

## 1. THEORY QUESTIONS

### Question 1 [10% of mark]:

During discussions in class you were introduced to the fatigue strength ( $\frac{\Delta\sigma_R}{\gamma} - N_R$ ) curve for welded detail. You were also introduced to hammer peening and its benefit on the fatigue strength. What will be the benefit factor and the fatigue strength (assume partial factor for fatigue  $\gamma_{Mf} = 1.0$ ) at  $N_c = 2 \times 10^6$  cycles for the following detail categories according to the rules of IIW Bulletin 520:

- 100 [50% of mark]
- 50 [50% of mark]

Assume the material is steel with  $f_y = 380$  MPa.

Please motivate your answers.

#### Answer:

According to the IIW Bulletin 520 the benefit factor for steel at joints improved by hammer peening is as summarised below. For this problem, the benefit factor is 1.6 with maximum possible fatigue strength after improvement of 125. Therefore, for the problem given, the fatigue strength at  $N_c = 2 \times 10^6$  cycles will be:

- $1.6 \times 100 = 160$ . However, the maximum possible strength after improvement is 125. Therefore, the fatigue strength of the improved detail increase from 100 MPa to 125 MPa.
- $1.6 \times 50 = 80$ . In this case that maximum benefit of the improvement is possible and the characteristic strength at  $N_c = 2 \times 10^6$  cycles will be 80 MPa.

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

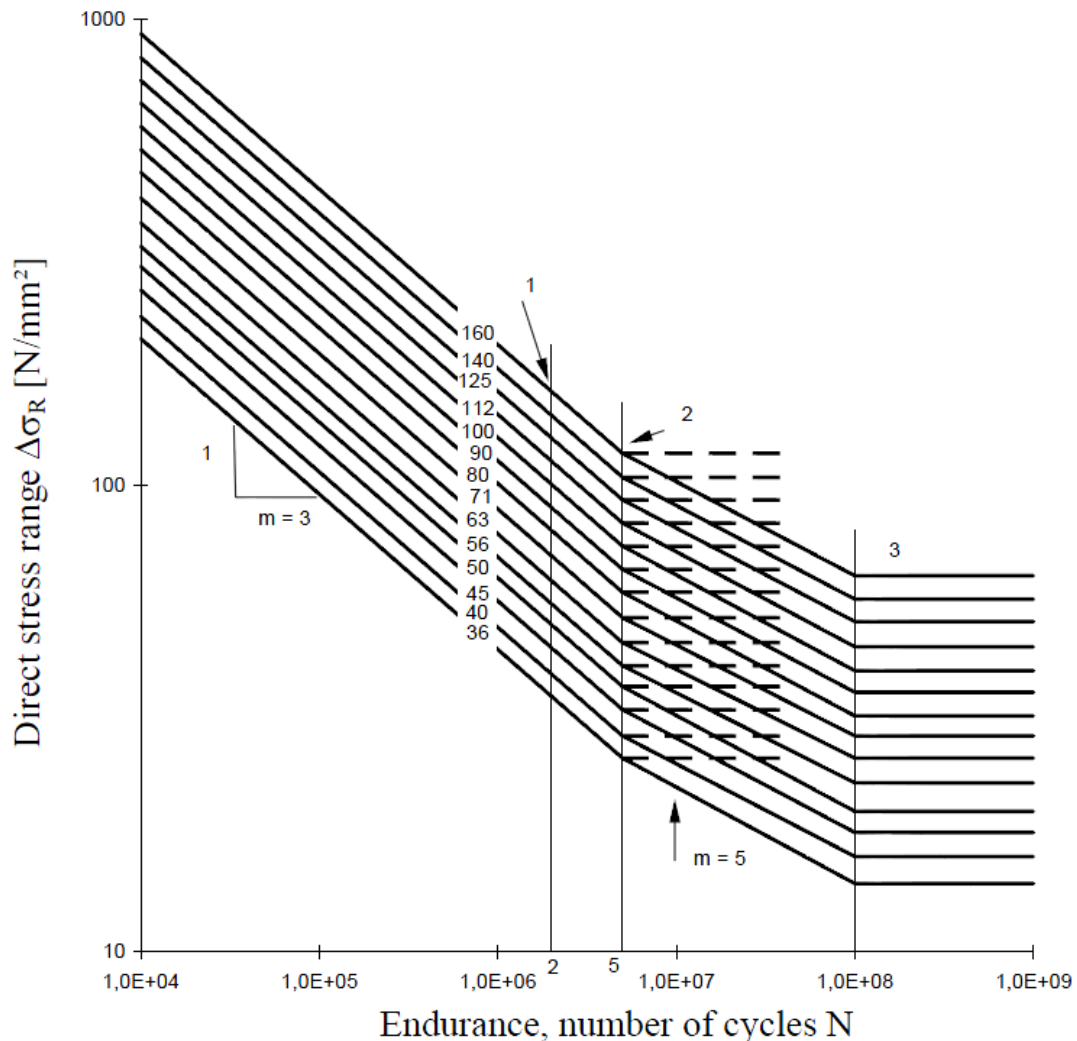
Area of application and maximum possible claim	Mild steel $f_y < 355$ MPa	Steel $f_y \geq 355$ MPa	Aluminium
Benefit at details classified in as-welded condition as FAT $\leq$ 90 for steel or FAT $\leq$ 32 for aluminium	1.3	1.6	1.6
Max possible FAT after improvement	FAT 112	FAT 125	FAT 56

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

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

**Question 2 [20% of mark]:**

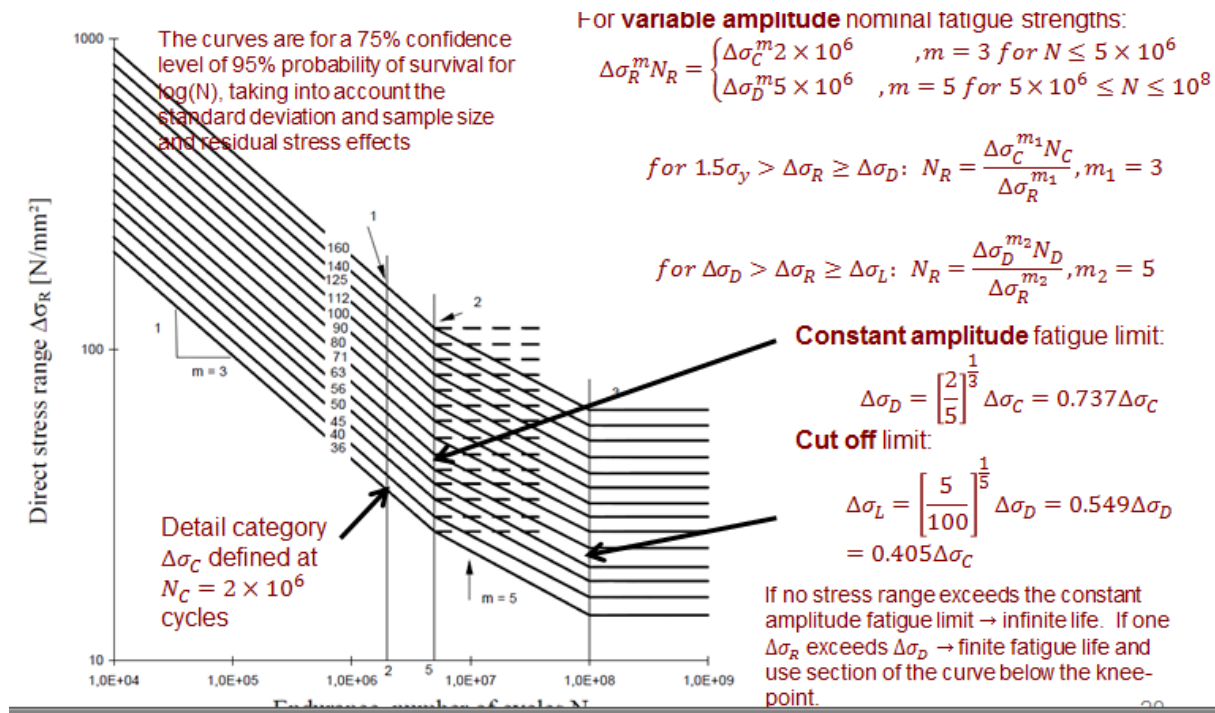
The fatigue strength curve below was used during the class presentation of fatigue design according to EN 1993-1-9. The fatigue strength curve is for a 75% confidence level of 95% probability of survival.



Please answer the following (use calculations and not interpolations on the S-N curve above to solve stresses and endurance):

- What is the constant amplitude fatigue limit for detail category 80 and partial factor for fatigue  $\gamma_{Mf} = 1.35$ ? **[20% of mark]**
- What is the cut-off limit for detail category 80 and partial factor for fatigue  $\gamma_{Mf} = 1.35$ ? **[20% of mark]**
- What will be the endurance for detail category 100, partial factor for fatigue  $\gamma_{Mf} = 1.35$  at constant amplitude stress range  $\Delta\sigma = 121$  MPa? **[20% of mark]**
- A constant amplitude test is carried out on a specimen with joint detail category 50. The applied stress range is 25 MPa. What is the endurance, in cycles, for a 75% confidence level of a 5% probability of crack initiation? **[20% of mark]**
- A constant amplitude test is carried out on a specimen with joint detail category 40 at stress amplitude 20 MPa. For a partial factor for fatigue of  $\gamma_{Mf} = 1.0$  what is the endurance for a 75% confidence level of 95% probability of survival? **[20% of mark]**

Answers:

**Question 3 [20% of mark]:**

The weld fatigue strength curve ( $\Delta\sigma - N$  - curve) can be used to calculate the endurance at any applied constant amplitude stress range. In practice, a low number of stress cycles above the constant amplitude fatigue limit imply that the stress ranges between the cut-off and constant amplitude limit will not have infinite endurance and can result in fatigue crack initiation. For such a case where there are a low number of cycles exceeding the constant amplitude fatigue limit, please provide the equations that you will apply to calculate endurance for:

1. Stress ranges between the cut-off limit and constant amplitude fatigue limit. **[30% of mark]**
2. Stress ranges below the cut-off limit. **[30% of mark]**

The above is just a mathematic model to describe the behaviour of the material at imperfections/defects.

3. What is the mechanism that causes this effect that the small number of cycles exceeding the constant amplitude fatigue limit results in finite life for the cycles below the constant amplitude fatigue limit? That is, why does this happen? **[40% of mark]**

**Question 4 [10% of mark]:**

You experience continuous crack initiation at a weld toe and decide to implement improvement techniques after completion of the repair work in an attempt to increase fatigue life (and fatigue strength) of the joint. You are advised to first grind the weld toe and then hammer peen the weld to produce compressive residual stress on the surface. What will be the joint benefit of these two techniques on the fatigue life of the joint detail if the original detail category was 50? Use the IIW Bulletin 520 benefit factors. These are in the slides used in the class.

Answer:

**Question 5 [20% of mark]:**

During the presentation on the fatigue design of weld detail according to the requirements of EN 1993-1-9, you were introduced to Tables 8.1 to 8.10 of the standard. Comparing the longitudinal loading of welded built-up sections no size effects are required as shown in the extract from Table 8.2 below. However, where the weld is loaded in the transverse direction, size effects need to be taken into account as shown in the extract from Table 8.3 further below. Please answer the following question:

- a) Why does size reduce fatigue strength as shown in Table 8.3 but not for the detail shown in Table 8.2?

**Table 8.2: Welded built-up sections**

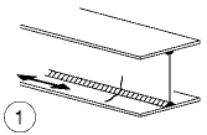
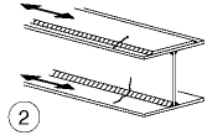
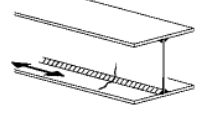
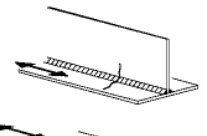
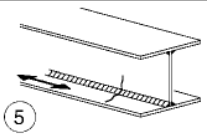
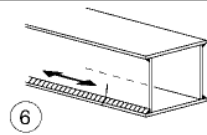
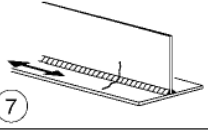
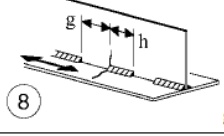
Detail category	Constructional detail	Description	Requirements
125	 	<u>Continuous longitudinal welds:</u> 1) Automatic butt welds carried out from both sides. 2) Automatic fillet welds. Cover plate ends to be checked using detail 6) or 7) in Table 8.5.	<u>Details 1) and 2):</u> No stop/start position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

Table 8.3: Transverse butt welds

Detail category	Constructional detail	Description	Requirements
112		<p><u>Without backing bar:</u></p> <ol style="list-style-type: none"> <li>1) Transverse splices in plates and flats.</li> <li>2) Flange and web splices in plate girders before assembly.</li> <li>3) Full cross-section butt welds of rolled sections without cope holes.</li> <li>4) Transverse splices in plates or flats tapered in width or in thickness, with a slope <math>\leq 1/4</math>.</li> </ol>	<ul style="list-style-type: none"> <li>- All welds ground flush to plate surface parallel to direction of the arrow.</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> </ul> <p><u>Detail 3):</u> Applies only to joints of rolled sections, cut and rewelded.</p>
90		<ol style="list-style-type: none"> <li>5) Transverse splices in plates or flats.</li> <li>6) Full cross-section butt welds of rolled sections without cope holes.</li> <li>7) Transverse splices in plates or flats tapered in width or in thickness with a slope <math>\leq 1/4</math>. Translation of welds to be machined notch free.</li> </ol>	<ul style="list-style-type: none"> <li>- The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> </ul> <p><u>Details 5 and 7:</u> Welds made in flat position.</p>

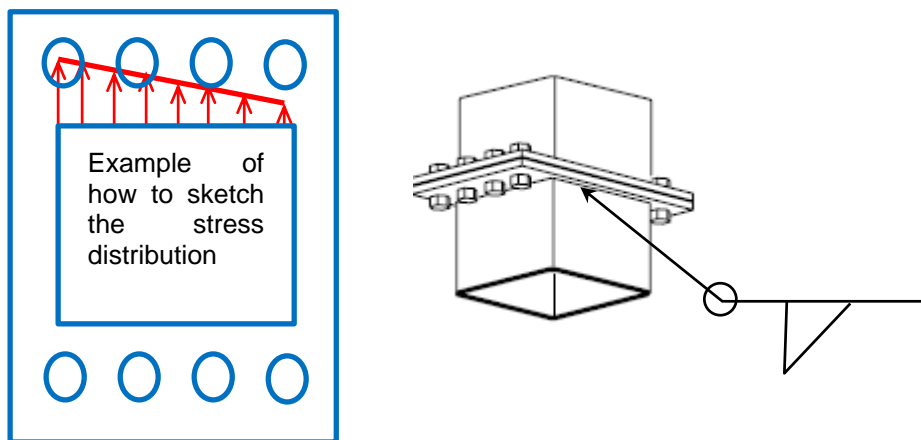
Answers:

More volume of weld material is subject to the stress in the load-carrying welds as function of thickness. More volume of material implies potential more imperfections from where cracks can initiate. This is similar to the volume effect in fatigue life discussed in stress life.

**Question 6 [20% of mark]:**

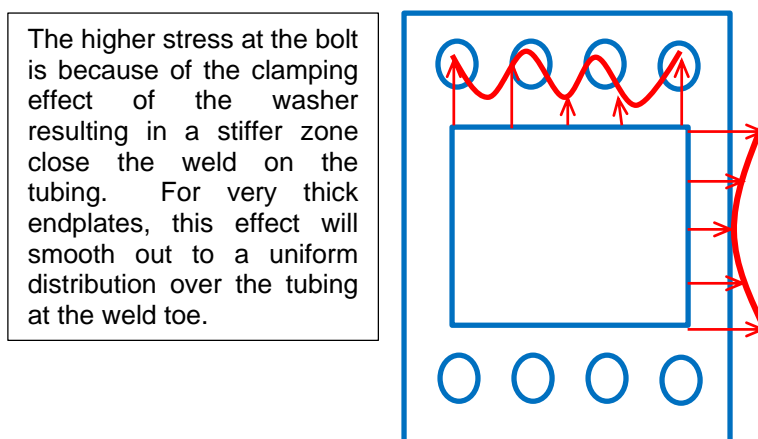
The splice connection below is used to connect the rectangular tubing as shown.

1. Make a simple sketch of the cross-section of the tube as shown, and, without any scaling, sketch how you expect the stress distribution at the weld toe on the tubing for the following nominal stress away from the splice:
  - a. The cross-section nominal stress is tensile under uni-axial loading away from the splice.
  - b. The cross-section nominal stress under uni-axial loading is in compression away from the splice.
2. Are these joint dependent stress concentrations included in the standard detail category summarised in EN 1993-1-9 from where the detail category dependent characteristic strength at  $N_c = 2 \times 10^6$  cycles are given?
3. How will you calculate stress in these joint in practice, if subjected to tensile nominal stress, for fatigue design of the welded joint?

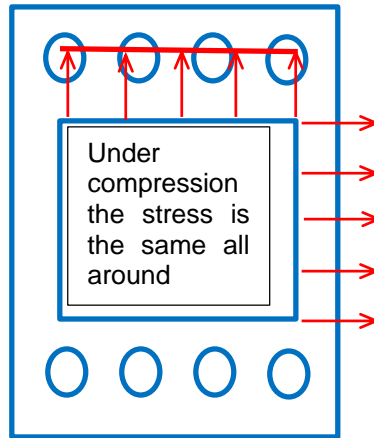
**Answer:**

The answers are as follows:

1. Because of the stiffness of the splice plate and bolts, under tensile nominal stress the contact surface where there is no bolts can separate. However, at the bolt line, the splices will remain in contact at the bolt line, resulting in bending of the plate at larger tensile loads.
  - a. Under tensile nominal stress, the stress will be higher on the bolt side **[30% of the marks]**.



- b. Under compression loading the stress will transfer directly from the one tube to the other tube. This will result in uniform stress distribution of same magnitude **[30% of the marks]**.



- The joint dependent stress concentrations are not included in the EN 1993-1-9 tables. The EN 1993-1-9 tables make provision for the stress concentration by the weld or bolt detail, not the geometry of the joint. **[20% of the marks]**
- In practice a finite element model can be used to calculate the stress distribution due to the joint geometry. If the joint shown in this case is only subject to compressive stress, no geometry dependent stress concentration is expected and a manual calculation is sufficient based on nominal stress. For tensile stress, the higher stress on the top and side sections can also be calculated from the Euler beam theory. **[20% of the marks]**

**It took the lecturer 13 minutes to answer this question in MSWord. This will be similar to what students will need and time allocation for this question is 15 minutes.**

## 2. ADVANCED WELD FATIGUE DECISION-MAKING **[40 Minutes = ?? MARKS]**

### 2.1. Problem Statement

A flat section of thickness 28.95 mm is joined to a flat section of thickness 20 mm using a manual shielded metal arc welding process to produce the double V-groove weld of the butt joint shown in Figure 1. Both sections are from 300W structural steel and a normal-match electrode was used. The 2 mm root face has a root opening of 1 mm and the sections chamfered to produce a groove angle  $\alpha = 60^\circ$ . The weld preparation was done in compliance with AWS D1.1:2008 as summarised in Table 2. The thick section is ground in the direction of the principal stress to produce a taper of 1:5. The height of the weld convexity is measured at 8% of the weld width with smooth transition to the plate surface. The welding procedure specification required the use of weld run-on and run-off pieces that were removed afterwards. The edges are ground flush with the surface with grinding marks in the direction of the axial stress, which is also the direction of the principal stress in this case. Welding was done from both sides and ultrasonic testing done to confirm the absence of sub-surface defects in the weld.

The stress spectrum of the joint over a period of 2 years is as summarised in Table 1. For your information, the following has been included:

- EN 1993-1-9:2005 Table 8.3.

The design requires a safe life assessment method with high consequence of failure. The operating temperature is 25 °C and the surfaces corrosion protected using Universal Paint's Interzone 954 epoxy paint. No post weld heat treatment was done. No post weld improvement (peening, grinding, dressing, etc.) were done to the weld detail.

Table 1: Stress spectrum on the joint over a period of two years

$\sigma_{max}$ [MPa]	$\sigma_{min}$ [MPa]	Number of cycles
250	100	100 000
75	-75	50 000
45	0	1 000 000

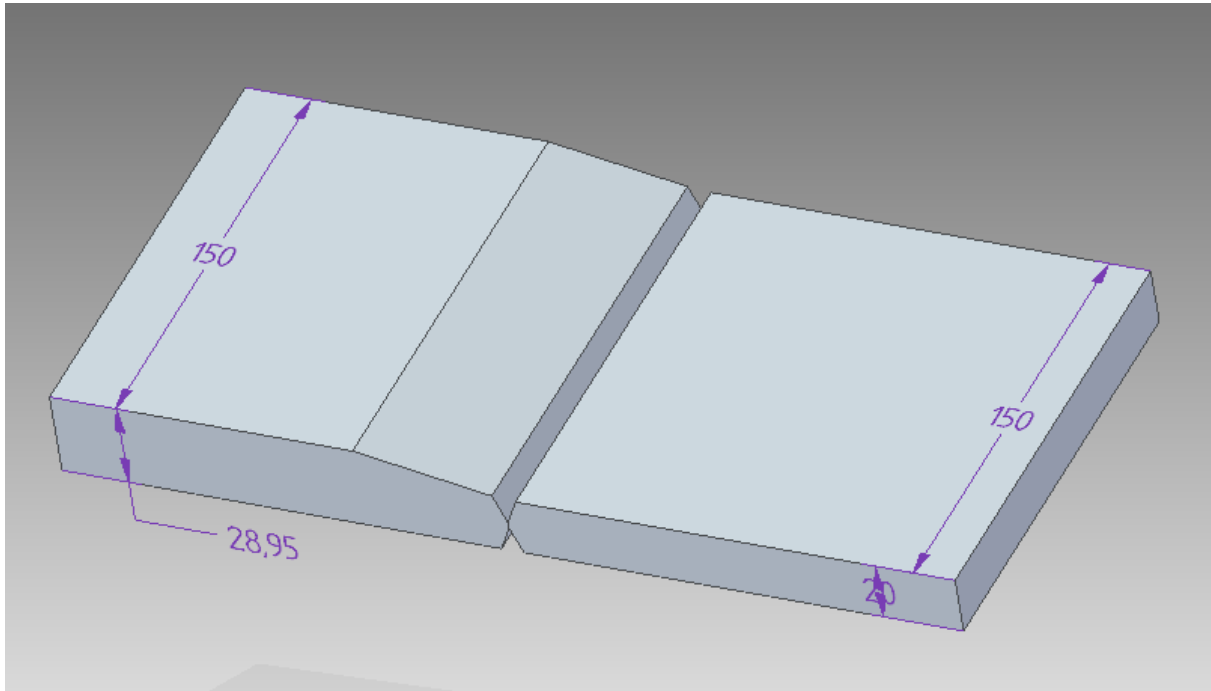


Figure 1: Tapered joint

Table 2: AWS D1.1 double V-groove weld for butt joints (2008:96)

Double-V-groove weld (3) Butt joint (B)		Base Metal Thickness (U = unlimited)		Groove Preparation			For B-U3c-S only		
				Root Opening Root Face Groove Angle	Tolerances		T <sub>1</sub>		S <sub>1</sub>
Welding Process	Joint Designation	T <sub>1</sub>	T <sub>2</sub>		As Detailed (see 3.13.1)	As Fit-Up (see 3.13.1)	Over	to	Notes
SMAW	B-U3b	U	—	R = 0 to 1/8 f = 0 to 1/8 α = β = 60°	+1/16, -0 +1/16, -0 +10°, -0°	+1/16, -1/8 Not limited +10°, -5°	All	—	d, e, h, j
GMAW FCAW	B-U3-GF	U	—	R = 0 f = 1/4 min. α = β = 60°	+1/16, -0 +1/4, -0 +10°, -0°	+1/16, -0 +1/4, -0 +10°, -5°	All	Not required	a, d, h, j
SAW	B-U3c-S	U	—	R = 0 f = 1/4 min. α = β = 60°	+1/16, -0 +1/4, -0 +10°, -0°	+1/16, -0 +1/4, -0 +10°, -5°	F	—	d, h, j
To find S <sub>1</sub> see table above: S <sub>2</sub> = T <sub>1</sub> - (S <sub>1</sub> + f)									



Please answer the following (Please use EN 1993-1-9:2005 as reference):

1. What is the partial factor for fatigue for this problem? **[5% of marks]**
2. What other factors need to be taken into account in this problem? **[5% of marks]**
3. What is the detail category for this joint? **[5% of marks]**
4. What value must you take into account for the thickness effect in this case? **[5% of marks]**
5. Where do you expect the crack to initiate first in this joint? **[5% of marks]**
6. If the stress spectrum 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% - that is, for a probability of survival of 95%? **[70% of marks]**
7. What improvement in detail category is possible in this case with hammer peening? **[5% of marks]**

Table 3: EN 1993-1-9 Table 8.3 for transverse butt welds (2005:22)

Detail category	Constructional detail	Description	Requirements
112	<p>1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope <math>\leq 1/4</math>.</p>	<p><u>Without backing bar:</u></p>	<ul style="list-style-type: none"> <li>- All welds ground flush to plate surface parallel to direction of the arrow.</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> </ul> <p><u>Detail 3):</u> Applies only to joints of rolled sections, cut and rewelded.</p>
90	<p>5) Transverse splices in plates or flats. 6) Full cross-section butt welds of rolled sections without cope holes. 7) Transverse splices in plates or flats tapered in width or in thickness with a slope <math>\leq 1/4</math>. Translation of welds to be machined notch free.</p>		<ul style="list-style-type: none"> <li>- The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> </ul> <p><u>Details 5 and 7:</u> Welds made in flat position.</p>
90	<p>8) As detail 3) but with cope holes.</p>		<ul style="list-style-type: none"> <li>- All welds ground flush to plate surface parallel to direction of the arrow.</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> <li>- Rolled sections with the same dimensions without tolerance differences</li> </ul>
80	<p>9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.</p>		<ul style="list-style-type: none"> <li>- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface.</li> <li>- Weld not ground flush</li> <li>- Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress.</li> <li>- Welded from both sides; checked by NDT.</li> </ul> <p><u>Detail 10:</u> The height of the weld convexity to be not greater than 10% of the</p>

## 2.2. Solution

### 1. Partial factor for fatigue

According to the safe life assessment method with high consequence of failure, the partial factor for fatigue is:  $\gamma_{Mf} = 1.35$  from the table below.

Assessment method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1,00	1,15
Safe life	1,15	1,35

### 2. Improvement and other factors

No improvement factors are applicable because no post-weld improvements were done.

### 3. Detail category

The joint detail category is 90. Therefore, the characteristic strength at  $N_C = 2 \times 10^6$  cycles is 90 MPa that still needs to be modified by factors.

### 4. Thickness effect

No thickness effect needs to be implemented because the thickness prescribed by the detail category includes the 20 mm used in the thinner section where the weld detail is.

### 5. Point of crack initiation

The crack is expected to initiate at the notch in the weld toe on the surface of the 20 mm plate.

### 6. Fatigue calculations

Detail category					90	
Characteristic strength					90	
Partial factor for fatigue					1.35	
Reduced characteristic strength					66.667 MPa	
Endurance: Characteristic strength					2.00E+06	
Endurance: Constant amplitude fatigue limit					5.00E+06	
Endurance: Cut-off limit					1.00E+08	
Slope above const.amp.fat.limit					3.0	
Slope below knee-point					5.0	
Constant amplitude fatigue limit					49.1 MPa	
Cut-off limit					27.0 MPa	
Stress						
Maximum	Minimum	n <sub>i</sub>	Range	N <sub>i</sub>	D <sub>i</sub>	
250	100	100 000	150	175 583	0.570	
75	-75	50 000	150	175 583	0.285	
45	0	1 000 000	45	7 748 503	0.129	
				Total damage	0.983	
				Period	2 years	
				Life	2.034 years	

### 7. Weld improvement by peening

According to IIW Bulletin 520 with peening the weld detail can be improved by factor 1.3 with maximum detail category 112. This shall be applied before division with the partial factor for fatigue. Therefore, for this problem, the detail category will become  $1.3 \times 90 = 117$ , which exceeds 112. Therefore, the detail category may be assumed to increase to 112 with characteristic strength 112 MPa at  $N_c = 2 \times 10^6$  cycles.

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

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

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

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