 150 mm
    - Aluminium: 4 to 50 mm
  - Apply with the nominal stress or structural hot spot stress verification techniques
  - Improvement techniques apply solely to the weld toe and hence to a potential fatigue crack growth from this point
  - Benefit factors apply to the as-welded joint
  - Techniques can be joined (grinding then peening), but, must be proofed by testing to confirm a higher benefit factor than the last improvement
  - No benefit factors for joints operating under free corrosion

Weld improvement effects according to IIW Bulletin 520

Grinding

- Weld toe fatigue cracks initiate at:
  - Undercuts
  - Cold laps
  - Sharp edge-like imperfections

- Aim:
  - Remove imperfections
  - Create smooth transition between weld and plate

Therefore, remove stress concentrations

- Benefit factor:

$$\Delta\sigma_C = max \begin{cases} 1.3 \times \Delta\sigma_C \\ 112 \end{cases}$$

Tab. 3.5-2a: FAT classes for use with nominal stress at joints improved by grinding

Area of application and maximum possible claim	Steel	Aluminium
Benefit at details classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.3
Max possible FAT class after improvement	FAT 112	FAT 45

Tab. 3.5-2b: FAT classes for use with structural hot-spot stress at joints improved by grinding

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, $f_y < 350$ MPa	112	125
Higher strength steel, $f_y \geq 350$ MPa	112	125
Aluminium alloys	45	50

TIG Dressing

- Remelt the toe in order to:
  - Remove imperfections
  - Produce smooth transition from the weld to plate surface
- Apply to PJP and CJP

- Benefit factor:
  - For steels with $f_y \leq 900\ MPa$ and thickness $\geq 10\ mm$

$$\Delta\sigma_C = max\begin{cases}1.3 \times \Delta\sigma_C \\ 112\end{cases}$$

Tab. 3.5-3a: FAT classes for use with nominal stress at joints improved by TIG dressing

Area of application and maximum possible claim	Steel	Aluminium
Benefit at details classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.3
Max possible FAT class after improvement	FAT 112	FAT 45

Tab. 3.5-3b: FAT classes for use with structural hot-spot stress at joints improved by TIG dressing

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, f_y < 350 MPa	112	125
Higher strength steel, f_y > 350 MPa	112	125
Aluminium alloys	45	50

Hammer peening

- Plastic deformation at the weld toe:
  - Introduce compressive residual stresses

- Apply for thicknesses:
  - Steel: 10 to 50 mm
  - Aluminium: 5 to 25 mm
  - Arc welded fillet welds with minimum leg length $0.1t$ where t is the thickness of the stressed plate
- Special requirements
  - Maximum of nominal compressive stress including proof loading $< 0.25 f_y$
  - Dependent on stress ratio:
    - $R < 0$ effective stress range = $\Delta\sigma$
    - $0 < R \leq 0.4$ effective stress range = maximum applied stress σ
    - $R > 0.4$ no benefit

Tab. 3.5-4a: FAT classes for use with nominal stress at joints improved by hammer peening

Area of application and maximum possible claim	Mild steel f_y < 355 MPa	Steel f_y ≥ 355 MPa	Aluminium
Benefit at details classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.6	1.6
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Tab. 3.5-4b: FAT classes for use with structural hot-spot stress at joints improved by hammer peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, f_y < 350 MPa	112	125
Higher strength steel, f_y> 350 MPa	125	160
Aluminium alloys	56	63

Needle peening

- Plastic deformation at the weld toe:
  - Introduce compressive residual stresses

Tab. 3.5-5a: FAT classes for use with nominal stress at joints improved by needle peening

Area of application and maximum possible claim	Mild steel fy <355 MPa	Steel fy ≥355 MPa	Aluminium
Benefit at details with FAT≤90 at steel or FAT≤32 at aluminium, as welded	1.3	1.6	1.6
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

Tab. 3.5-5b: FAT classes for use with structural hot-spot stress at joints improved by needle peening

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, f_y < 350 MPa	112	125
Higher strength steel, f_y > 350 MPa	125	160
Aluminium alloys	56	63

- Special requirements
  - Maximum of nominal compressive stress including proof loading $< 0.25f_y$
  - Dependent on stress ratio:
    - $R < 0$ effective stress range = benefit factor $\times \Delta\sigma$
    - $0 < R \leq 0.4$ effective stress range = benefit factor x maximum applied σ
    - $R > 0.4$ no benefit

Problem

Problem Statement

The flange of a welded steel girder is classified as Detail category 125 according to BS EN 1993-1-9. The component is subject to 500 000 cycles for stress range 200 MPa. Adopt a safe life strategy with low consequence of failure. The partial factor for equivalent constant amplitude stress range is $\gamma_{Ff} = 1.0$. Is this design acceptable?

Do in class

Problem

Problem statement
The fatigue performance of a welded detail in a steel linkspan structure can be represented by a fatigue curve corresponding to BS EN 1993-1-9 Detail Category 36. The linkspan carries typical vehicles of weight 1, 2 and 5 ton. A linear elastic finite beam element analysis revealed the stress ranges in the welded detail as summarised in the table on the right with the proportion of vehicles carried by the ferry 70%, 28% and 2% respectively as summarised in the table. The linkspan is used twice per day. No more than one vehicle can occupy the linkspan at any one time. The design life required is equal to the service life of 40 years. Is this design sufficient if a damage tolerant with high consequence of failure strategy is implemented? A total of 50 vehicles are carried per day, and two stress cycles are caused to the linkspan per vehicle (on- and off loading).

Frequency of vehicles			50	per day
Stress cycles per vehicle			2	
Design life			40	years
Vehicle mass [ton]	**Stress range [MPa]**	**Proportion [%]**	**Applied cycles n_i**	
1	20	70%	1022000	
2	30	28%	408800	
5	40	2%	29200	

Fatigue verification where data for $\Delta\sigma_{E,2}$ or $\Delta\tau_{E,2}$ are available

Nominal, modified nominal or geometric stress ranges due to frequent loads $\psi_1 Q_k$ (EN 1990) should not exceed:

$$\Delta\sigma \leq 1.5 f_y \; for\ direct\ stress\ range$$
$$\Delta\tau \leq \frac{1.5 f_y}{\sqrt{3}} \; for\ shear\ stress\ range$$

Verify that under fatigue loading:

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\frac{\Delta\sigma_C}{\gamma_{Mf}}} \leq 1.0$$

and

$$\frac{\gamma_{Ff}\Delta\tau_{E,2}}{\frac{\Delta\tau_C}{\gamma_{Mf}}} \leq 1.0$$

This design approach is used only for cyclic loading where loads are prescribed at 2 million cycles

Note, BS EN 1993-1-9 Tables 8.1 to 8.9 require stress ranges to be based on principal stress for some details

For **combined stress** ranges, except if BS EN 1993-1-9 Tables 8.1 to 8.9 indicate otherwise:

$$\frac{\gamma_{Ff}\Delta\sigma_{E,2}}{\frac{\Delta\sigma_C}{\gamma_{Mf}}} + \frac{\gamma_{Ff}\Delta\tau_{E,2}}{\frac{\Delta\tau_C}{\gamma_{Mf}}} \leq 1.0$$

This implies that damage due to shear and direct stresses at a point must be accumulated

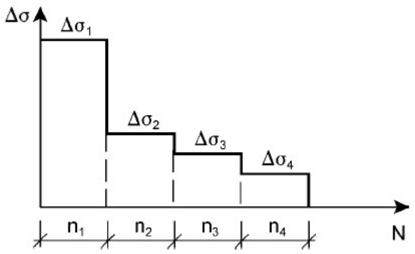
Fatigue verification where NO data for $\Delta\sigma_{E,2}$ or $\Delta\tau_{E,2}$ are available

- Loading events
  - Loading sequences that represent credible estimated upper bound of all service load events expected during that fatigue design life
- Stress history
  - Determine from loading events at the structural detail
    - Take into account type and shape of relevant influence lines to be considered and effects of dynamic magnification of structural response
  - Determine stress histories from measurements or dynamic/transient calculations of structural response (finite element modelling or manual)
- Cycle counting
  - Rainflow method
  - Reservoir method

The result is:

1. Stress ranges and their number of cycles
2. Mean stresses, where the mean stress influence needs to be taken into account

- Stress range spectrum
  - Present stress ranges and associated number of cycles in descending order
  - May be modified neglecting peak values of stress ranges representing less than 1% of total damage and stress ranges below the cut off limit
  - May be standardized according to their shape e.g. with the coordinates $\overline{\Delta\sigma} = 1.0\ and\ \overline{\sum n} = 1.0$



Using applied stresses (from FEA with un-factored inputs or measurements)

- Damage calculation with applied stress ranges $\Delta\sigma_i$:
  - Applied stress ranges shall be factored to obtain stress range to use on the $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve as follows:

$$\Delta\sigma_{Ri} = \Delta\sigma_i \times \gamma_{Ff}$$
$$where\ \gamma_{Ff} = 1.0\ for\ most\ applications$$

  - Use the $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve to find the **endurance value N_{Ri} at each $\Delta\sigma_{Ri}$**
  - Damage is then:

$$D_d = \sum_{i=1}^{n} \frac{n_{Ei}}{N_{Ri}} \leq 1.0$$

Where

n_{Ei} = number of cycles associated with stress $\gamma_{Ff}\Delta\sigma_i$

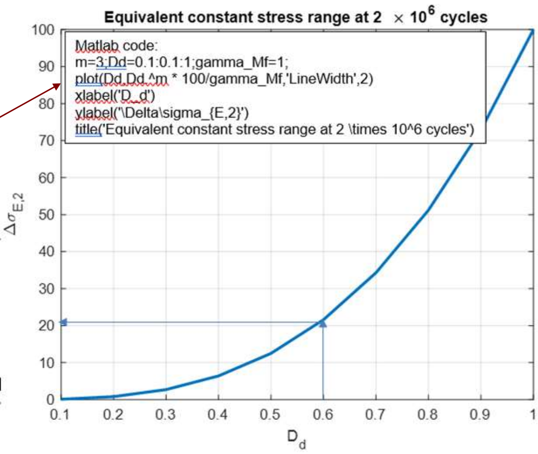
N_{Ri} = endurance (in cycles) form the factored $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve for stress range $\Delta\sigma_{Ri} = \gamma_{Ff}\Delta\sigma_i$

From this it is clear that the fatigue curve is dropped in strength from $\Delta\sigma_C - N_R$ to the $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve, and the actual stress is used on this curve. Where applicable, the curve is further dropped by other factors (size, temperature, etc.).

- Verification
  - Based on damage accumulation: $D_d \leq 1.0$
  - Based on stress range at 2 million cycles:

$$\gamma_{Ff}\Delta\sigma_{E,2} \leq \sqrt[m]{D_d}\frac{\Delta\sigma_C}{\gamma_{Mf}}$$
$$m = 3$$

- Conversion of damage by any signal into that by a constant amplitude at any number of cycles
  - Use equivalence of D_d
  - Calculate the fatigue equivalent load Q_e associated with the cycle number $n_{max} = \sum n_i$
    - or $Q_{E,2}$ associated with cycle number $N_C = 2 \times 10^6$



To calculate a stress range at any number of cycles that will cause same damage as stress spectrum

- Calculate the damage that was caused by the spectrum.
- Calculate the damage equivalent stress range at 2 x 10^6 cycles:

$$\Delta\sigma_{E,2} = D_d^{\frac{1}{m}}\left(\frac{\Delta\sigma_C}{\gamma_{Mf}}\right)$$

- Calculate the equivalent stress range at any number of cycles:

$$\Delta\sigma_E = \Delta\sigma_{E,2}\left(\frac{2\times10^6}{N_E}\right)^{\frac{1}{m}}$$

- $m = 3$ because it will not make sense to test below the constant amplitude fatigue limit

Determine the $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve and read off, or calculate with the applicable parameters

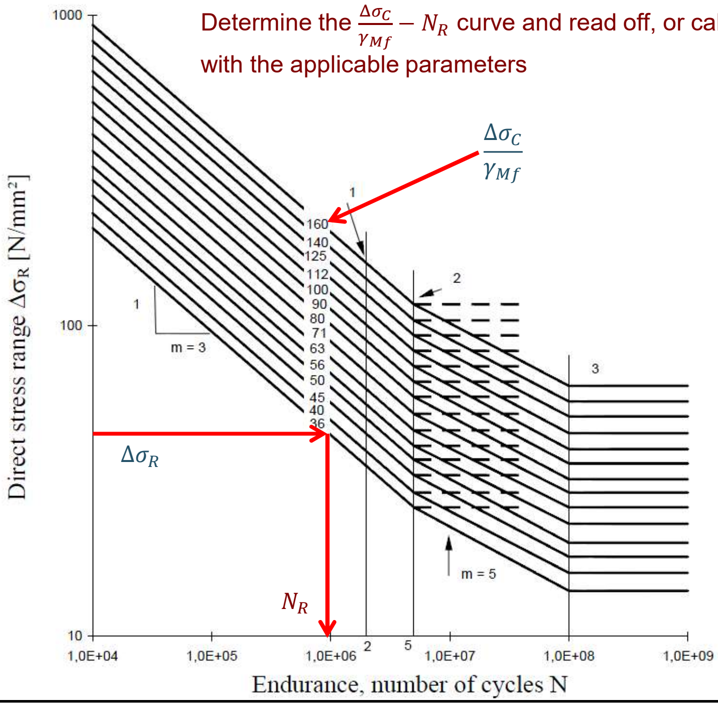


Table 8.2: Welded built-up sections

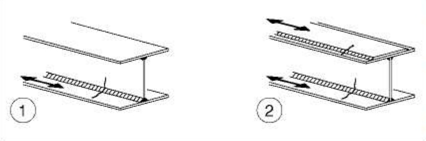
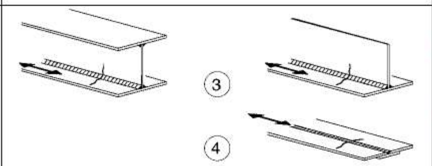
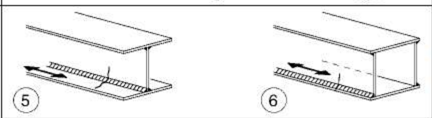
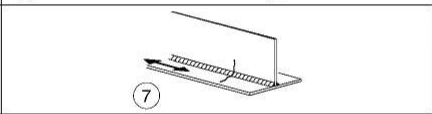
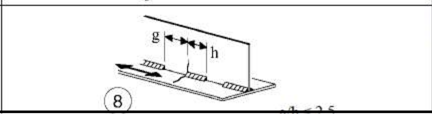
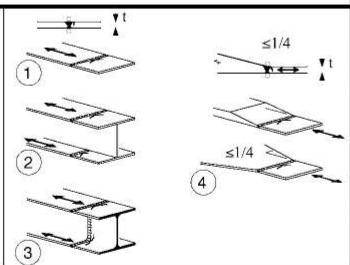
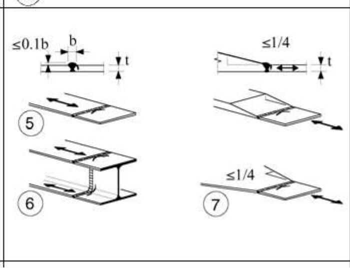
Detail category	Constructional detail	Description	Requirements
125		Continuous longitudinal welds: 1) Automatic butt welds carried out from both sides. 2) Automatic fillet welds. Cover plate ends to be checked using detail 6) or 7) in Table 8.5.	Details 1) and 2): No stop/start position is permitted except when the repair is performed by a specialist and inspection is carried out to verify the proper execution of the repair.
112		3) Automatic fillet or butt weld carried out from both sides but containing stop/start positions. 4) Automatic butt welds made from one side only, with a continuous backing bar, but without stop/start positions.	4) When this detail contains stop/start positions category 100 to be used.
100		5) Manual fillet or butt weld. 6) Manual or automatic butt welds carried out from one side only, particularly for box girders	5), 6) A very good fit between the flange and web plates is essential. The web edge to be prepared such that the root face is adequate for the achievement of regular root penetration without break-out.
100		7) Repaired automatic or manual fillet or butt welds for categories 1) to 6).	7) Improvement by grinding performed by specialist to remove all visible signs and adequate verification can restore the original category.
80		8) Intermittent longitudinal fillet welds.	8) Δσ based on direct stress in flange.

Table 8.3: Transverse butt welds

Detail category		Constructional detail	Description	Requirements
112	size effect for t>25mm: $k_s=(25/t)^{0,2}$		Without backing bar: 1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ≤ ¼.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 3): Applies only to joints of rolled sections, cut and rewelded.
90	size effect for t>25mm: $k_s=(25/t)^{0,2}$		5) Transverse splices in plates or flats. 6) Full cross-section butt welds of rolled sections without cope holes. 7) Transverse splices in plates or flats tapered in width or in thickness with a slope ≤ ¼. Translation of welds to be machined notch free.	- The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Details 5 and 7: Welds made in flat position.

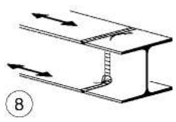
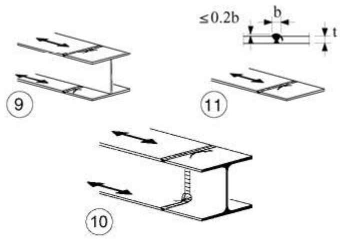
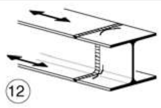
Detail category		Constructional detail	Description	Requirements
				Welds made in flat position.
90	size effect for t>25mm: $k_s=(25/t)^{0,2}$		8) As detail 3) but with cope holes.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. - Rolled sections with the same dimensions without tolerance differences
80	size effect for t>25mm: $k_s=(25/t)^{0,2}$		9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 10: The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.
63			12) Full cross-section butt welds of rolled sections without cope hole.	- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides.

Table 8.3 (continued): Transverse butt welds

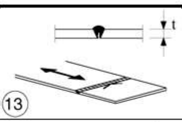
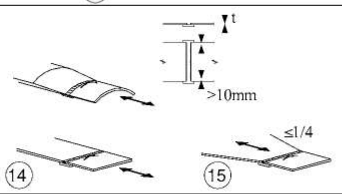
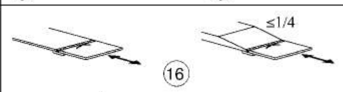
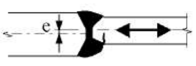
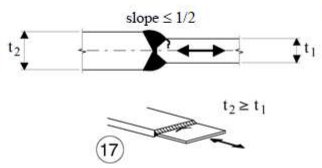
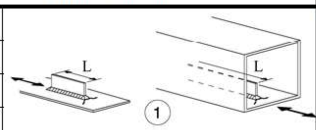
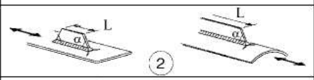
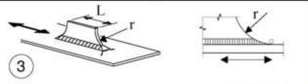
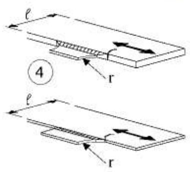
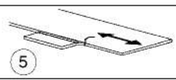
Detail category		Constructional detail	Description	Requirements
36			13) Butt welds made from one side only.	13) Without backing strip.
71	size effect for t>25mm: $k_s=(25/t)^{0,2}$		13) Butt welds made from one side only when full penetration checked by appropriate NDT.	
71	size effect for t>25mm: $k_s=(25/t)^{0,2}$		With backing strip: 14) Transverse splice. 15) Transverse butt weld tapered in width or thickness with a slope ≤ ¼. Also valid for curved plates.	Details 14) and 15): Fillet welds attaching the backing strip to terminate ≥ 10 mm from the edges of the stressed plate. Tack welds inside the shape of butt welds.
50	size effect for t>25mm: $k_s=(25/t)^{0,2}$		16) Transverse butt weld on a permanent backing strip tapered in width or thickness with a slope ≤ ¼. Also valid for curved plates.	16) Where backing strip fillet welds end < 10 mm from the plate edge, or if a good fit cannot be guaranteed.
71	size effect for t>25mm and/or generalization for eccentricity: $k_s=\left(\frac{25}{t_1}\right)^{0,2}\Big/\left(1+\frac{6e}{t_1}\frac{t_1^{1,5}}{t_1^{1,5}+t_2^{1,5}}\right)$  $t_2 \geq t_1$		17) Transverse butt weld, different thicknesses without transition, centrelines aligned.	

Table 8.4: Weld attachments and stiffeners

Detail category	Constructional detail		Description	Requirements
80	L≤50mm		Longitudinal attachments: 1) The detail category varies according to the length of the attachment L.	The thickness of the attachment must be less than its height. If not see Table 8.5, details 5 or 6.
71	50<L≤80mm			
63	80<L≤100mm			
56	L>100mm			
71	L>100mm α<45°		2) Longitudinal attachments to plate or tube.	
80	r>150mm	 reinforced	3) Longitudinal fillet welded gusset with radius transition to plate or tube; end of fillet weld reinforced (full penetration); length of reinforced weld > r.	Details 3) and 4): Smooth transition radius r formed by initially machining or gas cutting the gusset plate before welding, then subsequently grinding the weld area parallel to the direction of the arrow so that the transverse weld toe is fully removed.
90	$\frac{r}{L} \geq \frac{1}{3}$ or r>150mm	 L: attachment length as in detail 1, 2 or 3	4) Gusset plate, welded to the edge of a plate or beam flange.	
71	$\frac{1}{6} \leq \frac{r}{L} \leq \frac{1}{3}$			
50	$\frac{r}{L} < \frac{1}{6}$			
40			5) As welded, no radius transition.	

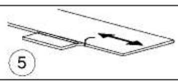
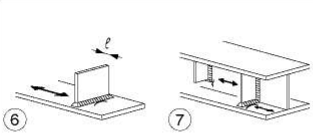
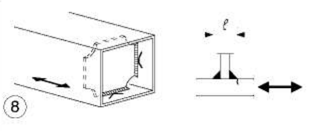
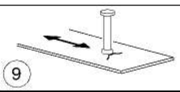
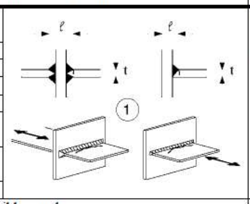
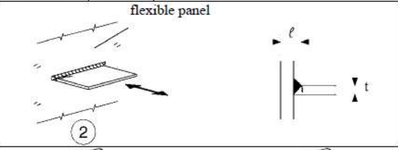
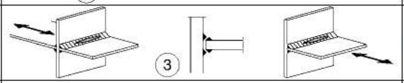
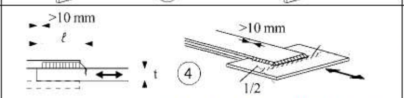
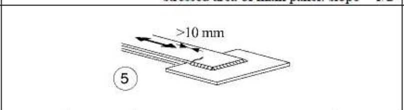
Detail category	Constructional detail		Description	Requirements
40			5) As welded, no radius transition.	
80	ℓ≤50mm		Transverse attachments: 6) Welded to plate. 7) Vertical stiffeners welded to a beam or plate girder. 8) Diaphragm of box girders welded to the flange or the web. May not be possible for small hollow sections. The values are also valid for ring stiffeners.	Details 6) and 7): Ends of welds to be carefully ground to remove any undercut that may be present. 7) Δσ to be calculated using principal stresses if the stiffener terminates in the web, see left side.
71	50<ℓ≤80mm			
80			9) The effect of welded shear studs on base material.	

Table 8.5: Load carrying welded joints

Detail category	ℓ	t [mm]	Constructional detail	Description	Requirements
80	ℓ<50 mm	all t		Cruciform and Tee joints: 1) Toe failure in full penetration butt welds and all partial penetration joints.	1) Inspected and found free from discontinuities and misalignments outside the tolerances of EN 1090. 2) For computing Δσ, use modified nominal stress. 3) In partial penetration joints two fatigue assessments are required. Firstly, root cracking evaluated according to stresses defined in section 5, using category 36* for $\Delta\sigma_w$ and category 80 for $\Delta\tau_w$. Secondly, toe cracking is evaluated by determining Δσ in the load-carrying plate. Details 1) to 3): The misalignment of the load-carrying plates should not exceed 15 % of the thickness of the intermediate plate.
71	50<ℓ≤80	all t			
63	80<ℓ≤100	all t			
56	100<ℓ≤120	all t			
56	ℓ>120	t≤20			
50	120<ℓ≤200 ℓ>200	t>20 20<t≤30			
45	200<ℓ≤300 ℓ>300	t>30 30<t≤50			
40	ℓ>300	t>50			
As detail 1 in Table 8.5			 	2) Toe failure from edge of attachment to plate, with stress peaks at weld ends due to local plate deformations.	
36*				3) Root failure in partial penetration Tee-butt joints or fillet welded joint and effective full penetration in Tee-butt joint.	
As detail 1 in Table 8.5			 	Overlapped welded joints: 4) Fillet welded lap joint.	4) Δσ in the main plate to be calculated on the basis of area shown in the sketch. 5) Δσ to be calculated in the overlapping plates. Details 4) and 5): - Weld terminations more than 10 mm from plate edge. - Shear cracking in the weld should be checked using detail 8).
45*			 	Overlapped: 5) Fillet welded lap joint.	

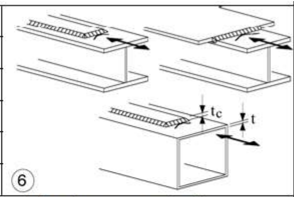
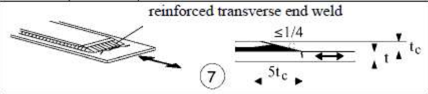
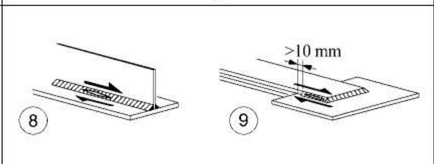
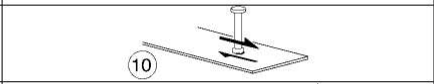
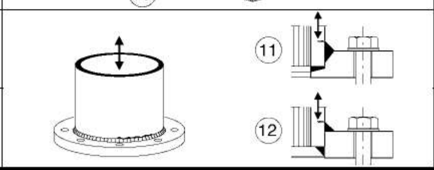
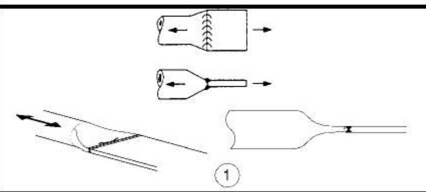
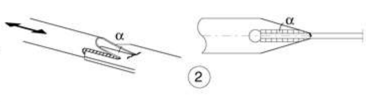
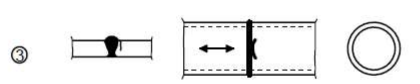
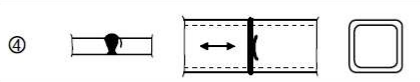
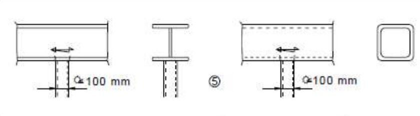
Detail category	$t_c<t$	$t_c \geq t$	Constructional detail	Description	Requirements
56*	t≤20	-		Cover plates in beams and plate girders: 6) End zones of single or multiple welded cover plates, with or without transverse end weld.	6) If the cover plate is wider than the flange, a transverse end weld is needed. This weld should be carefully ground to remove undercut. The minimum length of the cover plate is 300 mm. For shorter attachments size effect see detail 1).
50	20<t≤30	t≤20			
45	30<t≤50	20<t≤30			
40	t>50	30<t≤50			
36	-	t>50			
56			 	7) Cover plates in beams and plate girders. $5t_c$ is the minimum length of the reinforcement weld.	7) Transverse end weld ground flush. In addition, if t_c>20mm, front of plate at the end ground with a slope < 1 in 4.
80 m=5			 	8) Continuous fillet welds transmitting a shear flow, such as web to flange welds in plate girders. 9) Fillet welded lap joint.	8) Δτ to be calculated from the weld throat area. 9) Δτ to be calculated from the weld throat area considering the total length of the weld. Weld terminations more than 10 mm from the plate edge, see also 4) and 5) above.
see EN 1994-2 (90 m=8)				Welded stud shear connectors: 10) For composite application	10) Δτ to be calculated from the nominal cross section of the stud.
71				11) Tube socket joint with 80% full penetration butt welds.	11) Weld toe ground. Δσ computed in tube.
40				12) Tube socket joint with fillet welds.	12) Δσ computed in tube.

Table 8.6: Hollow sections (t ≤ 12,5 mm)

Detail category		Constructional detail	Description	Requirements
71			1) Tube-plate joint, tubes flatted, butt weld (X-groove)	1) $\Delta\sigma$ computed in tube. Only valid for tube diameter less than 200 mm.
71	α≤45°		2) Tube-plate joint, tube slitted and welded to plate. Holes at end of slit.	2) $\Delta\sigma$ computed in tube. Shear cracking in the weld should be verified using Table 8.5, detail 8).
63	α>45°			
71			Transverse butt welds: 3) Butt-welded end-to-end connections between circular structural hollow sections.	Details 3) and 4): - Weld convexity ≤ 10% of weld width, with smooth transitions. - Welded in flat position, inspected and found free from defects outside the tolerances of EN 1090. - Classify 2 detail categories higher if t > 8 mm.
56			4) Butt-welded end-to-end connections between rectangular structural hollow sections.	
71			Welded attachments: 5) Circular or rectangular structural hollow section, fillet-welded to another section.	5) - Non load-carrying welds. - Width parallel to stress direction ℓ ≤ 100 mm. - Other cases see Table 8.4.

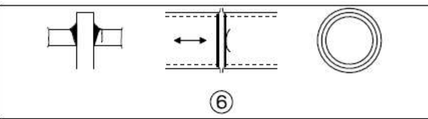
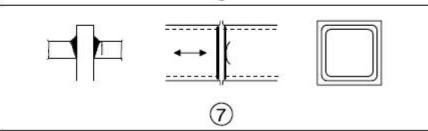
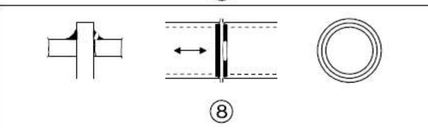
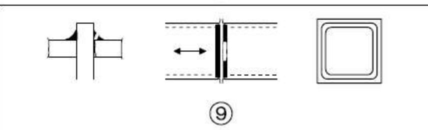
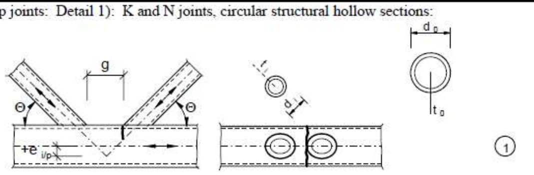
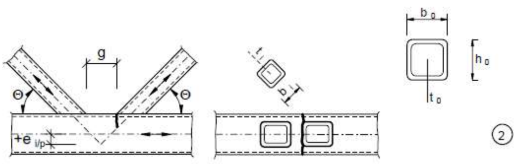
50		Welded splices: 6) Circular structural hollow sections, butt-welded end-to-end with an intermediate plate.	Details 6) and 7): - Load-carrying welds. - Welds inspected and found free from defects outside the tolerances of EN 1090. - Classify 1 detail category higher if t > 8 mm.
45		7) Rectangular structural hollow sections, butt welded end-to-end with an intermediate plate.	
40		8) Circular structural hollow sections, fillet-welded end-to-end with an intermediate plate.	Details 8) and 9): - Load-carrying welds. - Wall thickness t ≤ 8 mm.
36		9) Rectangular structural hollow sections, fillet-welded end-to-end with an intermediate plate.	

Table 8.7: Lattice girder node joints

Detail category		Constructional detail	Requirements
90 m=5	$\frac{t_0}{t_i} \geq 2,0$	Gap joints: Detail 1): K and N joints, circular structural hollow sections:  	Details 1) and 2): - Separate assessments needed for the chords and the braces. - For intermediate values of the ratio t_o/t_i interpolate linearly between detail categories. - Fillet welds permitted for braces with wall thickness $t \leq 8$ mm. - t_0 and $t_i \leq 8$mm - $35° \leq \theta \leq 50°$ - $b_0/t_0 \times t_0/t_i \leq 25$ - $d_0/t_0 \times t_0/t_i \leq 25$ - $0,4 \leq b_i/b_0 \leq 1,0$ - $0,25 \leq d_i/d_0 \leq 1,0$ - $b_0 \leq 200$ mm - $d_0 \leq 300$ mm - $-0,5h_0 \leq e_{i/p} \leq 0,25h_0$ - $-0,5d_0 \leq e_{i/p} \leq 0,25d_0$ - $e_{o/p} \leq 0,02b_0$ or $\leq 0,02d_0$ [$e_{o/p}$ is out-of-plane eccentricity] Detail 2): $0,5(b_o - b_i) \leq g \leq 1,1(b_o - b_i)$ and $g \geq 2t_o$
45 m=5	$\frac{t_0}{t_i} = 1,0$		
71 m=5	$\frac{t_0}{t_i} \geq 2,0$	Gap joints: Detail 2): K and N joints, rectangular structural hollow sections:  	
36 m=5	$\frac{t_0}{t_i} = 1,0$		

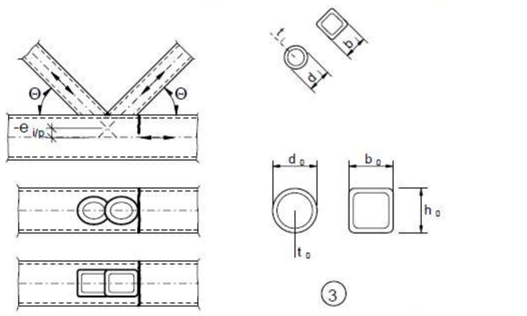
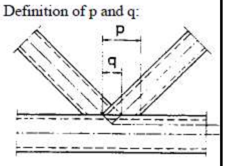
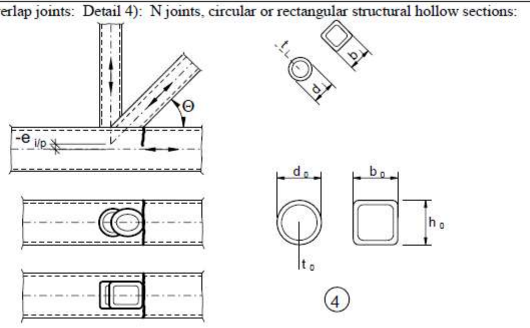
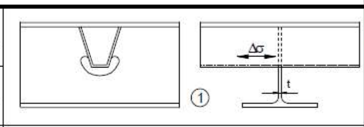
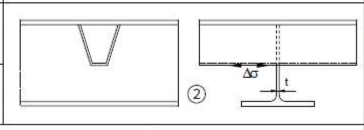
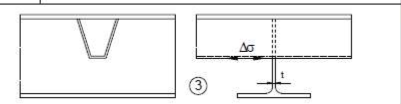
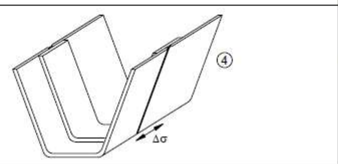
71 m=5	$\frac{t_0}{t_i} \geq 1,4$	Overlap joints: Detail 3): K joints, circular or rectangular structural hollow sections:  	Details 3) and 4): - 30 % ≤ overlap ≤ 100 % - overlap = (q/p) × 100 % - Separate assessments needed for the chords and the braces. - For intermediate values of the ratio t_o/t_i interpolate linearly between detail categories. - Fillet welds permitted for braces with wall thickness $t \leq 8$ mm. - t_0 and $t_i \leq 8$mm - $35° \leq \theta \leq 50°$ - $b_0/t_0 \times t_0/t_i \leq 25$ - $d_0/t_0 \times t_0/t_i \leq 25$ - $0,4 \leq b_i/b_0 \leq 1,0$ - $0,25 \leq d_i/d_0 \leq 1,0$ - $b_0 \leq 200$ mm - $d_0 \leq 300$ mm - $-0,5h_0 \leq e_{i/p} \leq 0,25h_0$ - $-0,5d_0 \leq e_{i/p} \leq 0,25d_0$ - $e_{o/p} \leq 0,02b_0$ or $\leq 0,02d_0$ [$e_{o/p}$ is out-of-plane eccentricity] Definition of p and q: 
56 m=5	$\frac{t_0}{t_i} = 1,0$		
71 m=5	$\frac{t_0}{t_i} \geq 1,4$	Overlap joints: Detail 4): N joints, circular or rectangular structural hollow sections:  	
50 m=5	$\frac{t_0}{t_i} = 1,0$		

Table 8.8: Orthotropic decks – closed stringers

Detail category	Constructional detail		Description	Requirements
80	t≤12mm		1) Continuous longitudinal stringer, with additional cutout in cross girder.	1) Assessment based on the direct stress range Δσ in the longitudinal stringer.
71	t>12mm			
80	t≤12mm		2) Continuous longitudinal stringer, no additional cutout in cross girder.	2) Assessment based on the direct stress range Δσ in the stringer.
71	t>12mm			
36			3) Separate longitudinal stringer each side of the cross girder.	3) Assessment based on the direct stress range Δσ in the stringer.
71			4) Joint in rib, full penetration butt weld with steel backing plate.	4) Assessment based on the direct stress range Δσ in the stringer.

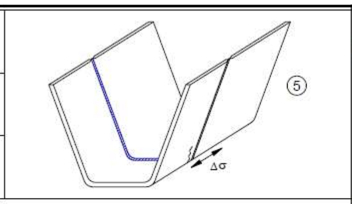
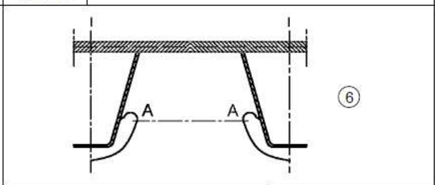
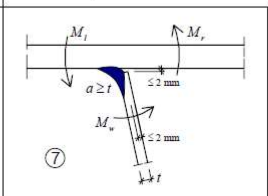
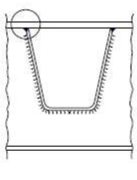
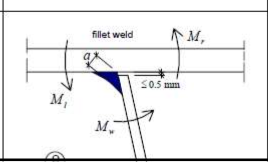
112	As detail 1, 2, 4 in Table 8.3		5) Full penetration butt weld in rib, welded from both sides, without backing plate.	5) Assessment based on the direct stress range Δσ in the stringer. Tack welds inside the shape of butt welds.
90	As detail 5, 7 in Table 8.3			
80	As detail 9, 11 in Table 8.3			
71			6) Critical section in web of cross girder due to cut outs.	6) Assessment based on stress range in critical section taking account of Vierendeel effects. **NOTE** In case the stress range is determined according to EN 1993-2, 9.4.2.2(3), detail category 112 may be used.
71		$\Delta\sigma = \frac{\Delta M_w}{W_w}$ 	Weld connecting deck plate to trapezoidal or V-section rib 7) Partial penetration weld with a ≥ t	7) Assessment based on direct stress range from bending in the plate.
50			8) Fillet weld or partial penetration welds out of the range of detail 7)	8) Assessment based on direct stress range from bending in the plate.

Table 8.9: Orthotropic decks – open stringers

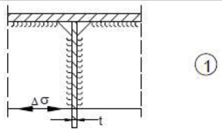
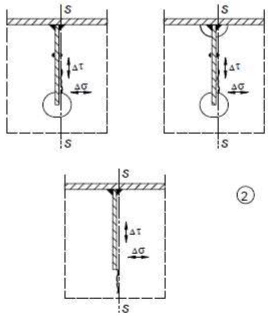
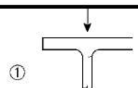
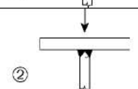
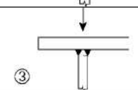
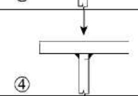
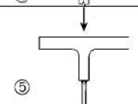
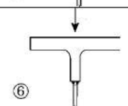
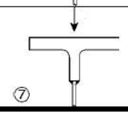
Detail category		Constructional detail	Description	Requirements
80	t≤12mm		1) Connection of longitudinal stringer to cross girder.	1) Assessment based on the direct stress range $\Delta\sigma$ in the stringer.
71	t>12mm			
56			2) Connection of continuous longitudinal stringer to cross girder. $\Delta\sigma = \frac{\Delta M_s}{W_{net,s}}$ $\Delta\tau = \frac{\Delta V_s}{A_{w,net,s}}$ Check also stress range between stringers as defined in EN 1993-2.	2) Assessment based on combining the shear stress range $\Delta\tau$ and direct stress range $\Delta\sigma$ in the web of the cross girder, as an equivalent stress range: $\Delta\sigma_{eq} = \frac{1}{2}\left(\Delta\sigma + \sqrt{\Delta\sigma^2 + 4\Delta\tau^2}\right)$

Table 8.10: Top flange to web junction of runway beams

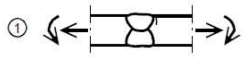
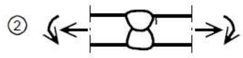
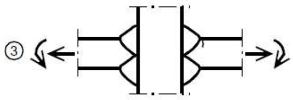
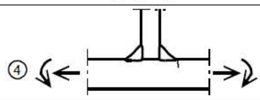
Detail category	Constructional detail	Description	Requirements
160		1) Rolled I- or H-sections	1) Vertical compressive stress range $\Delta\sigma_{vert.}$ in web due to wheel loads
71		2) Full penetration tee-butt weld	2) Vertical compressive stress range $\Delta\sigma_{vert.}$ in web due to wheel loads
36*		3) Partial penetration tee-butt welds, or effective full penetration tee-butt weld conforming with EN 1993-1-8	3) Stress range $\Delta\sigma_{vert.}$ in weld throat due to vertical compression from wheel loads
36*		4) Fillet welds	4) Stress range $\Delta\sigma_{vert.}$ in weld throat due to vertical compression from wheel loads
71		5) T-section flange with full penetration tee-butt weld	5) Vertical compressive stress range $\Delta\sigma_{vert.}$ in web due to wheel loads
36*		6) T-section flange with partial penetration tee-butt weld, or effective full penetration tee-butt weld conforming with EN 1993-1-8	6) Stress range $\Delta\sigma_{vert.}$ in weld throat due to vertical compression from wheel loads
36*		7) T-section flange with fillet welds	7) Stress range $\Delta\sigma_{vert.}$ in weld throat due to vertical compression from wheel loads

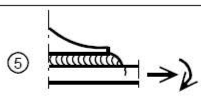
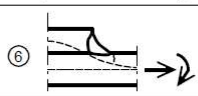
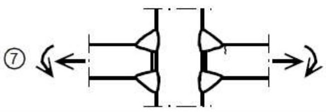
Geometric (hot spot) method

Applicable for cracks initiating from:

- Toes of butt welds
- Toes of fillet welded attachments
- Toes of fillet welds in cruciform joints

with geometric (hot spot) stress method

Detail category	Constructional detail	Description	Requirements
112		1) Full penetration butt joint.	1) - All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides, checked by NDT. - For misalignment see NOTE 1.
100		2) Full penetration butt joint.	2) - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides. - For misalignment see NOTE 1.
100		3) Cruciform joint with full penetration K-butt welds.	3) - Weld toe angle ≤60°. - For misalignment see NOTE 1.
100		4) Non load-carrying fillet welds.	4) - Weld toe angle ≤60°. - See also NOTE 2.

Detail category	Constructional detail	Description	Requirements
100		5) Bracket ends, ends of longitudinal stiffeners.	5) - Weld toe angle ≤60°. - See also NOTE 2.
100		6) Cover plate ends and similar joints.	6) - Weld toe angle ≤60°. - See also NOTE 2.
90		7) Cruciform joints with load-carrying fillet welds.	7) - Weld toe angle ≤60°. - For misalignment see NOTE 1. - See also NOTE 2.

Not covered by these tables:

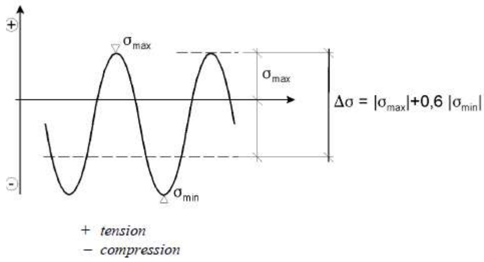
1. Effects of misalignment. Consider explicitly in the determination of stress. This means, the finite element analysis results will model the effect of misalignment.
2. Fatigue initiation from the root followed by propagation through the throat.

Fatigue strength modifications

- Non-welded or stress-relieved welded details in compression

$$\Delta\sigma = \sigma_{max} - 0.6\sigma_{min}$$

Is easily implemented by multiplying part of signal < 0 with 0.6

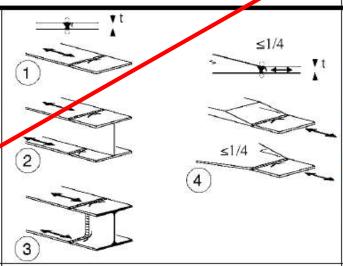


This is also how the mean stress effect is modelled for these detail to ensure a lower stress range for the parts in compression

Size effect

Take into consideration as per Tables 8.1 to 8.10 and reduce the fatigue strength:

$$\Delta\sigma_{C,red} = k_s \Delta\sigma_C$$

Detail category	Constructional detail		Description	Requirements
112	size effect for t>25mm: $k_s=(25/t)^{0,2}$		Without backing bar: 1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ≤ ¼.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 3): Applies only to joints of rolled sections, cut and rewelded.

In some instances a different fatigue strength curve is recommended

Allowable stress example

Note, the example in the notes assumes grinding, high temperature, etc, not included here

- **Problem statement**
  - A complete joint penetration butt weld made from both sides will be used in a joint between two 16 mm structural steel plates
  - The weld will be as-welded and no post weld improvements will be made
  - Design philosophy is infinite life and consequence of failure is severe
  - Stress is mainly cyclic of nature
  - What is the allowable stress?
- **Solution**

Step 1: Partical factor for fatigue strength

From the table below, the partial factor for fatigue strength $\gamma_{Mf} = 1.35$

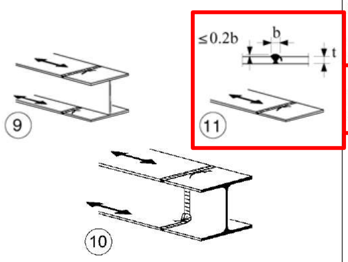
Assessment method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1.00	1.15
Safe life	1.15	1.35

Reference: BS EN 1993-1-9, 2005:11

The weld structural detail dependant fatigue strength is

Step 2: Find the detail category

The characteristic fatigue strength is $\Delta\sigma_C = 80$ for Detail category 80, and, no thickness effect need to be considered because the allowable thickness is 25 mm



80	size effect for t>25mm: $k_s=(25/t)^{0.2}$	9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 10: The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.

Step 3: Calculate the constant amplitude fatigue limit

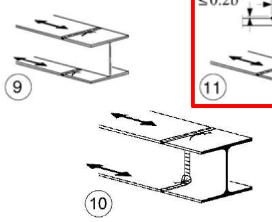
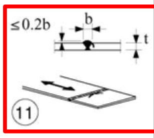
The fatigue limit for constant amplitude stress is then:

$$\Delta\sigma_D = 0.737\frac{\Delta\sigma_C}{\gamma_{Mf}}$$
$$= 0.737\frac{80}{1.35}$$
$$= 43.7\ MPa$$

This is the allowable stress to comply with the design requirement.

- If the stress is in the plate with the following configuration, the allowable stress range that should be used in design is:

$$\Delta\sigma_D = 0.737\frac{80}{1.35} = 43.7\ MPa$$

80	size effect for t>25mm: $k_s=(25/t)^{0.2}$	 	9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 10: The height of the weld convexity to be not greater than 10% of the weld width, with smooth

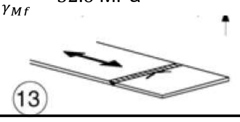
Example 2

Problem statement

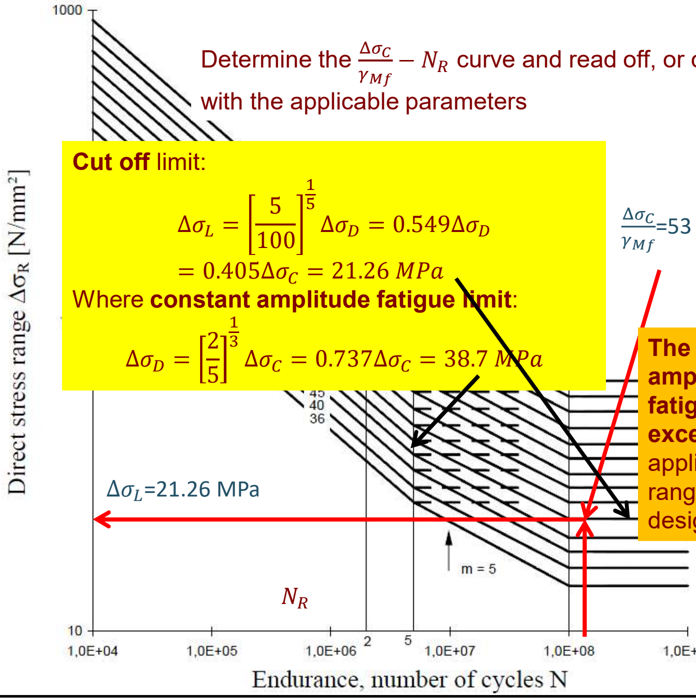
- If a design was made to have a maximum stress range in the structural detail of 25 MPa (nominal stress calculated by FEA – include part geometry but not that of weld) for the following joints:
  - As-welded joints
    - CJP Butt welds made from one side, non-destructive examination tested to confirm absence of defects
    - CJP T-joints and C-joints from both sides
  - No post-weld improvements and treatment
  - Operating at room temperature
  - Surface is corrosion protected
- Will be exposed to 300 million cycles
- Use safe-life assessment method and high consequence of failure
- Do you expect crack initiation with confidence level of 75% of a 95% probability of survival?

Solution

- Use standard fatigue strength from Tables 8.1 to 8.10. Find the lowest fatigue curve from the detail mentioned above
  - Value found is $\Delta\sigma_C = 71$
- The partial factor for fatigue strength is $\gamma_{Mf} = 1.35$
- The S-N curve to use $\frac{\Delta\sigma_C}{\gamma_{Mf}} = 52.6$ MPa

71	size effect for t>25mm: $k_s=(25/t)^{0.2}$		13) Butt welds made from one side only when full penetration checked by appropriate NDT.

Determine the $\frac{\Delta\sigma_C}{\gamma_{Mf}} - N_R$ curve and read off, or calculate with the applicable parameters



Cut off limit:

$$\Delta\sigma_L = \left[\frac{5}{100}\right]^{\frac{1}{5}} \Delta\sigma_D = 0.549\Delta\sigma_D$$

$$= 0.405\Delta\sigma_C = 21.26\ MPa$$

Where **constant amplitude fatigue limit**:

$$\Delta\sigma_D = \left[\frac{2}{5}\right]^{\frac{1}{3}} \Delta\sigma_C = 0.737\Delta\sigma_C = 38.7\ MPa$$

The constant amplitude fatigue limit exceeds the applied stress range and the design complies

Towers, masts and chimneys

Applicable standard: BS EN 1993-3-2:2006 Section 9 for Chimneys

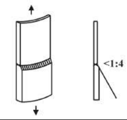
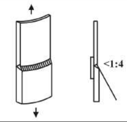
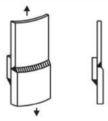
Summary of fatigue on Chimneys:

- General
  - Consider fatigue effects from stress ranges induced by in-line forces and cross wind forces
    - Fatigue from cross wind vortex vibrations normally governs design
  - Consider temperature induced damage with fatigue damage for chimneys made of heat resistant alloy steels and used at $T > 400\ °C$
  - Apply BS EN 1993-1-9 for fatigue
- Along-wind vibrations
  - Take gust effect into account
  - Apply BS EN 1993-3-1 Paragraph 9.2.1
- Cross-wind vibrations
  - Determine stress ranges and number of cycles from BS EN 1991-1-4 Annex E Paragraphs 2.4 and 1.5.2.6
  - No fatigue verification needed for chimneys lower than 3 m in height
  - If the critical speed of the chimney for vortex excitation is $> 20\ m/s$ the correlation lengths below 16 m above ground need not be taken into account (EN 1991-1-4)
  - Consider higher modes where the critical wind speed for those modes is below the limiting value (EN 1991-1-14)
- High cycle fatigue resistance
  - Find detail categories according to BS EN 1993-1-9
  - If there is corrosion allowance for plate thickness instead of corrosion protection system, classify the detail one category lower than given in BS EN 1993-1-9 tables
- Safety assessment
  - Use $\Delta\sigma_{E,2} = \lambda\Delta\sigma_E$
    - λ is the equivalence factor to transfer $\Delta\sigma_E$ to $N_C = 2 \times 10^6$ cycles
    - $\Delta\sigma_E$ is the stress range associated with N cycles
  - Equation:
  - $\lambda = \left(\frac{N}{2\times10^6}\right)^{\frac{1}{m}}$
  - Use $\gamma_{Ff} = 1.0$ and γ_{Mf} according to the assessment method and consequence of failure

Towers, masts and chimneys

The BS EN 1993-3-2 standard allocates detail to BS EN 1993-1-9 detail categories for most weld detail, of which the section below is an extraction

Table C.1 Allocation of details to detail categories

Reference	Sketch of the detail	Description
EN 1993-1-9 Table 8.3 Detail 4 and 7		Transverse splices in shell. Butt weld carried out from both sides.
EN 1993-1-9 Table 8.3 Detail 14		Transverse splices in shell. Butt weld made from one side only.
EN 1993-1-9 Table 8.3 Detail 16 (<1:4)		Transverse splices in shell. Butt weld made on a permanent backing strip.

Steel bridges

Standard: BS EN 1993-2:2006 Section 9

Available for non-commercial purposes at: https://law.resource.org/pub/eur/ibr/en.1993.2.2006.pdf

For fatigue load models use: BS EN 1991-2:2003 Section 4.6

- The applicable section of the standard will be paged through to demonstrate the application of the method

Cranes

Table 2 — Groups of loads and dynamic factors to be considered as one characteristic crane action

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Load	Symbol	Clause	Groups of loads										
			Ultimate limit state								Test load		
			1	2	3	4	5	6	7	8	9		
Self-weight of crane	$Q_{c,k}$	5.6	ϕ_1	ϕ_1	1	ϕ_4	ϕ_4	ϕ_4	ϕ_4	1	ϕ_1		
Hoist load	$Q_{hl,k}$	5.6	ϕ_2	ϕ_3	–	ϕ_4	ϕ_4	ϕ_4	ϕ_4	–	–		
Part of hoist load	$\eta Q_{hl,k}$ [a]	5.6	–	–	–	–	–	–	–	1			
Acceleration of crane bridge	H_T, H_L	5.7	ϕ_5	ϕ_5	ϕ_5	ϕ_5	–	–	–	–	ϕ_5		
Skewing of crane bridge	H_S	5.7	–	–	–	–	1	–	–	–	–		
Acceleration or braking of crab or hoist block	$H_{T,3}$	5.7	–	–	–	–	–	1	–	–	–		
Misalignment of crane wheels or gantry rails	H_M	5.7	–	–	–	–	–	–	1	–	–		
Test load	Q_T	5.10	–	–	–	–	–	–	–	–	ϕ_6		
Buffer force	H_B	5.12	–	–	–	–	–	–	–	–	–		
Tilting force	H_{TA}	5.12	–	–	–	–	–	–	–	–	–		

[a] $\eta Q_{hl,k}$ is the part of the hoist load that remains when the payload is removed, but is not included in the self-weight of the crane.

Standard: SANS 10160-6, Section 5.11

Fatigue loads:

- Effects of fatigue on crane supporting structures shall be considered
  - Carried out for loading groups 1, 2, 3, 4, 6, 7 and 8
- Number of stress cycles for fatigue shall be determined in accordance with the intended use and design life of the structure

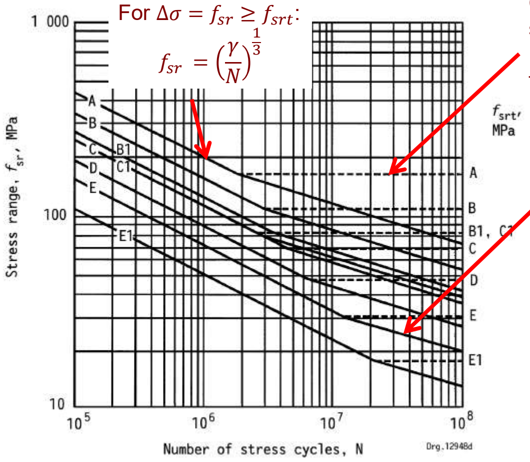
Process followed:

- Calculated stress response for load cases
- Determine stress range
- Apply assessment method and consequence of failure
- Do fatigue according to SANS 10162-1:2005 Section 26

SANS 10162-1 fatigue curves

For $\Delta\sigma = f_{sr} \geq f_{srt}$:

$$f_{sr} = \left(\frac{\gamma}{N}\right)^{\frac{1}{3}}$$



Constant amplitude threshold stress range, similar to the BS EN 1993-1-9 constant amplitude fatigue limit

For $\Delta\sigma = f_{sr} < f_{srt}$:

$$f'_{sr} = \left(\frac{\gamma'}{N}\right)^{\frac{1}{5}}$$

Obtain γ' by setting:

$$\left(\frac{\gamma}{N_{f_{srt}}}\right)^{\frac{1}{3}} = \left(\frac{\gamma'}{N_{f_{srt}}}\right)^{\frac{1}{5}}$$

at $f_{sr} = f_{srt}$

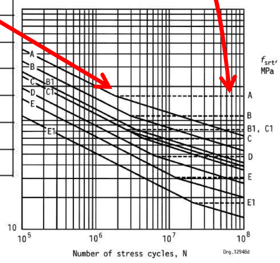
NOTE Dotted lines show values of f_{srt}. (SANS 10162-1, 2005:86)

SANS 10162-1 fatigue curves

Table 9 — Fatigue constant for various detail categories

1	2	3	4	5
Detail category	Fatigue life constant γ MPa	Constant amplitude threshold stress range f_{srt} MPa	Cycles $n \cdot N'$	Fatigue life constant γ', MPa
A	8 190 x 10^9	165	1,82 x 10^6	223 x 10^{15}
B	3 930 x 10^9	110	2,95 x 10^6	47,6 x 10^{15}
B1	2 000 x 10^9	83	3,50 x 10^6	13,8 x 10^{15}
C	1 440 x 10^9	69	4,38 x 10^6	6,86 x 10^{15}
C1	1 440 x 10^9	83	2,52 x 10^6	9,92 x 10^{15}
D	721 x 10^9	48	6,52 x 10^6	1,66 x 10^{15}
E	361 x 10^9	31	12,1 x 10^6	0,347 x 10^{15}
E1	128 x 10^9	18	22,0 x 10^6	0,0415 x 10^{15}

(SANS 10162-1, 2005:85)



NOTE Dotted lines show values of f_{srt}.

Slope of the curve is $m = 3$ for $\Delta\sigma = f_{sr} \geq f_{srt}$ and $m = 5$ for $\Delta\sigma = f_{sr} < f_{srt}$

Fatigue according to SANS 10162-1

Standard: SANS 10162-1:2005 Section 26

General

- Members shall comply with STATIC conditions and FATIGUE
- Maximum loads are specified by the standard
  - Specified loads less than the maximum specified loads that occur for large number of cycles may govern failure and must be considered
- Design, detail and fabricate members and connections to minimize stress concentrations and abrupt changes in cross-section
- Take life as 50 years except if indicated otherwise
- Sizing of members for fatigue shall be done where loads are repetitive

Live load induced fatigue

- Use elastic analysis and principles of mechanics of materials to calculate stress range
- Only stress range due to live load need to be calculated
- Load-induced fatigue provisions need be applied only at locations that undergo a net applied tensile stress
  - That is, stress ranges that are completely in compression need not be investigated for fatigue
- Design criteria for load-induced fatigue:

$$f_{tr} \geq f_{sr} = \left(\frac{\gamma}{nN}\right)^{\frac{1}{3}} \geq f_{srt}$$

Where:
f_{tr} is the fatigue resistance
f_{sr} is the calculated stress range at the detail due to the variable load
γ is the fatigue constant
n is the number of stress ranges applied at a given detail
N is the number of applications of the load
f_{srt} is the constant amplitude threshold stress range

Total damage:
Apply Miner's rule:

$$D = \sum \frac{(nN)_i}{N_{s_i}} \leq 1.0$$

Where:
$(nN)_i$ is the number of expected stress ranges at $\Delta\sigma_i$
N_{si} is the endurance at $\Delta\sigma_i$

Limited number of cycles
Except for fatigue sensitive details with high $\Delta\sigma$, and compliance is achieved with STATIC requirements (where factored loads are used), fatigue life calculations are not required if:

$$nN < max \begin{cases} \dfrac{\gamma}{f_{sr}^3} \\ 20\,000 \end{cases}$$

Detail categories: See SANS 10162-1:2005 pp. 85-94

Problem solved from IIW Bulletin 520

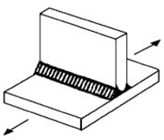
- Open the standard and point on the important principles
- Apply the standard in the problem specified and compare results with fatigue analysis according to BS EN 1993-1-9

IIW Bulletin 520 applied to problem

Problem statement

The 12 mm stiffener is welded to the 12 mm plate with 8 mm fillet welds as shown in the figure below. The nominal stress range in the plate is $\Delta\sigma = 100\ MPa$ with $R = -1$.

1. What is the fatigue life of the weld detail for a 95% probability of survival using the following methods:
   1. Nominal stress method
   2. Weld notch analysis method

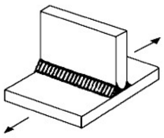


IIW Bulletin 520 applied to problem

Solution

Step 1: Joint classification

The joint is classified as FAT 80 joint, Type 511.



Step 2: Joint description

- Transverse non-load-carrying attachment, not thicker than the main plate
- Two sided fillet welds, as welded
- Note, that an angular misalignment corresponding to $k_m = 1.2$ is already covered

Step 3: Threshold stress range

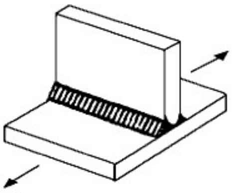
The stress applied to the joint exceeds the FAT class and life below 2 million cycles is expected

Step 4: Stresses to use

Use nominal stress in the stressed plate

Step 5: Modification factors to consider

- Grinding: Not applicable.
- Hammer and needle peening: Not applicable.
- TIG Dressing: Not applicable.
- Thickness: Not required, plate is less than 25 mm thick
- Corrosion: Not required.
- Temperature: Not required.
- Mean stress: Not required. No enhancement possible in this case
- Safety factor: Not required.



Step : Partial safety factor for partial loading

Step 6: Partial factor for fatigue resistance

- Normally the characteristic stress range $\Delta\sigma_{R,k}$ is determined from the S-N curve at the number of cycles and modified to obtain the design stress range $\Delta\sigma_{S,d} \leq \frac{\Delta\sigma_{R,k}}{\gamma_M}$
- Partial safety factor obtained as shown in the table below

The design stress range was given in this case as 100 MPa

The characteristic stress range to use for life calculation is then:

$$\Delta\sigma_{R,k} = 1.4 \times \Delta\sigma_{S,d}$$
$$= 140\ MPa$$

Tab. {6.4}-4: Possible example for partial safety factors γ_M for fatigue resistance

Partial safety factor γ_M → Consequence of failure	Fail safe and damage tolerant strategy	Safe life and infinite life strategy
Loss of secondary structural parts	1.0	1.15
Loss of the entire structure	1.15	1.30
Loss of human life	1.30	1.40

Step 6: Obtain S-N curve parameters

Step 7: Obtain the $\Delta\sigma - N$ curve parameters

- The FAT class represents the stress range at a life of 2 million cycles

$$N = \frac{C}{\Delta\sigma^m}$$

- $m = 3$ for this problem
- Therefore, C is:

$$N = \frac{C}{\Delta\sigma^m}$$
$$C = N\Delta\sigma^m$$
$$= 2 \times 10^6 \times 10^3$$
$$= 1.024 \times 10^{12}$$

Step 8: Calculate endurance from the $\Delta\sigma - N$ curve

Stress range = 140 MPa

$$N = \frac{C}{\Delta\sigma}$$
$$= \frac{1.024 \times 10^{12}}{140^3}$$
$$= 373{,}177\ cycles$$

Using NOTCH stress approach

Step 1: Joint fatigue resistance

- A finite element model of the joint was created modelling weld toe and root radius as 1 mm
- Stress was calculated in the stress concentrations and compared with the applicable S-N curve (FAT class) of 225 as shown in the tables below

Step 2: Calculate the maximum stress in the weld stress concentration

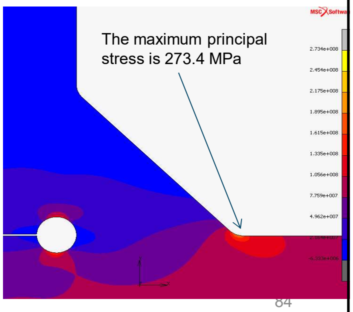
From the finite element analysis the stress was calculated as 273.4 MPa in the weld toe

Tab. {3.4}-1: Effective notch fatigue resistance for steel

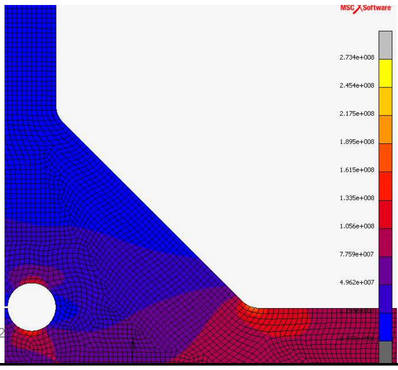
No.	Quality of weld notch	Description	FAT
1	Effective notch radius equalling **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	225

Tab. {3.4}-2: Effective notch fatigue resistance for aluminium

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equalling **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	71



- Element size need to be small enough to obtain accurate stress distributions in the stress concentrations
- Note, in this case, crack initiation is expected to first occur at the weld toe
- Notch stress at the root lower



- The characteristic stress range:

$$\Delta\sigma_{R,k} = 1.4 \times \Delta\sigma_{S,d}$$
$$= 1.4 \times 273.4$$
$$= 382.2\ MPa$$

- Calculate the parameter C for $m = 3$:

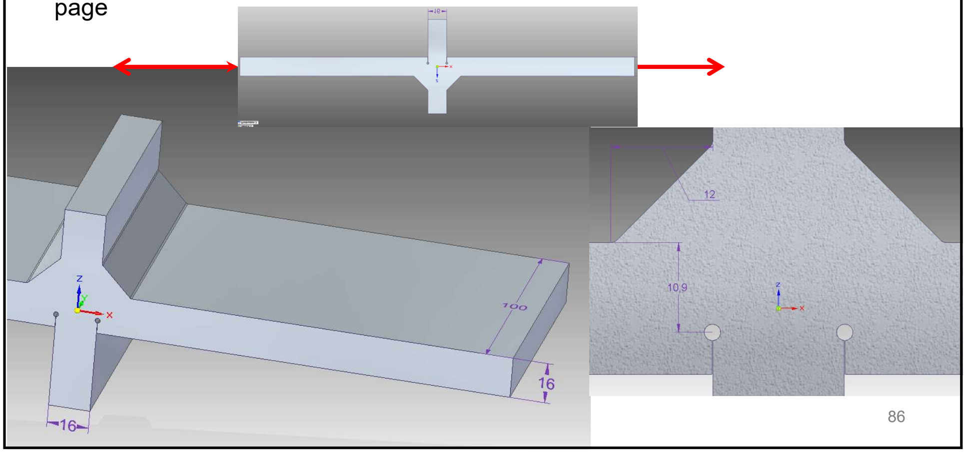
$$N = \frac{C}{\Delta\sigma^m}$$
$$C = N\Delta\sigma^m$$
$$= 2 \times 10^6 \times 225^3$$
$$= 2.278 \times 10^{13}$$

- Number of cycles to failure is then:

$$N = \frac{C}{\Delta\sigma}$$
$$= \frac{2.278 \times 10^{13}}{382.2^3}$$
$$= 408{,}042\ cycles$$

Misalignment in the joint : Example

The cruciform joint is made between plates with thickness 16 mm
The fillet weld is a 12 mm weld
The weld is loaded in the directions shown according to the table on the next page



Loading

Loading

From a strain measurement far away from the weld detail, the following nominal stress ranges and number of cycles were calculated

- $\Delta\sigma$ – The nominal stress range
- n_i - number of cycles at each stress range

$\Delta\sigma$	n_i
5	1 000 000
10	500 000
15	100 000
20	50 000
25	20 000
30	10 000

The stress spectrum above is applicable over a period of one year

The design shall make provision for a safe life and infinite life strategy because the possible consequence of failure is loss of human life

The component is used under room temperature conditions

Questions:

What is the fatigue life of the component in months according to:

- Assessment using S-N curves
- Weld notch stress analysis

What weld improvements would you recommend and why?

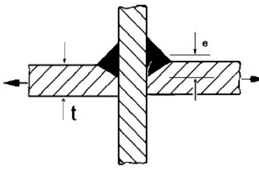
Design considerations

Solution: Apply nominal stress and S-N curves

- In this case, the "design" stress is the stress measured on the component
- The characteristic stress to use on the S-N curves is:

$$\Delta\sigma_{R,k} = \Delta\sigma_{S,d} \times \gamma_M$$

Where, the partial safety factor was selected as 1.4



Crack initiation first to occur at the weld root
Remember to also check for crack initiation at weld toe

Joint classification

- The joint is classified as FAT 71 for steel and FAT 25 for Aluminium and is of Type 416

Where to calculate stress:

Analysis shall be based on axial and bending stress in the weld throat. The eccentricity e to be considered as follows to calculate stress at the weld root:

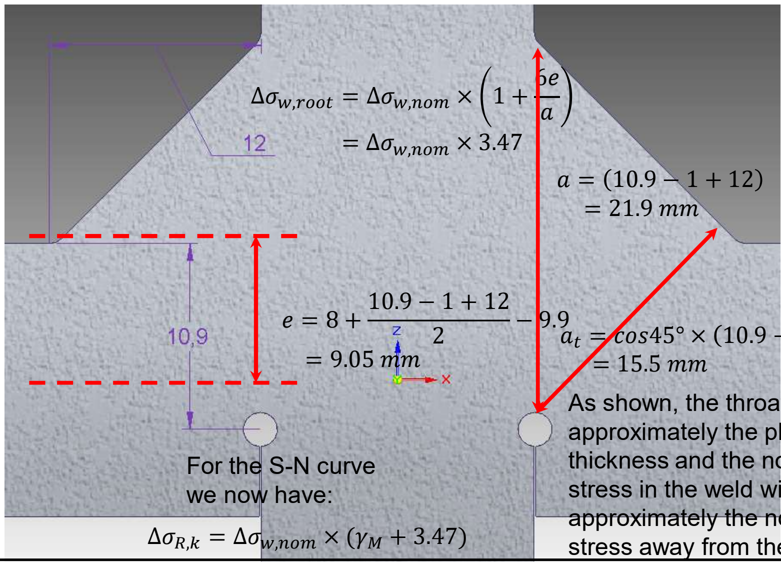
$$\Delta\sigma_{w,root} = \Delta\sigma_{w,nom} \times \left(1 + \frac{6e}{a}\right)$$

Where:
e is the eccentricity between midpoints plate
a is the weld throat, including the penetration, rotated into the vertical leg plane

Tab. {6.4}-4: Possible example for partial safety factors γ_M for fatigue resistance

Partial safety factor γ_M – Consequence of failure	Fail safe and damage tolerant strategy	Safe life and infinite life strategy
Loss of secondary structural parts	1.0	1.15
Loss of the entire structure	1.15	1.30
Loss of human life	1.30	1.40

Analyse geometry to determine a and e



$$\Delta\sigma_{w,root} = \Delta\sigma_{w,nom} \times \left(1 + \frac{6e}{a}\right) = \Delta\sigma_{w,nom} \times 3.47$$

$$a = (10.9 - 1 + 12) = 21.9\ mm$$

$$e = 8 + \frac{10.9 - 1 + 12}{2} - 9.9 = 9.05\ mm$$

$$a_t = cos45° \times (10.9 - 1 + 12) = 15.5\ mm$$

As shown, the throat size is approximately the plate thickness and the nominal stress in the weld will be approximately the nominal stress away from the weld

For the S-N curve we now have:

$$\Delta\sigma_{R,k} = \Delta\sigma_{w,nom} \times (\gamma_M + 3.47)$$

S-N curve and equations

- The S-N curve applicable has a knee-point at 10 million cycles
  - Slope for stress ranges above the knee-point is $m = 3$

$$N = \frac{C}{\Delta\sigma^m}$$

  - Slope for stress ranges below the knee-point is $m_{knee} = 5$

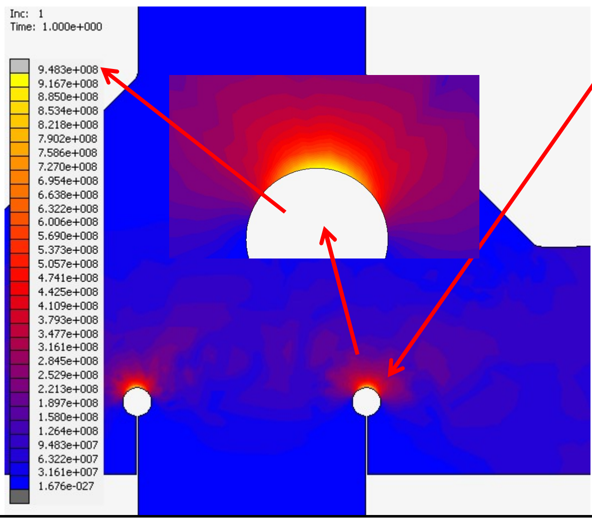
$$N = N_{knee}\left[\frac{\Delta\sigma_{knee}}{\Delta\sigma}\right]^{m_{knee}}$$

  - This is because the of the variable amplitude that is applicable in this case

FAT	71	C =	7.15822E+11	m_knee	5
m	3	$\Delta\sigma_{R,k,knee}$	41.5	MPa	
$\Delta\sigma$	n_i	$\Delta\sigma_{R,k}$	N	D	
5	1 000 000	24	145 950 021	0.01	
10	500 000	49	6 243 563	0.08	
15	100 000	73	1 849 945	0.05	
20	50 000	97	780 445	0.06	
25	20 000	121	399 588	0.05	
30	10 000	146	231 243	0.04	
		Total Damage		0.30	
		Life in years		3.35	

Using principal stress at the weld Notch

Solution: Apply the notch stress approach



For a 100 MPa load and linear elastic analysis, the stress in the stress concentration is 948 MPa

Stress concentration is at the weld root

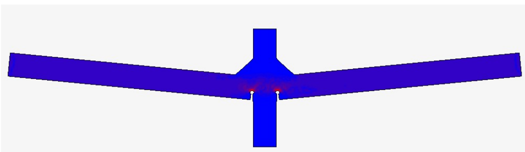
This is where the crack will initiate and from where it will propagate through the specimen

The stress concentration factor on the nominal stress is then 9.48

Finite element analysis driven life

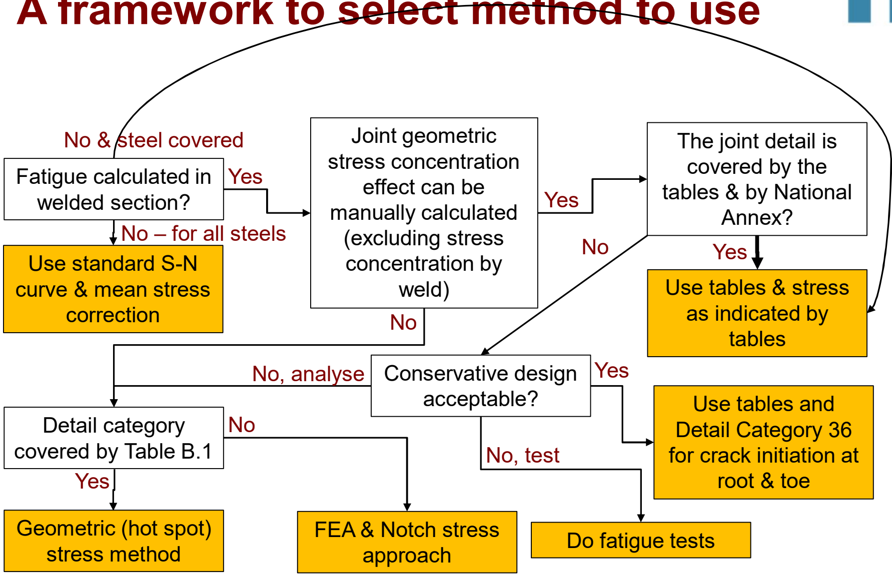
Based on the notch stress approach, the fatigue life is 5.26 years as calculated below:

FAT	225	C =	2.27813E+13	m_knee	5
m	3	$\Delta\sigma_{R,k,knee}$	131.6	MPa	
$\Delta\sigma$	n_i	$\Delta\sigma_{R,k}$	N	D	
5	1 000 000	66	306 500 154	0.00	
10	500 000	133	9 744 699	0.05	
15	100 000	199	2 887 318	0.03	
20	50 000	265	1 218 087	0.04	
25	20 000	332	623 661	0.03	
30	10 000	398	360 915	0.03	
		Total Damage		0.19	
		Life in years		5.26	



This life is slightly more than predicted using S-N curve. FEA analysis models bending moment effect accurately
Deformation of the joint also clarifies the reason for the high stress at the weld root notch
This deformation caused by the bending moment because of the off-centre weld
Note, the finite element model already makes provision for the bending moment

A framework to select method to use



The Notch stress approach can always be used. Just expensive for many problems that can be analysed by tables and nominal stress(es).

Class discussion

- Discuss the case of a shaft joined with welding where the torque, bending and axial loads are transmitted through the weld only

Corrosion

- http://www.corrosionanalysisnetwork.org/home

Very-high cycle fatigue and BS 7608

Fry:

- Collected data that confirms that constant amplitude fatigue limits (endurance limits) at 1×10^7 (BS 7608) and 5×10^6 (EN 1993-1-9 & other) not valid for fabricated, corrosion protected, vibrating equipment operating in a mine process plant (corrosive environment)
- Found that continuing Sr-N curves at slope $m = 3$ for cycles from constant amplitude fatigue limits onward is overly conservative for unprotected details in process plants
- Recommends the following:
  - Continue Sr-N curve beyond 1×10^7 cycles at slope $m + 2$
  - Endurance limit:
    - 4×10^8 cycles: Corrosion protected detail
    - 1×10^9 cycles: Areas that are continuously wet with poor corrosion protection

BS 7608, 2.3 % probability of failure

Weld detail	$S_o, 10^7 cycles$	Endurance limit for typical conditions on vibrating screens, S_r at 4×10^8 cycles, knee at 10^7, $slope = m + 2$	Endurance limit for areas at bottom of screen that are exposed to corrosion, S_r at 1×10^9 cycles, knee at 10^7, $slope = m + 2$
B	100	54	46
C	78	40	34
D	53	26	21
E	47	22	19
F	40	19	16
F2	35	17	14
G	29	14	12
W	25	12	10

Source: (Fry, 2014, p. 182)

Other crack repair techniques

- Metal stitching or metalocking
  - See the following video: http://www.youtube.com/watch?v=Pq0wfU4ZaKk
  - http://www.lockstitch.com/AboutCSeries.htm
  - http://www.lockstitch.com/AboutLSeries.htm

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