Fatigue and fracture - TME260

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Assignment 3
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Executive summary

Assignment

The assignment consists of the evaluation of fatigue life for welded joints, specifically with consideration to the weld roots and weld toes, on a ship structure. The structures design and dimensions are given in the assignment and will not be repeated in this report. The estimations are conducted according to IIW Recommendations for fatigue design for welded joints and component. The first task consists of finding the longitudinal stress over the weld toe and computing its fatigue life using FE-analysis in Ansys. Secondly two different methods will be deployed to estimate the nominal stress and using that in combination with FAT to estimate the fatigue life of the weld roots. Thirdly the estimations for fatigue life in both the weld roots and the weld toes will be compared with experimental results. Lastly the fatigue life for a stress relieved specimen will be computed and compared to IIW recommendations.

Result

- The longitudinal stress in the weld toe is estimated as 157 MPa and the corresponding fatigue limit becomes $N_{f,toe} \approx 520\,000$ cycles.
- The nominal stresses are estimated using method 1 and 2 as $\sigma_{m1} = 183$ MPa and $\sigma_{m2} = 150$ MPa respectively which corresponds to the fatigue lives $N_{f,m1} \approx 20\,000$ cycles, and $N_{f,m2} \approx 37\,000$ cycles.
- Comparison with experimental result show a vast difference between them and the estimations.
- Stress relieved specimen gives the following corresponding fatigue limits for as $N_{f,toe,sr} \approx 100\,000\,000$ cycles, $N_{f,m1,sr} \approx 45\,000$ cycles, and $N_{f,m2,sr} \approx 80\,000$ cycles

Technical documentation

The following sections includes the detailed derivations and calculations behind the result presented on the first page as well as more detailed results.

Provided information

Provided to the assignment was a given CAD model that had been created using Cativa V5 as well as a schematic over the structure with all its dimensions. Further, it was given that the structure was manufactured using SAE 1015 steel with $E = 210\,\text{GPa}$ and $\nu = 0.3$. The assignment further provides the applied force at the top of the vertical plate as $F = 15 \pm 25\,\text{kN}$. Finally the experimental result that the computed fatigue lives are to be compared with was given in Figure 3 in the assignment. Provided this, the following assessments was performed.

Ansys model

The following section goes through the setup in Ansys and what assumptions that are made.

Material model

The applied material model in the Ansys FE-model is shown in Figure 1.

Properties of Outline Row 3: SAE 1015

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Isotropic Elasticity				
4	Derive from	Young's ...			
5	Young's Modulus	2,1E+11	Pa		
6	Poisson's Ratio	0,3			
7	Bulk Modulus	1,75E+11	Pa		
8	Shear Modulus	8,0769E+10	Pa		
9	S-N Curve	Tabular			
10	Interpolation	Linear			
11	Scale	1			
12	Offset	0	Pa		
13	Tensile Ultimate Strength	4,15E+08	Pa		

Figure 1: *Material properties of SAE 1015 steel*

The Whöler S-N curve highlighted in Figure 1 is compted using Table 9.1 in Mechanical Behaviour of Materials (Dowling N., 4th, 2013, Pearson, p.424). This gives the fatigue life for different stress amplitudes as

$$\sigma_a = AN_f^B \tag{1}$$

with $A = 927$ and $B = -0138$ given for SAE 1015 steel. Using this formula a Whöler S-N curve is coomputed using data points given in Figure 2.

Table of Properties Row 9: S-N Curve		
	A	B
1	Cycles	Alternating Stress (Pa)
2	10	6,7462E+08
3	100	4,9097E+08
4	1000	3,5732E+08
5	10000	2,6005E+08
6	1E+05	1,8926E+08
7	1E+06	1,3774E+08
8	1E+07	1,0024E+08
9	1E+08	7,2955E+07
10	1E+09	5,3096E+07
11	1E+10	3,8642E+07

Figure 2: *S-N curve data-sheet*

Mesh

Figure 3 represents meshed model of the test specimen, 112531 elements was used for meshing this particular specimen.

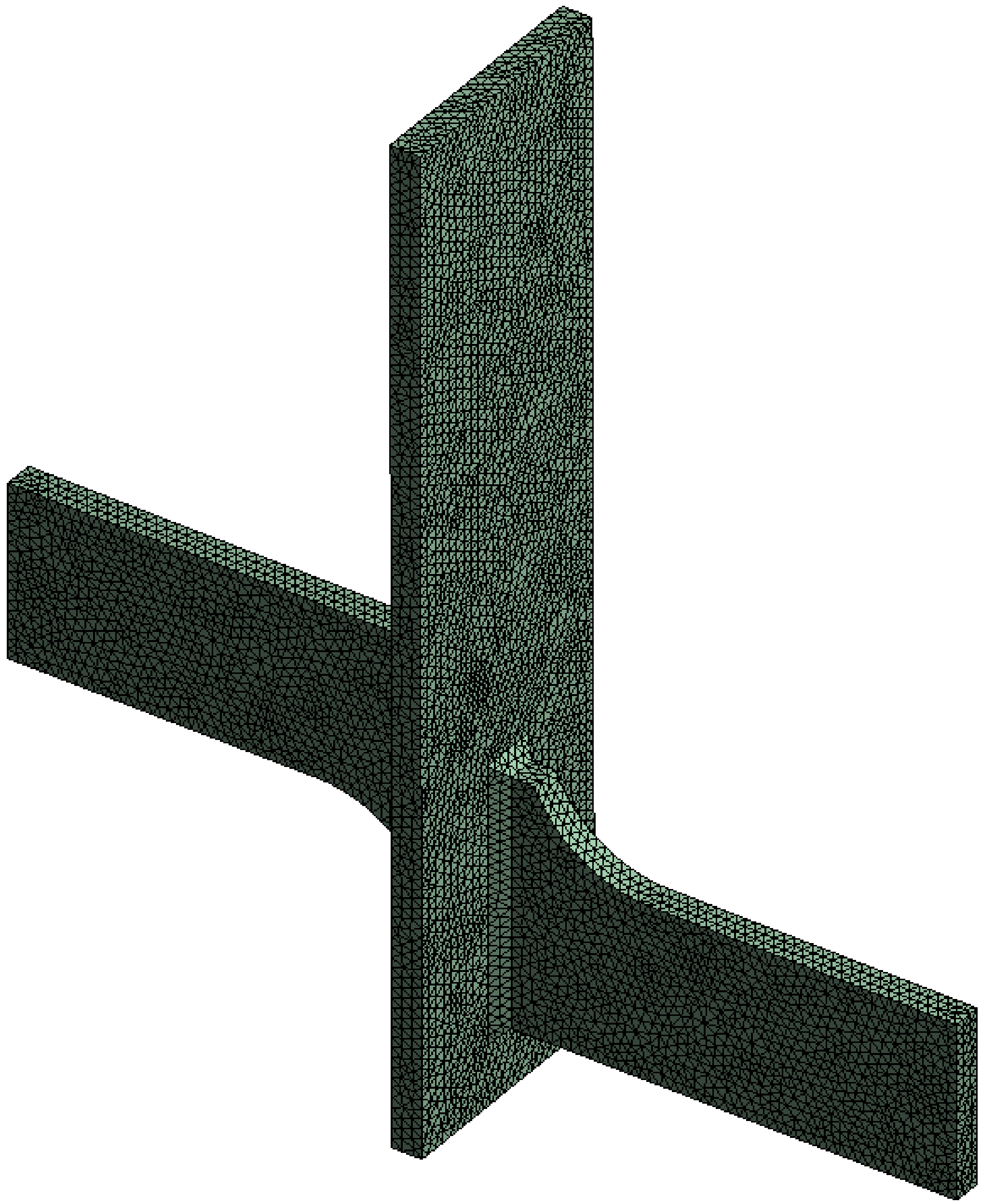

Figure 3: *FE model of the test specimen*

Loads and Boundaries

The structures applied load and boundaries is shown in Figure 4. It is loaded with a force $F = 50\,\mathrm{kN}$ and is fixed at both ends of the horizontal plate.

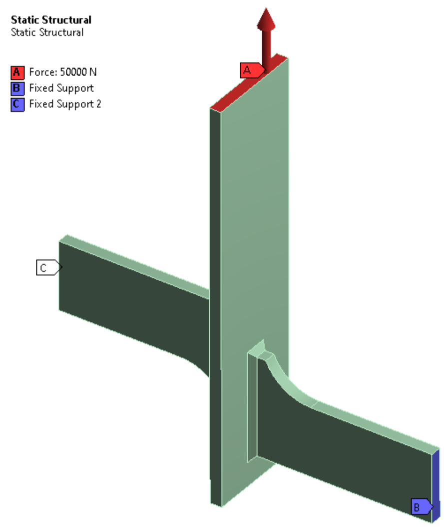

Figure 4: *Boundary condition applied to the test specimen*

Weld toe

To compute the fatigue life for the weld toe, hot spot stress is used. This is computed using the longitudinal stress in the equation below

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{10t} \tag{2}$$

The longitudinal stress over the path is shown in Figure 5.

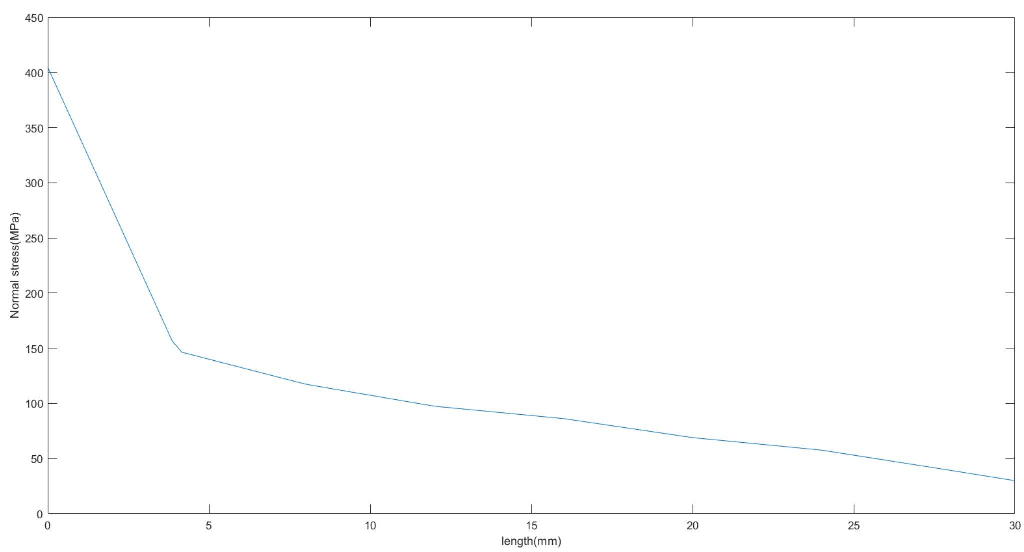

Figure 5: Longitudinal stress versus the distance from the weld.

With $\sigma_{0.4t} = 122\,\mathrm{MPa}$ and $\sigma_{10t} = 70\,\mathrm{MPa}$ Eq.(2) becomes equal to

$$\sigma_{hs} = 157\,\mathrm{MPa}. \tag{3}$$

The fatigue life can then be computed using the expression

$$N_f = C\left(\frac{FAT}{\sigma}\right)^m \tag{4}$$

with $C = 2 \cdot 10^6$, $m = 3$ chosen since the case regards steel, and FAT taken from IIW. In this case FAT is given equal to 100 The fatigue limit in the weld toe then becomes

$$N_{f,toe} \approx 520\,000\,\mathrm{cycles} \tag{5}$$

Weld root

The following section regards the two methods used to estimate the nominal stress and the following the fatigue lives. Afterwards a comparison is conducted with the experimental results presented in the assignment.

Method 1

The first methods assumes that the bending moment is carried by a band of weld material. From this the nominal stress can be computed using

$$\sigma = \frac{Fl_0}{2W_b} \tag{6}$$

where F is the force amplitude, l_0 is the bending moments distance to the zero point, and W_b is the section modulus of the weld throat computed as

$$W_b = ha\left(t + \frac{h}{3}\right) \tag{7}$$

with h being the height of the horizontal plate, t is the plates thickness and a is the throat thickness of the weld. This given the nominal stress according to method 1 as

$$\sigma_{m1} = 183\,\mathrm{MPa} \tag{8}$$

This given Eq.(4) for method 1 estimated as

$$N_{f,m1} \approx 20\,000\,\mathrm{cycles} \tag{9}$$

with FAT in that equation taken from page 59 in IIW and weld design No. 414. Since $a/t \geq 1/3$ in this case FAT is given equal to 40.

Method 2

The second method instead estimates the nominal stress at the weld toe (σ_w) by using horizontal force equilibrium at the weld toe. Using the figures given in the assignment, the two sides of the force equilibrium are given as

$$A_w \sigma_w = A\sigma \tag{10a}$$
$$A_w = 2at + a^2 \tag{10b}$$
$$A = t^2/2 \tag{10c}$$

The nominal stress can then be computed using

$$\sigma_w = \frac{A\sigma}{A_w} \tag{11}$$

To compute this, σ first has to be found. This is done using the FE-model in Ansys. A path is created along the upper edge of the weld and the stress variation along this path is then evaluated. σ is then chosen as the average stress between the start of that path and 6 mm along it. Using this method the stress is given as

$$\sigma = \sigma_{avg} = 233\,\mathrm{MPa} \tag{12}$$

which in turn makes it possible to compute the nominal stress using Eq.(11) as

$$\sigma_{m2} = \sigma_w = 150\,\mathrm{MPa} \tag{13}$$

The fatigue life for method two is then evaluated using Eq.(4) with the same value for FAT as in method 1 but with σ chosen as σ_{m2} which gives

$$N_{f,m2} \approx 37\,000\,\text{cycles} \tag{14}$$

Comparison

This section addresses the comparison of the above estimated fatigue lives for the weld roots and weld toes with the experimental results given in Figure 3 in the assignment.

In the case of hot spot stress, used to estimate the fatigue limit in the weld toe, the fatigue limit is estimated to $N_f \approx 520\,000$ cycles. The experimental data gives for a similar stress level $N_{exp,toe} \approx 250\,000$ cycles. According to the two methods for estimating weld root fatigue life it should be roughly between 20 000 cycles (for method 1) and 37 000 cycles (for method 2). Reading Figure 3 in the assignment gives the data points for the weld root fatigue life for stress similar to that found in method 1 as slightly above 100 000 cycles. Since the nominal stress for method 2 is about the same for this rough estimations the same experimental life is used. Both methods therefore drastically underestimates the fatigue life of the weld root.

Stress relieved specimen

As per IIWR recommendation for unwelded base material and wrought products, fatigue enhancement factor $f(R)$ is given in Eq.(15). Multiplying the fatigue class with fatigue enhancement factor, stress relief in welded joints is achieved.

$$f(R) = (-0.4 * R) + 1.2 \quad \text{for} \quad -1 \leq R \leq 0.5 \tag{15}$$

The fatigue life can be evaluated again using the same Eq.(4) with updated fatigue class. Hence after stress relief, following fatigue life cycle is achieved for hot-spot stress, method 1, and method 2 respectively.

$$N_{f,hs,sr} \approx 1\,000\,000\,\text{cycles} \tag{16}$$

$$N_{f,m1,sr} \approx 45\,000\,\text{cycles} \tag{17}$$

$$N_{f,m2,sr} \approx 80\,000\,\text{cycles} \tag{18}$$

A Matlab

Below is given the MATLAB code used by the project to solve the tasks addressed in the report.

Material data

```
E=210e9; %youngs modulus
nu=0.3; %poissons ratio
F_min=-10e3; %min force
F_max=40e3; %max force
l_o=133; %
t=12; %plate thickness
a=4; %weld thickness
h=100; %height of welded horizontal plate
m=3; %slope for steels
FAT=40; %fatigue class for method 1&2
FAT_hs=100; %fatigue class for hot spot stress
F_r=F_max-F_min; %force range
R=F_min/F_max;
```

Method 1

```
W_b=(h*a)*(t+(h/3)); %section modulus
sigma_nom1=(F_r*l_o)/(2*W_b); %nominal stress in MPa
N_f1= 2*(10^6)*(FAT/sigma_nom1)^m; %fatigue life cycle from method 1
```

Method 2

```
sigma_avg=233.6538; %average stress using method 2 in MPa
A_w= (2*a*t)+(a^2); %weld area
A= (t^2)/2; %area along longitudinal stress
sigma_nom2=(sigma_avg*A)/A_w; %nominal stress in MPa
N_f2= 2*(10^6)*(FAT/sigma_nom2)^m; %fatigue life cycle from method 2
```

Hot spot stress

```
sigma_04t=121.98;
sigma_10t=70.317;
sigma_hs=(1.67*sigma_04t)-(0.67*sigma_10t); %hot spot stress in MPa
N_fhs= 2*(10^6)*(FAT_hs/sigma_hs)^m; %fatigue life cycle from hot spot stress
```

Stress relieved specimen

```
f=(-0.4*R)+1.2;
FAT_sr=FAT*f;
```

```
FAT_hs_sr=FAT_hs*f;
N_f1_sr= 2*(10^6)*(FAT_sr/sigma_nom1)^m; %fatigue life cycle from method 1...
    % for stress relieve
N_f2_sr= 2*(10^6)*(FAT_sr/sigma_nom2)^m; %fatigue life cycle from method 2...
    % for stress relieve
N_fhs_sr= 2*(10^6)*(FAT_hs_sr/sigma_hs)^m; %fatigue life cycle from hot spot...
    % stress for stress relieve
```

B Ansys-report

The following appendix is an auto-generated report from Ansys over the FE-model and operations conducted in it.