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Design of aluminium alloys structures

IAB Module 3.10

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Summary

This document presents the study notes for the fatigue design of aluminium alloy structures.

Software applications

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Product Name	Version
MSWord	2010
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Input Data Files

The following input files are applicable:

Description	File Name
PowerPoint slides	Investmech - Structural Integrity (Design of aluminium alloys structures) R0.0.pptx

Output Data Files

The following output files are applicable:

Description	File Name
MS Word document with problems done in class as well as notes made in class. This document will be submitted by e-mail to class members after completion of the module	Class notes.docx. The same notes document is used for both days to have all in one document.
MS Excel document with calculations done in class	Class calculations.xlsx. The same Excel document is used for both days to have all in one document.

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1. INTRODUCTION

This document presents the class notes for the fatigue design of aluminium alloy structures.

2. STUDY MATERIAL

The student shall arrange access to the following documents:

EN 1999-1-3. 2007. Design of aluminium structures – Part 1-3: Structures susceptible to fatigue. *European Committee for Standardization, Ref. No. EN 1999-1-3:2007/A1:2011:E.*

Other materials are referenced and used in the slides. In the references section of this document information used are referenced.

3. MODULE DETAIL

3.1. Objectives

The objective of this section is to understand in detail the behaviour of welded aluminium structures with respect to strength, stresses and design.

3.2. Scope – Teaching hours = 4

The scope of theory covered is:

1. Comparison of design between steel and aluminium structures
2. Lightweight structures
3. Standard alloys for practical use and relevant stresses and strains
4. Effects of heat affected zone (HAZ) (softening)
5. Special design principles regarding profiles
6. Significance of defects
7. Range of application:
    a. Vehicles
    b. Rolling stock
    c. Ships
    d. Aircraft
    e. Vessels
    f. Space
8. Dimensioning according to different standards and specifications
9. Worked examples

3.3. Outcome

After completion of this section you will be able to:

1. Explain fully the occurrence of softening in the heat affected zone (HAZ).
2. Design aluminium profiles for a given use.
3. Explain fully how to solve the most common imperfections on aluminium welds.
4. Detail the causes and development of stresses and strains in an aluminium weld.
5. Detail the strength of different alloys.
6. Deduce the correct selection of alloys for given applications.

Presentation used in class:	Investmech - Structural Integrity (Design of aluminium alloys structures) R0.0.pptx
Download link for slides:	www.investmech.com/weld

4. BACKGROUND

Wrought Aluminium is produced by smelting pure Al ingots with specific alloying elements required to make the specific grade of aluminium. Wrought aluminium has exceptional mechanical properties and can be formed into the required shapes.

Wrought aluminium an be identified by four-digit number as follows:

ABCD

where:

A Indicates the principal alloying elements. Is the most important indication.

B Indicates, unless it is a 0, a modification of the alloy.

C and D are identification numbers for the specific alloy.

Cast Aluminium contains larger percentages of alloying elements than wrought aluminium. Casting defects results in cast aluminium having a generally lower tensile strength than wrought aluminium.

4.1. The heat-affected zone

According to: http://www.esabna.com/us/en/education/knowledge/qa/Heat-Affected-Zone-of-Arc-Welded-Aluminum-Alloys.cfm

1. Considering the seven aluminium series used for wrought alloys, the main alloying elements used for producing each of the alloy series are immediately identifiable:
   a. **1xxx**: Aluminium – >= 99.00%
      i. Almost pure aluminium
      ii. Will respond to strain hardening (especially if containing appreciable amounts of impurities such as iron & silicon)
      iii. Have very low strength in the strain hardened condition compared to other Al alloys
      iv. Applications:
         1. Aluminium foil
         2. Electrical buss bars
         3. Metalizing wire
         4. Chemical tanks
         5. Chemical piping
   b. **2xxx**: Copper (Al + Cu)
      i. Contain between 2% to 6% copper + small additions of other elements
      ii. Cu:
         1. Provides substantial increase in strength
         2. Facilitates precipitation hardening
      iii. Include some of the highest strength heat treatable aluminium alloys
      iv. Applications:
         1. Aerospace
         2. Military vehicles
         3. Rocket fins
   c. **3xxx**: Manganese (Al + Mn)
      i. Addition of Mn:
         1. Increases strength to through solution strengthening
         2. Improves strain hardening

            3. Does not significantly reduce ductility or corrosion resistance
    ii. Moderate strength non-heat treatable materials that retain strength at elevated temperatures
    iii. Rarely used for major structural applications
    iv. Applications:
        1. Cooking utensils
        2. Radiators
        3. Air condition condensers
        4. Evaporators
        5. Heat exchangers
        6. Beverage containers
        7. Residential siding
        8. Handling equipment
        9. Storage equipment

d. **4xxx**: Silicon (Al + Si)
    i. Addition of Si:
        1. Reduces T_{melt}
        2. Improves fluidity
        3. +Si alone produces non-heat treatable alloy
        4. +Si + Mg produces precipitation heat treatable alloy
    ii. Applications of Al + Si:
        1. Al castings
    iii. Application of Al + Si + Mg:
        1. Filler wires for fusion welding & brazing of Al

e. **5xxx**: Magnesium (Al + Mg)
    i. Addition of Mg:
        1. Increases mechanical properties through solid strengthening
        2. Improves strain hardening ability
            a. Strain hardens quickly → difficult and expensive to extrude
    ii. Are the highest strength non-heat treatable alloys
    iii. Optimal and extensively used for structural applications
    iv. Produced as sheet & plate & extrusions
    v. Applications:
        1. Truck and train bodies
        2. Buildings
        3. Armored vehicles
        4. Ships and boats
        5. Chemical tankers
        6. Pressure vessels
        7. Cryogenic tanks

f. **6xxx**: Magnesium and Silicon (Al + Mg_2Si)
    i. Al + Mg + Si:
        1. Produces compound magnesium-silicide (Mg_2Si)
        2. Provides heat treatability
    ii. Extrude easily and economically
    iii. Forms an important complementary system with 5xxx series alloys
        1. 5xxx used as plate
        2. 6xxx used in extruded form
    iv. Applications:
        1. Handrails
        2. Drive shafts
        3. Automotive frame sections
        4. Bicycle frames

        5. Tubular lawn furniture
        6. Scaffolding
        7. Stiffeners & braces used on trucks, boats & other structural fabrications
  g. **7xxx**: Zinc (Al + Zn)
    i. Al + Zn
        1. +Mg and or +Cu
            a. Heat treatable aluminium alloys of the highest strength
        2. Increases strength
        3. Permits precipitation hardening
        4. Susceptible to stress corrosion cracking
            a. Not usually fusion welded
        5. Other alloys within 7xxx series often fusion welded with excellent results
    ii. Applications:
        1. Aerospace
        2. Armored vehicles
        3. Baseball bats
        4. Bicycle frames

2. Aluminium and its strength
    a. Al alloys both heat treatable and non-heat treatable
    b. Addition of alloying elements:
        i. Is the principal method used to produce selection of different materials
        ii. Facilitates improvement in alloy physical and/or mechanical properties
        iii. Provide improvement in work hardening and/or precipitation hardening characteristics
3. Work hardening
    a. Used to produce strain-hardened tempers in non-heat treatable Al alloys
    b. Important process that increases strength that heat treatment cannot strengthen
    c. Involves change of shape
        i. As deformation proceeds alloy becomes
            1. Stronger
            2. Less ductile
        ii. Strain hardened temper of H18, full-hard material is obtainable with a cold work equal to about a 75% reduction in area
        iii. H16, H14 & H12 tempers obtained with lesser amounts of cold working represent ¾ hard, ½ hard and ¼ hard conditions, respectively
4. Precipitation hardening
    a. Also called age hardening or particle hardening. It is a heat treatment technique used to increase σ_0 (yield strength) of malleable materials (most structural alloys of aluminium, magnesium, nickel, titanium, and some steels and stainless steels).
    b. Precipitation heat treatment follows solution heat-treating
    c. Solution heat-treating:
        i. Achieved by heating material to suitable temperature
        ii. Hold at that T for long enough time to allow constituents to enter the solid solution (alloying elements dissolve in a solid solution in the aluminium).
        iii. Cool rapidly to hold constituents in solution, that is, prevent the alloying elements from precipitating on cooling.
    d. Followed by precipitation hardening = artificial aging
        i. Re-heat alloy to lower T
        ii. Hold at this T for prescribed period (T- & t- controlled)
            1. To produce a metallurgical structure that provides superior mechanical properties

        2. Do not hold too long or T too high
            a. Become over aged → decrease in strength
5. Affect of arc welding on heat affected zone (HAZ)
    a. Melting of the base material occurs
    b. Heat transfers through conduction into base material adjacent to the weld
    c. Weldment divided into following areas
        i. Weld metal
        ii. Heat-affected zone (HAZ)
        iii. Base material (unaffected by welding operation)
    d. HAZ:
        i. Experiences cycles of heating and cooling during welding
        ii. Materials that were strengthened by work or precipitation hardening:
            1. Change its properties
            2. May be extremely different than that of the original base alloy & base material
    e. Non-heat treatable alloys & HAZ:
        i. Al alloys strengthened by strain hardening
            1. Can be restored to a full soft, ductile condition by annealing
        ii. Annealing:
            1. Eliminates the strain hardening
            2. Eliminates the microstructure caused by cooled working
        iii. <u>THEREFORE</u>
            1. <u>Tensile strength for as-welded non-heat treatable alloys = annealed strength of the base alloy, see typical values below</u>

Typical Tensile Strength Properties of Groove Welds

Non-Heat Treatable Alloys

Base Alloy & Temper	Base Alloy Tensile Strength - ksi	As welded Tensile Strength - ksi
1060-H18	19	10
5052-H32	33	27
5052-H39	42	27
5086-H34	47	38
5086-H38	53	38
5083-H116	46	43
3003-H34	35	16
3004-H38	41	24

    f. Heat treatable alloys:
        i. HAZ:
            1. Not maintained at adequate T for sufficient period
            2. Will not be fully annealed
        ii. Affect on HAZ of heat treatable alloys welded in the solution heat-treated and artificially aged condition one of partially annealed and over-aged
        iii. The higher the heat input the lower the as-welded strength
        iv. See values below

Typical Tensile Strength Properties of Groove Welds

Heat Treatable Alloys

Base Alloy & Temper	Base Alloy Tensile Strength - ksi	As welded Tensile Strength - ksi
6063-T6	31	19
6061-T6	45	27
6061-T4	35	27
2219-T81	66	35
2014-T6	70	34
7005-T53	57	43

4.2. Stress-strain response of aluminium

According to Höglund (1999:18-19) the manufacturing and heating process aluminium is subject to, result in different stress-strain relationships for aluminium alloys, even for materials of the same alloys. For aluminium the elastic limit is defined as $f_{0.2}$. This limit is not enough for defining the stress-strain behavior of aluminium because the variations in modulus of elasticity and strain hardening of the material need to be taken into account. Therefore, different than with steel, these factors need to be taken into account for each different aluminium alloy. Analysis must be based upon generalized inelastic stress-strain relationships for which the Ramberg-Osgood law is commonly used.

Höglund (1999:21) summarises in Tables 2.01 and 2.02 minimum characteristic values of yield strength f_o, ultimate strength f_a and strength in the HAZ f_{HAZ} for some wrought Al alloys.

The Ramberg-Osgood constitutive model is used for Aluminium as follows:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{B}\right)^n$$

Where E is the modulus of elasticity (Young's modulus) at the origin. Parameters B and n are as follows:

$$B = \frac{f_{0.2}}{(0.002)^{\frac{1}{n}}}$$

And

$$n < 10 - 20\ for\ non - heat\ treated\ alloys$$
$$n > 20 - 40\ for\ heat - treated\ alloys$$

See Eurocode 9, Annex E.

For the calculation of stress in aluminium alloys for fatigue purposes, a linear elastic model is used for the aluminium alloy. The detail category strength are then presented for the different alloys covered by Eurocode 9.

5. FATIGUE DESIGN ACCORDING TO EN 1999-1-3

This section presents the fatigue design of aluminium alloys and focusses predominantly on the differences between the approaches for aluminium in Eurocode 9 and that of steel in Eurocode 3. At this stage the student were already exposed to the requirements of Eurocode 3 and this section will be easy to align and/or differentiate with that of Eurocode 3.

5.1. Scope of EN 1999

EN 1999:

1. Applies to the design of buildings & civil engineering & civil structural works in aluminium
2. Complies with principles and requirements for safety & serviceability of structures and the basis of their design
3. Concerned with requirements for:
    a. Resistance
    b. Serviceability
    c. Durability
    d. Fire resistance

EN 1999-1-3:

1. Gives basis for design of aluminium alloy structures with respect to limit state of fracture induced by fatigue.
2. Gives rules for:
    a. Safe life design
    b. Damage tolerant design
    c. Design assisted by testing
3. Does not cover pressurised containment vessels or pipe-work

Because of weakening in heat-affected zones with aluminium, an instruction shall be compiled forbidding any modification of the structure without qualified analysis of any structural consequences, including:

1. Making of holes
2. Welding

5.2. Assessment methods

Assessment methods are the same as that of steel, of which the following is a summary:

1. Safe life design (SLD)
    a. Calculation of damage accumulation during the structure's design life, or, comparing the maximum stress range with the constant amplitude fatigue limit.
    b. Provides a conservative estimate of fatigue strength and does not normally depend on in-service inspection for fatigue damage.
    c. Use upper bound loads and lower bound fatigue strength.
    d. This design approach is similar to that of steel. Only the $\Delta\sigma_C - N_R$ curves are slightly different.
    e. Safe life design I (SLD-I):
        i. Requires no programme for regular inspection
    f. Safe life design II (SLD-II):
        i. Requires a programme for general inspection
        ii. Owners to ensure that the inspection programme is followed during the lifetime of the structure
2. Damage tolerant design (DTD)
    a. DTD-I (Annex L):
        i. Based on crack detected during inspection being repaired or the component being replaced
    b. DTD-II (Annex L):

        i. Allows fatigue induced cracks in the structure provided that the crack is monitored and kept under control by means of a fracture mechanics based fracture control plan
    c. Guidelines:
        i. Select details, materials & stress levels so that in the event of the formation of cracks a low rate of crack propagation and a long critical crack length would result
        ii. Choose structural concepts where in the event of fatigue damage a redistribution of load effects within the structure or within the cross-section of a member can occur
        iii. Provide crack arresting detail
        iv. Assure that critical components and details are readily inspectable during regular inspection
        v. Ensure that cracks can be kept under control by monitoring, or, that components are readily repairable or replaceable
3. Design assisted by testing
    a. Use where:
        i. Loads are unknown
        ii. Response data are unknown
        iii. Fatigue strength is unknown/unavailable
        iv. Crack growth data not available
    b. Must be done under controlled environment

Fatigue loading is similar to that of steel. Difference is in the use of a shift in the load spectrum as follows:
"The confidence limit to be used for the intensity of the design load spectrum should be based on the mean predicted value plus k_F standard deviations. The confidence limit to be used for the number of cycles in the design load spectrum should be based on the mean predicted value plus k_N standard deviations. Values of k_F and k_N may be defined in the national annex. The numerical values $k_F = 2$ and $k_N = 2$ are recommended." (EN 1999-1-3, 2007:20).

The EN 1999-1-3 recommended partial factors for fatigue are summarised in Table 1.

Table 1: Recommended partial strength for fatigue (γ_{Mf}) values in relation to design approach and consequence class (EN 1999-1-3, 2007:100)

Design approach	Design procedure	Consequence class		
		CC1	CC2	CC3
		$\gamma_{Mf}^{a\,b\,c\,d}$	$\gamma_{Mf}^{a\,b\,c\,d}$	$\gamma_{Mf}^{a\,b\,c\,d}$
SLD-I	Damage accumulation	1.1	1.2	1.3
	Constant amplitude fatigue (i.e. $\max(\Delta\sigma_{E,d} < \Delta\sigma_{D,d})$	1.1	1.2	1.3
SLD-II	Damage accumulation	1.0	1.1	1.2
	Constant amplitude fatigue (i.e. $\max(\Delta\sigma_{E,d} < \Delta\sigma_{D,d})$	1.0	1.1	1.2
DTD-I	Damage accumulation	1.0	1.0	1.1
DTD-II	Damage accumulation	1.0	1.0	1.1

NOTES:

a. The values of the table may be reduced according to footnotes a to d below provided that the value of $\gamma_{Mf} \geq 1.0$

b. The above tabled γ_{Mf} values may be reduced by 0.1 if one of the following conditions apply:
   - i. Non-welded areas of welded components
   - ii. Detail categories where $\Delta\sigma_C < 25\ MPa$
   - iii. Welded components where the largest stress range represents all cycles
   - iv. Additional NDT for a minimum of 50% is carried out
   - v. For adhesively bonded joints see EN 1999-1-3 Annex E(5)

c. The above tabled γ_{Mf} values may be reduced by 0.2 if one of the following conditions apply:
   - i. Non-welded areas of welded component where the largest stress range represents all cycles
   - ii. Detail categories where $\Delta\sigma_C < 25\ MPa$ & where the largest stress range represents all cycles.
   - iii. Non-welded components and structures.
   - iv. Additional NDT for a minimum 50% is carried out where the largest stress range represents all cycles.
   - v. If additional NDT of 100% is carried out

d. The above tabled γ_{Mf} values may be reduced by 0.3 if one of the following conditions apply:
   - i. Non-welded components and structure where the largest stress range represents all cycles
   - ii. Additional NDT for 100% is carried out where the largest stress range represents all cycles

Consequence classes:
CC1: Low
CC2: Moderate
CC3: Severe, loss of human life

5.3. Partial factors for fatigue loads

The design load (F_{Ed}) to use in terms of the fatigue loads (F_{Ek}):

$$F_{Ed} = \gamma_{Ff} F_{Ek} \qquad (1)$$

Where:

γ_{Ff} is the partial factor for fatigue loads and $\gamma_{Ff} = 1.0$ is recommended (**Same as with steel**).

However, where fatigue loads have been based on confidence limits other than those in two standard deviation shifts of the mean, the values in Table 2 are recommended

Table 2: Recommended partial factors for fatigue loads, γ_{Ff}, for intensity and number of cycles in the fatigue load spectrum (EN 1999-1-3, 2007:21)

k_F	γ_{Ff}	
	$k_N = 0$	$k_N = 2$
0	1.5	1.4
1	1.3	1.2
2	1.1	1.0

5.4. Materials, constituent products and connecting devices

EN 1999-1-3:

1. Apply to constituent products in components and structures listed in 1999-1-1:05-2005 with the exception of low strength alloys:
   a. EN AW 3005 in all tempers
   b. EN AW 3103 in all tempers
   c. EN AW 5005 in all tempers
   d. EN AW 8011A in all tempers
   e. EN AW 6060 in temper T5

   No reliable fatigue data exist for the above mentioned low strength alloys. Tests shall be carried out to obtain fatigue strength data. Or, use peer reviewed research papers.
2. Covers components:
   a. With hollow and open sections
   b. Member built up from combinations of these
3. Covers the following connecting devices:
   a. Arc welding (metal inert gas & tungsten inert gas)
   b. Steel bolts shall be analysed as listed in EN 1999-1-1 Table 3.4.
   c. Adhesive bonding.
4. Apply EN 1993-1-9 Table 8.1 for fatigue design & verification of steel bolts in tension and shear.
5. Fatigue strength data applicable under:
   a. Normal atmospheric conditions with $T \leq 100\,°C$
   b. For EN AW 5083 only applicable for $T \leq 65\,°C$ unless an efficient corrosion preventing coating is provided

5.5. Finite element analysis

In the calculation of stress using a finite element analysis, a **linear elastic constitutive model** shall be used except where strain data have been obtained from prototype structures or scaled physical models.

Beam elements:

1. Should be applicable for global analysis of beam, framed or latticed structures.
2. Should not be used:

   a. Fatigue analysis of stiffened plate structures of flat or shell type members or for cast or forged members unless of simple prismatic form
3. Use linear elastic theory assuming plane sections remain plain to calculate:
   a. Axial stiffness
   b. Bending stiffness
   c. Shear stiffness
   d. Torsional stiffness

   Consider warping due to torsion.
4. Open section members or hollow section members prone to warping, which are subjected to torsional forces:
   a. Give beam elements at least 7 degrees of freedom including warping
   b. Alternatively, use shell elements to model the cross-section
5. Take the increased stiffness due to the size of the joint and the presence of additional components (gussets, splice plates, etc.) into account in the section properties for beam elements adjacent to member intersections
6. "Stiffness properties of beam elements used to model joint regions at angled intersections between open or hollow members where their cross-sections are not carried fully through the joint (unstiffened tubular nodes, etc.), or where the constructional detail is semi-rigid (bolted end plate connections, angle cleat connections, etc.), should be assessed either using shell elements or by connecting the elements via springs. The springs should possess sufficient stiffness for each degree of freedom and their stiffness should be determined either by tests or by shell element models of the joint." (EN 1993-1-3, 2007:23).
7. Rigid link elements should be used at positions where beam elements are used to model a structure with eccentricities between member axes at joints or where actions and restraints are applied to members other than at their axes.

<u>Use of membrane, shell and solid elements:</u>

1. Should only be applicable to those parts of a structure where out-of-plane bending stresses are known to be negligible.
2. Should be applicable to all structural types except where cast, forged or machined members of complex shape involving three-dimensional stress fields are used. Use solid elements in this case.
3. Should have a small enough mesh size in the part of the member containing the initiation site to assess the effect fully. See EN 1999-1-3 Annex D.

5.6. Stresses

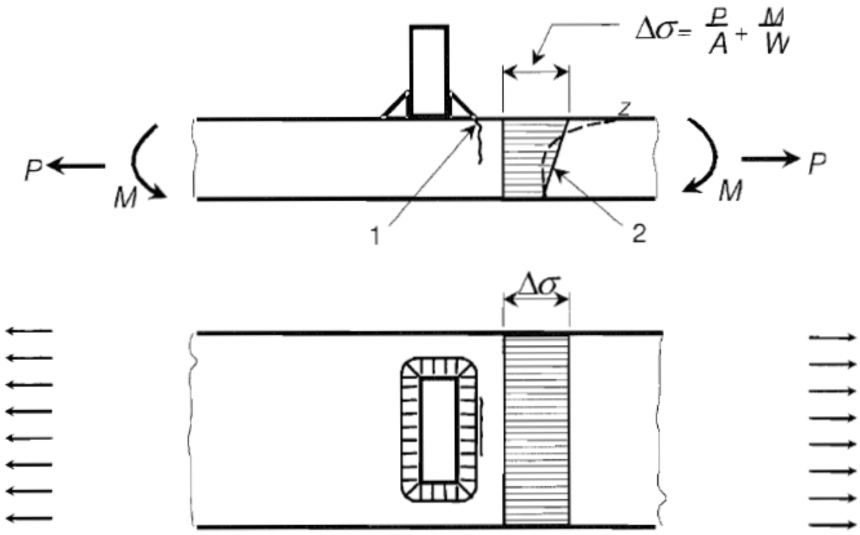
The same stresses as for steel are calculated:

1. Nominal stresses
2. Modified nominal stresses
3. Hot spot stresses
   a. Note that due to the large influence of the heat-affected zone in the strength of welded aluminium components, the experience from structural steel details is not generally applicable for aluminium

5.7. Nominal and modified stresses

Figures 1 to 3 summarises the relationship between the modified nominal and nominal stresses for:

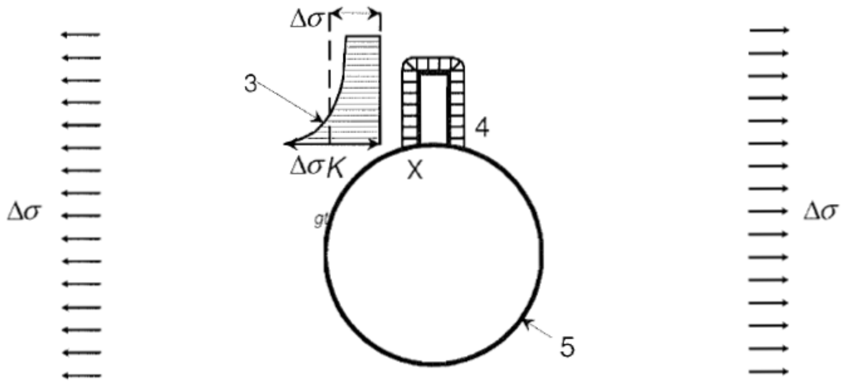
1. Weld toes
2. Large openings
3. Hard points in connections



a) Local stress concentration at weld toe;

1– crack initiation site; 2 – linear stress distribution, weld toe stress factor at z not calculated

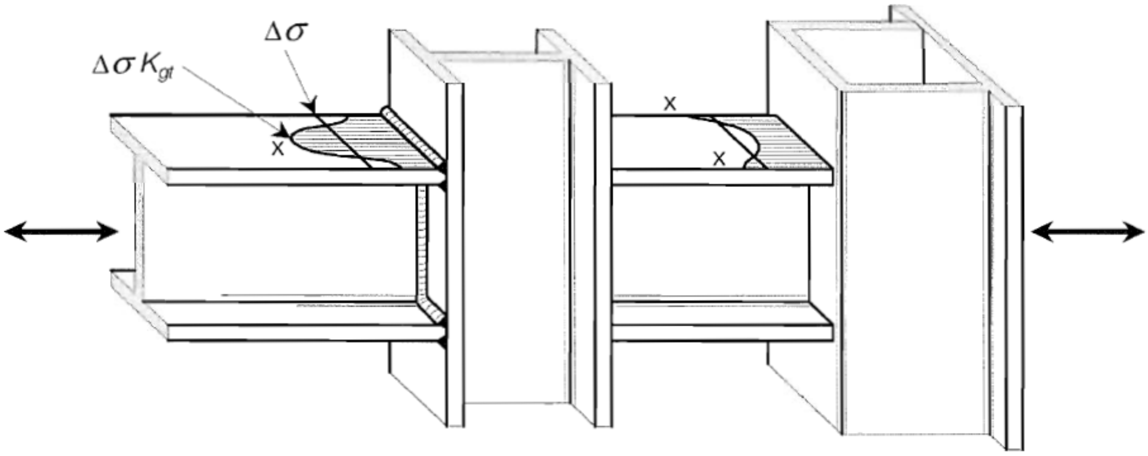
Figure 1: Local stress concentration at a weld toe (EN 1999-1-3, 2007:26)



b) Gross stress concentration at large opening

$\Delta\sigma$ = nominal stress range; $\Delta\sigma K_{gt}$ = modified nominal stress range at initiation site X due to the opening;3 – non-linear stress distribution; 4 – weld; 5 – large opening

Figure 2: Gross stress concentration at a large opening (EN 1999-1-3, 2007:26)



c) Hard point in connection;

$\Delta\sigma$ = nominal stress range; $\Delta\sigma K_{gt}$ = modified nominal stress range at initiation site X due to the geometrical stress concentration effects

Figure 3: Hard point dependent stress concentration (EN 1999-1-3, 2007:26)

Stresses are calculated similarly to that done for steel and discussed in earlier lectures.

5.8. Calculation of equivalent stress range for standardised fatigue load models

Same as for steel.

5.9. Fatigue resistance and construction details

For aluminium constructional details are divided into the following main groups (because of different alloys used and heat-affected zone affects):

1. Plain-members, welded members and bolted joints - Annex J
2. Adhesively bonded joints – Annex E
3. Castings – Annex I

The fatigue strength data, $\Delta\sigma - N$ relationship, is represented by the mean line minus 2 standard deviation from the experimental data. The $\Delta\sigma - N$ fatigue strength is modelled similarly to steel, but, the $\Delta\sigma - N$ curves are slightly different. **The same terminology is used as for steel:**

1. Reference fatigue strength for the detail category
2. Constant amplitude fatigue limit
3. Cut-off limit

5.10. Mean stress effects

The fatigue strength data, $\Delta\sigma - N$ curves, refer to high tensile mean stress conditions. Compressive mean stress or low tensile mean stress may result in longer life under certain conditions.

5.10.1. Plain material and mechanically fastened joints

For applied stress ration values of $R \leq 0.5$, an enhanced fatigue strength $\Delta\sigma_{C(R)}$ may be used in place of $\Delta\sigma_C$:

$$\Delta\sigma_{C(R)} = f(R)\Delta\sigma_C \qquad (2)$$

Note that drawn tubes and formed profiles (folded, roll-formed) may have residual stress, which are not negligible, so that an enhancement may not be allowed.

Enhancement Case I

1. Applies to initiation site in the base material and wrought products in structural elements remote from connections
2. Make allowance for pre-action or lack of fit in addition to applied stress
3. Enhancement factor is:

$$\mathrm{f(R)} = \begin{cases} 1.6 & for\ R \leq -1 \\ 1.2 - 0.4\mathrm{R} & for\ -1 < R < 0.5 \\ 1.0 & for\ R \geq 0.5 \end{cases} \qquad (3)$$

Enhancement Case II

1. Applies to initiation sites associated with welded or mechanically fastened connections in simple structural elements where the residual stress, σ_{res}, has been established and pre-actions and lack of fit is taken into account
2. Enhancement factor is:

$$\mathrm{f(R)} = \begin{cases} 1.3 & for\ R_{eff} \leq -1 \\ 0.9 - 0.4\mathrm{R} & for\ -1 < R_{eff} < -0.25 \\ 1.0 & for\ R_{eff} \geq -0.25 \end{cases} \qquad (4)$$

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

Enhancement Case III

1. Applies near welded connections and to complex structural assemblies where control of residual stresses is not practicable.
2. In this case $f(R) = 1$ for all R-ratios.

5.10.2. Welded joints

No allowance should be made for mean stress except:

1. Test results demonstrate a consistent increase in fatigue strength with decreasing mean stress
2. Improvement techniques are used causing residual compressive stresses that will not be reduced by yielding in service

5.10.3. Adhesive joints

No allowance without testing.

5.10.4. Low endurance range

See Annex G

5.10.5. Cycle counting for R-ratio calculations

See Annex A Figure A.2.

5.11. Effect of exposure conditions

Detail category number should be downgraded for certain combinations of aluminium alloys and exposure conditions. Unless efficient corrosion prevention is provided the EN 1999-1-3 fatigue strength data do not apply where the ambient temperature is:

1. $T > 30\,°C$ in marine environment
2. $T > 65\,°C$ in structural environment

Table 3 gives the reduction of categories (according to exposure conditions and alloy) for the fatigue data given in EN 1999-1-3 Annex G.

Table 3: Number of detail categories which should be reduced according to exposure conditions and alloy (EN 1999-1-3, 2007:36)

Material			Exposure conditions							
Alloy Series[1)]	Basic composition	Protection ratings (En 1999-1-1)	Rural	Industrial/urban		Marine			Immersed	
				Moderate	Severe	Non-industrial	Moderate	Severe[2)]	Fresh water	Sea Water[2)]
3xxx	AlMn	A	0	0	(P)[1)]	0	0	0	0	0
4xxx	AlMg	A	0	0	(P)[1)]	0	0	0	0	0
5xxx	AlMgMn	A	0	0	(P)[1)]	0	0	0	0	1
6xxx	AlMgSi	B	0	0	(P)[1)]	0	0	1	0	2
7xxx	AlZnMg	C	0	0	(P)[1)]	0	0	2	1	3

[1)] (P) very dependent on exposure conditions. Regularly maintained protection may be required to avoid risk of local exposures which may be particularly detrimental to crack initiation.

[2)] The value of N_D should be increased from 5×10^6 cycles to 10^7 cycles.

NOTE: Downgrading is not needed for detail categories < 25 MPa.

5.12. Post-weld improvement techniques

According to EN 1999-1-3 improvement techniques are generally expensive to apply and present quality control difficulties and should not be relied upon for general design purposes, unless fatigue is particularly critical to the overall economy of the structures (2007:36). Several research papers on this topic are listed in the references of this document.

According to EN 1993-1-3 Annex H the following enhancements are applicable for welds (2007:75 – 76):

1. Will be beneficial where fatigue cracks would initiate at the weld toe.
2. Apply techniques at the most highly stressed welds, not all.
3. Methods:
    a. Machining or grinding
    b. Dressing by TIG or plasma
    c. Peening (shot peening, needle peening or hammer peening)
4. Double improvements, correctly chosen off course (**remember our discussion in steel**), may yield the highest improvement by the combination of machining (or grinding) and peening. Be careful when you apply this.
5. Mid- and long fatigue life region may be increased by 30%
6. Improvement is lost under freely corroding conditions in water. Corrosion protection is needed if the improvement is to be achieved.
7. Verify design values for improved welds by testing

5.13. Conditions for fatigue susceptibility

According to EN 1999-1-3 the following should be taken into account in assessing the likelihood of susceptibility to fatigue (2007:38):

1. High ratio of dynamic to static loading:
    a. Moving or lifting structures (land & sea transport vehicles, cranes, etc.)
    b. Bridges
2. Frequent applications of load:
    a. High number of cycles.
    b. Slender structures or members with low natural frequencies prone to resonance.
    c. Structures subject to fluid loads like wind.
    d. Structures supporting machinery should be checked for resonance.
3. Use of welding:
    a. Welded details have low fatigue strength
    b. Also applies for attachments, even if the attachment is not considered to be structural
4. Complexity of joint detail:
    a. Complex joints can result in high stress concentrations due to local variations in stiffness and load path
        i. Can have severe effect on fatigue whilst these often have little effect on ultimate static capacity
        ii. Ensure smoothness and simplicity of joint design
5. Thermal and chemical exposure:
    a. Fatigue strength may reduce if the surface of the metal is unprotected.

5.14. Inspection strategy for damage tolerant design

EN 1999-1-3 prescribes the following inspection strategy for damage tolerant design as summarised in Figure 4:

1. Find the safe value of detectable crack length, l_d, in mm

Table 4: Recommended safe values of detectable surface crack length (EN 1999-1-3, 2007:43)

Method of Inspection	Crack location		
	Plain smooth surface	Rough surface (weld cap)	Sharp corner (weld toe)
Visual, with magnifying aid	20	30	50
Liquid penetrant testing	5	10	15
The above values assume close access, good lighting and removal of surface coatings			

2. Find the fracture critical crack length l_f
    a. **Remember plastic collapse and fracture discussed as in steel**
3. Calculate the fastest growing curve based on fracture mechanics principles with an upper bound defined as mean plus two standard deviations on the stress. This is for the crack to propagate from l_d to l_f under mean plus two standard deviation applied stress. Determine the duration T_f from the fastest growing curve.
    a. EN 1999-1-3 Annex B provides the material properties to use and the relevant equations. Just show the curves to students. It is not expected from them to perform the calculations in this course.
    b. Discuss the crack growth curves in EN 1999-1-3 Annex B.
4. The inspection intervals is then given by:

$$T_i = \frac{T_f}{2} \qquad (5)$$

5. Calculate the actual crack propagation curve if information is available. This forms the curve for fracture control on the damage tolerant design.
6. Immediately take the structure out of service when the measured crack length exceeds l_f.

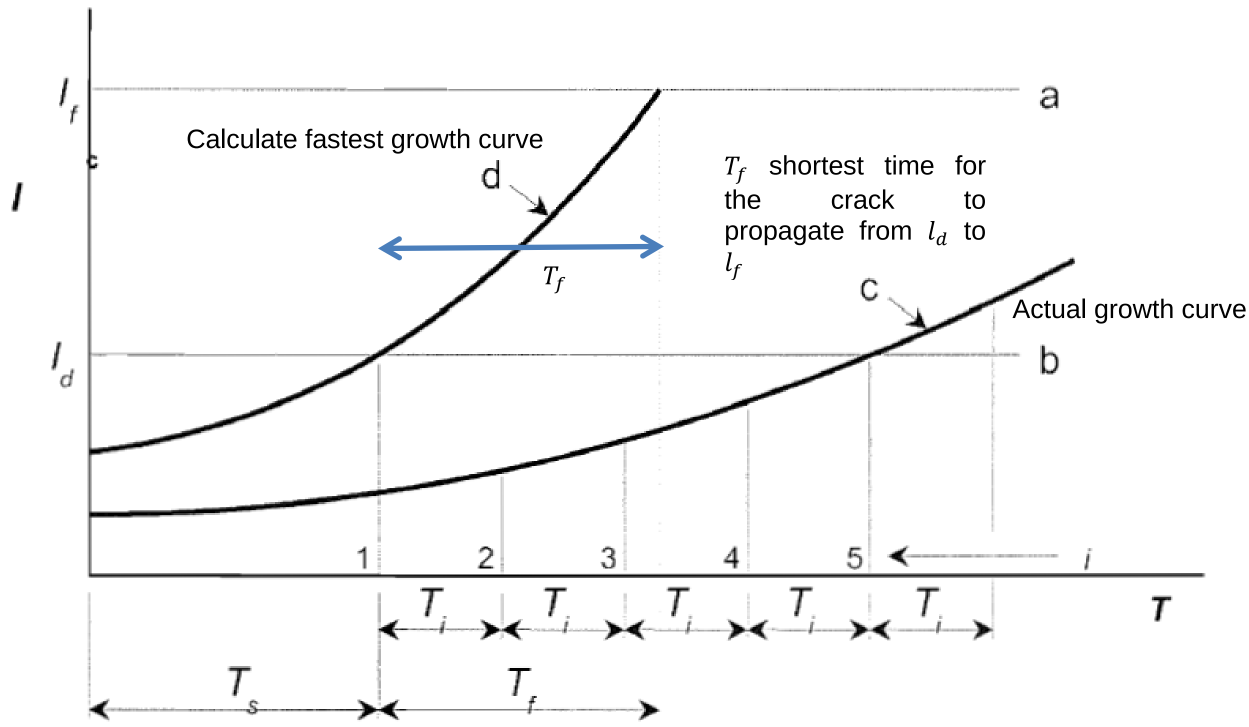


Figure 4: Inspection strategy for damage tolerant design (EN 1999-1-3, 2007:43)

5.15. Castings – Detail categories

This section summarises fatigue strength data for castings as follows:

1. For plain castings see Table 5.
2. Fatigue strength values for welded castings are not covered by EN 1999-1-3.
3. For Mechanically joined castings of Category A Bearing Type bolts see Table 6

Table 5: Numerical values of $\Delta\sigma$ [in MPa] for plain material (EN 1999-1-3, 2007:77)

Detail category ($N_C = 2 \times 10^6$)		$N = 10^5$	$N_D = 2 \times 10^6$	$N_L = 1 \times 10^8$
$\Delta\sigma_C$	$m_1 = m_2$	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
71[1)]	7	108.9	71	40.6
50	7	76.7	50	28.6
40	7	61.4	40	22.9
32	7	49.1	32	18.3
25	7	38.4	25	14.3
[1)] see NOTE below				

NOTE: The additional limitations concerning maximum pore diameter should be observed:

Detail category ($N_C = 2 \times 10^6$)	71	50	40	32	25
Maximum pore diameter	0.2	0.5	0.9	1.5	2.0 (normal)

Table 6: Numerical values of $\Delta\sigma$ [in MPa] for bolted joints (EN 1999-1-3, 2007:78)

Detail category ($N_C = 2 \times 10^6$) for plain material	**Corresponding detail category for bolted joints $N_C = 2 \times 10^6$**		$N = 10^5$	$N_D = 5 \times 10^6$	$N_L = 1 \times 10^8$
	$\Delta\sigma_C$	$m_1 = m_2$	$\Delta\sigma$	$\Delta\sigma_D$	$\Delta\sigma_L$
71[1)]	45	4	95.2	35.8	16.9
50	40	4	84.6	31.8	15.0
40	25	4	52.9	19.9	9.4
32	20	4	42.3	15.9	7.5
25	16	4	33.8	12.7	6.0

5.16. Detail categories for aluminium

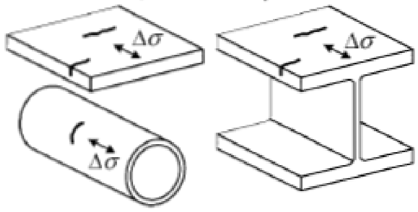
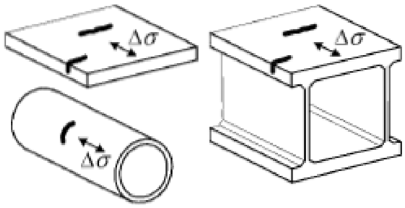
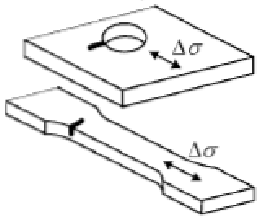
The following applies for the detail categories in EN 1999-1-3 Annex J (2007:79):

1. Detail categories are valid for ambient temperature, exposure conditions and do not require surface protection.
2. Apply with execution requirements EN 1090-3.
3. Applicable for stress ratio $R \geq 0.5$.

Note the alloy restrictions in the fatigue data, which is different that it was for steel in EN 1993-1-9.

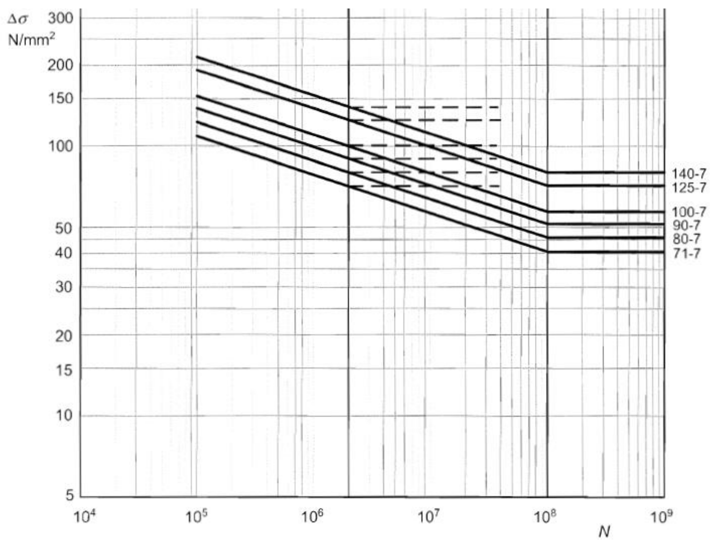
5.16.1. For plain members

Table 7: Detail categories for plain members - extraction from EN 1999-1-3 Table J.1 (2007:79)

Detail type	Detail category $\Delta\sigma - m_1$ 1) Alloy restriction	Product forms Constructional detail Initiation site	Stress orientation	Stress analysis	Execution requirements	
1.1	**125-7** 7020 only	Sheet, plate and simple extruded rod and bar, machined parts  Surface irregularity	Parallel or normal 2) to rolling or extrusion direction	Principal nominal stress at initiation site	Surface free of sharp corners unless parallel to stress direction, edges free of stress raisers	No re-entrant corners in profile, no contact with other parts Machined with a surface finish $R_{z5} < 40\ \mu m$ Visual inspection
1.2	**90-7**					
1.3	**80-7** 7020 only	Sheet, plate, extrusions, tubes, forgings  Surface irregularity				Hand grinding not permitted unless parallel to stress direction No score marks transverse to stress direction Visual inspection
1.4	**71-7**					
1.5	**140-7** 7020 only	Notches, holes  Surface irregularity		Account for stress concentration: see D.2		Holes drilled and reamed No score marks transverse to stress orientation Visual inspection
1.6	**100-7**					

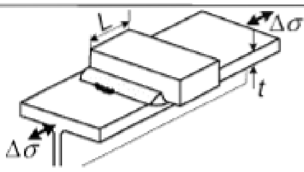
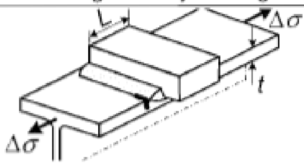
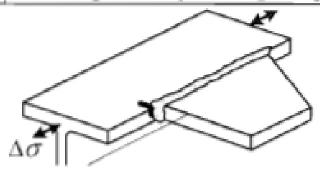
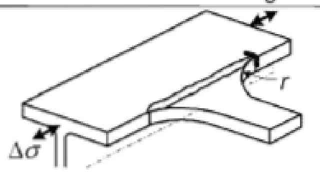
Notes:

1. $m_1 = m_2$, **constant amplitude fatigue limit at $N_C = 2 \times 10^6$**
2. **If the stress orientation is normal to the extrusion direction** the manufacturer should be consulted concerning the quality assurance in case of extrusions by port hole or bridge die
3. R_{z5} see EN-ISO 4287 and EN-ISO 4288



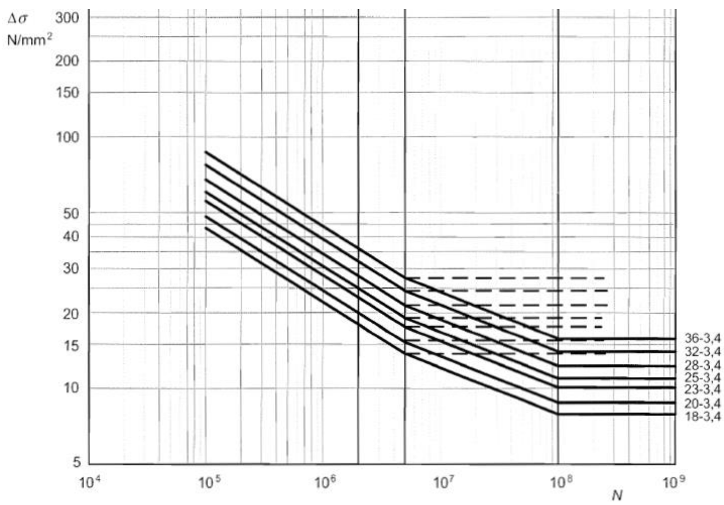
5.16.2. Members with welded attachments – transverse weld toe

Table 8: Detail categories for members with welded attachments – transverse weld toe - extraction from EN 1999-1-3 Table J.3 (2007:81)

Detail type	Detail category $\Delta\sigma - m_1$ 1) 2)	Constructional detail Initiation site	Dimensions (mm)	Stress analysis: Stress parameter	Stress analysis: Stress already allowed for	Execution requirements	Quality level 3)
3.1	**32-3,4**	 At transverse weld toe on stressed member, away from edge (weld continued longitudinally at flange edge)	$L \leq 20$	Nominal stress at initiation site	Stiffening effect of attachment	Grind undercut smooth	C
3.2	**25-3,4** $t \leq 4$ **23-3,4** $4 < t \leq 10$ **20-3,4** $10 < t \leq 15$		$L > 20$				
3.3	**28-3,4**	 At transverse weld toe on stressed member at corner (weld continued longitudinally at flange edge)	$L \leq 20$				
3.4	**23-3,4** $t \leq 4$ **20-3,4** $4 < t \leq 10$ **18-3,4** $10 < t \leq 15$		$L > 20$				
3.5	**18-3,4**	 Member surface on edge	No radius				
3.6	**36-3,4**	 In ground weld toe on edge	$r \geq 50$			Grind radius parallel to stress direction.	

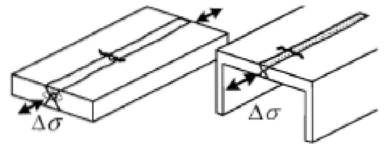
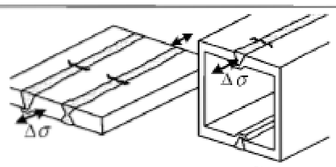
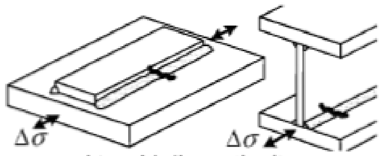
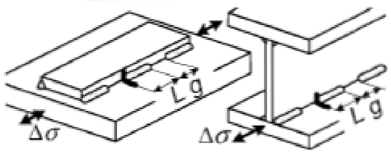
Notes:

1. $m_2 = m_1 + 2$
2. For flat members under bending stresses see 6.2.1(11) and increase by two detail categories.
3. According to EN ISO 10042:2005



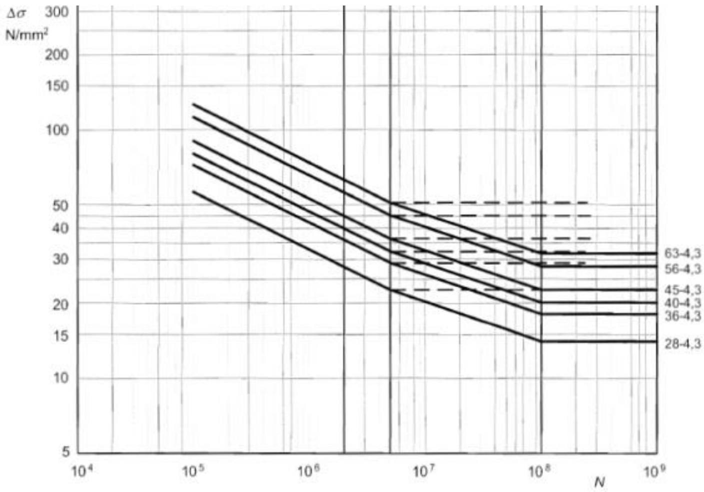
5.16.3. Detail categories for members with longitudinal welds

Table 9: Detail categories for members with longitudinal welds - extraction from EN 1999-1-3 Table J.5 (2007:83)

Detail type	**Detail category** $\Delta\sigma - m_1$ 1)	Constructional detail Initiation site	Weld type	Stress analysis: Stress parameter	Stress analysis: Stress concentrations already allowed for	Execution requirements: Welding characteristics	Quality level 3): internal	Quality level 3): surface and geometric	additional
5.1	**63-4,3**	 At weld discontinuity	Full penetration butt weld Weld caps ground flush	Nominal stress at initiation site		Continuous automatic welding	B	C	
5.2	**56-4,3**						C	C	
5.3	**45-4,3**	 At weld discontinuity	Full penetration butt weld			Any backing bars to be continuous	C	D	2)
5.4	**45-4,3**	 At weld discontinuity	Continuous fillet weld				B	C	
5.5	**40-4,3**						C	D	
5.6	**36-4,3**	 Weld toe or crater	Intermittent fillet weld $g \leq 2{,}5L$				C	D	

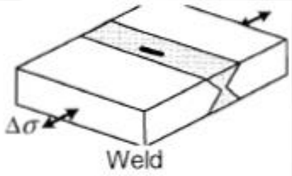
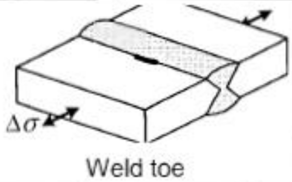
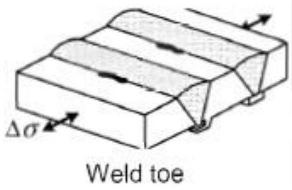
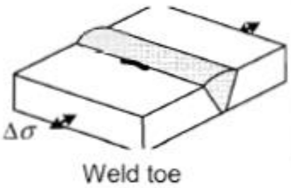
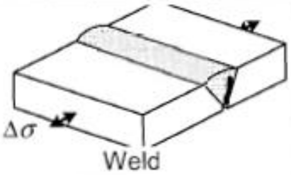
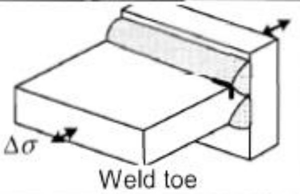
Notes:

1. $m_2 = m_1 + 2$
2. Discontinuity in direction of longitudinal weld should not be longer than 1/10 of the plate thickness or exhibit a slope steeper than 1:4.
3. According to EN ISO 10042:2005.



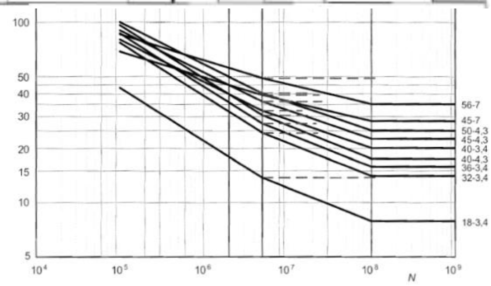
5.16.4. Butt-welded joints between members

Table 10: Detail categories for butt-welded joints between members - extraction from EN 1999-1-3 Table J.7 (2007:85)

Detail type	Detail category $\Delta\sigma - m_1$ 1)	Constructional detail / Initiation site	Type of weld	Joint Part	Stress analysis	Execution requirements: Welding requirements	Execution requirements: Welding requirements	Execution requirements: Quality level 3) internal	Execution requirements: Quality level 3) surface and geometric	Execution requirements: additional
7.1.1	**56-7**		Full penetration, caps ground flush both sides	Flats, solids	Net section	Root ground off	Extension plates used on ends, cut off and ground flush in direction of stress	B	B	6)
7.1.2	**45-7**			Open shapes				C	C	
7.2.1	**50-4,3**		Welded from both sides, full penetration	Flats, solids				B	B	4) 6)
7.2.2	**40-3,4**			Open shapes				B	C	6)
7.2.3	**36-3,4**							C	C	
7.3.1	**40-4,3**		Welded one side only, full penetration with permanent backing	Flats, solids				C	C	6)
7.3.2	**32-3,4**			Open shapes, hollow, tubular				C	C	
7.4.1	**45-4.3**		Welded one side only, full penetration without backing	Flats, solids				B	B	5) 6)
7.4.2	**40-4,3**							C	C	6)
7.4.3	**32-3,4**			Open shapes, hollow, tubular				C	C	
7.5	**18-3,4**		Partial penetration		Net throat			D	D	
7.6	**36-3,4**		Full penetration		Net section 2)			B	B	

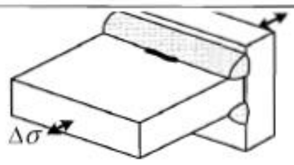
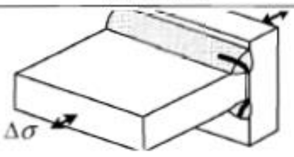
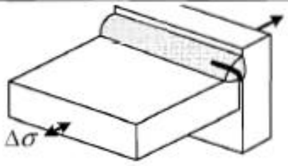
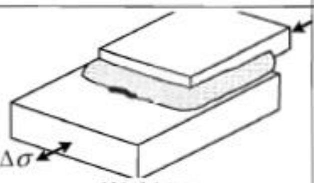
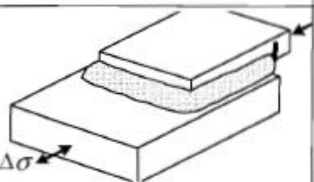
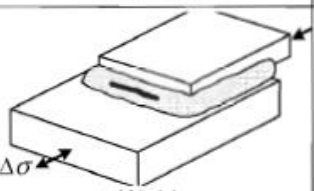
Notes:

1. $m_2 = m_1 + 2$
2. Stress concentration of stiffening effect of transverse element already allowed for.
3. According to EN ISO 10042:2005.
4. Overfill angle $\geq 150°$ for both sides of the weld.
5. Overfill angle $\geq 150°$
6. Taper slope $< 1:4$ at width or thickness changes



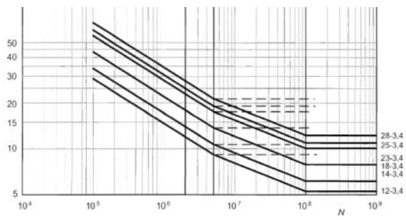
5.16.5. Fillet-welded joints between members

Table 11: Detail categories for fillet-welded joints between members - extraction from EN 1999-1-3 Table J.9 (2007:87)

Detail type	**Detail category $\Delta\sigma - m_1$ 1)**	Constructional detail Initiation site	Type of weld	Stress analysis: Stress parameter	Stress analysis: Stress concentrations already allowed for	Execution requirements: Welding requirement	Execution requirements: Quality level 3): internal	Execution requirements: Quality level 3): surface and geometric	Execution requirements: additional
9.1	**28-3,4**	 Weld toe	Double fillet weld partial penetration; toe crack for $a/t > 0,6$	Net section	Stiffening effect of transverse element	Extension plates used on ends, cut off and ground flush in direction of $\Delta\sigma$	C	C	
9.2	**25-3,4**	 Weld	Double fillet weld partial penetration; root crack for $a/t \leq 0,6$	Net throat			C	C	
9.3	**12-3,4**	 Weld	One sided fillet weld 2), root crack for $a/t \leq 0,6$				C	C	
9.4	**23-3,4**	 Weld toe	Fillet weld	Net section	Stress peak at weld ends		C	C	
9.5	**18-3,4**	 Weld toe	Fillet weld				C	C	
9.6	**14-3,4**	 Weld	Fillet weld	Net throat, see 5.4.2			C	C	

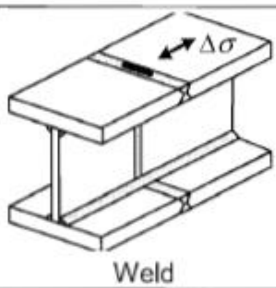
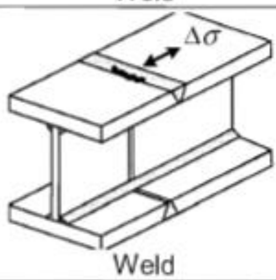
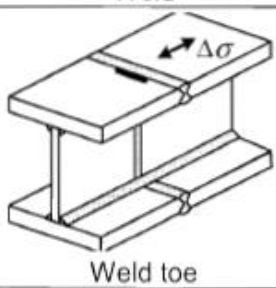
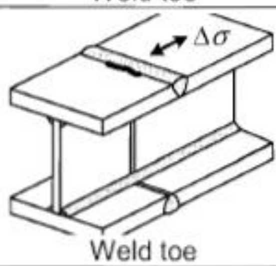
Notes:

1. $m_2 = m_1 + 2$
2. In case of tubular cross section design to detail type 9.1 or 9.2 accordingly.
3. According to EN ISO 10042:2005.



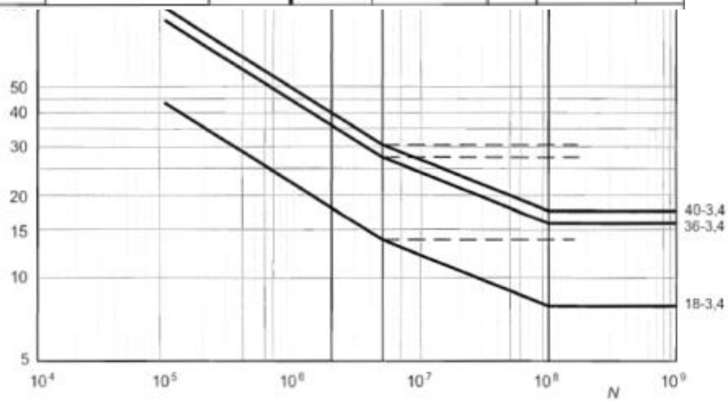
5.16.6. Crossing welds on built-up beams

Table 12: Detail categories for crossing welds on built-up beams - extraction from EN 1999-1-3 Table J.11 (2007:89)

Detail type	Detail category $\Delta\sigma - m_1$ 1)	Constructional detail Initiation site	Type of weld 2) 3)	Stress analysis	Execution requirements: Welding requirements		Execution requirements: Quality level 4): internal	Execution requirements: Quality level 4): surface and geometric	Execution requirements: additional
11.1	**40-3,4**		Double sided butt weld, full penetration, caps ground flush both sides	Net section	Extension plates used on ends, cut off and ground flush in direction of $\Delta\sigma$	Root ground off	B	B	For web-to-flange fillet welds, see Table J.5, type no. 5.4 or 5.5
11.2	**40-3,4**		Single sided butt weld, full penetration, root and cap ground flush				B	B	
11.3	**36-3,4**		Double sided butt weld, full penetration			Overfill angle ≥150° root ground off	B	C	
11.4	**32-3,4**		Single sided butt weld, full penetration				C	C	

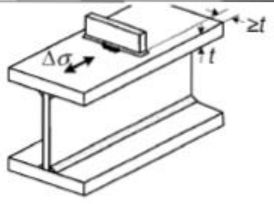
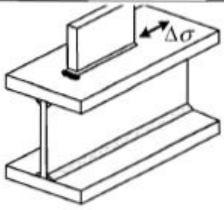
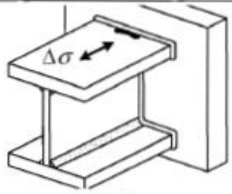
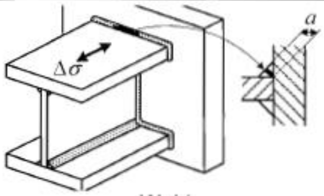
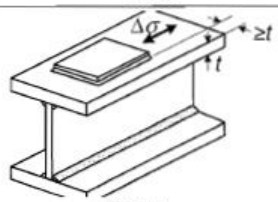
Notes:

1. $m_2 = m_1 + 2$
2. Transverse web and flange butt joint before final assembly of beam with longitudinal welds.
3. Taper slope $< 1:4$ at width or thickness change.
4. According to EN ISO 10042:2005.

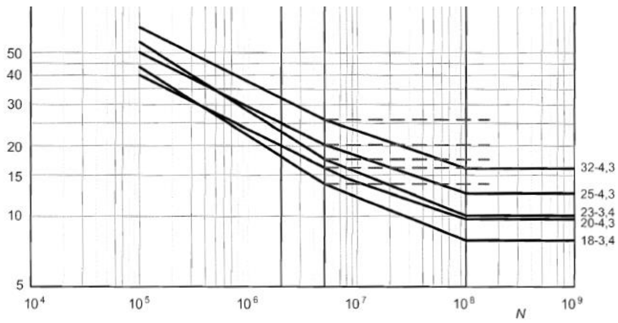


5.16.7. Attachments on built-up beams

Table 13: Detail categories for attachments on built-up beams - extraction from EN 1999-1-3 Table J.13 (2007:91)

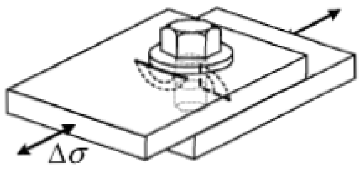
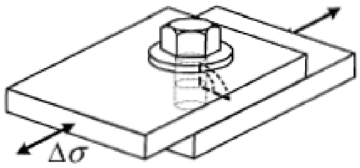
Detail type	Detail category $\Delta\sigma - m_1$ 1)	Constructional detail / Initiation site	Type of weld	Stress analysis: Stress parameter	Stress analysis: Stress concentrations already allowed for	Execution requirements: Quality level 2): internal	Execution requirements: Quality level 2): surface and geometric	Execution requirements: additional
13.1	**23-3,4**	 Weld toe	Transverse attachment, thickness < 20 mm, welded on one or both sides	Net section	Stiffening effect of attachment / stress concentration at "hard point" of connection (compare to Figure 5.2)	C	C	For web-to-flange fillet welds, see Table J.5, type no. 5.4 or 5.5
13.2	**18-3,4**	 Weld toe	Longitudinal attachment length ≥ 100 mm, welded on all sides					
13.3	**32-4,3**	 Weld toe	Cruciform or tee, full penetration					
13.4	**25-4,3**	 Weld	Cruciform or tee, double sided fillet welds; root crack for a/t ≤ 0,6	Net throat				
13.5	**20-4,3**	 Weld toe	Coverplate length ≥ 100 mm, welded on all sides	Net section				

Notes:
1. $m_2 = m_1 + 2$
2. According to EN ISO 10042:2005



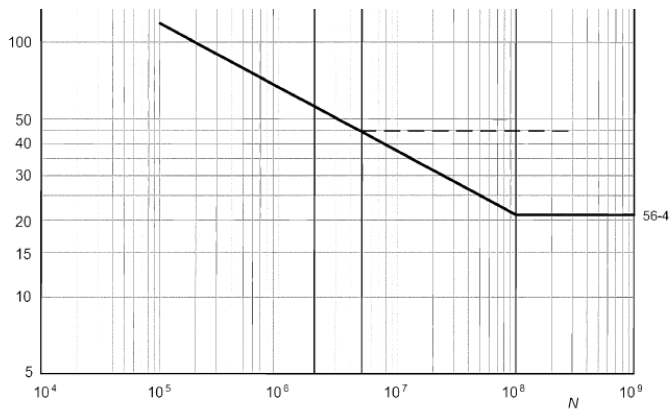
5.16.8. Bolted joints

Table 14: Detail categories for bolted joints - extraction from EN 1999-1-3 Table J.15 (2007:93)

Detail type	**Detail category** $\Delta\sigma - m_1$ 1)	Constructional detail Initiation site	Stress analysis Stress parameter	 Stress concentrations already allowed for	Execution requirements
15.1	**56-4**	Preloaded (friction type), high strength steel bolt  In front of hole (sometimes at edge of hole)	Nominal stress based on gross section properties	Surface texture, fastener hole geometry; unequal load distribution between rows of bolts;	Lap joint with flat parallel surfaces Machining only by high speed milling cutter; holes drilled (with optional rea-ming) or punched (with compulsory reaming if thickness > 6 mm) For preloaded bolts the quality should be 8.8 ($f_y \geq 640$ N/mm²) or higher see EN 1999-1-1.
15.2	**56-4**	Non-preloaded (bearing type) steel bolt  At edge of hole	Nominal stress based on net section properties	eccentricity of load path in symmetrical double covered lap joints only	Lap joint with flat parallel surfaces Machining only by high speed milling cutter; holes drilled (with optional reaming) or punched (with compulsory reaming if thickness > 6 mm) For bolts see EN 1999-1-1.

Notes:

1. $m_2 = m_1$
2. Verification of the resistance of steel bolts: See EN 1993-1-9.



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