1. ELEMENTARY FATIGUE STRESS RANGE PREDICTION [10 MARKS – 10 Minutes]

1.1. Question

If the equation of the S-N curve for the nominal stress spectra with stress ranges above and below the constant amplitude fatigue limit $\Delta\sigma_D$ is as follows:

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

$$\Delta\sigma_R^m N_R = \Delta\sigma_D^m \times 5 \times 10^6 \quad with\ m = 5\ and\ 5 \times 10^6 \leq N \leq 10^8$$

Calculate the following for a FAT 90 structural detail for a safe life assessment method and high consequence of failure:

1. The constant amplitude fatigue limit stress range **[5 Marks]**.
2. The cut-off limit stress range **[5 Marks]**.

Please show the steps followed in your calculations. Answers only are not sufficient.

Ignore mean stress, temperature, size and other effects.

The material is structural steel with yield strength 350 MPa and is used at room temperature. Further assume that the material is adequately protected against corrosion.

For your information, the following has been supplied:

1. Partial factors for fatigue strength – see Table 1.
2. Structural detail dependant S-N curves – see Figure 1.

Table 1: 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

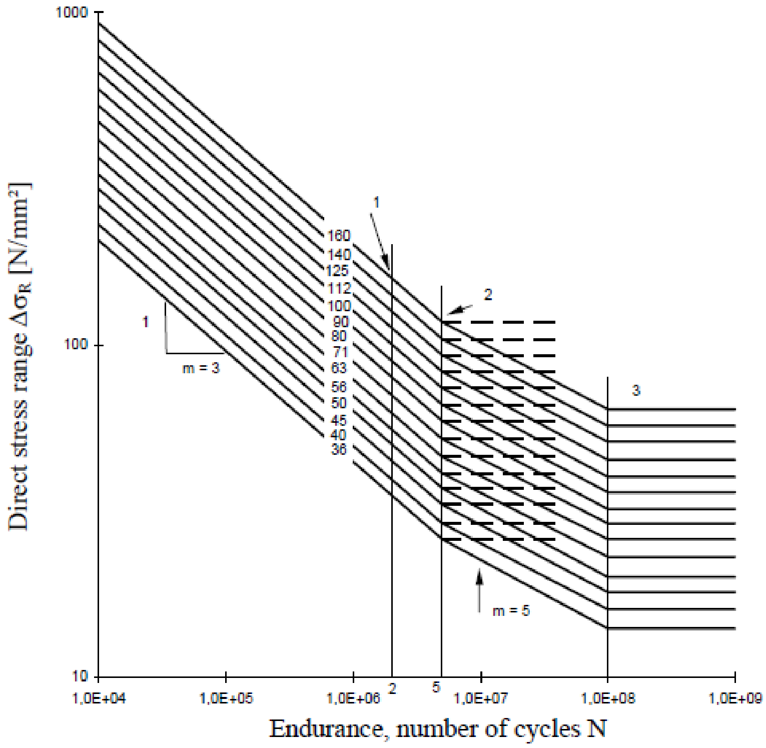


Figure 1: S_R-N curves

1.2. Answer [10 Marks]

For the infinite life assessment method and high consequence of failure, the partial factor for fatigue strength is $\gamma_{Mf} = 1.35$ as can be seen 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 Marks for the correct partial factor for fatigue

No other factors need to be considered. The structural detail is FAT 90. Therefore, the detail category for calculation purposes is:

$$\Delta\sigma_C = \frac{FAT}{\gamma_{Mf}} = \frac{90}{1.35} = 66.7\ MPa$$

2 Marks for the correct use of the equation

Note, some students may include the partial factor directly in the equations – which is also correct

1. The constant amplitude fatigue limit is assumed to be at an endurance 5 million cycles (no indication of an asterisk implying that it should be 10 million cycles (BS EN 1993, 2005:16)). To this endurance, the slope of the S-N curve is $m = 3$. Therefore, the constant amplitude fatigue limit stress range is:

$$\Delta\sigma_D^m \times 5 \times 10^6 = \left(\frac{FAT}{\gamma_{Mf}}\right)^m \times 2 \times 10^6$$

$$\Delta\sigma_D = \left(\frac{\left(\frac{90}{1.35}\right)^3 \times 2 \times 10^6}{5 \times 10^6}\right)^{\frac{1}{3}} = 49.1\ MPa$$

2 Marks for the correct use of the equation
1 Mark for correct answer

FAT	90		
Partial factor for fatigue	1.35		
Structural detail stress range	66.7	MPa	
Slope 1	3		
Slope 2	5		
Constant amplitude fatigue limit endurance	5.00E+06	cycles	
FAT class endurance	2.00E+06	cycles	
Constant amplitude fatigue limit stress range	49.1	MPa	

2. The cut-off limit stress range exists at endurance 100 million cycles. The slope of the S-N curve between 5 million and 10 million cycles is $m = 5$. Therefore, the cut-off limit is:

$$\Delta\sigma_R^m N_R = \Delta\sigma_D^m \times 5 \times 10^6$$

$$\Delta\sigma_R = \left(\frac{5}{100}\right)^{\frac{1}{5}} \Delta\sigma_D = 27\ MPa$$

The table now becomes:

2 Marks for the correct use of the equation
1 Mark for correct answer

FAT		90		% of structural detal stress range
Partial factor for fatigue		1.35		
Structural detail stress range		66.7	MPa	
Slope 1		3		
Slope 2		5		
Constant amplitude fatigue limit endurance		5.00E+06	cycles	
FAT class endurance		2.00E+06	cycles	
Constant amplitude fatigue limit stress range		49.1	MPa	74%
Cut-off limit endurance		1.00E+08		
Cut-off limit stress range		26.98		40%

2. LINEAR DAMAGE RULE [10 MARKS – 10 Minutes]

2.1. Question

A structural detail is subjected to the nominal stress ranges and number of cycles over a period of 5 years as summarised in Columns 1 and 2 of Table 2. The third column summarises the endurance as was calculated from the applicable S-N curve.

Table 2: Stress spectrum over a period of 5 years with the S-N curve endurance

Stress range [MPa]	Number of cycles over 5 years	Endurance from the S-N curve $[P_{surv,75\%\ conf.level} = 95\%]$
100	50,000	2,000,000
50	2,000,000	34,744,545
20	5,000,000	Infinity

Please calculate the following:

1. The damage done on the structural detail over a period of 5 years **[4 Marks]**.
2. The damage done on the structural detail over a period of 10 years **[3 Marks]**.
3. The fatigue life of the structural detail for a 75% confidence level of a 95% probability of survival **[3 Marks]**.

2.2. Answer

The following was only used to compile the question and is provided for reference only.

Reference strength of the detail	100	MPa
Reference strength endurance	2.00E+06	cycles
Constant amplitude fatigue limit endurance	5.00E+06	cycles
Constant amplitude fatigue limit stress range	73.68	MPa
Cut-off limit endurance	1.00E+08	cycles
Cut-off limit stress range	40.47	MPa

Stress range	Cycles	Endurance	Damage	
100	50000	2000000	0.03	
50	2.00E+06	34744545	0.06	
20	5.00E+06	3393022021	0.00	
		Damage per block	0.08	
		Duration/block	5	years
		Damage over 5 yrs	0.08	
		Damage over 10 yrs	0.17	
		Life	60.56	years

Answer:

1. The total damage is the accumulation of damage and failure occurs when the total damage is larger or equal to 1.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = 0.08$$

1 Marks for 0.03 and 0.06 and 0 <u>each</u> damage in the D_i column
1 Mark for the total damage of 0.08 over five years.

The duration of one block is 5 years, so the damage done over a period of 5 years is 0.08.

2. The damage done on the structural detail over a period of 10 years is 0.16.
3. The fatigue life of the structural detail for 75% confidence level of a 95% probability of survival is 5/0.08 = 60 years.

2 Marks for applying the correct principle to obtain the life for 10 years.
1 Mark for the correct answer of 0.016.

2 Marks for applying the correct principle to calculate the total life.
1 Mark for the correct answer of 60.6 years.

Notes:
1. **Allow a ±10% tolerance on answers.**

3. ELEMENTARY WELD FATIGUE DECISION-MAKING [15 MARKS – 15 minutes]

3.1. Problem statement

The construction of the longitudinally stressed built-up section below has a detail category FAT 80. The non-staggered intermittent weld size is 12 mm. The 16 mm plate material is structural steel with yield strength 350 MPa and is used at room temperature. Further assume that the material is adequately protected against corrosion and that the welding electrode matches that of the plate.

Please answer the following:

1. Where do you expect the first point(s) of crack initiation in this built-up section? Motivate your answer. **[25% of the mark]**
2. According to BS EN 1993-1-9:2005, what is the effect of thickness of members on the fatigue life of this built-up section? Motivate the reason(s). **[25% of the mark]**
3. What will you recommend, with reasons, to improve the fatigue performance of the built-up section? Name at least three improvements that can be considered and evaluate their applicability. **[37.5% of the mark]**
4. What will be the effect of toe burring on the fatigue life of this built-up section? **[12.5% of the mark]**

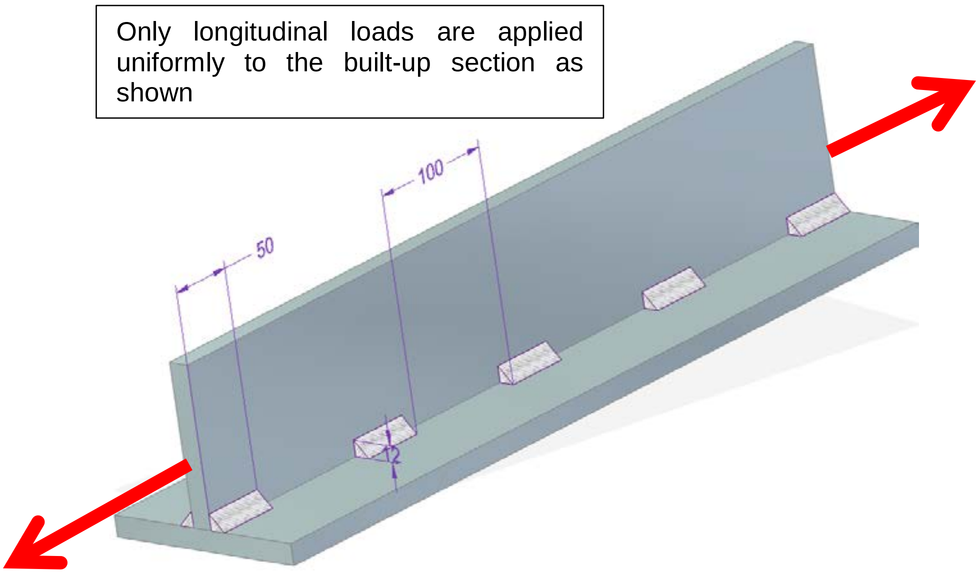


Figure 2: Solid model sketch of the non-staggered intermittent weld

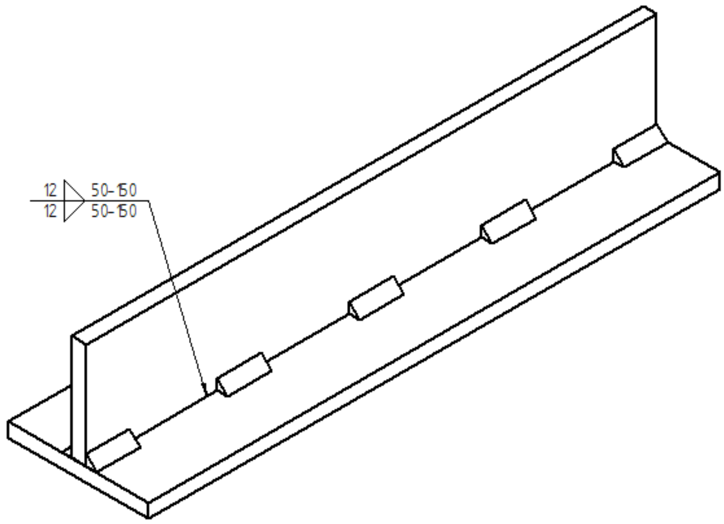


Figure 3: Weld symbol for the non-staggered intermittent weld

3.2. Answers

The answers are as follows:

1. The cack will initiate at the weld toe of the weld start and stops. This is because of the notch stress concentration at the weld toe at this position and because there is no transverse stress on the plate. Due to the longitudinal load applied, the stress is highest at these starts/stops. **[2 Marks = 1 for the correct identification of the points of crack initiation +1 for understanding the notch effect on weld fatigue].**
2. Due to the longitudinal stress on this weld detail, the fatigue life and construction detail FAT class is not sensitive to the thickness of members. **[2 Marks = 1 for indicating that no thickness effect need to be considered + 1 for mentioning that it is in the case applicable due to the longitudinal loading of the members]**
3. The following can be done **[3 Marks = 1 for any of the following. Where the student mentioned other reasons of the many, Michiel will evaluate accordingly]**:
   a. Make the weld a continuous longitudinal weld, not intermittent. This will increase the construction detail to FAT 100.
   b. Do automatic fillet welding from both sides. This will increase the construction detail category to FAT 112.
   c. Toe burring will increase the weld detail FAT class by 1.3 according to IIW (2007:86) up to a limit of FAT 112. Toe burring will result in reduction of notch stress at the intermittent weld toes and the weld category will increase to FAT 104.
   d. TIG dressing will have the same effect on the weld toe at the stop/start positions as toe burring.
   e. The effect of hammer peening could be as high as 1.6 for steel with yield strength larger than 355 MPa. In this case the steel has a yield strength of 350 MPa and the benefit will be 1.3, same as with toe burring in this case.
4. Toe burring will not have an improvement on the longitudinal section of the weld because of the direction of the principal stress. However, at the start/stop positions of the intermittent welds toe burring will have a benefit factor of 1.3 on the FAT class. **[1 Mark for the correct answer]**

[The question is answered out of 8. The answer will be scaled during marking by Mark/8 × 15]

4. WELD FATIGUE CALCULATION AND DECISION-MAKING [30 MARKS – 30 Minutes]

4.1. Problem Statement

Figure 4 shows a transverse splice in a flat member used as link in a large ground moving machine. Although the joint is subject to rain and coal, assume for the purpose of this assessment that it is properly corrosion protected. Under normal operating conditions the temperature of the member can be assumed to be at room temperature. The following information is given on the welding procedure specification of the joint:

1. The height of the weld convexity shall be less than 20% of the weld width with smooth transition to the plate surface.
2. The weld shall be as made and not ground flush with the plate surface.
3. Weld run-on and run-off pieces shall be used and subsequently removed whereafter plate edges shall be ground flush in the direction of stress.
4. The weld shall be welded from both sides.
5. The weld shall be checked and eliminated from defects using an ultrasonic testing method.

The plate thickness is given as $t = 30\ mm$.

The stress spectrum of the joint over a period of 2 years is as summarised in Table 1.

Table 3: 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

The design philosophy is damage tolerant design with high consequence of failure.

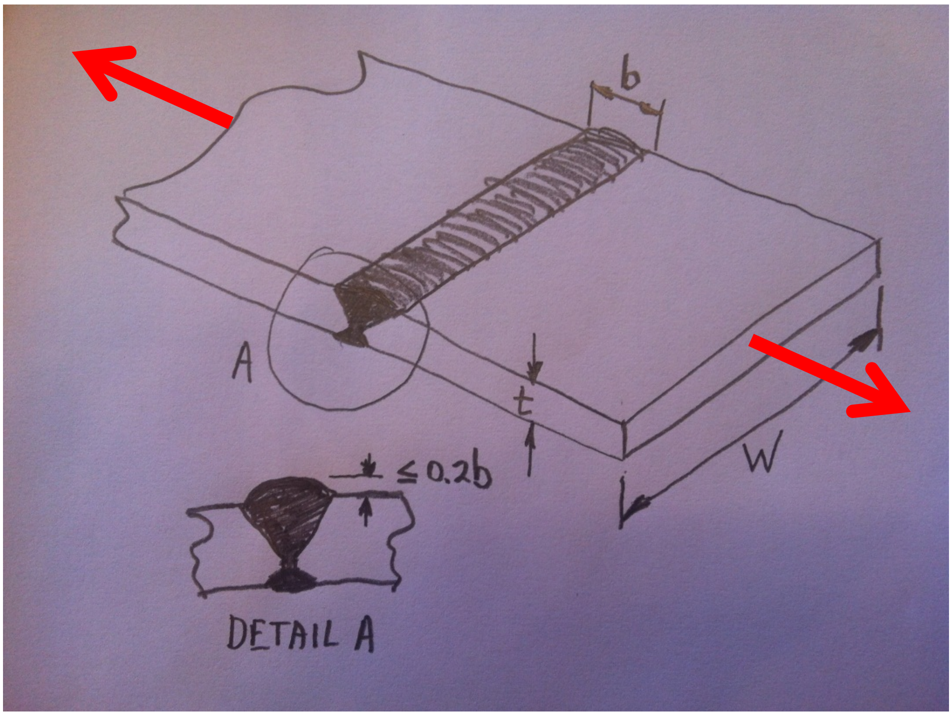


Figure 4: Complete joint penetration butt weld in a splice

The following are given as extra information:

1. The partial factor for fatigue – See Table 3
2. An extraction of typical structural detail from BS EN 1993-1-9 as shown in Table 4.

Table 4: 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

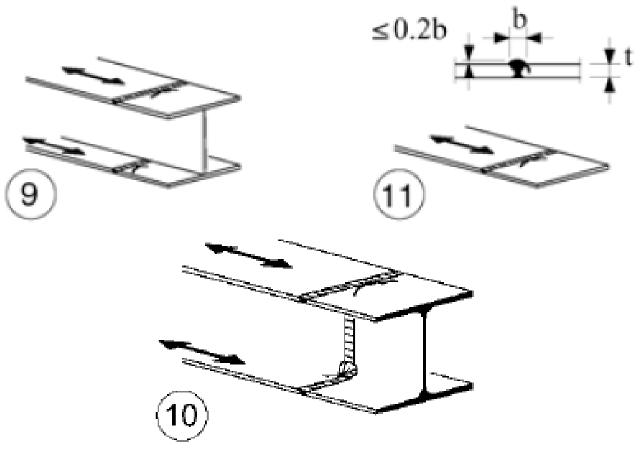
Provide all equations used and answer the following:

1. What is the detail category dependant FAT class for the joint? **[4.8% of the mark]**
2. Where can crack initiation be expected and why? **[9.5% of the mark]**
3. What is the partial factor for fatigue strength that needs to be included in this design? **[4.8% of the mark]**
4. What is the thickness correction factor that needs to be included in the analysis? **[9.5% of the mark]**
5. What is the reference value for the fatigue strength $\Delta\sigma_C$ of the joint at $N_C = 2 \times 10^6$ cycles if no thickness correction is required? **[4.8% of the mark]**
6. What is the reduced fatigue strength $\Delta\sigma_{C,red}$ after consideration of the size effect? **[9.5% of the mark]**
7. What is the reduced fatigue strength after consideration of the size and partial factor for fatigue effects? **[9.5% of the mark]**
8. For the following calculations, assume that the fatigue strength of the material including applicable partial factors and size effects is $\Delta\sigma_C = 48\ MPa$:
    a. Calculate the constant amplitude fatigue limit stress range. **[9.5% of the mark]**
    b. Calculate the cut-off limit stress range. **[9.5% of the mark]**
    c. Assume that the nominal stress ranges on the section exceeds the constant amplitude fatigue limit. Calculate the endurance for the following stresses:
        i. $\Delta\sigma_1 = 100\ MPa$ **[14.3% of the mark]**
        ii. $\Delta\sigma_2 = 25\ MPa$ **[14.3% of the mark]**

    Assume that the S-N curve is described by:

$$\Delta\sigma_R^m N_R = \Delta\sigma_C^m \times 2 \times 10^6 \qquad with\ m = 3\ and\ N \leq 5 \times 10^6$$
$$\Delta\sigma_R^m N_R = \Delta\sigma_D^m \times 5 \times 10^6 \quad with\ m = 5\ and\ 5 \times 10^6 \leq N \leq 10^8$$

Table 5: Category detail from BS EN 1993-1-9 (2005:22)

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 weld width, with smooth transition to the plate surface.

4.2. Answers

The answers are as follows:

1. According to the applicable detail category information the class is FAT 80. **[1 Mark]**
2. The crack can initiate at the weld toe **[1 Mark]** at any position along the length of the weld, but, is more likely to initiate in the centre of the plate width **[1 Mark]** because of the grinding that is requested for the plate edges. In the plate centre a plane strain condition effects increase the stress slightly more than at the predominantly plane stress condition at the edge corners.
3. For the design philosophy of damage tolerant assessment method with high consequence of failure, the partial factor for fatigue is $\gamma_{Mf} = 1$ **[1 Mark]**

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

4. In this case thickness correction needs to be done **[1 Mark for identifying need for correction]**. For a plate thickness of 30 mm, the thickness correction factor is 0.6944 as follows **[1 Mark for correct answer]**:

$$k_s = \left(\frac{25}{t}\right)^{0.2} = \left(\frac{25}{30}\right)^{0.2} = 0.6944$$

5. The reference value for fatigue strength for the joint with no thickness and partial factor correction is **[1 Mark]**:

$$\Delta\sigma_C = 80\ MPa$$

6. The reduced fatigue strength of the joint after application of the thickness correction is **[2 Marks =1 for application of correct formula + 1 for correct answer – NOTE, IF THE STUDENT FIRST APPLIED PARTIAL SAFETY FACTORS AS SHOWN IN THE FOLLOWING ITEM, ALLOCATE MARKS ACCORDINGLY]**:

$$\Delta\sigma_{C,red} = k_s \Delta\sigma_C = 0.6944 \times 80 = 55.6\ MPa$$

7. The reduced fatigue strength of the joint after application of the thickness correction and partial factor for fatigue effects is **[2 Marks =1 for application of correct formula + 1 for correct answer]**:

$$\Delta\sigma_{C,Red} = \frac{FAT \times k_s}{\gamma_{Mf}} = \frac{80 \times 0.6944}{1.15} = 48.3\ MPa$$

8. For an S-N curve with reference fatigue strength at 2 million cycles of 48 MPa, the following applies:
   a. The constant amplitude fatigue limit stress range $\Delta\sigma_D$ of the material is at 5 million cycles **[2 Marks =1 for application of correct formula + 1 for correct answer]**:

$$\Delta\sigma_D = \Delta\sigma_C \times \left(\frac{2 \times 10^6}{5 \times 10^6}\right)^{\frac{1}{3}} = 35.4\ MPa$$

   b. The cut-off limit for the material is at 100 million cycles where the stress range is **[2 Marks =1 for application of correct formula + 1 for correct answer]**:

$$\Delta\sigma_L = \Delta\sigma_c \left(\frac{2\times10^6}{5\times10^6}\right)^{\frac{1}{3}} \times \left(\frac{5\times10^6}{100\times10^6}\right)^{\frac{1}{5}}$$
$$= 19.43\ MPa$$

c. The endurance of the material for the following stress ranges are:

i. At $\Delta\sigma = 100\ MPa,\ N_{100} = 221{,}000\ cycles$ **[3 Marks =2 for application of correct formula + 1 for correct answer]**:

$$N_{100} = \left(\frac{\Delta\sigma_C}{\Delta\sigma_R}\right)^m \times 2\times10^6$$
$$= \left(\frac{48}{100}\right)^m \times 2\times10^6$$
$$= 221{,}000\ cycles$$

ii. At $\Delta\sigma = 25\ MPa, N_{25} = 28.343\times10^6$ cycles **[3 Marks =2 for application of correct formula + 1 for correct answer]**:

$$N_{25} = \left(\frac{\Delta\sigma_D}{\Delta\sigma_R}\right)^5 \times 5\times10^6$$
$$= \left(\frac{35.37}{25}\right)^5 \times 5\times10^6$$
$$= 28.343\times10^6\ cycles$$

[Note, the question is marked out of 21. Marks will be scaled to 30 as required for the question]

5. EFFECT OF ELEVATED TEMPERATURE [8 MARKS – 8 minutes]

5.1. Question

During the lectures the effect of elevated temperature was discussed using the International Institute of Welding guidelines for fatigue assessment as reference. Please answer the following according to this IIW guideline:

1. How can the fatigue resistance of structural detail be calculated at elevated temperature? **[33% of the mark]**
2. If the fatigue resistance of a structural steel at room temperature is FAT 100, what is the approximate fatigue resistance at 350 °C? **[67% of the mark]**

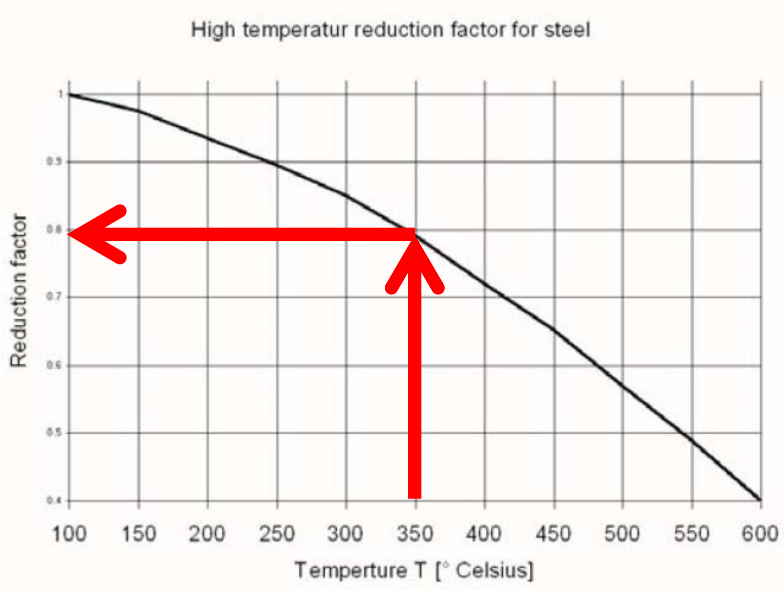
5.2. Answer

AS follows:

1. The fatigue resistance is scaled according to the modulus of elasticity at the reference and elevated temperatures. For example, if the modulus of elasticity is $E_{20\,°C}$ at 20 °C and E_{HT} at the elevated temperature, the relevant fatigue resistance is as follows **[1 Mark]**:

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

The temperature dependant fatigue resistance modification factor for structural steel is shown in the figure below.



2. At 350 °C the fatigue reduction factor is approximately 0.8. Therefore, the fatigue resistance at the elevated temperature is FAT 80, or 80 MPa stress range. **[2 Marks = 1 for the correct factor + 1 for correct application]**

[Note, the question is marked out of 3. Scale accordingly to the mark allocated to the problem]