1. WELD STATIC DESIGN [10 MARKS – 10 Minutes] – QUESTION 2 IN THE PAPER

1.1. Question

A complete joint penetration groove weld is made to join two 200 mm wide 350W plates of thickness 20 mm. The ultimate tensile strength of the weld metal is 480 MPa.

1. What is the factored resistance of the welded section?
2. What is the factored resistance of the steel plate?
3. Where is the joint expected to fail under static loading?

1.2. Answer

The cross section area of the weld and plate are is **[2 marks for the correct area calculation right through the answer]**:

$$A = 0.2 \times 0.02$$
$$= 0.004\ m^2$$

1. The factored resistance of the welded section is **1,286 kN** as follows **[3 marks – 2 marks if concept applied but calculation error]**:

$$T_{rw} = 0.67 \times A \times f_{uw}$$
$$= 0.67 \times 0.004 \times 480 \times 10^6$$
$$= 1{,}286.4\ kN$$

2. The factored resistance of the steel plate is **1,260.0 k**N as follows **[3 marks – 2 marks if concept applied but calculation error]**:

$$T_r = 0.9 \times A \times f_y$$
$$= 0.9 \times 0.004 \times 350 \times 10^6$$
$$= 1{,}260\ kN$$

3. The joint is expected to fail in the base plate during increasing static load **[2 marks for the interpretation. If calculation error in one equation results in different interpretation, still allow 2 marks. The marks is for identifying the lowest resistance from the equations above.]**.

Note, some students may use structural mechanics equations with factored yield or ultimate strengths. That is full marks.

2. FILLET WELD AND TORSION [10 MARKS – 10 Minutes] – QUESTION 3 IN THE PAPER

2.1. Question

A fillet weld with leg size 8 mm made with an E70XX electrode was used to join the 50 mm diameter bar to the 20 mm thick block as shown in Figure 1 below. Using the factored resistance approach, what is the torque T that can be resisted by the weld?

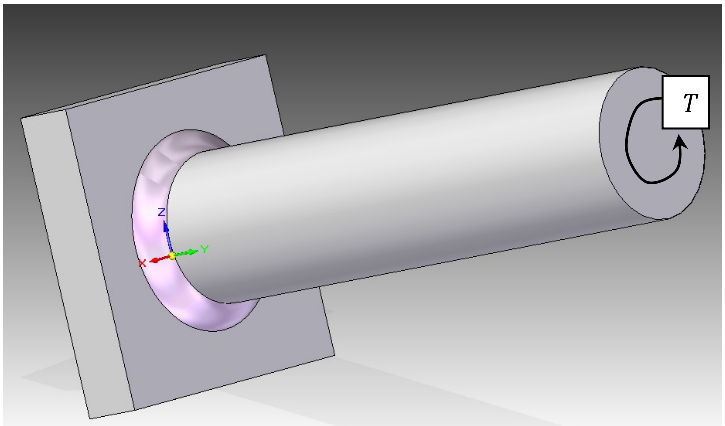


Figure 1: Fillet weld joining a bar to a block.

2.2. Answer

In the application of the factored resistance approach, the weld factored strength can be taken as:

$$\sigma_w = 0.67\phi_w x_u$$
$$= 0.67 \times 0.67 \times 490 \times 10^6$$
$$= 219\ MPa$$

The total length of the weld is **[2 Marks]**:

$$L_w = \pi D$$
$$= \pi \times 0.05$$
$$= 0.1571\ m$$

The shear area of the weld is the throat size times the weld length **[3 Marks]**:

$$A_w = L_w \times (0.707 \times 0.008)$$
$$= 8.884 \times 10^{-4}\ m^2$$

From this, the force in the weld around the bar is **[3 Mark]**:

$$F_w = 0.67\phi_w A_w x_u$$
$$= 0.67 \times 0.67 \times 8.884 \times 10^{-4} \times 490 \times 10^6$$
$$= 195.4\ kN$$

The torque as a result of this force is **[2 Marks]**:

$$T = RF_w$$
$$= 0.025 \times 195.4$$
$$= 4.9\ kNm$$

Therefore, the weld can resist a torque of 4**.9 kNm**.

Answer Concept 2:

The student could decide to calculate the second moment of the weld throat area and use that with the factored strength of the weld.

The second moment of area for the weld group can be simplified as the throat size times length of the weld as the area at a radius equal to that of the bar **[2 Marks]**:

$$I_w = 0.707 \times 0.008 \times \pi \times 0.05 \times 0.025^2$$
$$= 5.5528 \times 10^{-7}\ m^4$$

The shear stress produced by the torque T is then **[8 Marks]**:

$$\tau = \frac{TR}{I_w}$$
$$T = \frac{\tau I_w}{R}$$
$$= \frac{0.67 \times 0.67 \times 490 \times 10^6 \times 5.5528 \times 10^{-7}}{0.025}$$
$$= 4.9\ kNm$$

3. LINEAR DAMAGE RULE [10 MARKS – 10 Minutes] – QUESTION 4 IN THE PAPER

3.1. Question

Explain application of the linear fatigue damage rule to assess fatigue damage accumulation on a material of which the fatigue life is mean stress dependant. Use the completely reversed stress amplitude S-N curve as reference in your explanation and include relevant equations. At least the following need to be addressed:

- Goodman mean stress correction.
- The completely reversed S-N curve.
- Cycles applied versus cycles to failure.
- Damage accumulation.

3.2. Answer

In the answer allocate marks for the following:

1. The peak-valley reduced signal is counted to provide the stress amplitude (σ_a) and mean stress (σ_m) with the number of cycles that it occurred (n_i). **[2 Marks]**
2. Due to the fact that fatigue life of this material is mean stress dependant, a mean stress correction is required to obtain the equivalent completely reversed stress amplitude (S_a) that will cause the same damage. This is done by means of mean stress correction, for which the Goodman correction provides good results for most metals. **[2 Marks]**

$$\frac{\sigma_a}{S_a} + \frac{\sigma_m}{S_u} = 1$$

3. The S-N curve is then used to obtain the number of cycles to failure (N_i) for each of the calculated completely reversed stress amplitudes (S_a) above. **[2 Marks]**
4. The damage for each completely reversed stress amplitude is then calculated by dividing the counted number of stress cycles by the number of cycles to failure **[2 Marks]**:

$$D_i = \frac{n_i}{N_i}$$

5. The total damage is then the accumulation of damage and failure occurs when the total damage is larger or equal to 1. **[2 Marks]**

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

Note, the student may use a totally different approach to explain the concept. Evaluate according to the key elements in this memorandum.

4. ELEMENTARY WELD FATIGUE DECISION-MAKING [15 MARKS – 15 minutes] – QUESTION 5 IN THE PAPER – Examination paper indicates mark out of 14

4.1. Problem statement

A Class F Type 8.1 weld detail is shown in Figure 2 where an E70XX electrode was used to weld the 350 WA steel parts together to achieve a normal-matched welded joint. You are requested to generate a table that summarises the allowable stress range for a 2.3% probability of failure on the Class F weld detail for the following plate thickness:

- 10 mm.
- 16 mm.
- 32 mm.

The allowable stress ranges shall be provided at the following number of cycles:

- 100,000
- 10,000,000
- 100,000,000

Clearly summarise equations used with motivation.

Use the following template as an example.

Cycles	Plate thickness		
	10 mm	16 mm	32 mm
Stress range @ 100,000 cycles			
Stress range @ 10 million cycles			
Stress range at 100 million cycles			

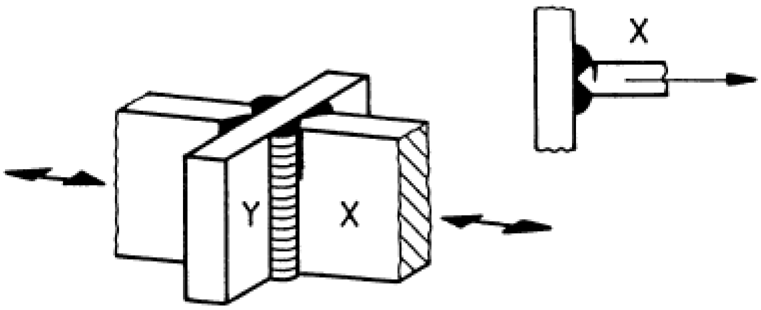


Figure 2: Class F weld detail.

4.2. Solution

The procedure followed in the population of the requested table is as follows:

1. The Design Sr-N curve coefficient and exponents were obtained for the Class F weld detail provided. For the Class F weld detail and the Sr-N relationship shown in Equation 1, the values are as included **[1 Marks]**:

$$S_r^m N = C_2$$

$$S_r = \left(\frac{C_2}{\mathrm{N}}\right)^{\frac{1}{\mathrm{m}}} \qquad (1)$$

$$m = 3$$
$$C_2 = 0.63 \times 10^{12}$$
$$S_o = 40\,MPa$$

[1 Marks] for the equation above.

2. The fatigue strength (stress range) is then calculated for the number of cycles. **[1 Marks]**
3. Thereafter, effects of high cycles was calculated where the following equation was applied to determine fatigue strength at cycles above 10 million cycles. Note that the non-propagating stress range is exceeded in this example, and, therefore, stress ranges below the non-propagating stress range limit will result in fatigue failure. For stress ranges below the non-propagating stress range, the following equation shall be used to calculate number of cycles to failure on the design S_r-N curve: **[1 Marks for the concept] [1 Marks for the equation below]**

$$N = \left[\frac{1}{10^7}\left(\frac{S_r}{S_o}\right)^{m+2}\right]^{-1}$$

$$\frac{1}{N} = \left[\frac{1}{10^7}\left(\frac{S_r}{S_o}\right)^{m+2}\right]$$

$$\frac{10^7}{N} = \left(\frac{S_r}{S_o}\right)^{m+2} \qquad (2)$$

$$S_r = S_o\left(\frac{10^7}{N}\right)^{\frac{1}{m+2}}$$

$$= 40\left(\frac{10^7}{N}\right)^{\frac{1}{5}}$$

4. Thickness modification factors were then applied to model thickness effect. **[1 Marks]**

$$S = S_B\left(\frac{\mathrm{t_B}}{\mathrm{t}}\right)^{0.25} \qquad (3)$$

Where:

S_B = the fatigue strength at t_B = 16 mm thickness.

S = the fatigue strength at thickness t, where $t > t_B$.

Applying the methodology resulted in the following results: **[3 Marks, one for each Column]**:

Weld detail parameters	
Class F	
C_2	6.30E+11
m	3
S_o	40

Cycles	S_{16}	S_{10}	S_{32}
100000	184.7	184.7	155.3
1.00E+07	40.0	40.0	33.6
1.00E+08	25.2	25.2	21.2

[This gives a total of 9 Marks that shall be scaled by 15/9 to obtain a mark out of 15]
Multiply by 14/9 for the 2011 examination paper.

Where a student did everything correct but forgot to include the stress ranges below the non-propagating stress range, allocate a maximum of 80 % because of the importance of this effect on weld fatigue life.

5. ADVANCED WELD FATIGUE DECISION-MAKING [30 MARKS – 30 Minutes] – QUESTION 6 IN THE PAPER counts only out of 28!!

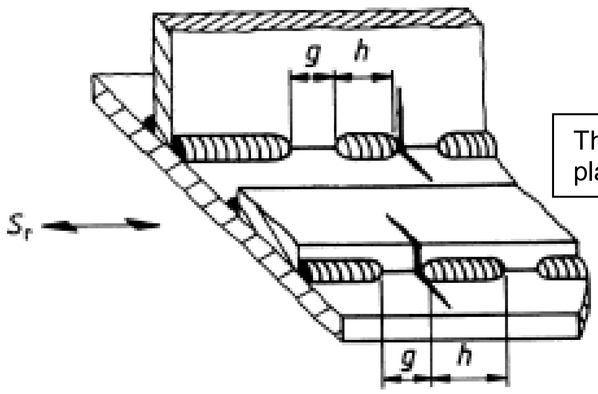
5.1. Problem Statement

The weld detail on a part with intermittent fillet weld is shown in Figure 2. The limiting gap ratio is less than 2.5 (i.e. $\frac{g}{h} \leq 2.5$) 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 1. For your information, the following has been included:

- BS 7608 Table 14.
- A few weld categories.

Table 1: 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 thickness of all plates is 12 mm

Figure 3: Intermittent fillet weld on part.

Please answer the following:

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 2.3% - that is, according to the design S_r-N curve? **[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 more than 2.5h (i.e. $g \geq 2.5h$)? **[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]**

5.2. BS 7608:1993 information

Table 14 — Details of basic *S-N* curves

Class	C_o	C_o		m	Standard deviation, σ		C_2	S_o ($N = 10^7$ cycles) N/mm²
		Log₁₀	Logₑ		Log₁₀	Logₑ		
B	2.343×10^{15}	15.3697	35.3900	4.0	0.1821	0.4194	1.01×10^{15}	100
C	1.082×10^{14}	14.0342	32.3153	3.5	0.2041	0.4700	4.23×10^{13}	78
D	3.988×10^{12}	12.6007	29.0144	3.0	0.2095	0.4824	1.52×10^{12}	53
E	3.289×10^{12}	12.5169	28.8216	3.0	0.2509	0.5777	1.04×10^{12}	47
F	1.726×10^{12}	12.2370	28.1770	3.0	0.2183	0.5027	0.63×10^{12}	40
F2	1.231×10^{12}	12.0900	27.8387	3.0	0.2279	0.5248	0.43×10^{12}	35
G	0.566×10^{12}	11.7525	27.0614	3.0	0.1793	0.4129	0.25×10^{12}	29
W	0.368×10^{12}	11.5662	26.6324	3.0	0.1846	0.4251	0.16×10^{12}	25
S	2.13×10^{23}	23.3284	53.7156	8.0	0.5045	1.1617	2.08×10^{22}	82
T	4.577×10^{12}	12.6606	29.1520	3.0	0.2484	0.5720	1.46×10^{12}	53[a]

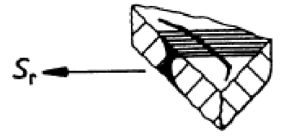
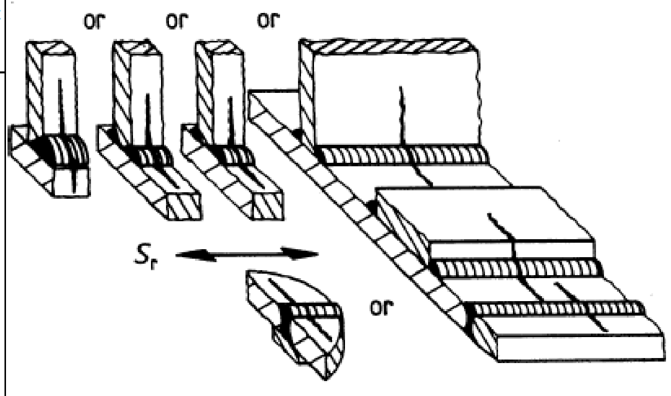
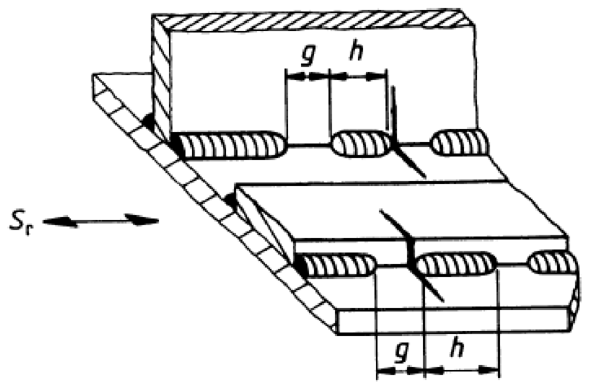
NOTE For details of the *S-N* curve for class X see **4.2.2**.

For example the *T* curve expressed in terms of $\log_{10}$ is:

$$\log_{10}(N) = 12.6606 - 0.2484d - 3\log_{10}(S_r)$$

[a] Idealized hot spot stress.

Table 4 — Classification of details: continuous welded attachments essentially parallel to the direction of applied stress

Product form	Location of potential crack initiation	Dimensional requirements	Manufacturing requirements	Special inspection requirements	Design stress area	Type number	Class	Notes	Sketch
Rolled steel structural plates, sections and built-up members	At a long welded attachment (in the direction of S_r), away from the weld end	Butt weld with full penetration and no backing strip	Weld reinforcement dressed flush	Proved free of all flaws which are likely to degrade the joint below its stated classification (see 2.4.3)	Minimum transverse cross section of member at location of potential crack initiation	4.1	B	Finish machining should be in the direction of S_r. The significance of flaws should be determined with the aid of specialist advice and/or by the use of a fracture mechanics analysis. The non-destructive testing (NDT) technique should be selected with a view to ensuring the detection of such significant flaws. This type is only recommended for use in exceptional circumstances.	
		Butt or fillet welded web or attachment with width not greater than 50 mm	Automatic weld with no stop/starts			4.2	C	Accidental stop/starts are not uncommon in automatic processes. Repair to the standard of a C classification should be the subject of specialist advice and inspection and as a result, the use of this type is not recommended.	
			Welds with stop/starts			4.3	D	For situation at the ends of flange cover plates see joint type 5.4. Backing strips, if used, need to be continuous and either not attached or attached by continuous fillet welds. If the backing strip is attached by discontinuous fillet welds see type 4.6.	
	At an intermediate gap in a longitudinal weld	Intermittent fillet weld with $\frac{g}{h} \le 2.5$				4.4	E	The limiting gap ratio g/h applies even though adjacent welds may be on opposite sides of a narrow attachment (as in the case of a longitudinal stiffener with staggered fillet welds). Long gaps between intermittent fillet welds are not recommended as they increase the risk of corrosion and, in the case of compression members, may cause local buckling. If intermediate gaps longer than $2.5h$ are required the class should be reduced to F.	

5.3. Solution

This section provides the answers in numbered sequence:

1. Question 1 **[16 Marks, as distributed as shown]**:
   a. According to the table presented above, this weld detail can be categorised as:
      i. Class E using nominal stress in the base section. This is for crack initiation at the weld toe. **[1 Marks]**
   b. The mathematical model for the design S_r-N curve for the weld detail is as follows:
      i. Class E: **[1 Marks]**
         1. $C_2 = 1.04 \times 10^{12}$
         2. m = 3.0
         3. S_o = 47 MPa
      ii. Equation applicable for both cases **[1 Marks]**:

$$S_r^m N = C_2$$

$$N = \frac{C_2}{S_r^m} \qquad (4)$$

      iii. For stress ranges below the non-propagating stress range, the following equation shall be used to calculate number of cycles to failure on the design S_r-N curve **[1 Marks]**:

$$N = \left[\frac{1}{10^7}\left(\frac{S_r}{S_o}\right)^{m+2}\right]^{-1} \qquad (5)$$

   c. Calculation of damage and life:
      i. The stresses and the damage are as summarised in Table 2. Note that the change in slope needs to be taken into account for stress ranges below the non-propagating stress range. **[9 Marks – three for each line in the table].**
      ii. From the results, it is clear that damage of D = 0.208 was done to the Class E weld detail over the two year period and that the weld detail fatigue life estimated with 2.3% probability of failure is 9.6 years. **[3 Marks].**

Table 2: Damage for Class E and Class F weld detail over one period of 2 years.

				Class E			Class F	
C_2				1.04E+12			6.30E+11	
m				3			3	
S_o				47			40	
Stress signal maximum				60.0			60.0	
Include damage at			$\Delta\sigma \leq S_o$	Yes			Yes	
Loading			Class E			Class F		
σ_{max} [MPa]	σ_{min} [MPa]	ni	Δσ [MPa]	Ni	Di	Δσ [MPa]	Ni	Di
40	0	1000000	40.0	2.24E+07	0.045	40.0	9.84E+06	0.1
25	-22	800000	47.0	1.00E+07	0.08	47.0	6.07E+06	0.13
0	-60	400000	60.0	4.81E+06	0.083	60.0	2.92E+06	0.14
				D	0.208			0.37
				Period	2	years		
				Life	9.634	years		

2. Question 2:
   a. The weld detail is expected to initiate a crack in the weld toe between gaps. This is where the predominant stress concentration will be due to the direction of the stress. **[1 Marks].**
3. Question 3:
   a. No, thickness effects are required to consider for thickness exceeding 16 mm as per BS 7608. Further, the welds in this case are longitudinal welds that are not so sensitive to thickness effects. **[1 Marks].**

4. Question 4 **[2 Marks, distributed as shown in each of the different scenarios]**:
    a. Note that the crack in this weld detail tends to initiate at start-stop positions between the welds where it is difficult to peen. The stress is also parallel to the direction of the weld and the area that will benefit from peening is not the area where the crack will initiate. A marginal increase in life will be obtained. **[2 Marks]**.
    b. Where students discuss the benefits of peening, allocate according to this: 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 9.6 years, or approximately 28.8 years. **[1 Marks]**
5. Question 5 **[2 Marks, distributed as shown]**:
    a. In this case it is not easy to burr the weld toe for improvement in the direction of the stress. Consider this in allocation of marks.
    b. Tow burring can have the following benefits according to the UK Healtch and Safety Executive:
        a. Factor 1.3 on fatigue strength.
        b. Factor 2.2 on life.
    c. 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]**
    d. As shown, this technique is a high stress life improvement technique and is not efficient for high stresses and a low stress life.
    e. 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 9.6 years or approximately 21 years. **[1 Marks]**
6. Question 6:
    a. The intermittent weld can be modified to a continuous weld that would improve the weld detail to Class D. **[1 Marks]**
7. Question 7:
    a. If the gaps are more than 2.5h the weld detail change to Class F. **[1 Marks]**
8. Question 8:
    a. 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]**

The total marks allocated for this section is: 25 Marks.

Adjust by Multiplying with 30/25 to get a point out of 30.

But, the examination paper indicates count out of 28. Therefore, multiply with 28/25!!