Prevention of Fatigue Failure

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Shot Peening and Blast Cleaning Workshop

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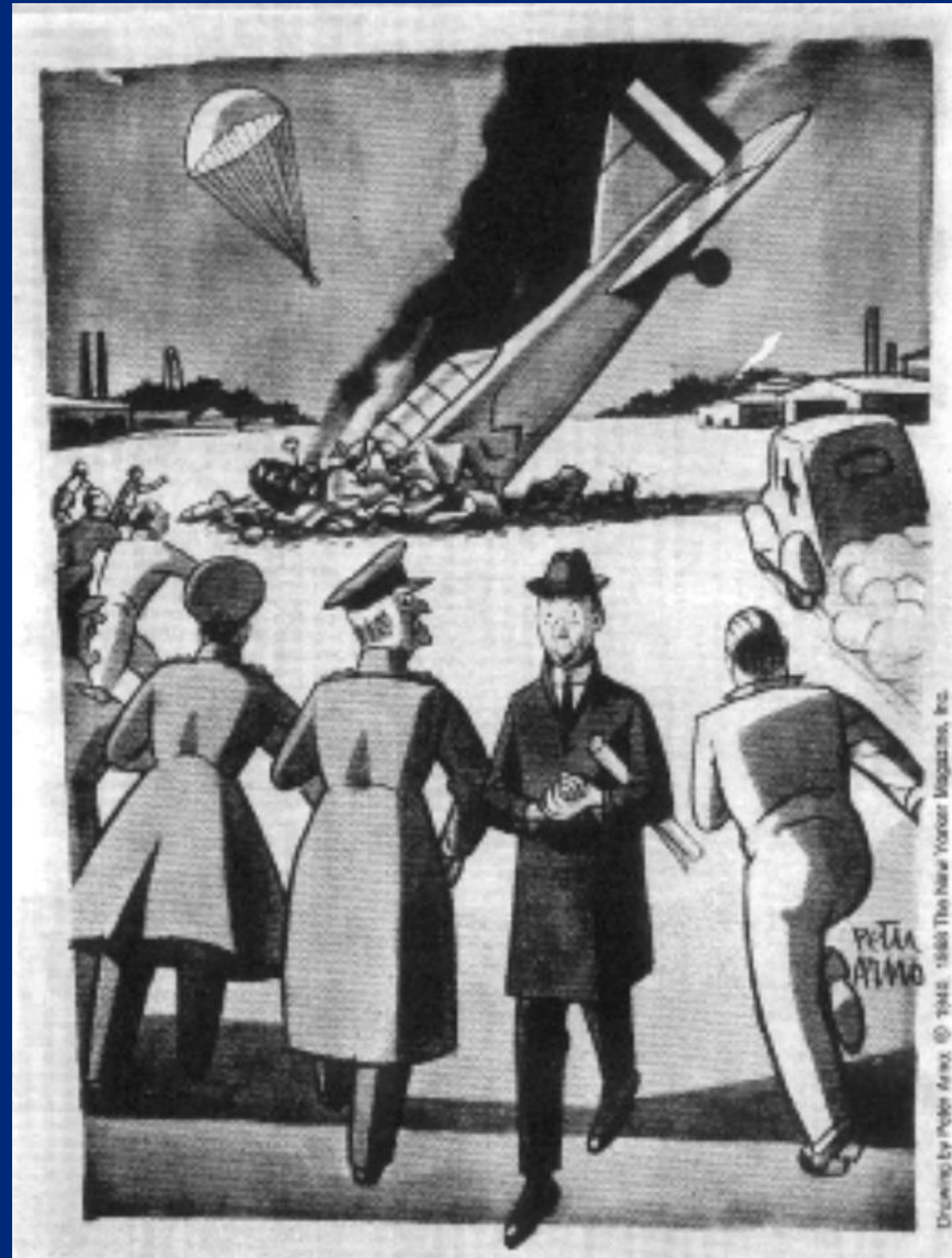
PURDUE UNIVERSITY

Purdue University Aeronautics & Astronautics

“Well, back to the old drawing board!”



Drawing by Peter Arno; © 1940, 1968, The New Yorker Magazine, Inc.

Lessons Learned from Failure

"On the contrary, our research revealed much information. First, the unit is quite unpredictable."

Objective

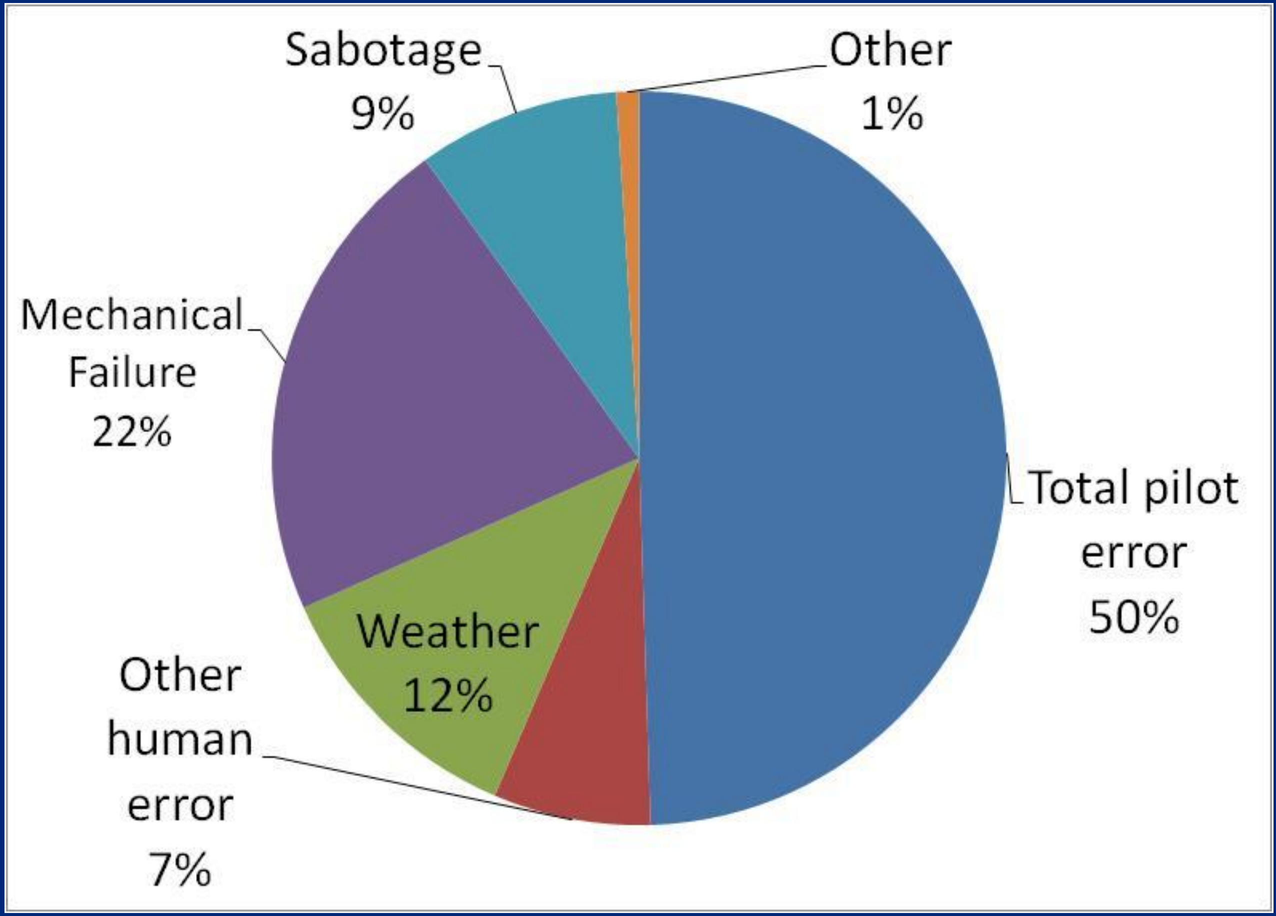
Overview current fatigue design criteria for aircraft

- Background
- Overview failure modes
- Fatigue design criteria

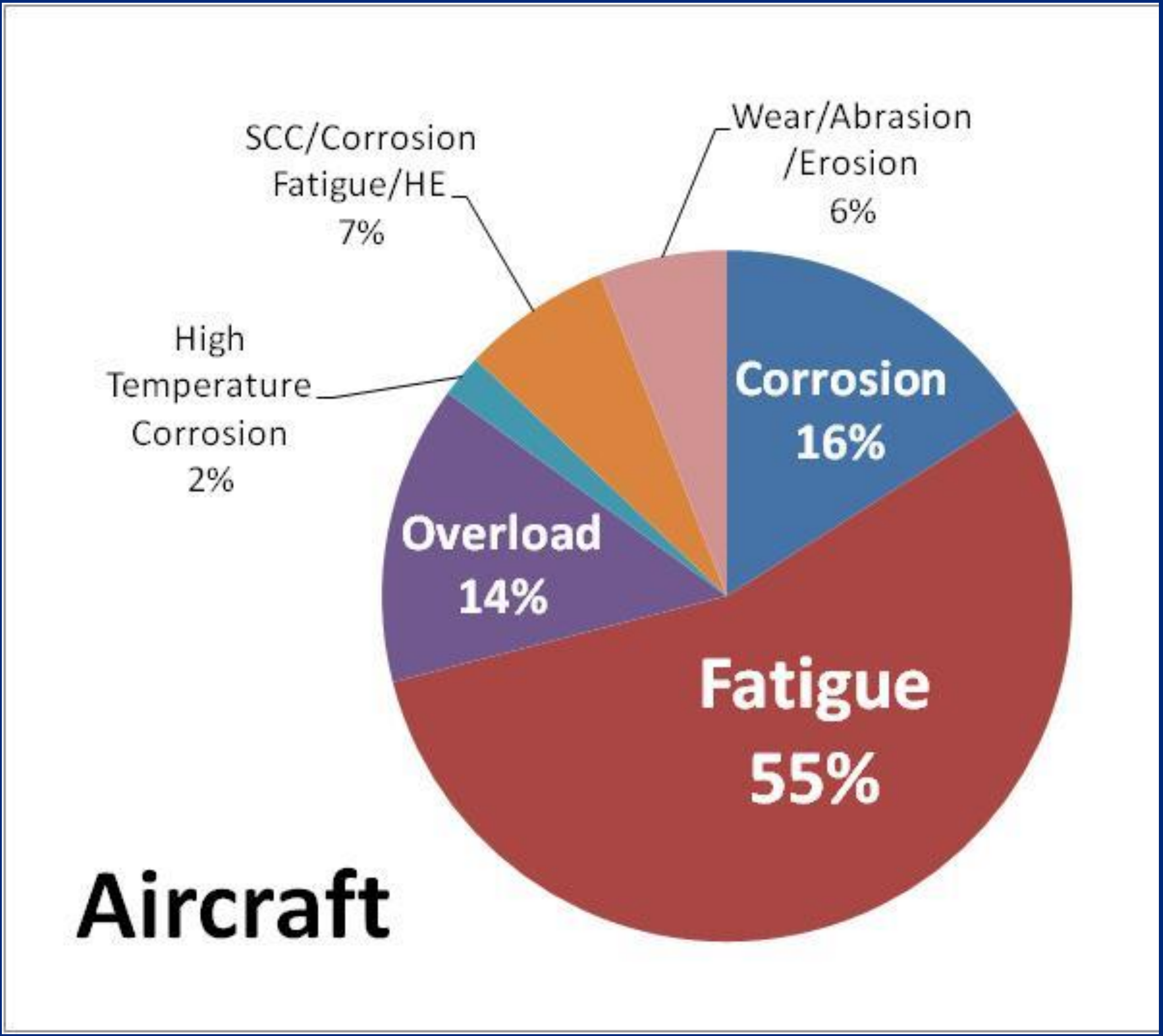
Principal Causes of Fatal Aircraft Accidents (1950 -2008)

- 1300 fatal commercial aircraft accidents world wide
- Excludes military, private, helicopter, and aircraft with less than 10 people aboard

Ref: http://www.planecrashinfo.com/cause.htm

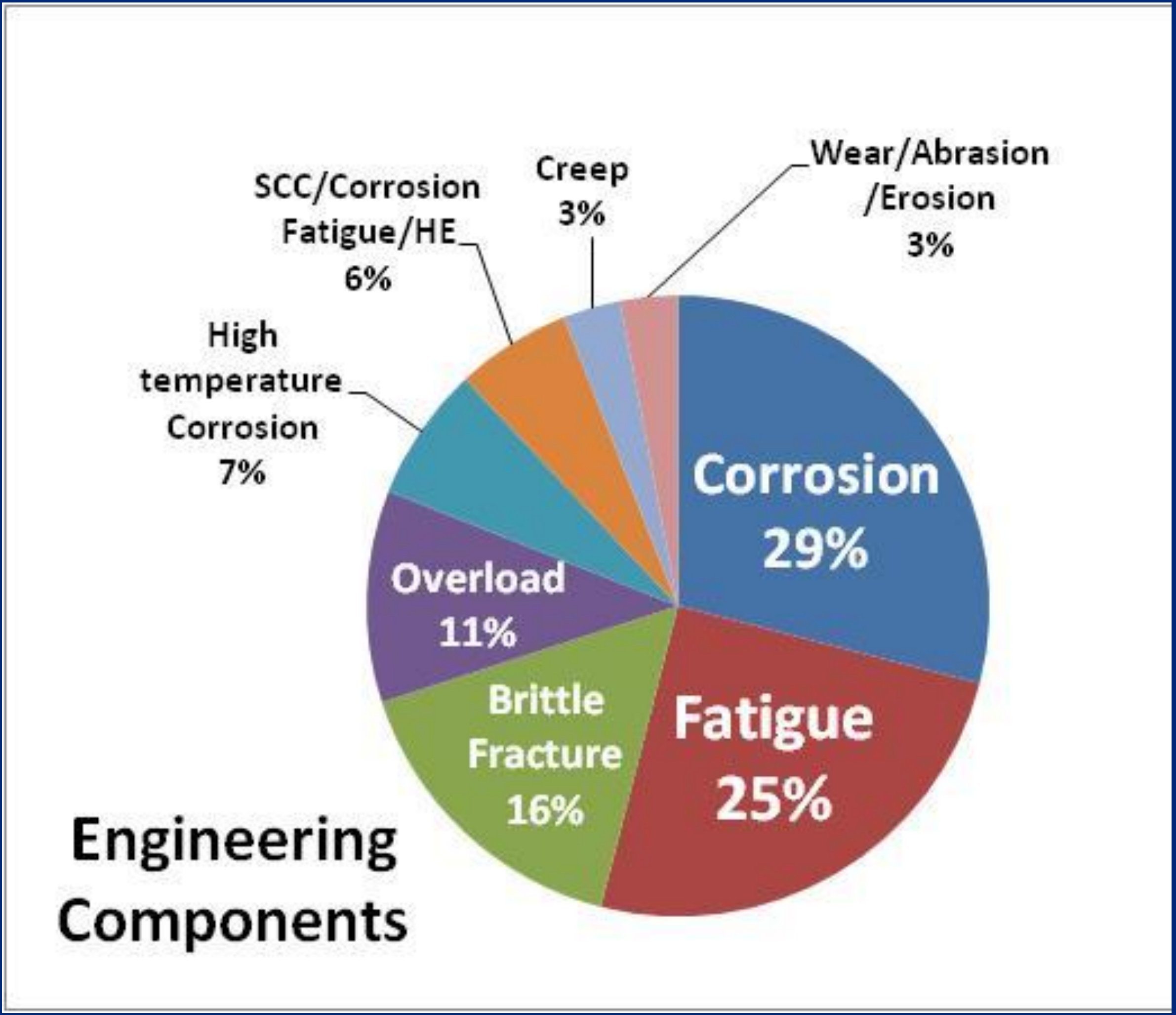


Failure Modes: Aircraft



- **QinetiQ study based on approximately 3000 case histories**
- **Ref. Findlay & Harrison, "Why Aircraft Fail,"** ***Materials Today*****, Nov. 2002**

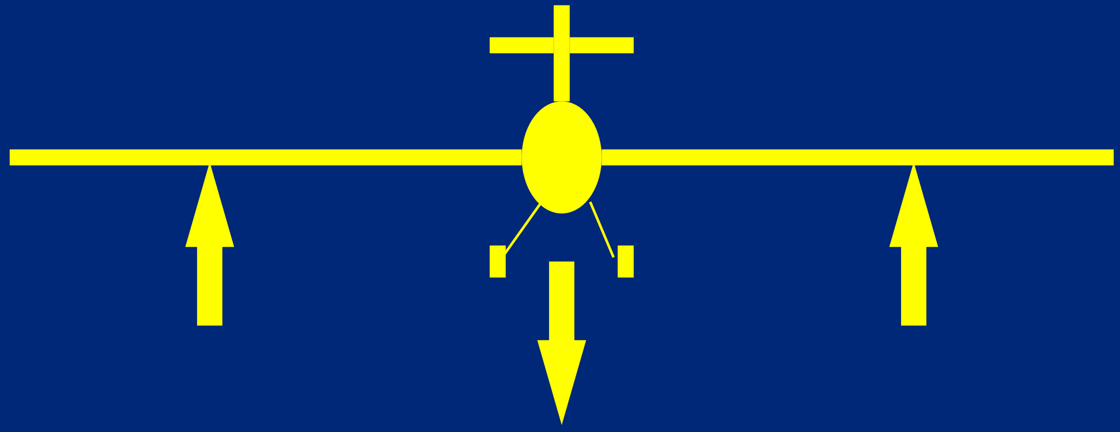
Failure Modes: Engineering Component



- **QinetiQ study based on approximately 3000 case histories**
- **Ref. Findlay & Harrison, "Why Aircraft Fail," *Materials Today*, Nov. 2002**

Structural Failure Modes

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



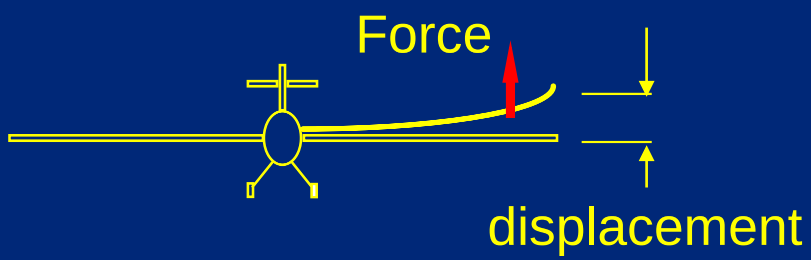
Sun Tzu: The Art of War

(circa 500 B.C.)

Know the Enemy

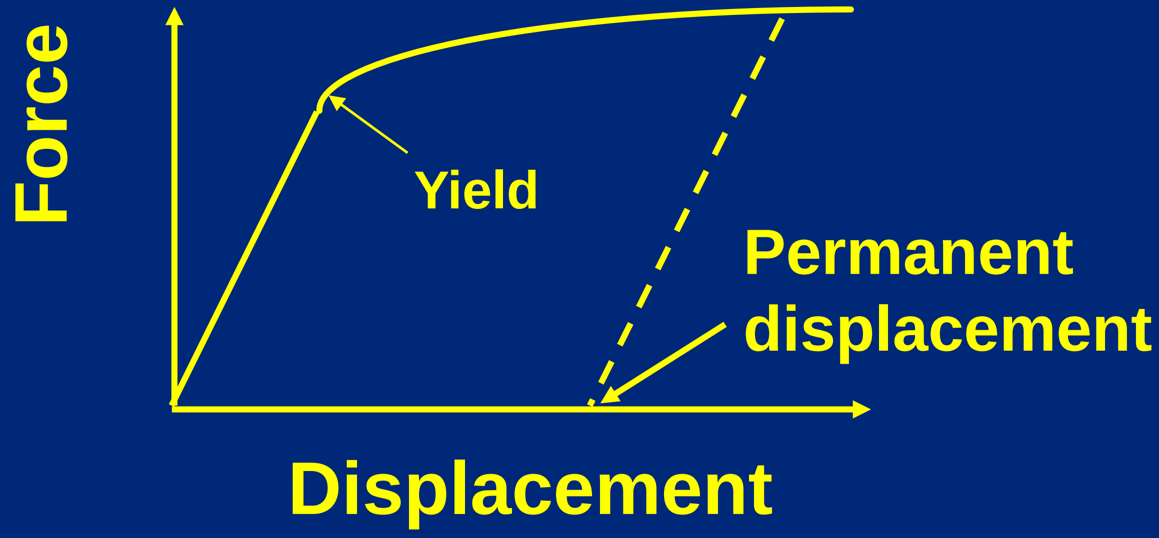
“If you know the enemy and know yourself, your victory will not stand in doubt”

Deformation

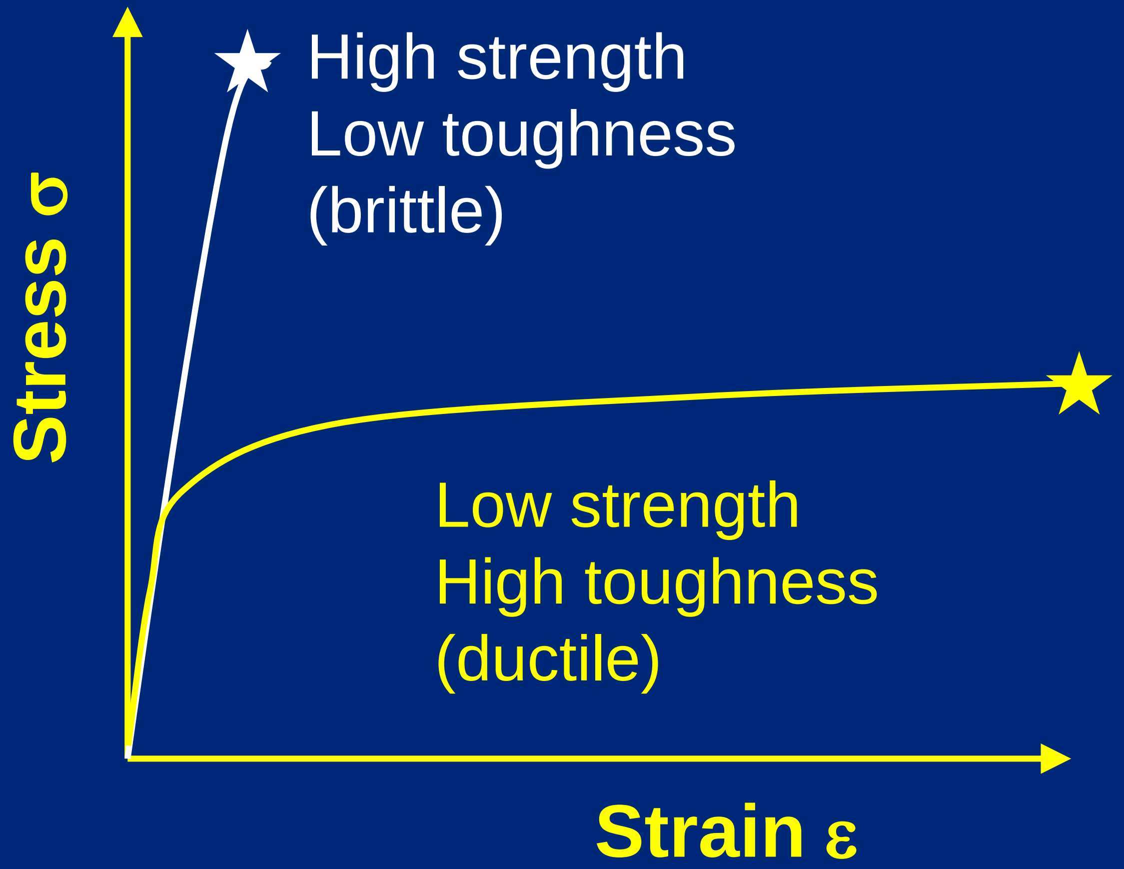


Change in component size/shape

- Elastic (recoverable)
- Inelastic (permanent)



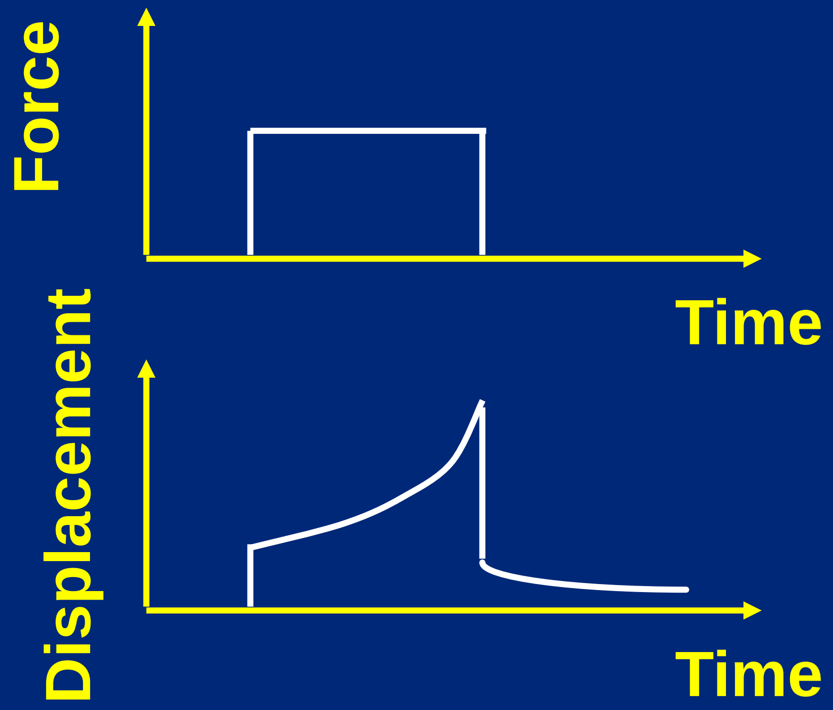
Toughness vs Strength

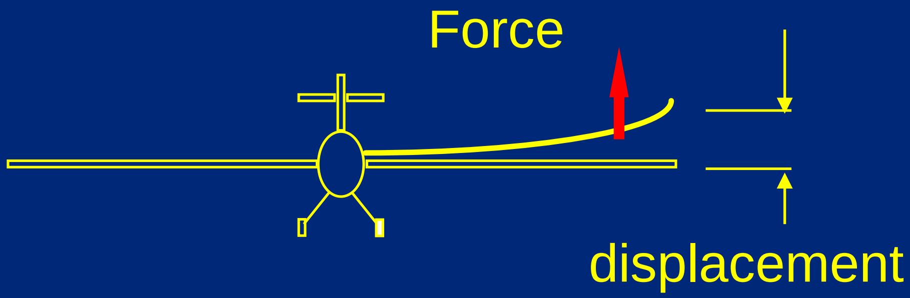


- **Recall high strength alloys more brittle than low strength**
- **Strength vs toughness trade-off has important consequences for material selection**
- **Must decide which failure mode(s) controls particular component**

Creep

- **Time dependent deformations caused by sustained loading**
- **Aggravated by elevated temperature**

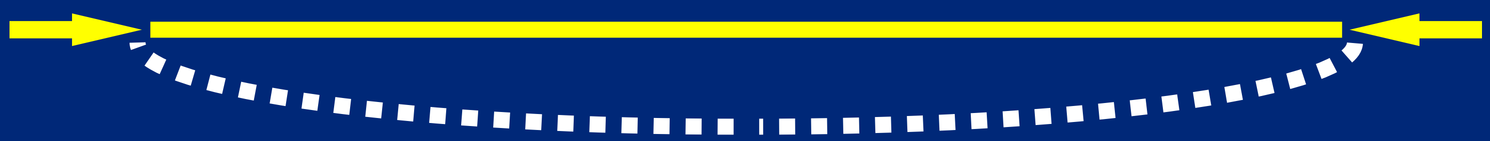


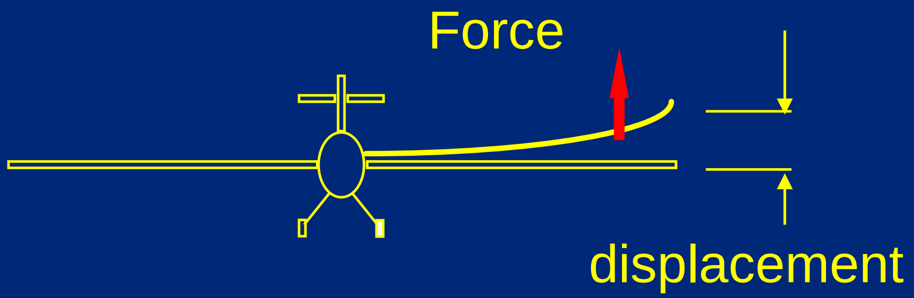


Buckling

Failure of "slender" members

- compressive loads cause an "instability"
- Results in catastrophic collapse





Corrosion

- Time dependent chemical reaction between material & environment
- Many forms: uniform, pitting, galvanic, stress corrosion, hydrogen embrittlement
- Causes general and/or local material loss
  - thickness loss > increased stress
  - local pits > stress concentrations
- Prevent by design, coatings, material selection
- Maintenance critical

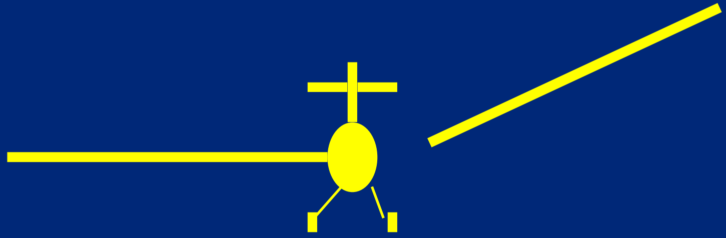
Photo: ASTM Standardization News, April 96

Corrosion Costs

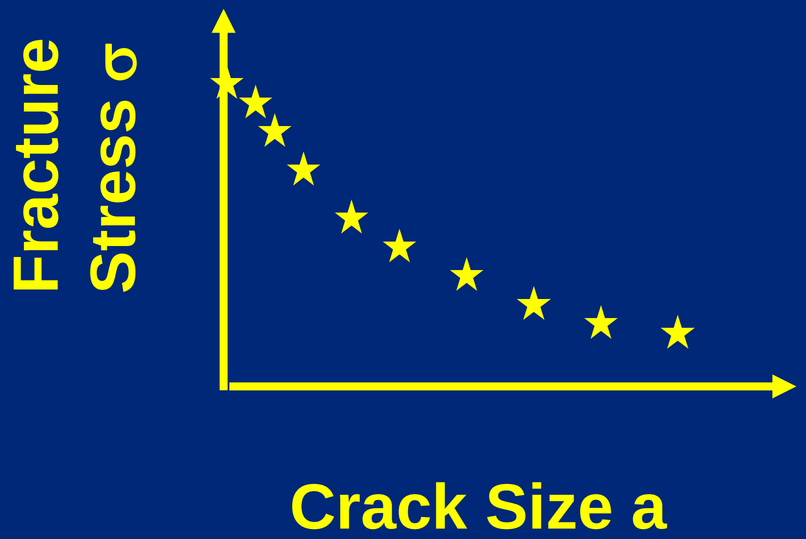
- $13 B/yr – Aircraft Industry (North America)
- $3 B/yr – Military aircraft (USA)
- $2 B/yr – US Army
- ~2% GDP – Australia
- 0.8 – 1% GNP – Japan (1997 estimate)
- $30 B – Bridges (US highway)
- $4 B – US Army helicopters (1998 estimate)
- $5 B – Power Generation (USA)

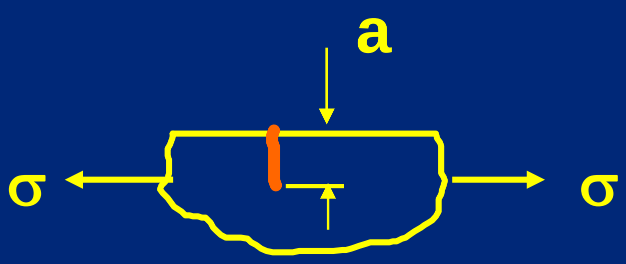
Ref: The Shot Peener, Spring 2006

Fracture



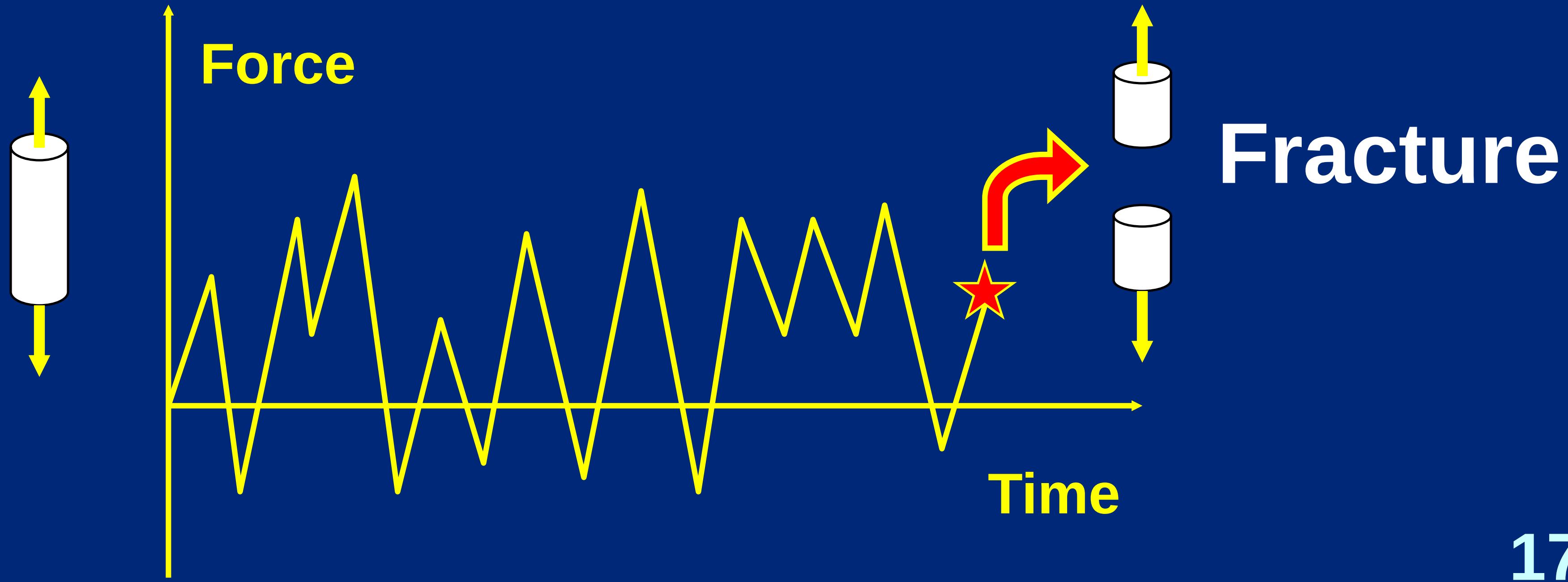
- Catastrophic failure
- Very sensitive to pre-existent crack and tensile loading
- Final stage of fatigue





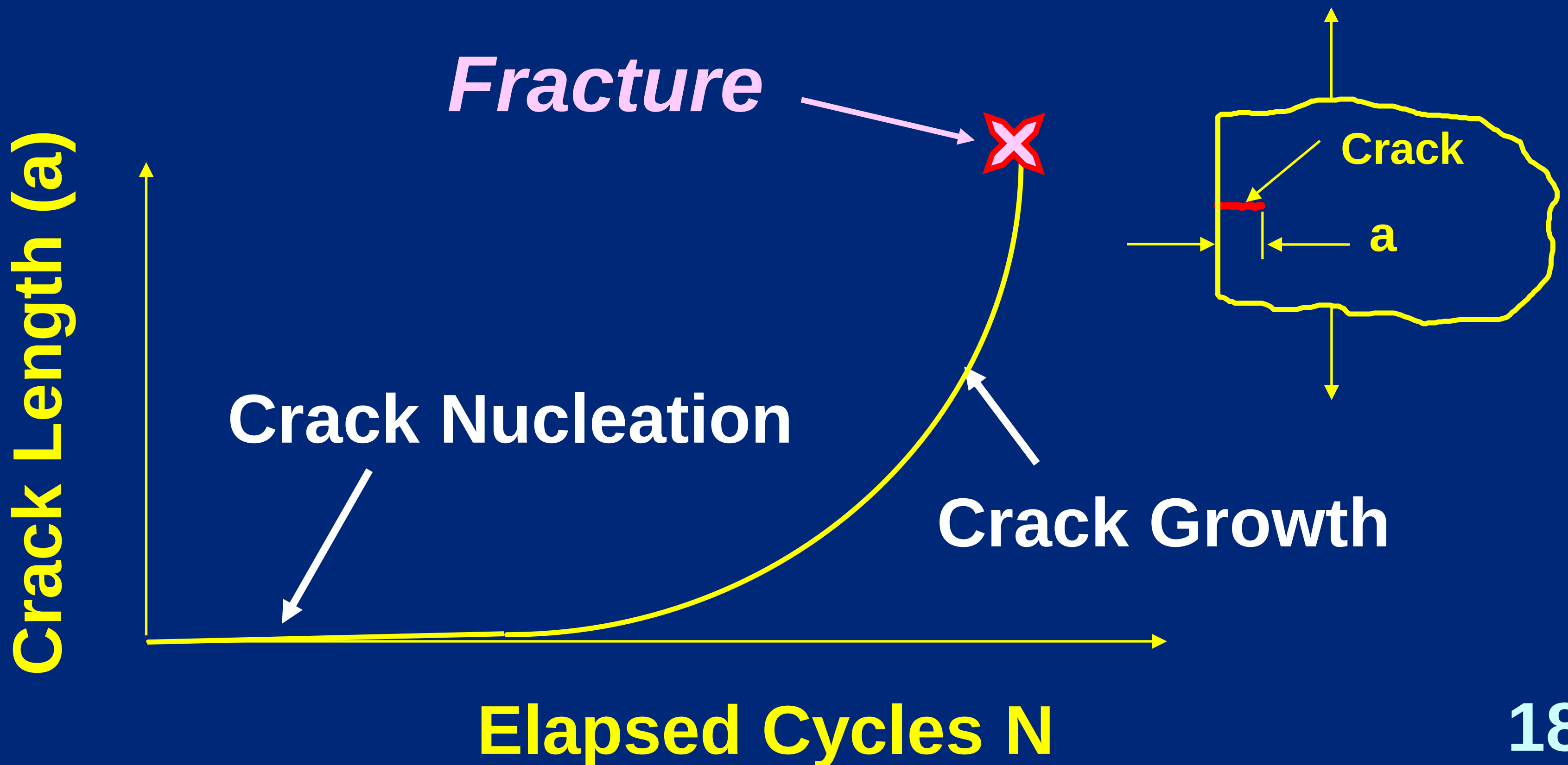
Fatigue

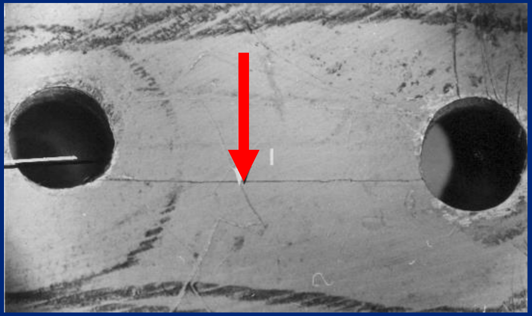
- Failure due to cyclic loading
- Involves crack formation and propagation
- Very sensitive to initial “damage”

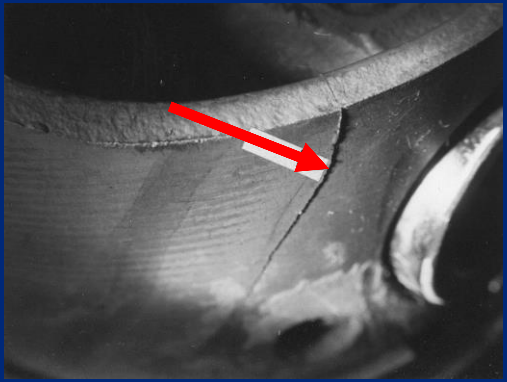


Fatigue Failure Mechanism

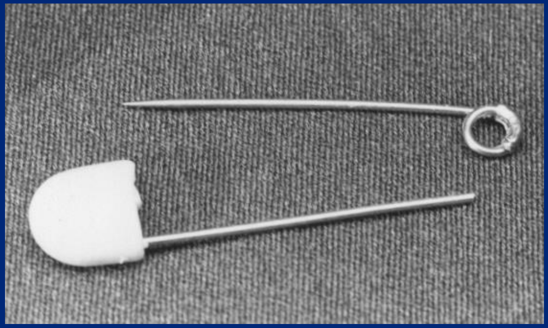
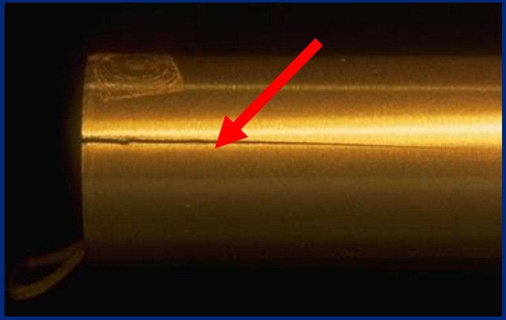
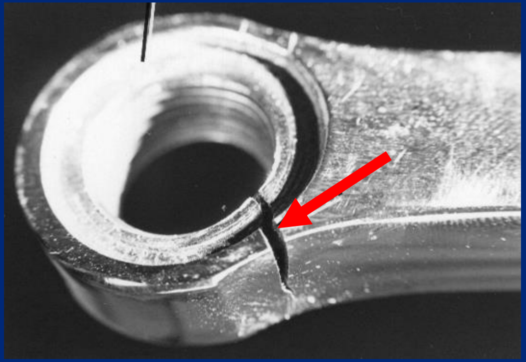
- Crack formation, growth, and fracture
- Life depends on initial quality, load, . . .
- Much "scatter" in data







Fatigue is problem for many types of structures

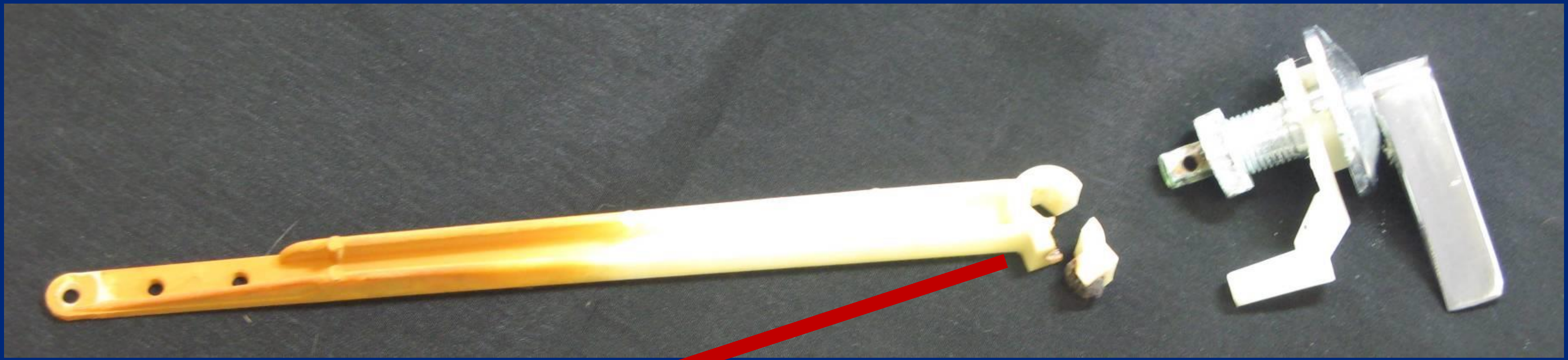




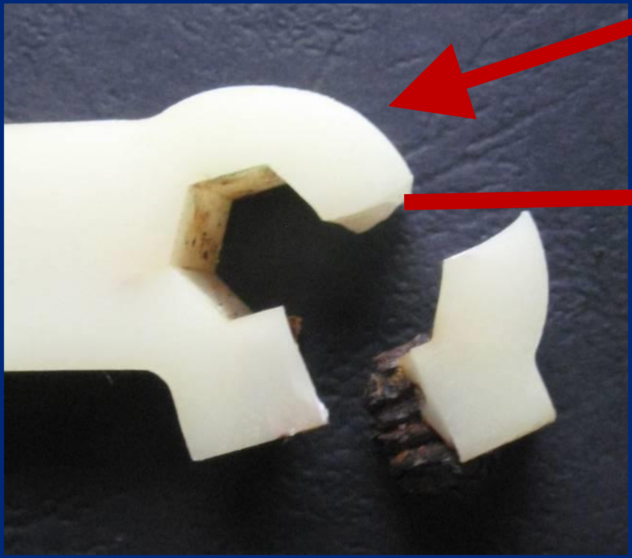
Fatigue Failure of Toilet Seat

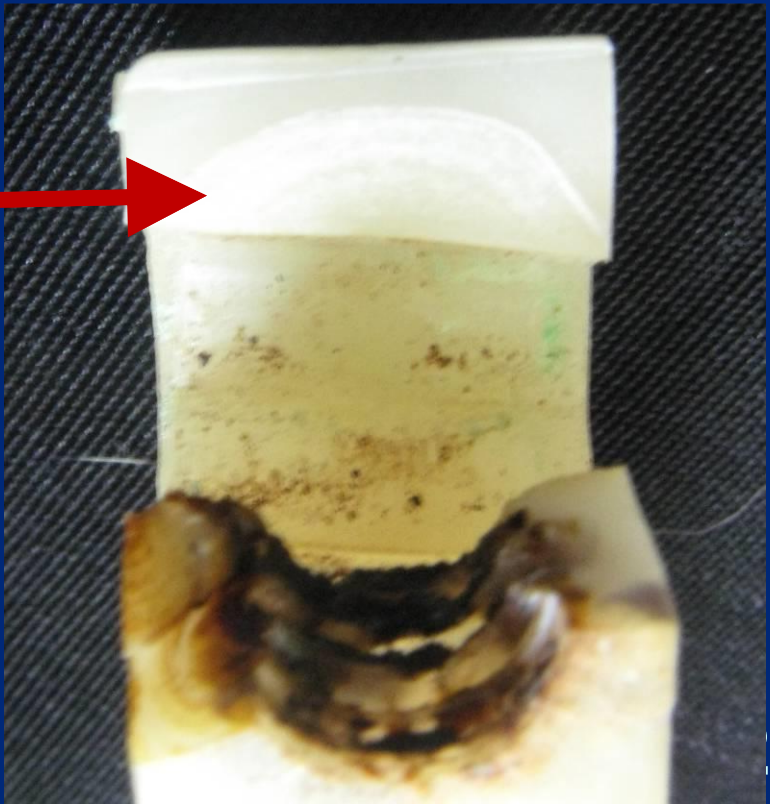
Note:

- Fatigue cracks started at stress concentrations
- Characteristic beach marks

Fatigue Failure of Toilet Lever

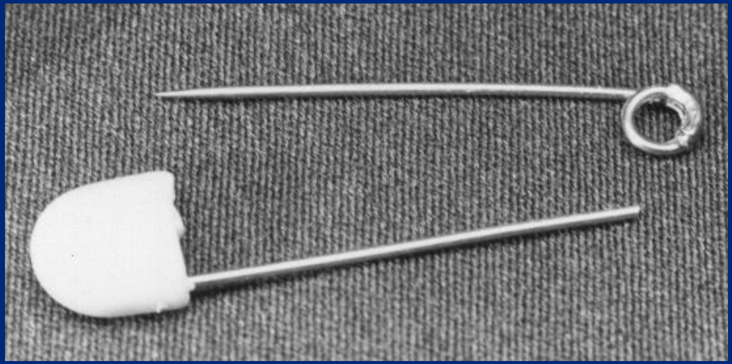


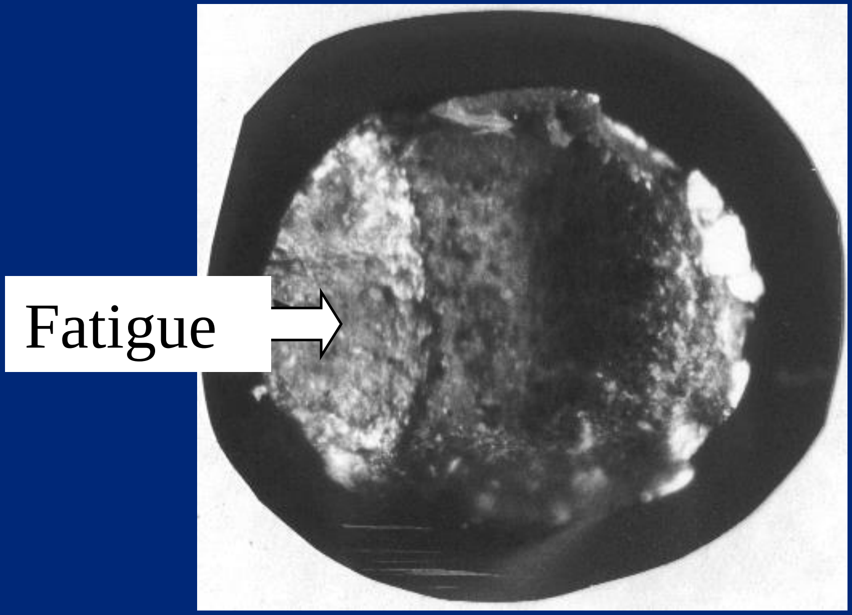




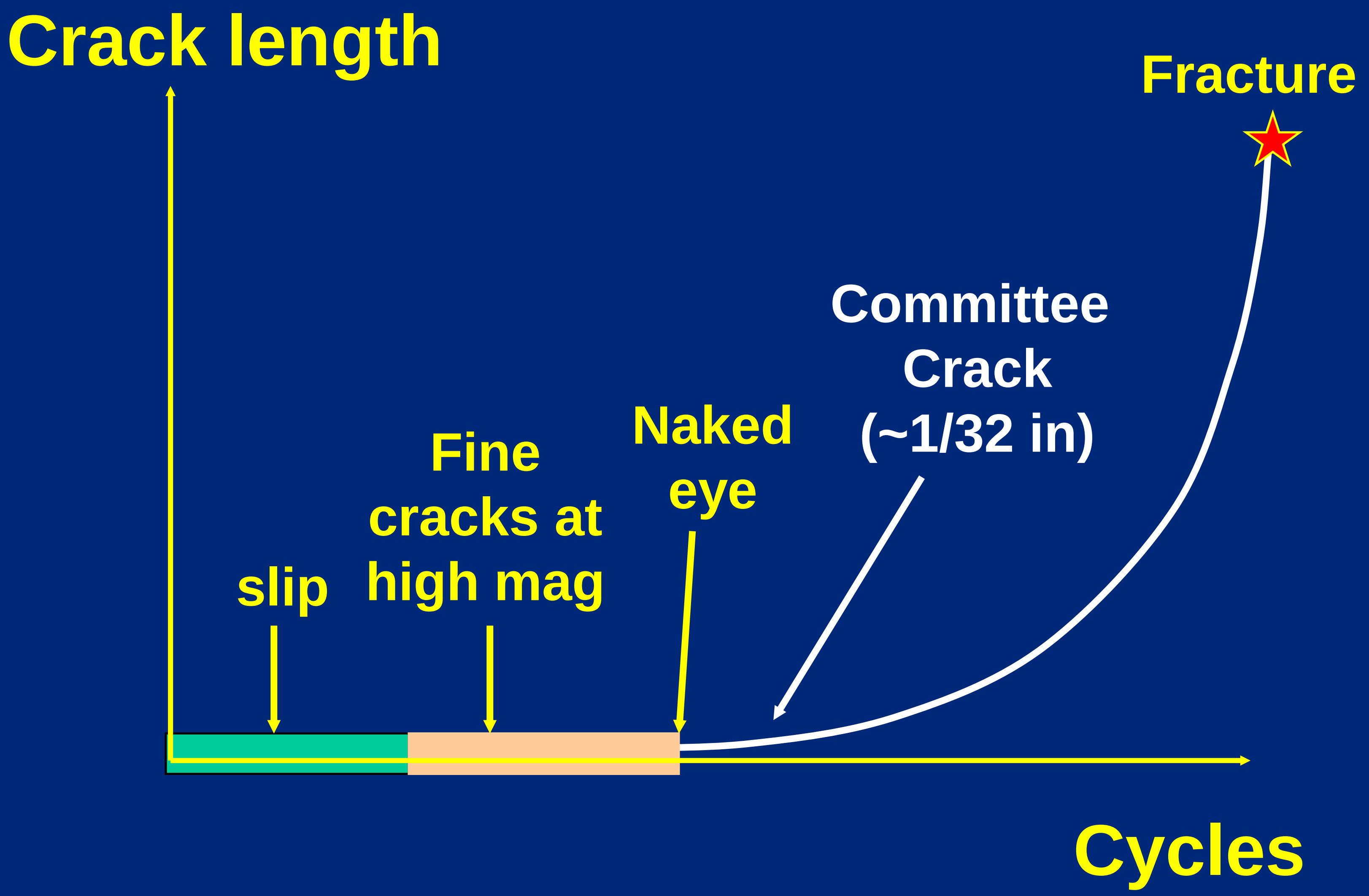
Note beach marks on fracture surface

Environmentally Assisted Fatigue Failure





Fatigue Crack Formation



Fatigue Crack Formation

- Cracks often form at free surfaces – Sources of
  - Slip (local plastic deformation)
  - “Nicks and dings” that act as stress concentrations
  - Exposure to corrosion
- Can also form at other internal or external material inhomogeneities or other structural damage

Fatigue is a “Defect Assisted” Degradation Mechanism

Extrinsic (manufacturing/service)

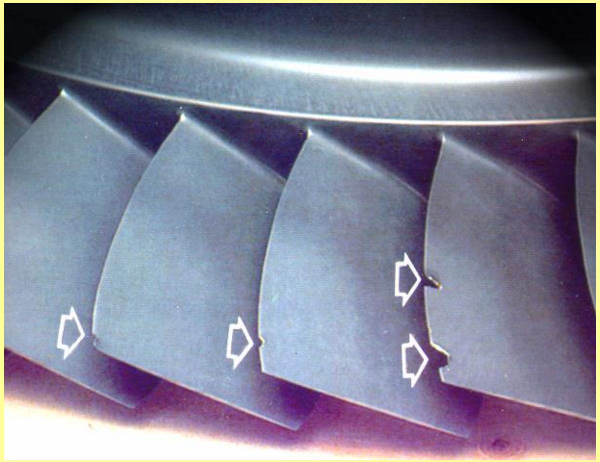
- Machining/manufacturing
- Corrosion
- Foreign Object Damage (FOD)
- Etc.

Intrinsic (inherent to material)

- Constituent particles
- Pores
- Inclusions,
- Etc.

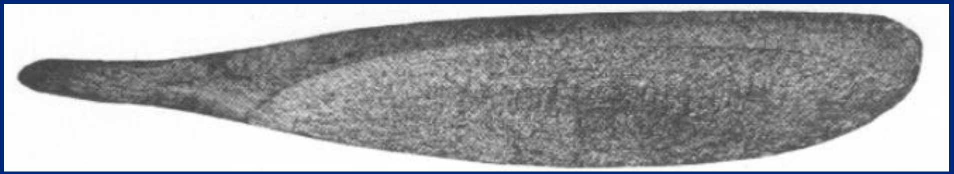
Extrinsic Damage

Fan Blade



FOD occurrence:
⇒ stage
⇒ span location
⇒ depth
⇒ shape

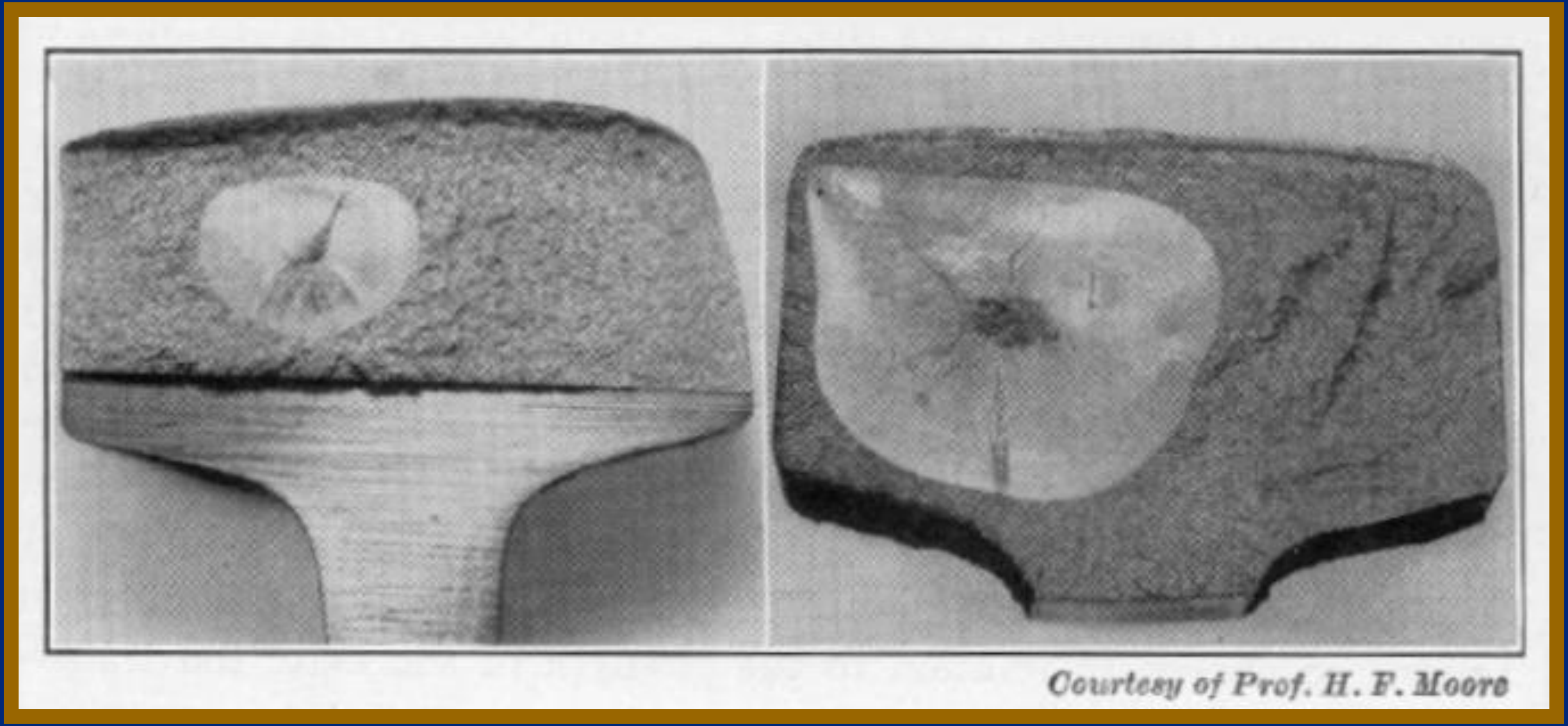
Propeller



Fracture Surface

Fatigue origin

Intrinsic: Material inclusion



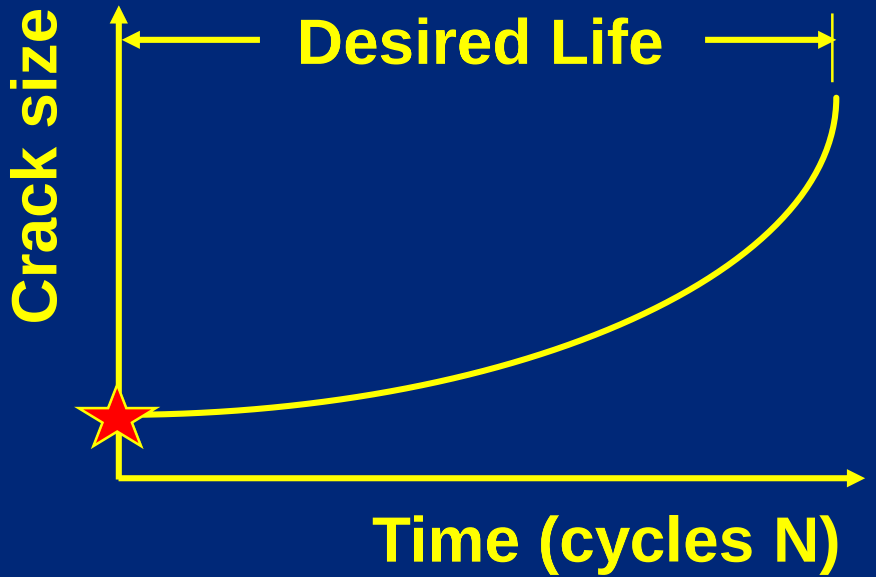
- Fatigue failure of Railroad Rails
- Cracks started at internal material anomaly

Damage Tolerance

The ability of a structure to resist <u>prior</u> damage for a specified period of <u>time</u>.

<u>Initial damage</u>

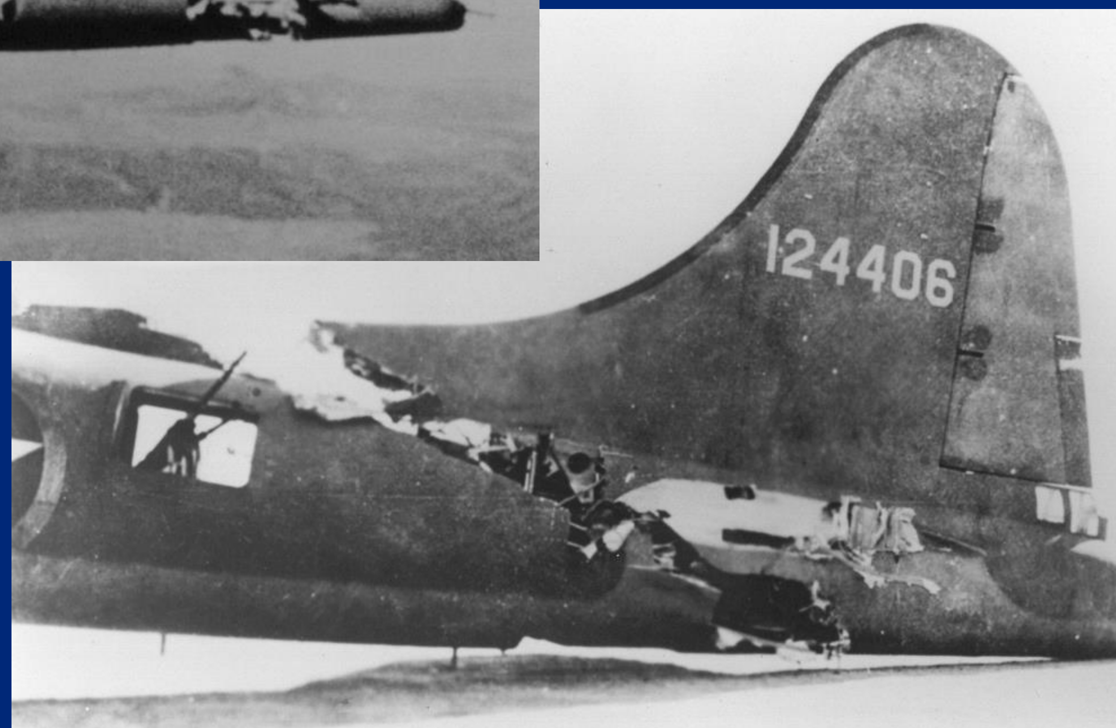
- **material**
- **manufacturing**
- **service induced**
- **size based on inspection capability, experience, . . .**



Key attribute for "critical" components

Damage Tolerant Aircraft

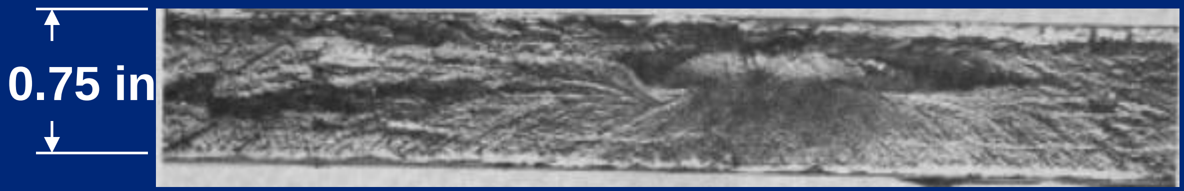
B-17F/Bf-109 midair collision on February 1,1943 over Tunisia



B-17 flew 90 minutes and landed safely

Fig. 1.1 USAF Museum photographs

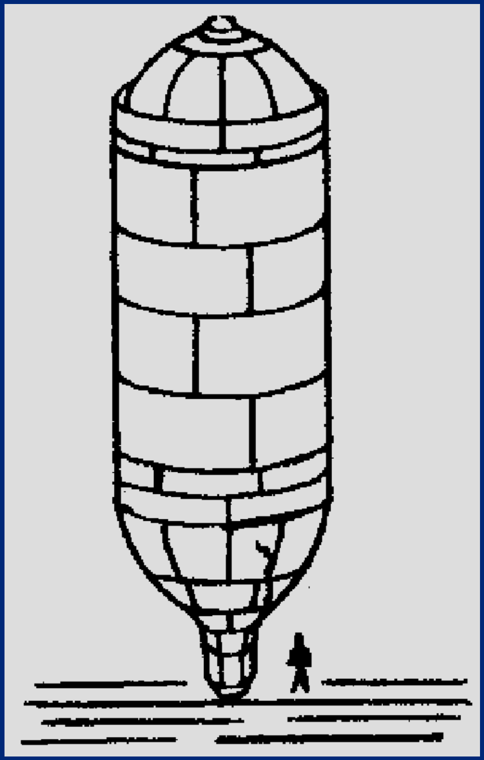
Rocket Motor Case Proof Test
(April 11, 1965)

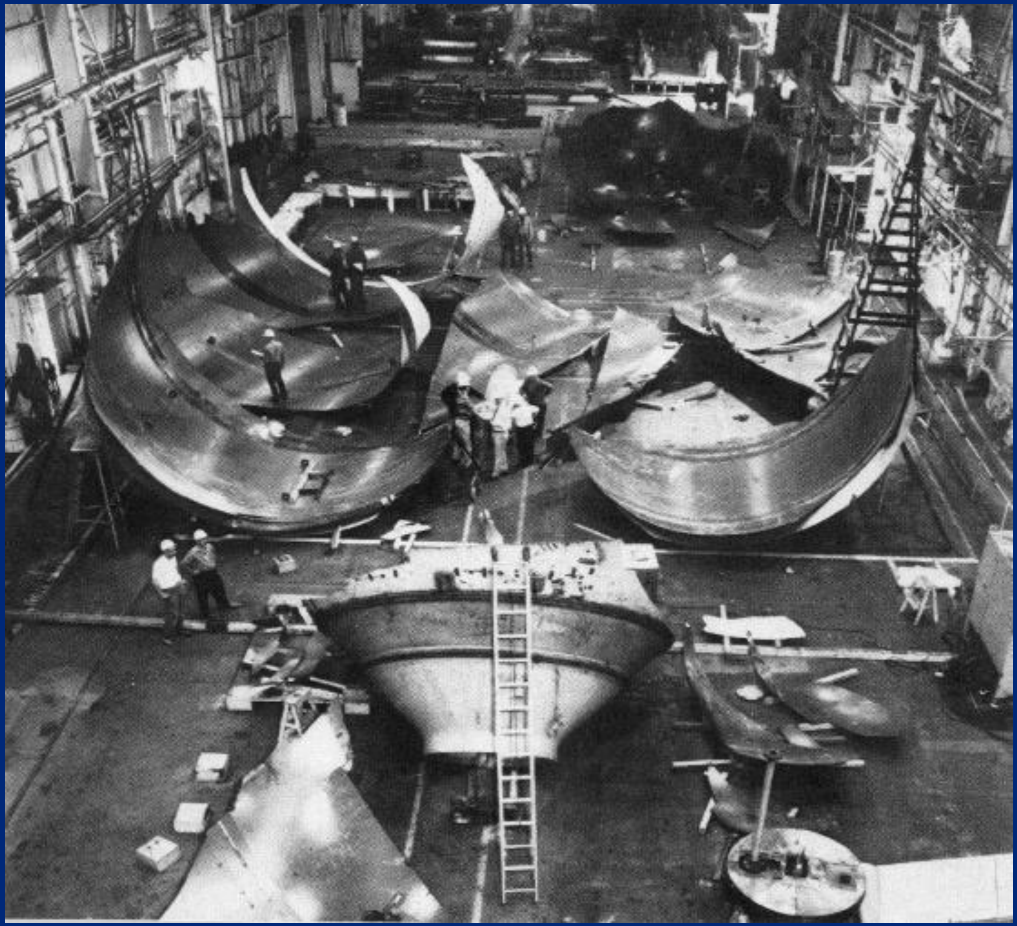


Undetected 1.5 inch weld flaw
failure at 50% design pressure

250 grade maraging steel

22 ft dia x 75 ft long (Fig. 1.2)





Silver Bridge Failure
(15 December 1967)

- **Point Pleasant, W. VA**
- **Operated 19 May 1928 – 15 Dec 1967 (39 years)**
- **Sudden Collapse at 5:00 p.m.**
  - **3 spans fell within 1 minute**
  - **46 deaths/ 37 vehicles**
- **Stress Corrosion cracking failure**
- **Critical crack size ~ 0.12 in.**

Figure 2.6 Point Pleasant Bridge after collapse (courtesy of Federal Highway Administration).

Point Pleasant, West Virginia Bridge Failure

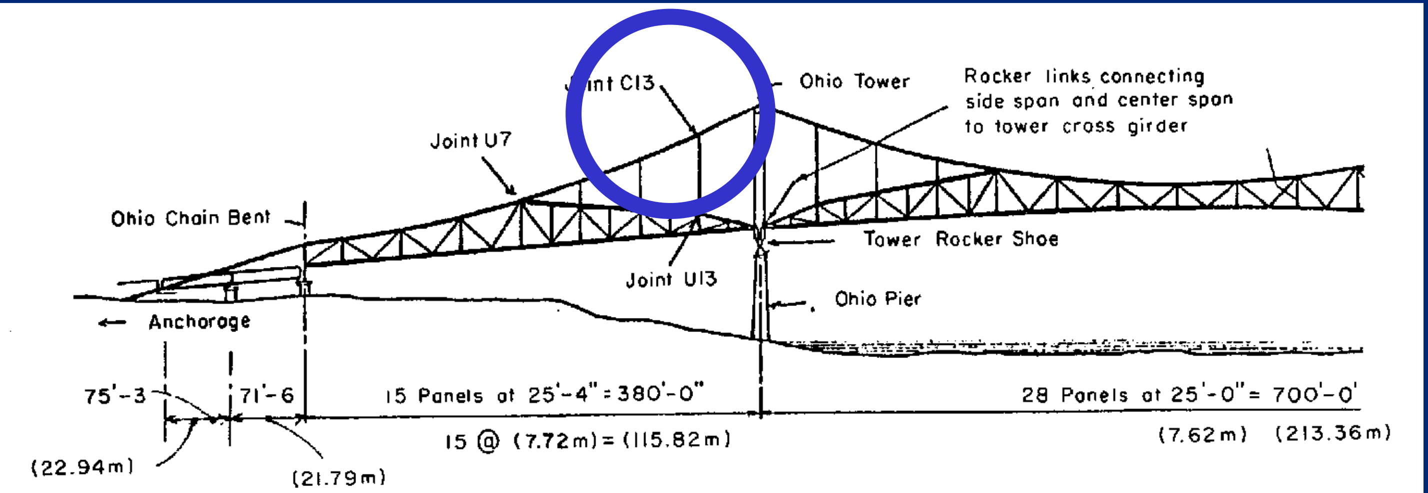
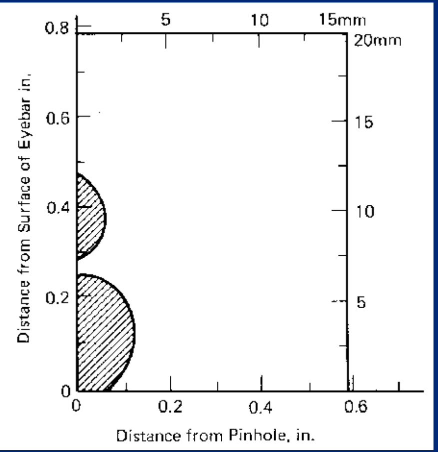


Figure 2.2 Elevation of Point Pleasant Bridge showing location of joints C13, U7, and U13.



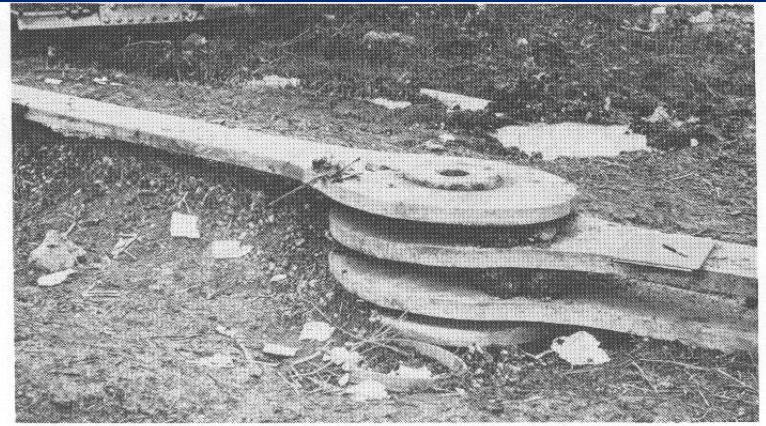


Figure 2.7 One of the eyebar joints after collapse (courtesy of Federal Highway Administration).

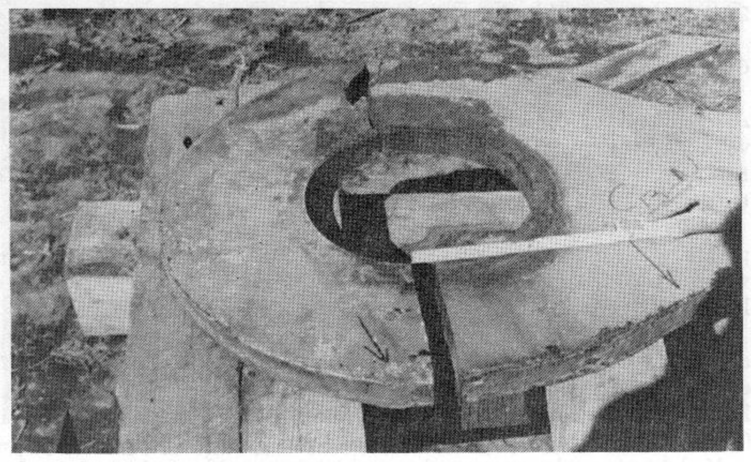


Figure 2.8 Fractured C13N eyebar (courtesy of Federal Highway Administration).

Poor Damage Tolerance

1969 F-111 Accident

- **Forging defect in wing attachment**
- **Caused failure after 100 flight hours**
- **Promoted advances in damage tolerant design**

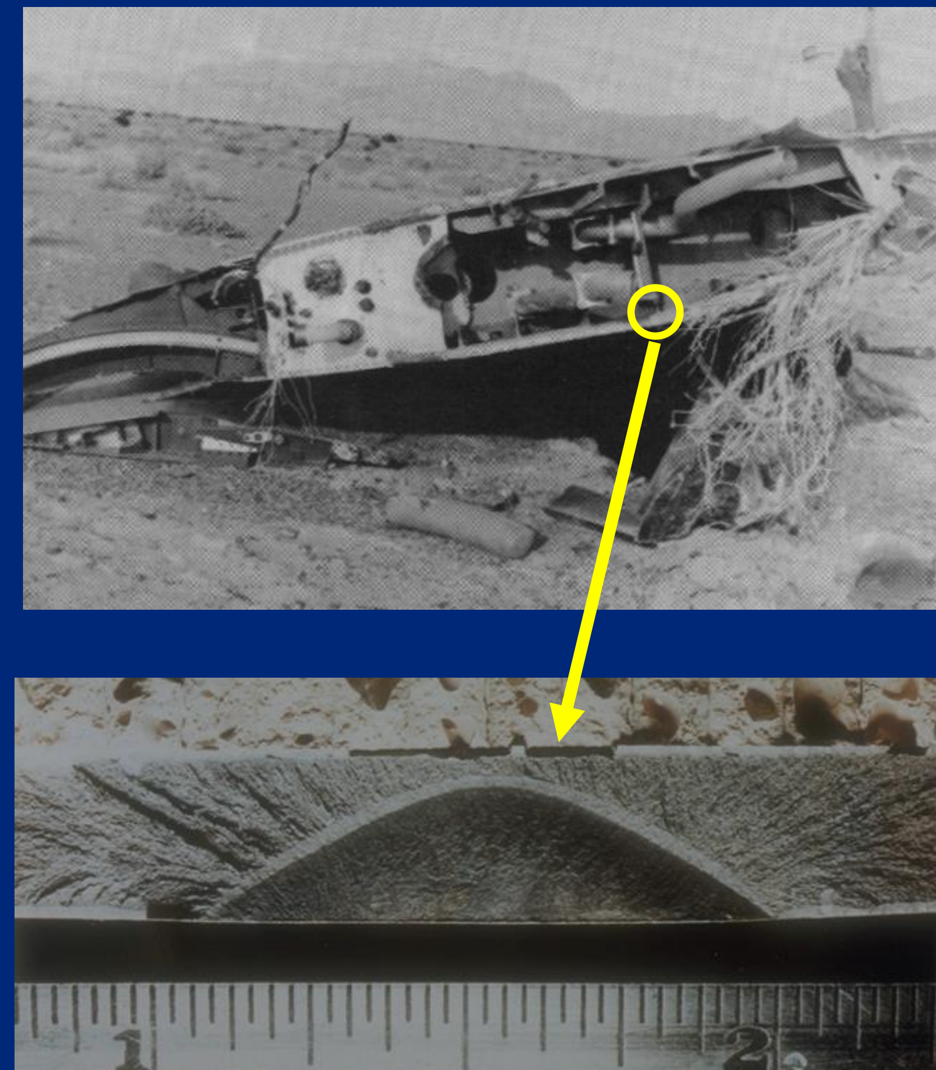


Fig. 1.4

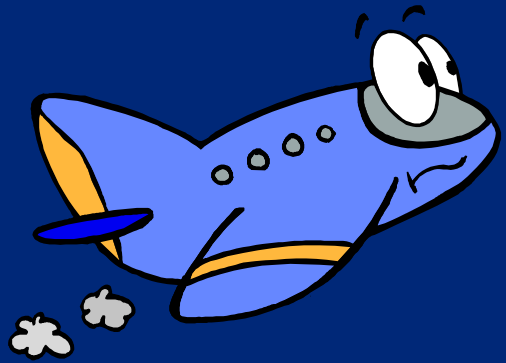
Thou Shalt Assume Cracks

Military Specification MIL-A-83444 (USAF) (2 July 1974)

"This specification contains the damage tolerance design requirement applicable to airplane safety of flight structure. The ***objective*** *is to* ***protect*** the **safety** of flight structure ***from*** potentially deleterious ***defects*** effects of material, manufacturing and processing through proper material selection and control, control of stress levels, use of fracture resistant design concepts, manufacturing and process controls and the use of careful inspection procedures."

". . . The analyses shall assume the presence of flaws placed in the most unfavorable location and orientation with respect to the applied stresses and material properties. . ."

Damage Tolerance Engineers

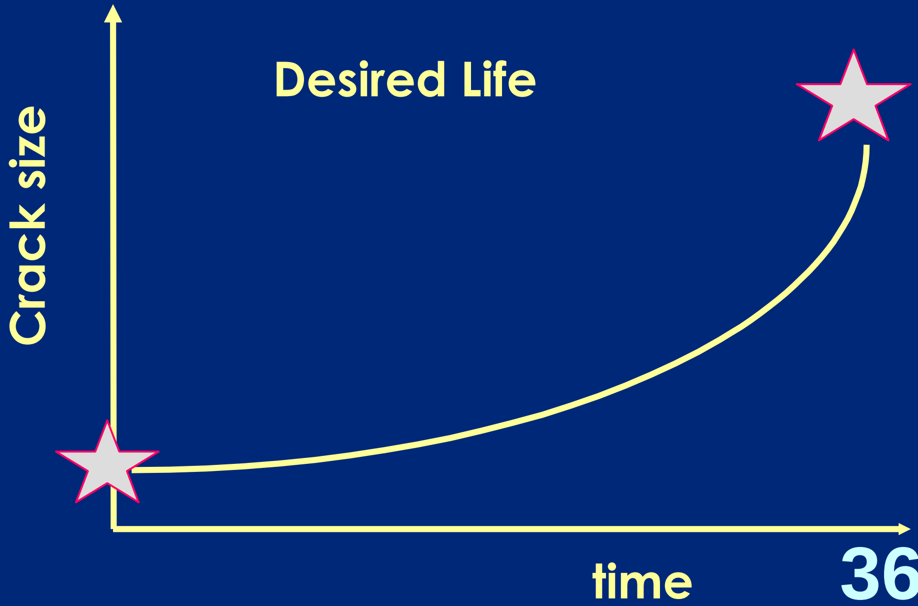


Contentment through worry!

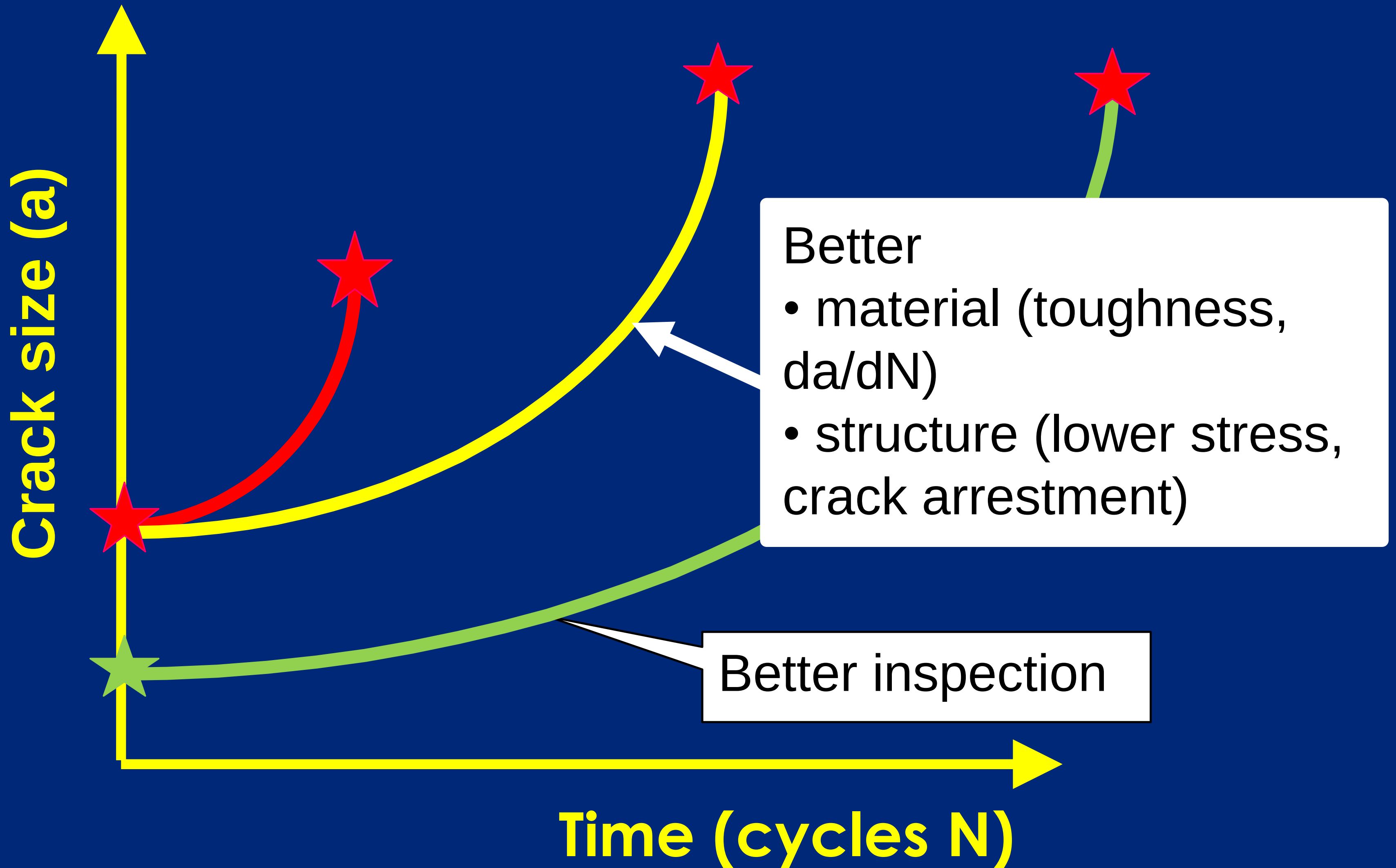
Damage Tolerant Design of B-1 Bomber

First aircraft designed to damage tolerance

- Requirements defined Feb. 1970
- Mil-Spec-83444, 1974
- Assumed initial crack ~ 0.05 inch



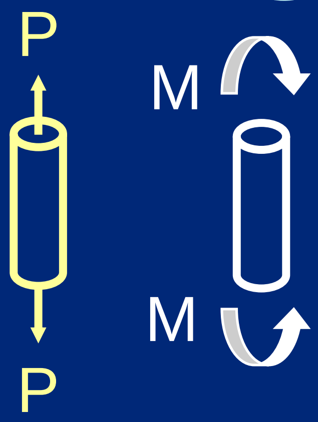
Damage Tolerant Design

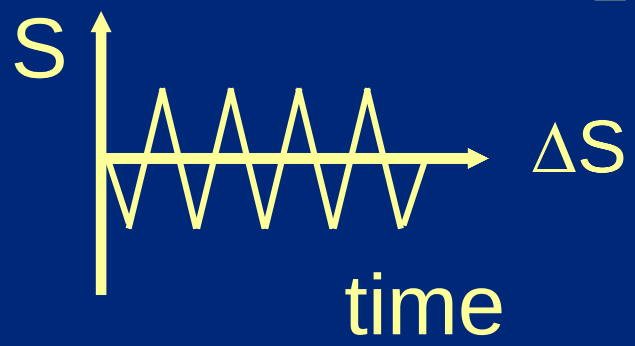


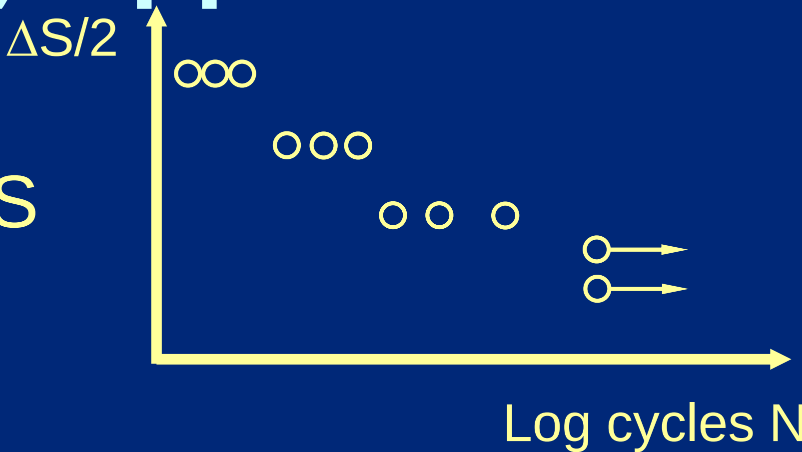
Fatigue Design Criteria

- Several ways to treat fatigue
- Criteria differ in their view of cracking and implementation of inspection
  - Infinite life
  - Safe-life
  - Fail-safe
  - Slow crack growth
  - Retirement for cause

Stress-life (S-N) Approach



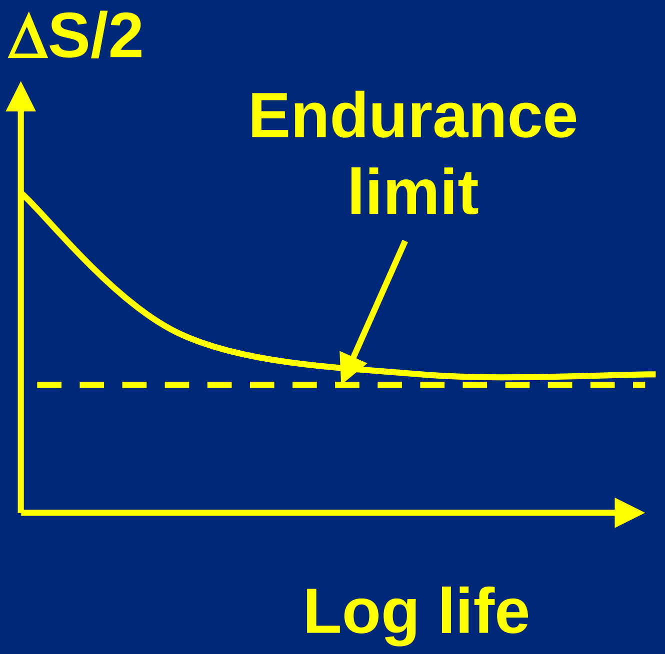




- **Test specimens at different constant ΔS**
  - **ΔS = ΔP/A or ΔMy/I**
  - **Measure life N (usually total cycles to failure)**
- **Life increases as load amplitude decreases**
- **Considerable scatter in data**
- **"Run-outs" suggest "infinite life" possible (mainly steels)**

Endurance Limit
(Fatigue Strength)

- **Maximum amplitude without fatigue failure**
  - $S_f \equiv S_e \equiv \Delta S/2$ for "infinite" life
  - "Infinite" > 10^6 or 10^7 cycles
  - For steels $S_e \cong S_{ult} / 2$
- **Not all materials have endurance limit**
  - Define quasi limit = $\Delta S/2$ at $\cong 10^7$ cycles
- **Highly dependent on specimen condition, prior load history, residual stresses, etc.**



Fatigue Design Criteria
Infinite Life

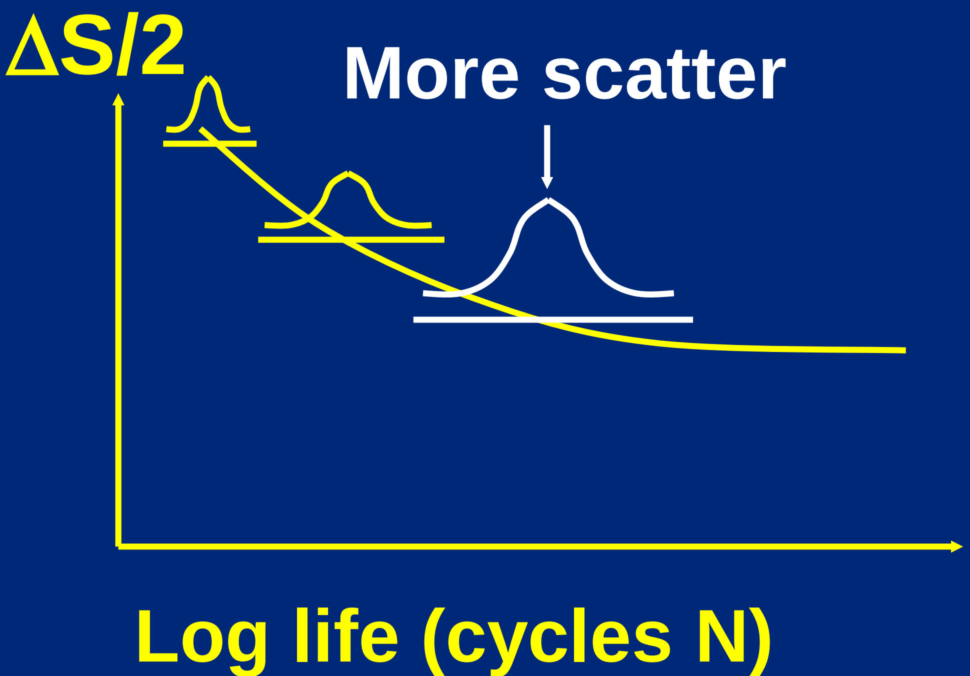
- Prevent fatigue damage from ever developing
- Based on endurance limit, threshold K concepts

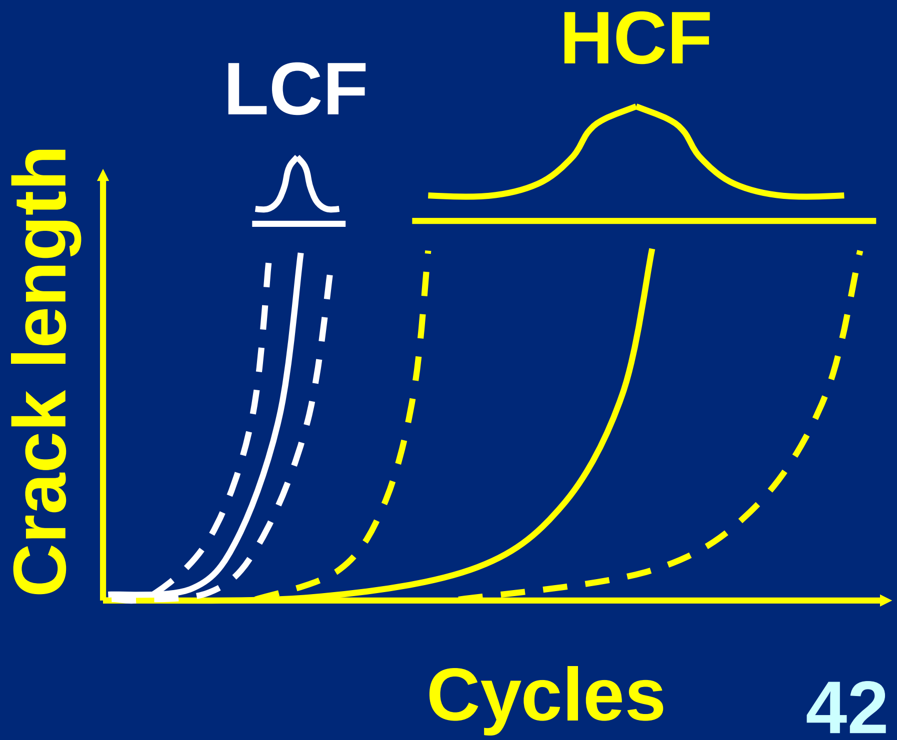
  ==> very low design stresses
- Used for simple components/loading (e.g. valve springs)
- Not achievable in many cases
  - weight critical structure
  - complex load histories

Susceptible to quality of component

S-N Scatter

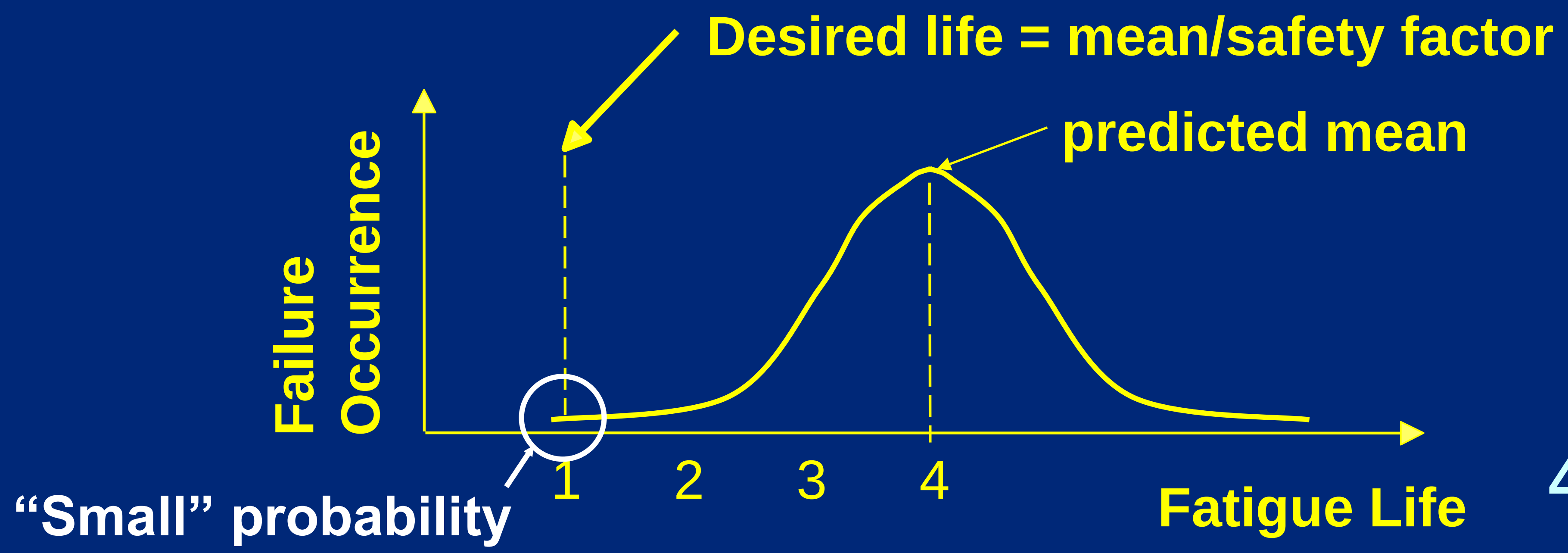
- More variability for HCF (high cycle fatigue) than LCF (low cycle fatigue)
- Due to early crack formation at high loads, random at lower loads





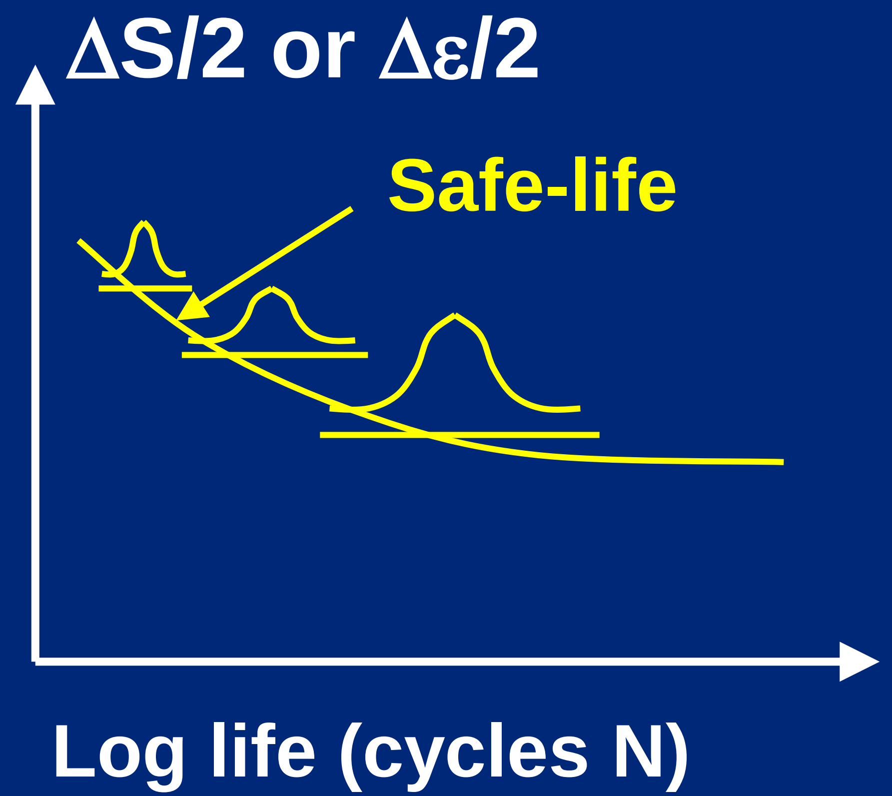
Design Criteria: Safe-Life

- Goal: remain crack free for finite life
- Assumes crack free initial structure
- Establish "mean life"
- Safety factors account for "scatter"



Safe-Life Design

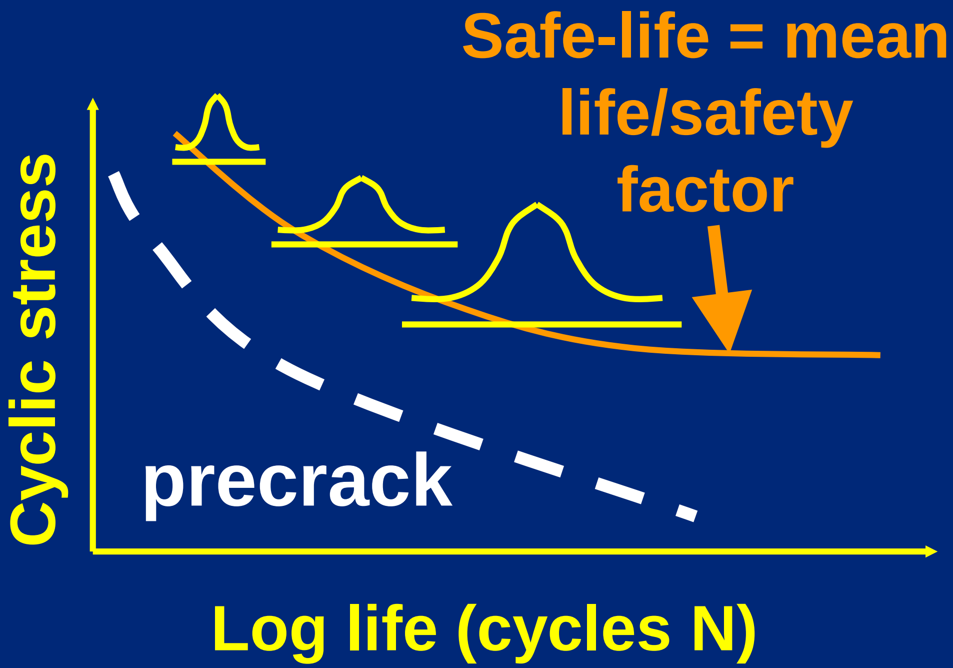
- Safe-life based on mean nucleation life/safety factor
- Assumes pristine structure
- Not damage tolerant
- Inspection required for new structure
- Would retire when safe-life expended
- For life extension use safety-by-inspection (SBI)

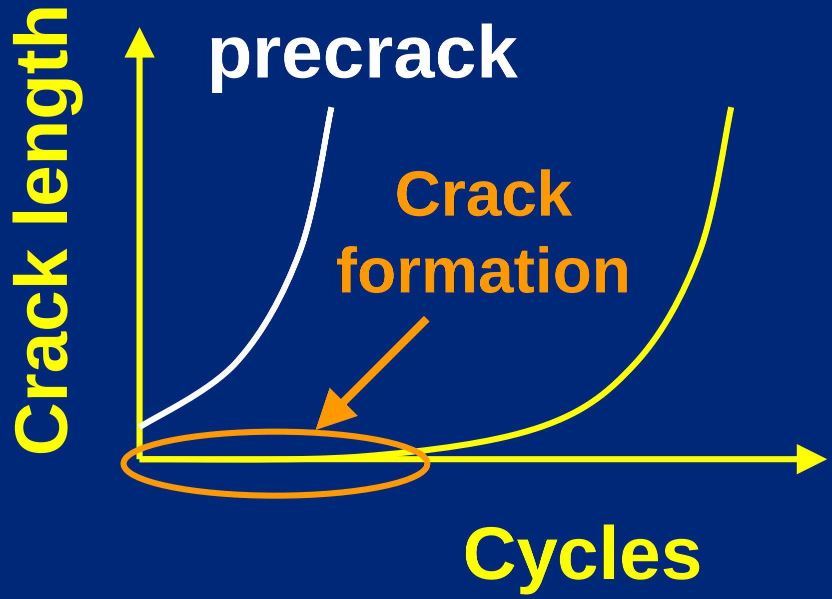


F-111 Lessons Learned

- **Safe-life design inadequate**
  - (6000 hrs with scatter factor of 4)
  - Full scale fatigue test of 16,000 hrs
- **Safe-life design did not protect against manufacturing or service induced defects**
  - Not damage tolerant
  - Allowed use of low ductility materials
  - Inspection procedures inadequate
- **Led to new additional damage tolerance requirements in 1974**

Safe-Life Limitation





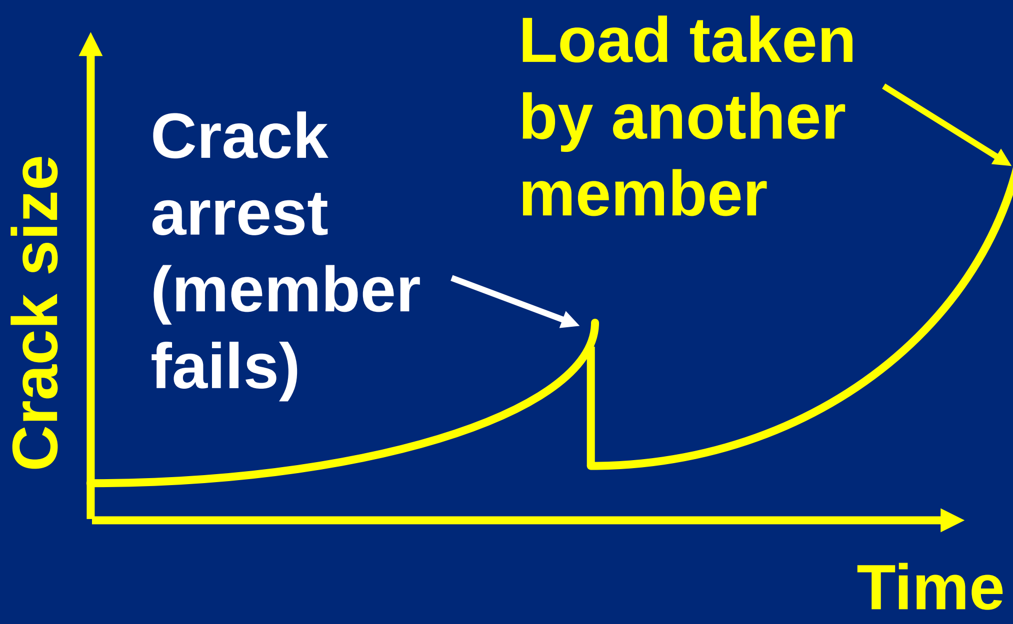
- **Safe-life defeated by pre-existent damage**
  - **F-111 “safe-life” 4000 hrs (failure at 104 hrs)**
  - **Not allowed by FAA (commercial transport), USAF**
- **Not damage tolerant**

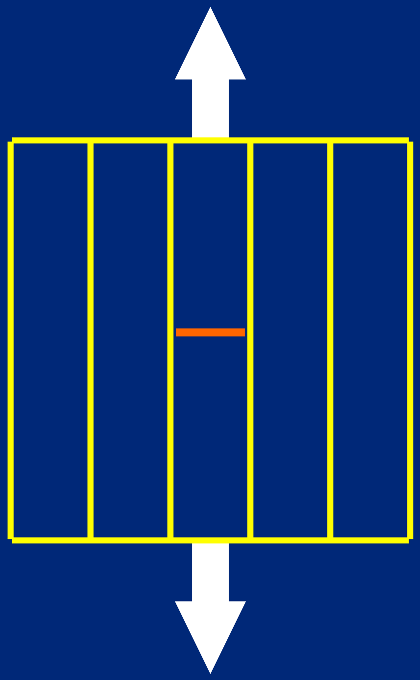
Fail-Safe (Damage Tolerant)

Contain single component failure

- Alternate load paths
- Redundant structure, crack stoppers

Requires detection of 1st failure





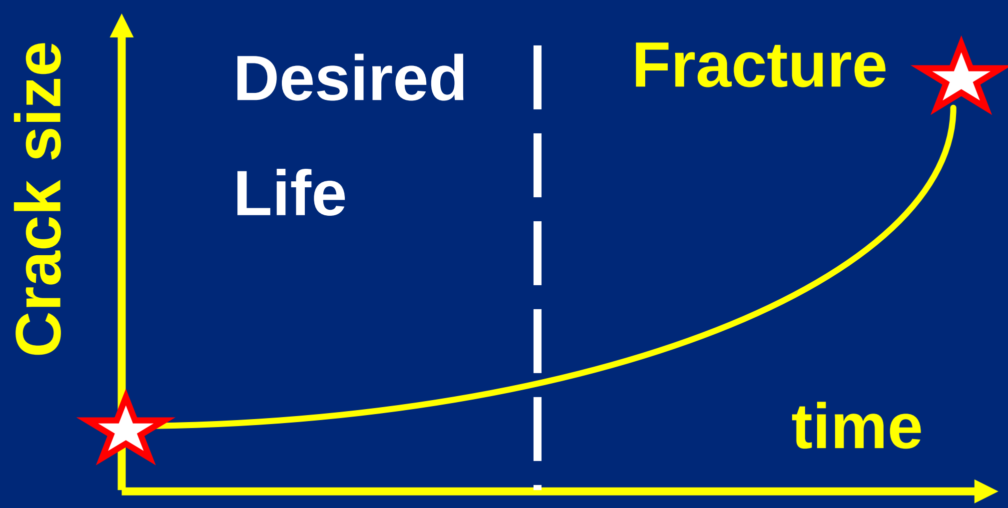
Slow Crack Growth (Damage Tolerant)

Assumes pre-existent crack

Crack growth life > desired service life x S.F.

Design for fatigue crack growth resistance

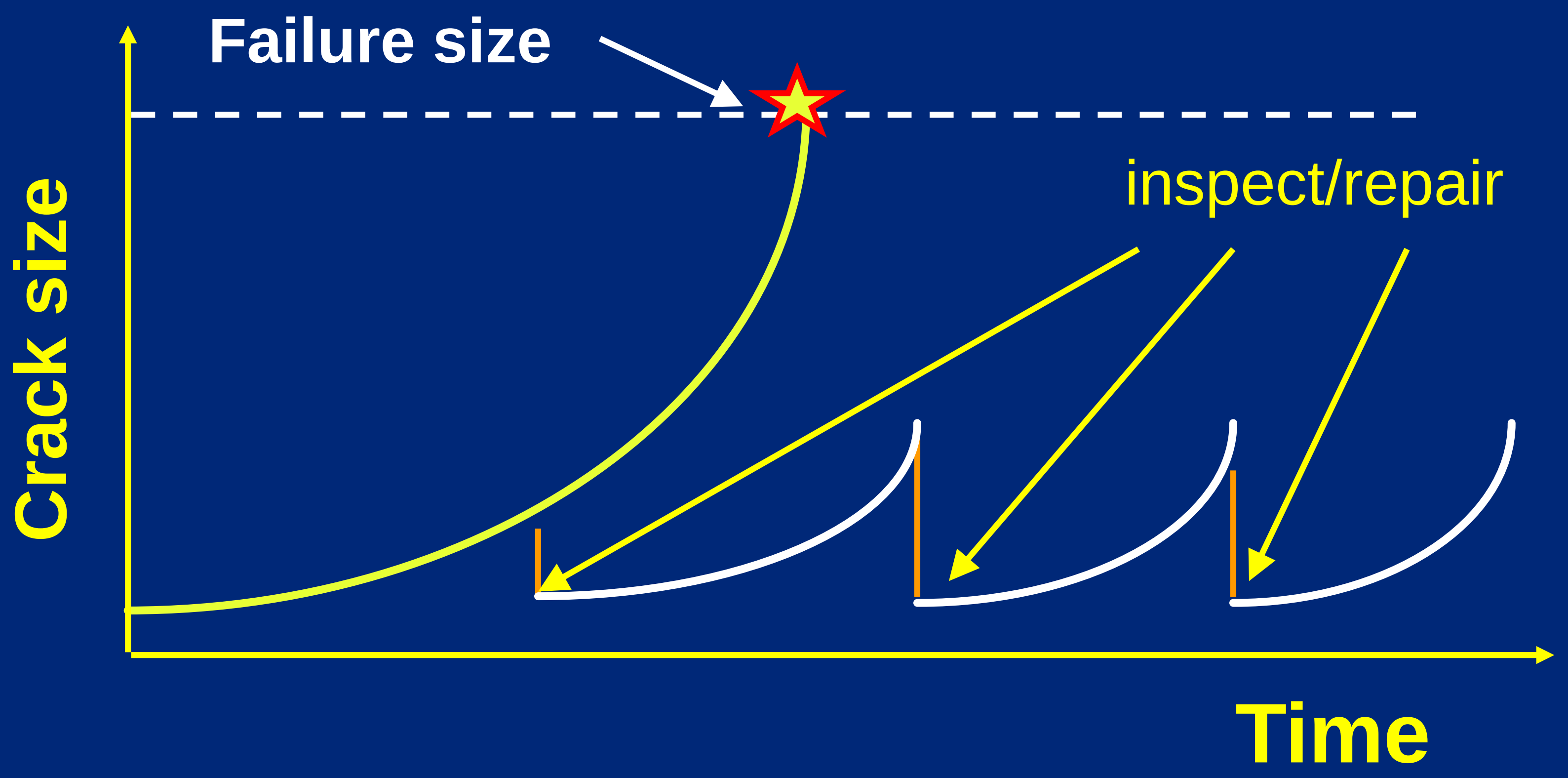
Emphasis on inspection



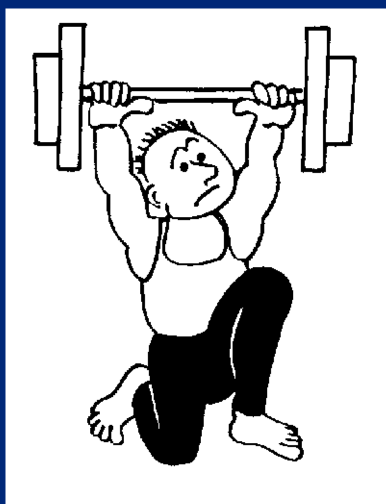
Safety by Inspection
(Retirement for Cause)

Maintain integrity by repeated inspection

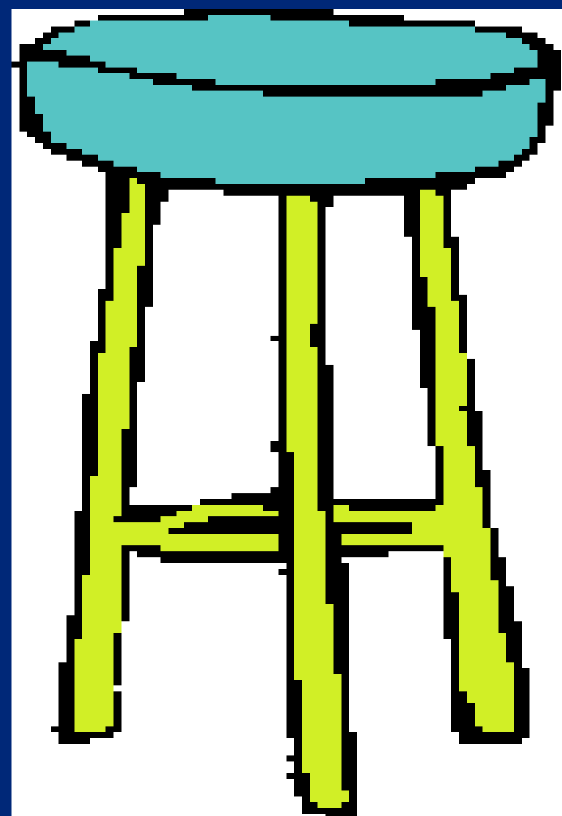
- Consider in original design plan
- Apply as life extension for older structure



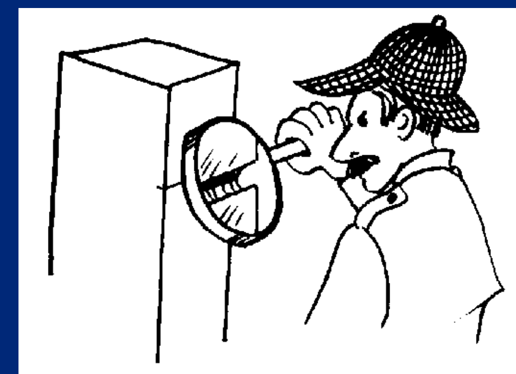
Damage Tolerance is a “3-Legged” Stool



Residual Strength



Crack Growth



Inspection

Back to the Drawing Board, Hell. You're Fired!!

"No Sweat" Schuffert