Fatigue

Samudra Dasgupta
Senior Lecturer in Aerospace Engineering
University of Bristol

Intended learning objectives

- Introduction and basic definitions of fatigue (primarily for metallic structures)
- Fatigue load cycles
- S-N curves
- Low & high cycle fatigue
- Mechanisms & stages of fatigue
- Design considerations to avoid fatigue in aircraft structure (including composites)
- Fatigue damage accumulation process & classical fatigue analysis

References

- Sandor – Fundamentals of Cyclic Stress and Strain
- Dieter – Mechanical Metallurgy
- Niu – Airframe Structural Design
- Engineering Science Data Units (ESDU) fatigue Data Sheets

University of BRISTOL

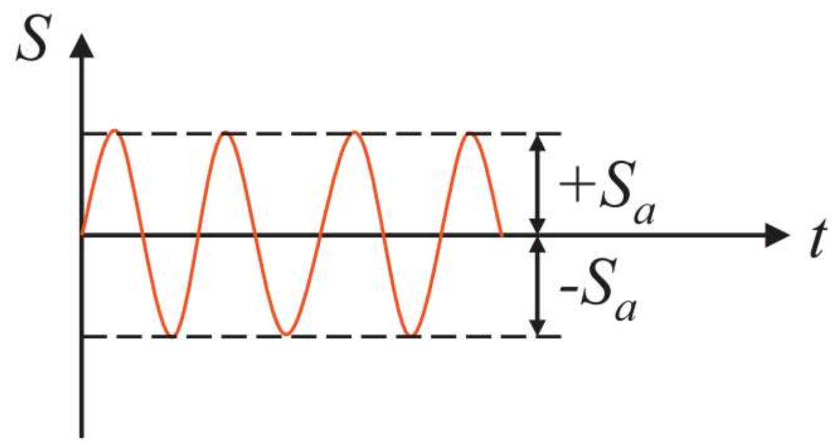
Fatigue

Part-1: Introduction

bristol.ac.uk

Definitions & load cycles

- Fatigue: Response to cyclic loads
  - Below elastic limit
  - Accumulation of microscopic damage leading to catastrophic failure
- Types of load cycles
  - Constant amplitude cycles
    - **Completely reversed cycle: $|S_{max}| = |S_{min}|$ & $S_m = 0$**
    - Non-zero mean stress / partly reversed cycle: $S_m \neq 0$
    - Tension-tension cycle: $S_{min} > 0$
  - Variable amplitude cycle
    - Constant mean stress cycle
    - Variable mean stress cycle / Random cycle



6 variables – only 2 independent

ΔS = Stress range = $S_{max} - S_{min}$

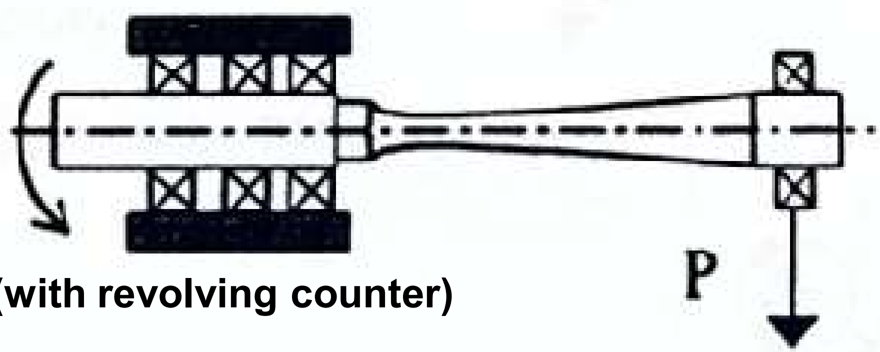
S_m = Mean stress = $(S_{max} + S_{min}) / 2$

S_a = Stress amplitude = $(S_{max} - S_{min}) / 2$

R = Stress ratio = S_{min} / S_{max}

Material level fatigue tests

- Axial loading fatigue tests
- Rotating beam fatigue test

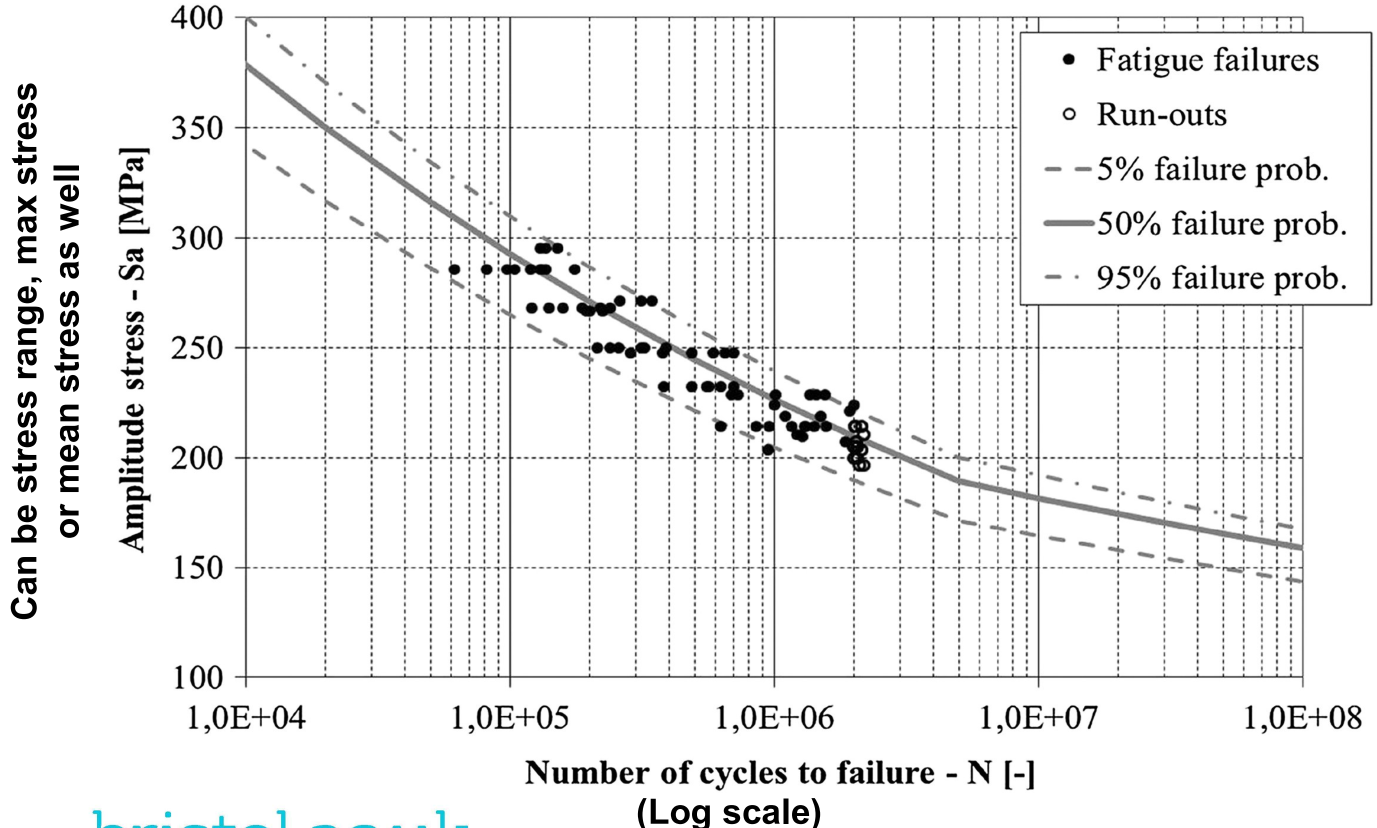


(with revolving counter)

Constant amplitude-completely reversed cycle

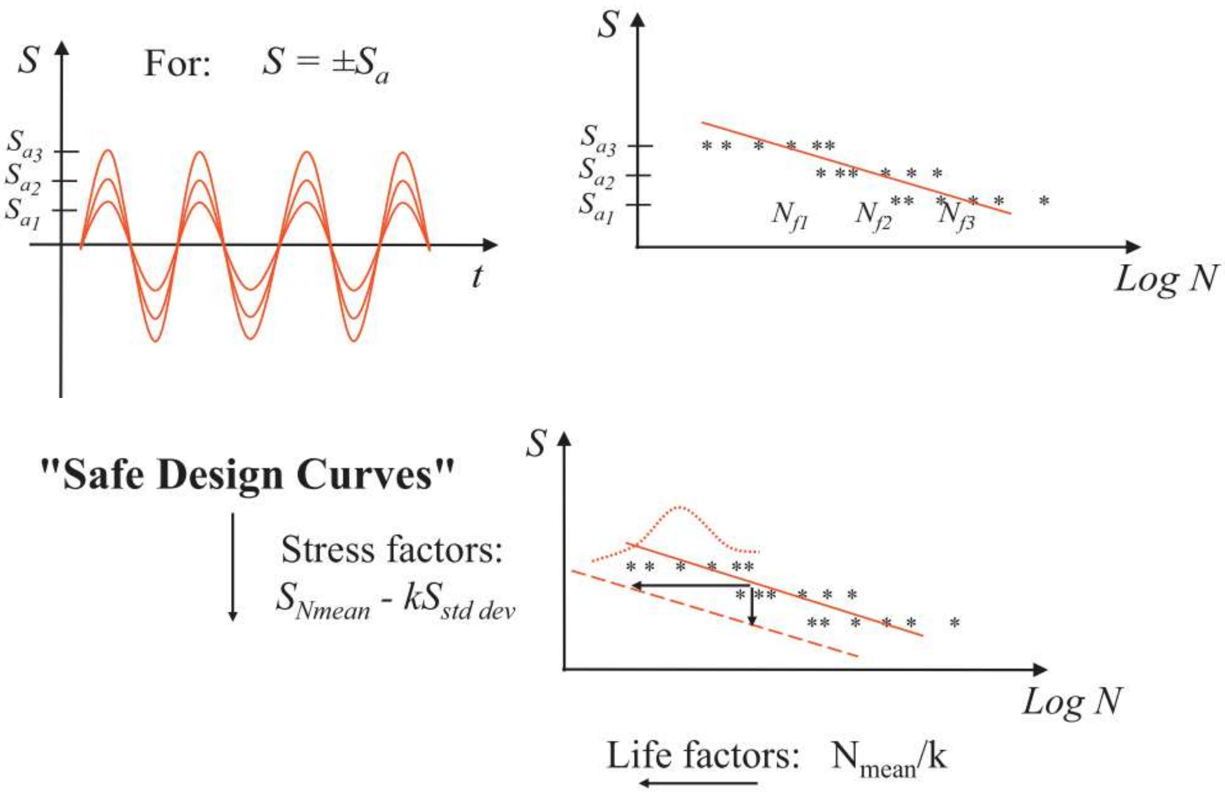
$$S_{max} = M \,.\, y \,/\, I = P \,.\, L \,.\, y \,/\, I = P \,.\, L \,.\, (d/2) \,/\, {}^{\Pi}/_{64}\, d^4$$

S-N-P curve



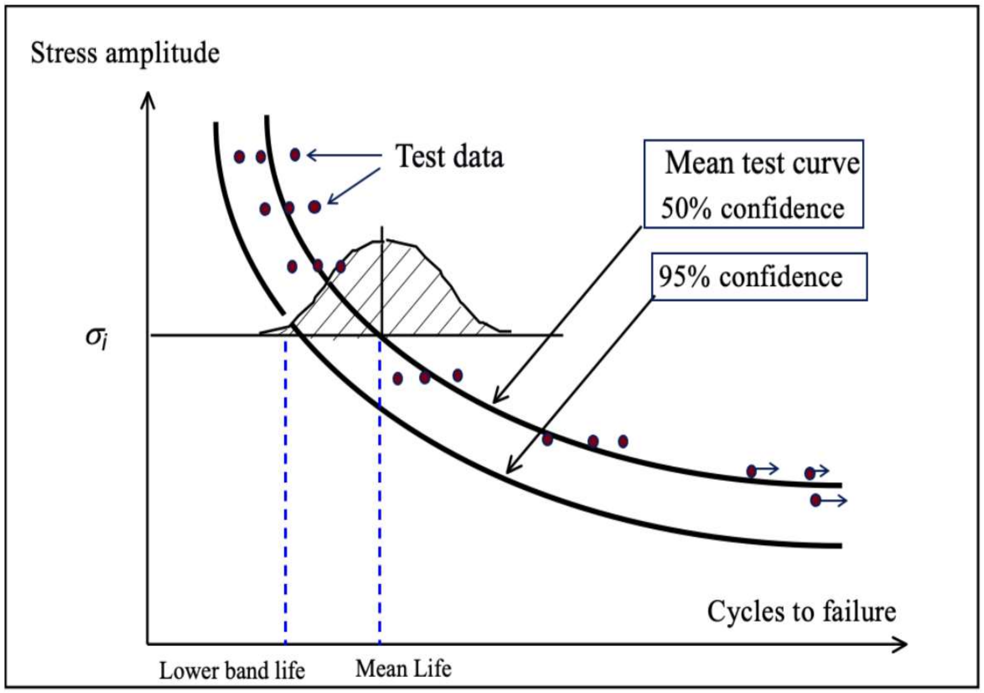
- S-N-P curve is generally presented as S-N curve with P=0.5
- S-N curve can be used for
  - Predicting component life for a given Smax
  - Estimating allowable Smax for an expected life
- Fatigue strength: Max stress that can be applied in cycles to give a specified fatigue life (normally 10^6 cycles)

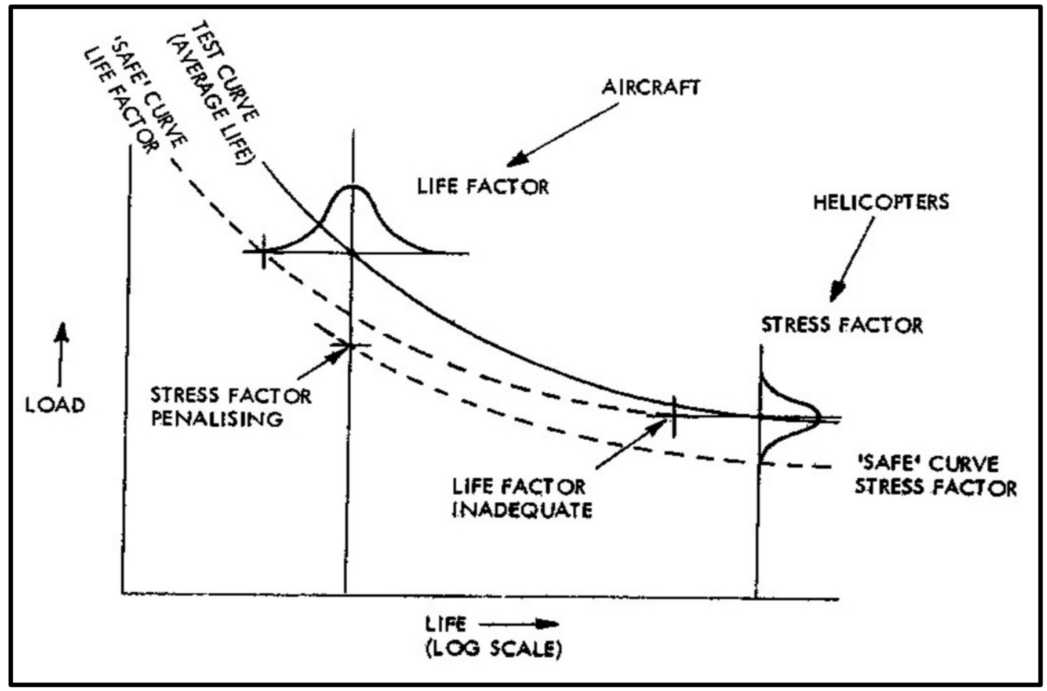
Safe design curve



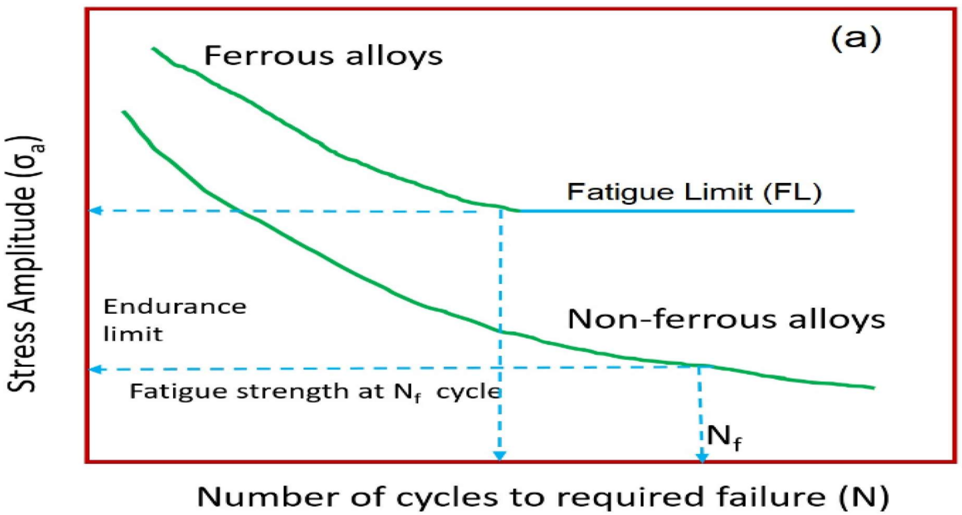
- Significant scatter (3-4times) in N_f is common, especially for HCF zone
- Value of K (scatter factor) is a fn. of no. of samples tested and std. dev. of the results
- For 6 samples, k is typically around 3-4 (ESDU Fatigue Data Sheets Vol 1)

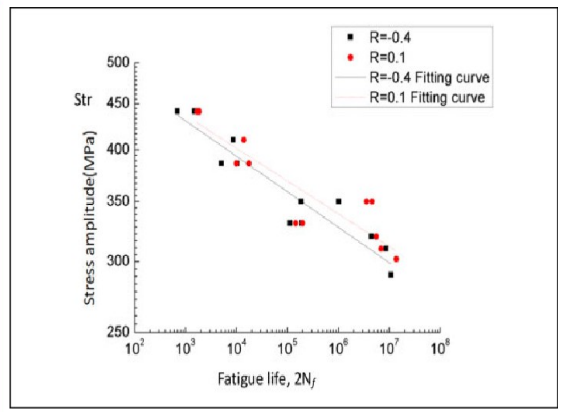
Safe design curve (contd.)

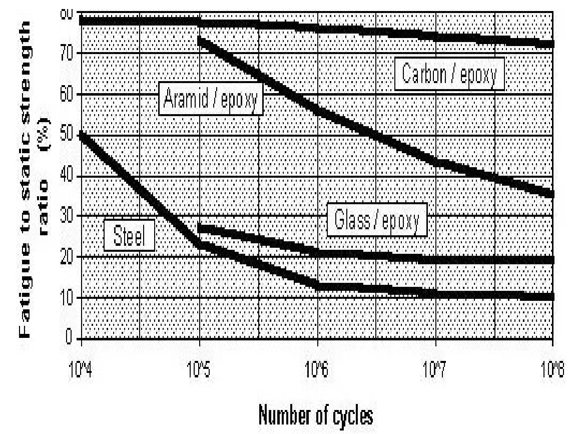


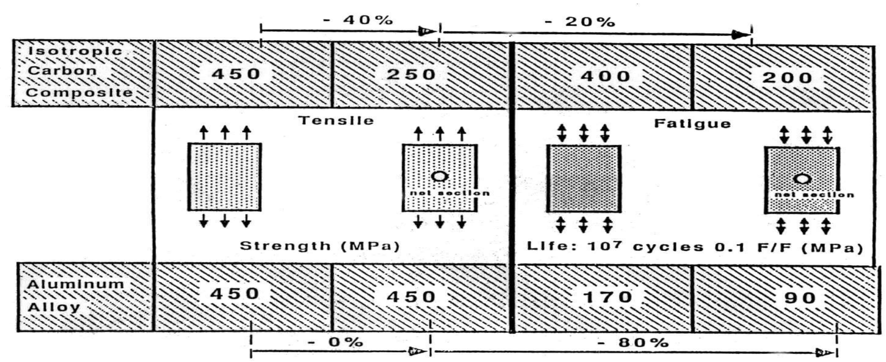


S-N curves for different materials





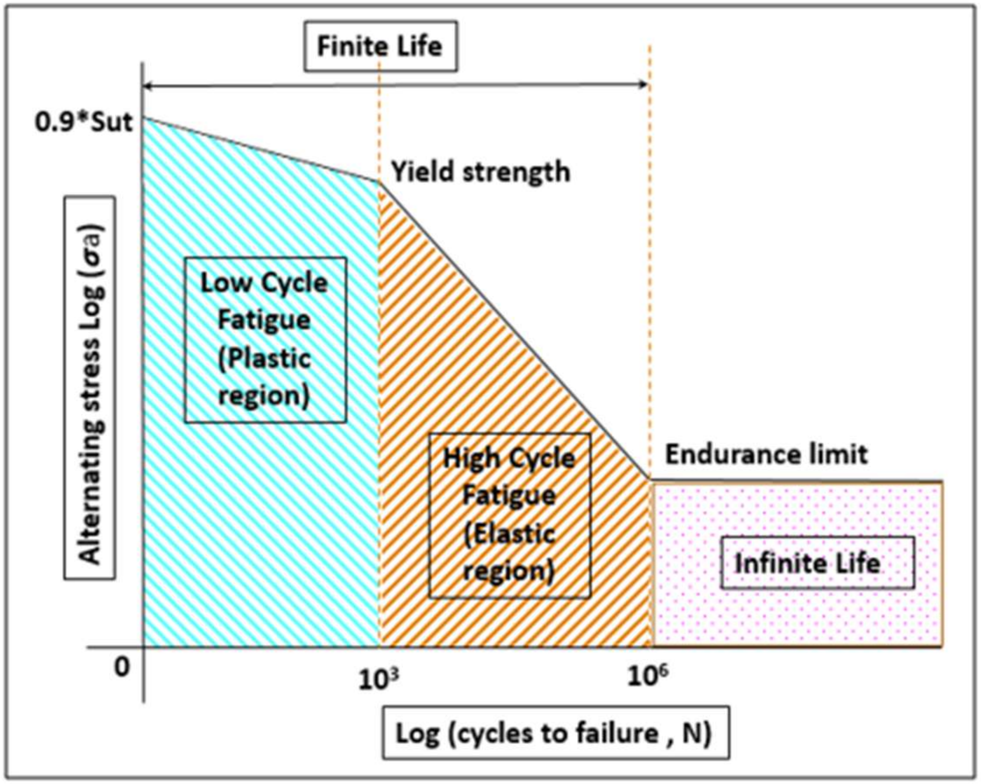




TENSILE STRENGTH AND FATIGUE LIVES OF ALUMINUM AND CARBONFIBER COMPOSITES

- Fatigue Limit (FL): Max stress that can be applied in cycles to give an infinite fatigue life (generally too low for airframe design)
  - Metals / alloys with yield point elongation show FL (Steel & Ti alloys)
  - Metals / alloys with no YPE, do not have FL (Cu & Al alloys)
  - Composites do not show FL, but generally have lesser fatigue slope

Low & high cycle fatigue

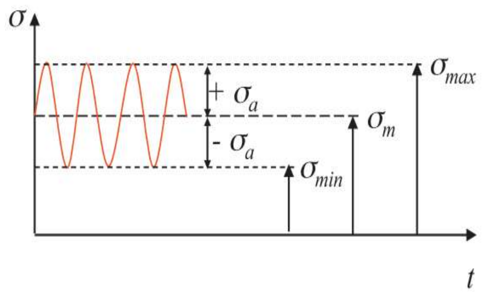


LCF	HCF	VHCF
Earthquake resistant structures	Bridges Wind turbine Aircraft	Gears Wheels Machining blades
High stress ……………. Low stress (S_{max} < Yield strength)		

For most practical applications, it is neither constant amplitude nor completely reversed cycle. We need to apply analytical tools to convert these S-N curve data

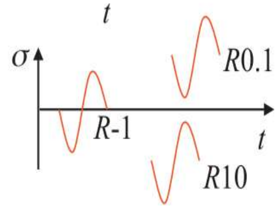
NB: Definition for transition from LCF to HCF may vary anything in between 10^4 to 10^6 cycles

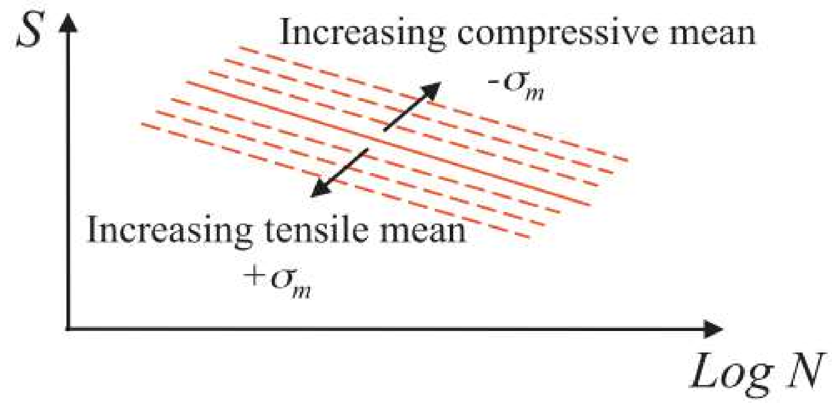
Non-zero mean stress cycles



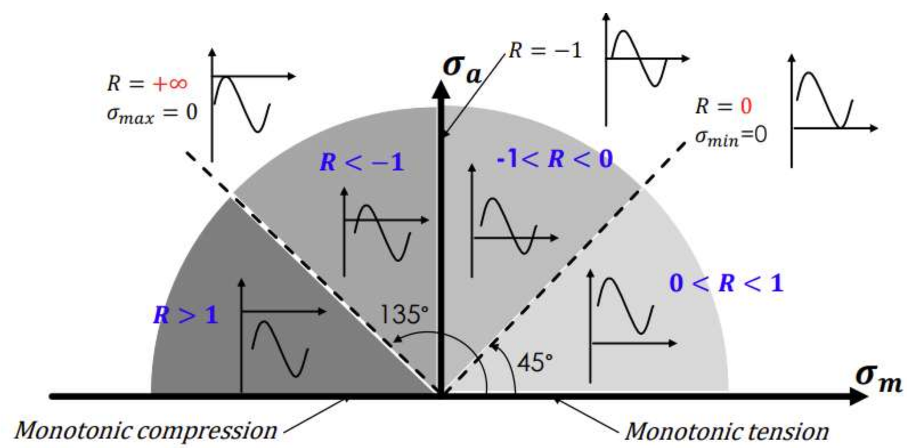
$$\sigma_{max} = \sigma_m + \sigma_a$$
$$\sigma_m = (\sigma_{max} + \sigma_{min})/2$$
$$\sigma_a = \pm(\sigma_{max} - \sigma_{min})/2$$
$$\sigma_{min} = \sigma_m - \sigma_a$$

R-Ratio $R = \dfrac{\sigma_{min}}{\sigma_{max}}$ E.g.



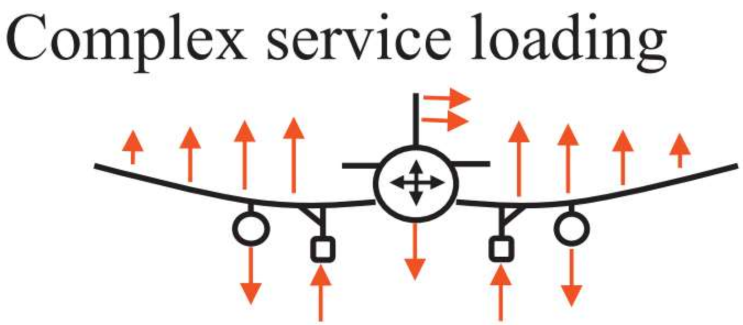


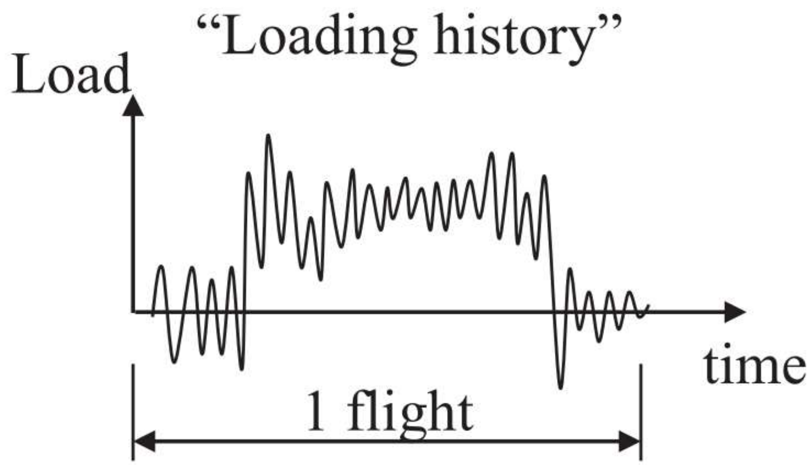
- Non-zero mean stress can induce phenomenon of creep in load control tests
- Even Zero mean stress cycles can induce creep in materials with different tensile and compressive responses (composites, cast iron etc.)

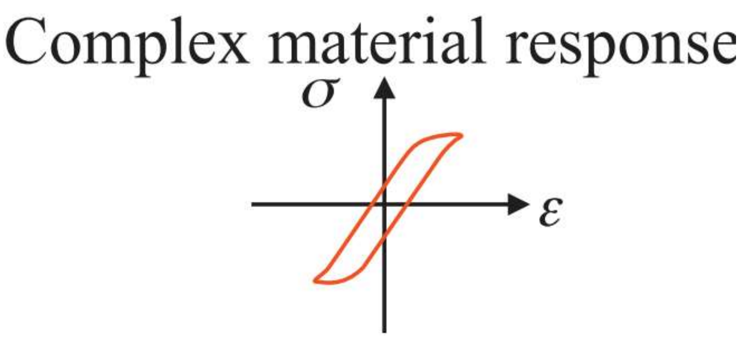


σ_m - σ_a plane to include all possible sine cycles.

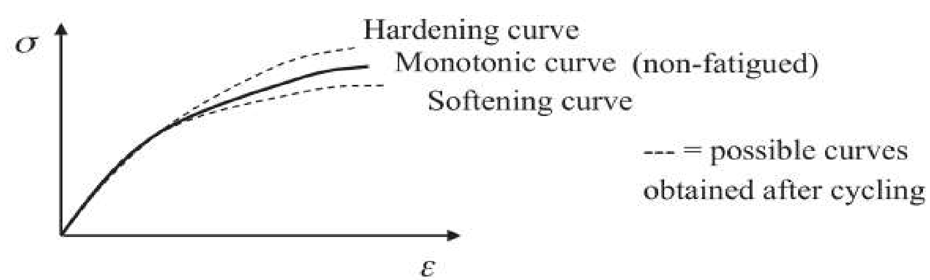
The challenges



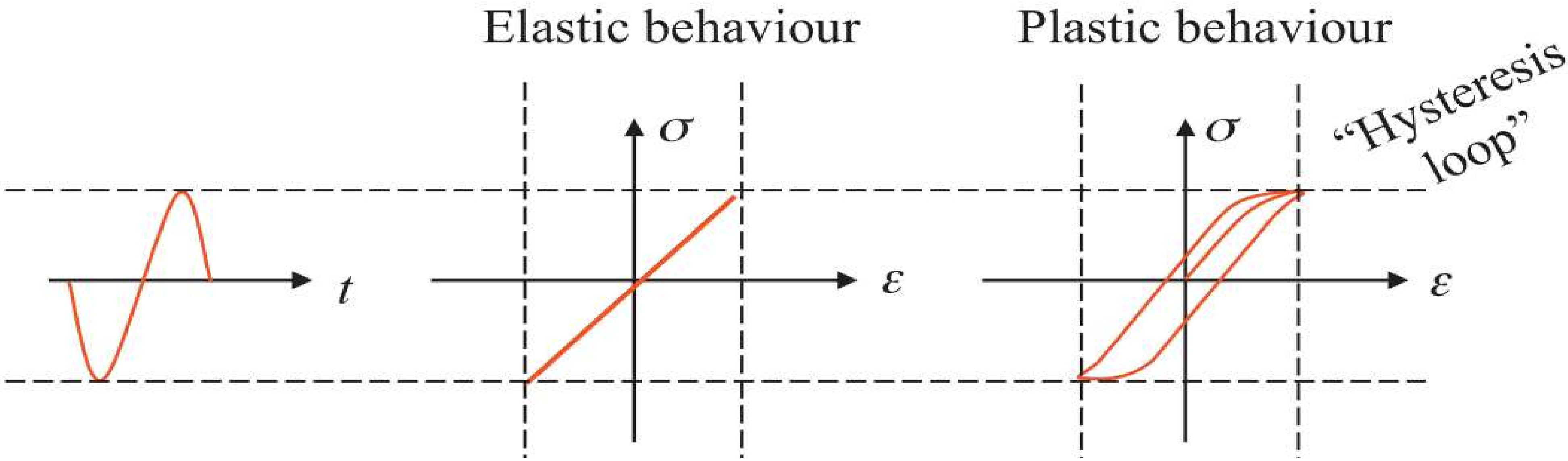




Risk of using static stress-strain curve

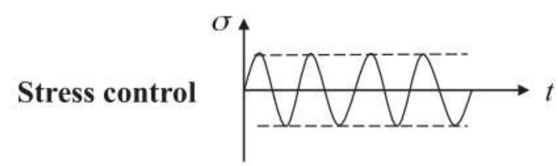


Complex material response

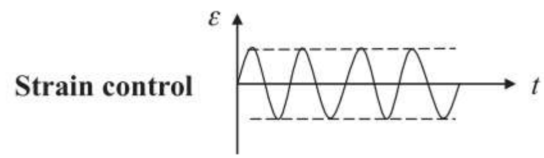


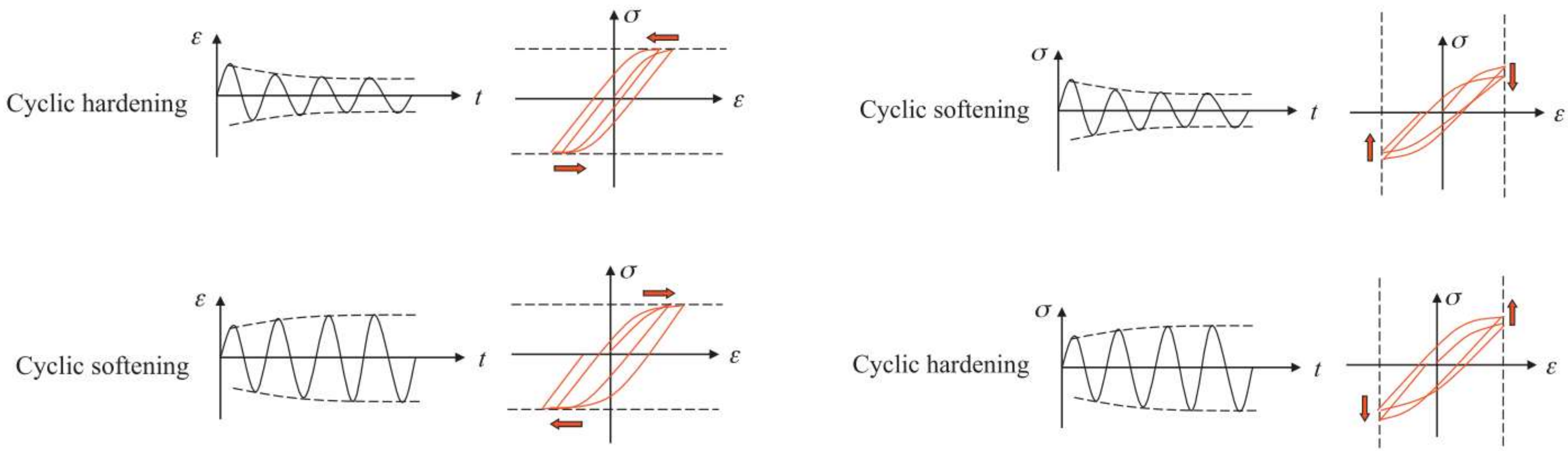
Work done / energy absorbed, i.e. fatigue damage accumulation

Hysteresis loop



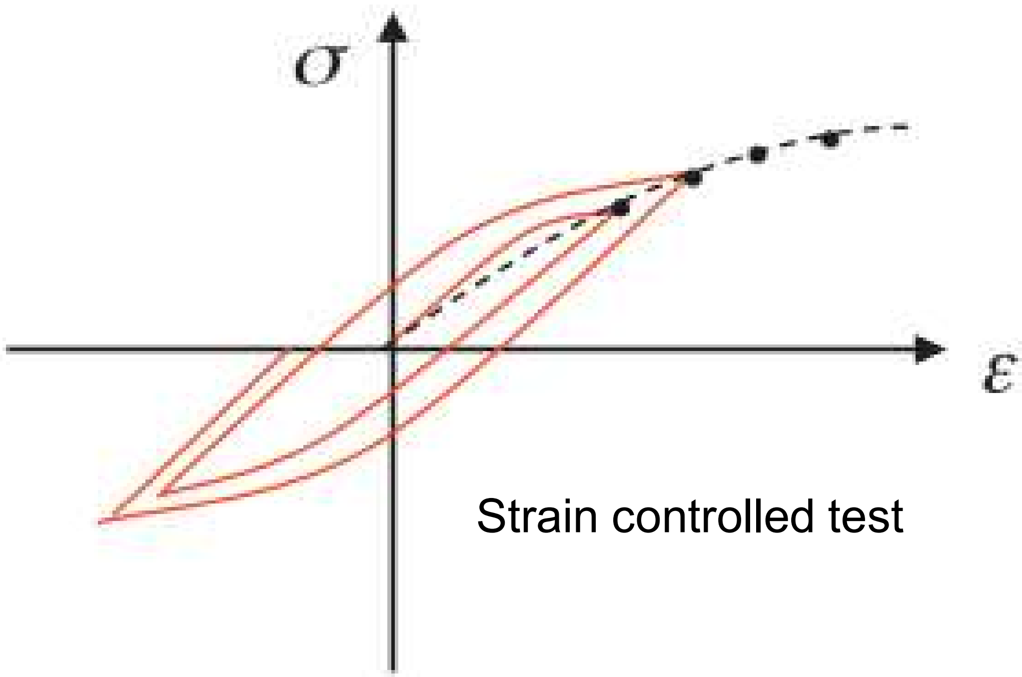
Exponential cyclic hardening / softening due to repeated loading; typically done till 'fatigue half life'



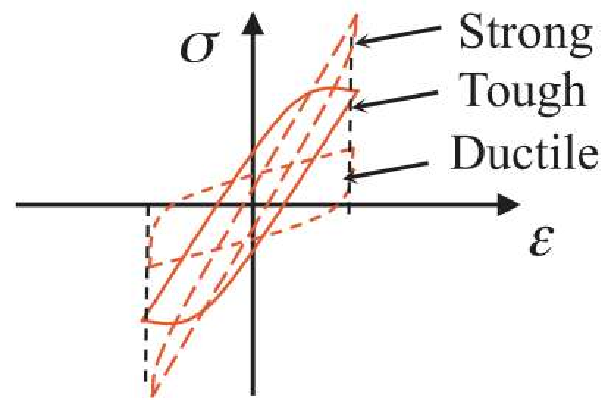


Max effects on YS / UTS, nominal effects on fracture toughness, no effect on modulus

Multiple step method



- Generate curves from hysteresis peaks



End of Part-1

Fatigue

Thank you

samudra.dasgupta@bristol.ac.uk

https://in.linkedin.com/in/samudradg