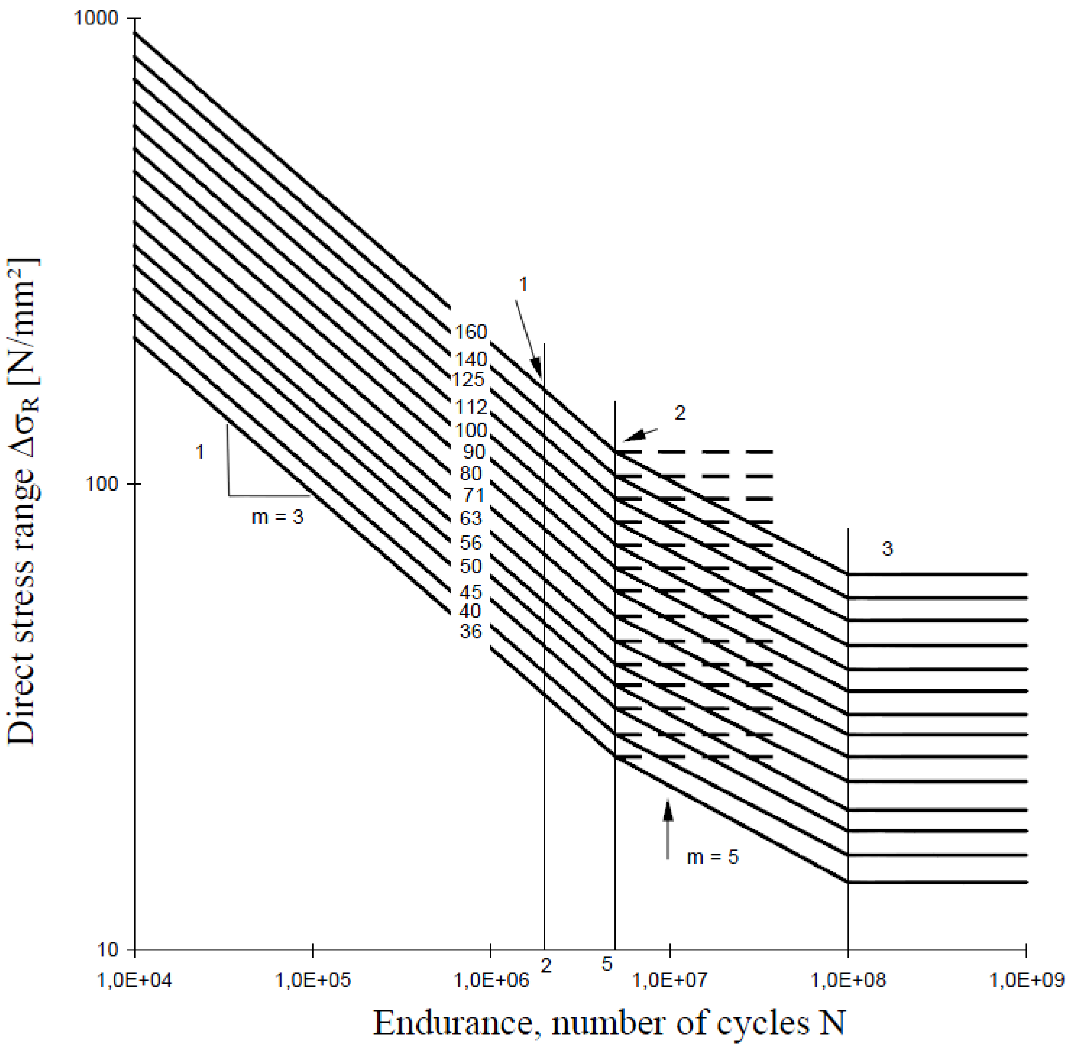
1. THEORY QUESTIONS [60% of paper for weld fatigue]

Note, to obtain maximum points for each problem clearly motivate solutions and equations used.

Because the students had digital versions of previous examinations using the same standard and Sr-N curves, Investmech formulated questions in such a way to ensure students know how to apply the theory. This was done by making modifications that should require changes to specifically partial factors for fatigue as well as characteristic strength values in calculations. Investmech previously had students getting the correct answers, but, when modelling their inputs and doing calculation correctly, yields the wrong answer. These are clear cases where a model without proper understanding was used.

Question 1 [70% of mark]:

The fatigue strength curves below were 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 (5% probability of crack initiation).



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

a) What is the constant amplitude fatigue limit for the S_r-N curve of Detail Category 112 with partial factor for fatigue $\gamma_{Mf} = 1.35$? **[20% of mark] = 3 marks**

b) What is the cut-off limit of the S_r-N curve of Detail Category 112 with partial factor for fatigue $\gamma_{Mf} = 1.35$? **[20% of mark] = 3 marks**

c) What will be the endurance for Detail Category 160, partial factor for fatigue $\gamma_{Mf} = 1.35$ at constant amplitude stress range $\Delta\sigma = 130\ MPa$? **[20% of mark] = 3 marks**

d) A constant amplitude fatigue test is carried out on a specimen with joint Detail Category 40. The partial factor for fatigue is $\gamma_{Mf} = 1.00$. The applied stress range is 20 MPa. What is the endurance, in cycles, for a 75% confidence level of a 5% probability of crack initiation? **[20% of mark] = 3 marks**

e) A constant amplitude fatigue test is carried out on a specimen with joint Detail Category 56 at stress amplitude 25 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] = 3 marks**

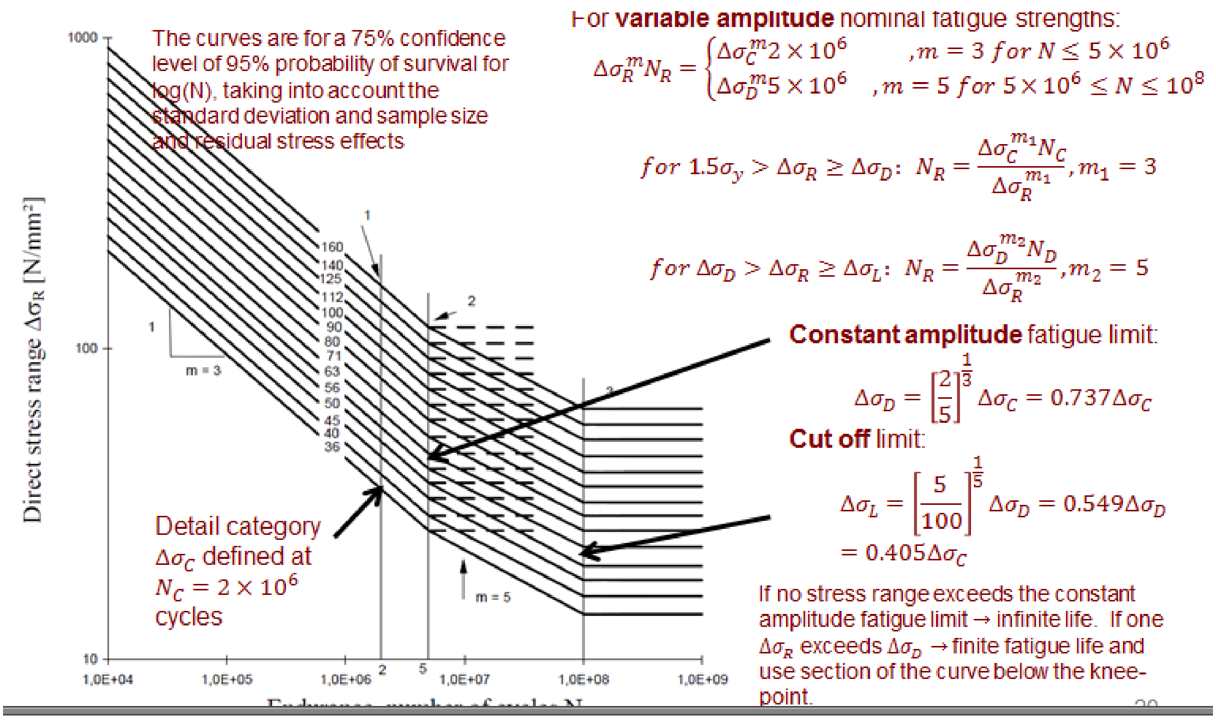
Answers:

a) The constant amplitude fatigue limit is:

$$\Delta\sigma_D = \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{\Delta\sigma_C}{\gamma_{Mf}}$$
$$= \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{112}{1.35}$$
$$= 61.1\ MPa$$

[20 %]

Description	Value	Units
Detail Category	112	MPa
Partial factor for fatigue	1.35	
Modified characteristic strength $\Delta\sigma_C$	82.96	MPa
Endurance @ Char. Strength: N_C	2.00E+06	
Endurance @ Const. Ampl. Limit: N_D	5.00E+06	
Endurance @ Cut-off: N_L	1.00E+08	
Slope 1: m_1	3	
Slope 2: m_2	5	
Constant amplitude limit $\Delta\sigma_D$	61.13	MPa
Cut-off limit: $\Delta\sigma_L$	33.58	MPa



b) The cut-off limit is given by:

$$\Delta\sigma_L = \left(\frac{5}{100}\right)^{\frac{1}{5}} \times \Delta\sigma_D$$
$$= \left(\frac{5}{100}\right)^{\frac{1}{3}} \times \left(\frac{2}{5}\right)^{\frac{1}{3}} \times \frac{\Delta\sigma_C}{\gamma_{Mf}}$$
$$= 33.6\ MPa$$

[20 %]

c) This stress range is clearly larger than the constant amplitude fatigue limit for detail category 160 and partial factor for fatigue 1.35, for which the S-N curve is:

$$\Delta\sigma_R^{m_1} N_R = \frac{\Delta\sigma_C^{m_1}}{\gamma_{Mf}} N_C$$

$$N_R = \left(\frac{\Delta\sigma_C / \gamma_{Mf}}{\Delta\sigma_R}\right)^{m_1} N_C$$

$$= 1\,515\,509\ cycles$$

[20 %]

Description	Value	Units
Detail Category	160	MPa
Partial factor for fatigue	1.35	
Modified characteristic strength $\Delta\sigma_C$	118.52	MPa
Endurance @ Char. Strength: N_C	2.00E+06	
Endurance @ Const. Ampl. Limit: N_D	5.00E+06	
Endurance @ Cut-off: N_L	1.00E+08	
Slope 1: m_1	3	
Slope 2: m_2	5	
Constant amplitude limit $\Delta\sigma_D$	87.33	MPa
Cut-off limit: $\Delta\sigma_L$	47.97	MPa
Type of test	ConstAmpl	
Stress range	130	MPa
Endurance	1 515 509	

d) We first need to calculate the constant amplitude fatigue limit to confirm if the stress range is not below this, in which case there will be infinite life. The constant amplitude fatigue limit is:

$$\Delta\sigma_D = \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{\Delta\sigma_C}{\gamma_{Mf}}$$

$$= \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{40}{1.00}$$

$$= 29\ MPa$$

The applied stress range is below the constant amplitude fatigue limit. Therefore, infinite life is expected.

If students explained the use of another partial factor for fatigue, evaluate accordingly.

[20 %]

Description	Value	Units
Detail Category	40	MPa
Partial factor for fatigue	1	
Modified characteristic strength $\Delta\sigma_C$	40.00	MPa
Endurance @ Char. Strength: N_C	2.00E+06	
Endurance @ Const. Ampl. Limit: N_D	5.00E+06	
Endurance @ Cut-off: N_L	1.00E+08	
Slope 1: m_1	3	
Slope 2: m_2	5	
Constant amplitude limit $\Delta\sigma_D$	29.47	MPa
Cut-off limit: $\Delta\sigma_L$	16.19	MPa
Type of test	ConstAmpl	
Stress range	20	MPa
Endurance	Infinite	

e) We first need to determine if the constant amplitude stress range exceeds the constant amplitude fatigue limit. The constant amplitude fatigue limit is:

$$\Delta\sigma_D = \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{\Delta\sigma_C}{\gamma_{Mf}}$$
$$= \left(\frac{2}{5}\right)^{\frac{1}{3}} \frac{56}{1.00}$$
$$= 41\ MPa$$

The applied stress range is 20 MPa, less than the constant amplitude fatigue limit. Therefore, we have infinite life.

Description	Value	Units
Detail Category	56	MPa
Partial factor for fatigue	1	
Modified characteristic strength $\Delta\sigma_C$	56.00	MPa
Endurance @ Char. Strength: N_C	2.00E+06	
Endurance @ Const. Ampl. Limit: N_D	5.00E+06	
Endurance @ Cut-off: N_L	1.00E+08	
Slope 1: m_1	3	
Slope 2: m_2	5	
Constant amplitude limit $\Delta\sigma_D$	41.26	MPa
Cut-off limit: $\Delta\sigma_L$	22.66	MPa
Type of test	ConstAmpl	
Stress range	50	MPa
Endurance	2 809 856	

[20 %]

Question 2 **[30% of mark]**:

The sketch below shows a plate of 50 mm thick and 300 mm wide that is subject to cyclic stress ranges above the constant amplitude fatigue limit in a non-corrosive environment. The component is difficult to handle and a decision was made to weld attachments to the surface. Three different attachment design concepts are presented as shown in the figures below. Apply the detail categories of EN 1993-1-9 and compare the three concepts against each other from a fatigue point of view. Then list the concepts in order from the highest fatigue strength to the lowest fatigue strength for crack initiation in the base plate. No loads are applied to the attachments during operation. Assume that the lugs are far away from the edges of the plate and that their contribution to the static strength of the plate is negligible.

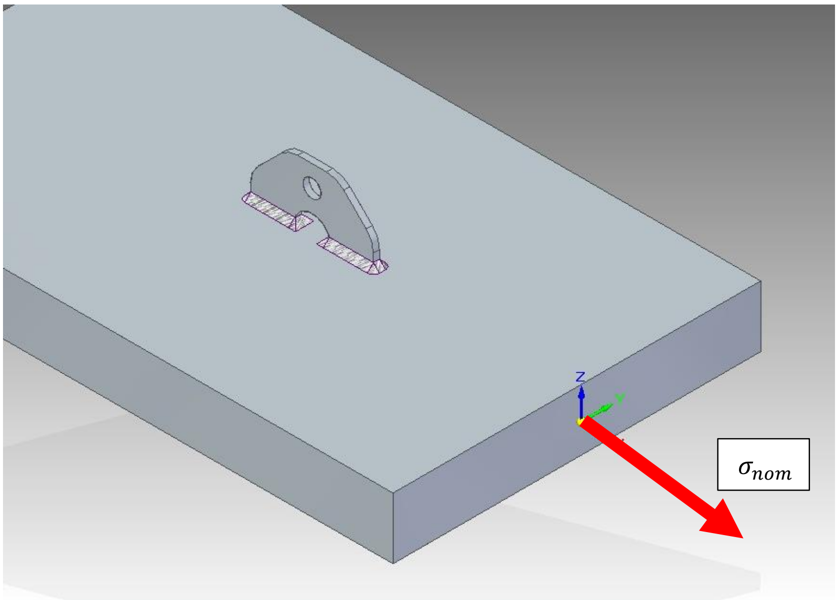


Figure 1: Concept 1: Lug mounted with a 5 mm fillet weld with cope hole of radius 15 mm

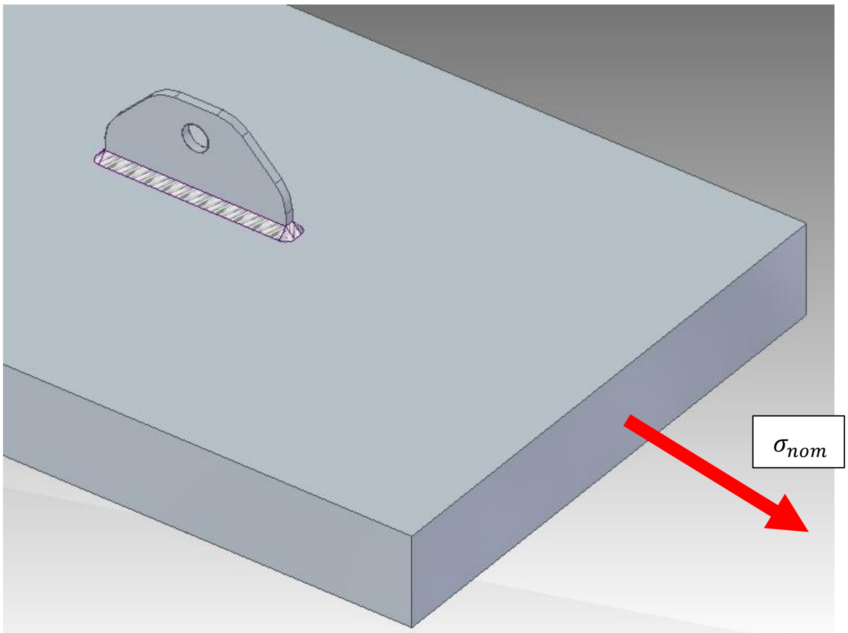


Figure 2: Concept 2: Longitudinal continuous 5 mm fillet weld

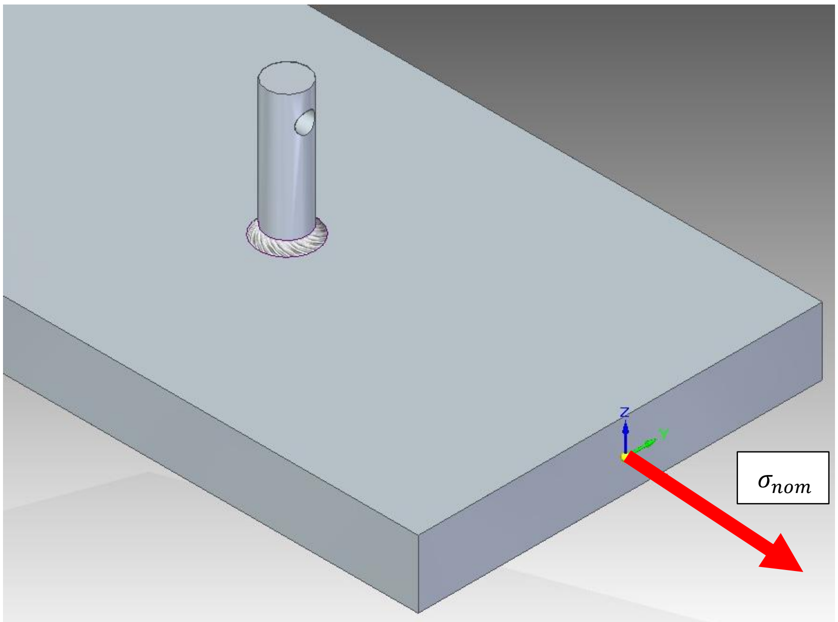


Figure 3: Concept 3: Solid bar of diameter 30 mm joined by 5 mm fillet weld to the plate

Answer: [4 Marks]

For Concept 1, the weld length was assumed to be shorter than 50mm. Hence, Detail Category 80 would be applicable. Crack initiation could however occur in two locations, as depicted in Figure 4.

1 Mark

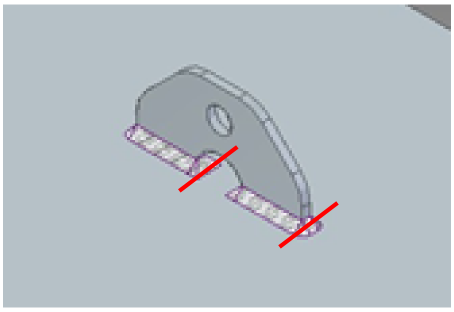
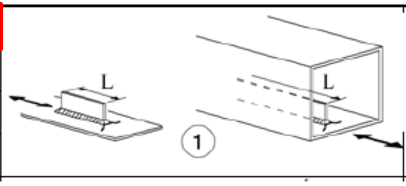


Figure 4: Possible crack initiation sites

80	L≤50mm		Longitudinal attachments: 1) The detail category varies according to the length of the attachment L.	The thickness of the attachment must be less than its height. If not see Table 8.5, details 5 or 6.
71	50<L≤80mm			
63	80<L≤100mm			
56	L>100mm			

For Concept 2, the weld length has increased, and was assumed to be larger than 100mm. Hence, a Detail Category 56 would be applicable. Crack initiation would only occur at the weld toe as depicted in Figure 5.

[1 Mark] Note, students may also select Detail Category 80 here.

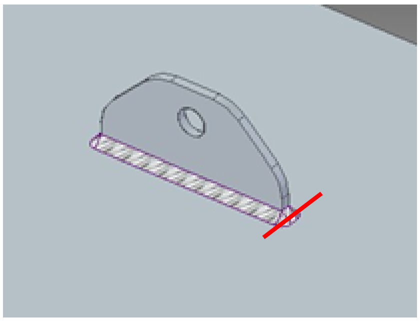
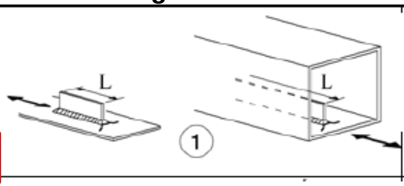
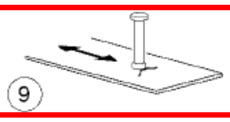


Figure 5: Possible crack initiation site

80	L≤50mm		Longitudinal attachments: 1) The detail category varies according to the length of the attachment L.	The thickness of the attachment must be less than its height. If not see Table 8.5, details 5 or 6.
71	50<L≤80mm			
63	80<L≤100mm			
56	L>100mm			

For Concept 3, a Detail Category 80 would be applicable.

1 Mark

80		9) The effect of welded shear studs on base material.	

The three concepts are listed below, in the order of highest fatigue life to lowest fatigue life:

1. Concept 3
2. Concept 1 (even though the detail category is the same as for concept 3, there are more crack initiation sites which makes this option not preferable)
3. Concept 2

1 Mark for ordering

2. ADVANCED WELD FATIGUE DECISION-MAKING [40% of paper for weld fatigue]

Note, to obtain maximum points for each problem clearly motivate solutions and equations used.

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 6. 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 $\alpha = 60°$. 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 250 °C and the surfaces corrosion protected using International Paint's HT-10 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

σ_{max} [MPa]	σ_{min} [MPa]	Number of cycles
200	100	100 000
50	-75	50 000
40	0	1 000 000

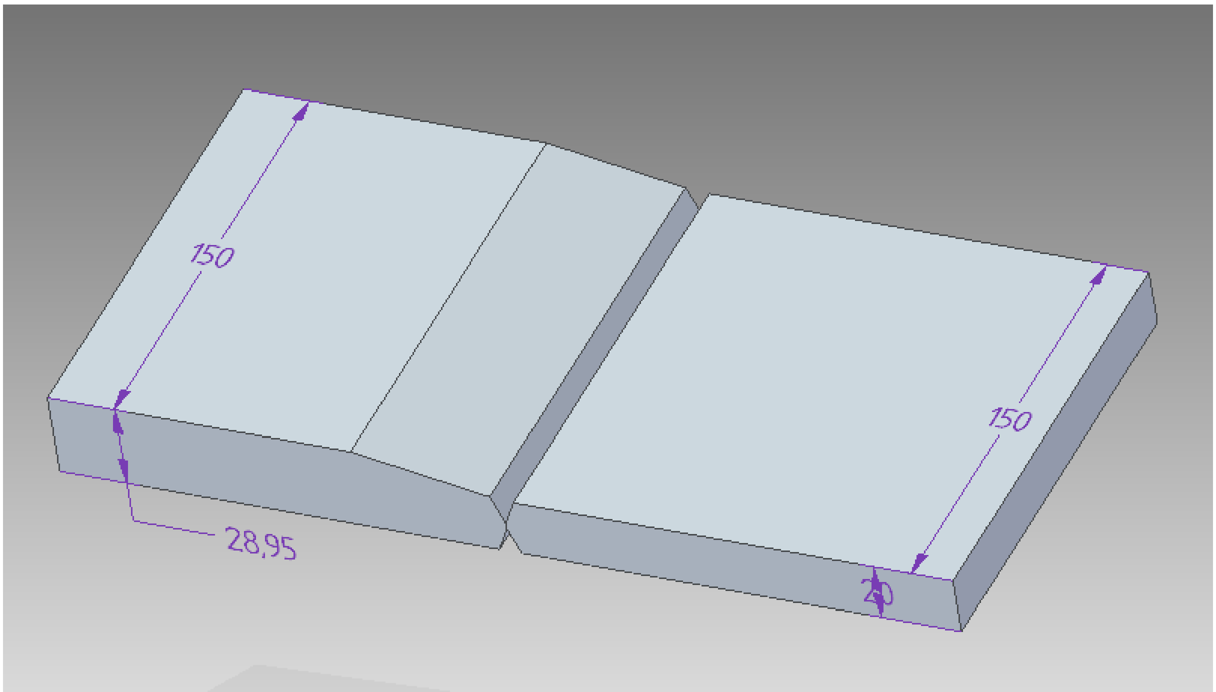
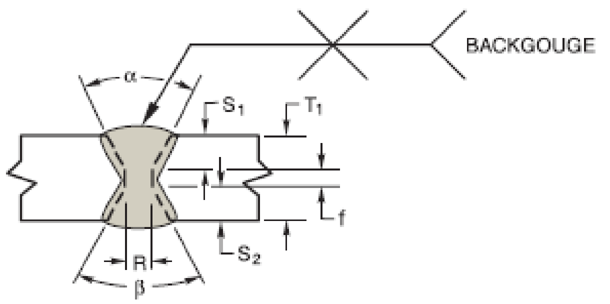


Figure 6: Tapered joint

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

Double-V-groove weld (3)
Butt joint (B)



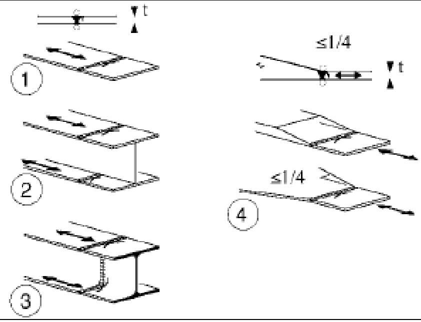
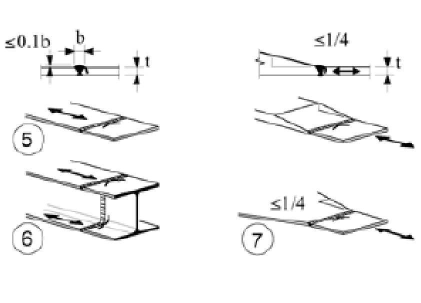
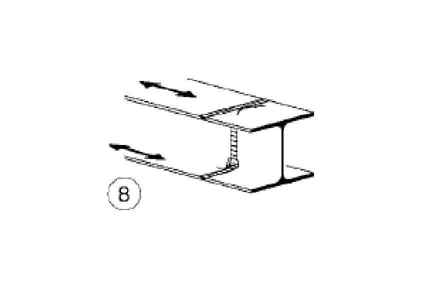
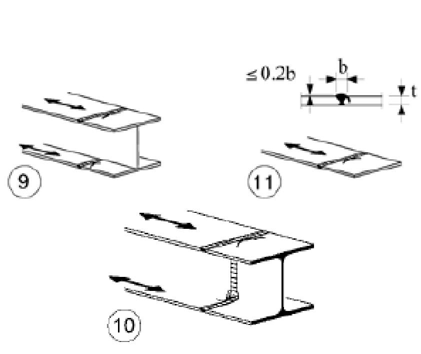
For B-U3c-S only		
T_1		S_1
Over	to	
2	2-1/2	1-3/8
2-1/2	3	1-3/4
3	3-5/8	2-1/8
3-5/8	4	2-3/8
4	4-3/4	2-3/4
4-3/4	5-1/2	3-1/4
5-1/2	6-1/4	3-3/4
For $T_1 > 6\text{-}1/4$ or $T_1 \leq 2$ $S_1 = 2/3\ (T_1 - 1/4)$		

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 3.13.1)	As Fit-Up (see 3.13.1)			
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						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_1 see table above: $S_2 = T_1 - (S_1 + f)$					

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 8 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	size effect for t>25mm: $k_s=(25/t)^{0.2}$		<u>Without backing bar:</u> 1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ≤ ¼.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. <u>Detail 3):</u> Applies only to joints of rolled sections, cut and rewelded.
90	size effect for t>25mm: $k_s=(25/t)^{0.2}$		5) Transverse splices in plates or flats. 6) Full cross-section butt welds of rolled sections without cope holes. 7) Transverse splices in plates or flats tapered in width or in thickness with a slope ≤ ¼. Translation of welds to be machined notch free.	- The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. <u>Details 5 and 7:</u> Welds made in flat position.
90	size effect for t>25mm: $k_s=(25/t)^{0.2}$		8) As detail 3) but with cope holes.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. - Rolled sections with the same dimensions without tolerance differences
80	size effect for t>25mm: $k_s=(25/t)^{0.2}$		9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. <u>Detail 10:</u> The height of the weld convexity to be not greater than 10% of the

2.2. Solution

1. Partial factor for fatigue

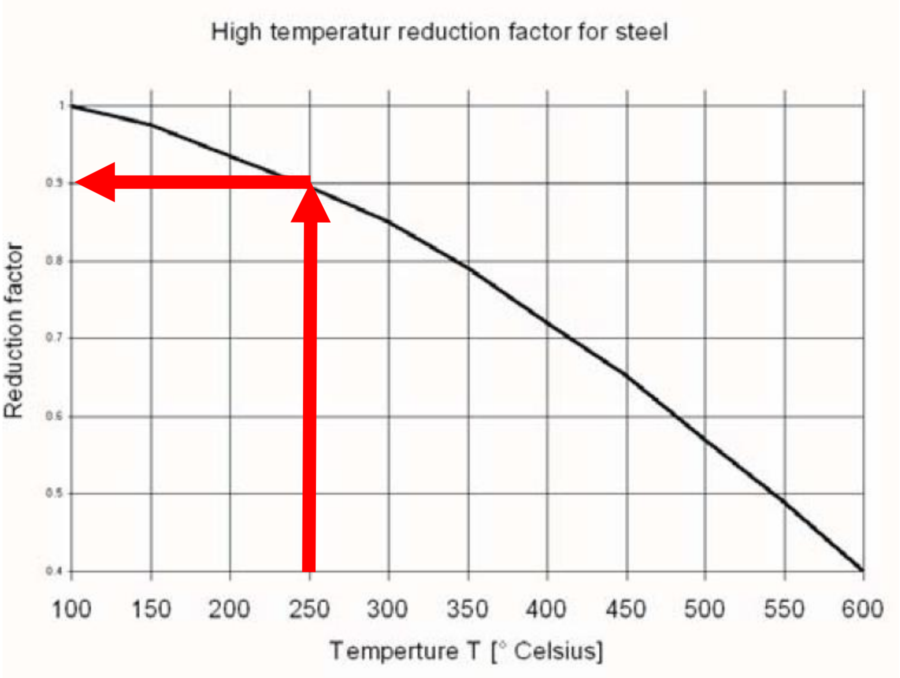
According to the safe life assessment method with high consequence of failure, the partial factor for fatigue is: $\gamma_{Mf} = 1.35$ from the table below.

[3 marks]

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. However, the system is operated at a temperature of 250 °C. According to the graph below, the temperature reduction factor is 0.9.



[3 marks]

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.

[3 marks]

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.

[3 marks]

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.

[3 marks]

6. Fatigue calculations

[32 marks]

Allocate marks as follows:

1. 4 points for each N_i – mark application of ideas, not the exact answer.
2. 4 points for each D_i
3. 2 point for total damage
4. 6 points for knowing how to calculate life.

Detail category				90		
Characteristic strength				90		
Partial factor for fatigue				1.35		
Temperature reduction factor				0.9		
Reduced characteristic strength				60.000	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				44.2	MPa	
Cut-off limit				24.3	MPa	
Stress						
Maximum	Minimum	n_i	Range	N_i	D_i	
200	100	100 000	100	432 000	0.231	
50	-75	50 000	125	221 184	0.226	
40	0	1 000 000	40	8 245 044	0.121	
				Total damage	0.579	
				Period	8	years
				Life	13.821	years