# Fatigue for Engineers

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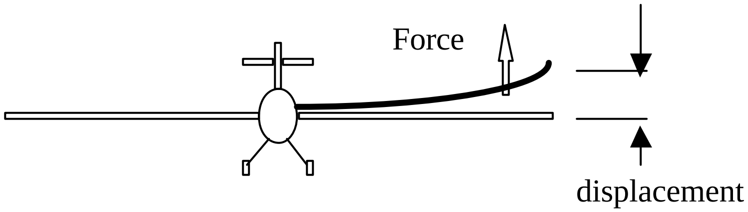
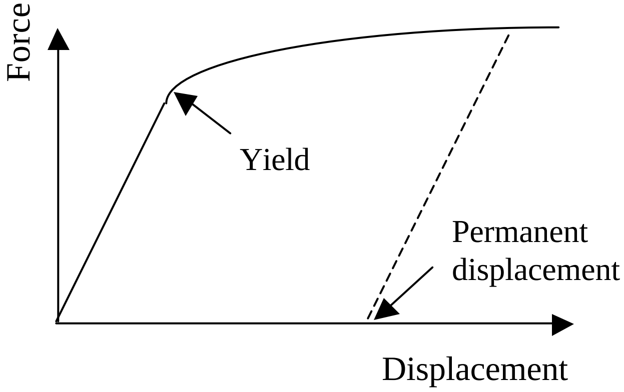
# *Objective*

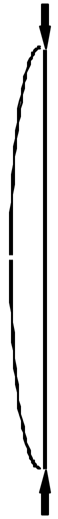
- Overview nature/consequences of the fatigue failure mechanism
- Determine number of cycles required to
  - develop a fatigue crack
  - propagate a fatigue crack
- Discuss implications of fatigue on design and maintenance operations

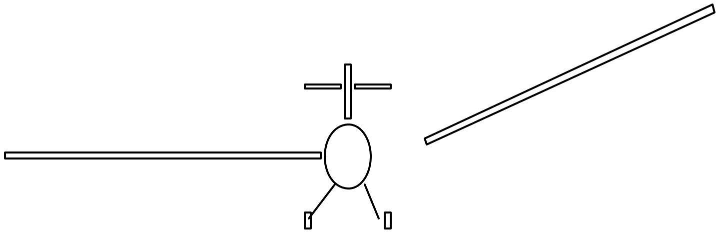
# Structural Failure Modes

- Excessive Deformation
  - Elastic
  - Plastic
- Buckling
- Fracture
- Creep
- Corrosion
- Fatigue



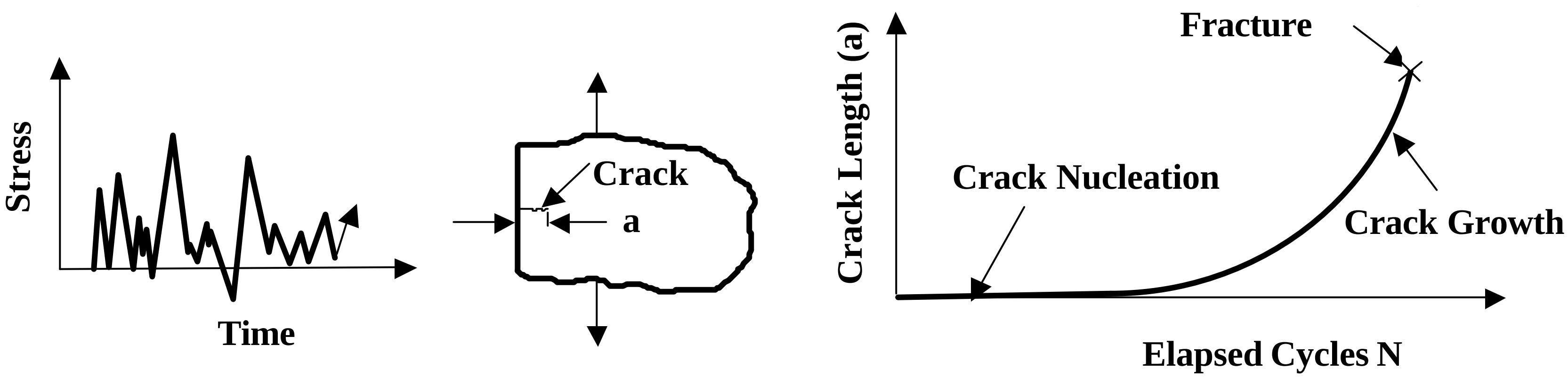






# *Fatigue Failure Mechanism*

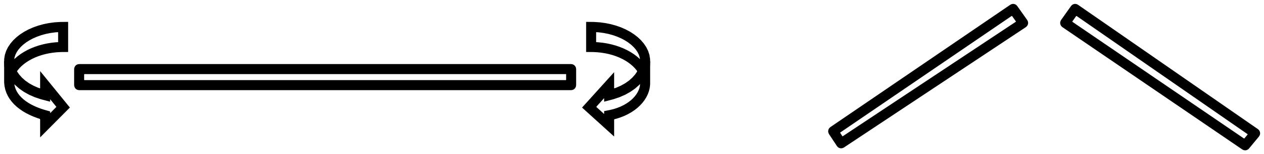
- Caused by repeated (cyclic) loading
- Involves crack formation, growth, and final fracture

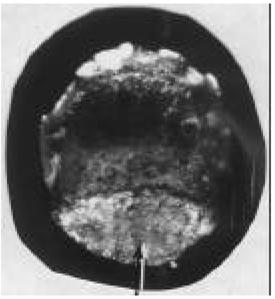


- Fatigue life depends on initial quality, load, . . .

# *Paper Clip Experiment*

- Bend wire repeatedly until fracture



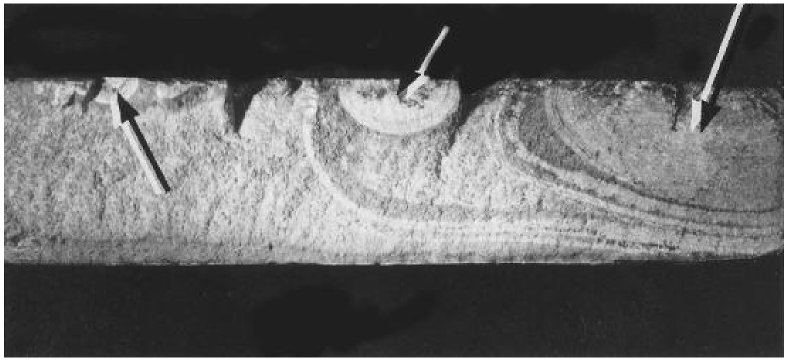


- Note:
  - – life (number of applied load cycles) depends on:
    - applied stress amplitude
    - component “quality” (notches, scratches, etc.)
  - – heat emitted >> plastic deformation

# *Characteristics of Fatigue*

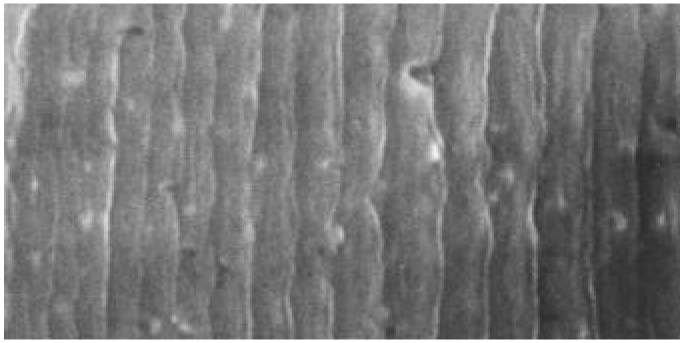
- “Brittle” fracture surface appearance
- Cracks often form at free surface
- Macro/micro “beach marks”/ “striations”

*Beach marks*



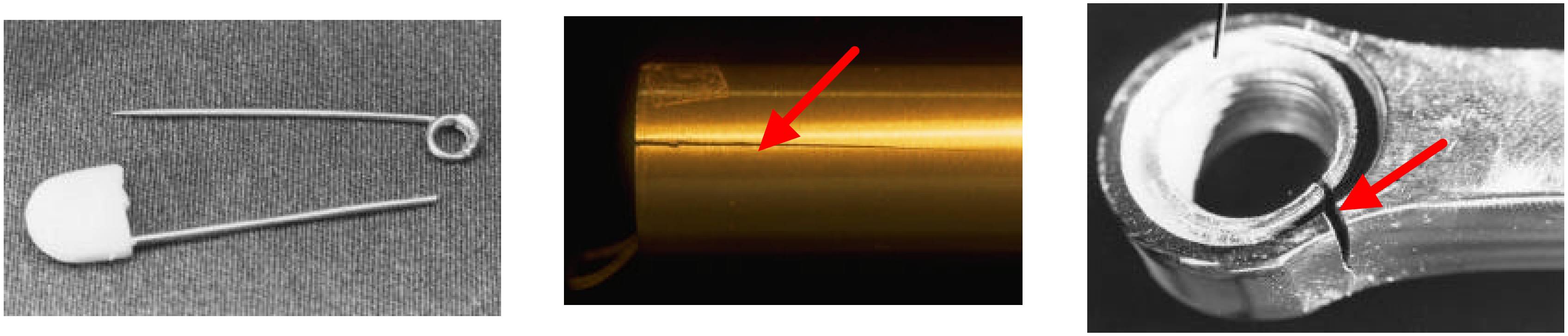
**0.3 in**

*Striations*



**20 μm**

# Fatigue is problem for many types of structures



# *Exercise*

Describe fatigue failures from your personal experience

- What was cause of fatigue failure?
- What was nature of cyclic load?
- Was initial quality an issue?
- How was failure detected?
- How was problem solved?

# Exercise

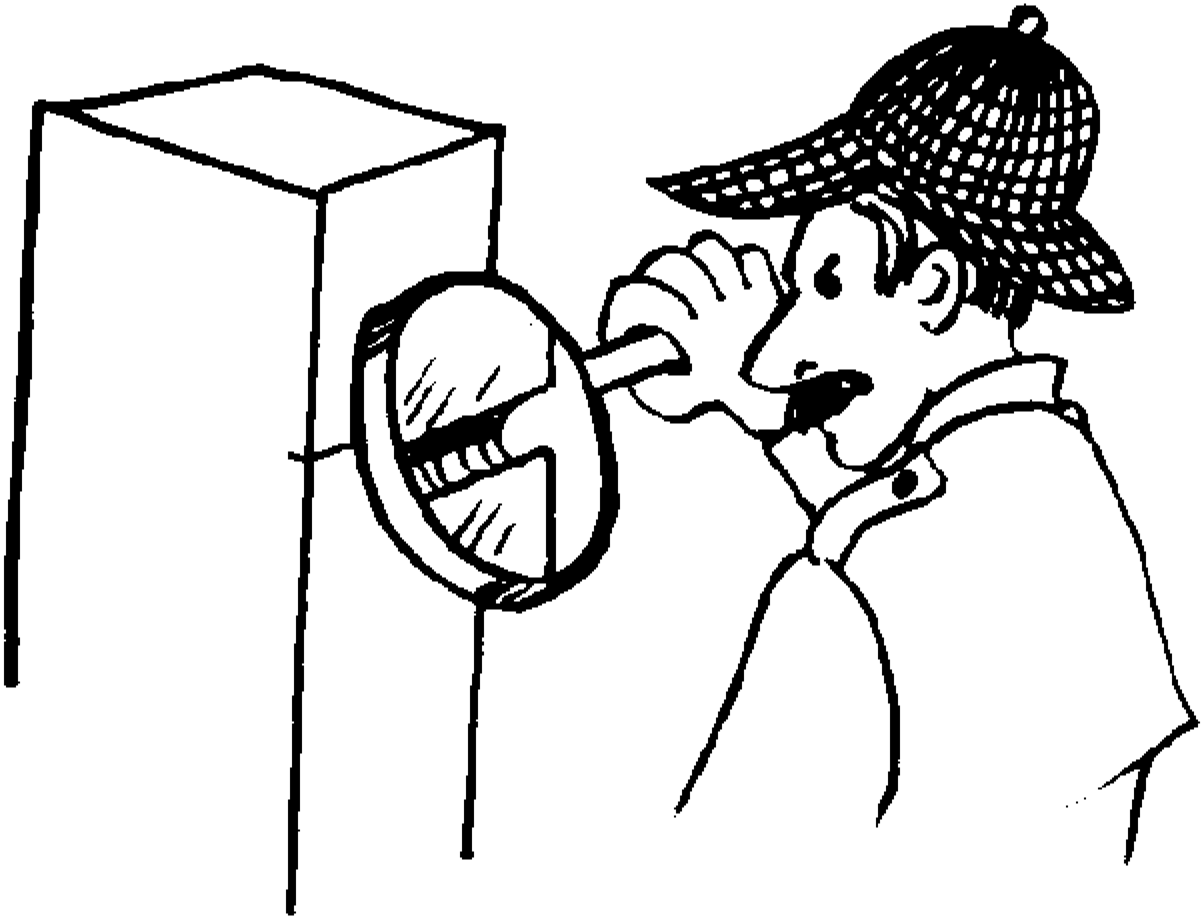
Estimate the fatigue lifetime needed for:

- Automobile axle
- Railroad rail
- Commercial aircraft components
  - landing gear
  - lower wing skin
- Highway drawbridge mechanism
- Space shuttle solid propellant rocket motor cases

# *Exercise*

- Give an example of a High Cycle Fatigue (HCF) application.
  - What is the required lifetime?
  - What are consequences of failure?
- Given an example of a Low Cycle Fatigue (LCF) application.
  - What is the required lifetime?
  - What are consequences of failure?

# Fatigue Crack Formation



# *Fatigue Crack Formation*

## Objective

- Characterize resistance to fatigue crack formation
- Predict number of cycles to "initiate" *small** fatigue crack in component

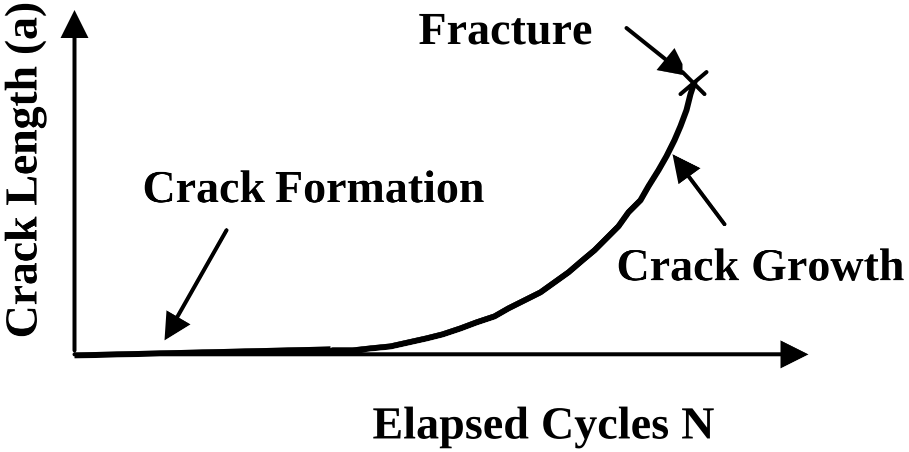
  *crack size ~ 0.03 inch

  = "committee" crack

## Approach

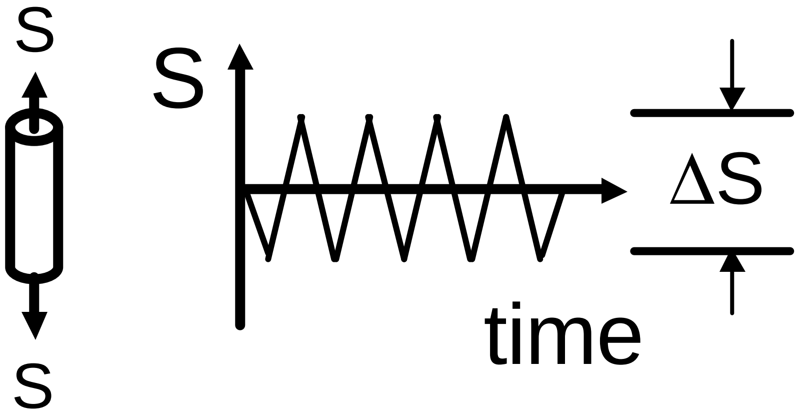
- Stress-life concepts

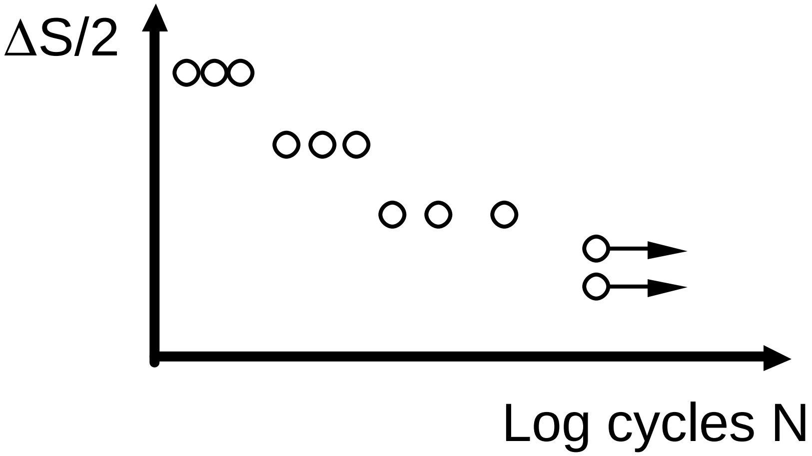
  (S-N curves)
- Strain-life concepts



# ***Stress-life (S-N) Approach***

Concept: Stress range controls fatigue life





Note:

- Life increases as load amplitude decreases
- Considerable scatter in data
- “Run-outs” suggest “infinite life” possible
- Life N usually total cycles to failure

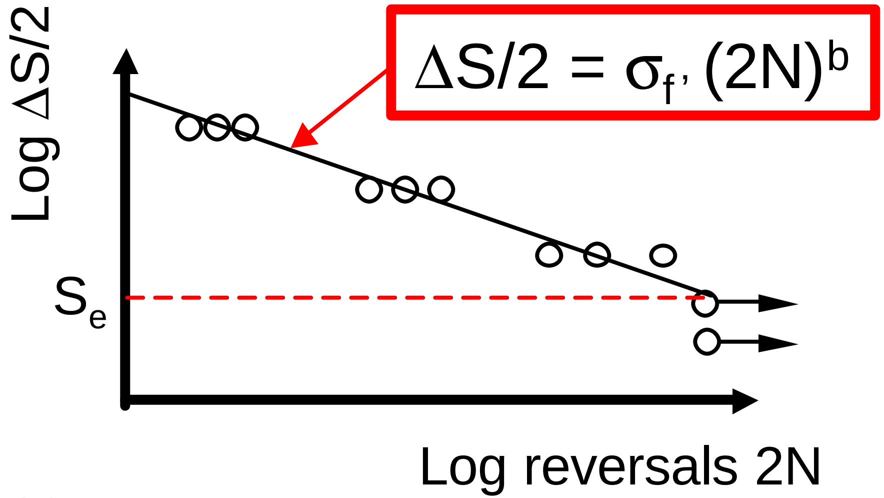
# *Model Stress-life (S-N) Curve*

- $S_e$ = endurance limit

  <u>for steels</u>

  – $S_e \sim 0.5$ ultimate stress $S_{ult}$

  – $S_e \sim 100$ ksi if $S_{ult}$ ⟨ 200 ksi



$\Delta S/2 = \sigma_{f'} (2N)^b$

- $\sigma_{f'}$ = fatigue strength coefficient
- b = fatigue strength exponent

  typically $-0.12 < b < -0.05$

<u>Note</u>: Measure life in terms of reversals 2N

(1 cycle = 2 reversals)

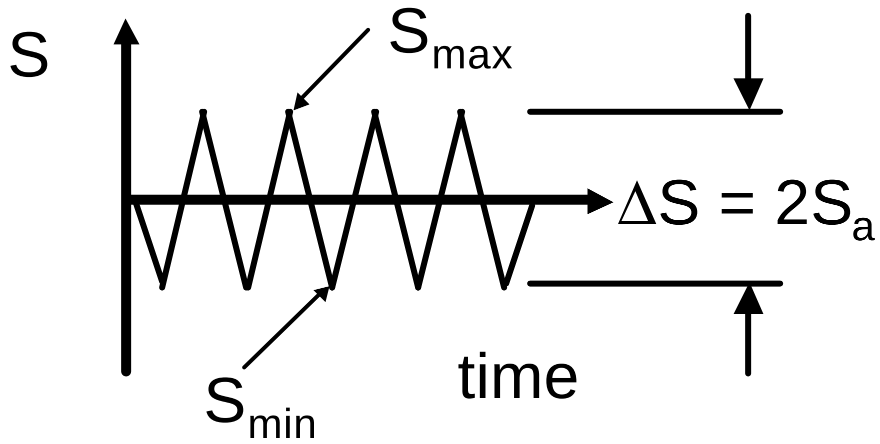
# S-N Curve: Mean Stress

Mean stress effects life

stress ratio $R = S_{min} / S_{max}$

$S_{mean} = 0.5(S_{min} + S_{max})$

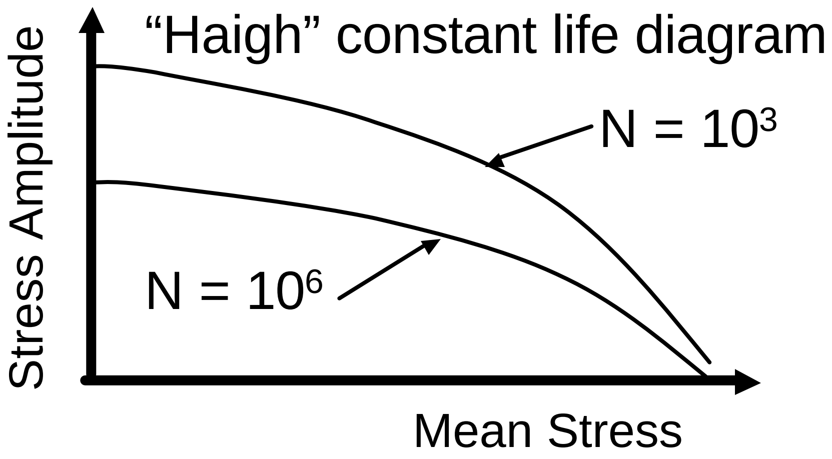
$S_a = 0.5(S_{max} - S_{min}) = \Delta S/2$



Mean stress models

$$\boxed{S_a/S_e + S_m/S_{ult} = 1}$$

$$\boxed{\Delta S/2 = (\sigma_{f}' - S_{mean})(2N)^b}$$



# S-N Curve:  Other Factors

- S-N curves are very sensitive to
  - surface finish, coatings, notches
  - prior loading, residual stresses
  - specimen size effects, etc.
- Many empirical “knock-down” factors
- S-N approach best suited for HCF (High Cycle Fatigue) applications
  - limited by local plastic deformation
  - strain-life approach better for LCF (Low Cycle Fatigue)

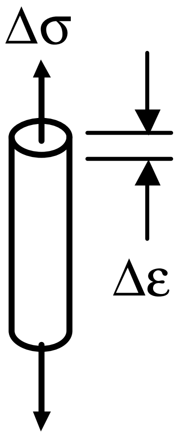
# ***Strain-life (ε - N) Approach***

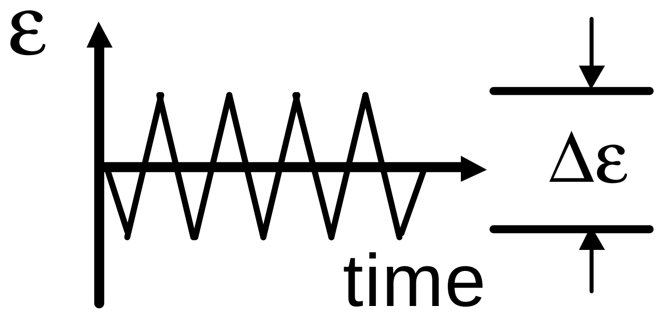
Concept: Strain range $\Delta\varepsilon$ controls life

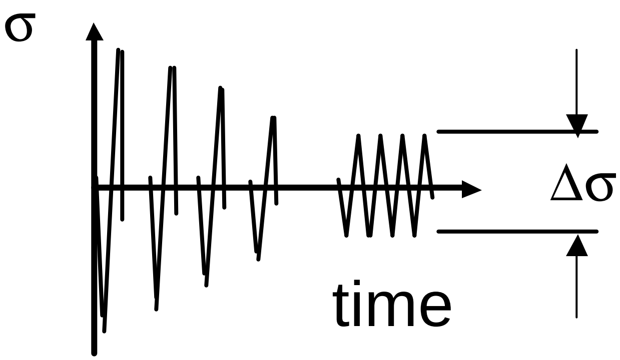
Experiment

- Control $\Delta\varepsilon$
- Measure
  - "Reversals" ($2N_f$) to failure (1 cycle = 2 reversals)
  - Stable stress range $\Delta\sigma$ needed to maintain $\Delta\varepsilon$

Note: "stable" $\Delta\sigma$ usually occurs by mid-life ($2N_f /2$)

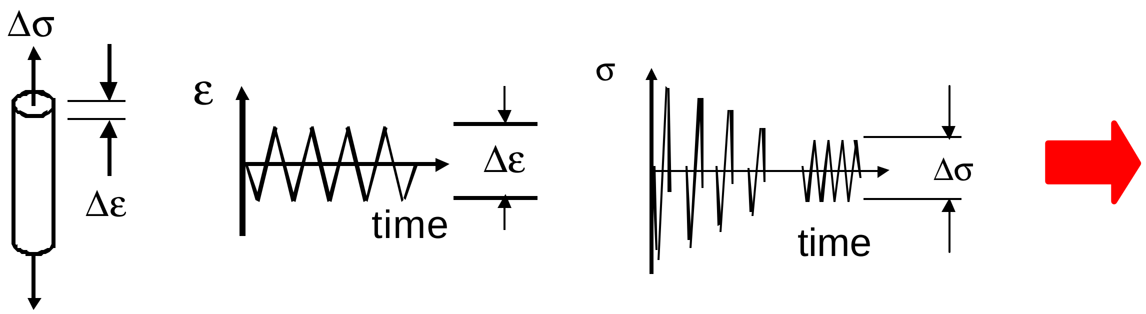


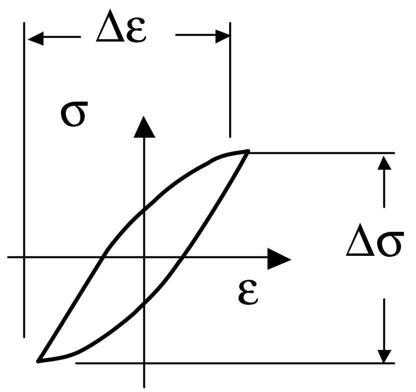




# Cyclic Stress-Strain Curve

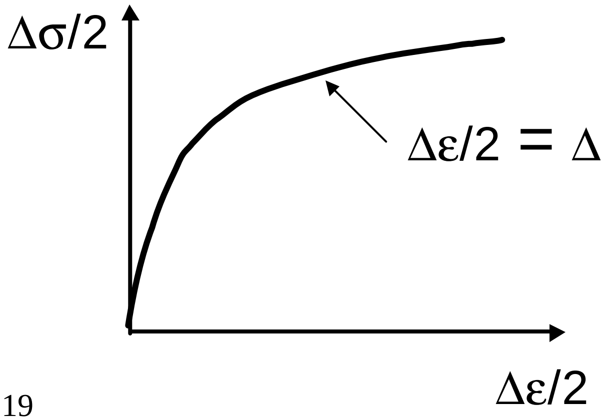
Relate stable cyclic stress and strain ranges





“Hystersis” loop

Cyclic stress-strain curve



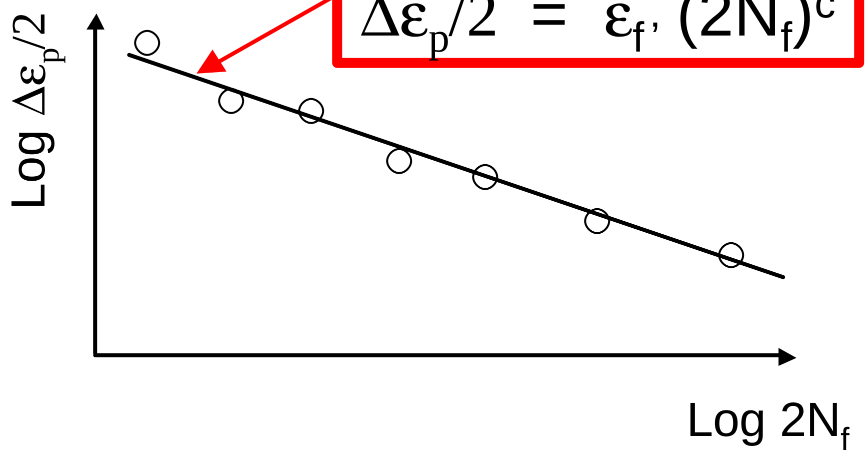
$\Delta\varepsilon/2 = \Delta\sigma/2E + (\Delta\sigma/2K')^{1/n'}$

E = elastic modulus
K’ = cyclic strength coefficient
n’ = strain hardening exponent

# *Plastic Strain-Life Curve*

Relate “plastic” strain amplitude $\Delta\varepsilon_p/2$ with reversals to failure $2N_f$

Compute $\Delta\varepsilon_p/2 = \Delta\varepsilon/2 - \Delta\sigma/2E$ = total - “elastic” strain amplitudes



$$\boxed{\Delta\varepsilon_p/2 \;=\; \varepsilon_{f'}\,(2N_f)^c}$$

$\varepsilon_{f'}$ = fatigue ductility coefficient

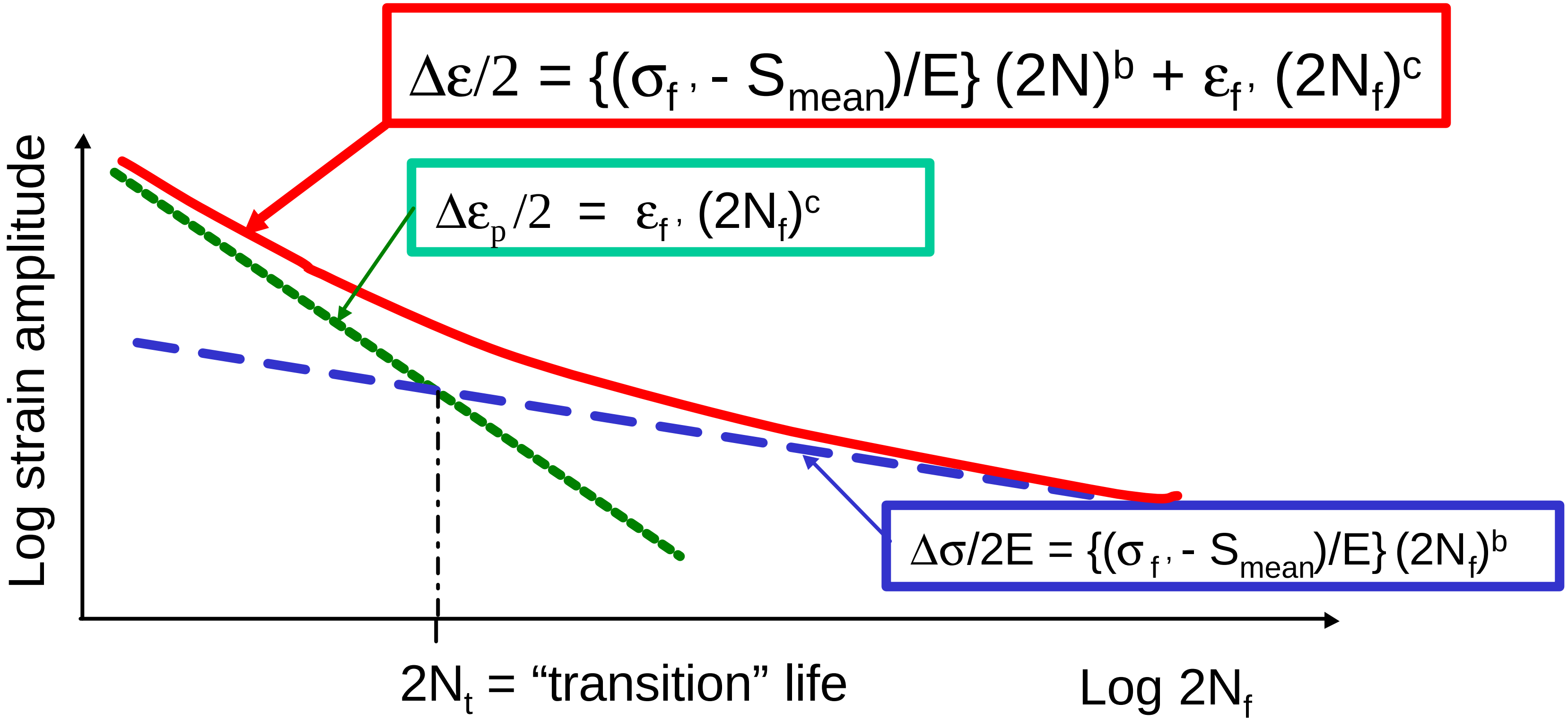
c = fatigue ductility exponent

typically $-0.7 < c < -0.5$

# ***Total Strain-Life Curve***

Plot total strain amplitudes versus life $2N_f$

$$\Delta\varepsilon_{total}/2 = \Delta\varepsilon/2 = 0.5\,\Delta\varepsilon_{elastic} + 0.5\,\Delta\varepsilon_{plastic} = \Delta\sigma/2E + 0.5\,\Delta\varepsilon_{plastic}$$

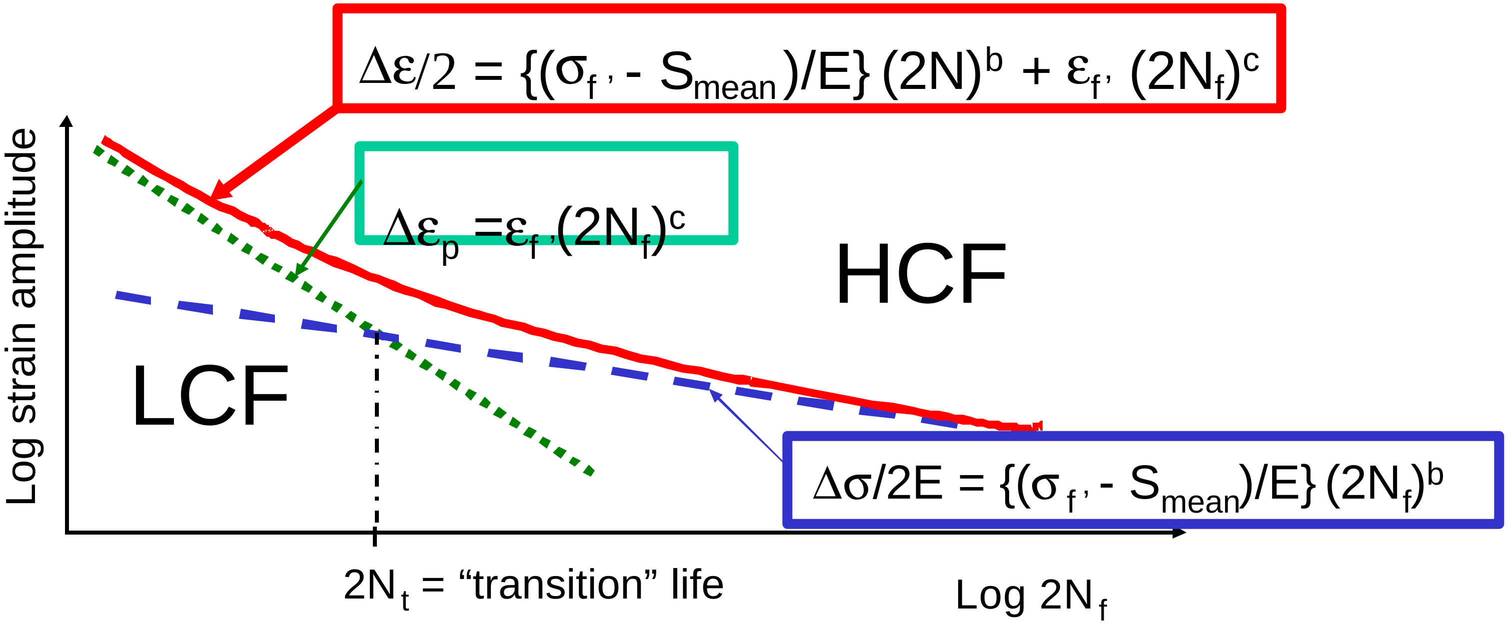


$$\Delta\varepsilon/2 = \{(\sigma_{f'} - S_{mean})/E\}\,(2N)^b + \varepsilon_{f'}\,(2N_f)^c$$

$$\Delta\varepsilon_p/2 = \varepsilon_{f'}\,(2N_f)^c$$

$$\Delta\sigma/2E = \{(\sigma_{f'} - S_{mean})/E\}\,(2N_f)^b$$

# ***Total Strain-Life***



$\Delta\varepsilon/2 = \{(\sigma_{f'} - S_{mean})/E\}\,(2N)^b + \varepsilon_{f'}\,(2N_f)^c$

$\Delta\varepsilon_p = \varepsilon_{f'}(2N_f)^c$

$\Delta\sigma/2E = \{(\sigma_{f'} - S_{mean})/E\}\,(2N_f)^b$

Note:

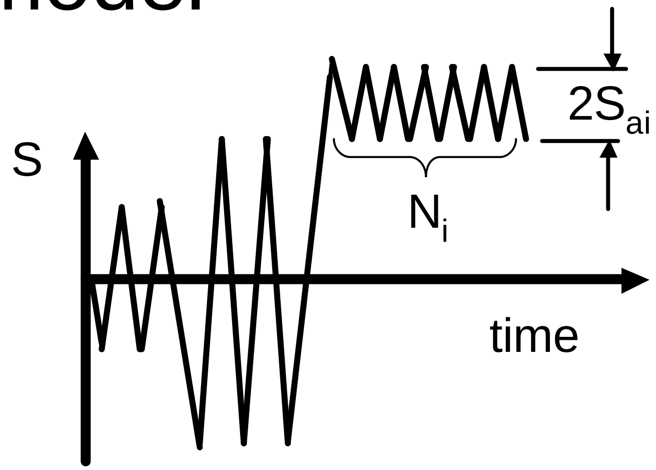
- Plastic strain dominates for LCF
- Elastic strain dominates for HCF
- Transition life $2N_t$ separates LCF/HCF

# *Variable Amplitude Loading*

- Load amplitude varies in many applications
- Use of constant amplitude S - N or ε - N data requires "damage model"
- Miner's rule*

$$\boxed{\Sigma(N_i/N_f) = 1}$$

*Use with caution!



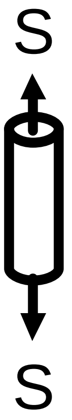
$N_i$ = number of applied cycles of stress amplitude $S_{ai}$
$N_f$ = fatigue life for $S_{ai}$ cycling only

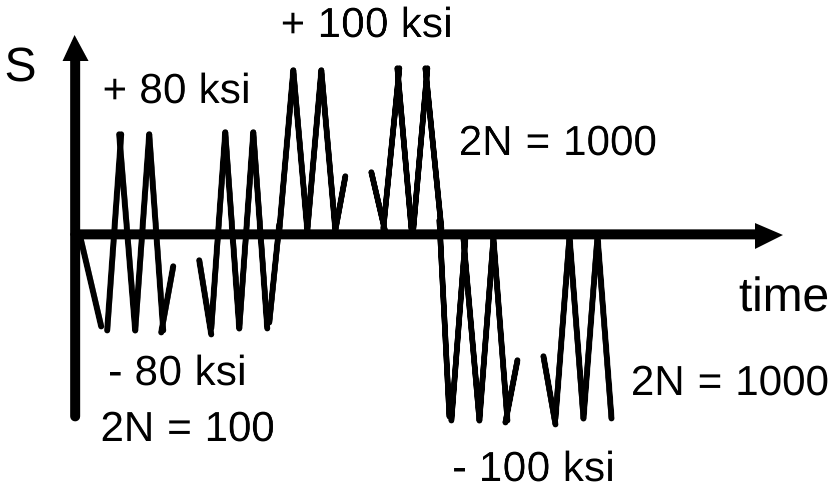
# Example Problem

Assume:

- $\sigma_{f'}$ = 220 ksi, b = - 0.1
- stress history shown (1 block of loading)

Find: number of blocks to failure





# Solution

$$\Sigma(N_i/N_f) = 1$$

$$2N_f = \{(\Delta S/2) / (\sigma_f' - S_{mean})\}^{1/b}$$

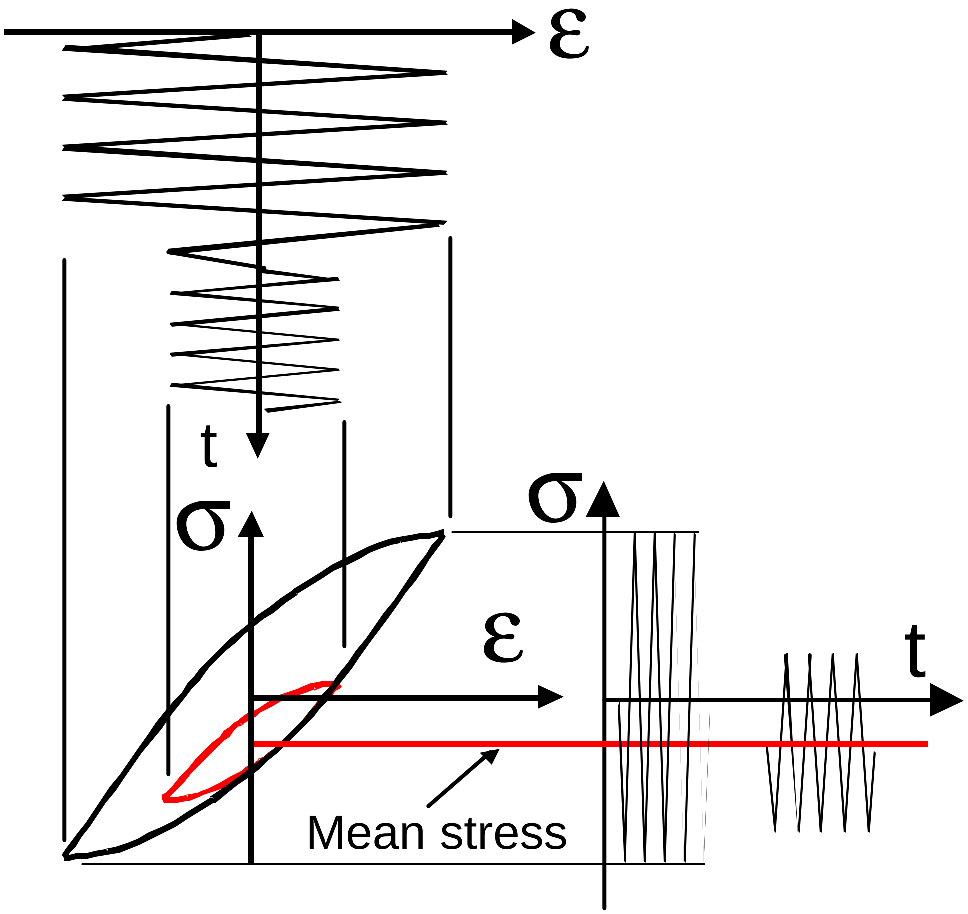
| $\Delta S/2$ (ksi) | $S_{mean}$ (ksi) | $2N_f$ | $2N_i$ | $N_i/N_f$ |
|---|---|---|---|---|
| 80 | 0 | 24,735 | 100 | 0.0040 |
| 50 | +50 | 206,437 | 1000 | 0.0048 |
| 50 | -50 | $21\ E^{6}$ | 1000 | $4.74\ E^{-6}$ |
|  |  |  |  | 0.0089 |

$\Sigma(N_i/N_f) = 1$

When:
1/0.0089
= 112.5

Answer
112 blocks

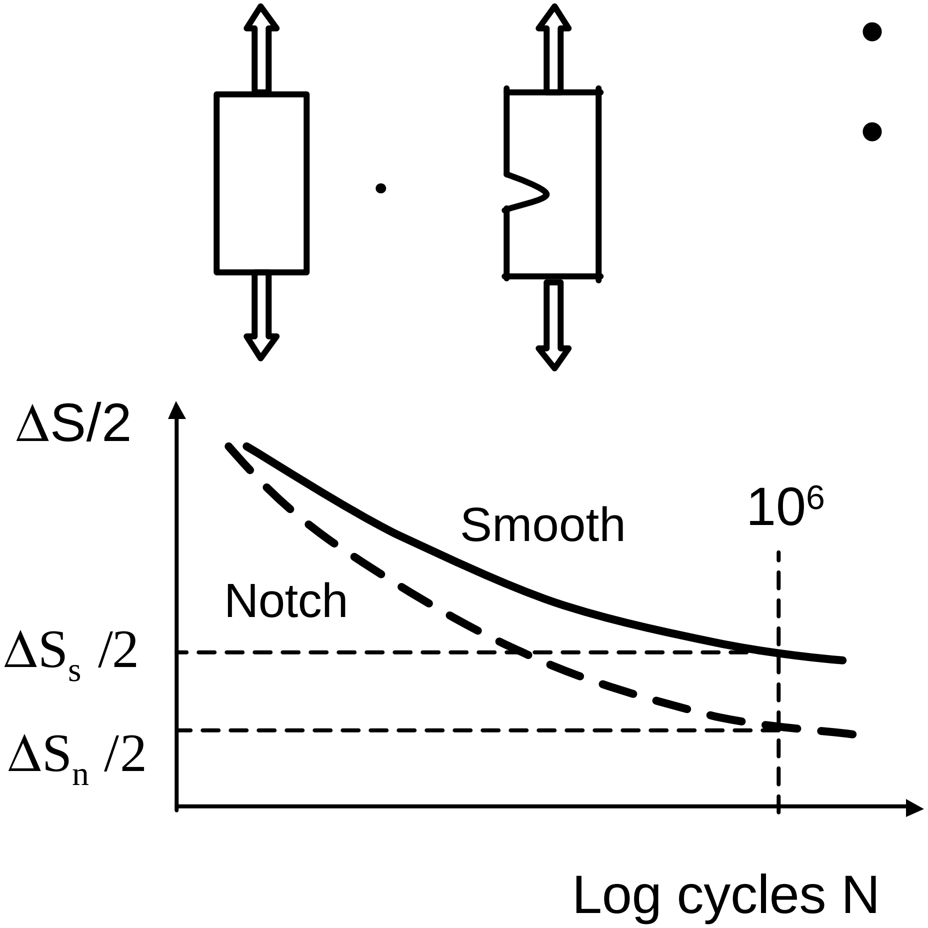
# *Load Sequence Effects*



- Hi-lo strain ε sequence results in <u>compressive</u> mean stress σ when last large ε peak is <u>tension</u>
- → <u>increases</u> life
- If last ε peak had been <u>compression</u>, would result in <u>tensile</u> mean stress
- → <u>decreases</u> life

Load sequence important!

# Notch Fatigue



- Notches can reduce life
- Define Fatigue Notch Factor $K_f$

$K_f$ = Smooth/notch fatigue strength at $10^6$ cycles

$= \Delta S_s / \Delta S_n$

$1 < K_f < K_t$

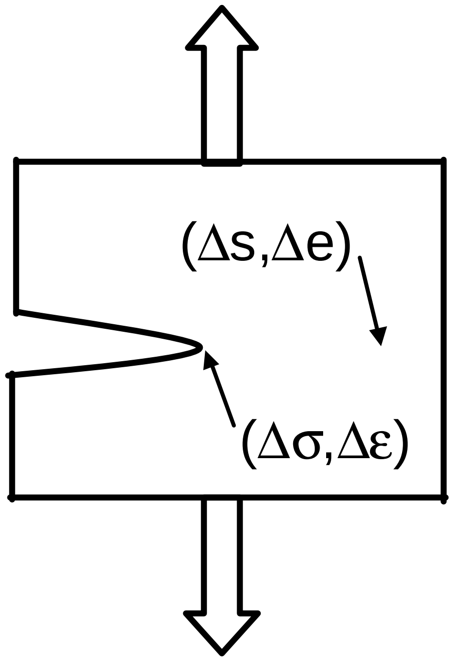
($K_t$ = elastic stress concentration factor)

$K_f = 1$ → no notch effect

$K_f = K_t$ → full notch effect

# Neuber's Rule

$$\boxed{K_f{}^2 \Delta s \Delta e = \Delta\sigma\Delta\varepsilon}$$



$K_f$ = fatigue notch concentration factor

$(\Delta s, \Delta e)$ = nominal stress/strain ranges (away from notch)

$(\Delta\sigma, \Delta\varepsilon)$ = notch stress/strain ranges

Neuber's rule relates notch and nominal stress/strain behavior

Solve with:

$$\boxed{\Delta\varepsilon/2 = \Delta\sigma/2E + (\Delta\sigma/2K')^{1/n'}}$$

$$\boxed{\Delta\varepsilon/2 = \{(\sigma_{f'} - S_{mean})\}(2N_f)^b + \varepsilon_{f'}(2N_f)^c}$$

# *Summary "Initiation" Methods*

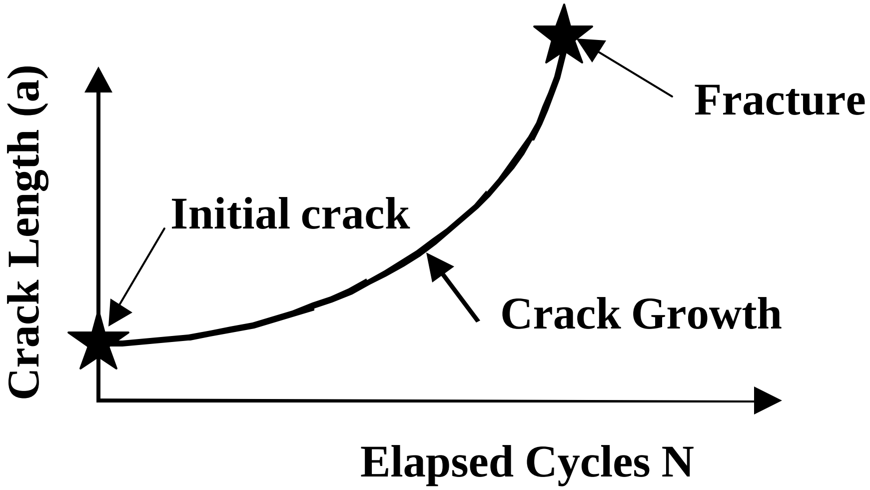
- <u>Total</u> strain-life approach <u>combines</u>:
  - – original S-N curve (best suited for HCF) and
  - – plastic strain-life method developed for LCF problems
- S-N and strain-life often viewed as crack "initiation" approaches
  - – actually deal with life to form "small" crack
  - – crack size implicit in specimen/test procedure
  - – typically assume "committee crack" ~ 0.03 in.

# *Initiation Summary Cont'*

- Notches increase local stress/strain and often are source for crack formation
  - – complex problem leads to local plasticity
  - – characterize by fatigue notch concentration factor $K_{f,}$, Neuber's rule
- Load interaction effects result in local mean stress
  - – can increase/decrease life
  - – invalidate Miner's rule

# Fatigue Crack Growth

# *Crack Growth Approach*



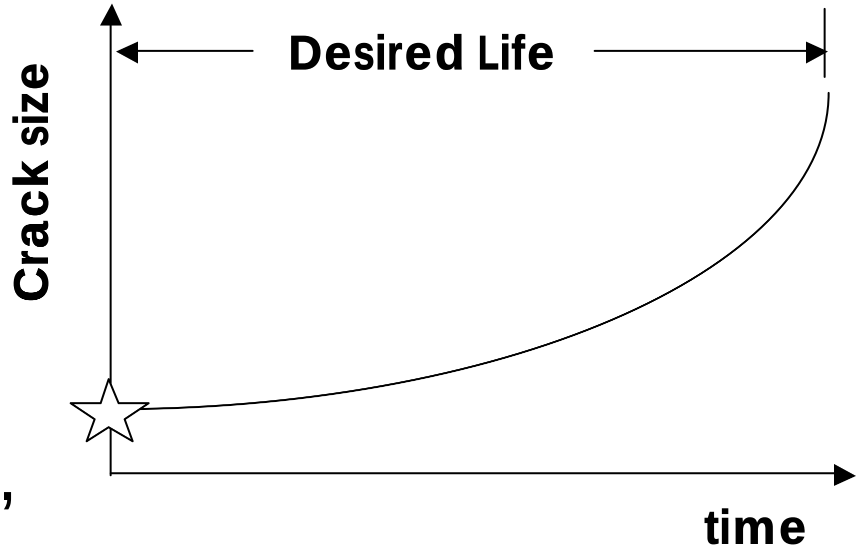
- Assumes entire life fatigue crack growth
  - – ignores "initiation"
  - – assumes component cracked <u>before</u> cycling begins
- Used with "damage tolerant design"
  - – protects from pre-existent (or service) damage
  - – based on linear elastic fracture mechanics

# *Damage Tolerance*

*The ability of a structure to resist prior damage for a specified period of time*

Initial damage

- material
- manufacturing
- service induced
- size based on inspection capability, experience, . . .



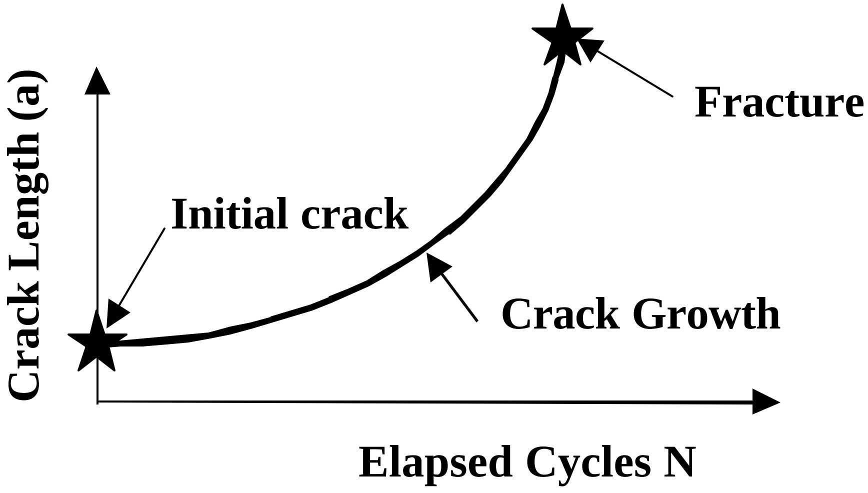
# *Fatigue Crack Growth*

## Objective

- Characterize material resistance to fatigue <u>crack growth</u>
- Predict catastrophic <u>fracture</u> and “<u>subcritical</u>” crack growth

## Approach

- Assume crack growth controlled by stress intensity factor K
  - fracture
  - growth rate da/dN



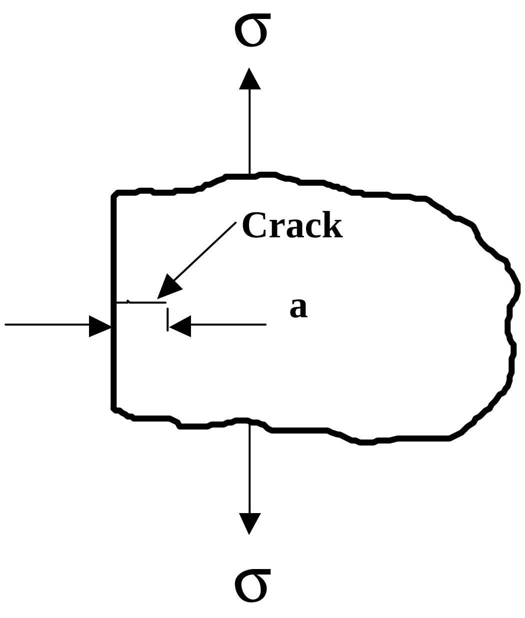
# Stress Intensity Factor $K_I$

$K_I$ is key linear elastic fracture mechanics parameter that relates:

- applied stress: σ
- crack length: a
- component geometry: β(a)

(β(a) is dimensionless)

$$\boxed{K_I = \sigma \sqrt{\pi a}\, \beta}$$



β = 1.12

Note units: stress-length$^{1/2}$

# Stress Intensity Factors

$$K = s\sqrt{pa}\left[Sec\left(\frac{pa}{W}\right)\right]^{1/2}$$

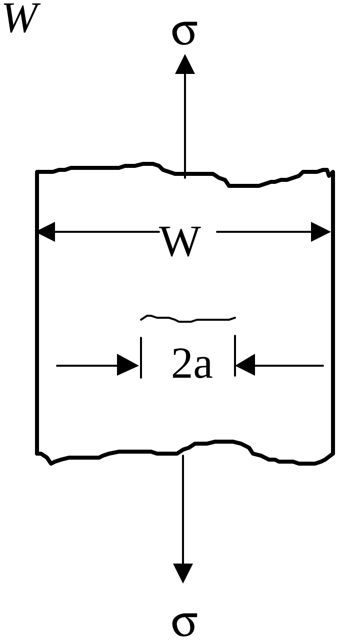
$s$ = Remote Stress

$$\frac{2a}{W} \leq 0.95$$

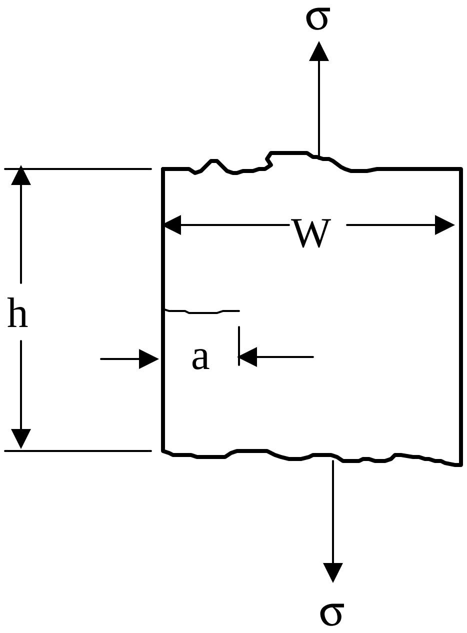
$$K = s\sqrt{p\,a}\,b\left(\frac{a}{W}\right)$$

$$b\left(\frac{a}{W}\right) = 1.12 - 0.231\left(\frac{a}{W}\right) + 10.55\left(\frac{a}{W}\right)^2 - 21.73\left(\frac{a}{W}\right)^3 + 30.39\left(\frac{a}{W}\right)^4$$

$$For\left(\frac{a}{W}\right) \leq 0.6 \quad and\left(\frac{h}{W}\right) \geq 1.0$$



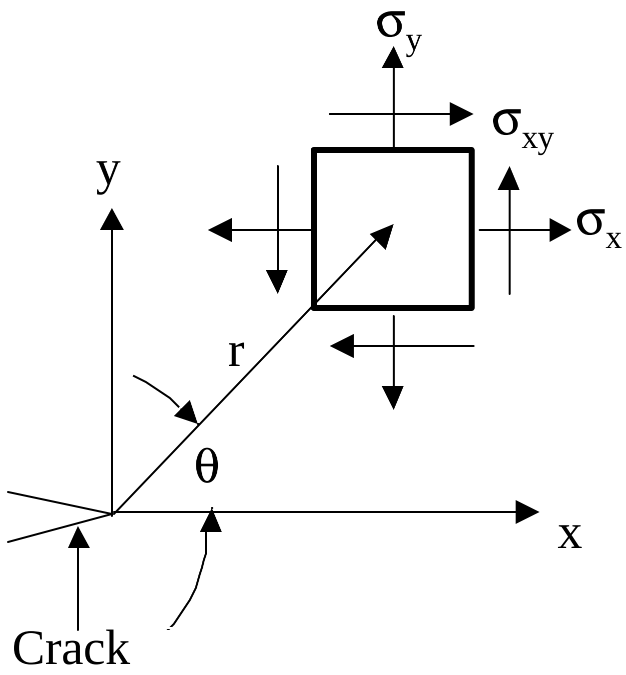
Many $K_I$ solutions available



# Crack tip Stress Fields

Theory of elasticity gives elastic stresses near crack tip in terms of stress intensity factor $K_I$

All crack configurations have same singular stress field at tip
(are similar results for other modes of loading, i.e., modes II and III)



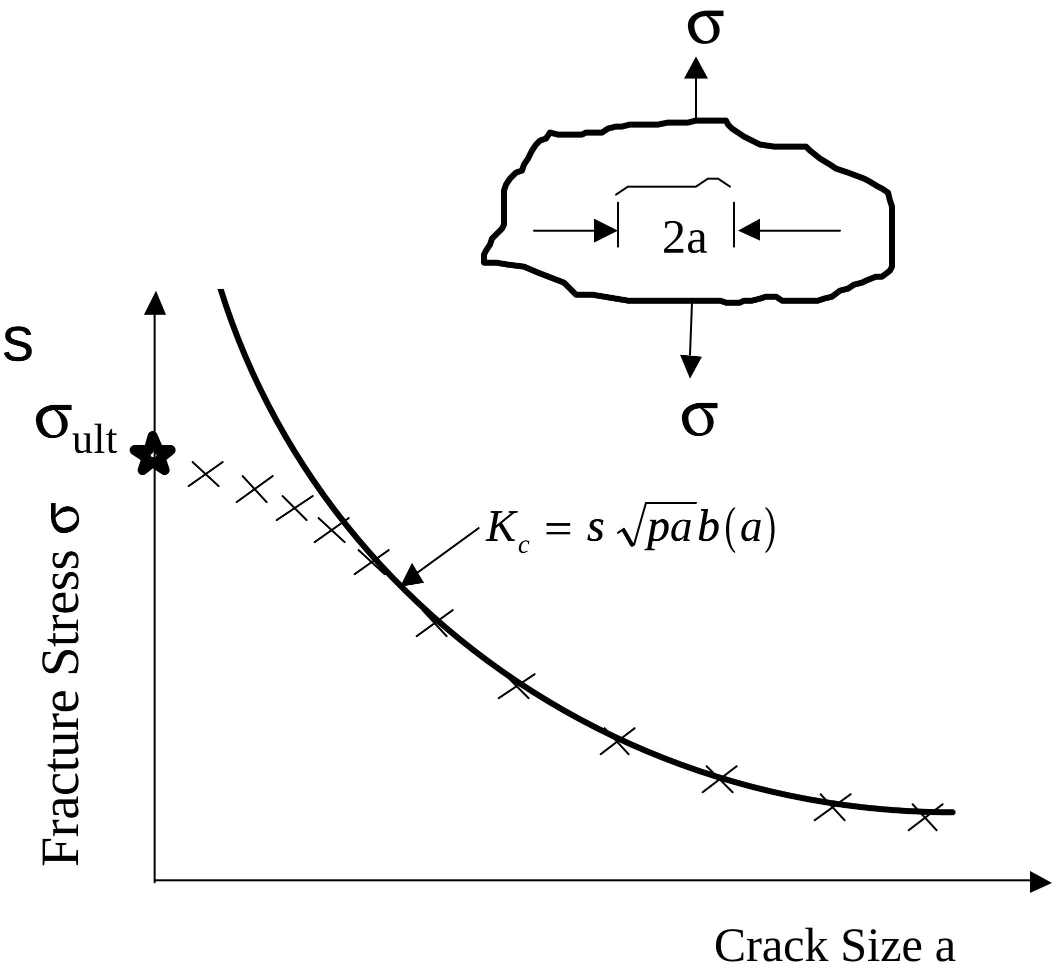
$$\left.\begin{aligned}
\sigma_x &= \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left\{1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right\}\\
\sigma_y &= \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left\{1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right\}\\
\sigma_{xy} &= \frac{K_I}{\sqrt{2\pi r}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\\
\sigma_{xz} &= \sigma_{yz} = 0\\
&\text{plane stress} \rightarrow \sigma_z = 0\\
&\text{plane strain} \rightarrow \sigma_z = \nu\left(\sigma_x + \sigma_y\right)
\end{aligned}\right\}$$

# $K_c$ Fracture Criterion

- Fracture occurs when

  K > constant = $K_c$
- $K_c$ = material property

  = fracture toughness
- Criterion relates:
  - crack size: a
  - stress: σ
  - geometry: β(a)
  - material: $K_c$
- Plasticity limits small crack applications



# *Fracture Toughness $K_c$*

Typical $K_c$ values (thick plate)

| Ματεριαλ<br>(τηιχκ πλατε) | 2024–T351<br>Αλυμ ινυμ | 7075–T651<br>Αλυμ ινυμ | Τι – 6 Αλ–4ς<br>Τιτανιυμ | 300 Μ στεελ<br>(235 κσι ψιελδ) | 18 Νιχκελ<br>(200 κσι ψιελδ) |
|---|---|---|---|---|---|
| Κχ<br>(κσι–ιν$^{1/2}$) | 31 | 26 | 112 | 47 | 100 |

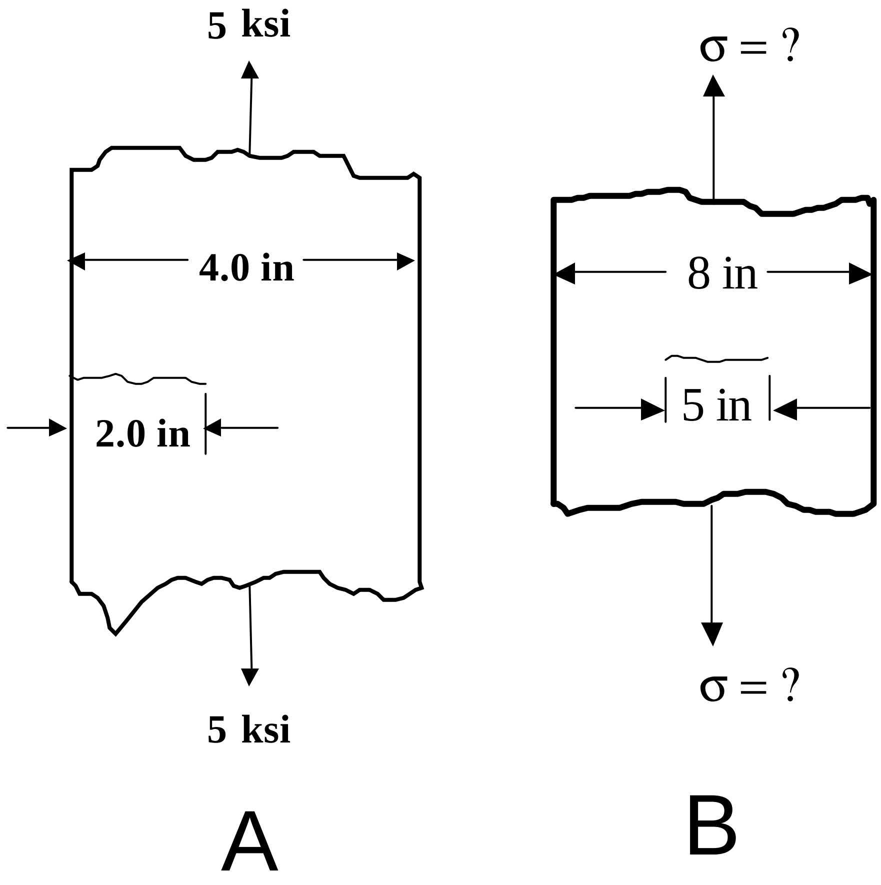
<u>Note</u> $K_c$ depends on:

- specimen thickness -- $K_c$ decreases as thickness increases until reaching minimum - $K_{Ic}$ = plane strain toughness
- crack direction (material anisotropy)

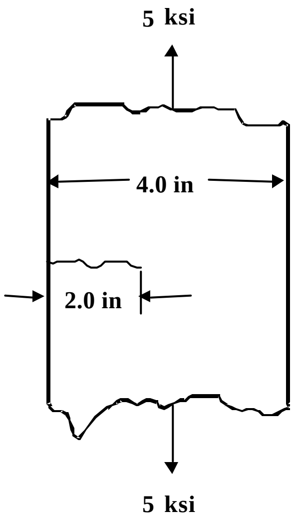
# Fracture Example

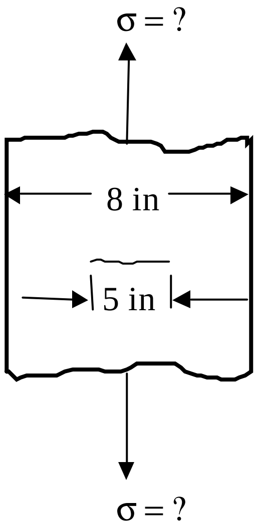
Member A fractures when crack length a = 2.0 inch and remote stress = 5 ksi

What stress will fracture member B (assume same material)?



# Fracture Example Solution





Edge crack

$$K = \sigma(\pi a)^{1/2}\,\beta(a) \;=\; K_c \text{ at fracture}$$

$$b\left(\frac{a}{W}\right) = 1.12 - 0.231\left(\frac{a}{W}\right) + 10.55\left(\frac{a}{W}\right)^2 - 21.73\left(\frac{a}{W}\right)^3 + 30.39\left(\frac{a}{W}\right)^4$$

$a/w = 2/4 \qquad \sigma = 5 \qquad a = 2 \qquad \rightarrow \beta = 2.83$

$K_c = 35.5$ ksi-in$^{1/2}$ = constant

Center Crack

$K = \sigma\,(\pi\, a)^{1/2}\beta(a) \qquad \beta(a) = [\mathrm{Sec}\,(\pi\, a/W)]^{1/2}$

$a = 2.5 \qquad W = 8 \qquad \rightarrow \beta = 1.34$

$K = K_c$ at fracture = 35.5

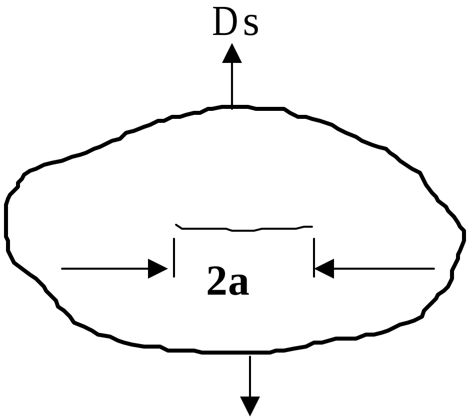
$$\boxed{\rightarrow \sigma_f \;= 9.5 \text{ ksi}}$$

# *Fatigue Crack Growth*

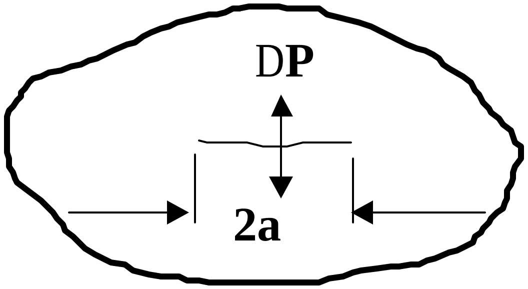
Goal: show cyclic stress intensity factor ΔK controls crack growth rate da/dN

Same material

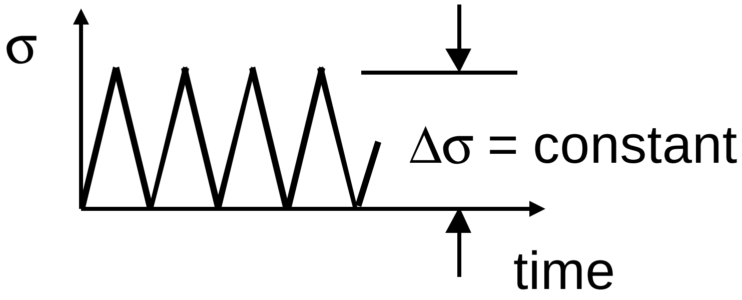
Different loadings

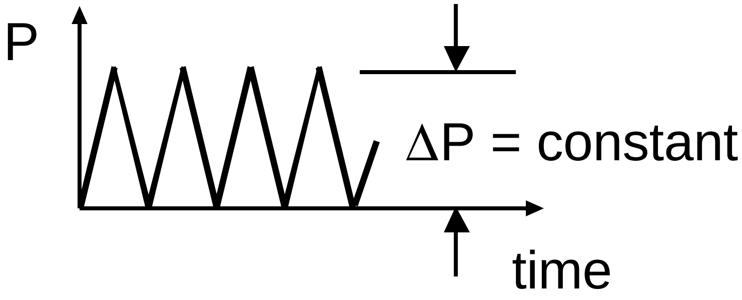


Remote Load



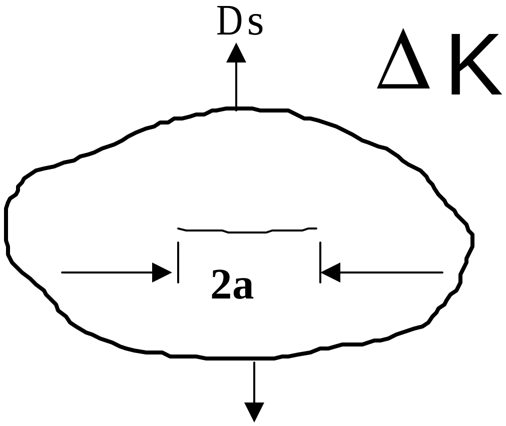
Crack Face Load





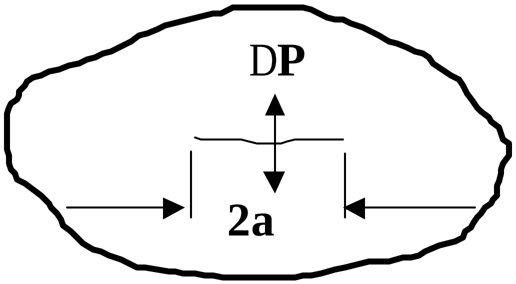
# Measure Crack Growth

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

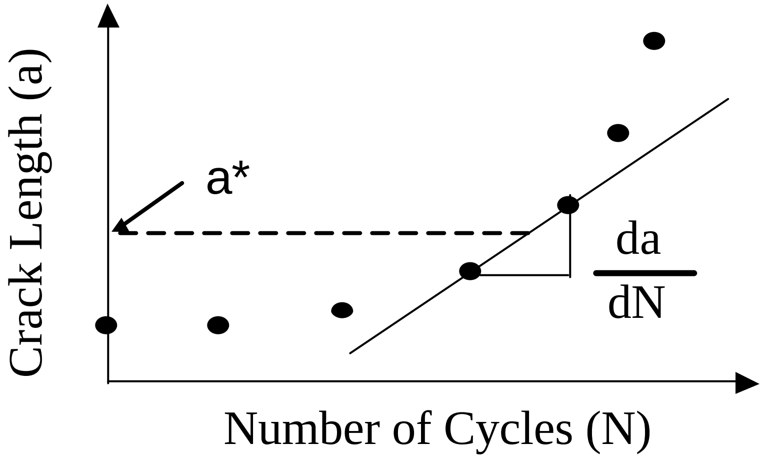


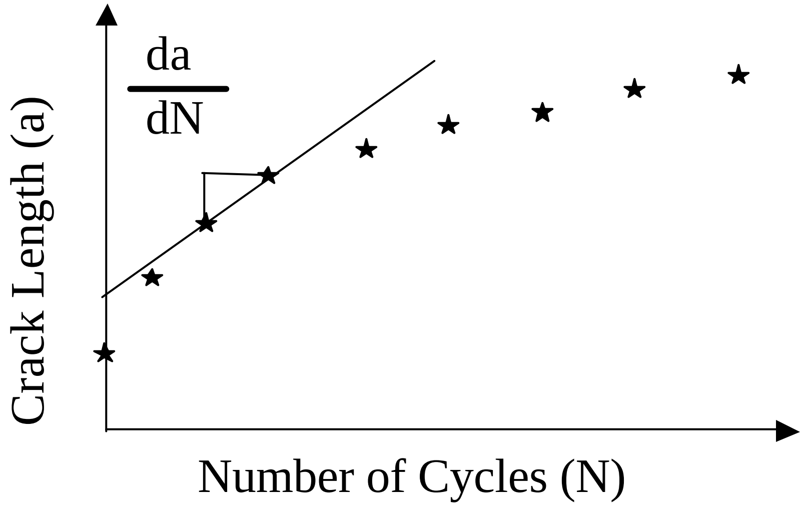
Remote Load

$$\Delta K = \frac{\Delta P}{B\sqrt{\pi a}}$$

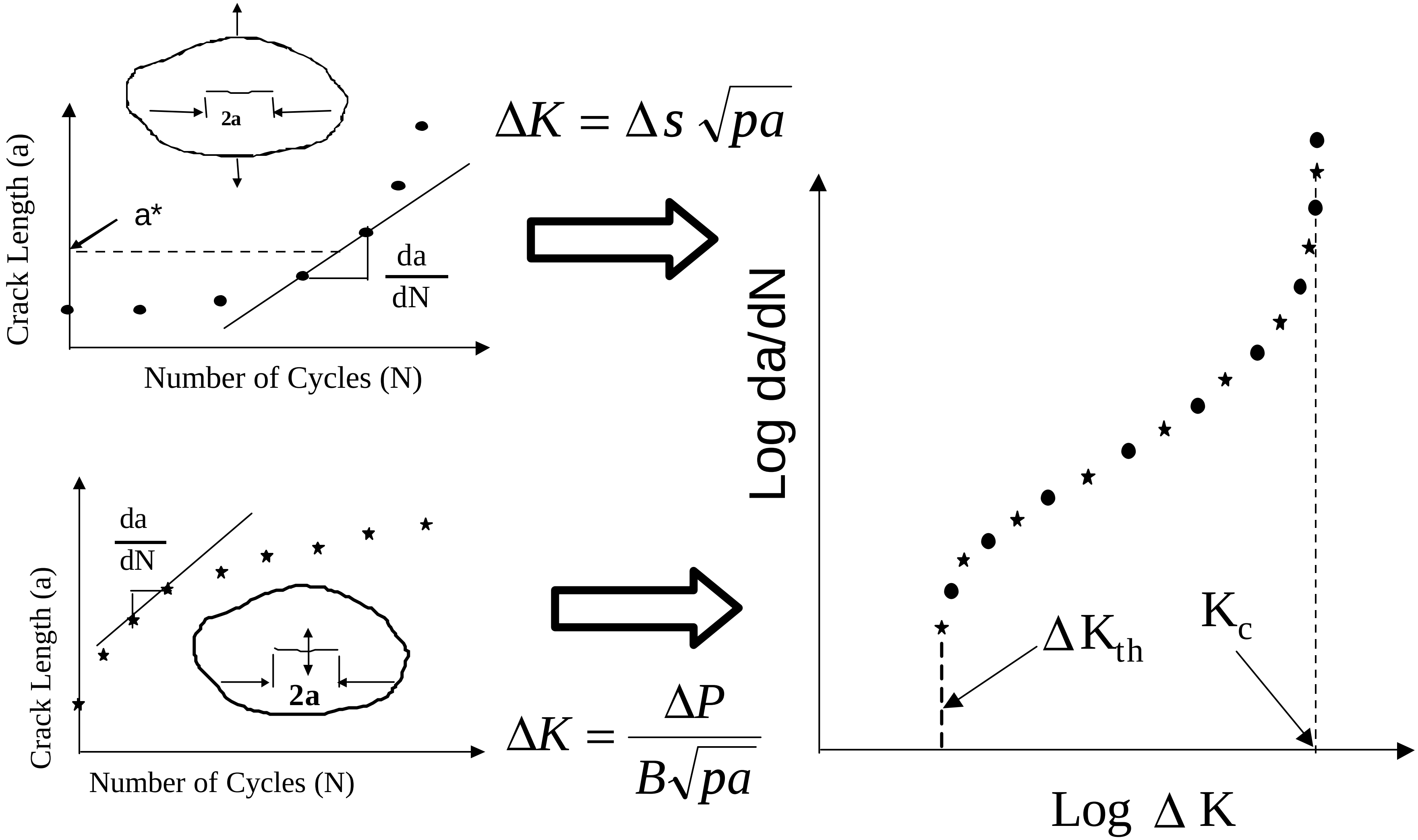


Crack Face Load





# Correlate Rate da/dN vs DK



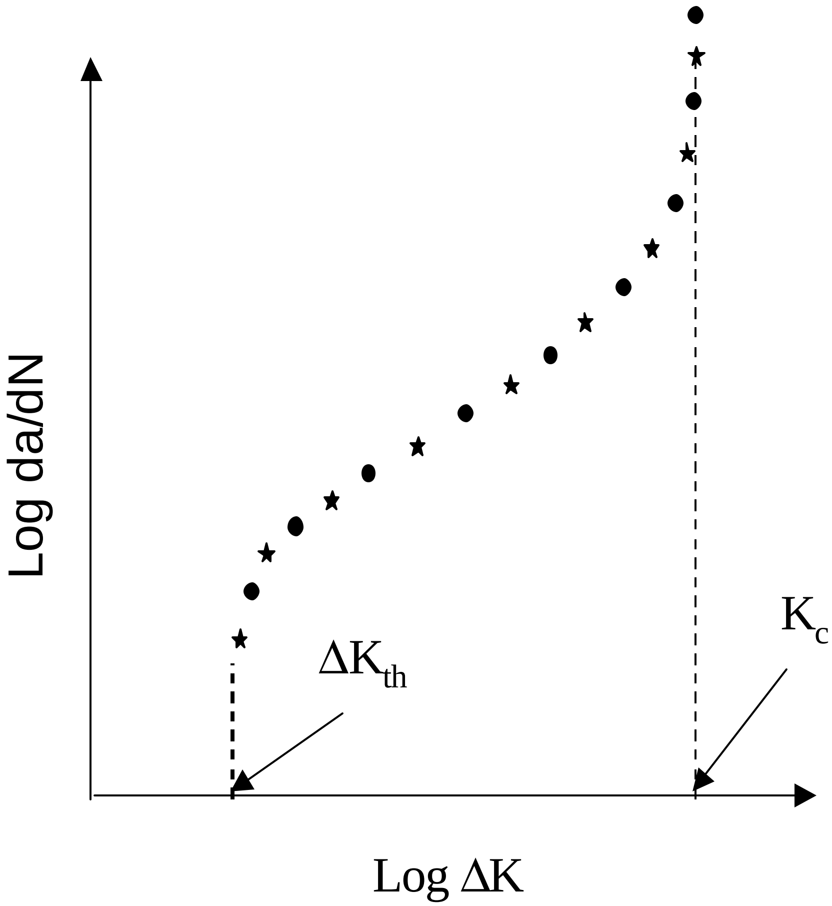
$$\Delta K = \Delta s\sqrt{pa}$$

$$\Delta K = \frac{\Delta P}{B\sqrt{pa}}$$

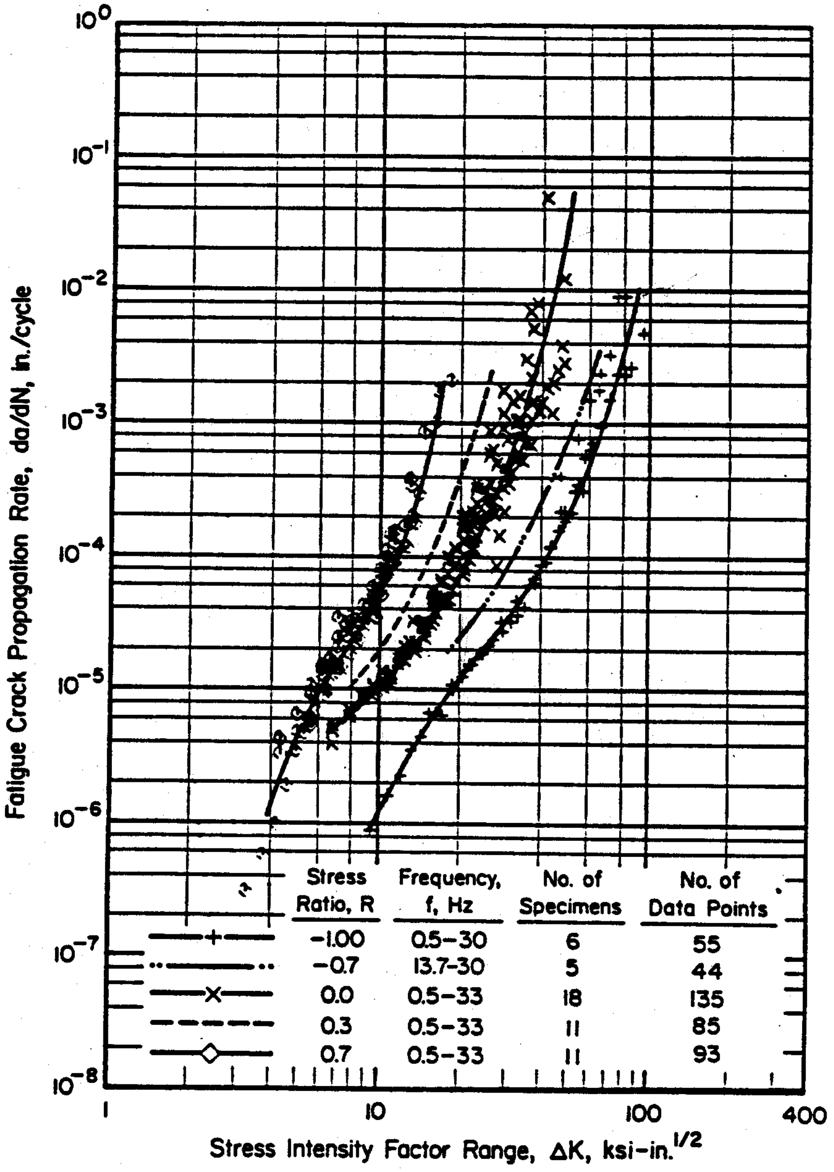
# da/dN Vs DK

<u>Note</u>:

- ΔK correlates fatigue crack growth rate da/dN
- ΔK accounts for crack geometry
- No crack growth for da/dN < $\Delta K_{th}$
- Fractures when $K_{max}$ in the ΔK range → $K_c$
- da/dN - ΔK curve is <u>material property</u>

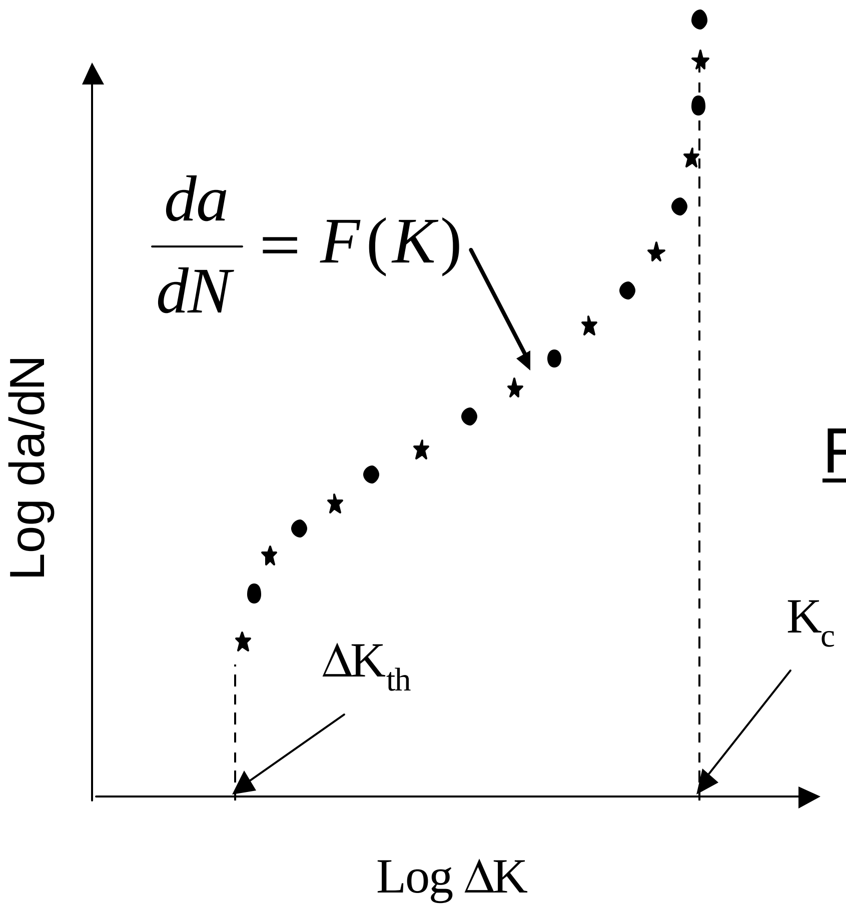


# *Sample Crack Growth Data*



- da/dN - ΔK data for 7075-T6 aluminum
- Note effect of stress ratio R = min/max stress (da/dN ↑as R↑)
- Reference: Military Handbook-5
- Other handbook data are available

# Model da/dN - DK Curve



Fit test data with numerical models such as:

<u>Paris</u>
$$\frac{da}{dN} = C\Delta K^{m}$$

<u>Forman</u>
$$\frac{da}{dN} = \frac{C\Delta K^{m}}{(1-R)K_c - \Delta K}$$

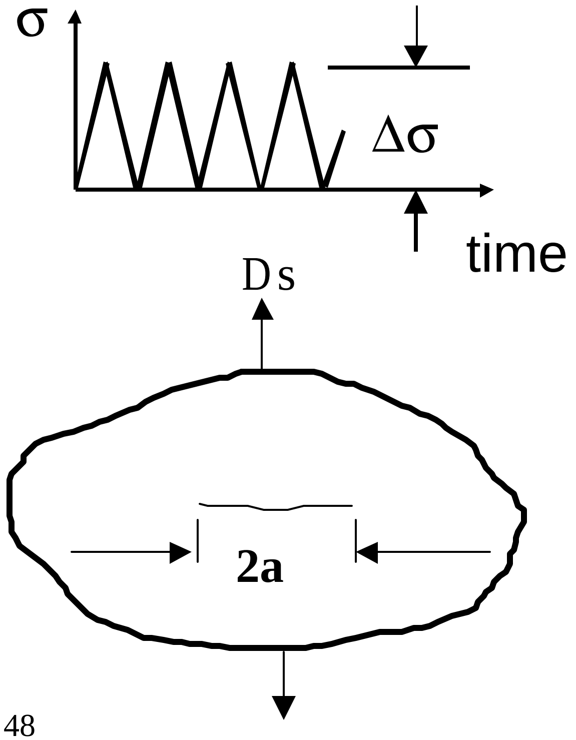
Here C, m, $K_c$ are empirical constants

R = min/max stress

(are many other models)

# Compute Fatigue Life $N_f$

$$\frac{da}{dN} = F(K) \Longrightarrow \boxed{N_f = \int_{a_o}^{a_f} \frac{da}{F(K)}}$$

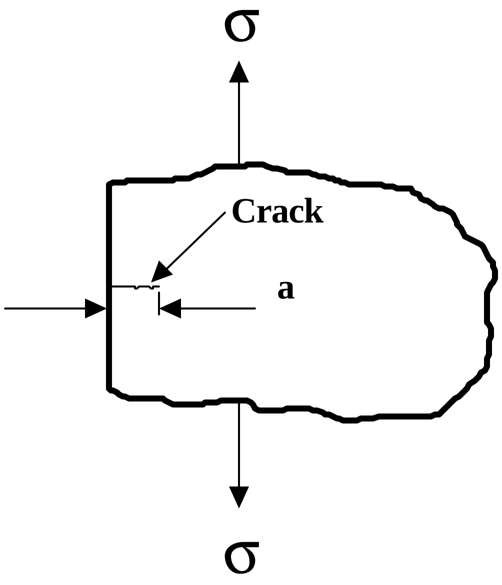


$a_o$, $a_f$ = initial, final crack sizes

F(K) = function of:

- cyclic stress: Δσ, R, . . .
- crack geometry: β(a)
- crack length: a
- material

# Example Life Calculation



Given: edge crack in wide plate

$K_c$= 63 ksi-in$^{1/2}$

initial crack $a_i$ = 0.5 inch

cyclic stress $\Delta\sigma$ = 10 ksi, R = 0

($\Delta\sigma = \sigma_{max}$ = 10 ksi)

$da/dN = 10^{-9}\Delta K^4$

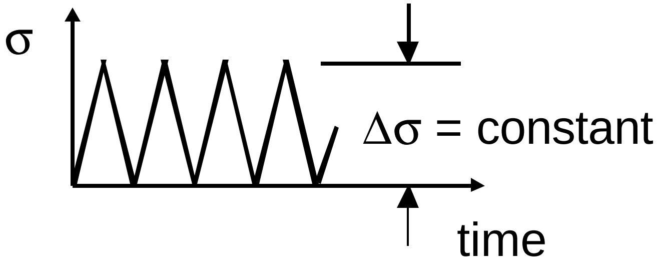
Find: a) cyclic life $N_f$

b) life if initial crack size decreased to $a_i$ = 0.1 inch

Note: at fracture

$K = K_c = 63 = 1.12\sigma_{max} (\pi a)^{1/2}$

→ final crack $a_f$ = 10 inch



# Solution

$$K = s\sqrt{pa}\,1.12 \qquad \frac{da}{dN} = C\Delta K^{m}$$

$$N_f = \int_{a_o}^{a_f} \frac{da}{C\Delta K^{m}} = \int_{a_o}^{a_f} \frac{da}{C\left[1.12\Delta s\sqrt{pa}\right]^{m}}$$

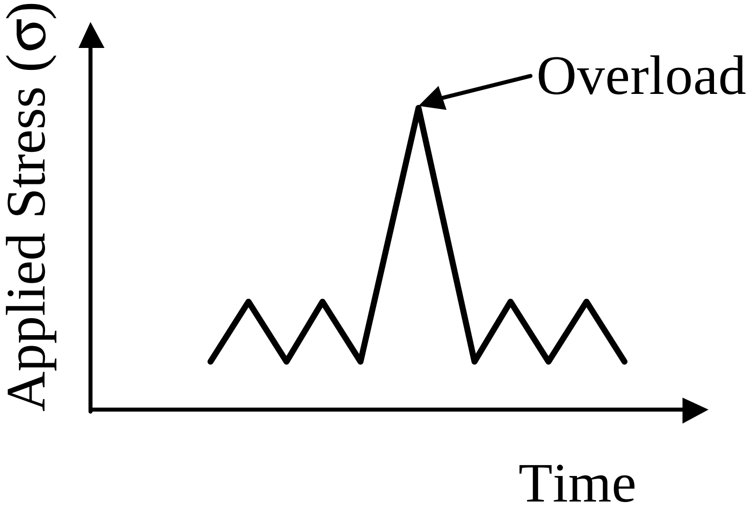
$$\boxed{N_f = \frac{1}{C\left(1.12\Delta s\sqrt{p}\right)^{m}(1-.5m)}\left[a_f^{\;1-.5m} - a_o^{\;1-.5m}\right]}$$

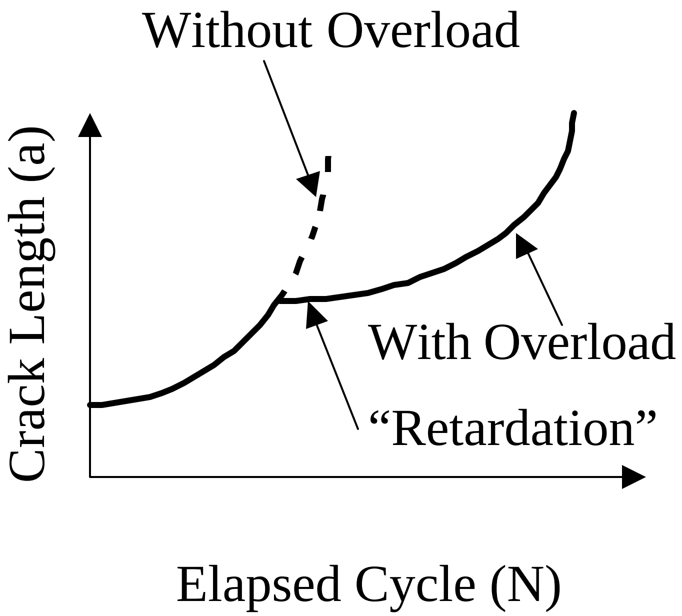
a) $N_f = 12{,}234$ cycles ($a_i = 0.5$)

b) $N_f = 63{,}747$ cycles ($a_i = 0.1$)

<u>Note:</u> big influence of initial crack length!

# *Fatigue Crack Retardation*

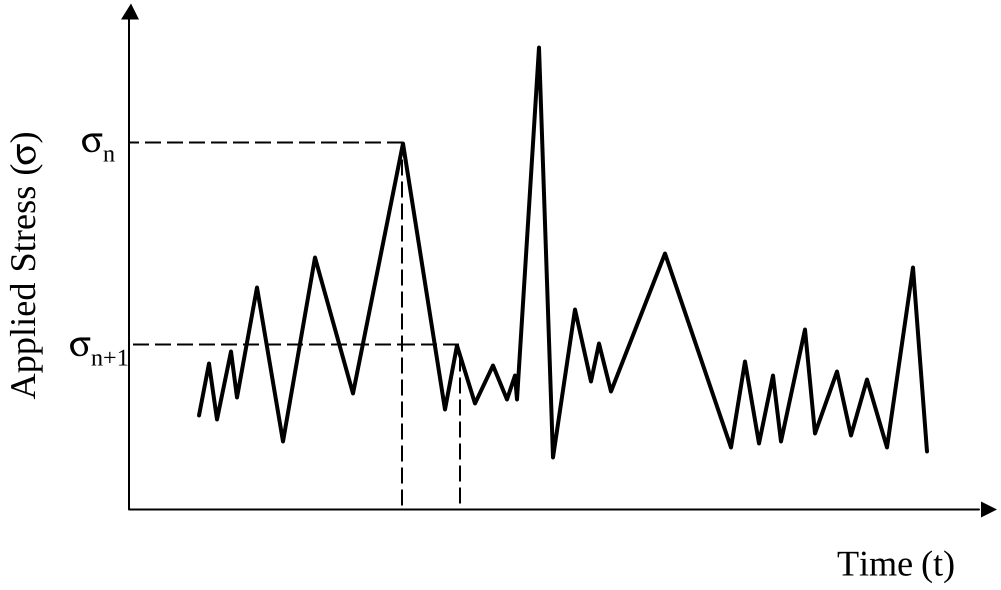




<u>Note</u> "load interaction effect"

- Tensile overload can "retard" crack growth (<u>increase</u> life)
- Life increase due to crack tip plasticity
- Depends on magnitude/sequence of overload, material, …
- Are empirical retardation models

# *Cycle-by-Cycle Calculation*



Variable amplitude loading prevents simple life integration

Compute cycle-by-cycle growth in crack length a

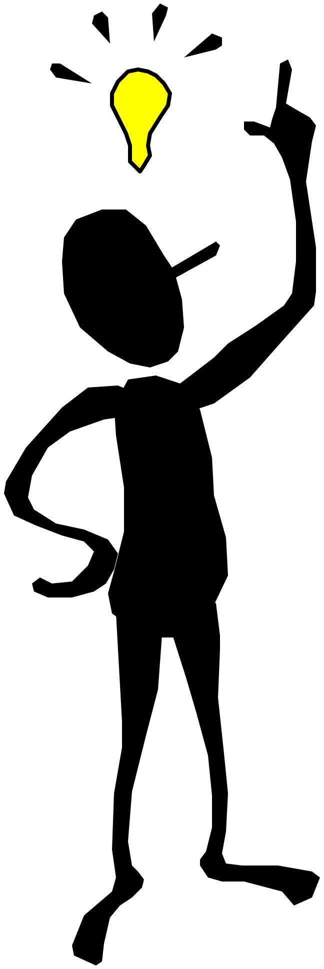
- $a_{current} = a_{prior} + da/dN_{current}$
- $da/dN_{current} = F(K_{current})$ * “Retardation” term
- Sum for all cycles in spectrum

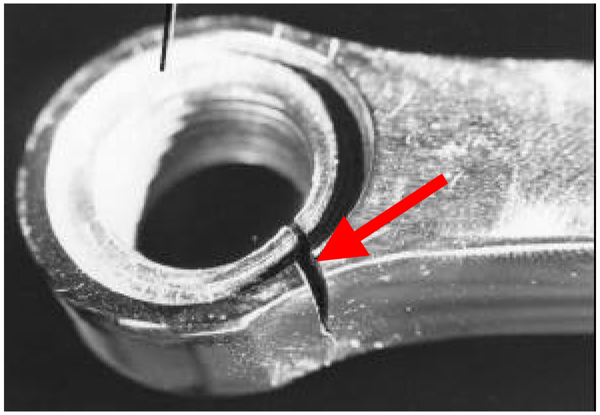
Powerful technique for computer programming

# *Crack Growth Summary*

- Fracture mechanics approach assumes entire fatigue life is crack growth
- Stress intensity factor K controls fracture and growth rate da/dN
  - $K = \sigma[\pi a]^{1/2} \beta(a)$
  - Fracture: $K = K_c$
  - Fatigue: $da/dN = F(\Delta K)$
  - Integrate da/dN for life
- Are load interaction and other effects (see references)

# Fatigue Design/Repair Concepts

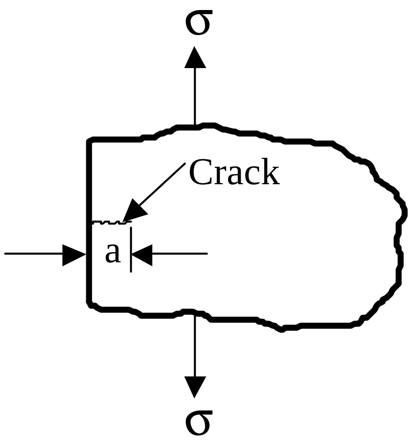


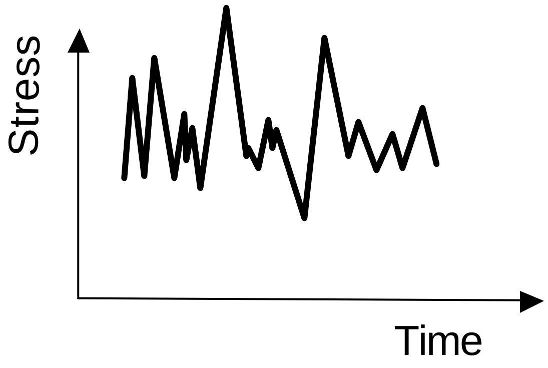


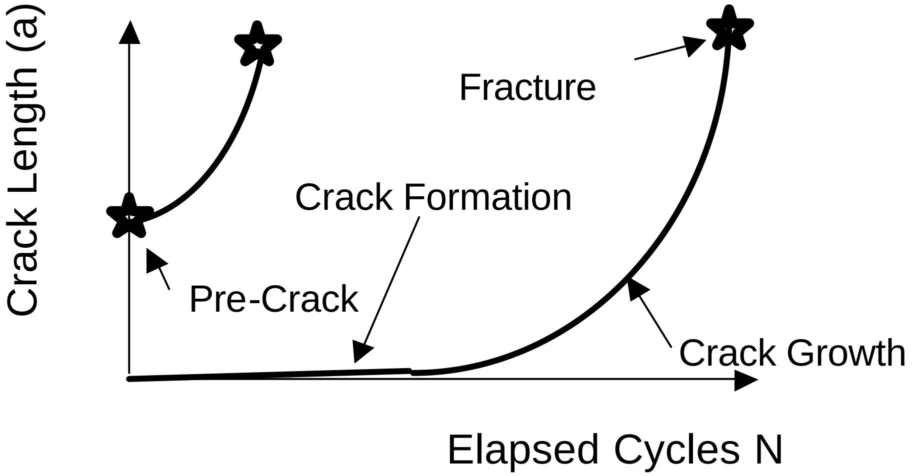
# *Design Philosophies*

<u>Fatigue Design Criteria</u>

- Infinite Life
- Safe-Life
- Damage Tolerant
  - Fail-safe
  - Slow crack growth
- Retirement-for-cause







# *Infinite Life Criterion*

Design Goal: prevent fatigue damage from ever
developing (i.e. infinite life)

- Usually based on endurance limit
- Could also employ threshold K concepts
- Leads to small design stresses/heavy members
- Limited to simple components/loading
- Often impractical/not achievable in practice
  - Weight critical structure
  - Complex loads

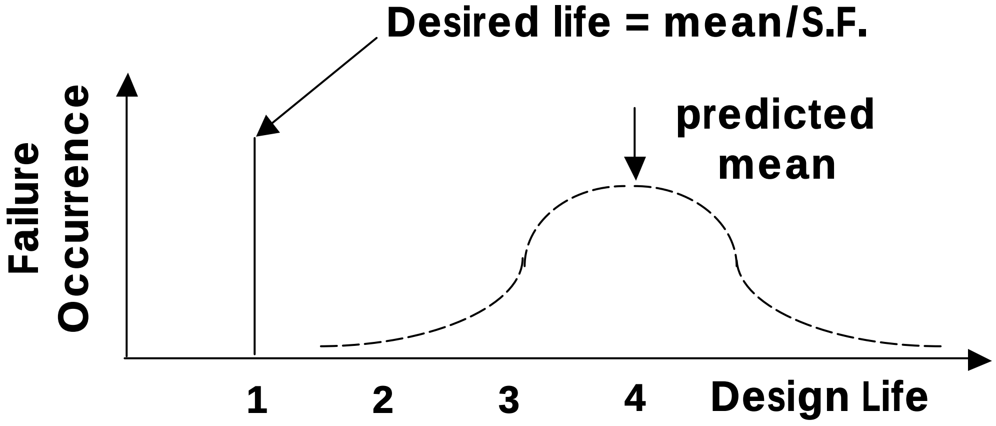
# *Safe-Life Criterion*

Design goal: component is to remain crack free for finite service life

- Assumes initial crack-free structure
- Establish "mean life" by test/analysis
- Safety factors account for "scatter"

Problems:

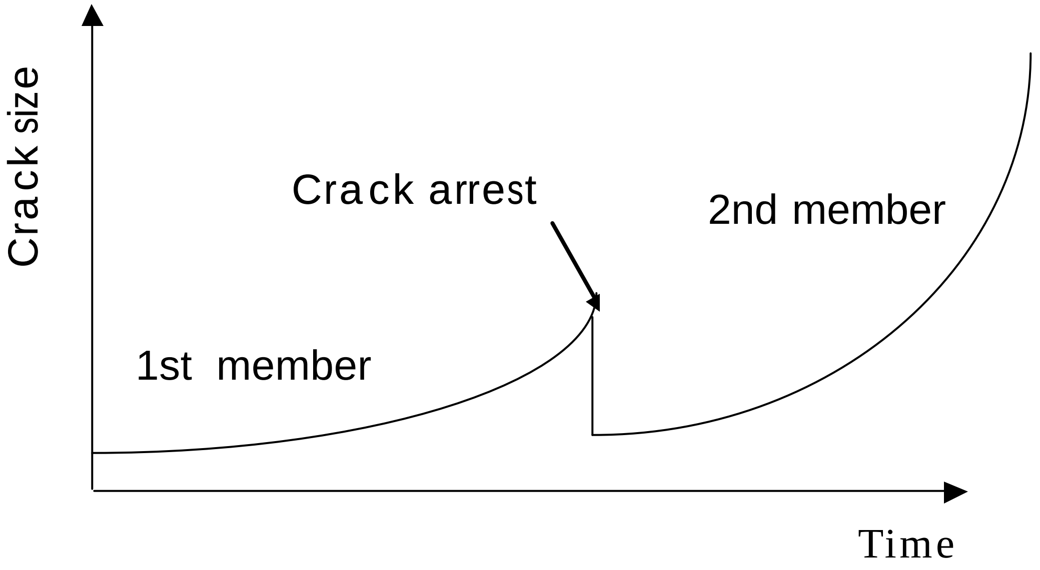
- large safety factor
- no protection from initial damage

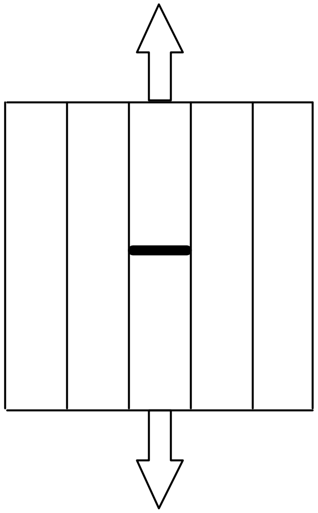


# *Fail-Safe Criterion*

Design goal: contain single component failure without losing entire structure

- Assumes crack is present
- Provide alternate load paths, redundant structure, crack stoppers, etc.
- Requires detection of 1st failure

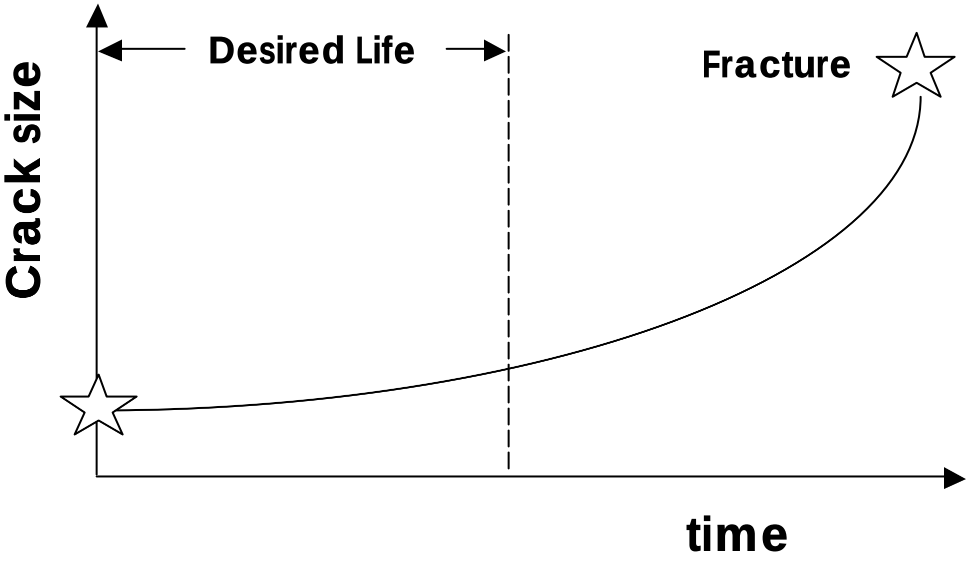




# *Slow Crack Growth Criterion*

Design goal: prevent initial crack from growing to
fracture during life of structure

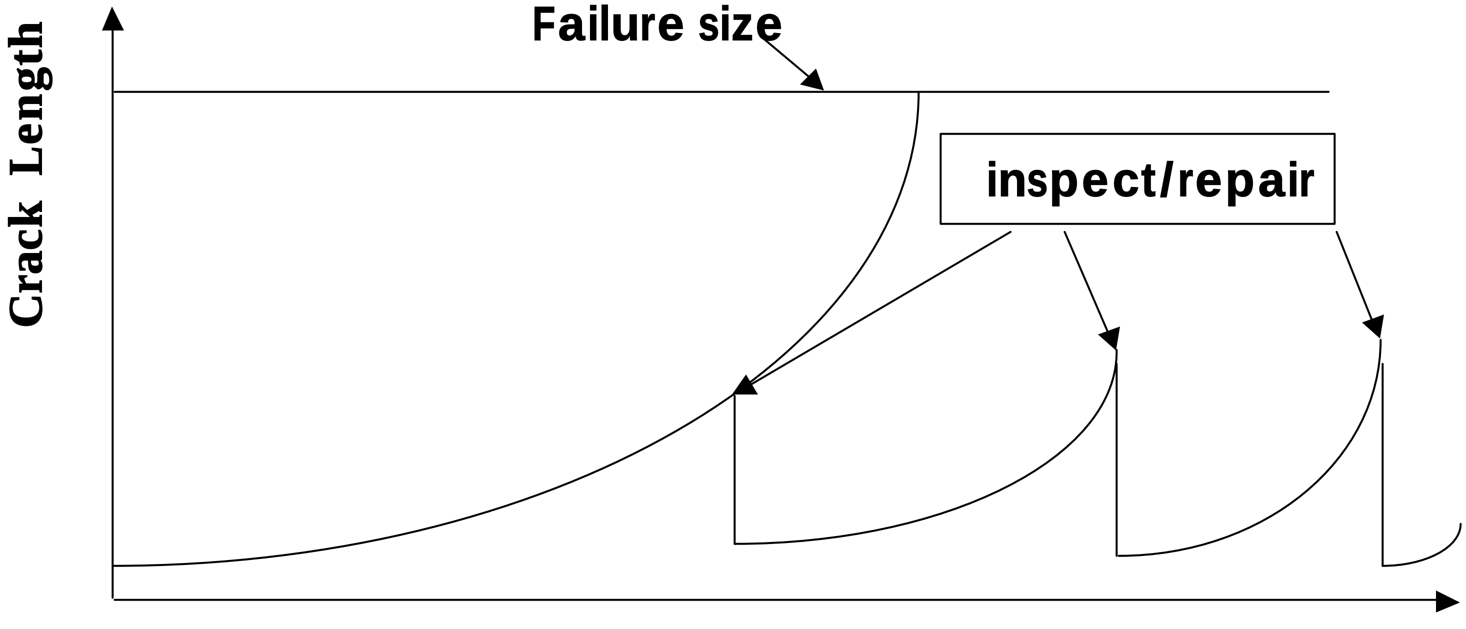
- Pre-existent crack size specified by inspection limits, experience
- Crack growth life
  > service life x S.F.
- Based on fatigue
  crack growth
  resistance
- Emphasizes nondestructive inspection



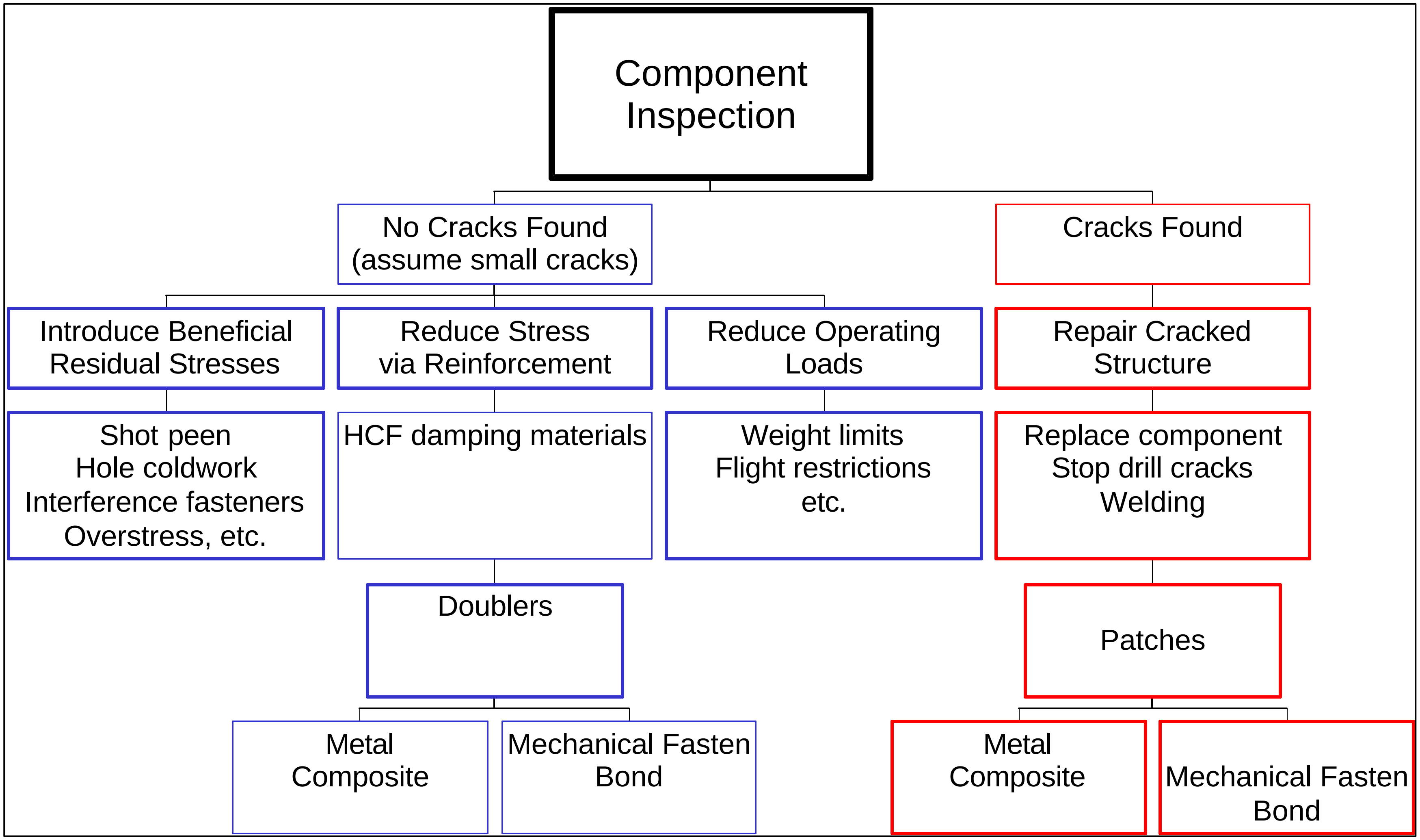
# *Retirement-for-Cause*

Design goal: Use periodic inspection/repair to achieve desired fatigue lives

Limited by repeated maintenance economics



# Life Extension Concepts



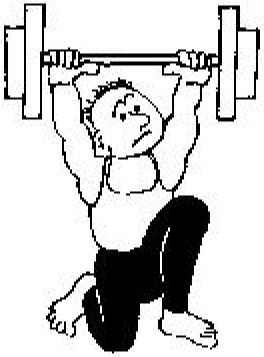
- Component Inspection
  - No Cracks Found (assume small cracks)
    - Introduce Beneficial Residual Stresses
      - Shot peen
      - Hole coldwork
      - Interference fasteners
      - Overstress, etc.
    - Reduce Stress via Reinforcement
      - HCF damping materials
      - Doublers
        - Metal
        - Composite
        - Mechanical Fasten
        - Bond
    - Reduce Operating Loads
      - Weight limits
      - Flight restrictions
      - etc.
  - Cracks Found
    - Repair Cracked Structure
      - Replace component
      - Stop drill cracks
      - Welding
      - Patches
        - Metal
        - Composite
        - Mechanical Fasten
        - Bond

# *Summary*

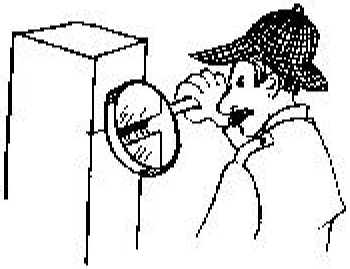
- Fatigue is complex problem that involves many disciplines
- Fatigue affects design and operation of many types of structures
- Fatigue may be treated by several methods/philosophies
  - Assume component cracked
  - Assume component uncracked
  - Probabilistic methods

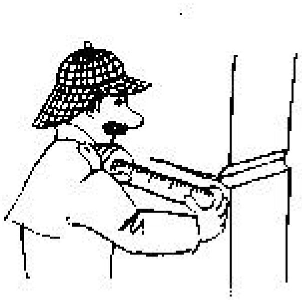
# FATIGUE
## AN INTERDISCIPLINARY PROBLEM

LOADS

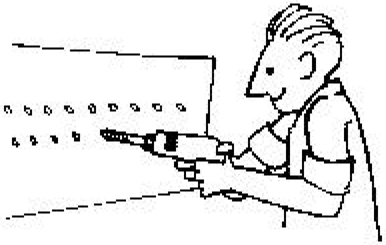


CRACK INITIATION AND DECTECTION



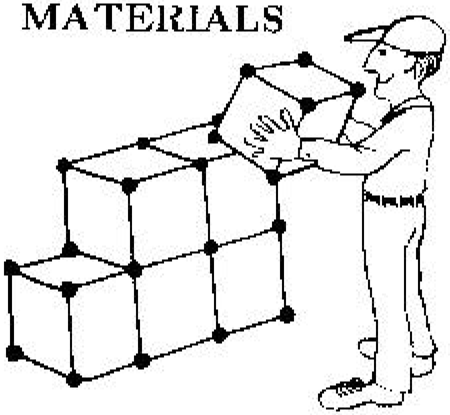


CRACK GROWTH



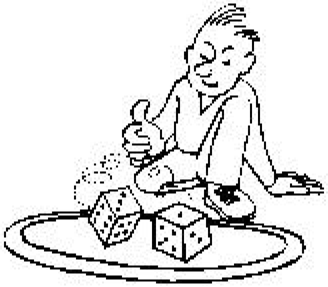
MANUFACTURING

MATERIALS



ENVIRONMENT

PROBABILITY



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