AE 737 - MECHANICS OF DAMAGE TOLERANCE

Lecture 16

Dr. Nicholas Smith

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Wichita State University, Department of Aerospace Engineering

SCHEDULE

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

EXTRA CREDIT

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- For now I do not have a due date for this project, but I may eventually allow students who have already completed a chart to complete a second one

OUTLINE

1. fatigue review
2. modeling real loads
3. mean stress effects
4. scatter
5. general stress

FATIGUE REVIEW

- One of the simplest assumptions we can make is that a load cycles between a constant maximum and minimum stress value

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- This is a good approximation for many cases (axles, for example) and can also be easily replicated experimentally

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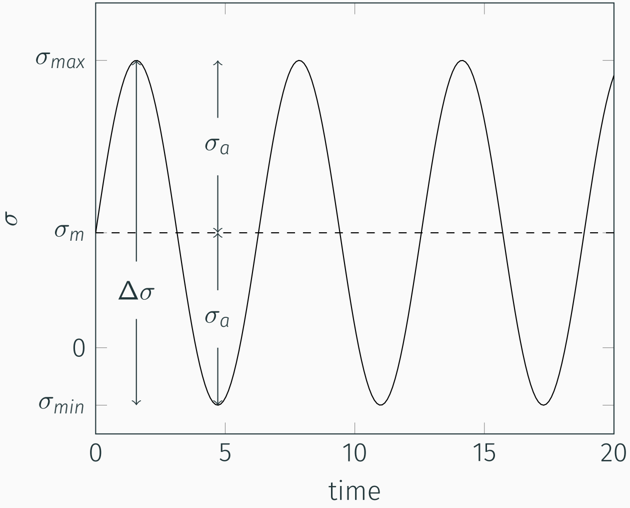
- This is referred to as constant amplitude stressing

CONSTANT AMPLITUDE STRESSING



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- σ_m is the mean stress, and can sometimes be zero, but this is not always the case
- σ_a is the stress amplitude, and is the variation about the mean
- We can express all of these in terms of the maximum and minimum stress

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{16.1}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{16.2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{16.3}$$

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- For many cases (bending, notches), $\sigma \neq S$ in general
- We must also be careful to note σ_y, in some cases $S < \sigma_y$ but at some locations $\sigma > \sigma_y$

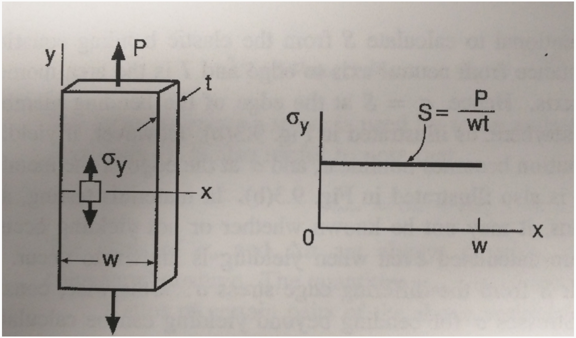


Figure 1: In this case $S = \sigma$

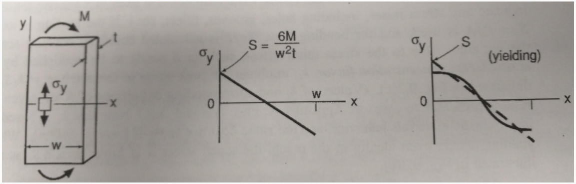
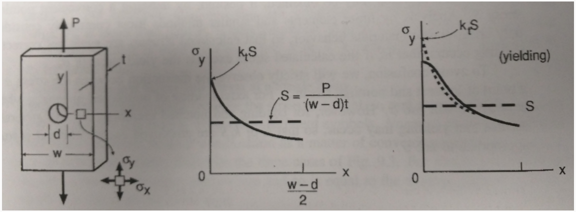


Figure 2: As long as $\sigma < \sigma_y$, σ varies linearly. If $\sigma > \sigma_y$ at any location, however, the relationship is non-linear



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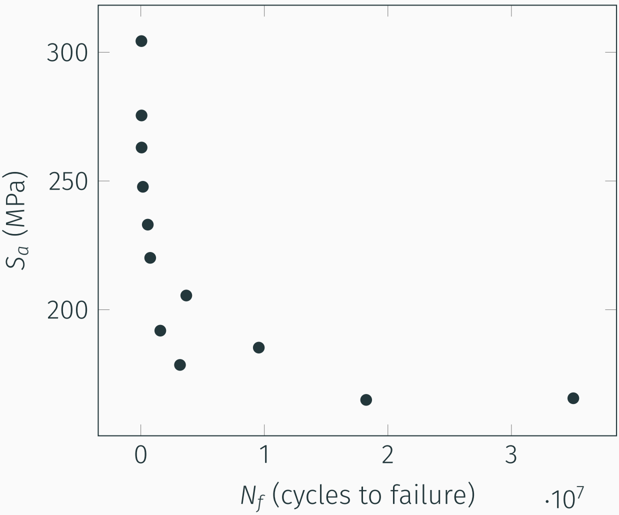
- Servohydraulic machines generally have a speed of 10 - 100 Hz.
- At a speed of 100 Hz, it would take 28 hours for 10^7 cycles, 12 days for 10^8 cycles, and nearly 4 months for 10^9 cycles
- While some machines can test at very high speeds, the inertia of the sample can interfere with results


300
250
200
S_a (MPa)
0
1
2
3
N_f (cycles to failure)
$\cdot 10^7$

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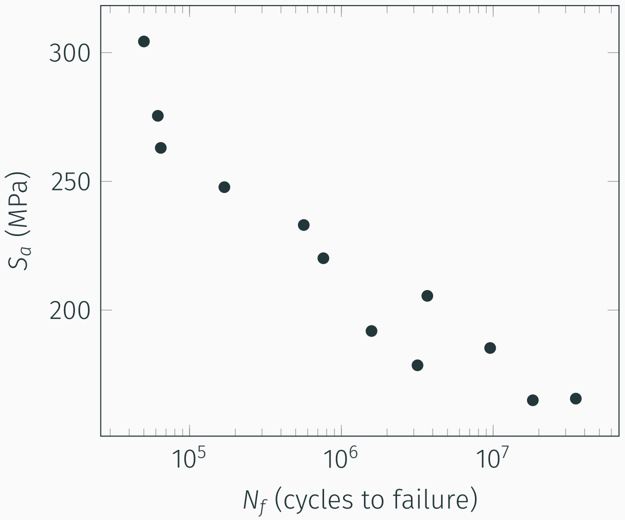
- It is also very difficult to differentiate between low-cycle fatigue failure stresses
- Instead S-N curves are often plotted on a semi-log or log-log scale, so pay attention to the axes


300
250
200
S_a (MPa)
10^5
10^6
10^7
N_f (cycles to failure)

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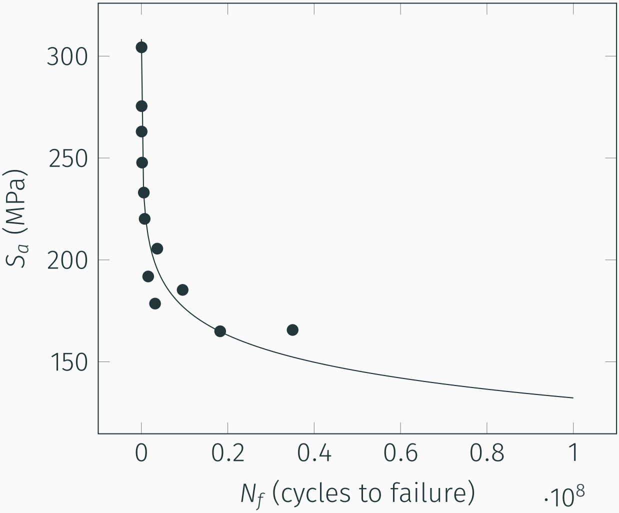
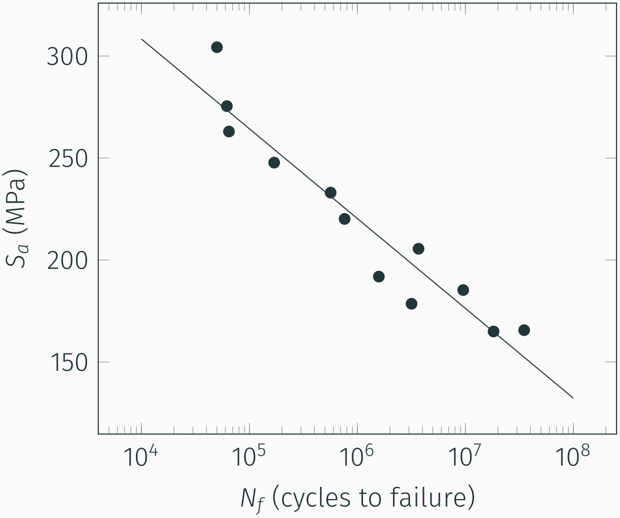
- $$\sigma_a = \sigma_f' \left(2N_f\right)^b \tag{16.5}$$
- σ_f' and b are often considered material properties and can often be looked up on a table (p. 235)



300
250
200
150
S_a (MPa)
0
0.2
0.4
0.6
0.8
1
$\cdot 10^8$
N_f (cycles to failure)


300
250
200
150
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FATIGUE LIMIT

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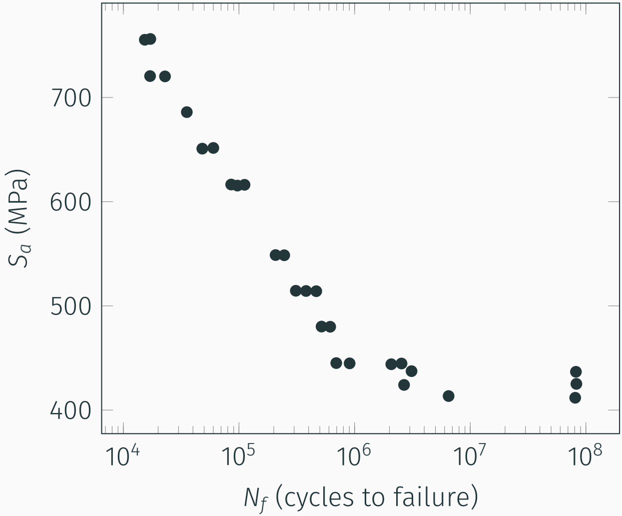
- This most notably occurs in plain-carbon and low-alloy steels
- In these materials, σ_e is considered to be a material property
- This phenomenon is not typical of aluminum or copper alloys, but is sometimes arbitrarily assigned using whatever the failure stress is at some large number of cycles (10^7 or 10^8)


700
600
500
400
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10^4
10^5
10^6
10^7
10^8
N_f (cycles to failure)

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HIGH AND LOW CYCLE FATIGUE

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- When yielding effects do dominate behavior, the strain-based approach is more appropriate

MODELING REAL LOADS

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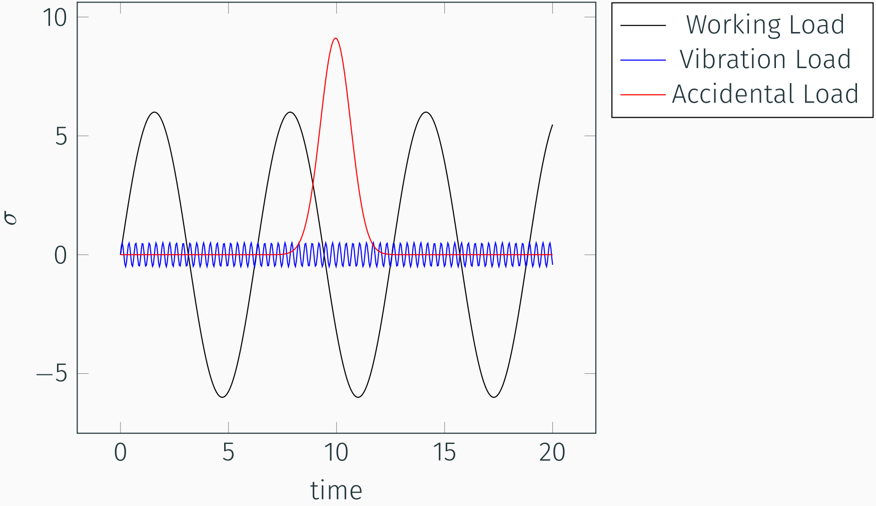
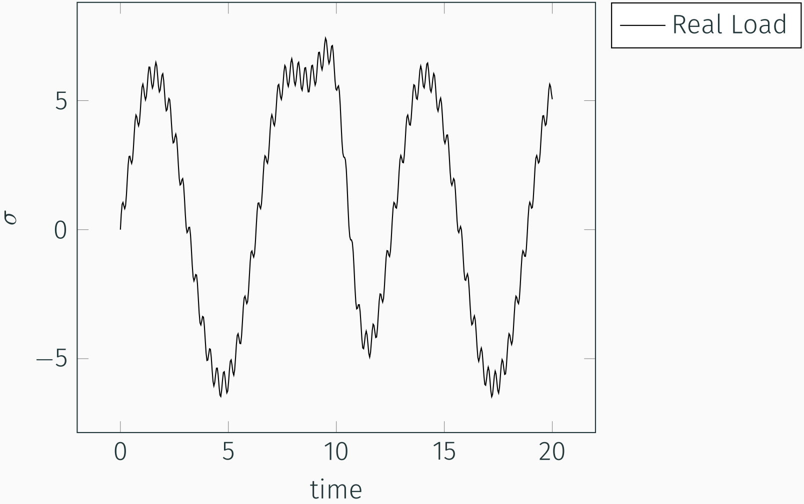
- Accidental loads can occur at a much lower frequency than working loads

REAL LOADS



10
5
0
−5
σ
0
5
10
15
20
time
Working Load
Vibration Load
Accidental Load

REAL LOADS



SIMPLIFIED LOAD

sketch book p 239

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$$\frac{N_1}{N_{f1}} + \frac{N_2}{N_{f2}} + \frac{N_3}{N_{f3}} + \ldots = \sum \frac{N_i}{N_{fi}} = 1 \qquad (16.6)$$

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EFFECT OF VARIABLE AMPLITUDE

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$$B\left[\sum \frac{N_i}{N_{if}}\right]_{rep} = 1 \tag{16.7}$$

VARIABLE AMPLITUDE LOAD EXAMPLE

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- Much work has been done to instead convert a zero-mean stress curve to different mean stress amplitudes

MEAN STRESS EFFECTS

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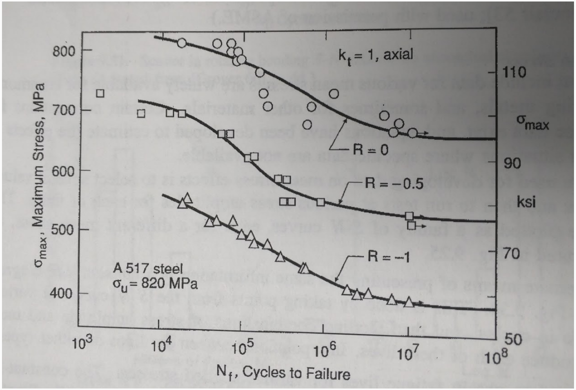
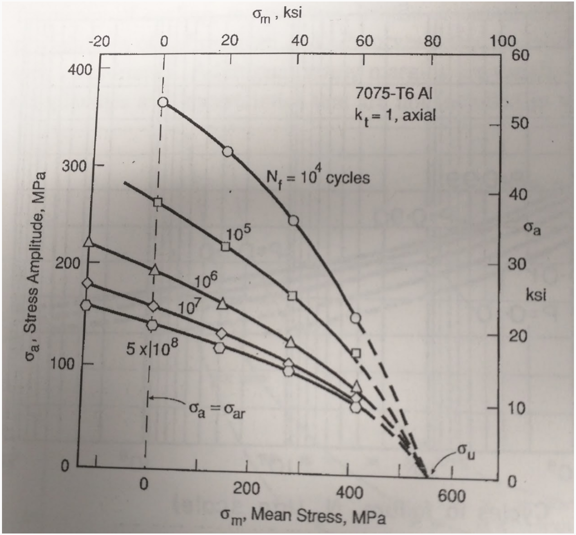
- One useful way of representing these data, instead of many S-N curves, is a constant-life diagram
- It is created by taking points from the S-N curves and plotting a line through constant N_f values


$k_t = 1$, axial
800
700
600
500
400
σ_{max}, Maximum Stress, MPa
110
90
70
50
σ_{max}
ksi
R = 0
R = −0.5
R = −1
A 517 steel
σ_u = 820 MPa
10^3
10^4
10^5
10^6
10^7
10^8
N_f, Cycles to Failure


σm , ksi
-20
0
20
40
60
80
100
60
400
7075-T6 Al
kt = 1, axial
50
300
Nf = 10^4 cycles
40
10^5
σa
200
30
10^6
ksi
10^7
20
5 x 10^8
100
10
σa = σar
σu
0
0
0
200
400
600
σm, Mean Stress, MPa
σa , Stress Amplitude, MPa

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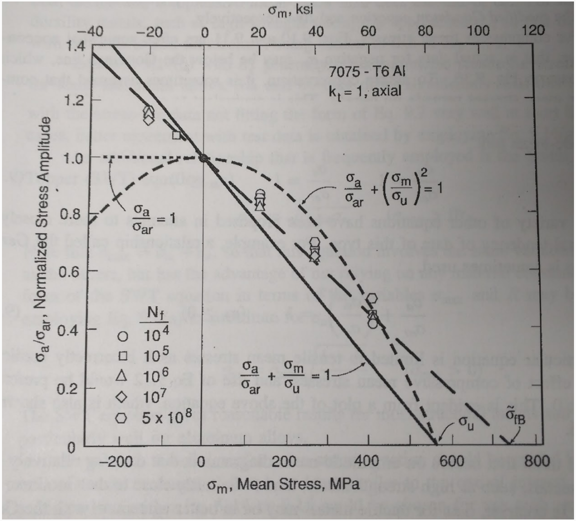
- Plotting σ_a/σ_{ar} vs. σ_m provides a good way to group all the data together on one plot with the potential to fit a curve


σ_m, ksi
−40
−20
0
20
40
60
80
100
120
7075 - T6 Al
$k_t = 1$, axial
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
σ_a/σ_{ar}, Normalized Stress Amplitude
$\frac{\sigma_a}{\sigma_{ar}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1$
$\frac{\sigma_a}{\sigma_{ar}} = 1$
N_f
10^4
10^5
10^6
10^7
5×10^8
$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_u} = 1$
σ_u
$\tilde{\sigma}_{fB}$
−200
0
200
400
600
800
σ_m, Mean Stress, MPa

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$$\frac{\sigma_e}{\sigma_{er}} + \frac{\sigma_m}{\sigma_u} = 1 \tag{16.9}$$

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- In general, the Goodman line is a good fit for brittle materials (steels) while the Gerber parabola is a better fit for more ductile materials

- The Goodman line can also be improved by replacing σ_u with the corrected true fracture strength $\tilde{\sigma}_{fB}$ or the constant σ_f' from the S-N curve fit

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- This is known as the Morrow Equation
- For steels, $\sigma_f' \approx \tilde{\sigma}_{fB}$, but for aluminums these values can be significantly different, and better agreement is found using $\tilde{\sigma}_{fB}$.

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- In general, it is best to use a form that matches your data
- If data is lacking, the SWT (16.12) and Morrow (16.11) equations generally provide the best fit

VARIABLE AMPLITUDE LOAD WITH MEAN STRESS

SCATTER

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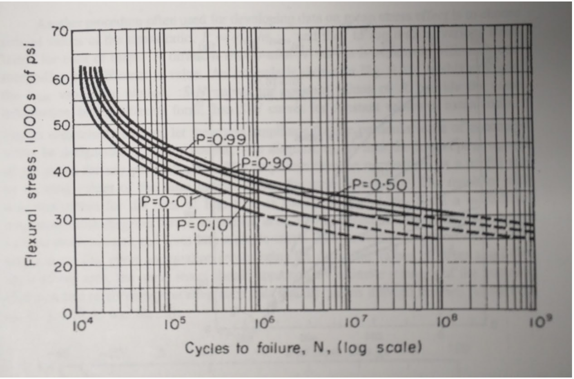
- In general, the scatter follows a lognormal distribution (or a normal distribution in $\log(N_f)$)

S-N-P CURVE



Flexural stress, 1000s of psi
70
60
50
40
30
20
0
P=0·99
P=0·90
P=0·50
P=0·01
P=0·10
10^4
10^5
10^6
10^7
10^8
10^9
Cycles to failure, N, (log scale)

GENERAL STRESS

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- This is surprising, but agrees well with experiments