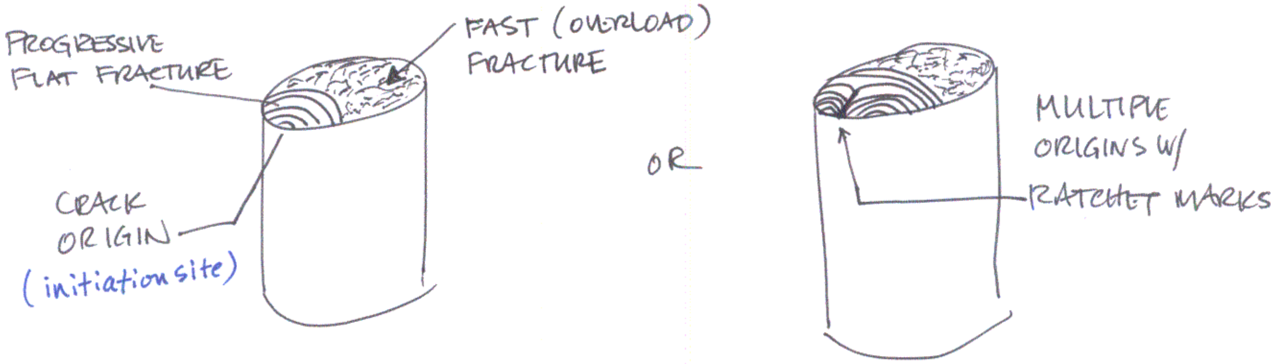
FATIGUE FAILURES

A. INTRODUCTION

- REPETITIVE OR FLUCTUATING STRESS LOWER THAN THAT REQUIRED TO CAUSE FRACTURE ON A SINGLE LOAD APPLICATION!

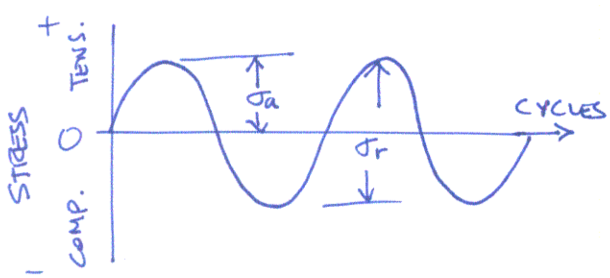
- > 90% OF ALL MECHANICAL FAILURES!

TYPICAL APPEARANCE:

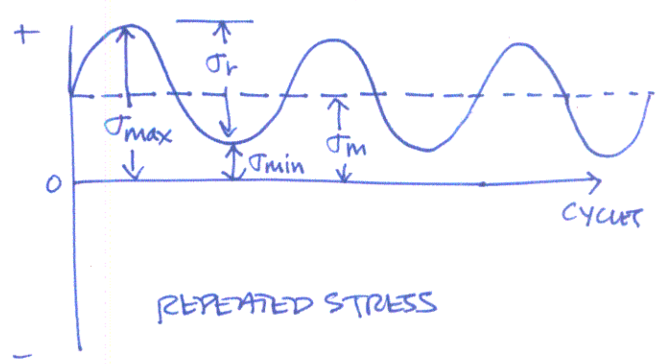


- THREE PHASES TO FATIGUE PROCESS:
  1. CRACK INITIATION
  2. CRACK PROPAGATION
  3. FINAL (FAST) FRACTURE

B. STRESS CYCLES



REVERSED STRESS

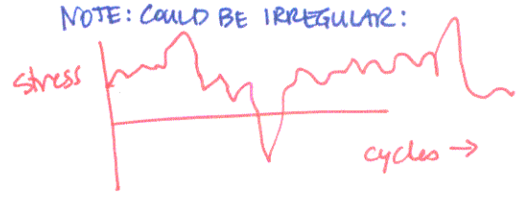


σ_a = ALTERNATING STRESS = $\dfrac{\sigma_r}{2} = \dfrac{\sigma_{max} - \sigma_{min}}{2}$

σ_r = RANGE OF STRESS = $\sigma_{max} - \sigma_{min}$

σ_m = MEAN STRESS = $\dfrac{\sigma_{max} + \sigma_{min}}{2}$

NOTE: COULD BE IRREGULAR:



STRESS RATIO = $R = \dfrac{\sigma_{min}}{\sigma_{max}}$

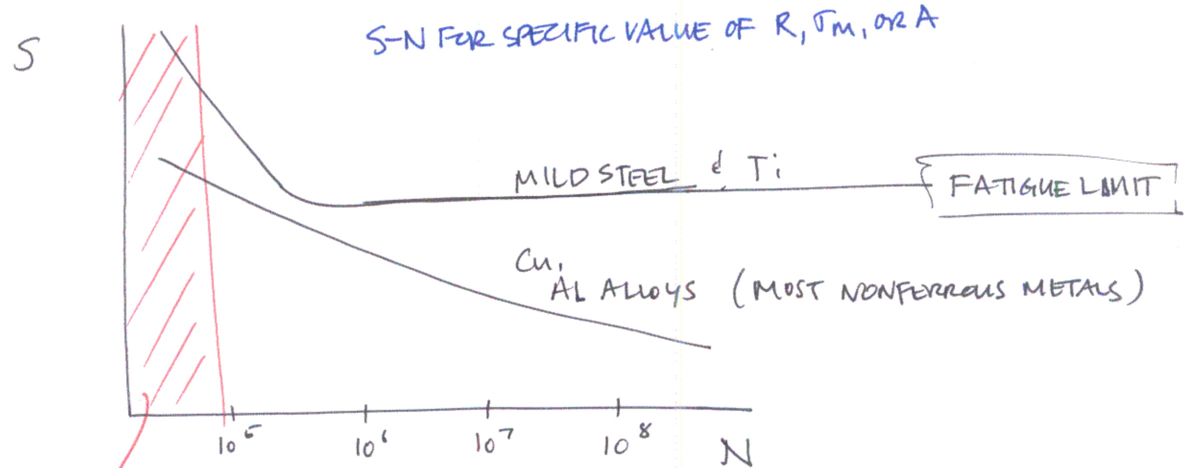
AMPLITUDE RATIO = $A = \dfrac{\sigma_a}{\sigma_m} = \dfrac{1-R}{1+R}$

C. S-N CURVES

S = STRESS (NOMINAL STRESS ... NO ADJUSTMENT FOR CONC.)

could be $\sigma_a, \sigma_{max}, \sigma_{min}$

N = CYCLES TO FAILURE (log scale)



$N < 10^4 - 10^3$: "LOW CYCLE FATIGUE"

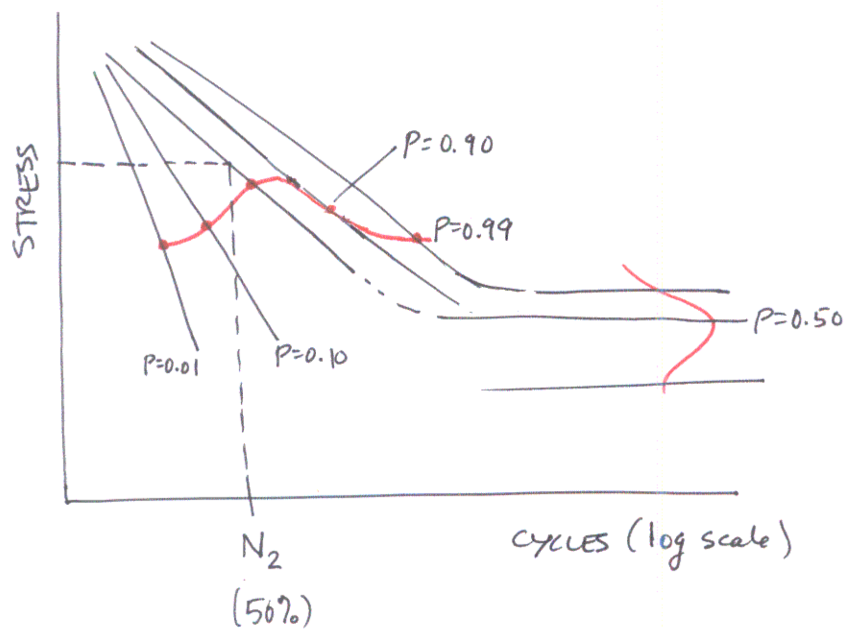
ABOVE 10^5, WE HAVE LOCALIZED PLASTIC DEFORMATION

TO TEST :
- POLISHED SPECIMEN
- REVERSED BENDING, $\sigma_m = 0$ (TYPICALLY)
- START AT HIGH STRESS & WORK DOWNWARD
- 8-12 TOTAL SPECIMENS

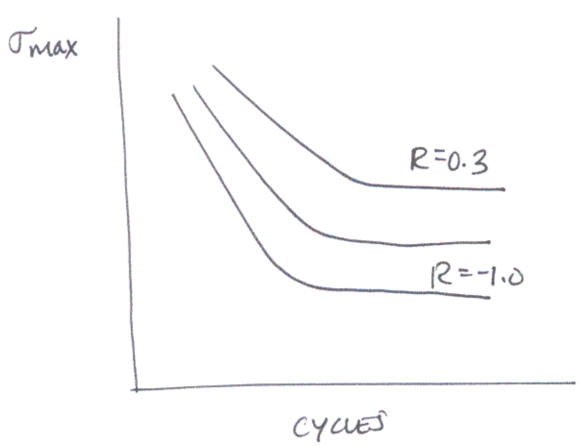
☆ LOTS OF SCATTER ☆

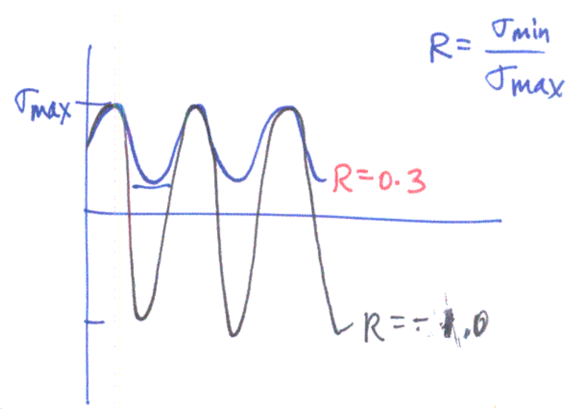
D. STATISTICAL NATURE OF FATIGUE

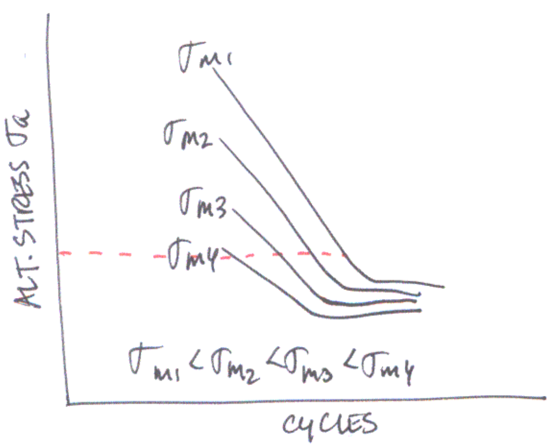
- GENERALLY ASSUME LOG NORMAL DISTRIBUTION OF FATIGUE LIFE N



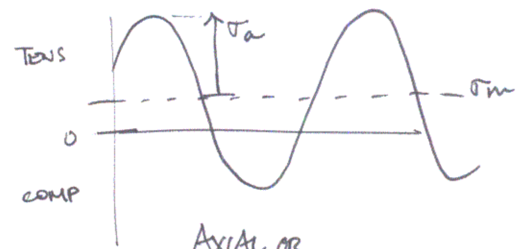
E. EFFECT OF MEAN STRESS



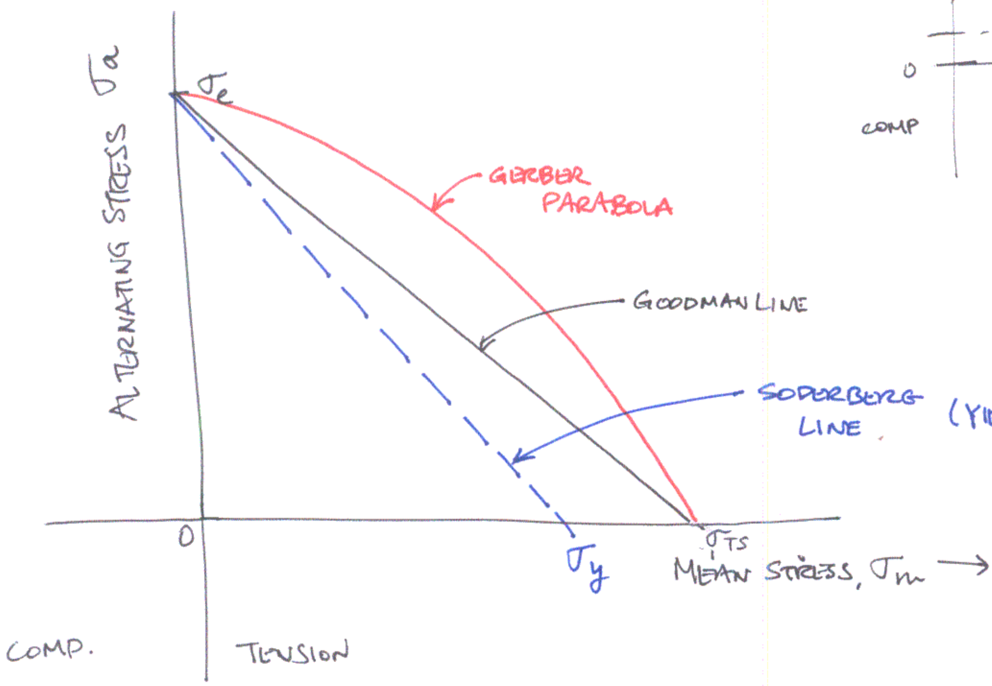




MEAN - AMPLITUDE STRESS RESPONSE



AXIAL OR BENDING STRESS!



σ_e = FATIGUE LIMIT AT COMPLETELY REVERSED LOADING

σ_{TS} = TENSILE STRENGTH

σ_y = YIELD STRENGTH

$$\sigma_a = \sigma_e \left[1 - \left(\frac{\sigma_m}{\sigma_{TS}} \right)^x \right]$$

X=1 FOR GOODMAN

X=2 FOR GERBER

USE σ_y, NOT σ_{TS}, FOR SODERBERG

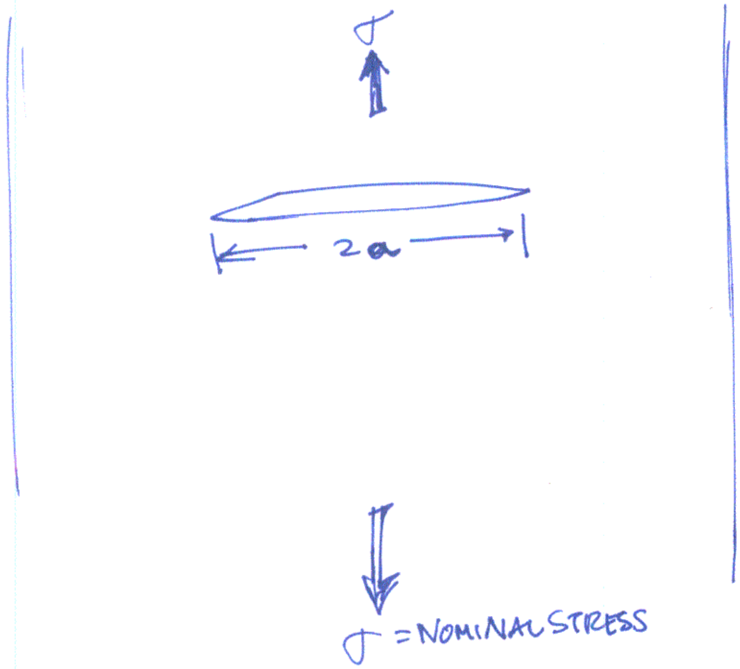
★ ASM HANDBOOK FIGURE - CONSTANT LIFE

F. FRACTURE MECHANICS APPROACH

* MOST FATIGUE CRACKS START IN AREAS OF STRESS CONCENTRATION (CRACKS, NOTCHES)

STRESS INTENSITY FACTOR, K (IRWIN)

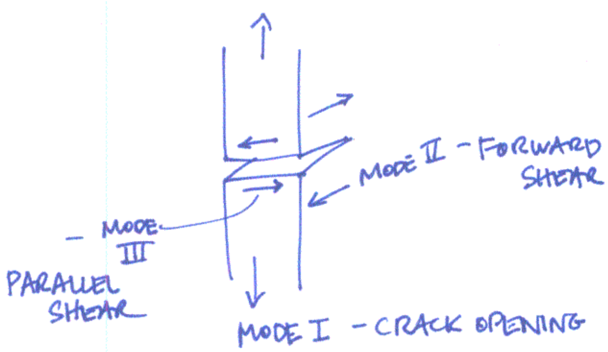
LOCAL STRESSES AT CRACK TIP ARE HIGH!



$$K = \alpha\sigma\sqrt{\pi a}$$

STRESS DISTRIBUTION AROUND A FLAW

α = GEOMETRICAL PARAMETER (SPECIMEN & CRACK GEOMETRY)



FOR MODE I, PLANE STRAIN CONDITIONS,

K_{IC} = CRITICAL STRESS INTENSITY OR "FRACTURE TOUGHNESS"

$$\boxed{K_{IC} = \sigma\sqrt{\pi a}} \quad (\alpha = 1)$$

MATERIAL	σ_y, MPa	K_{IC}, MPa$\sqrt{m}$
4340	1470	46
Ti-6-4	900	57
2024-T3	385	26
7075-T6	500	24

FATIGUE CRACK PROPAGATION

$$\frac{da}{dN} = C\,\sigma_a^{\,m}\,a^{n} \quad = \text{CRACK GROWTH RATE}$$

C = CONSTANT

σ_a = ALTERNATING STRESS

a = CRACK LENGTH

m : 2 TO 4
n : 1 TO 2
} DIFFERENT INVESTIGATIONS

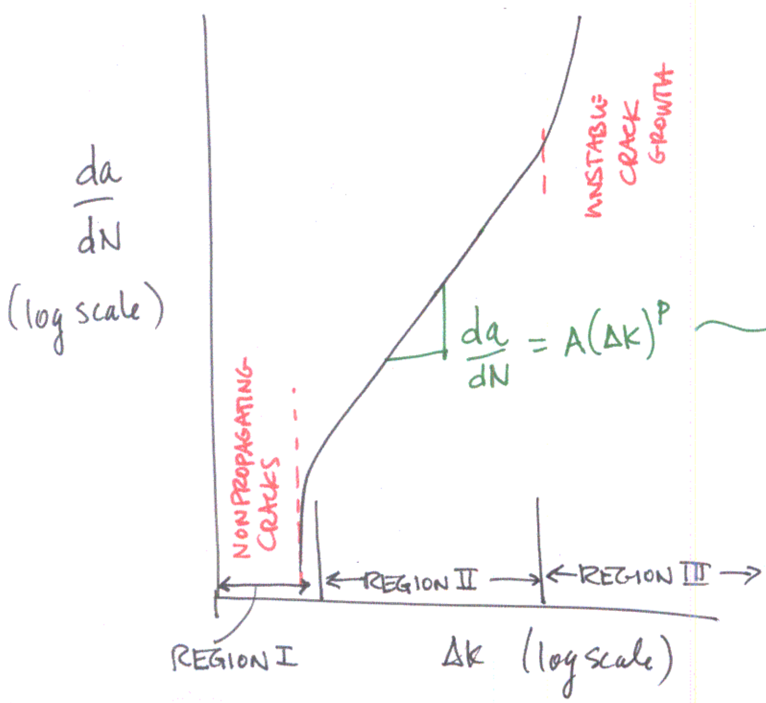
BUT, WE CAN RELATE $\frac{da}{dN}$ TO ΔK :

↳ RANGE OF STRESS INTENSITY FACTOR

$$\Delta K = K_{MAX} - K_{MIN}$$

$$\Delta K = \sigma_{max}\sqrt{\pi a} - \sigma_{min}\sqrt{\pi a} = \sigma_r\sqrt{\pi a}$$

NOTE: $K_{min} = 0$ IF σ_{min} is COMPRESSIVE



$\frac{da}{dN} = A(\Delta K)^p$ → STABLE CRACK GROWTH

p = slope
≃ 3 steel
≃ 3-4 Al alloys

NOTE: AS $R \uparrow$, $\frac{da}{dN} \uparrow$

$$R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{K_{min}}{K_{max}}$$

$R = -1.0$ FOR REVERSED LOADING

$$\frac{da}{dN} = \frac{A(\Delta K)^p}{(1-R)K_c - \Delta K}$$

WHERE K_c = FRACTURE TOUGHNESS FOR GIVEN MATERIAL & THICKNESS

FATIGUE LIFE – CYCLES TO FAILURE PREDICTION

$$\Delta K = \alpha \Delta\sigma \sqrt{\pi a} = \alpha \sigma_r \sqrt{\pi a}$$

$$\frac{da}{dN} = A(\Delta K)^p = A(\alpha \sigma_r \sqrt{\pi a})^p$$

$$= A(\alpha)^p (\sigma_r)^p (\pi a)^{p/2}$$

$$a_f = \frac{1}{\pi}\left(\frac{K_c}{\sigma_{max}\alpha}\right)^2$$

$$N_f = \int_0^{N_f} dN = \int_{a_i}^{a_f} \frac{da}{A(\alpha)^p(\sigma_r)^p(\pi a)^{p/2}}$$

$$N_f = \frac{1}{A\alpha^p(\sigma_r)^p \pi^{p/2}} \int_{a_i}^{a_f} \frac{da}{a^{p/2}}$$

IF $p \neq 2$, WE CAN SOLVE FOR N_f

(NOTE THAT $p \approx 2$ to 3 FOR STEELS)

DESIGN FOR FATIGUE APPLICATIONS

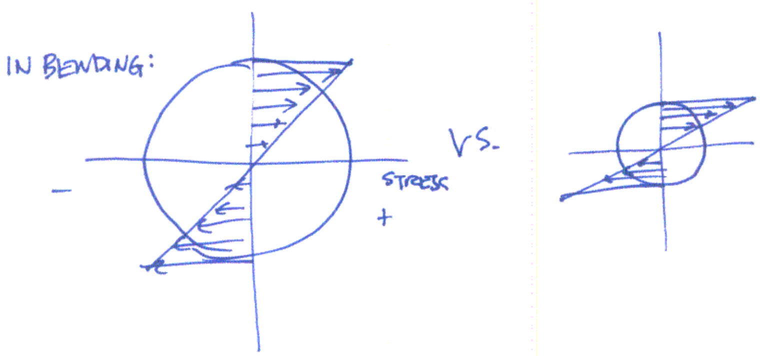
GOAL:
STAY AWAY (OR MINIMIZE) THINGS THAT REDUCE FATIGUE LIFE.

FATIGUE LIFE IS AFFECTED BY:

1. SIZE.

BIGGER SIZE → LOWER FATIGUE LIFE

WHY? MORE VOLUME...DEFECTS
MORE SURFACE AREA ... DEFECTS
GREATER STRESS OVER A LARGER VOLUME OF MAT'L



2. STRESS CONCENTRATIONS

· FILLETS, KEYWAYS, HOLES, THREADS, OR ANY GEOMETRICAL IRREGULARITY

3. SURFACE ROUGHNESS

· CRACKS START AT SURFACE DEFECTS! SMOOTH = GOOD!

4. SURFACE RESIDUAL STRESS

· COMPRESSIVE STRESSES AT SURFACE = GOOD!
→ SHOT PEENING OR SURFACE ROLLING

5. ENVIRONMENT (CORROSIVE ATTACK = BAD!)