1. ASSIGNMENT GUIDELINE

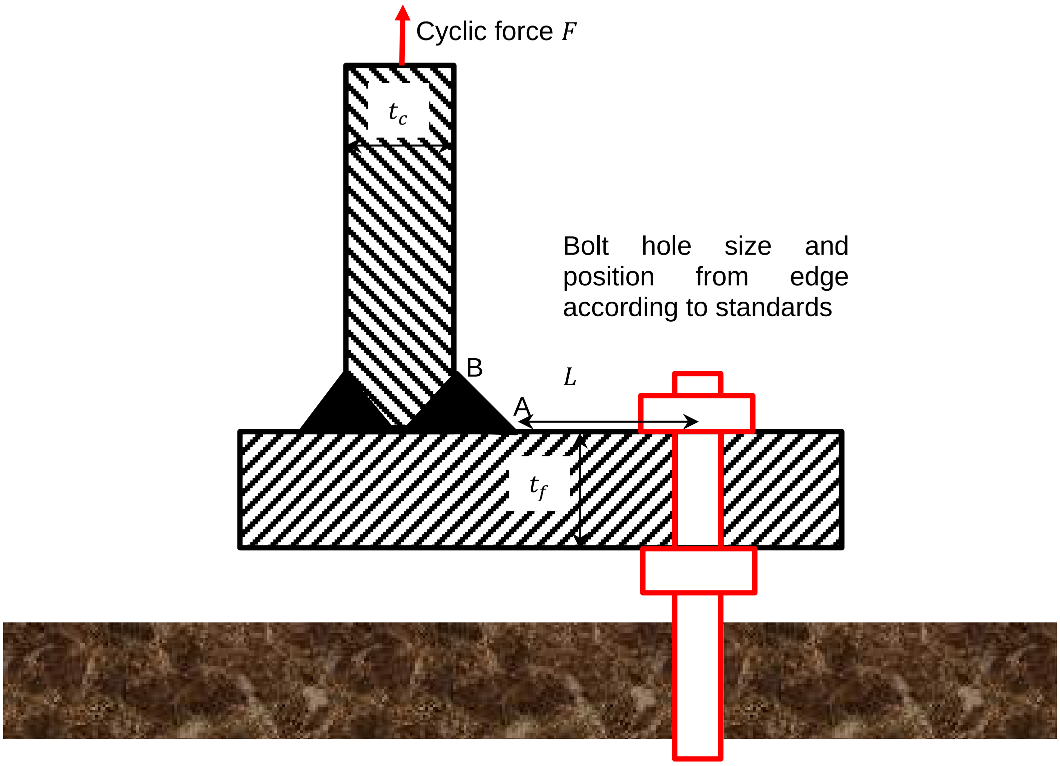
The following points are important to remember:

1. You must complete the assignment in this MS Word document, and rename the file as: Assignment by Student Name (Student Number).doc. The Excel file shall be saved as Assignment by Student Name (Student Number).xls
2. Submit the assignment and Excel file by e-mail to: **mheyns@investmech.com**. No faxed assignments will be evaluated. Please submit the documents to allow me to make changes and mark it directly in the document. This will also allow detail feedback on your assignment.
3. If you have to do the assignment in handwriting, please scan, pdf and then e-mail.
4. Number the answer correctly as per the original assignment.
5. Copy and paste all diagrams, tables, figures, etc. Into this document.
6. Include proper referencing to detail according to the Harvard Method.
7. Hand sketches may be scanned and copied into the document.
8. Delivery date: As arranged with the class controller.
9. Please contact me at the following should you require assistance:
    a. 082 445-0510
    b. 012 664-7604
    c. mheyns@investmech.com
10. The following documents make part of this assignment:
    a. This document.
    b. Excel file: Assignment1.xls.

2. GENERAL USE OF THE IDEAS [20 MARKS – 40 MINUTES]

2.1. Problem Statement

You are designated as the responsible person in charge of a steel chimney stack at a plant. You experience continuous failure of the weld at the bottom of the structure where the cylindrical shell is welded to the baseplate. A complete joint penetration butt weld is used and reinforced with a 12 mm fillet weld on the inside and outside of the cylinder. The cracks initiate at the fillet weld toe on the outside of the cylinder (Position B in the sketch) and at the weld toe of the fillet weld on the flange type base plate (Position A on the sketch), also on the outside. Assume that the bolt was correctly sized and positioned correctly from the mounting flange outer edge as prescribed by the applicable standard. Excessive deflection of the cantilevered chimney stack is visible during operation on a non-windy day, that increase in amplitude on windy days for specific wind speeds. An epoxy paint is used that offers sufficient surface protection.



Questions:

1. Make a sketch of how you expect the joint will deform under tensile loading **[10 %]**.
2. Make a sketch of how you expect the joint will deform under compressive loading **[10 %]**.
3. Discuss the sensitivity of the stress at weld Toe A under tensile and compressive loading (think of an infinite thick base plate versus a very thin base plate to motivate your answer) **[10 %]**.
4. How will the thickness t_f and distance L ratio influence the stress at weld Toe A? **[10 %]**
5. How will the same ration than above influence the stress at weld Toe B? **[10 %]**
6. What are the causes for the cyclic loading on this chimney stack? **[10 %]**
7. Discuss two modifications/redesign/solutions; excluding post weld improvement by burring, dressing, peening or surface protection; that you can implement to prevent the weld from initiating a crack at these weld toes in future. **[20 %]**
8. Choose one solution mentioned above and explain how you will use structural mechanic equations and BS EN 1993-1-9 to confirm the integrity of the solution for the relevant detail category. **[20 %]**

2.2. Solution

The answer should be typically as follows:

1. Under tensile loading, the bolt will not keep the section from the outside to just to the left of the bolt flat with the foundation as is the case in a bolted flange. This is because the nuts on the anchor studs are used to locate the hole at a specific position. If the bending stiffness of the bolt is ignored, the parts will deflect as shown below:
    a. If the joint was grouted, the bolt will pull the outer section to approximately the side of the bolt against the grouting. That is, this section will remain flat. This will increase the strength of the joint because of the additional constraint against rotation at the bolt.

   [10 %]
2. Under compressive loading, the flange tip will bend upwards resulting in a deflection shown below:
    a. If the joint was grouted, no deformation under compressive loading is expected.

   [10 %]
3. The stress at weld Toes A and B will be more than that of the weld toes on the inside because of the bending moment by the bolt reaction. If the baseplate thickness was infinite, no prying effect would result and the weld detail would have been subjected to. **[10 %]**
4. The thickness of the flange will prevent the magnitude of the deflection (prying action). A thicker section will also result in lower stress at the weld toe due to the bending moment as a result of the "prying". The higher the distance, L, the higher the bending moment at the weld toe due to the bolt reaction force. Bending moment due to the anchor bolt will result in a bending stress that is indirectly proportional to the third power of flange thickness. The bending moment, and the bending stress is proportional to the distance, L. Therefore, an increase in flange thickness will result in a significant reduction in bending stress at weld Toe A. A reduction in the L/t_f ratio will result in a reduction in stress at the weld toes. **[10 %]**
5. It will have the same effect that at Position A, just slightly smaller because of the deeper section and the deformation of the shell. **[10 %]**
6. Cyclic loading on a chimney stack can be due to the following:
    a. Vortex shedding that is magnified when the vortex shedding frequency is equal to the natural frequency of the stack.
    b. Earth movement.
    c. Wind pressure loading.
    d. Thermal stress.
    e. Turbulence of the gasses flowing in the stack exciting natural modes.
    f. Etc.

    [10 %]
7. The following can be done:
    a. Insert grouting. This will limit the deflection and subsequent stress at the weld toes during both tensile and compressive loading.
    b. Thicken the flange.
    c. Reduce the distance L by placing the bolts closer to the cylindrical section.
    d. Increase the bolt size. This will result in higher resistance against bending of the bolt that will reduce the deformed curvature of the flange and reduce stress range at the weld Toes A and B.

   [10 % x 2 = 20 %]
8. The process will be as follows:
    a. Calculate stress range.
    b. Find joint detail category dependent fatigue curve.
    c. Do fatigue calculation and ensure a sufficient design life.
    d. Do surface protection.

   [20 %]

3. NOTCH DEPENDENT DETAIL CATEGORY

3.1. Question

Explain how the detail category tables in BS EN 1993-1-9 make provision for the notches at weld detail and give an example. For the example, copy and paste the relevant detail categories from the tables into your assignment, reference and discuss.

3.2. Answer

There are many answer options here. I will mark according to accurate articulation of the approaches. EN 1993-1-9 makes provision for the notch detail by having detail category as function of the location of crack initiation, that is, at the root or at the toe (the student must include detail categories to demonstrate). Further, there are detail categories making provision for the longitudinal (staggered or continuous) as well as transverse loaded weld detail, specifically for this reason. Research has shown the even steels with higher fatigue strength give all approximately the same fatigue strength when welded. There are many reasons for that:

1. The notch at weld toe and root as high stress concentrations.
2. Changes in the weld metal on the preparation surfaces close to the edge of the weld.
3. Angle of reinforcement.
4. Etc.

4. OVERLOADING AND FATIGUE

4.1. Problem statement

You designed new weld detail for a machine subject to constant amplitude stresses. A consultant recommends a few overload cycles to improve the fatigue strength of the load-carrying as-welded fillet welds. The consultant claims that this will result in local yielding that will reduce the mean tensile stress at the weld root and toe. In the design, and from measured strains on previous versions of the machine, you ensured a cyclic stress range below the constant amplitude fatigue limit of the relevant detail category for a damage tolerant assessment method with low consequence of failure. That is, the partial factor for fatigue is $\gamma_{Mf} = 1.0$.

<u>Question:</u>

Explain in full how you will evaluate the advantages/disadvantages of the consultant's recommendation for the as-welded fillet welds.

4.2. Solution

With the new design, the stress ranges are already below the constant amplitude fatigue limit and there is no evidence that the joint will be subjected to stress ranges exceeding the constant amplitude fatigue limit. This will result in infinite life for the detail category.

However, if a few cycles during the overloading are applied that exceed the constant amplitude fatigue limit, micro-cracks can be caused that will result in crack propagation to detectable crack size during the stress cycles with range below the constant amplitude fatigue limit. Therefore, the overloading applied resulted in the joint which was designed for infinite life to have a finite life. Based on this, overloading at stress ranges above the constant amplitude fatigue limit will result in finite fatigue life by stress ranges below the constant amplitude fatigue limit. This has a disadvantage.

Because crack initiation at the notches of weld roots and toes is not sensitive to mean stress, overloading to reduce mean tensile stress does not have any advantage based on the information supplied by BS EN 1993-1-9.

6. WELD FATIGUE LIFE IMPROVEMENT TECHNIQUES [WEIGHT=5/10]

Discuss and compare, including relevant graphs and sketches, the improvement of weld detail by means of:

1. Weld toe treatment (burring).
2. Hammer peening.

Discuss how it is modelled by Bulletin 520 of the International Institute of Welding.

6.1. Answer

Please type your answer here.

Question1: Weld toe treatment (burring) [5 Marks]

The aim of burring/grinding the weld toe:

1. To remove imperfections which are an inherent feature of most arc welds like **[1 Mark]**:
   a. Undercut.
   b. Cold laps.
   c. Sharp crack-like imperfections.
2. Create a smooth transition between the weld an plate – reduce the stress concentration **[1 Mark]**.

The benefit of weld toe treatment:

A factor is calculated that is applied to the fatigue class of the non-improved joint **[1 Mark]**. The classes applicable are **[1 Mark]**:

Table 1: FAT classes for use with nominal stress at joints improved by grinding (IIW, 2007:86)

Area of application and maximum possible claim	Steel	Aluminium
Benefit at detail classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.3
Maximum possible FAT class AFTER improvement	FAT 112	FAT 45
Thickness correction exponent: $n = 0.2$		

[1 Mark] for the table below

Table 2: FAT classes for use with structural hot-spot stress at post-welding weld toe improvements by grinding (IIW, 2007:87)

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
Thickness correction exponent: $n = 0.2$		

Question 2: Hammer peening [13 Marks for this question]

Only marked for this paper the boldfaced marks

The material is plastically deformed at the weld toe **[1 Mark]** that introduces beneficial compressive residual stresses **[1 Mark]**. Note, this should be done under controlled environments because the weld toe can be over-peened.

Restricted to CONDITIONS FOR HAMMER PEENING:

1. Materials **[1 Mark]**:
    a. Steel with $f_y \leq 900\ MPa$
    b. Structural aluminium alloys.
2. Environment:
    a. Operating in non-corrosive environment or under corrosive protection **[1 Mark]**.
3. Thickness:
    a. Steel plate thickness from 10 mm to 50 mm **[1 Mark]**.
    b. Aluminium plate thickness from 5 mm to 25 mm **[1 Mark]**.
4. Arc welded fillet welds with minim weld length $0.1t$ ($t =$ thickness of the stressed plate) **[1 Mark]**.
5. Maximum amount of nominal compressive stress in the load spectrum (including proof loading) $< 0.25f_y$ for steel and the yield strength of the heat affected zone for aluminium **[1 Mark]**.
6. Applied stress ratio:
    a. For $R \leq 0$: $Effective\ stress\ range = BENEFIT\ FACTOR \times applied\ \Delta\sigma$ **[1 Mark]**
    b. For $0 < R \leq 0.4$: $Effective\ stress\ range = BENEFIT\ FACTOR \times maximum\ applied\ \sigma$ **[1 Mark]**
    c. For $R > 0.4$: NO BENEFIT **[1 Mark]**

Restricted to CONDITIONS FOR NEEDLE PEENING:

Restricted to:

1. Maximum amount of nominal compressive stress in the load spectrum (including proof loading) $< 0.25f_y$ for steel and the yield strength of the heat affected zone for aluminium [1 Mark].
2. Applied stress ratio:
    a. For $R \leq 0$: $Effective\ stress\ range = BENEFIT\ FACTOR \times\ \Delta\sigma$ [1 Mark]
    b. For $0 < R \leq 0.4$: $Effective\ stress\ range = BENEFIT\ FACTOR \times maximum\ applied\ \sigma$ [1 Mark]
    c. For $R > 0.4$: NO BENEFIT [1 Mark]

BENEFIT FACTOR

The benefit factor is applied to the FAT class of the as-welded weld **[1 Mark]** according to the limits and applications summarised in Tables 5 **[1 Mark]** and 6 [1 Mark].

3.

Table 3: FAT classes for use with nominal stress at joints improved by Hammer and Needle peening (IIW, 2007:88-89)

Area of application and maximum possible claim	Steel $f_y < 355\ MPa$	Steel $f_y \geq 355\ MPa$	Aluminium
Benefit at detail classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.6	1.6
Maximum possible FAT class AFTER improvement	FAT 112	FAT 125	FAT 56
Use the standard thickness correction for as-welded joints for wall thickness >25 mm			

Table 4: FAT classes for use with structural hot-spot stress at post-welding weld toe improvements by Hammer and Needle peening (IIW, 2007:88-89)

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, $f_y < 350\ MPa$	112	125
Higher strength steel, $f_y \geq 350\ MPa$	125	160
Aluminium alloys	56	63
Use the standard thickness correction for as-welded joints for wall thickness >25 mm		

7. WELD FATIGUE DESIGN ACCORDING TO BS EN 1993-1-9 [WEIGHT = 15/10]

7.1. Background

Figures 2 and 3 show weld geometries with the following detail and stresses:

1. Figure 2: Plate $t_1 = 20\,mm$ on which a stiffener with thickness $t_2 = 16\,mm$ is welded by means of a double fillet weld with size $e = 6\,mm$ and where the stresses are:
   a. Transversal stress σ_x has a nominal mean stress of 20 MPa and cyclic stress with amplitude 19 MPa and the longitudinal stress $\sigma_y = 0\,MPa$.
   b. Assume an infinite width for the plate W.
2. Figure 2: Plate $t_1 = 50\,mm$ on which a stiffener with thickness $t_2 = 30\,mm$ is welded by means of a double fillet weld with size $e = 12\,mm$ and where the stresses are:
   a. Longitudinal stress σ_y has a nominal mean stress of 20 MPa and cyclic stress with amplitude 19 MPa and the transversal stress $\sigma_x = 0\,MPa$.
   b. Assume an infinite width for the plate W.
3. Figure 3: Plate of $t_1 = 20\,mm$ on which an attachment of thickness $t_2 = 25\,mm$ is welded by means of an all-around fillet with size $e = 12\,mm$. $W_2 \ll W_1$ and the height $h = 55\,mm$.
   a. The nominal stress in the x-direction σ_x has a mean of 20 MPa and cyclic stress with amplitude 19 MPa superimposed. The stress in the y-direction $\sigma_y = 0\,MPa$.

Assume the following:

1. The material is 350W structural steel.
2. All weld filler metal matches that of the base metal.
3. The design philosophy is safe life with low consequence of failure.

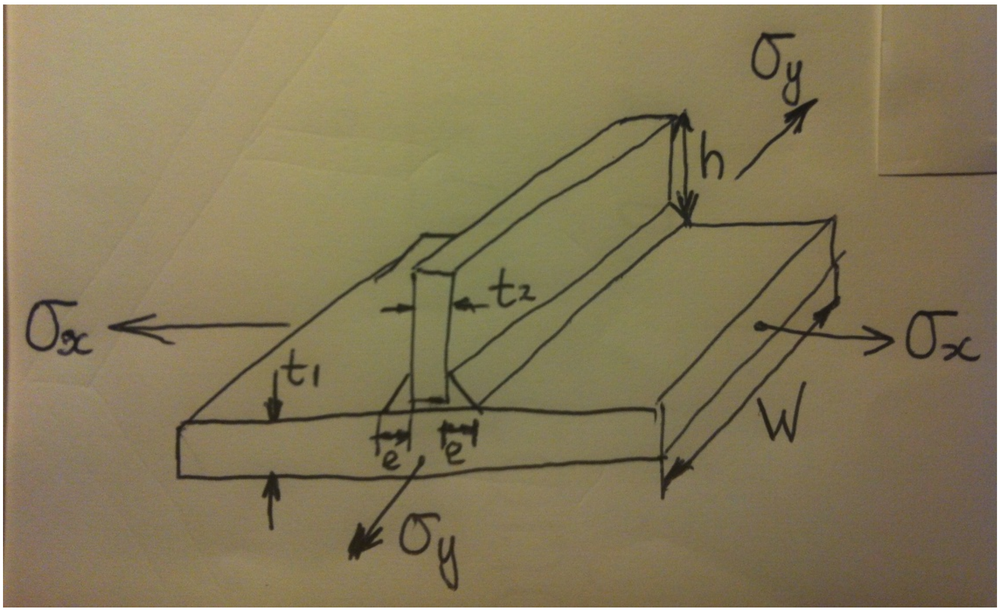


Figure 1: Fillet weld detail for loading in the transversal and longitudinal directions

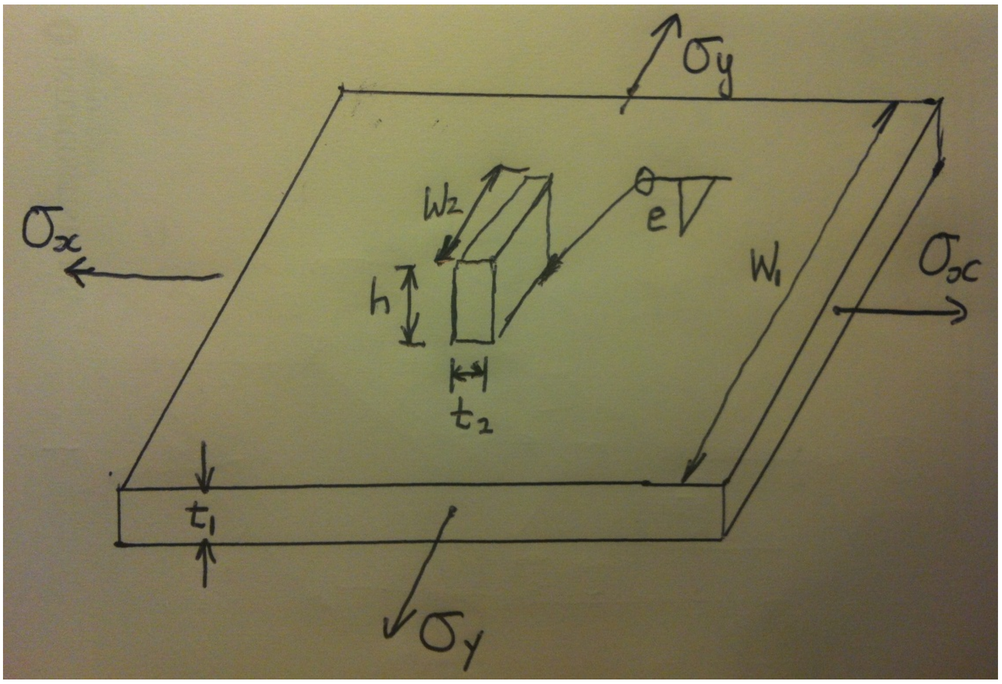


Figure 2: Attachment with fillet weld subjected transversal and longitudinal stress

The structure is used in a corrosive environment and is suitably surface protected against its environment. The operating temperature of the structure is between 18 °C and 22 °C. It may be assumed that the temperature remains constant. The surface condition of the steel plate is as it was received from the mill. No special surface smoothing was done. The welds were carried out to comply with the fabrication requirements specified in BS EN 1993-1-9.

7.2. Questions

Please complete the following:

1. What is the life expectancy, in cycles, for each as-welded joint detail for a probability of survival of 95 % according to:
    a. BS EN 1993-1-9?
2. What can be done to double the fatigue life of the welded joints?
3. What effect will corrosion have when the protective layer loose its integrity?
4. Explain what is meant by plastic collapse.
5. Explain what is meant by fracture.
6. Sketch a diagram showing the crack size dependant life of a component and explain how the critical crack size can be determined. Clearly indicate up to which point is fatigue analysis done, and from where up to what point can fracture mechanics be done to estimate total life of the component.

7.3. Answer

Due to the direction of stress application, in some instances thickness correction need to be considered. The following general equations of the S-N curve were used:

The partial factor for fatigue strength is 1.15 for safe life and low consequence of failure.

Table 5: Partial factor for fatigue strength γ_{Mf}

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

The following equations hold for the S-N curve: **[1 Mark for correct implementation of the equation]**

$$N_R = \begin{cases} \left[\frac{\Delta\sigma_C}{\Delta\sigma_R}\right]^m \times 2\times 10^6 & m = 3\ for\ N \le 5\times 10^6, or\ \Delta\sigma_R \le \Delta\sigma_D \\ \left[\frac{\Delta\sigma_C}{\Delta\sigma_R}\right]^m \times 5\times 10^6 & m = 5\ for\ 5\times 10^6 \le N \le 10^8, or\ \Delta\sigma_D \le \Delta\sigma_R \le \Delta\sigma_L \\ INF & N > 10^8, or\ \Delta\sigma_R < \Delta\sigma_L \end{cases}$$

Where $\Delta\sigma_C$ is the reference value of the REDUCED fatigue strength at an endurance of 2 million cycles. That is,

$$\Delta\sigma_C = \frac{Detal\ Category}{\gamma_{Mf}} \times Size\ Factor$$

From this, the constant amplitude fatigue limit is at 5 million cycles which is:

$$\Delta\sigma_D = \left[\frac{2\times 10^6}{5\times 10^6}\right]^{\frac{1}{3}} \Delta\sigma_C$$

The cut-off limit $\Delta\sigma_L$ at 100 million cycles is then:

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

The equations were programmed in the table below:

	Detail 1	Detail 2	Detail 3	Units
Detal category	80	100	56	
Partial factor for fatigue strength	1.15	1.15	1.15	
Size factor	1	1	1	
Reduced reference fatigue strength	69.6	87.0	48.7	MPa
Reference fat. strength endurance	2.00E+06	2.00E+06	2.00E+06	Cycles
Const. Ampl. endurance	5.00E+06	5.00E+06	5.00E+06	Cycles
Slope 1	3	3	3	
Slope 2	5	5	5	
Const. Ampl. fatigue strength	51.26	64.07	35.88	MPa
Cut-off limit endurance	1.00E+08	1.00E+08	1.00E+08	Cycles
Cut-off limit stress range	28.15	35.19	19.71	MPa
STRESS RANGE APPLIED WITH LIFE				
Applied stress range	**38**	**38**	**38**	**MPa**
Endurance at this stress range	**22 324 380**	**68 128 601**	**4 208 717**	**Cycles**

[1 Mark for calculation procedure given in the table]

8. WELD GEOMETRY CHANGE [10 MARKS – 10 MINUTES]

8.1. Problem statement

In the design of a joint the engineer recommended the use of the weld detail shown in the left layout of Figure 1. For the design, the weld was assumed to be made from both Sides A and B as shown. The weld joins the plates at an angle of 60 °. There is a pressure inside the container on the B-side. The consequence of failure is loss of life and a safe life infinite fatigue life strategy is important.

Due to access related problems the boilermaker wants to modify the weld detail to that shown in the right configuration of Figure 1. That is, the boilermaker wants to make the weld from Side A only without a backing strip.

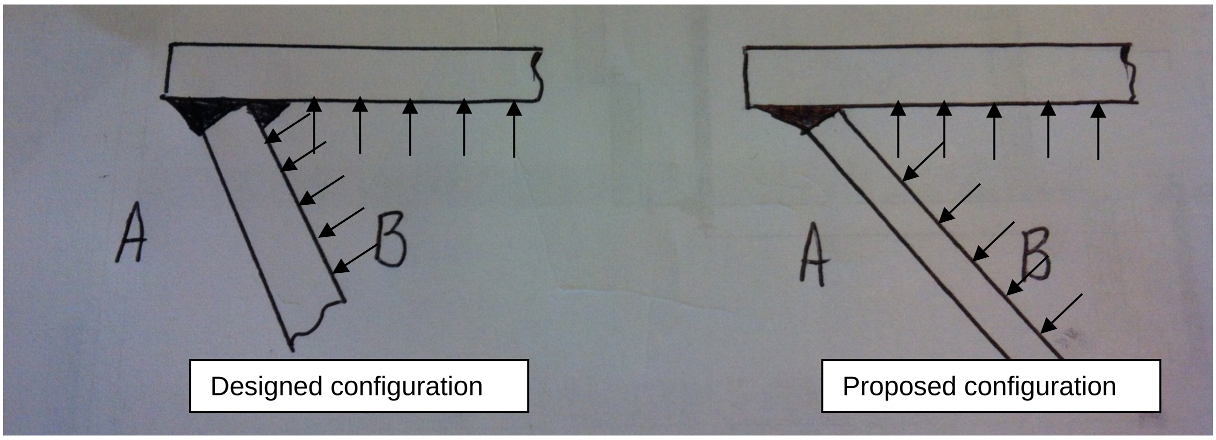


Figure 3: Designed and proposed modifications to joint detail

Please answer the following:

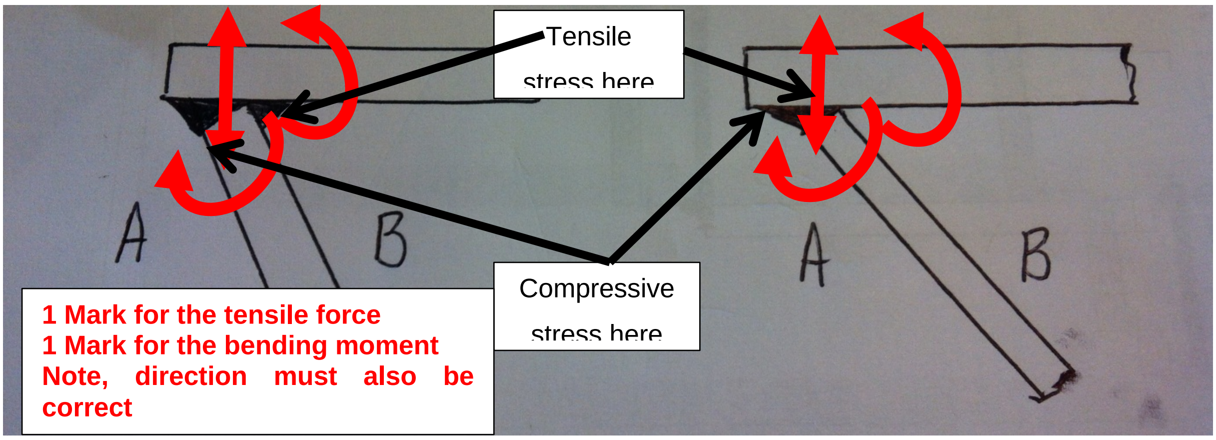
1. On a free body diagram, sketch how you anticipate forces and moments through the joint and plate sections **[25% of mark]**.
2. What are the disadvantages of the joint detail proposed by the boilermaker? Motivate. **[25% of mark]**.
3. Under what conditions will you approve the modification of the weld detail? Motivate. **[25% of mark]**
4. What method will you prefer to calculate the fatigue life of the proposed configuration? Motivate. **[25% of mark]**

8.2. Answer [8 Marks]

Answers as follows:

Question 1 [2 marks]

The forces and moments foreseen through the welded joint are as shown in the sketch below.



Question 2 [2 Marks]

There is tensile stress in the weld on the inside where the pressure is applied caused by the tensile force in the joint as well as the bending moment trying to open the joint **[2 marks – 1 for each of any two of the following]**.

1. In the "proposed" joint, there will be a high stress concentration at this point where the high tensile stress is, which provides a point for crack initiation.
2. Further, if the weld is not sealed on this side, corrosion can accelerate damage.
3. If it is not possible to weld properly in this area, then inspection could also be problematic to ensure that the weld does not have stress concentrations (defects) that could result in premature crack initiation.

Question 3 [2 Marks]

This weld detail can only be approved where **[2 marks - 1 for each of any two of the following]**:

1. The notch stress have been verified on a finite element analysis and found to comply with the allowable fatigue stress curve.
2. Inspection is done on the inside to eliminate an irregular weld profile that can result in stress concentrations and crack initiation.
3. The weld inside surface is protected against corrosive environments.
4. The weld is not critical, failure of the joint does not have any major consequence(s).

Question 4 [2 Marks]

The effective notch stress method **[1 mark]** because this will model both the bending moment and tensile force effects on the stress at the stress concentration of the weld root at the inside of the joint. Further, the geometric stress concentration will also be modelled. Another reason for the effective notch stress analysis is the fact that this weld detail is not included in the standard structural detail from which a FAT class can be derived **[1 mark if force and moments or stress concentration was addressed]**

This gives a total of 8 Marks allocated.

Multiply by the ration to get the mark on the examination paper.

9. ADVANCED WELD FATIGUE DECISION-MAKING [30 MINUTES = 30 MARKS]

9.1. Problem Statement

The weld detail on a part with intermittent fillet weld is shown in Figure 3. The limiting gap ratio is more than 2.5 (i.e. $\frac{g}{h} > 2.5$) and applies evenly. However, adjacent welds may be on opposite sides of a narrow attachment. The stress spectrum of the joint over a period of 2 years is as summarised in Table 3. Assume a damage tolerant structure with high consequence of failure.

Table 6: Stress spectrum on the joint over a period of two years.

σ_{max} [MPa]	σ_{min} [MPa]	Number of cycles
40	0	1,000,000
25	-22	800,000
0	-60	400,000

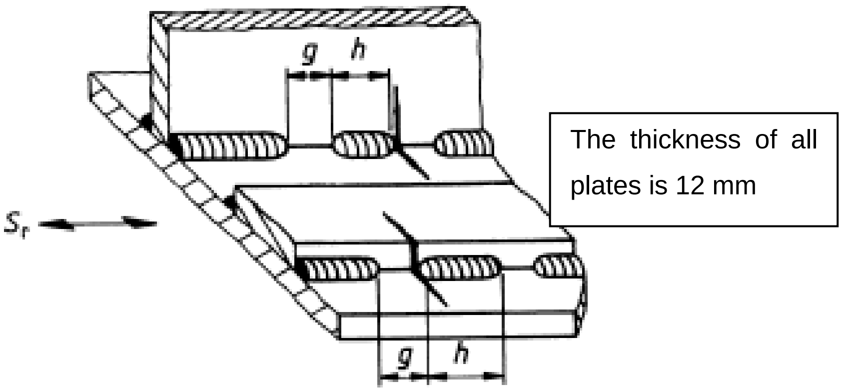


Figure 4: Intermittent fillet weld on part.

Please answer the following (Please use BS EN 1993-1-9 as reference):

1. If the stress spectrum above refers to a block loading applied to the joint over a period of 2 years, what estimate of fatigue life would you make for the welded joint for a probability of failure of 5%? **[64% of marks]**
2. Where do you expect the weld detail to fail, please motivate. **[4% of marks]**
3. Do you need to consider thickness effects on the fatigue life? Please motivate. **[4% of marks]**
4. What first order estimate for fatigue life would you recommend when peening is done to the surface before the joint is put in service? That is, just give a rough factor. **[8% of marks]**
5. What estimate for fatigue life would you make if toe burring has been applied? **[8% of marks]**
6. To which joint type do you recommend the joint should be modified to increase fatigue life? **[4% of marks]**
7. To what joint class does the joint change when the gaps are less than 2.5h (i.e. $g \leq 2.5h$)? **[4% of marks]**
8. If the joint could not be expressly classified, as what weld class would you treat it in this case? **[4% of marks]**

9.2. Solution

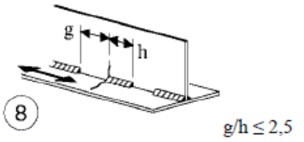
Question 1: **[6 Marks]**

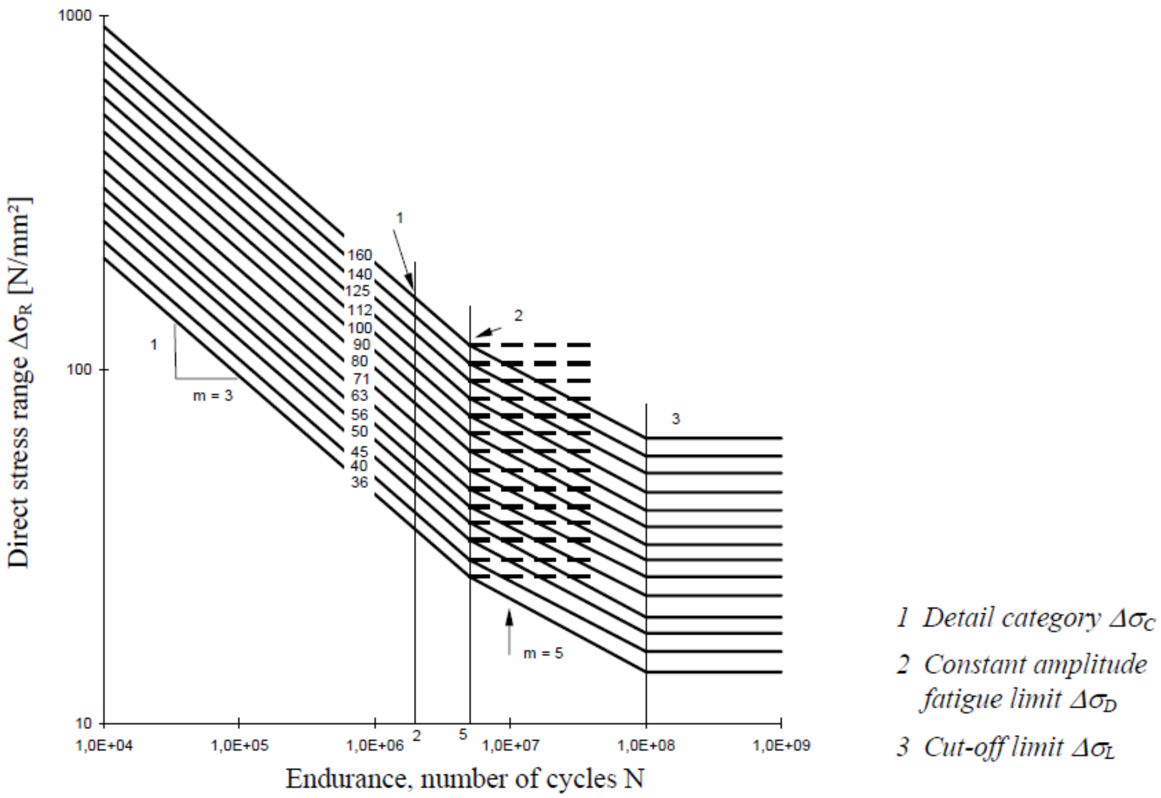
According to the detail supplied, the assessment method is damage tolerant with a high consequence of failure that gives a partial factor for fatigue strength of 1.15 as shown below.

Table 7: Partial factor for fatigue strength γ_{Mf}

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

Where the limiting gap ratio is less than or equal to 2.5, the detail category will be 80. However, in this case the problem indicates that the limiting gap ratio is more than 2.5. BS EN 1993-1-9 as well as Bulletin 520 does not provide any indication as to what to do with the weld class in this case. However, BS 7608 indicates that where the gap limiting ration exceeds 2.5, the weld class lower must be used. In this case, the weld detail category below 80 is 71. Therefore, this value was used. **[1 Mark for selecting the correct detail category. Do not penalise a student that missed the gap limiting ratio. Mark accordingly.]**

80	 g/h ≤ 2,5	8) Intermittent longitudinal fillet welds.	8) Δσ based on direct stress in flange.



The reference fatigue strength at 2 million cycles was taken as:

$$\Delta\sigma_{C,red} = \frac{\Delta\sigma_C}{\gamma_{Mf}} = \frac{71}{1.15}$$
$$= 61.7\ MPa$$

Where $\Delta\sigma_C$ is the reference value of the fatigue strength at an endurance of 2 million cycles. From this, the constant amplitude fatigue limit is at 5 million cycles which is:

$$\Delta\sigma_D = \left[\frac{2\times10^6}{5\times10^6}\right]^{\frac{1}{3}} \frac{\Delta\sigma_C}{\gamma_{Mf}}$$

The cut-off limit $\Delta\sigma_L$ at 100 million cycles is then:

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

In this analysis, it will be assumed that stress ranges below the cut-off limit does not cause any damage and will have infinite life. However, in this case, the endurance is required between the stress ranges that can be calculated as follows:

$$N_R = \begin{cases} \left[\frac{\Delta\sigma_{C,red}}{\Delta\sigma_R}\right]^m \times 2\times10^6 & m = 3\ for\ N \le 5\times10^6, or\ \Delta\sigma_R \le \Delta\sigma_D \\ \left[\frac{\Delta\sigma_{C,red}}{\Delta\sigma_R}\right]^m \times 5\times10^6 & m = 5\ for\ 5\times10^6 \le N \le 10^8, or\ \Delta\sigma_D \le \Delta\sigma_R \le \Delta\sigma_L \\ INF & N > 10^8, or\ \Delta\sigma_R < \Delta\sigma_L \end{cases}$$

[1 mark for using the correct equation for the S-N curve above the first knee-point]
[1 mark for using the correct equation for the S-N curve between the knee-points]

From the calculation it is clear that the life of the structural detail is 4.3 years for 5% probability of crack initiation.

Detail category			71			
Partial factor for fatigue strength			1.15			
Reduced reference fatigue strength			61.7	MPa		
Endurance: Reduced fatigue strength			2.00E+06	Cycles		
Endurance: Constant amplitude fatigue limit			5.00E+06	Cycles		
Slope 1			3			
Slope 2			5			
Const. Ampl. fatigue strength			45.49	MPa		
Cut-off limit endurance			1.00E+08	Cycles		
Cut-off limit stress range			24.99	MPa		
Stress-max	Stress-min	Range	Cycles	Endurance	Damage	
40	0	40	1 000 000	9 511 286	0.105	
25	-22	47	800 000	4 533 336	0.176	
0	-60	60	400 000	2 179 003	0.184	
				Total damage per block	**0.465**	
				Duration of block	**2.000**	**years**
				Life in blocks	**2.150**	
				Life in block durations	**4.299**	**years**

[1 Mark for using the stress range in calculations]
[1 Mark for calculation of the correct total damage per block – the answer must be correct]
[1 Mark for correctly inverting the total damage per block to the life in blocks. In this case the answer is not important, but the process]

Question 2 [1 Mark]
The crack is expected to initiate at the toe of the weld at an intermittent weld because of the stress concentration caused by the weld notch at that point.
[1 Mark]

Question 3 [1 Mark]
BS EN 1993-1-9 does not require thickness correction in this case because crack initiation will be at the weld toe at starts/stops where thickness has negligible effect. No thickness correction is required.
[1 Mark]

Question 4 **[2 Marks, distributed as shown]**:

Answer A:

Peening the weld surface and thus producing a compressive residual stress on the surface could result in the following:

i. According to Haagsens an increase of 60% in fatigue strength on the as-welded design Sr-N curve for all joints with no change in slope of the curves is a conservative lower bound, and is used to indicate increase in fatigue strength.

ii. According to Haagsens this result in an increase of 300% in fatigue life. This could also be confirmed by the student applying the Sr-N curve with increase in strength as parameter. **[1 Marks]**

iii. Therefore, using this, the fatigue life could now be 3 x 9.7 years, or approximately 29.1 years. **[1 Marks]**

OR

Answer B:

BENEFIT FACTOR FOR PEENING

The benefit factor FROM IIW BULLETING 520 is applied to the FAT class of the as-welded weld **[1 Mark]** according to the limits and applications summarised in Tables 11 **[1 Mark]** and 12.

1.

Table 8: FAT classes for use with nominal stress at joints improved by Hammer and Needle peening (IIW, 2007:88-89)

Area of application and maximum possible claim	Steel $f_y < 355\ MPa$	Steel $f_y \geq 355\ MPa$	Aluminium
Benefit at detail classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.6	1.6
Maximum possible FAT class AFTER improvement	FAT 112	FAT 125	FAT 56
Use the standard thickness correction for as-welded joints for wall thickness >25 mm			

Table 9: FAT classes for use with structural hot-spot stress at post-welding weld toe improvements by Hammer and Needle peening (IIW, 2007:88-89)

Material	Load-carrying fillet welds	Non-load-carrying fillet welds and butt welds
Mild steel, $f_y < 350\ MPa$	112	125
Higher strength steel, $f_y \geq 350\ MPa$	125	160
Aluminium alloys	56	63
Use the standard thickness correction for as-welded joints for wall thickness >25 mm		

Question 5 **[2 Marks, distributed as shown]**:

a. Tow burring can have the following benefits according to the UK Health and Safety Executive:
   a. Factor 1.3 on fatigue strength.
   b. Factor 2.2 on life.
b. For design the following conservative lower bounds can be taken:
   a. Increase of 30% in fatigue strength, the slope m = 3.
   b. This corresponds to a 120% increase in fatigue life provided that the life of the as welded joint is >10^6 cycles. **[1 Marks]**
c. As shown, this technique is a high stress life improvement technique and is not efficient for high stresses and a low stress life.
d. Based on this information, the fatigue life is expected to increase only for the low stress high cycle fatigue. In this case, the stresses are all low enough to have a fatigue life in excess of 1 million cycles. Therefore, the life is expected to be 2.2 times the life of 9.7 years or approximately 21 years. **[1 Marks]**

OR

The benefit of weld toe treatment according to Int. Inst. Welding Bulletin 520:

A factor is calculated that is applied to the fatigue class of the non-improved joint **[1 Mark]**. The classes applicable are **[1 Mark]**:

[As shown above, for this question no dicussions were required, just an indication of improvement. Both approaches are correct in this case.].

Table 10: FAT classes for use with nominal stress at joints improved by grinding (IIW, 2007:86)

Area of application and maximum possible claim	Steel	Aluminium
Benefit at detail classified in as-welded condition as FAT≤90 for steel or FAT≤32 for aluminium	1.3	1.3
Maximum possible FAT class AFTER improvement	FAT 112	FAT 45
Thickness correction exponent: $n = 0.2$		

Table 11: FAT classes for use with structural hot-spot stress at post-welding weld toe improvements by grinding (IIW, 2007:87)

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
Thickness correction exponent: $n = 0.2$		

Question 6 **[1 Mark]**

BS 7608 Answer

The intermittent weld can be modified to a continuous weld that would improve the weld detail to Class D. **[1 Mark]**

or

BS EN 1993-1-9 Answer:

The weld category will improve by one interval to 100 when the intermittent weld detail is modified to a continuous weld as shown in detail category 100. **[1 Mark]**

Question 7 **[1 Mark]**

BS 7608 Answer

If the gap is less than 2.5h the weld detail change to Class E. **[1 Mark]**

OR

BS EN 1993-1-9 Answer:

If the gap is less than 2.5h (gap limiting ration g/h<2.5) the weld improve to detail category 80. **[1 Mark]**

Question 8 **[1 Mark]**

BS 7608 Answer:

The weld is non-load carrying welds in this case. For unclassified details similar to that shown in the problem, use Class G weld detail parameters or find applicable fatigue curves in published literature. Special tests can also be carried out on the unclassified joint detail to obtain applicable fatigue curves. **[1 Marks]**

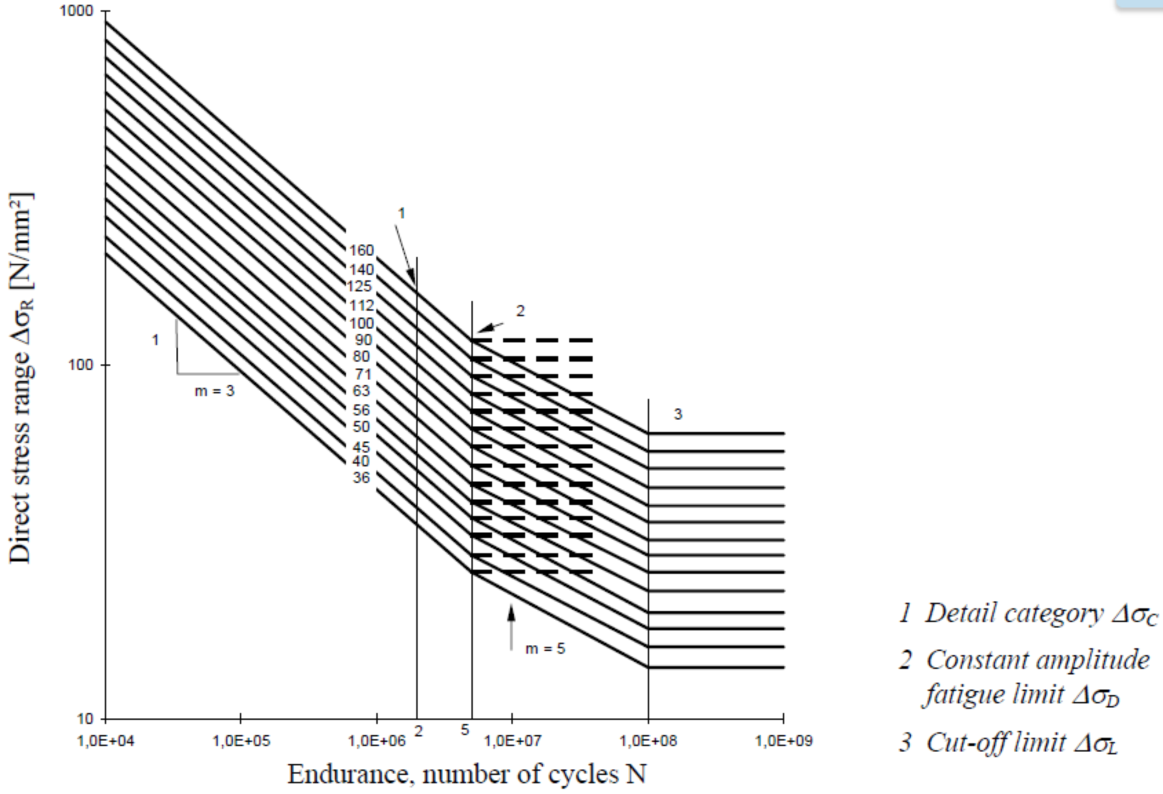
IIW Bulletin 520 Answer **[1 Mark]**

For unclassified weld detail, apply the effective notch stress method.

BS EN 1993-1-9 Answer **[1 Mark]**

According to BS EN 1993-1-9 (2005:16):

1. When test data were used to determine the appropriate detail category for a particular constructional detail, the value of the stress range $\Delta\sigma_C$ corresponding to a value of $N_C = 2 \times 10^6$ cycles were calculated for a 75% confidence level of 95% probability of survival for $logN$, taking into account the standard deviation and the sample size and residual stress effects. The number of data points (≥10) was considered in the statistical analysis (see Annex D of EN 1990).
2. The National Annex may permit the verification of a fatigue strength category for a particular application provided that it is evaluated in accordance with the Note above.
3. Test data for some details do not exactly fit the fatigue strength curves in the figure below. In order to ensure that non-conservative conditions are avoided, such details, marked with an *, 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 such details be one detail category provided that the constant amplitude fatigue limit $\Delta\sigma_D$ is defined as the fatigue strength at 10^7 cycles for $m = 3$.



Scale marks proportional to distribution in the question to get total mark. See the applicable Excel sheet

10. MATERIAL FATIGUE AT ELEVATED TEMPERATURE [15 MARKS]

A structural steel detail category 50 joint is subjected to the temperature and cyclic loads summarised in the table below that can be assumed to represent 1 block of loading.

Ignore creep effects. Assume a damage tolerant assessment method with high consequence of failure. Ignore other effects. Further assume that the loads are applied in the sequence given, that is, load Condition 1 is applied for 5 hours where after load Condition 2 is applied for 10 hours, etc.

Question:

How many blocks can be applied for a probability of survival of 95%? Show all steps followed in the calculations.

Load condition	Duration [h]	Stress range [MPa]	Temperature [°C]	Number of cycles
1	5	25	400	100000
2	10	50	200	10000
3	20	75	100	5000

10.1. Solution

10.2. Solution [10 Marks – scale as required]

Design philosophy

For a damage tolerant assessment method with high consequence of failure, the partial safety factor is $\gamma_M = 1.15$. **[1 Mark for the correct partial factor – note, if the student used the incorrect partial factor for fatigue, he only looses this one mark. The rest must be marked with the error]**

Table 12: Partial factor for fatigue strength γ_{Mf}

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

Elevated temperature

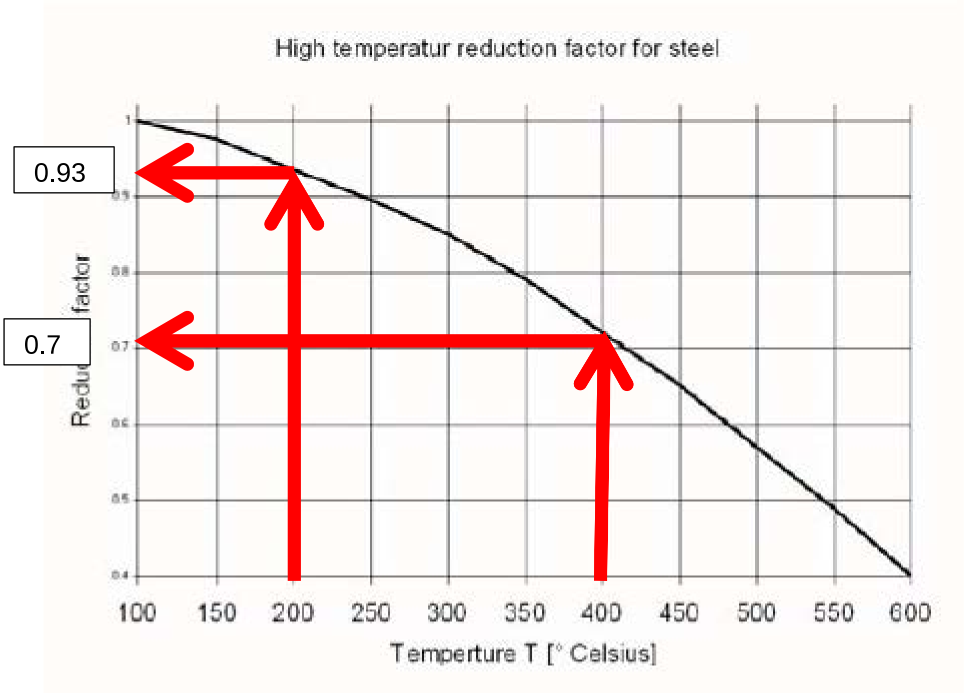
The effect of temperature was modelled by adjusting the FAT class of the weld detail according to the formula below:

$$FAT_{HT} = FAT_{20\,°C}\frac{E_{HT}}{E_{20\,°C}}$$

However, EN 1993-1-9 is using detail category to indicate life at 2 million cycles. Toe model the same effect, the detail category needs to be adjusted as shown above.

[1 Mark for giving the equation and using it correctly]

The values for the temperature used in this case were read from the curve below:



These factors were multiplied with the weld detail FAT class.

[1 Mark for the value close to 0.93]

[1 Mark for the value close to 0.70]

Damage per block

The S-N curve is modelled by the following equation:

$$N_R = \begin{cases} \left[\frac{\Delta\sigma_{C,red}}{\Delta\sigma_R}\right]^m \times 2 \times 10^6 & m = 3\ for\ N \leq 5 \times 10^6, or\ \Delta\sigma_R \leq \Delta\sigma_D \\ \left[\frac{\Delta\sigma_{C,red}}{\Delta\sigma_R}\right]^m \times 5 \times 10^6 & m = 5\ for\ 5 \times 10^6 \leq N \leq 10^8, or\ \Delta\sigma_D \leq \Delta\sigma_R \leq \Delta\sigma_L \\ INF & N > 10^8, or\ \Delta\sigma_R < \Delta\sigma_L \end{cases}$$

Where:

$$\Delta\sigma_{C,red} = \frac{\Delta\sigma_C}{\gamma_{Mf}} \frac{E_{HT}}{E_{20\,°C}}$$

[1 Mark for using the S-N curve correctly above the knee-point]

[1 Mark for using the S-N curve correctly below the knee-point]

The results are:

Weld detail category					50					
Partial factor for fatigue resistance					1.15					
N_C @ the detail category					2.00E+06					
N_D @ constant amplitude fatigue limit					5.00E+06					
N_L @ cut-off limit					1.00E+08					
Slope of the S-N curve					3					
Slope of the S-N curve below kneepoint					5					
Load case	**Duration [h]**	**Stress range [MPa]**	**Temp. [°C]**	**No. of cycles**	**Temp red. factor**	**Reduced fatigue strength**	$\Delta\sigma_D$	$\Delta\sigma_L$	**Endur-ance**	**Damage**
1	5	25	400	100 000.00	0.7	30.4	22.4	12.3	3 608 449	0.03
2	10	50	200	10 000.00	0.93	40.4	29.8	16.4	1 057 756	0.01
3	20	75	100	5 000.00	1	43.5	32.0	17.6	389 639	0.01
									Total damage	0.05
									Life in number of blocks	20.00
									Number of hours per block	35

[1 Mark for realising that a new $\Delta\sigma - N$ curve needs to be calculated for every temperature due to modifications to the detail class of the joint]

[1 Mark for correctly modifying the S-N curves]

[1 Mark for the correct total damage]

[1 Mark for converting it correctly (process only, not answer) to the life in number of blocks]

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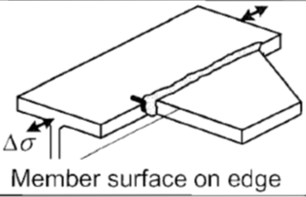
11. FATIGUE DESIGN OF ALUMINIUM [20 MARKS]

Problem statement

A 5xxx aluminium alloy plate is used with extruded 6xxx aluminium alloy sections in a moderate industrial environment. The sections are joined by complete joint penetration weld with detail Type 3.5, with no radius, as shown in the figure below. No post-weld treatment has been implemented. The flange thickness is 12 mm. No section is thicker than 15 mm.

3.5	**18-3,4**		No radius	Nominal s	Stiffening		C

The nominal BENDING stress in the 6xxx I-beam has been analysed by rainflow counting for which the results are summarised in the table below. The spectrum shown in the table was measured over a period of 2 years. There are no normal stress on the I-beam and the loading is dominated by bending stress.

Assume a safe life design level I and low consequence of failure.

max(Stress) [MPa]	min(Stress) [MPa]	Cycles
30	0	1000
50	20	1000
0	-20	1000
10	-10	1000
30	20	1000

NDT for a minimum of 50% is carried out.

What is the fatigue life of the system?

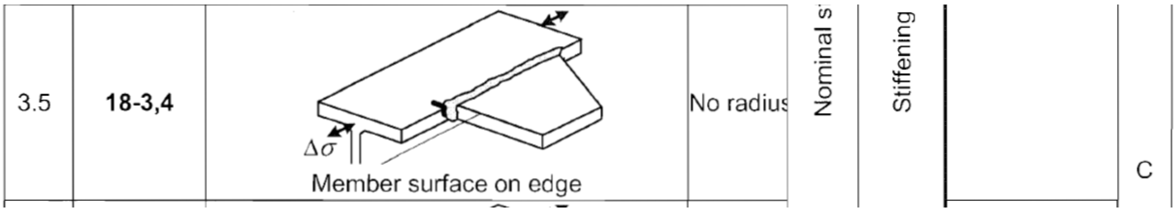
Solution:

Detail category and strength **[10% of marks]**

The detail category characteristic strength is $\Delta\sigma_C = 18\ MPa$ at $N_C = 2 \times 10^6$ cycles. The slopes of the $\Delta\sigma - N$ curve is $m_1 = 3.4$ and $m_2 = 5.4$.

Under bending stress, and where the thickness is less than 15 mm, the detail category may be increased by two detail categories. The area where the crack will initiate is on a flat surface and the detail category may be increased by 2 detail categories. Thus, for analysis use $\Delta\sigma_C = 23\ MPa$ at $N_C = 2 \times 10^6$ cycles.

[Students who did not include this modification will be penalised by 5%]



The constant amplitude fatigue limit endurance is at $N_D = 5 \times 10^6$ cycles and the cut-off limit is at $N_L = 100 \times 10^6$ cycles.

Assessment method and consequence class

For the safe-life design Level I and low consequence of failure, the partial factor for fatigue is $\gamma_{Mf} = 1.1$ as shown below **[5% of marks]**. However, based on the detail category of 23 and the 50% NDT done, the partial factor for fatigue may be reduced by 0.1 **[5% of marks]**. Therefore, the partial factor for fatigue to use is $\gamma_{Mf} = 1.0$ in this case.

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

Mean stress enhancements

The point of crack initiation is at the weld toe. Therefore, no mean stress enhancement is applicable and $f(R) = 1.0$.

Exposure conditions

The number of categories that the detail should be reduced because of the exposure conditions is 0 as shown below.

[10% of marks]

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.

Post-weld treatments

No post-weld improvements have been specified.

Stress concentrations effects

The stress concentration of the detail is already included in the detail category.

Calculations

The equations were programmed in the Excel sheet below from which it is clear that the total damage over the two year period is 0.0043 and total fatigue life of the detail is 466 years.

[10% of marks for applying the correct slopes]

[10% of marks for constant amplitude fatigue limit]

[10% of marks for cut-off limit]

[10% of marks for correct use of equation]

[10% of marks for application in the table]

[10% of marks for the correct total damage]

[10% of marks for knowing how to apply the total damage to quantify fatigue life – not the answer, but, the principle is tested]

Detail category			23			
Partial factor for fatigue (gamma)			1.1			
N_C			2.00E+06	cycles		
N_D			5.00E+06	cycles		
N_L			1.00E+08	cycles		
Slope m1			3.40			
Slope m2			5.40			
Reduced detail category			20.9	MPa		
Constant amplitude fatigue limit			16.0	MPa		
Cut-off limit			9.2	MPa		
max(Stress) [MPa]	min(Stress) [MPa]	Cycles	Range [MPa]	Endurance N	Damage d	
30	0	1000	30	586 080	0.001706	
50	20	1000	30	586 080	0.001706	
0	-20	1000	20	2 326 310	0.00043	
10	-10	1000	20	2 326 310	0.00043	
30	20	1000	10	62 626 401	1.6E-05	
			Total Damage =		0.004288	
				Period =	2	years
				Fatigue life =	466.3962	years