AE 737 - MECHANICS OF DAMAGE TOLERANCE

Lecture 17

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SCHEDULE

- 29 Mar - Influence of notches on fatigue, Homework 7 assigned, Homework 6 due
- 31 Mar - Strain based fatigue, project abstract due
- 5 Apr - Crack Growth, Homework 7 due, Homework 8 assigned
- 7 Apr - Crack Growth

OUTLINE

1. fatigue review
2. influence of notches
3. strain based fatigue

FATIGUE REVIEW

GROUP 1

- A part from AISI 4340 in a typical ”block” undergoes 100,000 cycles with $\sigma_{min} = 0$ ksi and $\sigma_{max} = 100$ ksi and an additional 10 cycles with $\sigma_{min} = 50$ ksi and $\sigma_{max} = 200$ ksi
- How many ”blocks” can this part support before failure?

GROUP 2

- Use the S-N-P chart on p. 245 for 7075-T6 Aluminum
- What is the probability of failure for 30 ksi at 10^6 cycles?
- To ensure that 99% of parts do not fail, after how many cycles should a fully reversed load of 35 ksi be inspected?
- How many cycles could the same part sustain if only 50% of parts are needed?

GROUP 3

- The fatigue limit for AISI 4142 steel is 58 ksi for completely reversed fatigue loads.
- What is the fatigue limit for fatigue loads with $\sigma_m = 10, 20, 30$ ksi?

GROUP 4

- A material made of 2024-T4 Aluminum undergoes the following load cycle
  - $\sigma_{x,min} = 10$, $\sigma_{x,max} = 50$
  - $\sigma_{y,min} = -20$, $\sigma_{y,max} = 20$
  - $\tau_{xy,min} = 0$, $\tau_{xy,max} = 30$
- How many cycles can it support before failure?

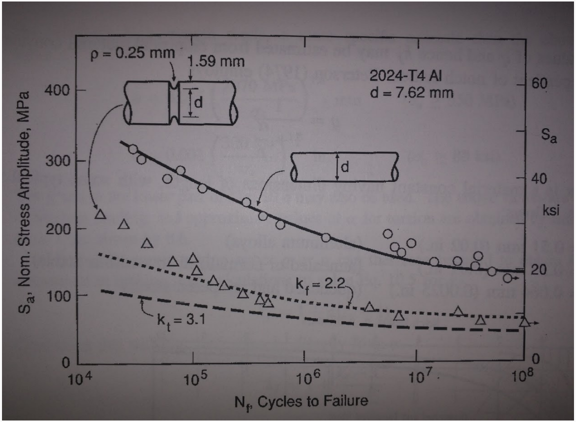
INFLUENCE OF NOTCHES

- In this discussion, we use ”notch” to refer to any geometric feature that increases the local stress (such as holes, fillets, grooves, etc.)
- We discussed notches and stress concentration factors in terms of stress concentration factors
- In our fatigue notation, $\sigma_{max} = K_t S$
- This relates local stress to the average, nominal stress
- The stress intensity factor can be used to characterize the ”strength” of a notch

- We might expect the fatigue life of a notched specimen to be similar to a pristine specimen with $S_{a,pristine} = \sigma_{max,notched}$
- If we look at actual test data, however, this estimate would be overly conservative
- Even when the stress is adjusted for some fatigue notch factor, k_f, it is only valid at longer cycles ($N_f > 10^6$)

$$k_f = \frac{\sigma_{ar}}{S_{ar}} \tag{17.1}$$

- Notches will have different effects, largely depending on their radius.
- The maximum possible fatigue notch factor is $k_f = k_t$



ρ = 0.25 mm
1.59 mm
d
2024-T4 Al
d = 7.62 mm
d
$k_f = 2.2$
$k_t = 3.1$
S_a, Nom. Stress Amplitude, MPa
S_a
ksi
N_f, Cycles to Failure

- To avoid generating fatigue data for every possible notch configuration, some empirical relationships have been developed
- A useful concept in these methods is the notch sensitivity factor

$$q = \frac{k_f - 1}{k_t - 1} \tag{17.2}$$

- When $k_f = 1$, $q = 0$, in which case the notch has no effect
- When $k_f = k_t$, $q = 1$, in which case the notch has its maximum effect

- Peterson developed the following relationship

$$q = \frac{1}{1 + \frac{\alpha}{\rho}} \tag{17.3}$$

- Where ρ is the radius of the notch
- α is a material property

Table 1: Table of α values for Peterson notch sensitivity equation

Material	α (mm)	α (in)
Aluminum alloys	0.51	0.02
Annealed or low-carbon steels	0.25	0.01
Quenched and tempered steels	0.064	0.0025

- For high-strength steels, a more specific α estimate can be found

$$\alpha = 0.025\left(\frac{2070}{\sigma_u}\right)^{1.8} \qquad \text{mm} \qquad \sigma_u \geq 550 \text{ MPa} \tag{17.4}$$

$$\alpha = 0.001\left(\frac{300}{\sigma_u}\right)^{1.8} \qquad \text{in} \qquad \sigma_u \geq 80 \text{ ksi} \tag{17.5}$$

- α predictions are valid for bending and axial fatigue
- For torsion fatigue, a good estimate can be found

$$\alpha_{torsion} = 0.6\alpha \tag{17.6}$$

- An alternative formulation for q was developed by Neuber

$$q = \frac{1}{1 + \sqrt{\frac{\beta}{\rho}}} \tag{17.7}$$

- Where the material property β is given by

$$\log \beta = -\frac{\sigma_u - 134}{586} \qquad \text{mm} \qquad \sigma_u \leq 1520 \text{ MPa} \tag{17.8}$$

$$\log \beta = -\frac{\sigma_u + 100}{85} \qquad \text{in} \qquad \sigma_u \leq 220 \text{ ksi} \tag{17.9}$$

- While the above methods are useful, they should be regarded as estimates only
- Physical complexities are not fully modeled by these methods
- All of these have been developed for relatively ”mild” notches
- For sharp notches, best results are found by treating the notch as a crack

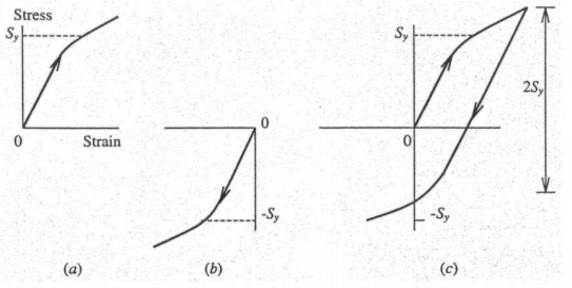
STRAIN BASED FATIGUE

- The strain based fatigue method uses local stresses and strains (instead of global, nominal values)
- The strain-based method gives greater detail, and validity at lower cycles
- It is still valid for high cycle fatigue
- Does not include crack growth analysis or fracture mechanics

- Similar to the S-N curves in stress-based fatigue analysis, we can plot the cyclic strain amplitude vs. number of cycles to failure
- This is most commonly done using axial test machines (instead of rotating bending tests)
- The test is run in strain control (not load control)
- Generally plotted on log-log scale

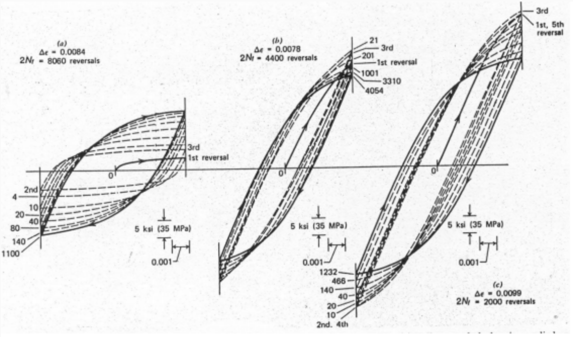
- We can separate the total strain into elastic and plastic components

$$\epsilon_a = \epsilon_{ea} + \epsilon_{pa} \tag{17.10}$$



Stress
S_y
0
Strain
(a)
0
$-S_y$
(b)
S_y
0
$-S_y$
$2S_y$
(c)

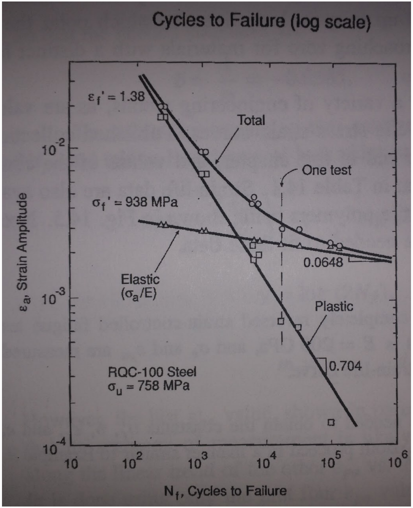
HYSTERESIS LOOPS

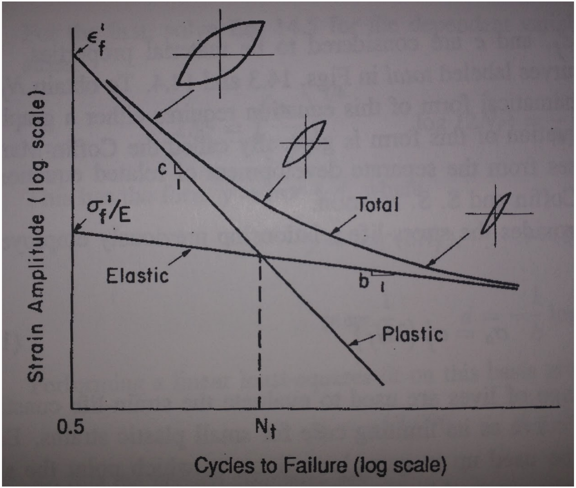


- While strain-life data will generally just report ϵ_a and ϵ_{pa}, some will also tabulate a form for the cyclic stress-strain curve

$$\epsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{\frac{1}{n'}} \tag{17.11}$$

- On strain life curves, the strain is often plotted three times per each experiment
- Once for total strain, once for plastic strain, and once for elastic strain
- Since plastic strain and elastic strain vary by the number of cycles, a hysteresis loop from half the fatigue life is generally used
- This is considered representative of stable behavior


Cycles to Failure (log scale)
$\varepsilon_f' = 1.38$
Total
One test
$\sigma_f' = 938$ MPa
0.0648
Elastic
(σ_a/E)
Plastic
0.704
RQC-100 Steel
$\sigma_u = 758$ MPa
ε_a, Strain Amplitude
10^{-2}
10^{-3}
10^{-4}
10
10^2
10^3
10^4
10^5
10^6
N_f, Cycles to Failure


ϵ_f'
σ_f'/E
c
1
Total
Elastic
b
1
Plastic
Strain Amplitude (log scale)
0.5
N_t
Cycles to Failure (log scale)

- We notice that the data for elastic and plastic strains are represented by straight lines, in the log-log scale
- If we recall the form used for a straight line in log-log plots for S-N curves:

$$\sigma_a = \sigma_f'(2N_f)^b \tag{17.12}$$

- We can convert this to find the elastic component of strain

$$\epsilon_{ea} = \frac{\sigma_f'}{E}(2N_f)^b \tag{17.13}$$

- We can use the same form with new constants for the plastic component of strain

$$\epsilon_{pa} = \epsilon_f'(2N_f)^c \tag{17.14}$$

- We can combine 17.13 with 17.14 to find the total strain-life curve

$$\epsilon_a = \frac{\sigma_f'}{E}(2N_f)^b + \epsilon_f'(2N_f)^c \tag{17.15}$$

EXAMPLE