Gas Turbine Mechanical Integrity

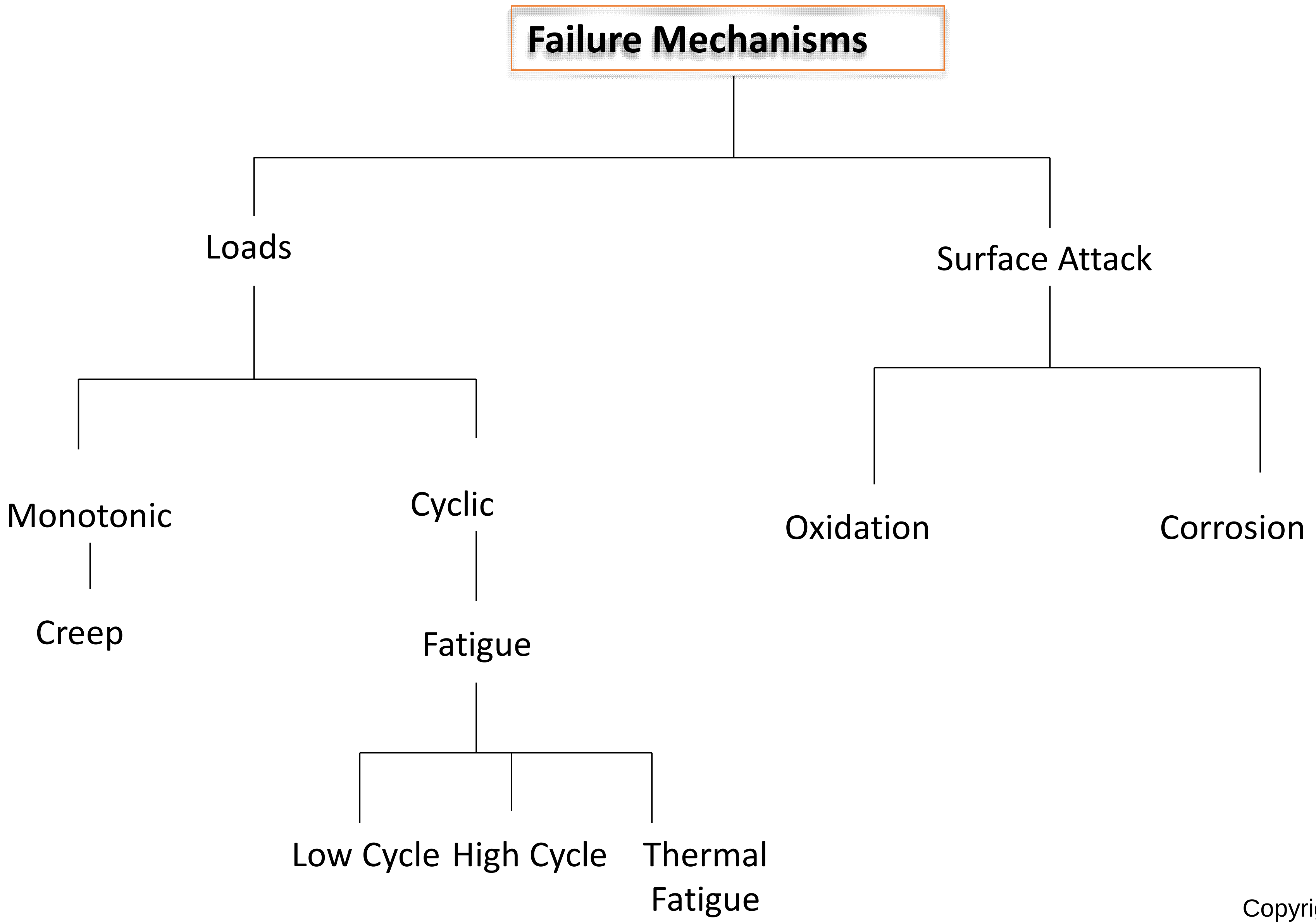
GT Performance Short Course

(Montreal 21-24 Sep 2022)

Dr. Suresh Sampath

www.cranfield.ac.uk

Failure Mechanism



Fatigue Failure- Case Study

- First jet engine commercial aircraft -need for high altitude/high speed
- There had been 1290 cycles and 900 cycles on each of 2 aircraft

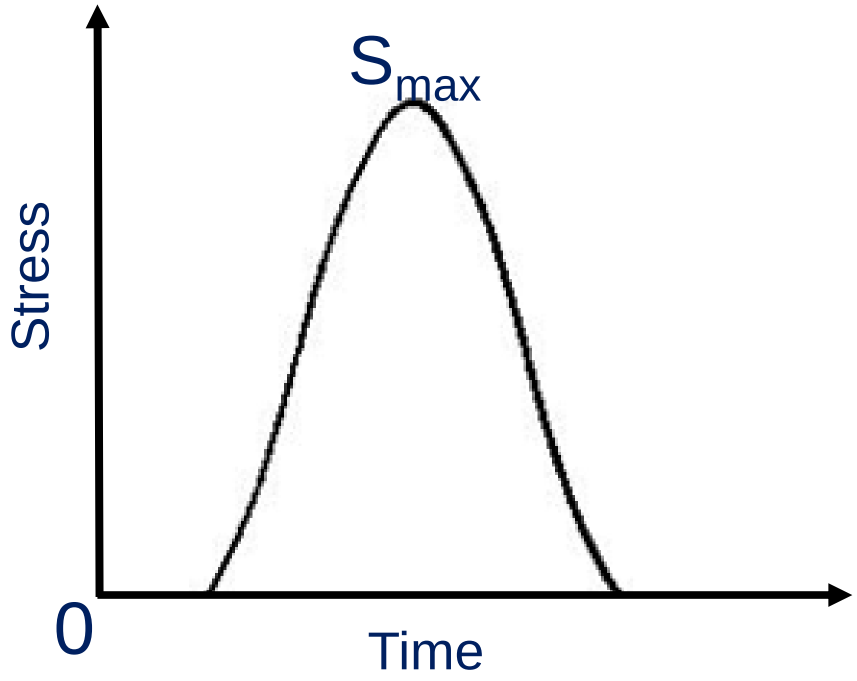
De Havilland designers believed that a cabin which would survive undamaged a test to more than double its working pressure would not fail in service under the action of fatigue’

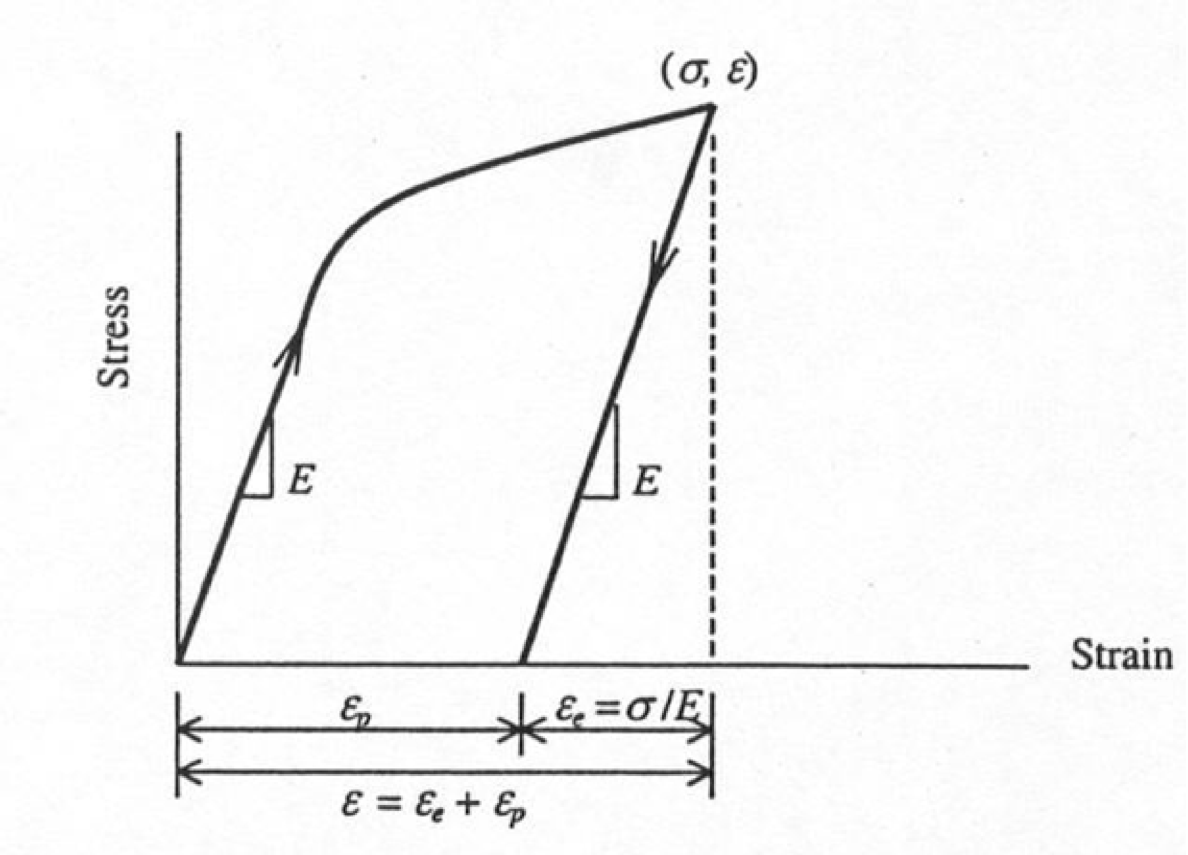
The working pressure of the fuselage was 57kPa above atmospheric and the cabin was designed to withstand a pressure of 138kPa

Fatigue Failure- Case Study

BOAC 781 Fatigue Failure - https://www.youtube.com/watch?v=_BZnn5OYcBc

Understanding Principles of Fatigue

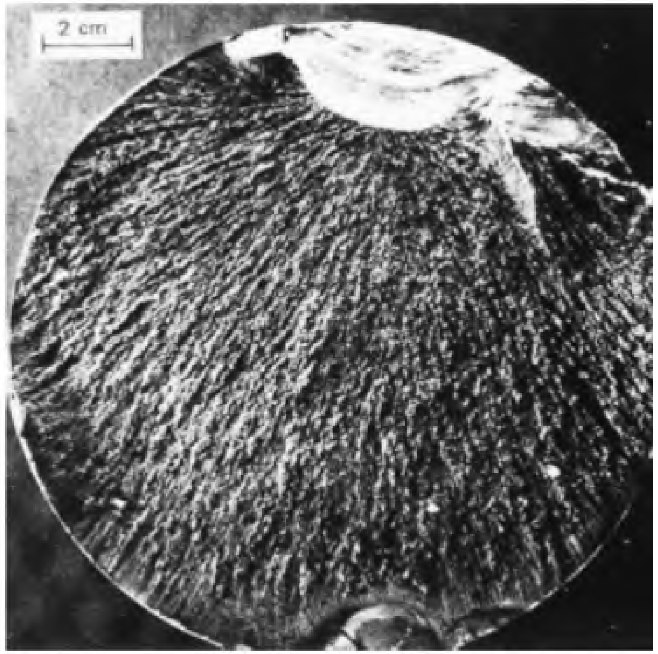




Fatigue Design Considerations

- Recognise the fatigue failures
- Proper fatigue design methods must by incorporated in the overall design process particularly when cyclic loading is involved
- Don’t rely on factor of safety in overcoming poor design procedures
- Rely on experimental data along with simulation and analysis
- Fatigue durability test as verification tool rather than design development tool
- Always consider other additive or synergistic effects of load , environment geometry, material micro structure etc..

Understanding Principles of Fatigue



Stages of fatigue failure

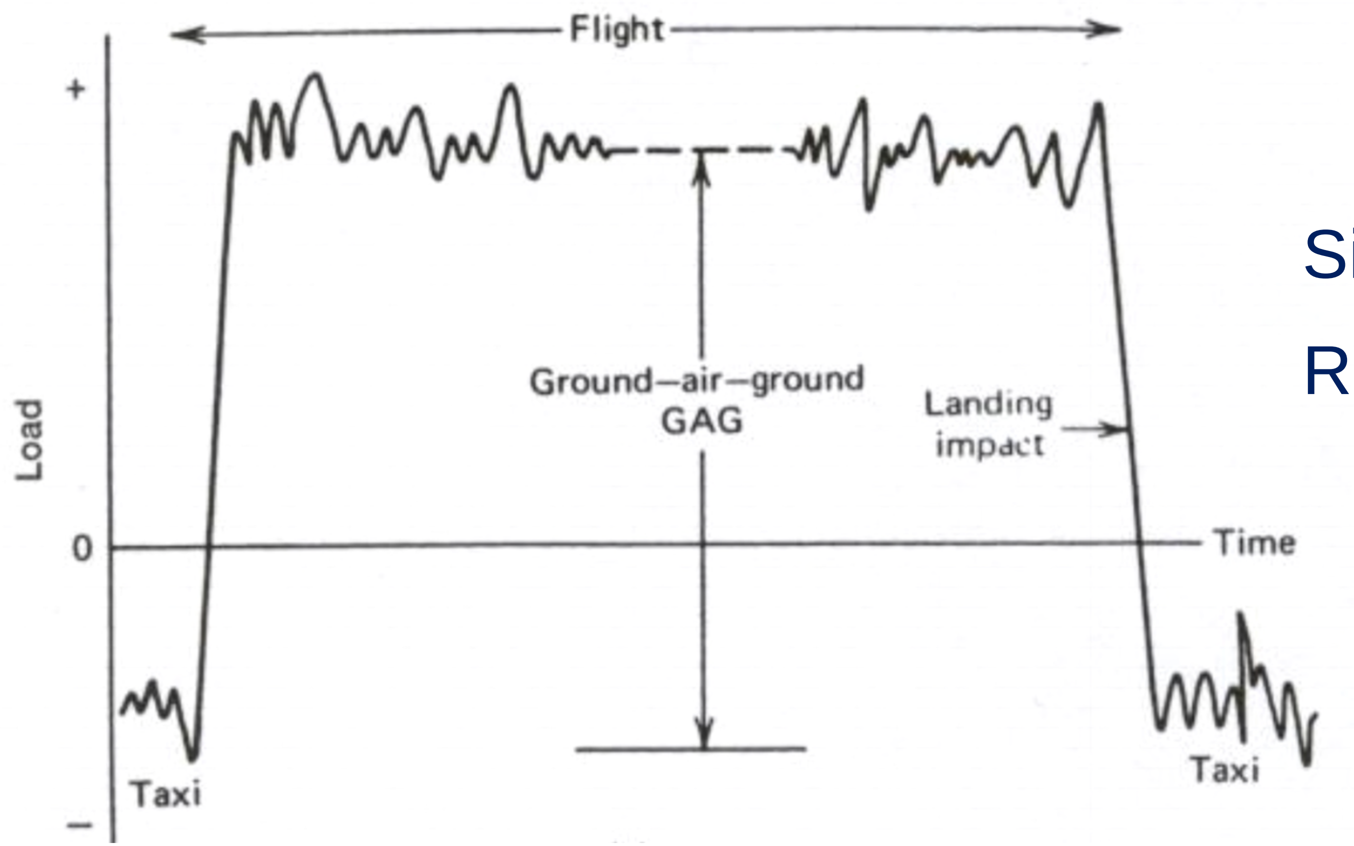
- Crack initiation (areas of stress concentration)
- Crack propagation
- Fracture after crack reaches critical size

$$N_f = N_i + N_p$$

N_f : Number of cycles to failure
N_i : Number of cycles for crack initiation
N_p : Number of cycles for crack propagation

High cycle fatigue (low loads): N_i is relatively high. With increasing stress level, N_i decreases and N_p dominates

Typical Fatigue load in Operation

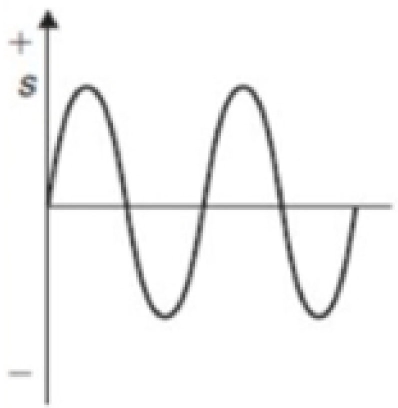


Simple repetitive loads

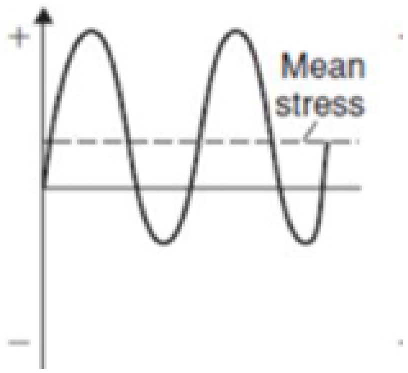
Random or complex loading

A typical take-off landing load cycle of an aircraft

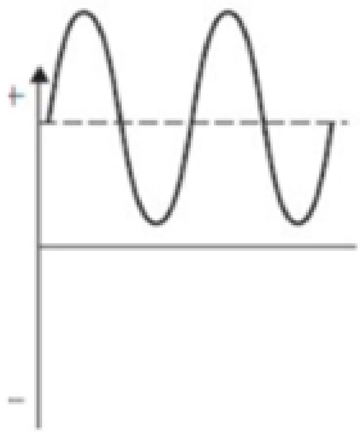
Classification of Fatigue Loads



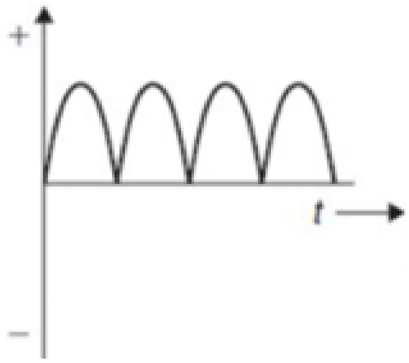
Fully reversible load



Alternating load



Fluctuating load



Repeating load

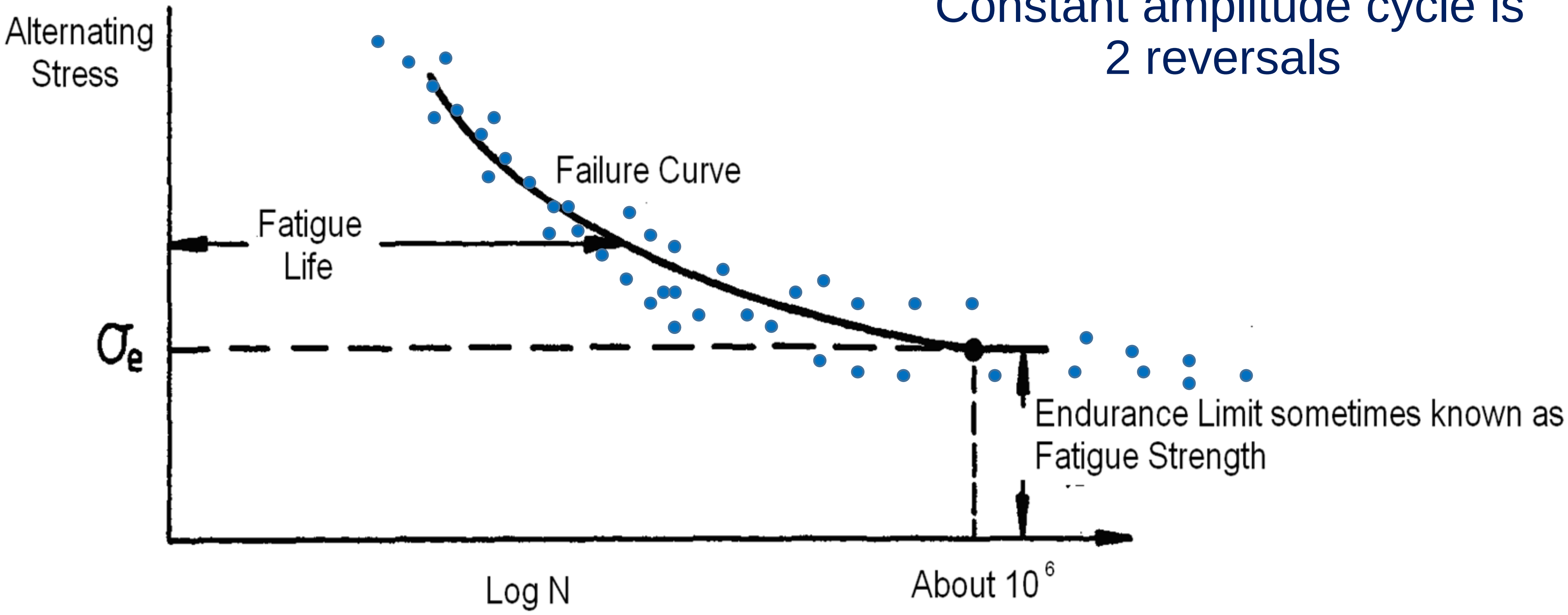
Change in magnitude or change in direction or change in both

Fatigue testing of components

Aircraft Wings subjected to continuous loading for fatigue testing

Video Courtesy – AIRBUS https://www.youtube.com/watch?v=6wHrfBs82Tk

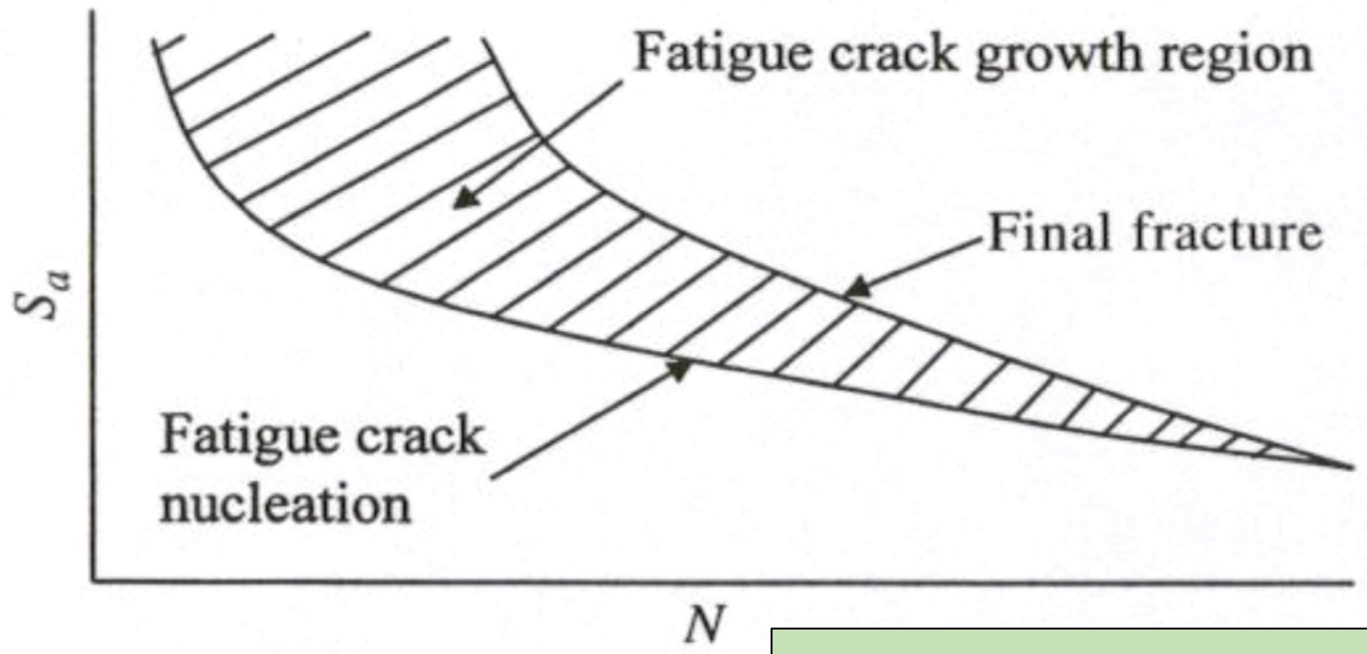
Understanding S-N Curve



Constant amplitude cycle is 2 reversals

Constant Amplitude fully reversible load with zero mean stress

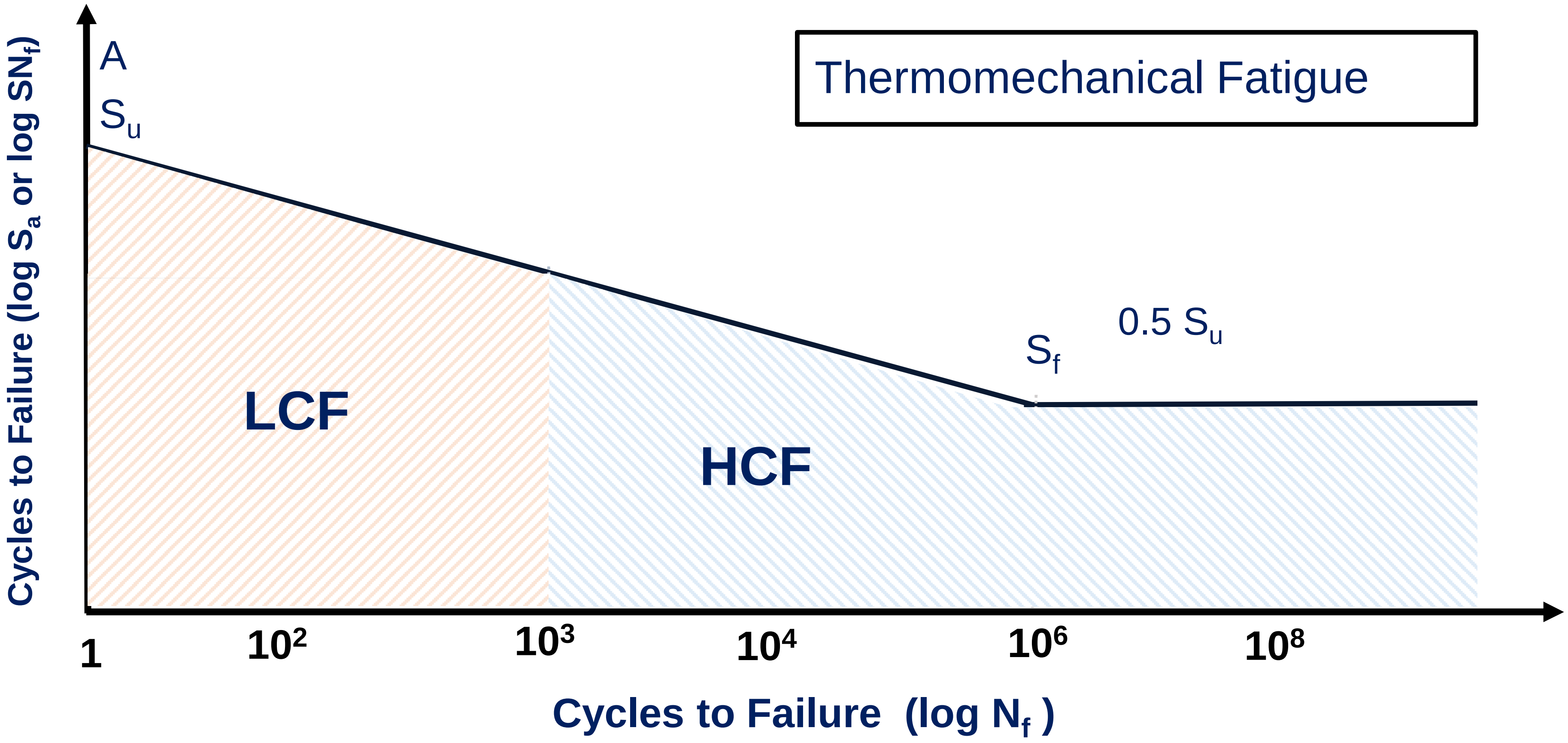
S-N Curves and Crack Initiation and Growth



A reasonable crack nucleation life can be defined by a crack length of 0.25mm (0.01in.).

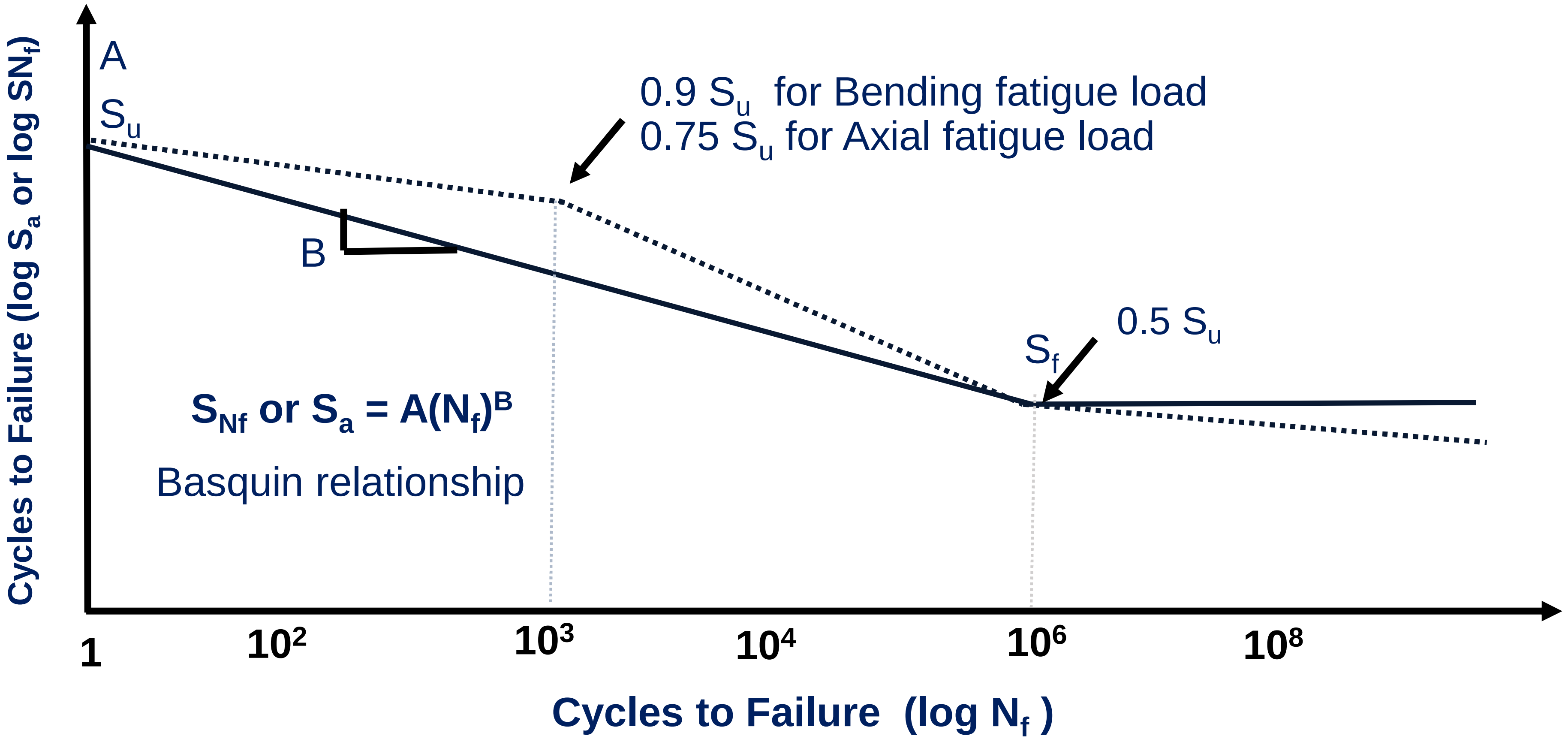
A larger fraction of life for crack growth – Higher Stress Levels and large fraction of life for crack nucleation - lower stress levels

Approximation of S-N Curve



Approximation of S-N Curve

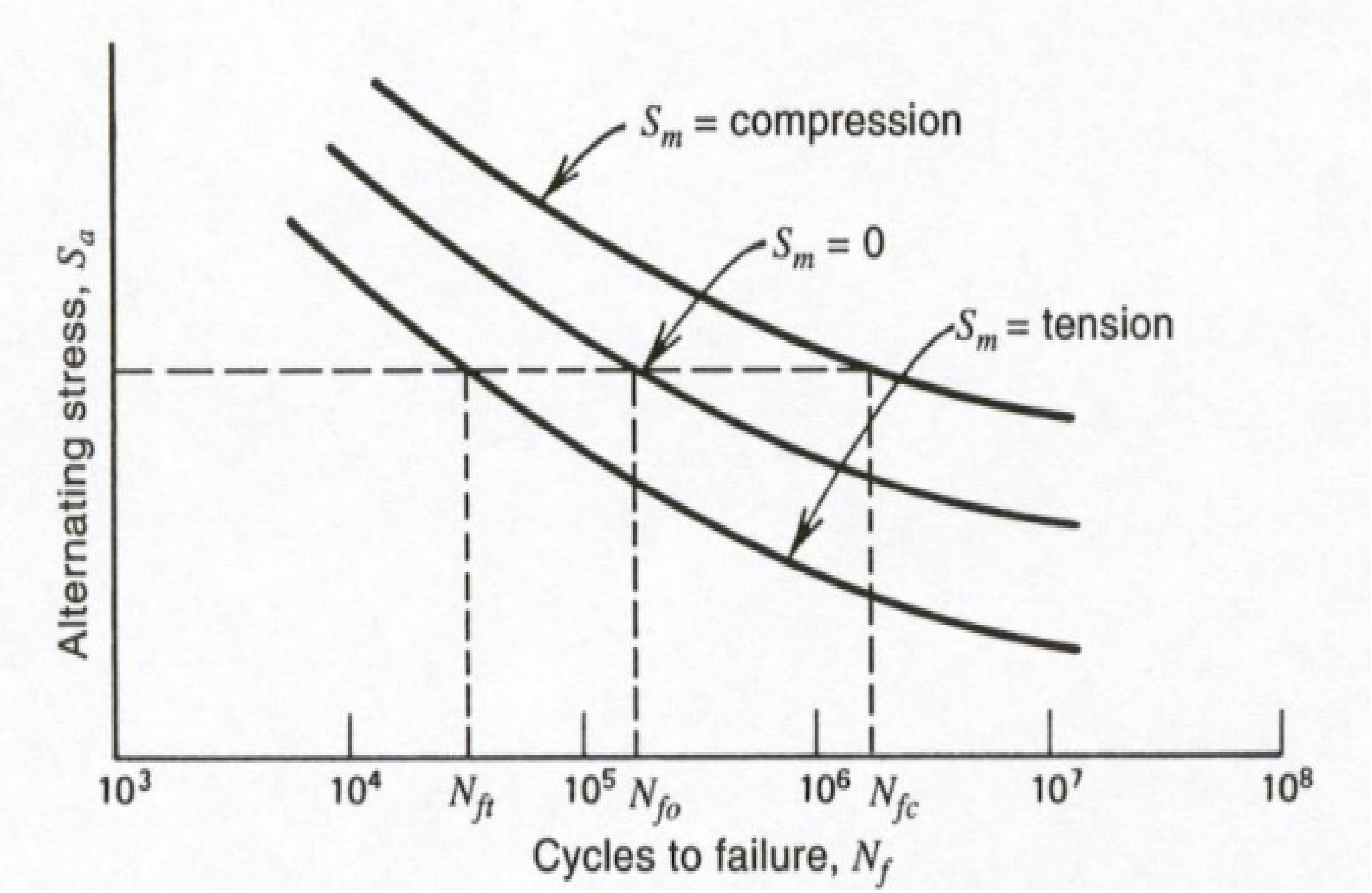
Tri-Slope Model



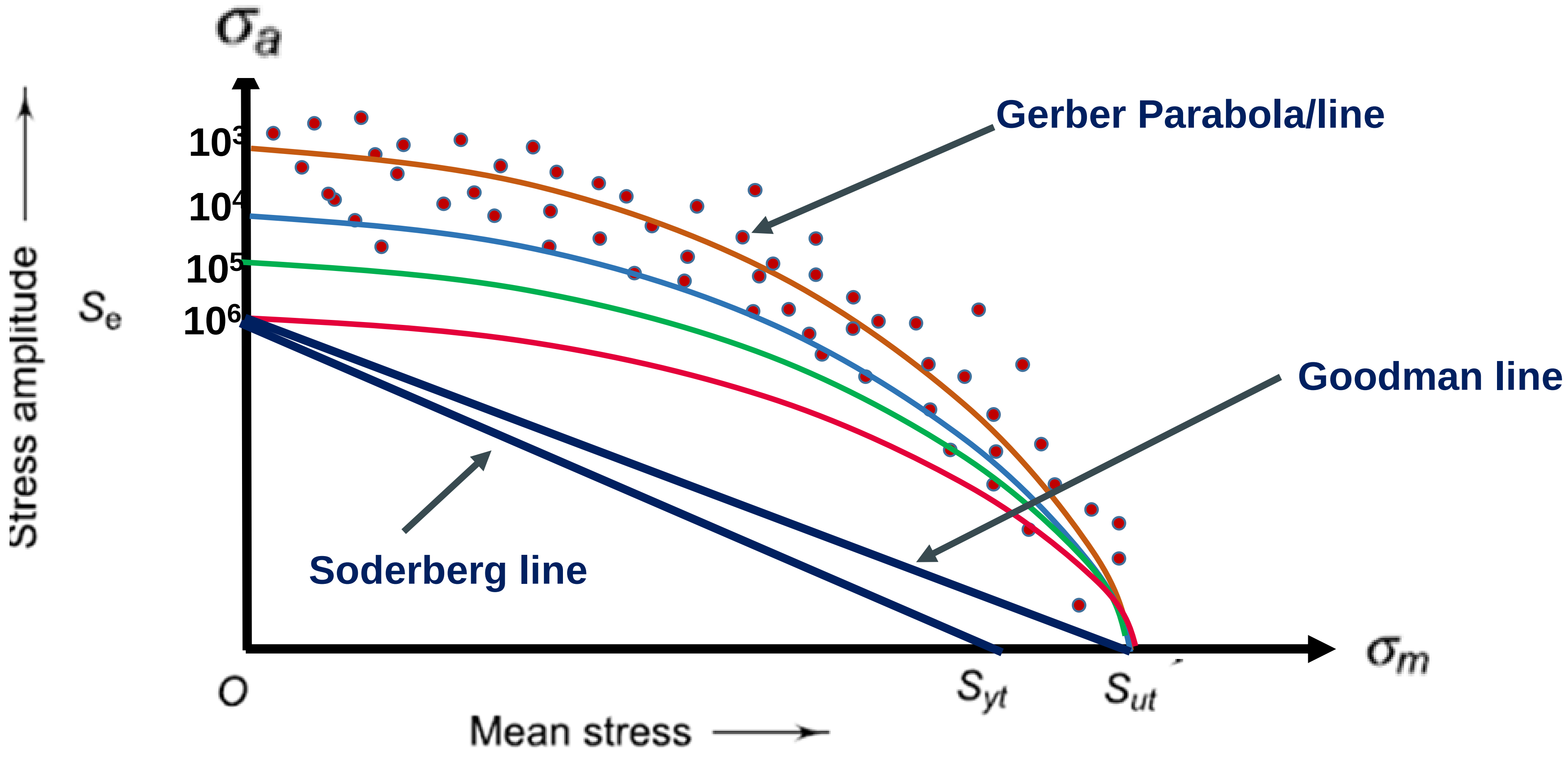
Factors Influencing S-N Behaviour

- Microstructure
- Size Effects
- Type and nature of loading
- Surface finish and directional properties
- Stress or strain concentrations
- Mean stress or strain
- Environmental effects
- Frequency

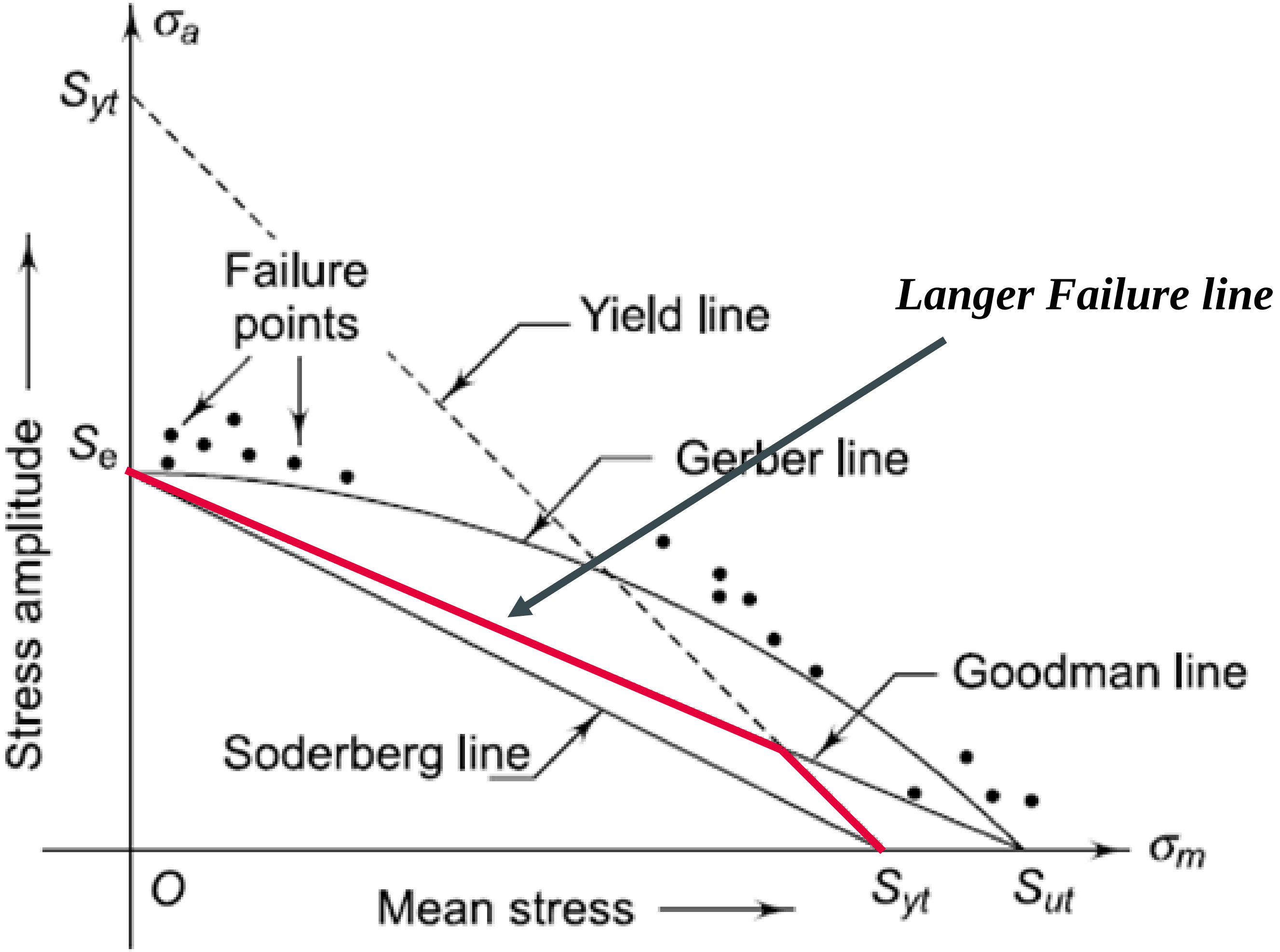
Influence of Mean Stress on S-N Behaviour



Gerber, Goodman and Soderberg Diagrams



Modified Goodman Diagram



Gerber $$\frac{\sigma_r}{\sigma_e} + \left(\frac{\sigma_m}{\sigma_{Ult}}\right)^2 = 1$$

Goodman $$\frac{\sigma_r}{\sigma_e} + \frac{\sigma_m}{\sigma_{Ult}} = 1$$

Soderberg $$\frac{\sigma_r}{\sigma_e} + \frac{\sigma_m}{\sigma_{Yield}} = 1$$

Notches and Fatigue

In real life situations, notches cannot be avoided in many structures and machines and notch effects have been a key problem in the study of fatigue.

- Thread roots and the transition between the head and the shank
- Rivet holes in sheets
- Welds on plates
- Keyways on shafts

Suitable treatment of notches often mitigates their effect or render them harmless.

Stress Concentrations

The degree of stress and strain concentration is a factor in the fatigue strength of notched parts.

Measured by the **elastic stress concentration factor, K_t**

As long as /= constant = E

$$K_t = \frac{\sigma}{S} = \frac{\varepsilon}{e} = \frac{\sigma}{\varepsilon} = \mathrm{E} \text{ or Constant}$$

Where:

σ and ε= the maximum stress or strain at the notch

S and e = the nominal stress and strain

Stress Concentrations

The stress concentration produced by a given notch is not unique number and depends on the following:

- Mode of loading
- Type of stress used to calculate K_t.

For a circular hole in a wide sheet we have-

In tension - 3

In bi-axial tension – 2

In Shear it is 4 based on maximum tension and 2 based on maximum shear

Estimating Stress Concentrations

Elastic stress concentration factors are obtained from:

- Theory of elasticity
- Numerical solutions
- Experimental measurements

FEA Method with fine mesh at stress concentrations points.

Experimental measurement techniques widely used include

- Brittle coatings
- Photoelasticity
- Thermoelasticity
- Strain gauges.

Notch Sensitivity and Fatigue Notch Factor, K_f

- The effect of the notch in the stress-life approach is taken into account by modifying the un-notched S-N curve through the use of the fatigue notch factor, K_f.
- Notched fatigue strength not only depends on the stress concentration factor, but also on other factors such as the notch radius, material strength, and mean and alternating stress levels.
- The ratio of smooth to net notched fatigue strengths, based on the ratio of alternating stresses is called K_f.

$$K_f = \frac{\text{Smooth fatigue strength}}{\text{Notched fatigue strength}}$$

Notch Sensitivity and Fatigue Notch Factor, K_f

Values of K_f for R= -1 generally range between 1 and K_t, depending on the **notch sensitivity of the material, q, which is defined by:**

Notch sensitivity of a material

$$q = \frac{K_f - 1}{K_t - 1}$$

A value of q= 0 (or K_f= 1) indicates no notch sensitivity, whereas a value of q= 1 (or K_f= K_t) indicates full notch sensitivity.

The fatigue notch factor can then be described in terms of the material notch sensitivity as

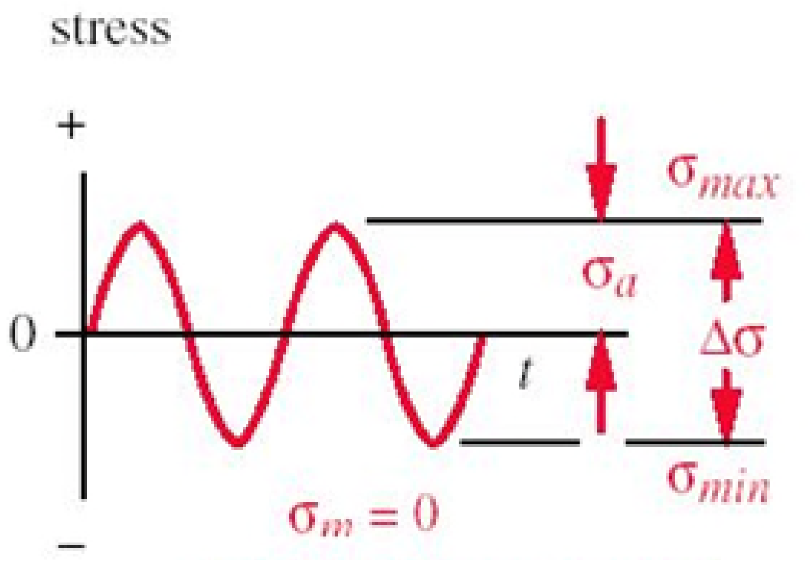
$$K_f = 1 + q(K_t - 1)$$

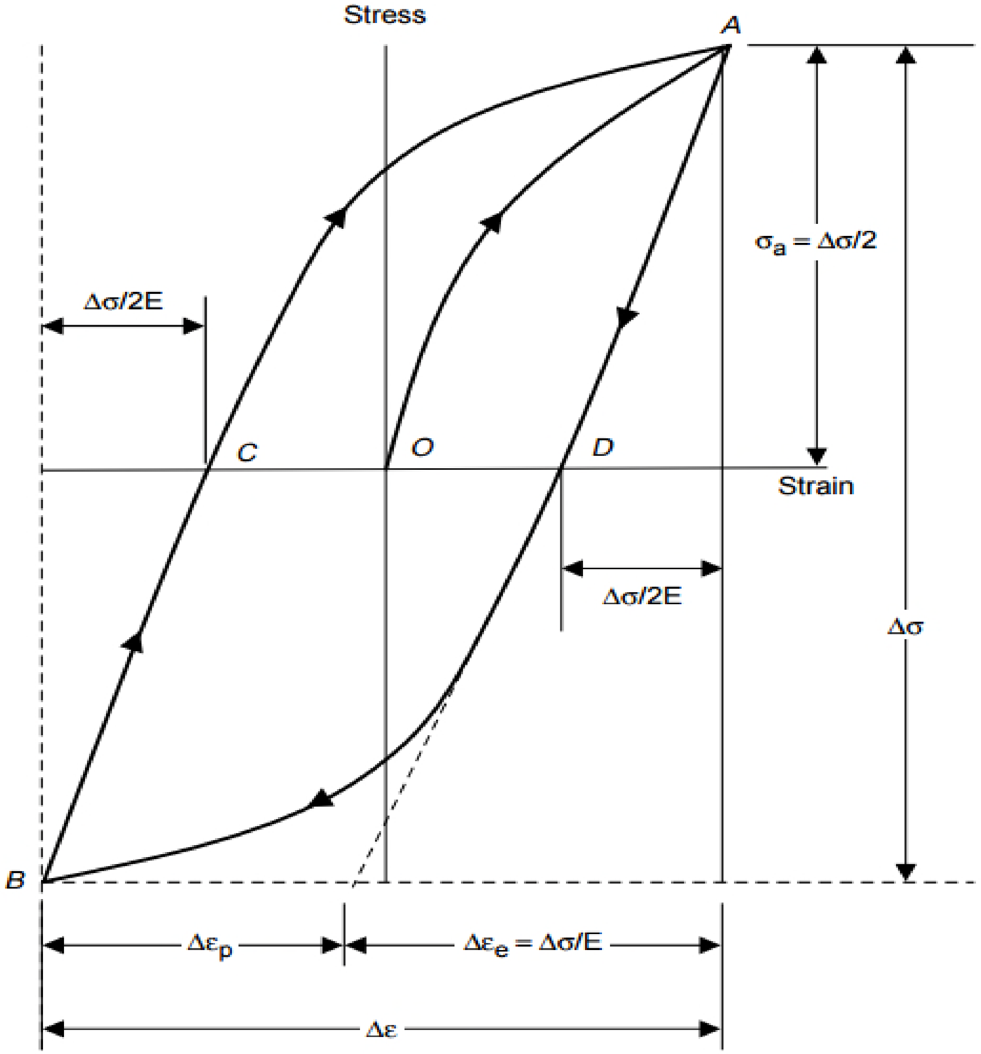
Fatigue Life Relationship

Measurable plastic deformation - ? **YES**

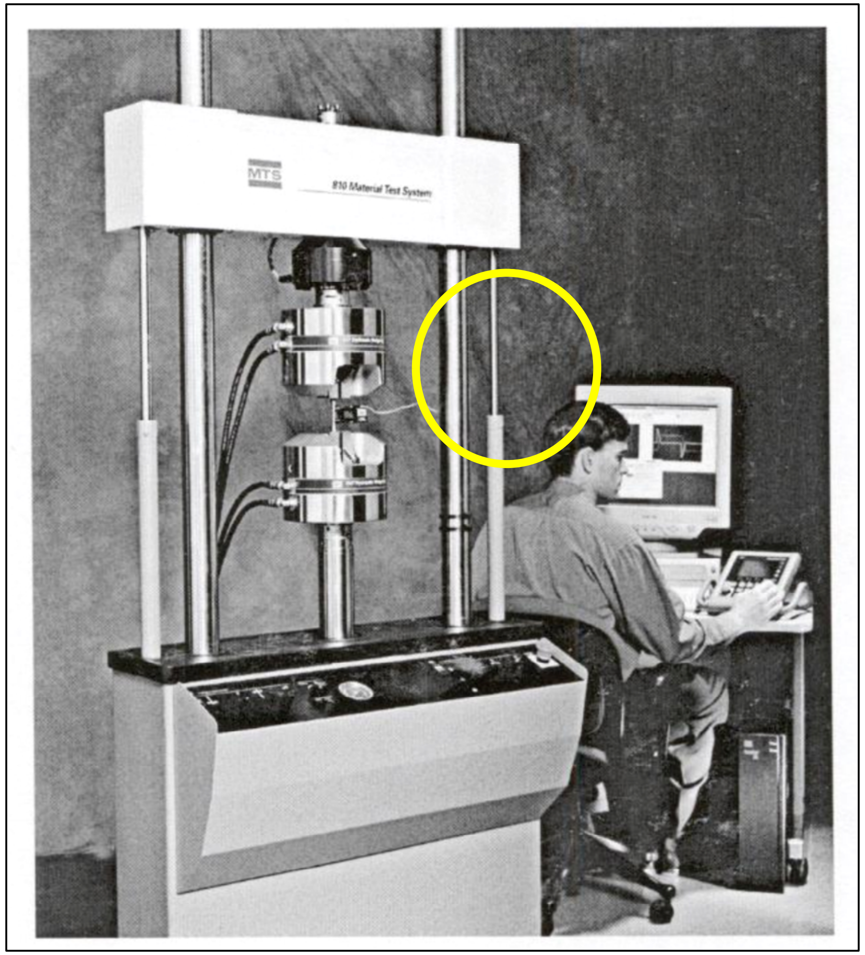
Stress Based Method	Strain Based Methods	LEFM
• Suited for HCF • Infinite Life approach • Easiest methods • Prevent crack initiation using strength criteria • Not very effective for LCF • Does not address crack growth	• Suitable for LCF • Accurate for crack initiation and growth • Complex process • Requires computation methods.	• Model based on existing crack. • Describes crack propagation • Predict remaining life • Models sensitive to accuracy of stress intensity factors.

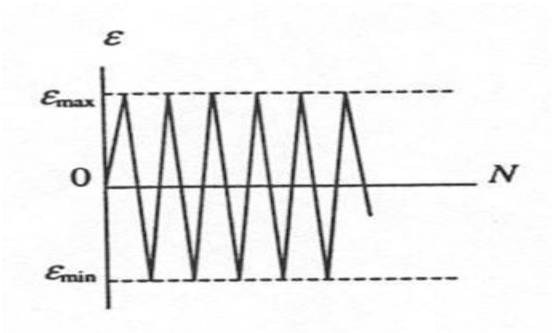
Ideal cyclic loading and response





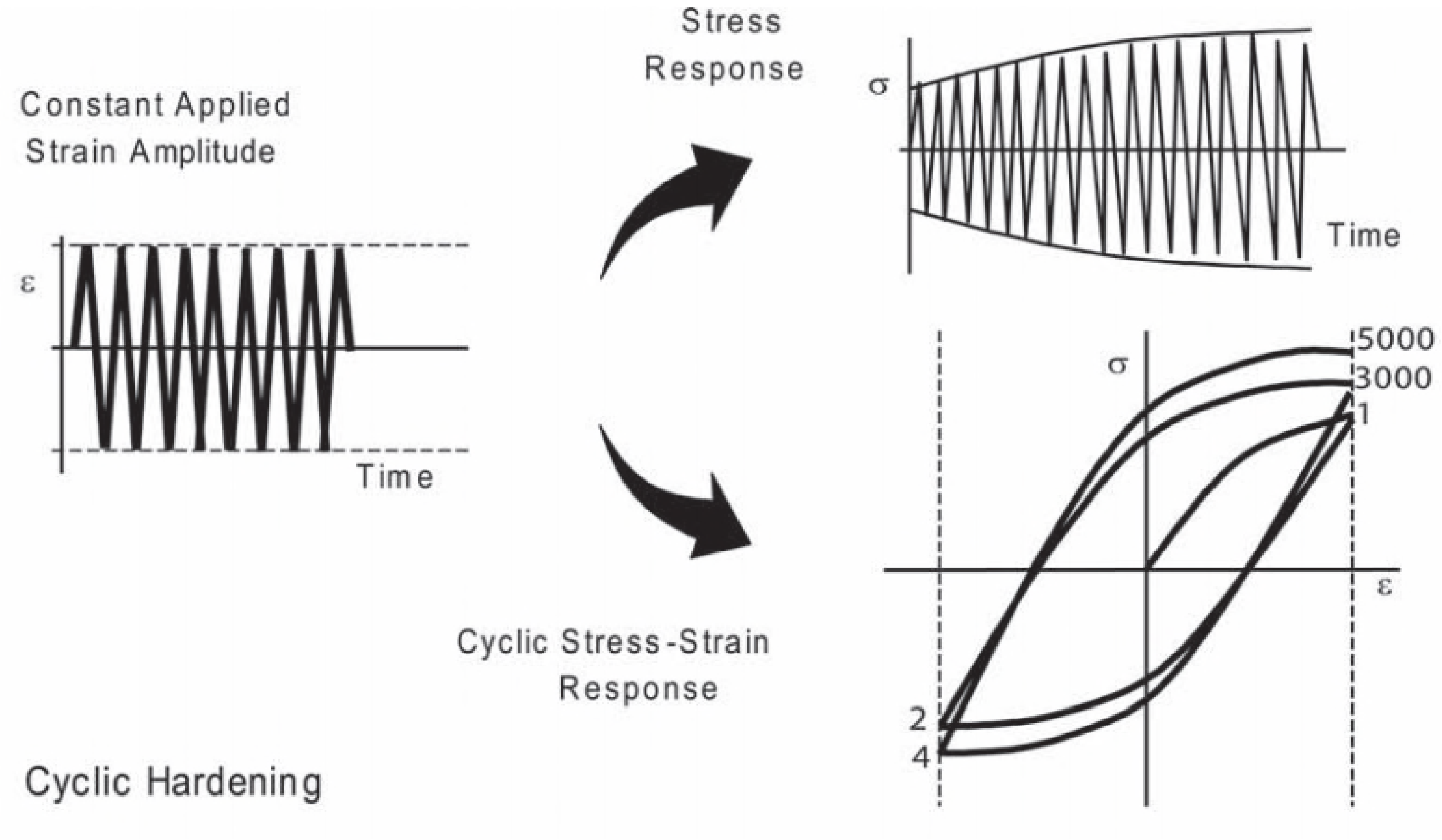
Strain Controlled Fatigue Tests



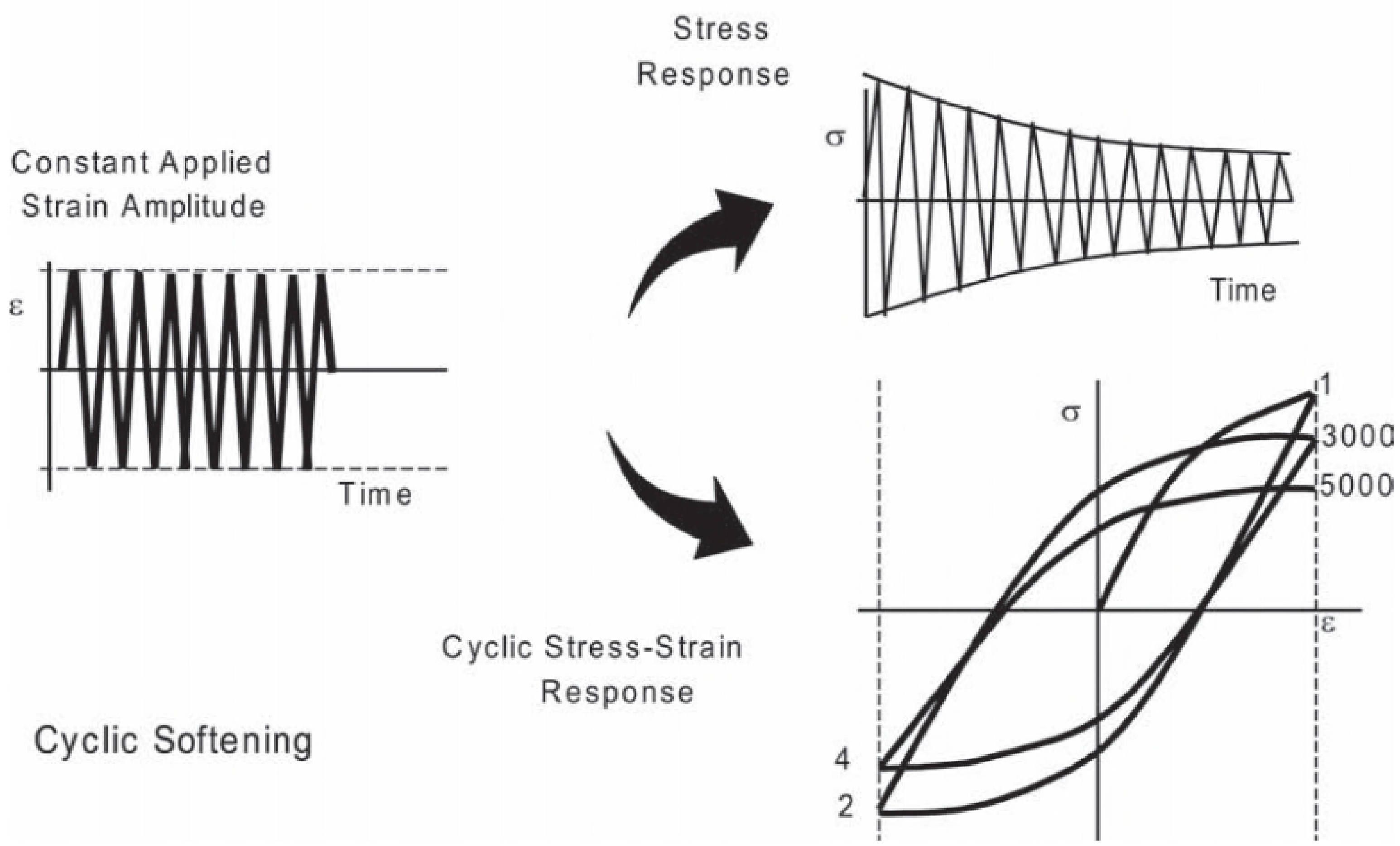


Strain-controlled fatigue testing are preferred , even though the testing equipment and control are more complicated and expensive than the traditional load or stress-controlled testing.

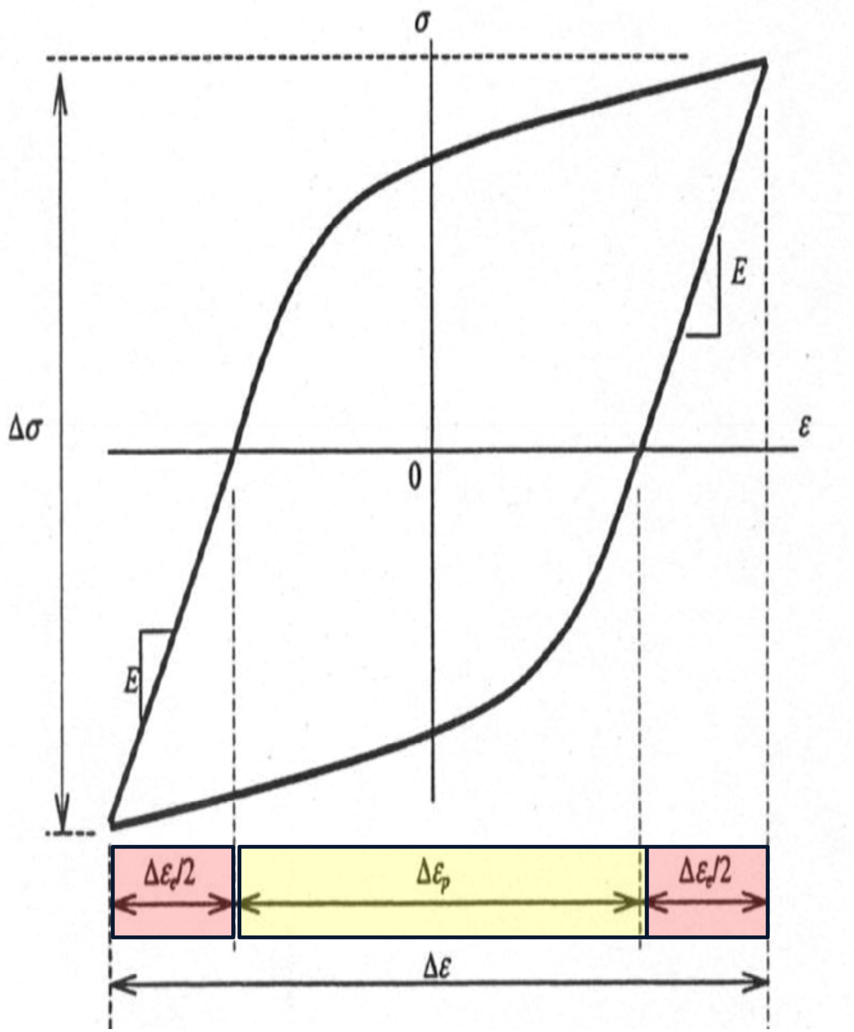
Cycle Hardening



Cycle Softening



Cyclic Deformation and Hysteresis



A hysteresis loop from about half the fatigue life is often used to represent the stable or steady-state cyclic stress-strain behaviour of the material

$\Delta\varepsilon =$ total true strain range

$\Delta\sigma =$ true stress range

$\Delta\varepsilon_e =$ true elastic strain range $= \Delta\sigma / E$

$\Delta\varepsilon_p =$ true plastic strain range

$$\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_e = \Delta\varepsilon_p + \frac{\Delta\sigma}{E}$$

ε-N Approach to Life Estimation

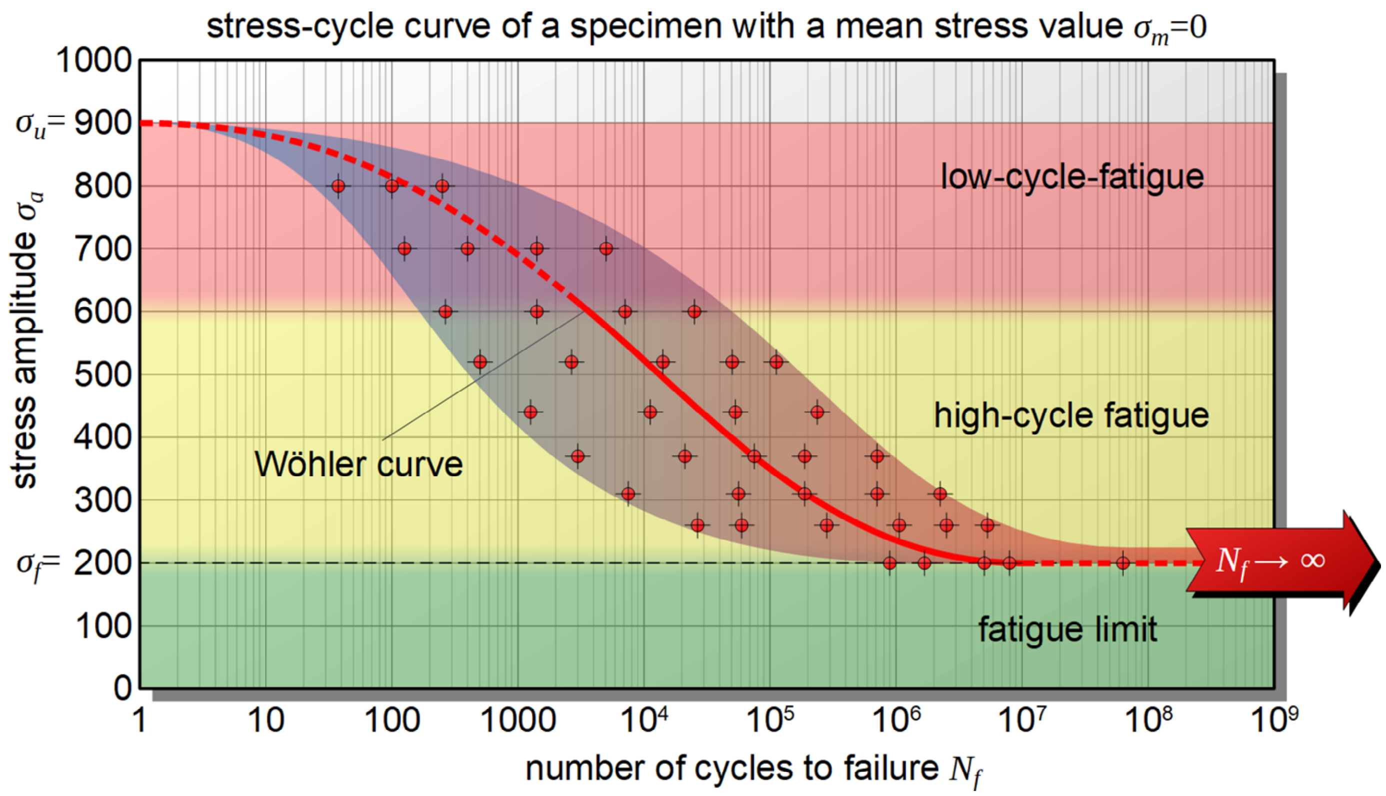
$$\varepsilon = \varepsilon_e + \varepsilon_p$$

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2}$$

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^{-b} + \varepsilon_f^{'}\left(2N_f\right)^{-c}$$

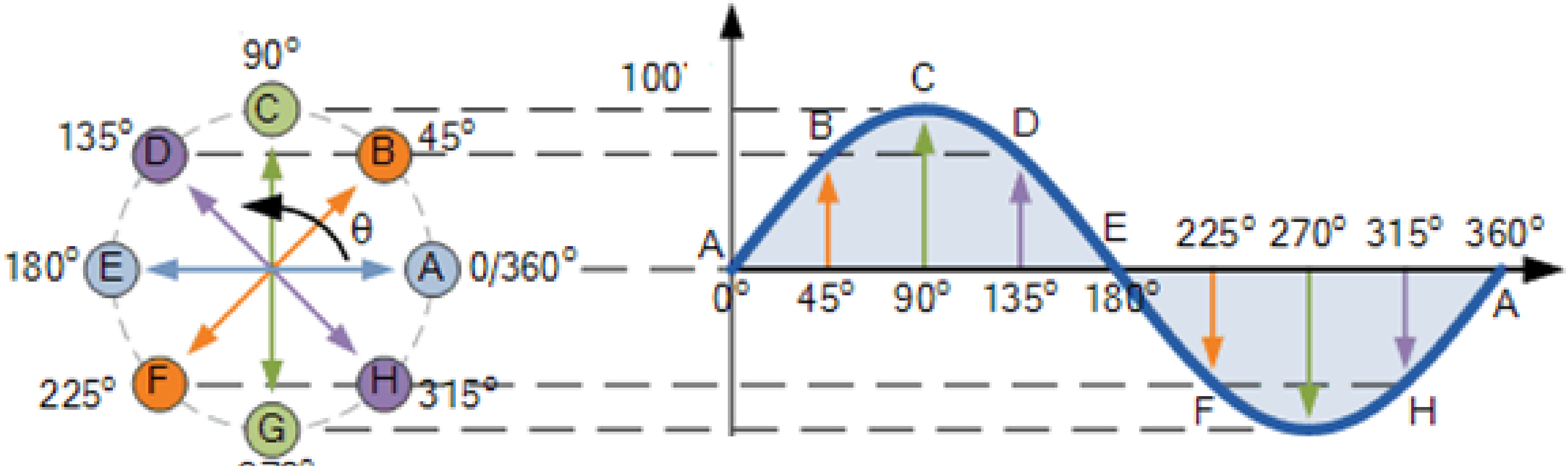
Coffin-Manson Equation

Vibrations monitoring

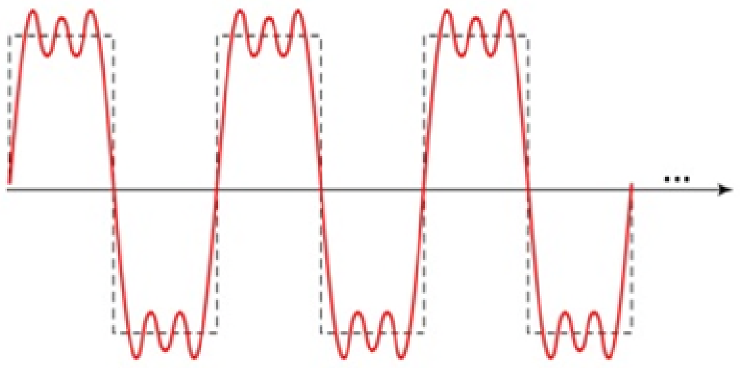


Ref- https://www.tec-science.com

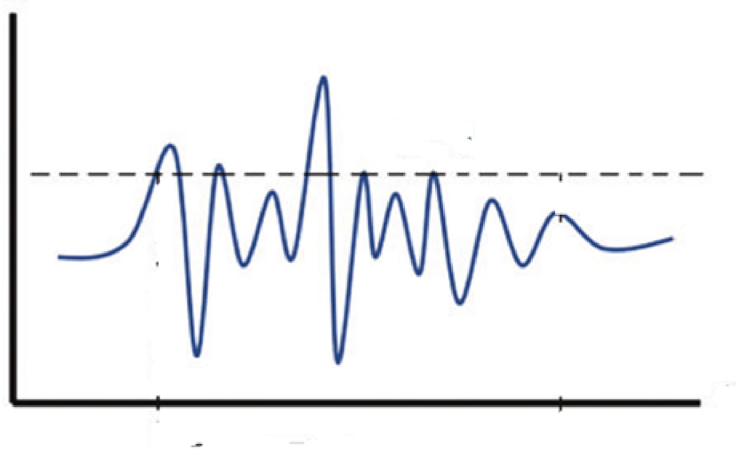
Understanding Vibration



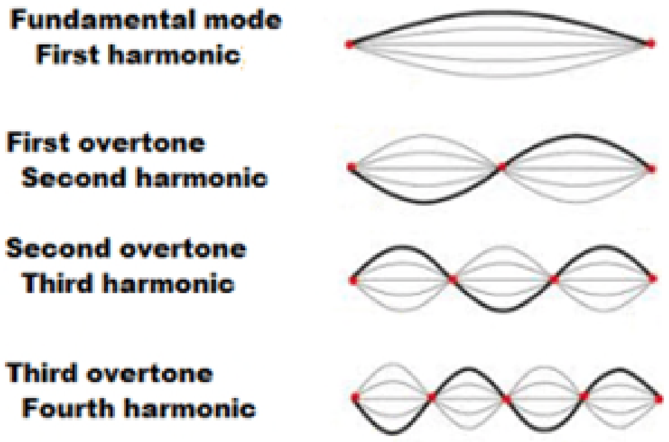
Nature of Vibration



Periodic Signal



Random Signal



Harmonics

Resonance

Types of Vibration

Free Vibrations

- Excitation force removed after initial displacement
- Body vibrates on its own

Damped Vibrations

- Resistance force restricts the displacement
- Amplitude of vibration reduces progressively

Forced Vibrations

- External excitation force is required to sustain the displacement
- Amplitude may vary

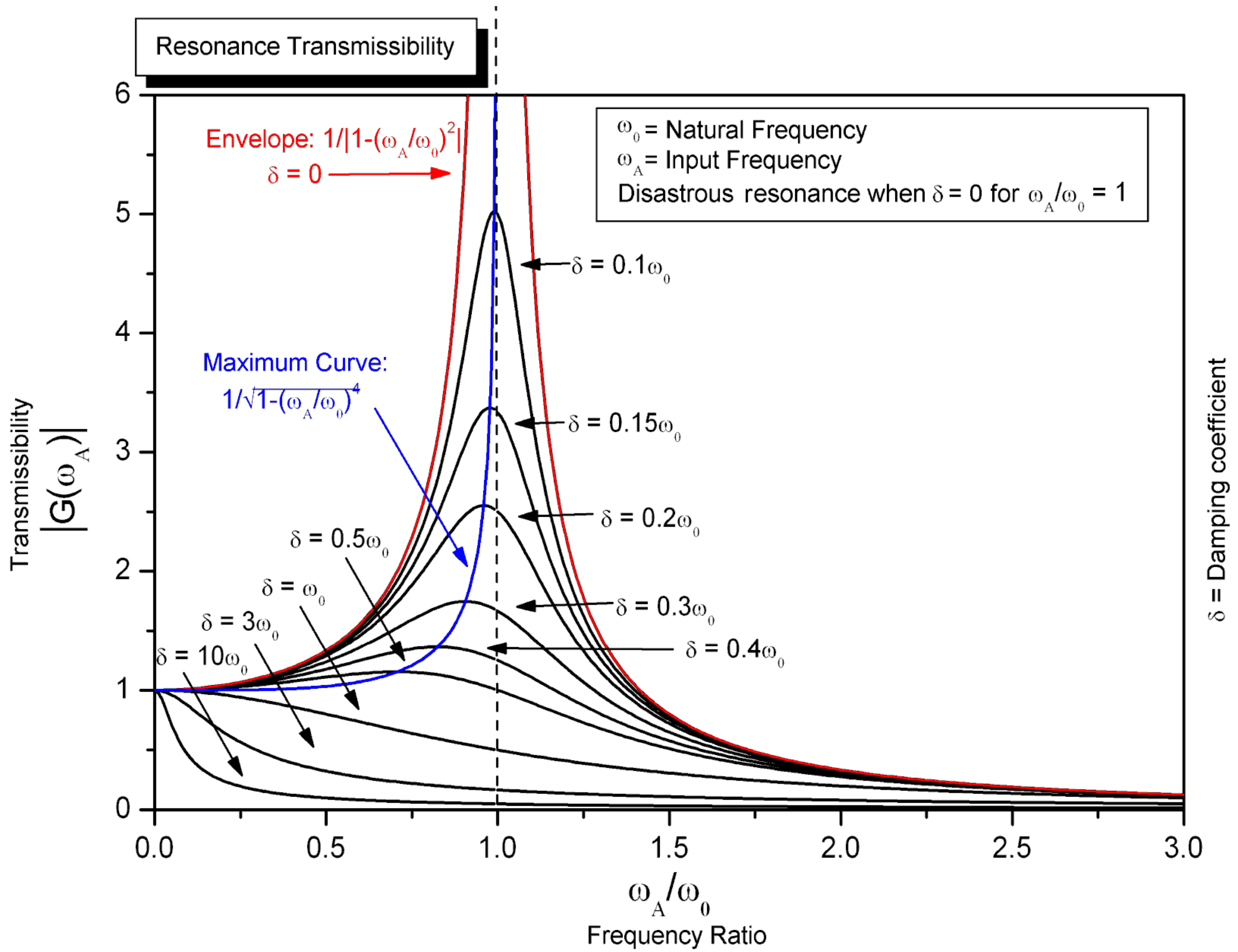
Forced Vibration- Magnification

Magnification Factor

$$\frac{X}{X_0} = \frac{1}{\sqrt{\left[\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\left(\frac{C}{C_{cr}}\right)\left(\frac{\omega}{\omega_n}\right)\right)^2\right]}}$$

Frequency Ratio

Forced Vibration



Magnification effect and damping

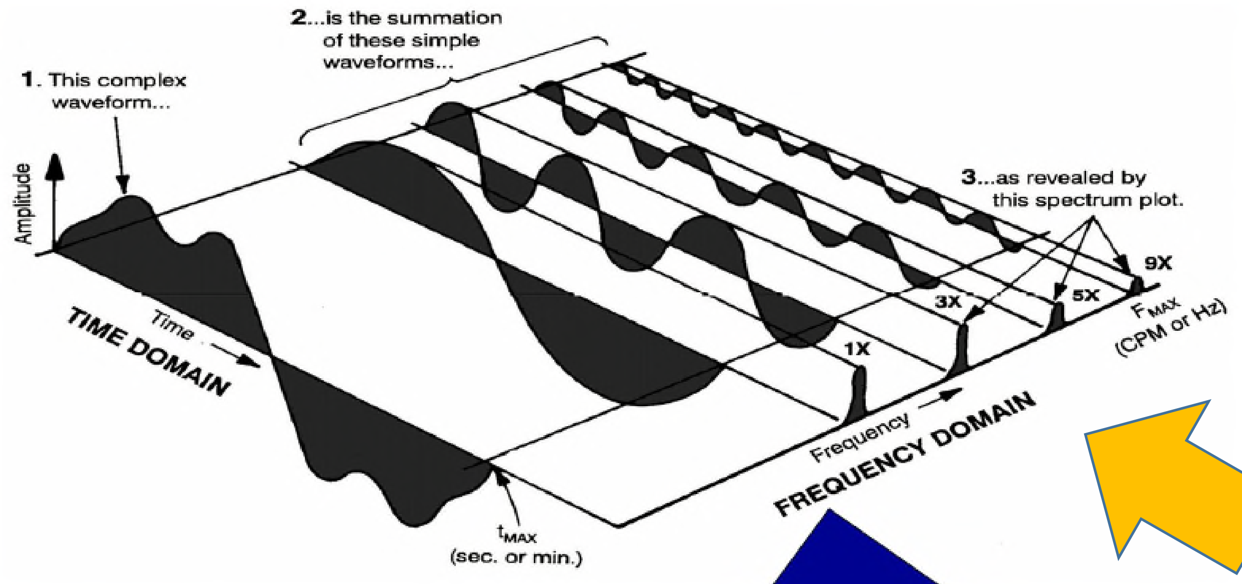
Causes of Vibration

- Looseness
- Unbalance
- Misalignment/shaft run-out
- General wear
- Spalling of bearing
- Rubs in components/casing
- Unequal flow path clearances
- Cavitation
- Self Excitation
- Gears teeth engagement

Vibrations Signature

Time & Frequency Domain

Time Domain

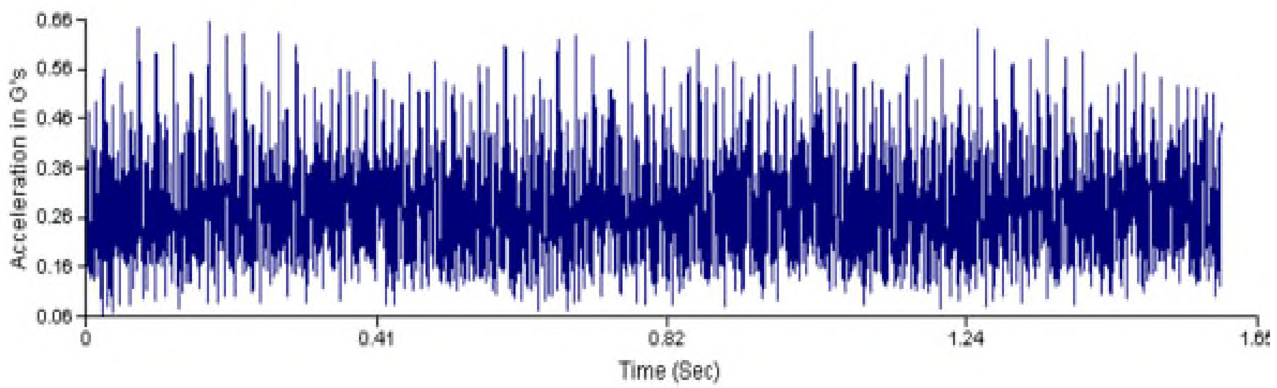


Fast Fourier Transform

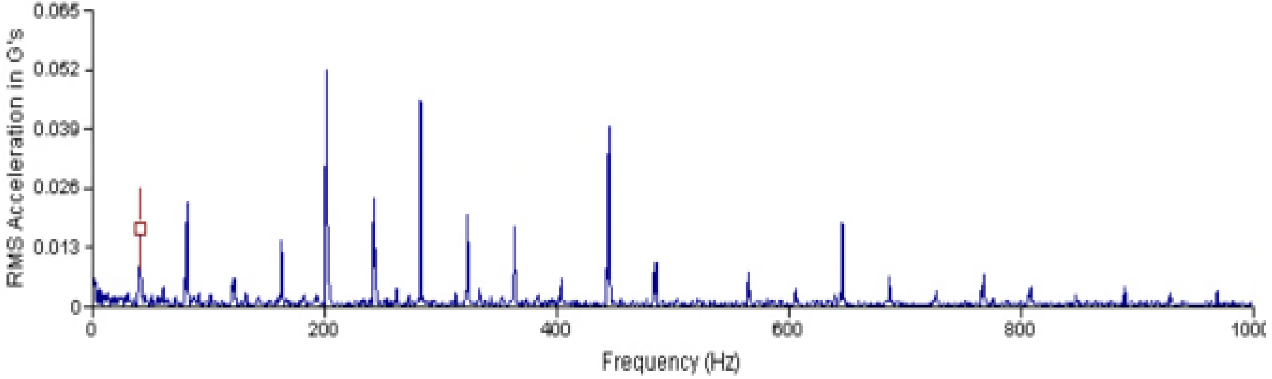
Frequency Domain

Time Domain waveform shown as many different frequencies and amplitudes

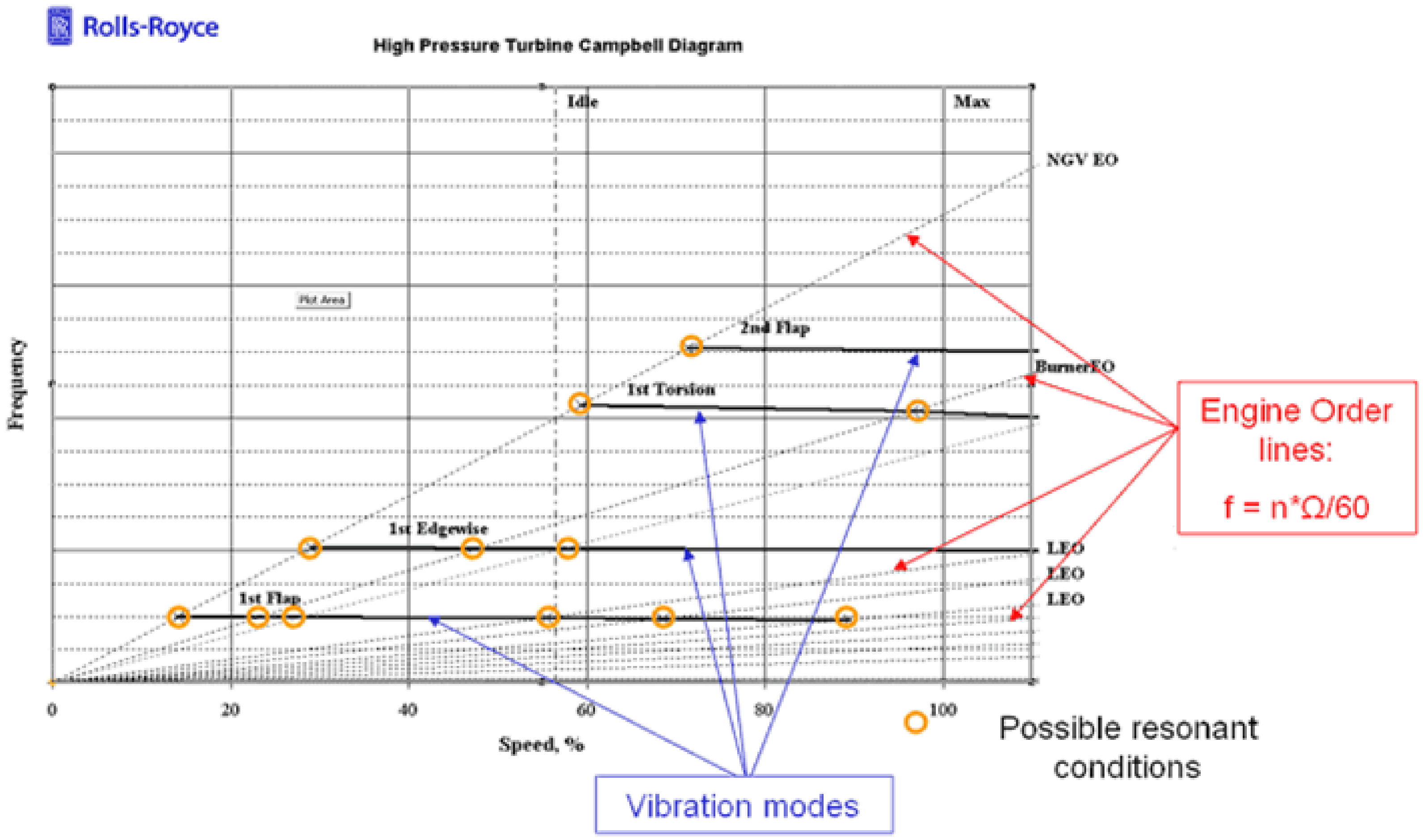
Time Domain vs Frequency Domain



Frequency Domain Signal



Vibrations signature Display methods

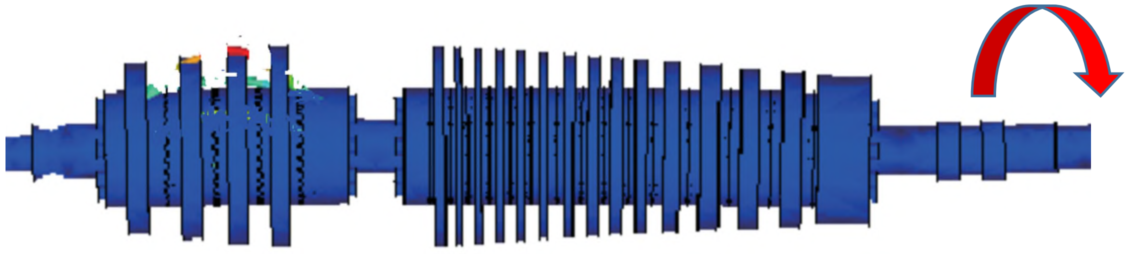


Campbell Diagram

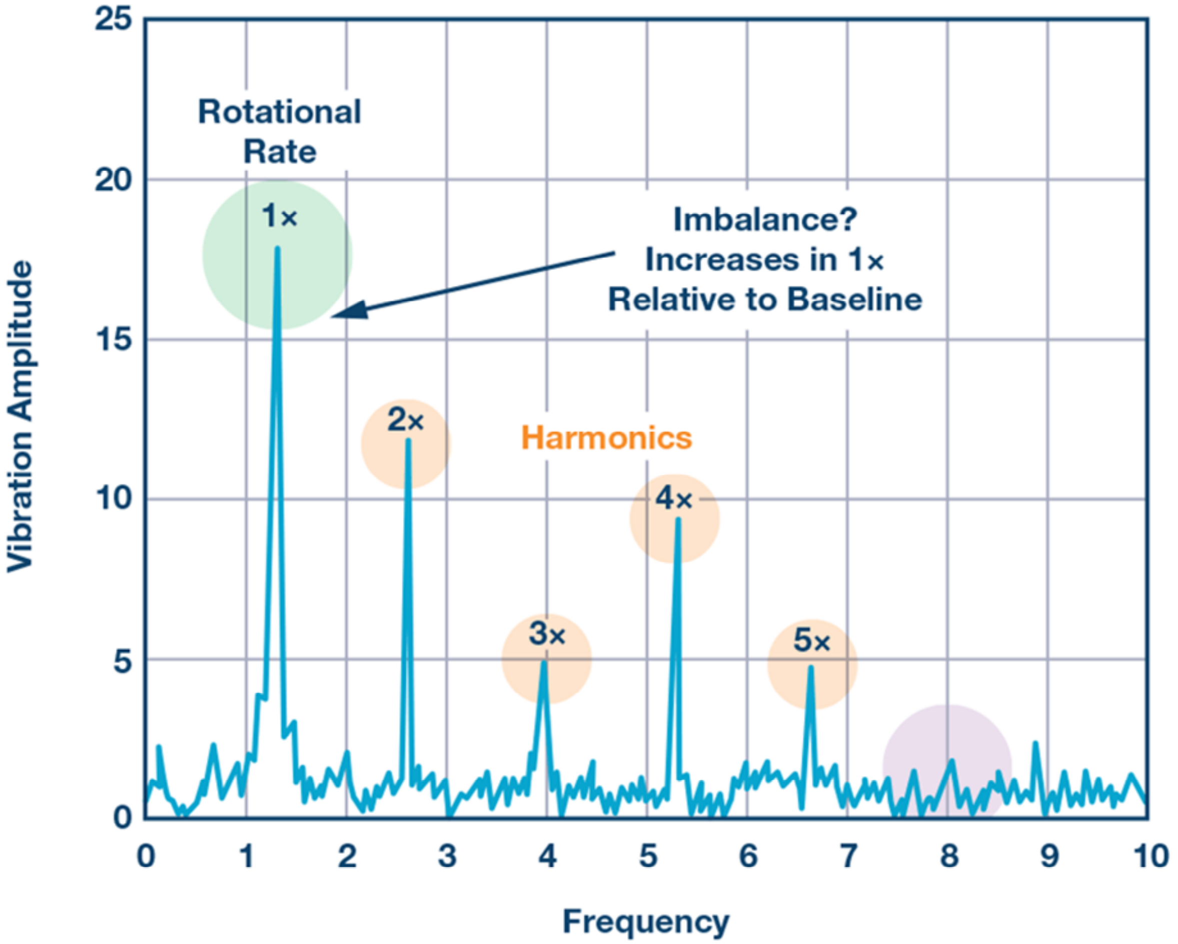
Vibration in Gas Turbine

- Rotor frequency
- Blade pass frequency
- Bearing frequency
- Shaft whirl frequency
- Gear mesh frequency
- Blade Rub
- Fixed wake excitation- Spokes, struts etc.
- Blade Flutter
- Rotating stall cell

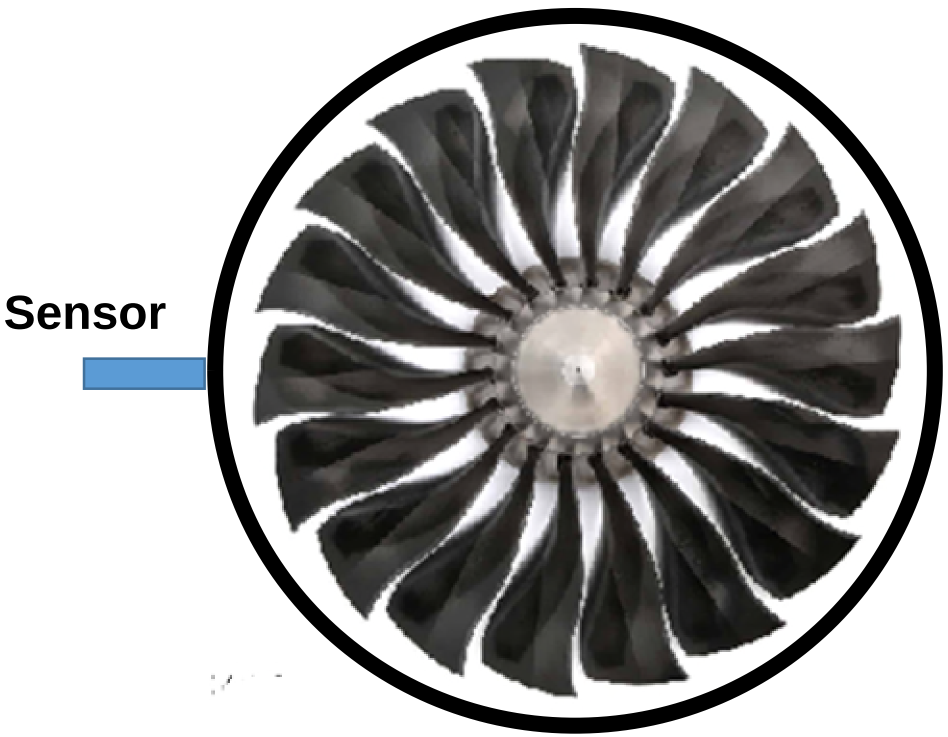
Rotor Frequency



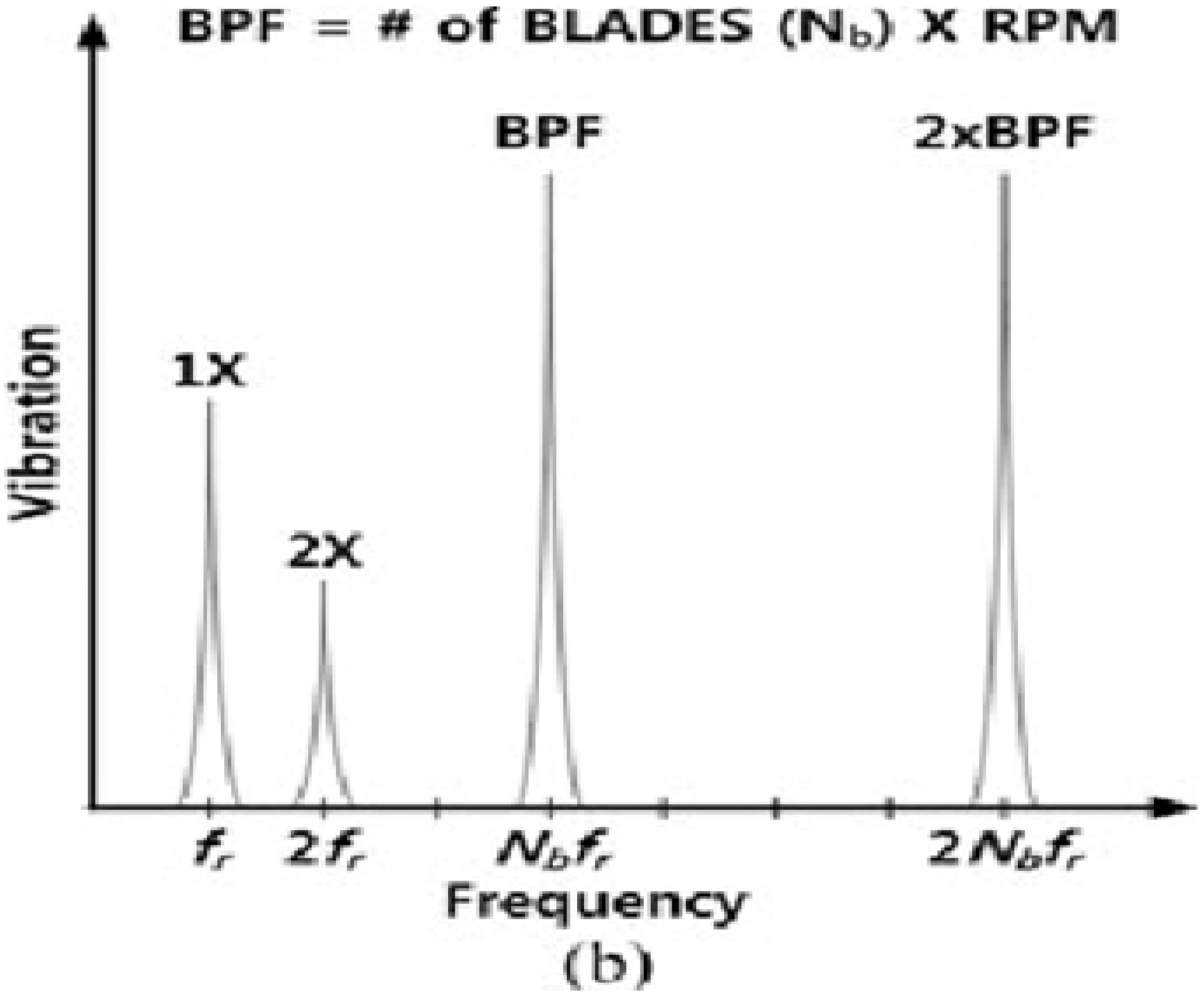
Rotor Frequency- x



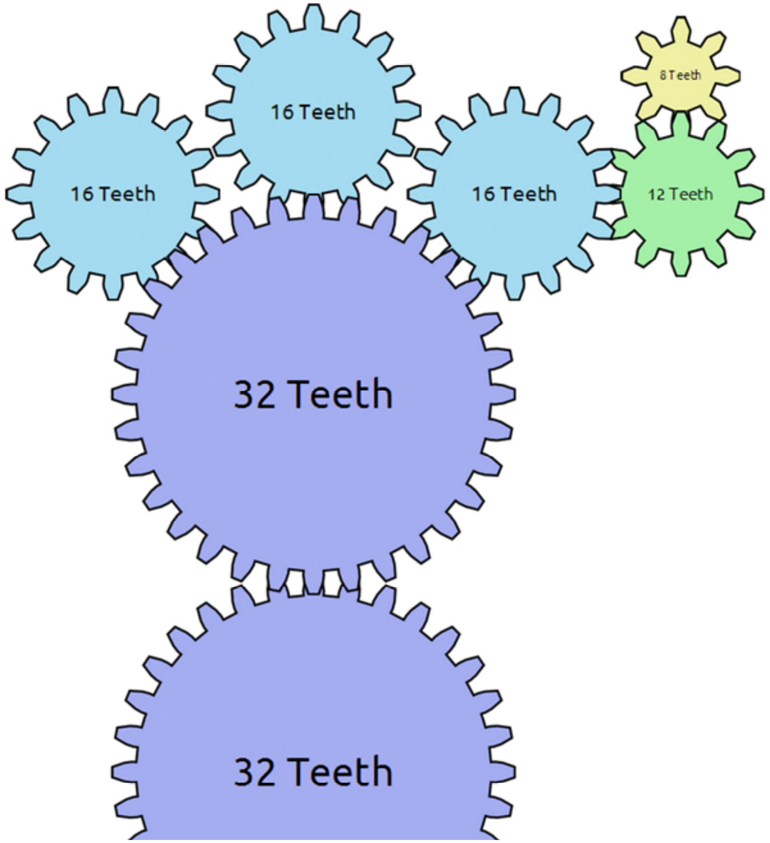
Blade Pass Frequency

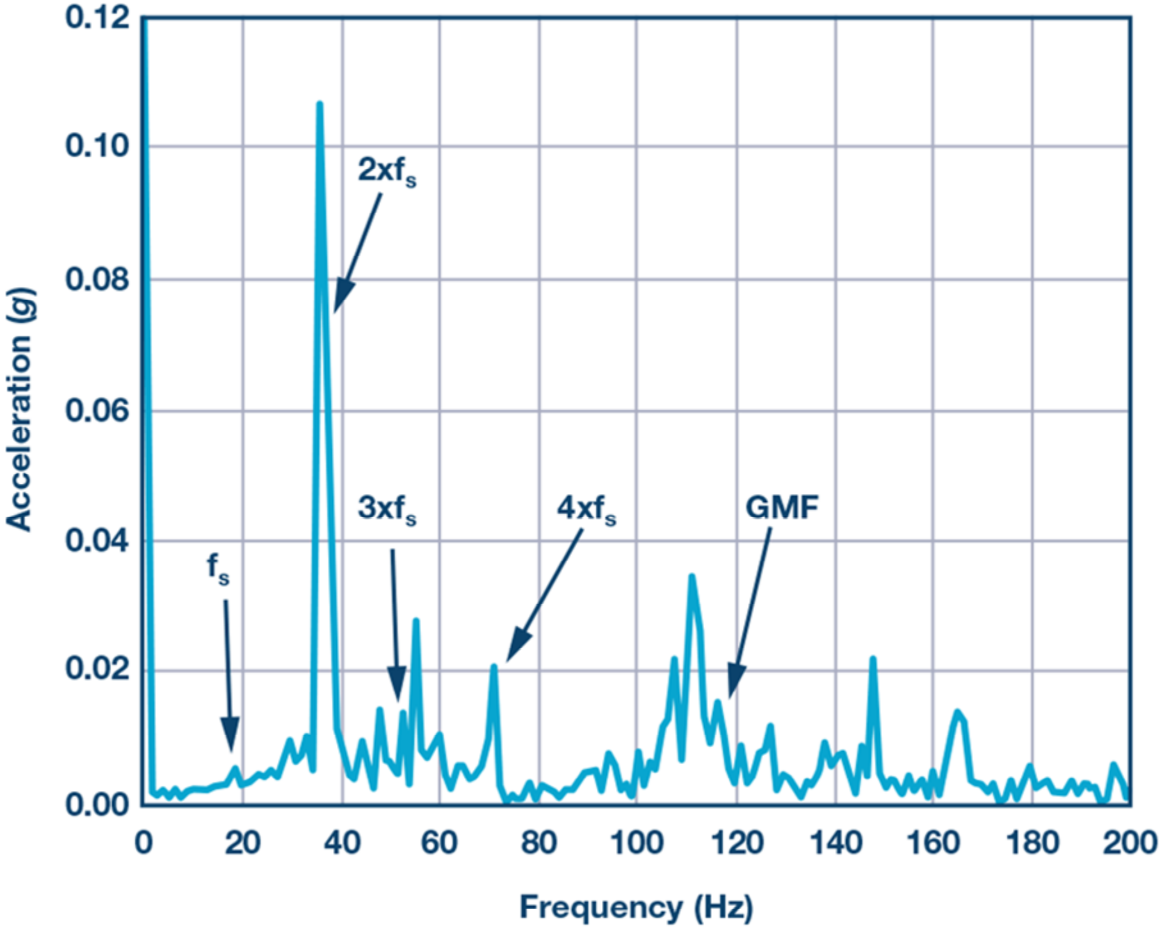


No of Blades - n

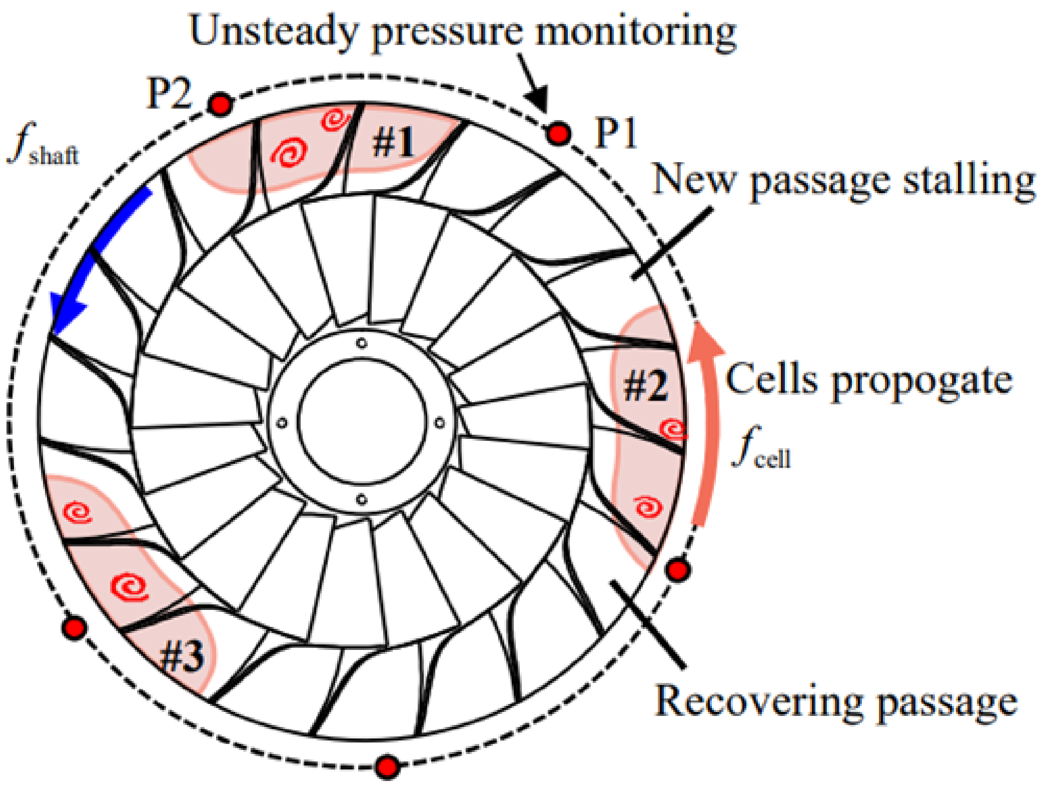


Gear Mesh frequency



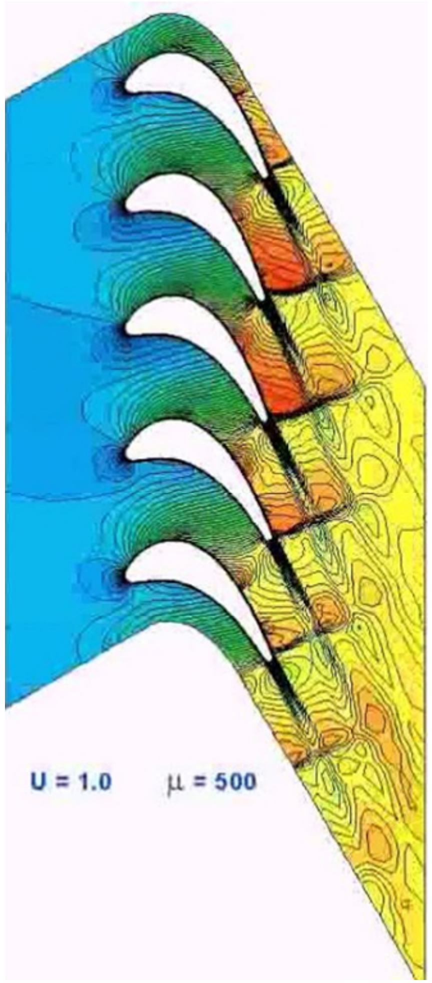


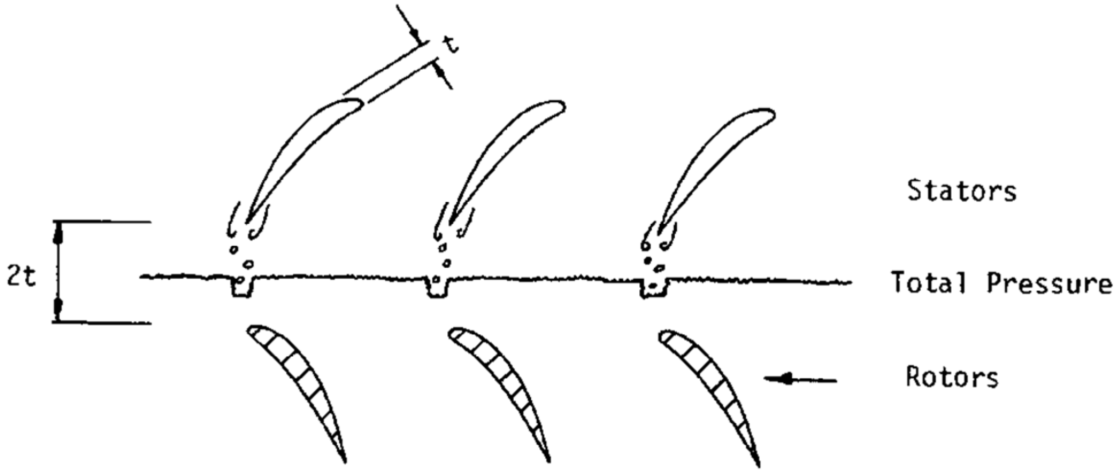
Rotating Stall

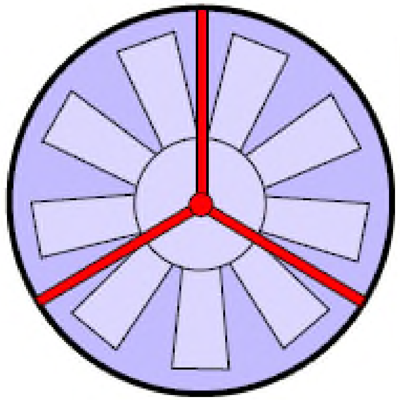


Sensors **2019**, *19*(22), 4995; https://doi.org/10.3390/s19224995

Wake Excitation frequency







Example characteristic frequency:

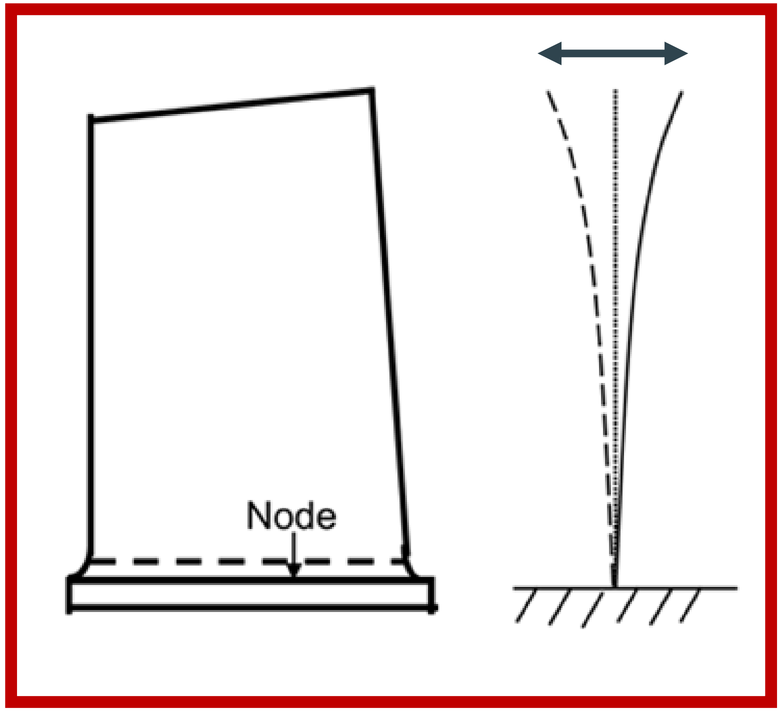
3 struts in the intake; x=3.

9 blades; B_n=9.

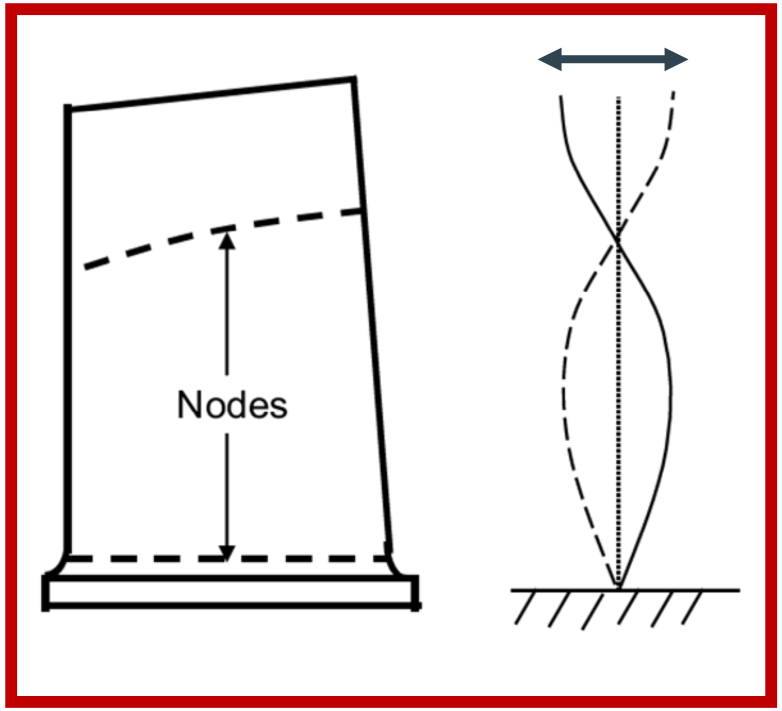
$f_{BP} \cdot x = N \cdot B_n \cdot x$

Characteristic frequency = N · 27

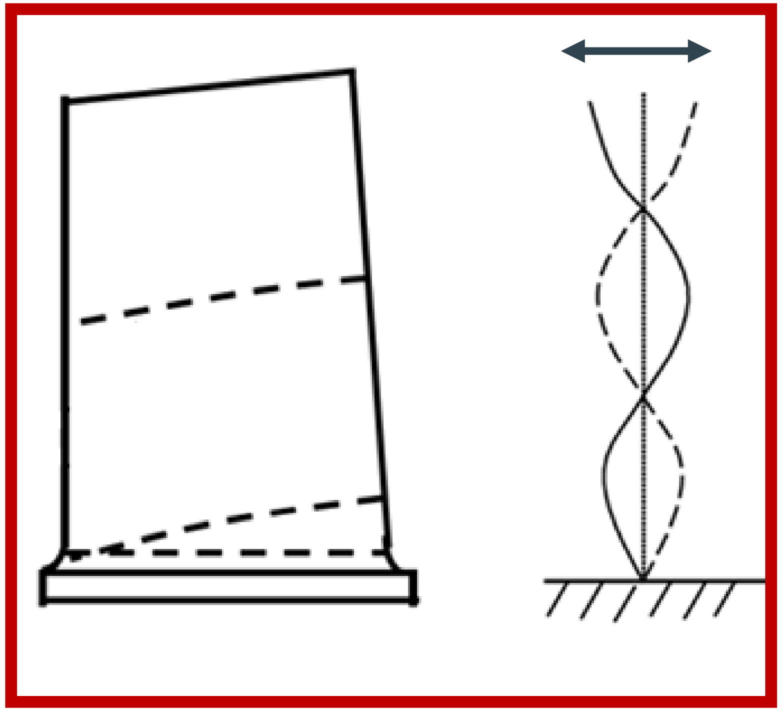
Blade Modes of Vibration



Fundamental Mode (1F)

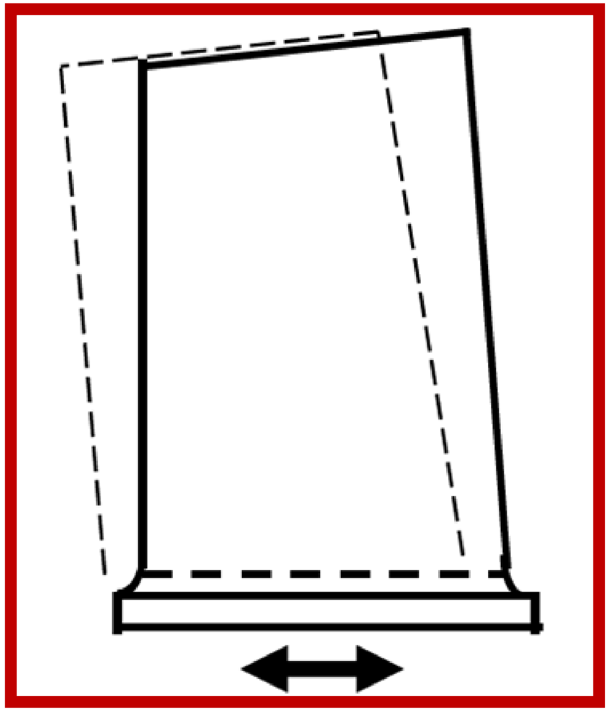


Second Flap Mode (2F)

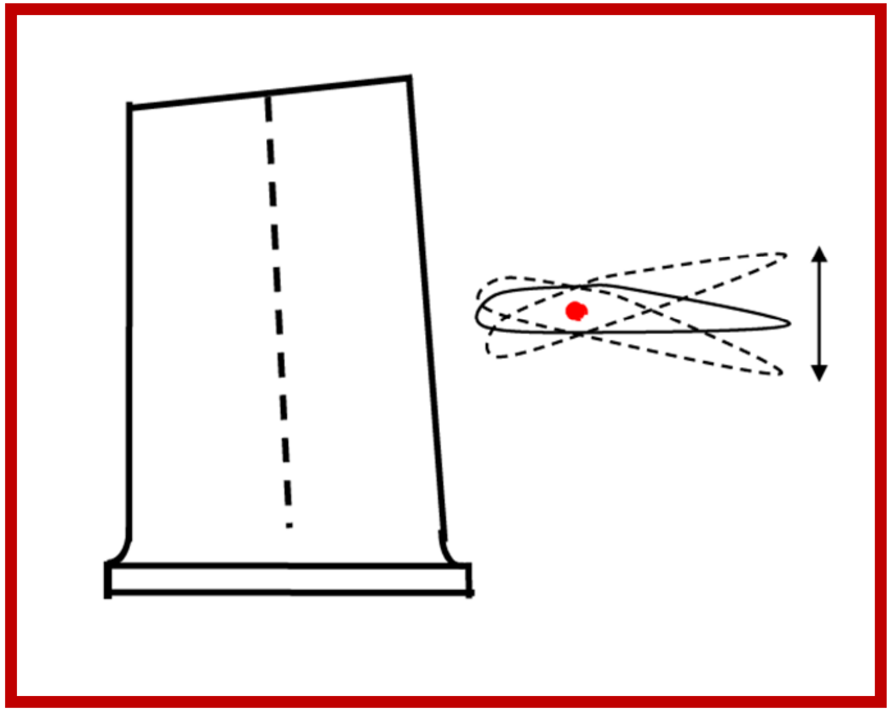


Third Flap Mode (3F)

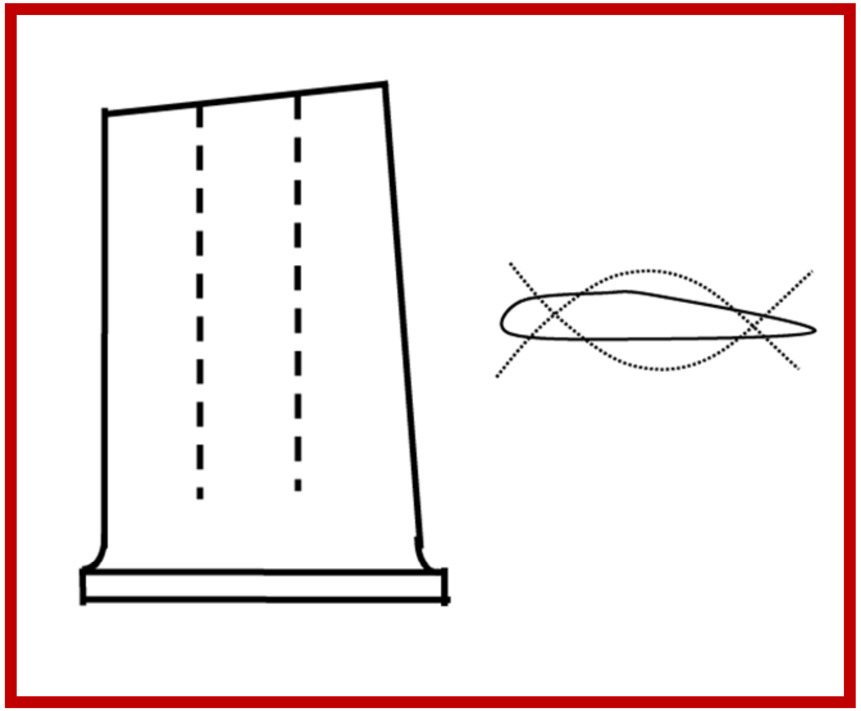
Blade Modes of Vibration



First Edgewise (1E)

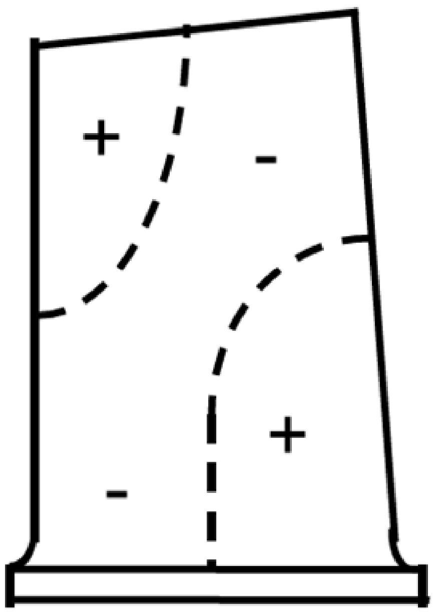


First Torsional (1T)

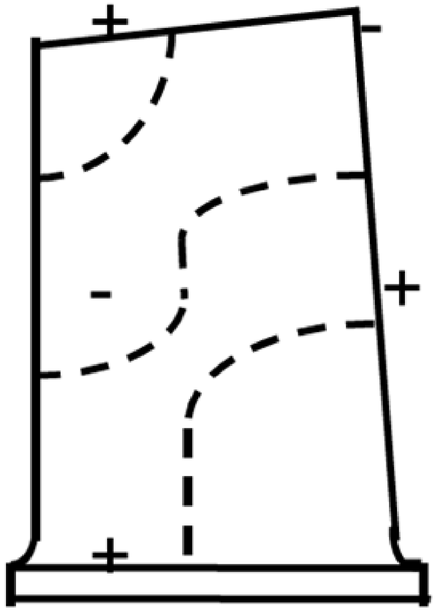


Second Torsional (2T) (Tramline)

Blade Modes of Vibration



Second Torsional Mode (2T)



Third Torsional Mode (3T)

Combined Flexural and Torsional Effect

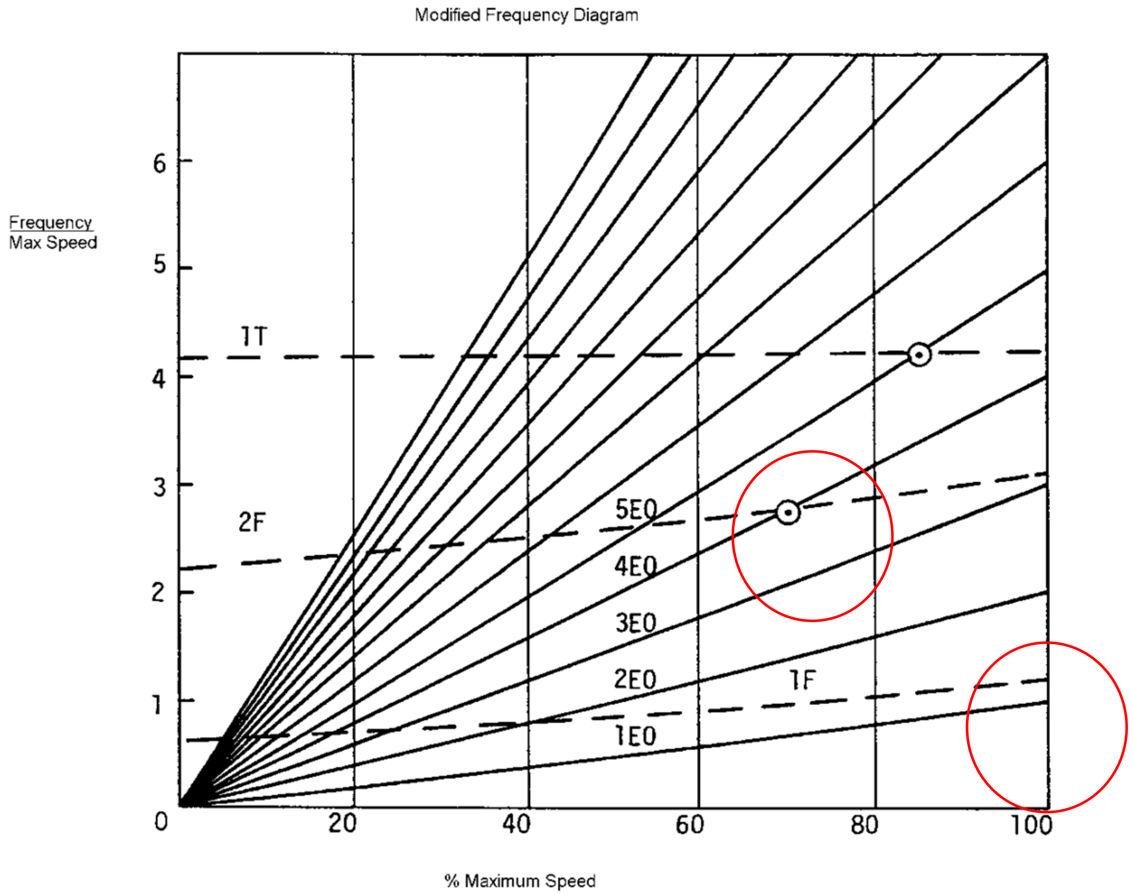
Altering Blade Natural Frequency

- Geometry, dimension and fixing
  - Thickness of blade and root
  - Change chord and taper
  - Root fixing method

- Altering the construction of flow passage, Bleed ports
  (conflict with other design considerations)

Largely depends on other design consideration like weight, stress, aerodynamic considerations

Managing Blade Natural Frequency



Natural Frequencies Altered to avoid conflict against engine operating condition

Rayleigh Ritz Method

$$f = \frac{1}{2\pi l^2}\sqrt{\frac{E}{\rho}\frac{\int_0^1 I\left(\frac{d^2y}{dx^2}\right)^2 dx}{\int_0^1 Ay^2\,dx}}$$

$$f = \frac{1}{2\pi l^2}\sqrt{\frac{E}{\rho}} \times f_p$$

Non-dimensional flap frequency

Cold Static Natural Frequency

Blade Natural Frequency

Effect of Blade Conditions

- Effect of Pre-Twist
- Effect of Temperature
- Effect of Centrifugal stiffening

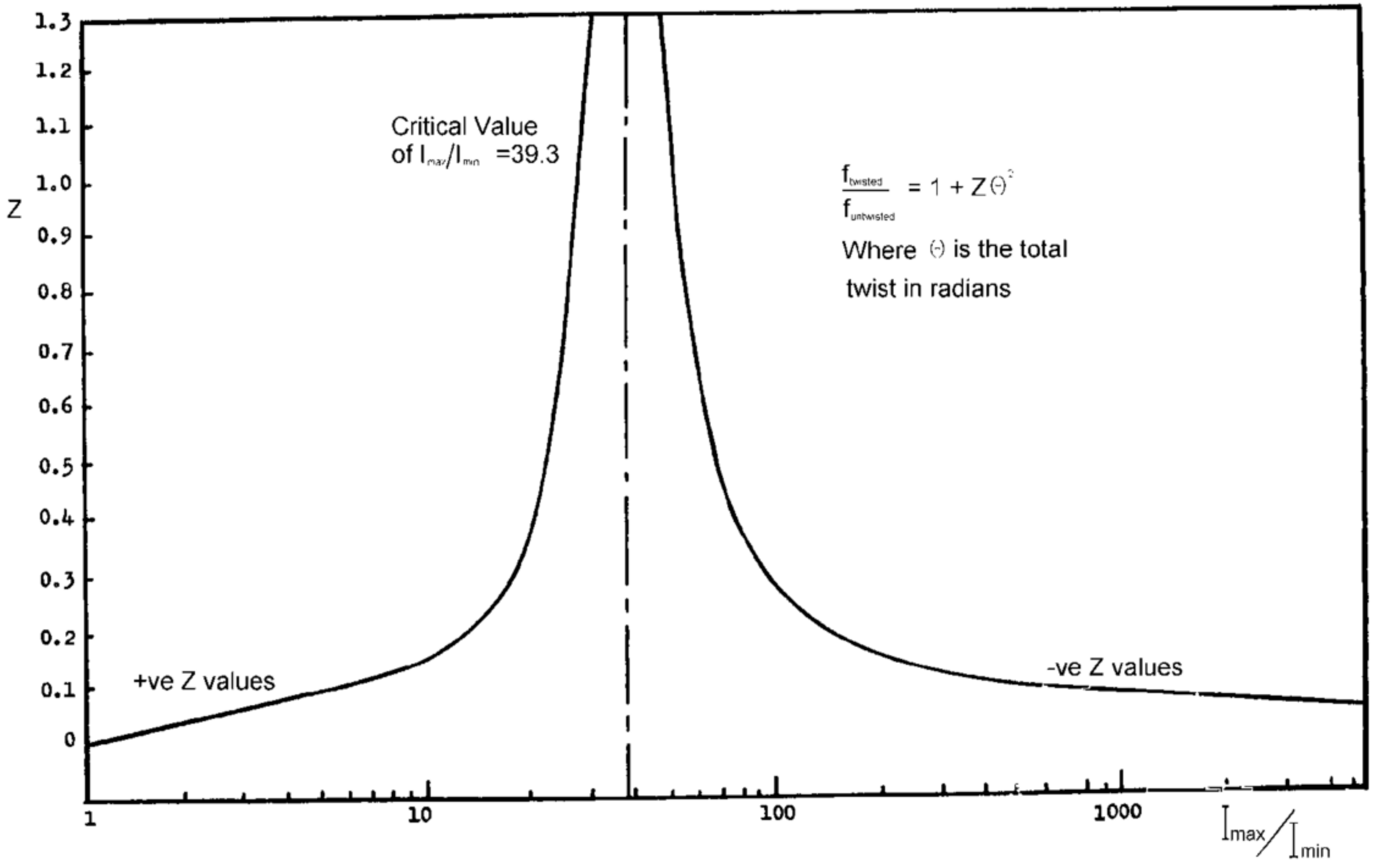
Blade Natural Frequency

$$f_{twisted} = (1 + z\theta^2) f_{untwisted}$$

From Graph

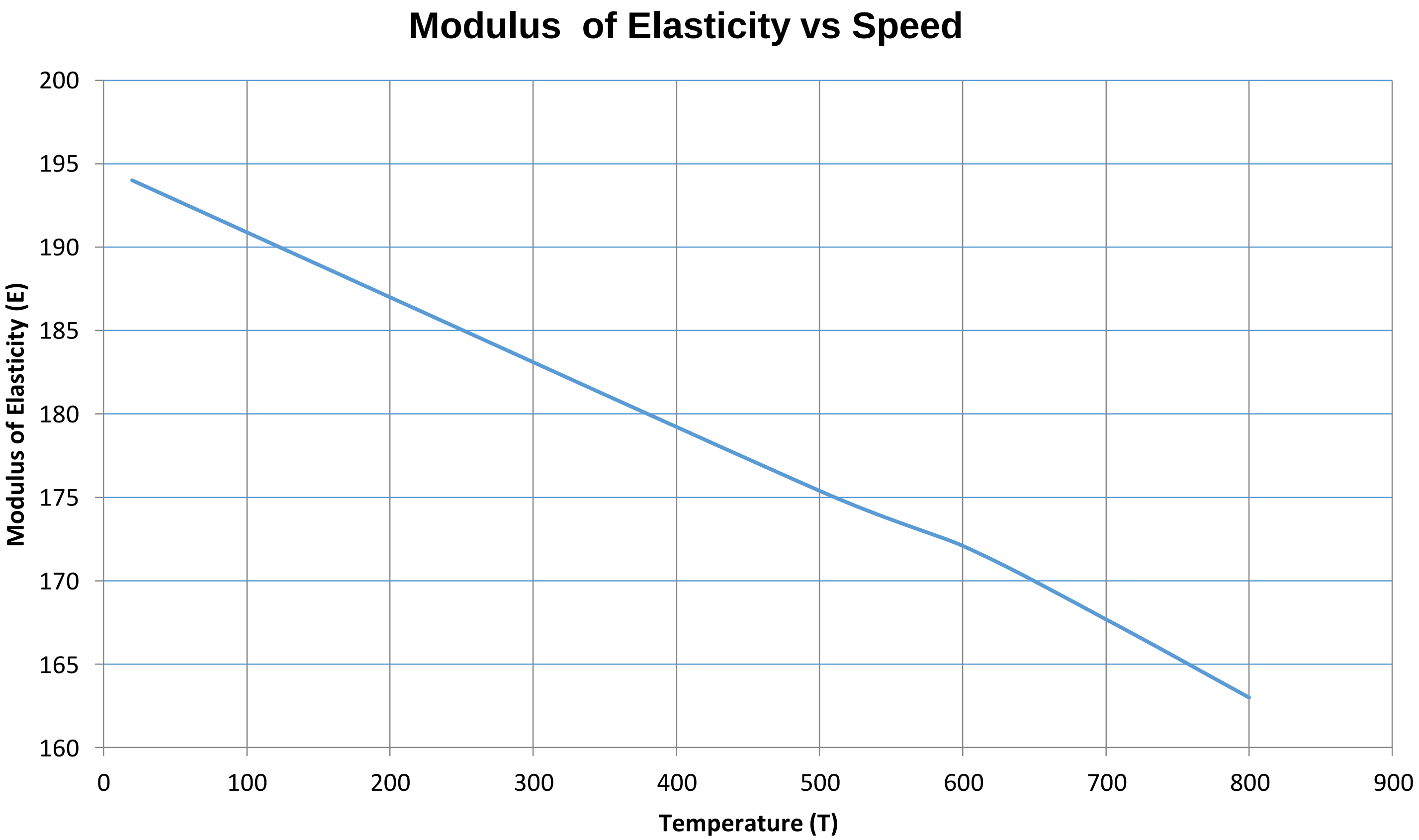
$$\theta = \frac{6\theta_{0.25} + 5\theta_{0.5} + 4\theta_{0.75} + 3\theta_{1.0} - 18\theta_0}{10}$$

Blade Natural Frequency



Pre-twist Correction Factor

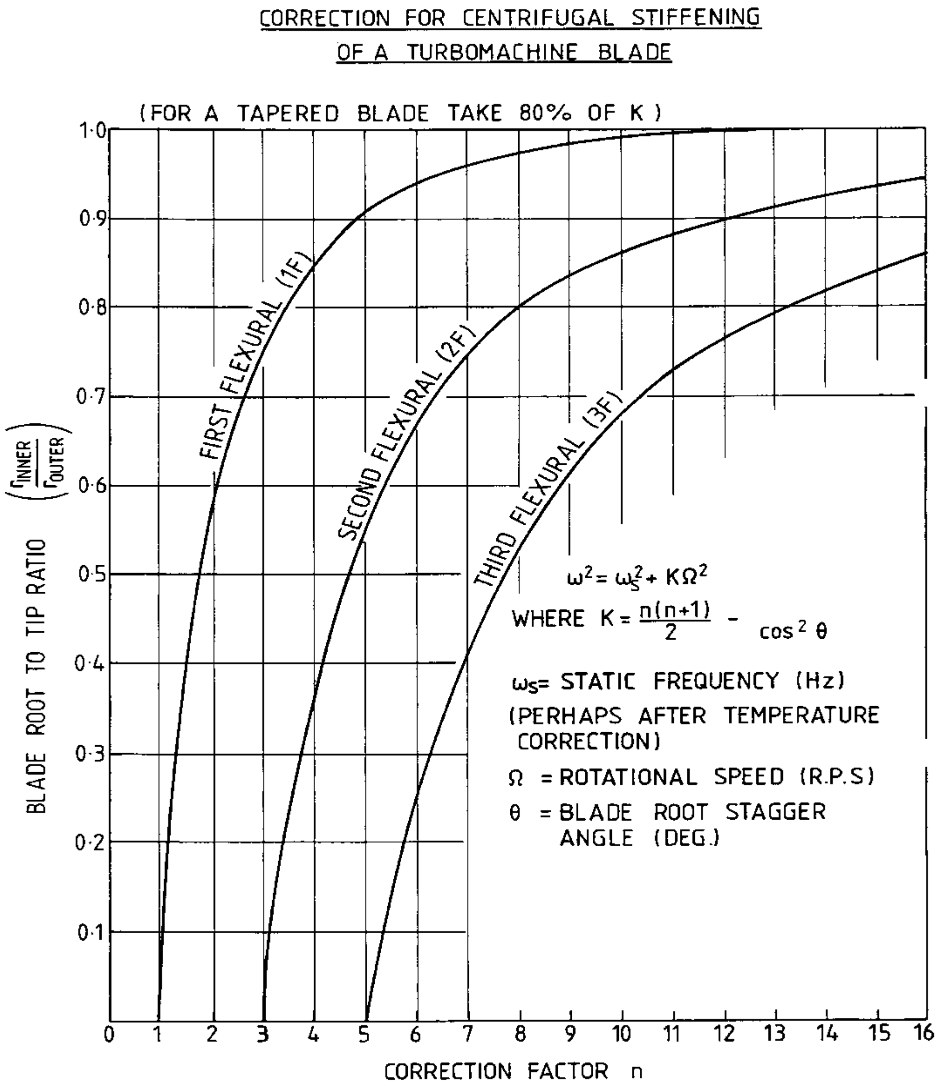
Blade Natural Frequency



$$f_T = f\sqrt{\frac{E_T}{E_0}}$$

Effect of Temperature on Blade Natural Frequency

Blade Natural Frequency

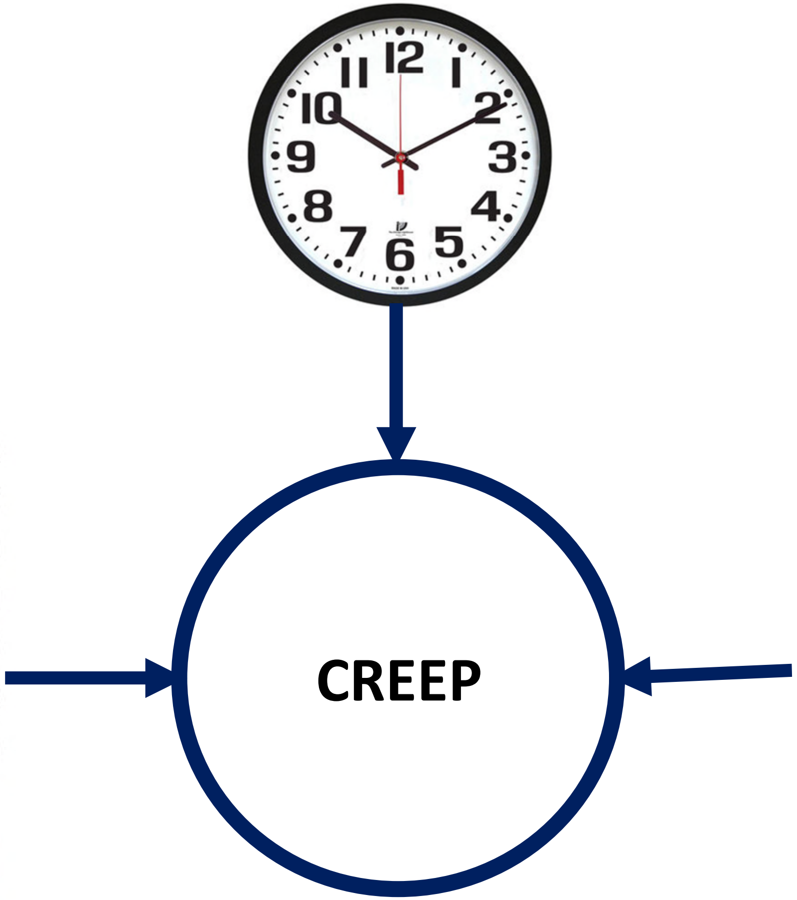


Effect of Centrifugal Force on Blade Natural Frequency

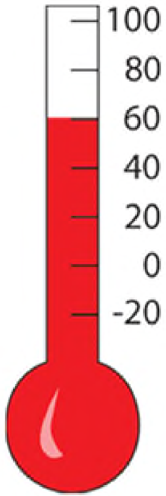
Blade Natural Frequency

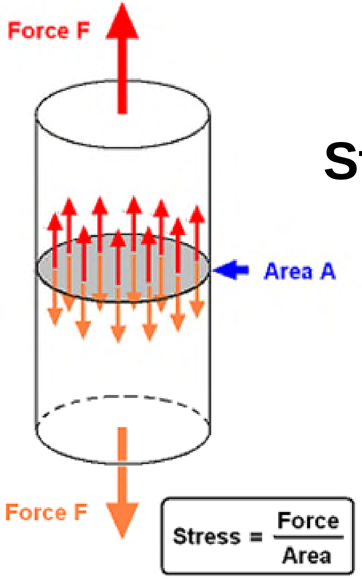
- Simple Desktop method helps evaluate lower order natural frequency
- Good for initial assessment
- Help identify the potential resonance conditions during operations

Mechanism of Creep



$T > 1/3$ to $1/2$ of T_m





Stress $< \sigma_{yield}$

Interaction with Time

Definition of Creep

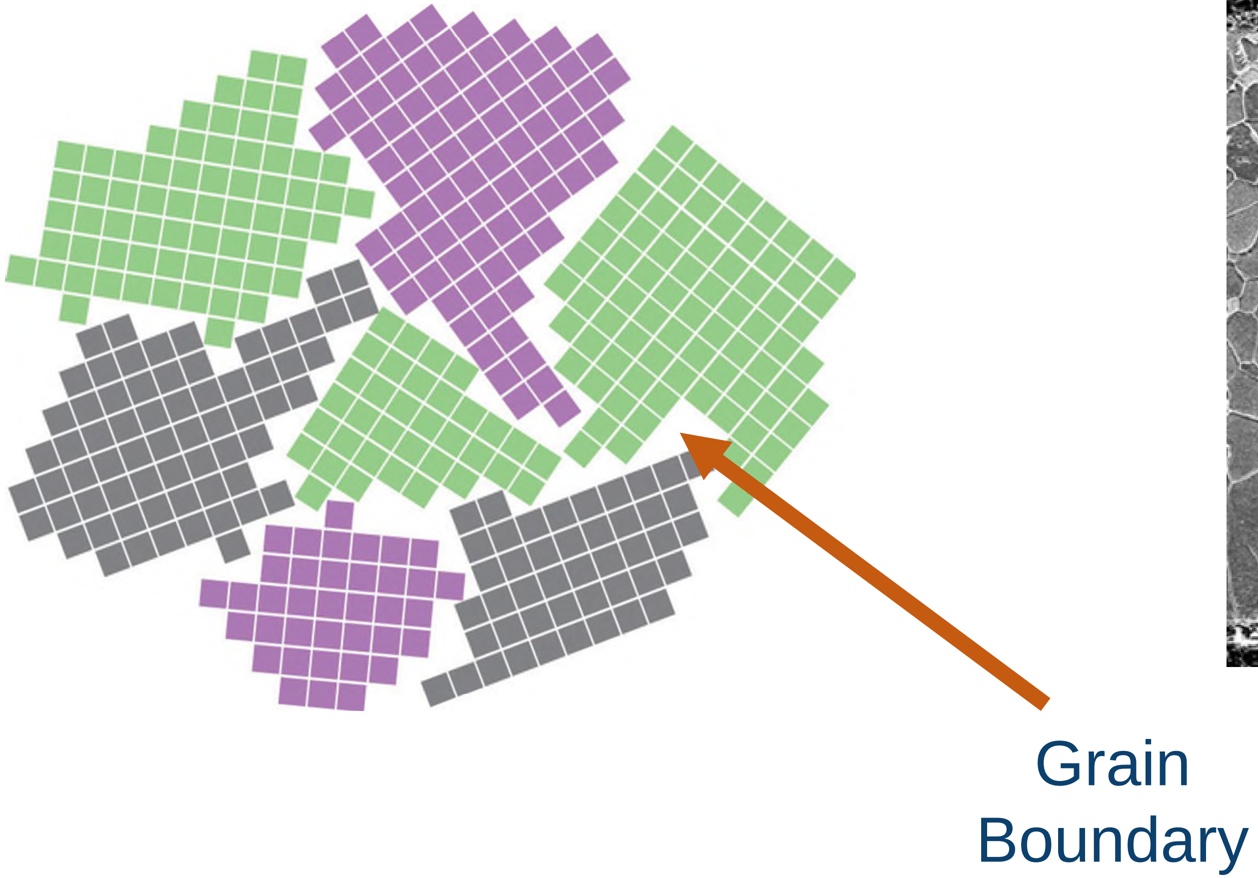
"Creep is a time and temperature dependent deformation that occurs when a material is subjected to a load for a prolonged period at elevated temperatures"

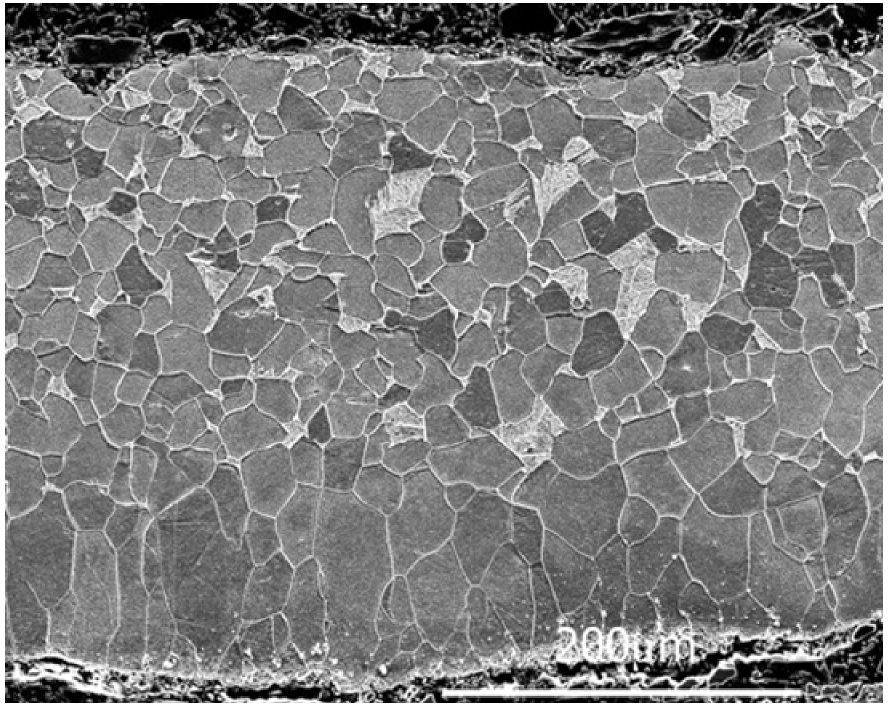
"Creep deformation is permanent and cannot be reversed"

Components affected by Creep

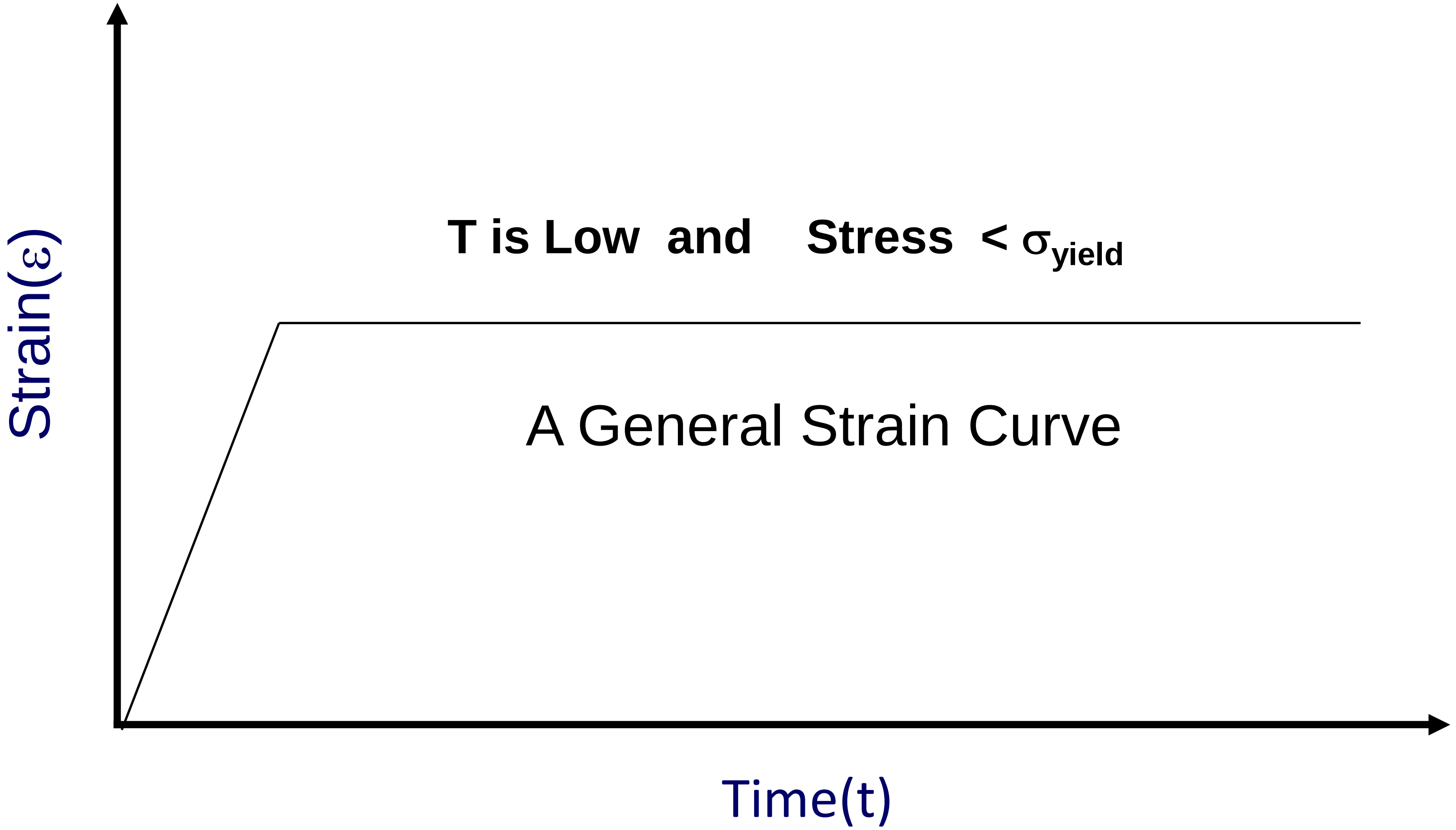
- Turbine blades – high stress and temperature
- NGVs – very high temperature, may be in a load path
- Turbine Discs – high stresses and temperatures at the rim
- Combustion cans – modest strength requirement but also subject to oxidation and thermal fatigue. May buckle under the effect of creep and thermal fatigue

Crystal formation in Material

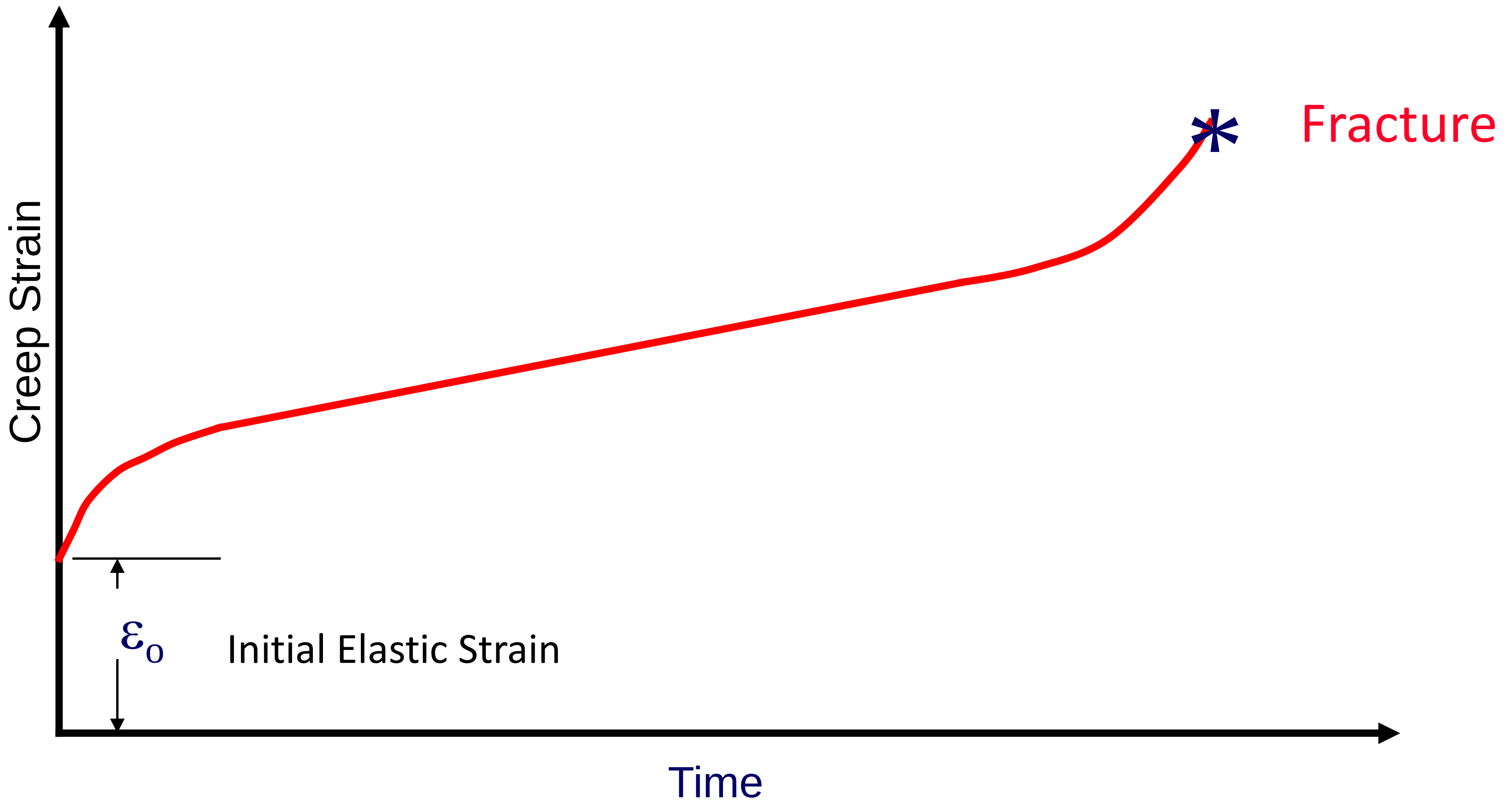




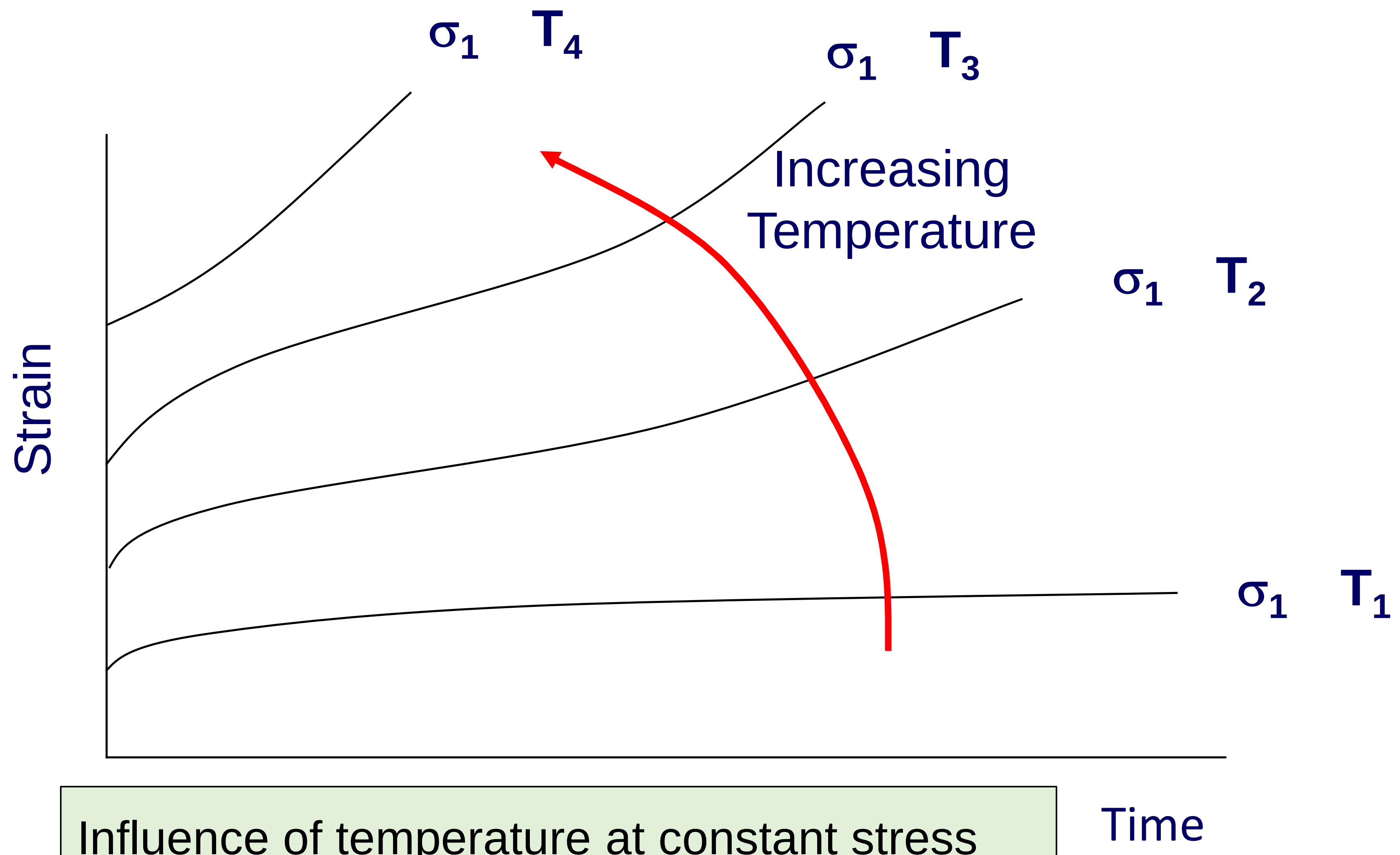
Monotonic Strain Curve



Creep Mechanism

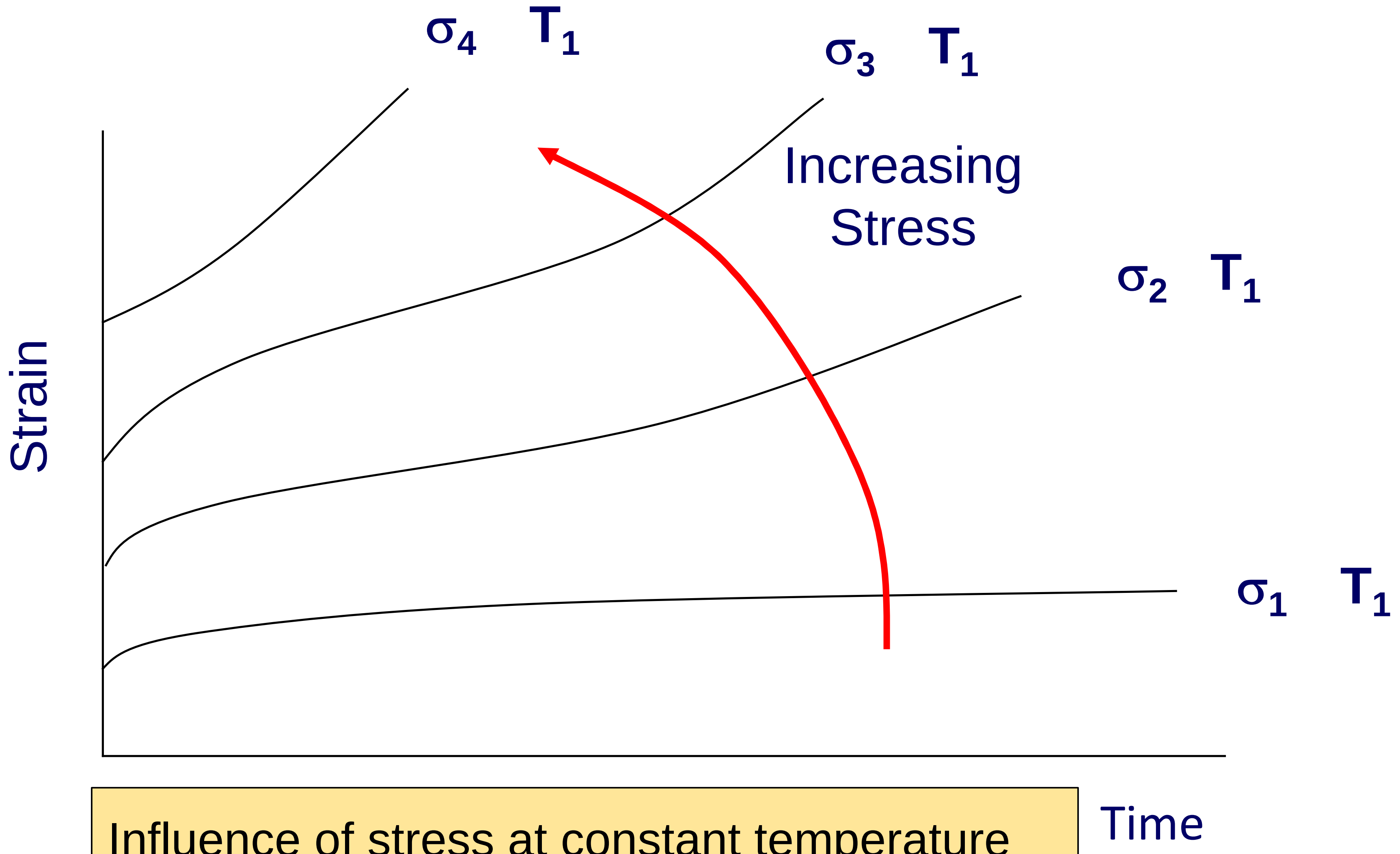


Creep Mechanism- Effect of Temperature



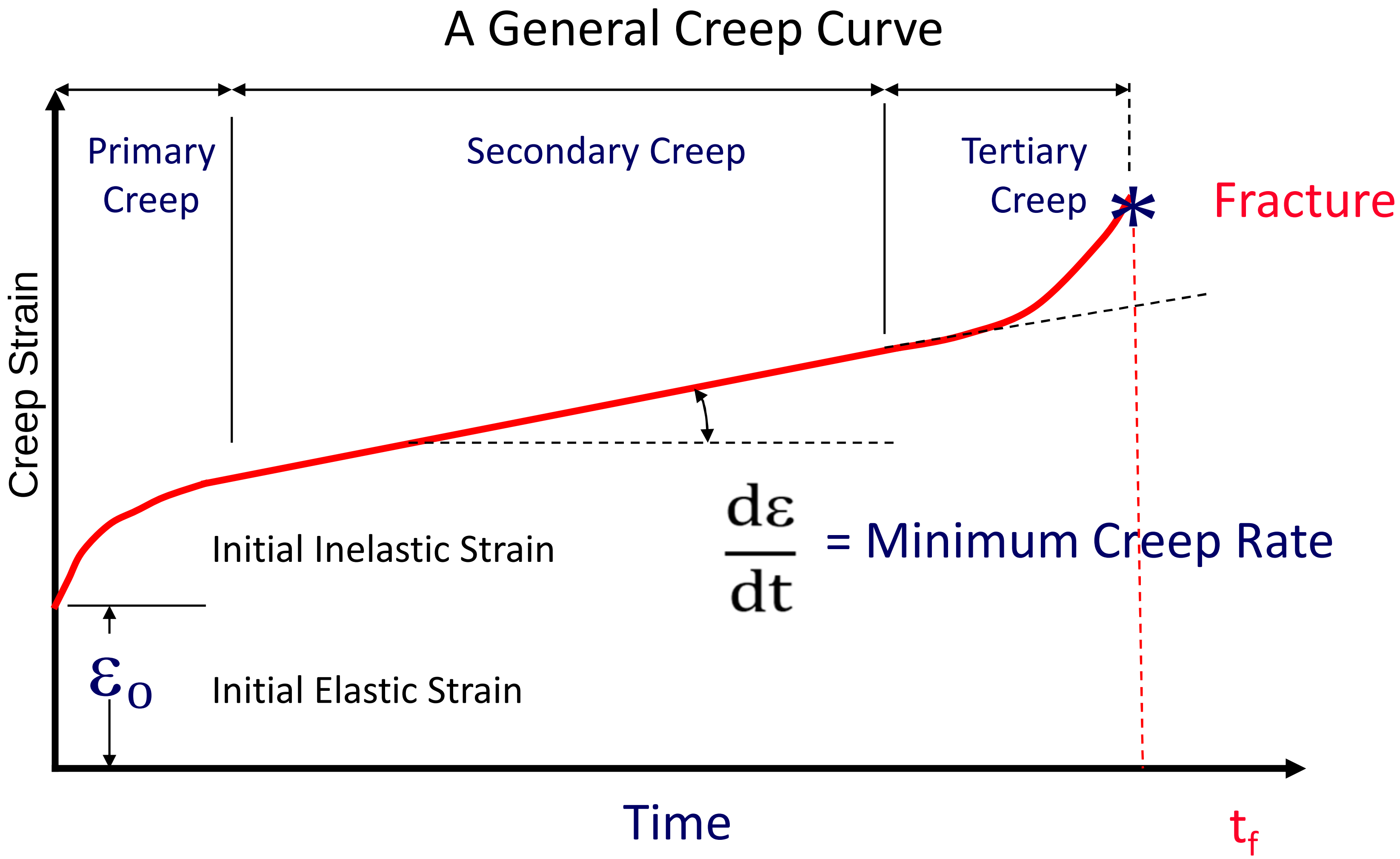
Influence of temperature at constant stress

Creep Mechanism- Effect of Stress



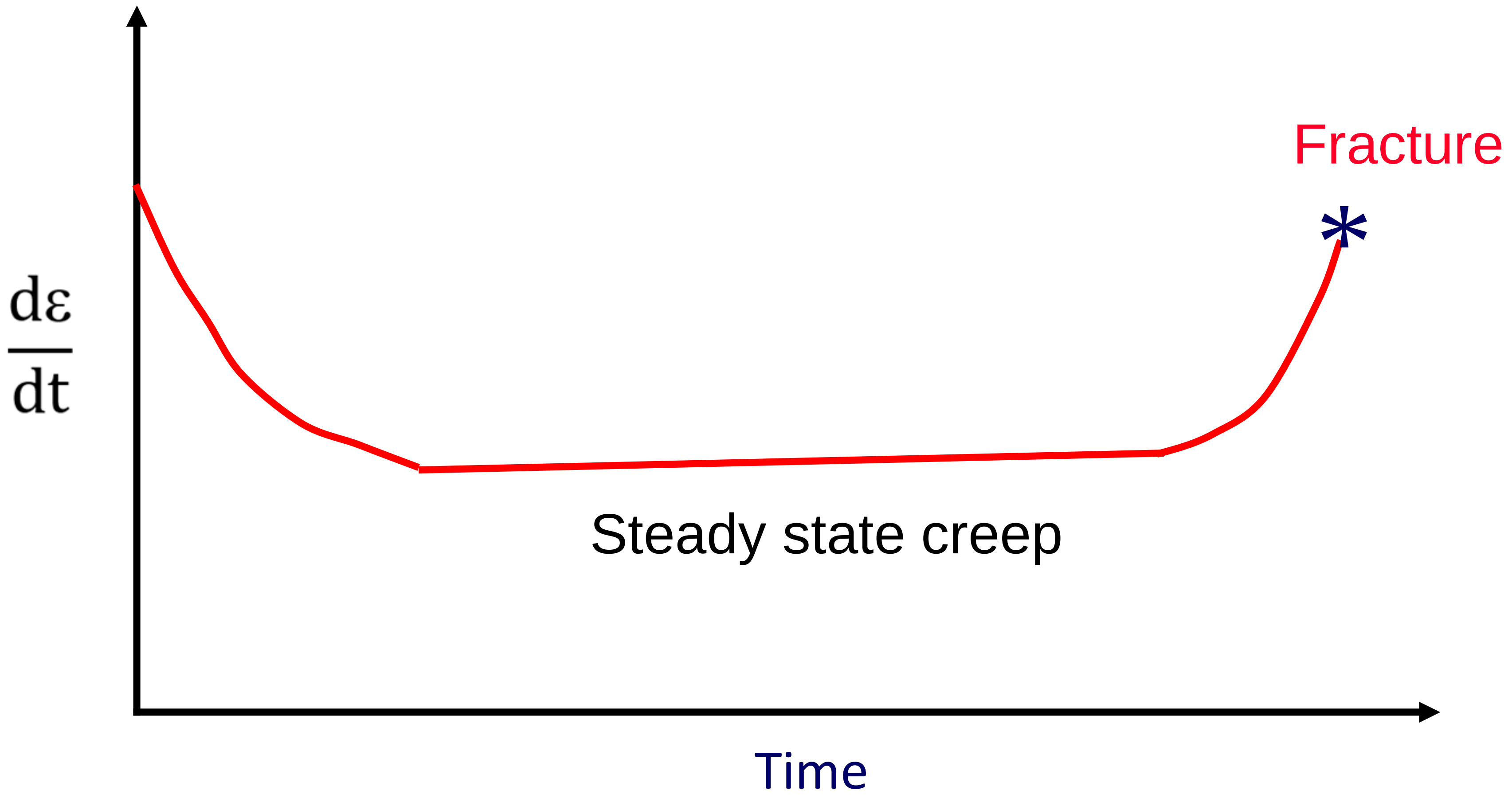
Influence of stress at constant temperature

Generalised Creep Curve



(Produced from creep test at constant stress and temperature)

Creep Strain Rate



Strain rate at steady is of most importance to us

Analysis of Creep Mechanism

General equation for Creep

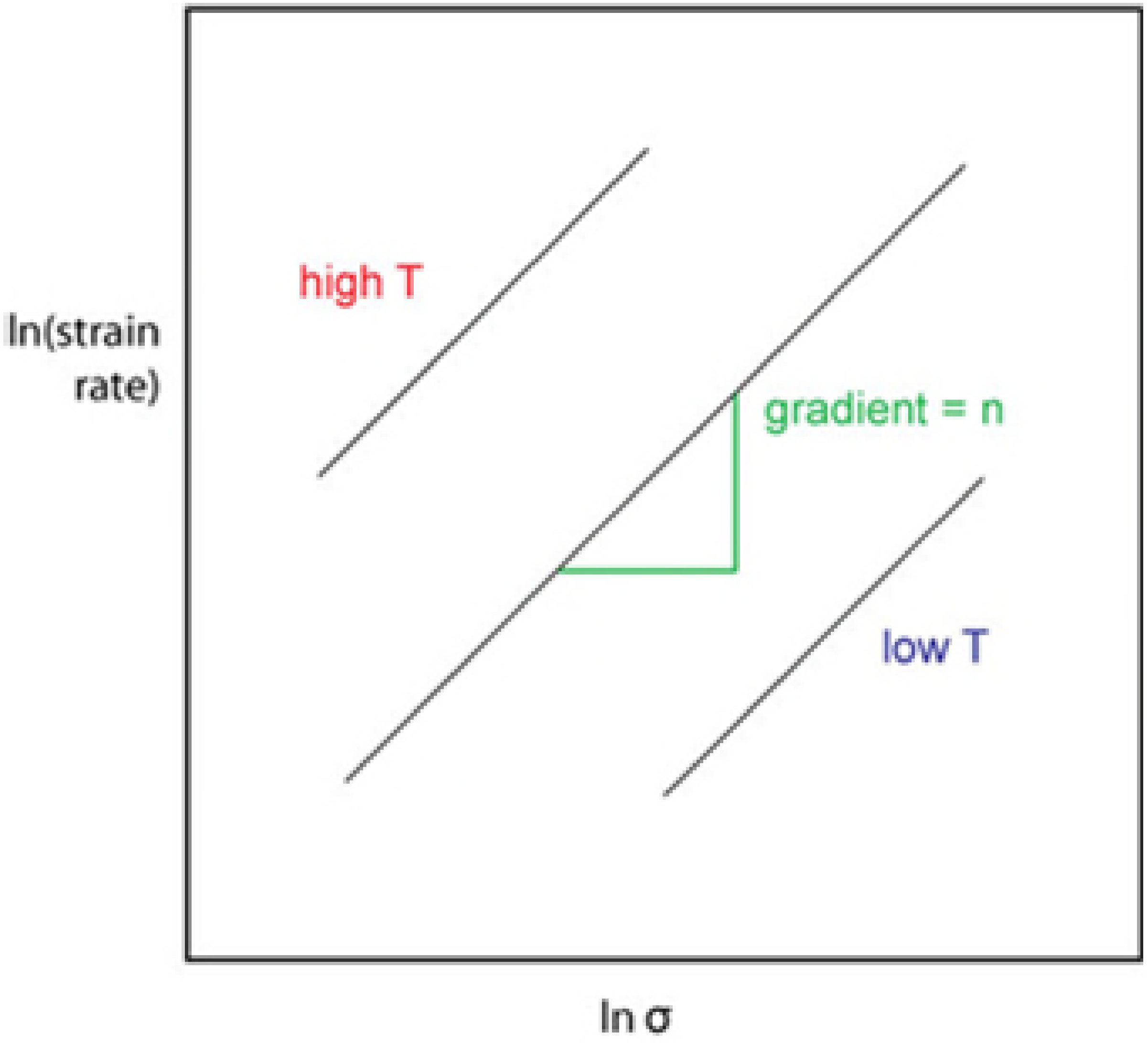
$$\dot{\varepsilon}_{ss} = B\sigma^{n}e^{\left(\frac{-Q}{RT}\right)}$$

'n' defines the type of creep mechanism

- Power Law dependence of stress
- Creep is thermally activated process

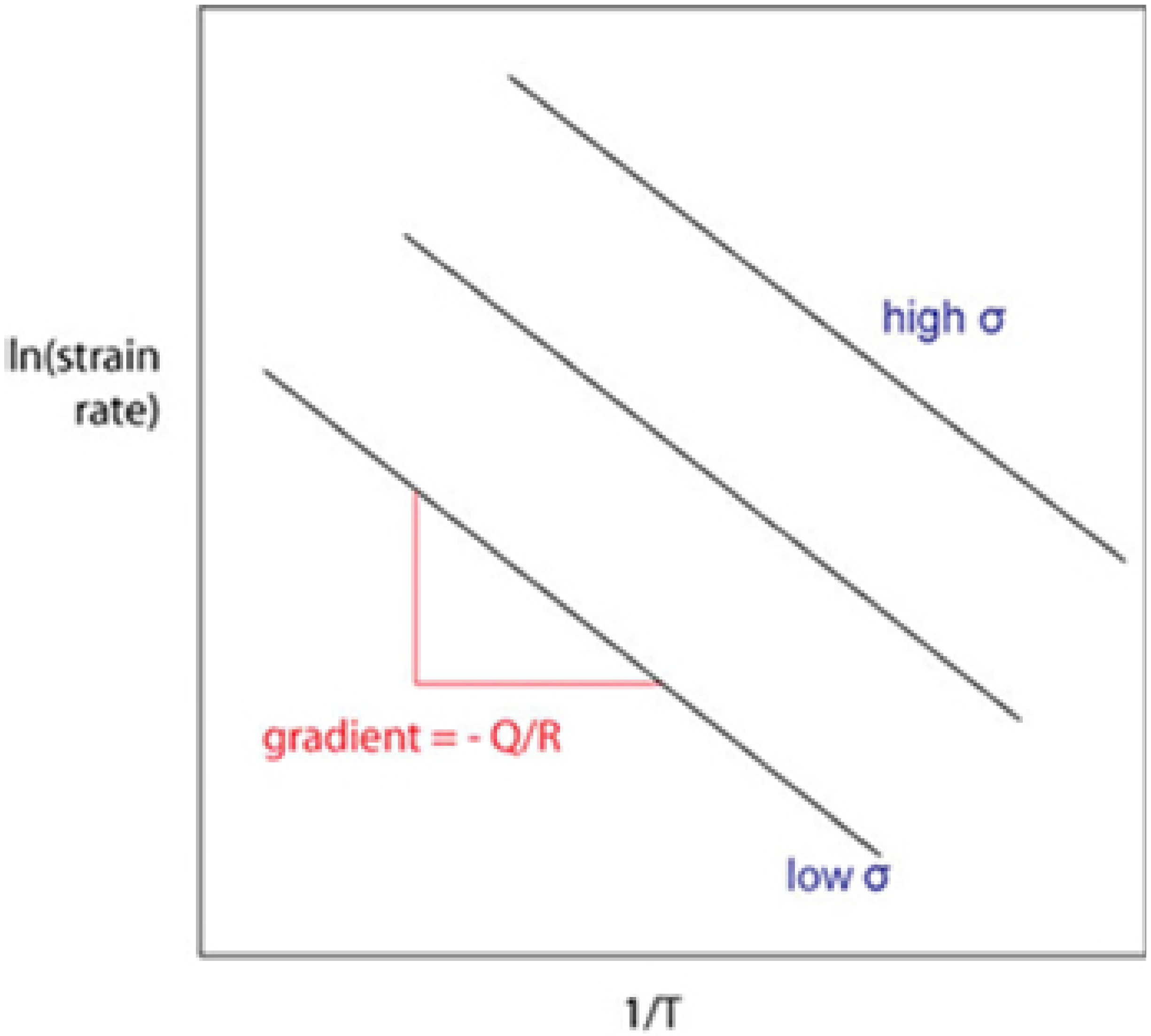
$$log\dot{\varepsilon}_{ss} = logB + nlog\sigma - \frac{Q}{RT}$$

Creep Strain vs Stress



$$log\dot{\varepsilon}_{ss} = logB + nlog\sigma - \frac{Q}{RT}$$

Influence of Temperature at Constant Stress

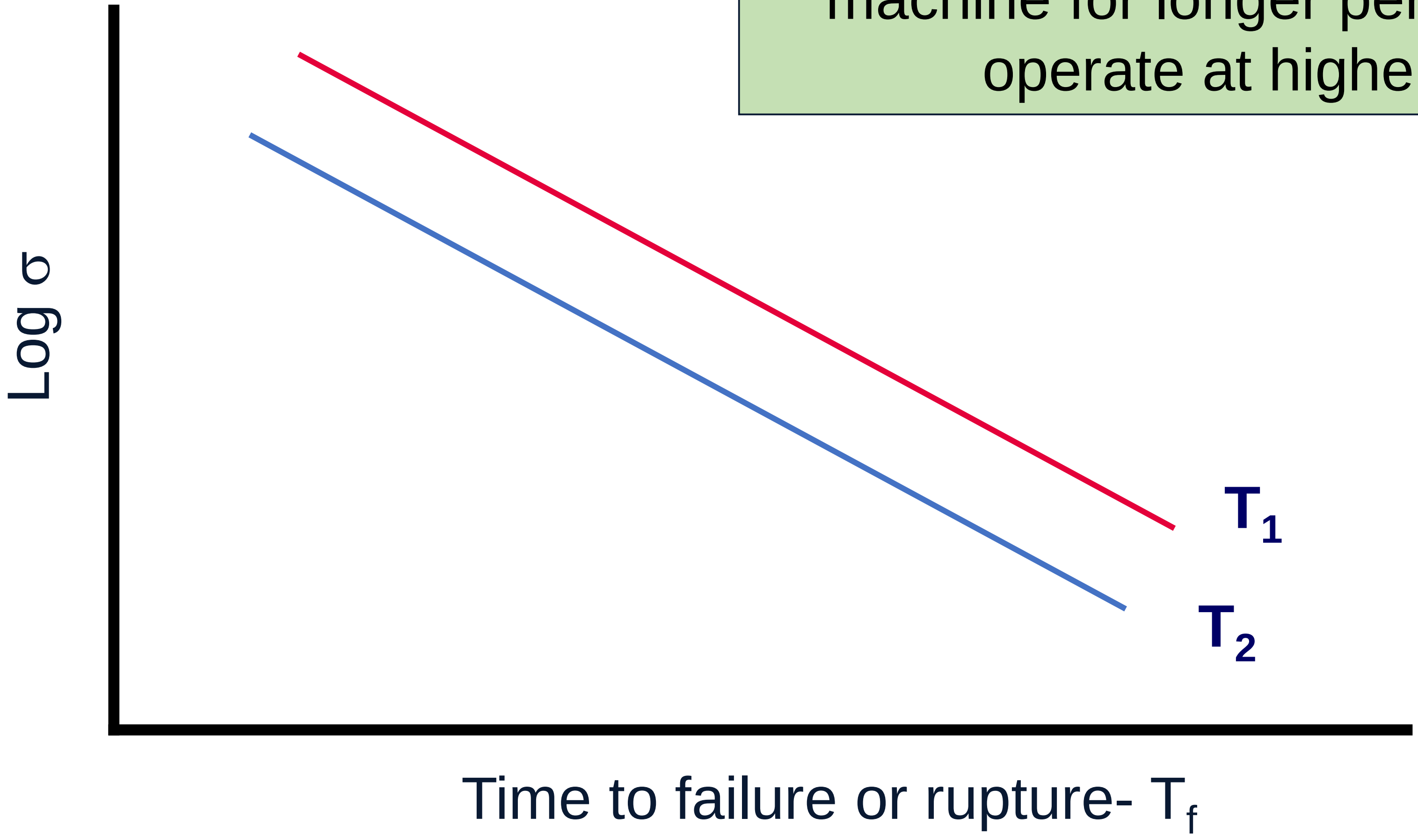


$$\log\dot{\varepsilon}_{ss} = \log B + n\log\sigma - \frac{Q}{RT}$$

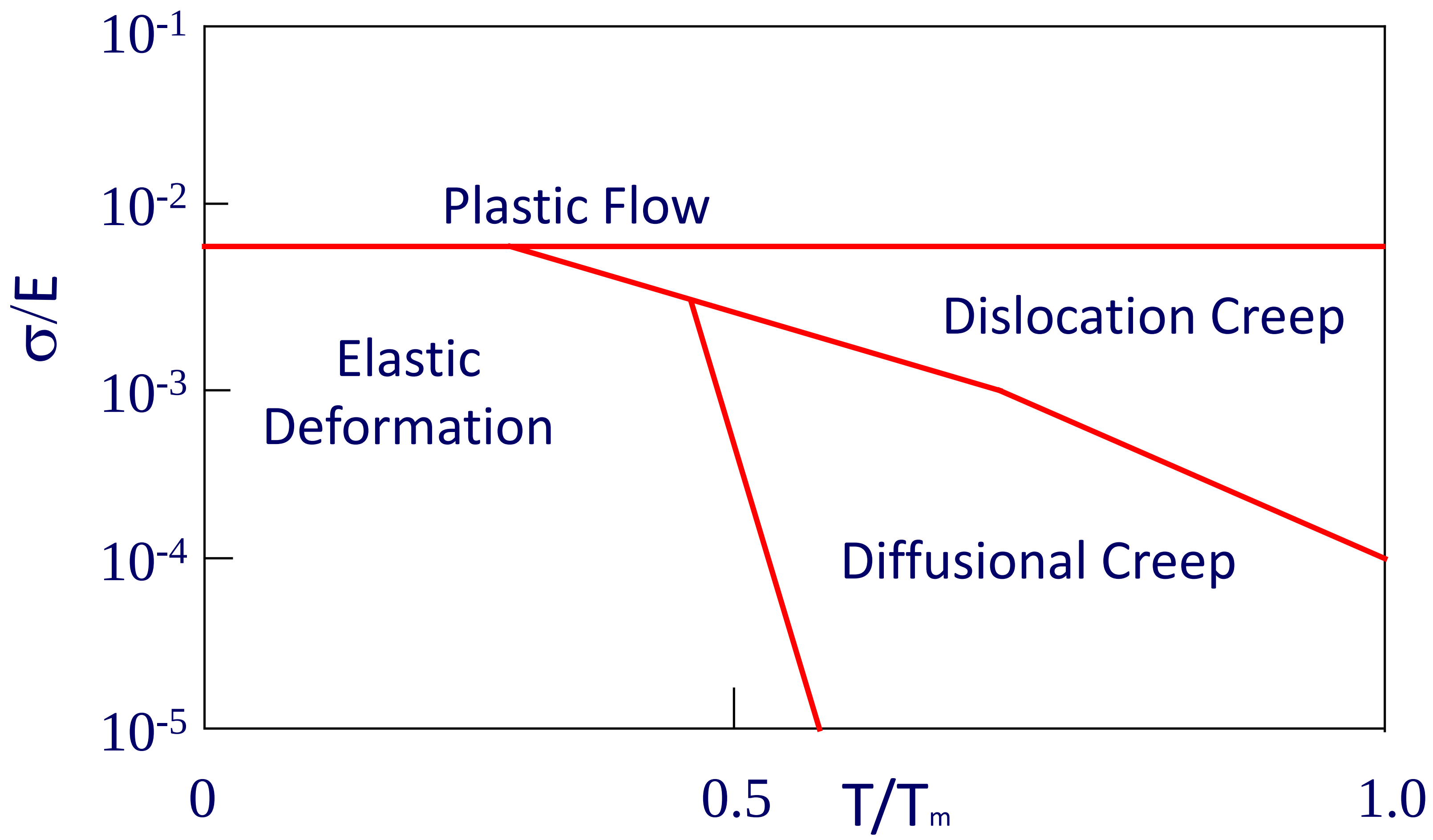
Where Q is the Activation Energy

Creep Mechanism- Time to Failure

Design Consideration-Operate a machine for longer period or able to operate at higher power



Creep Deformation Mechanism



Types of blades

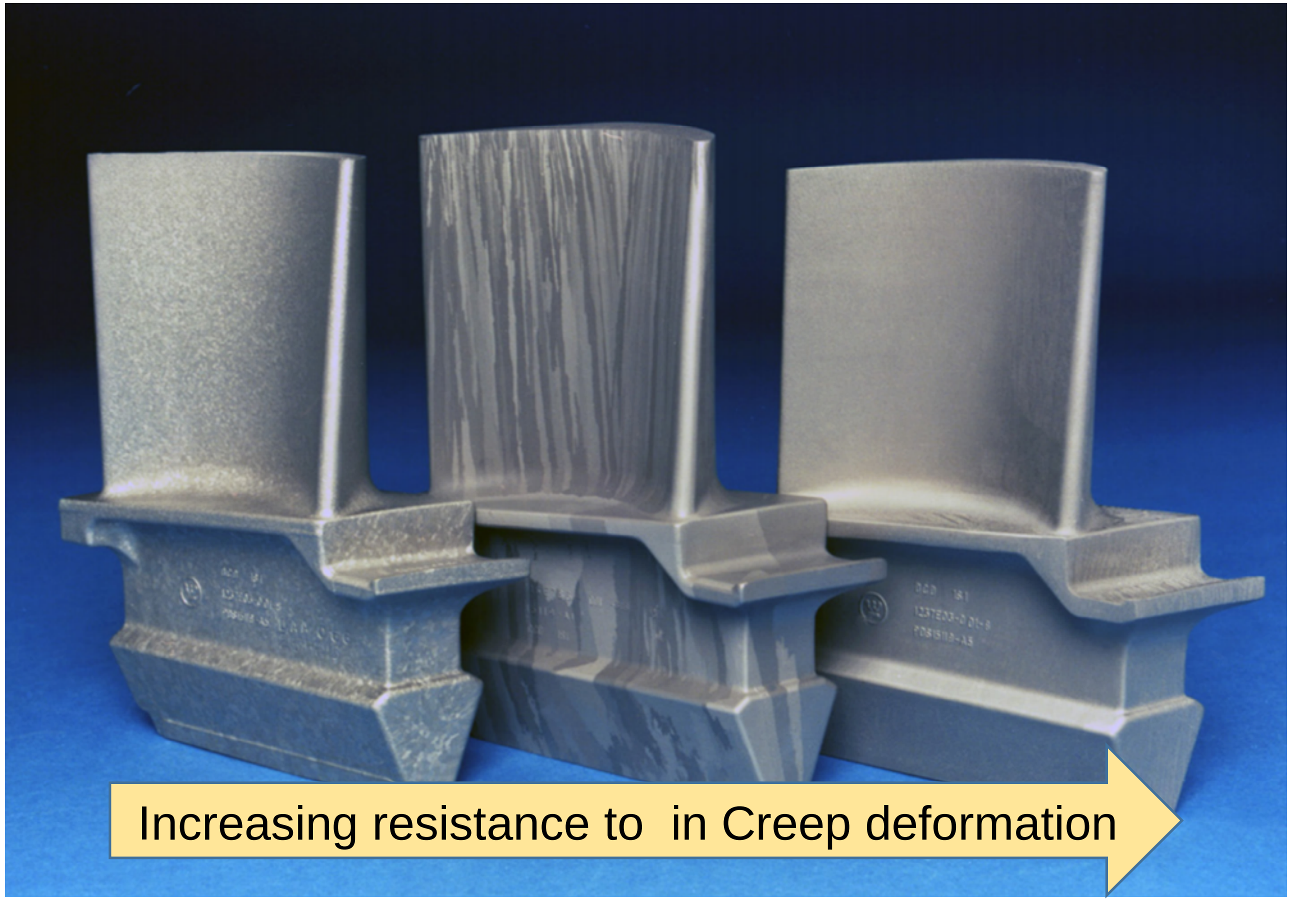
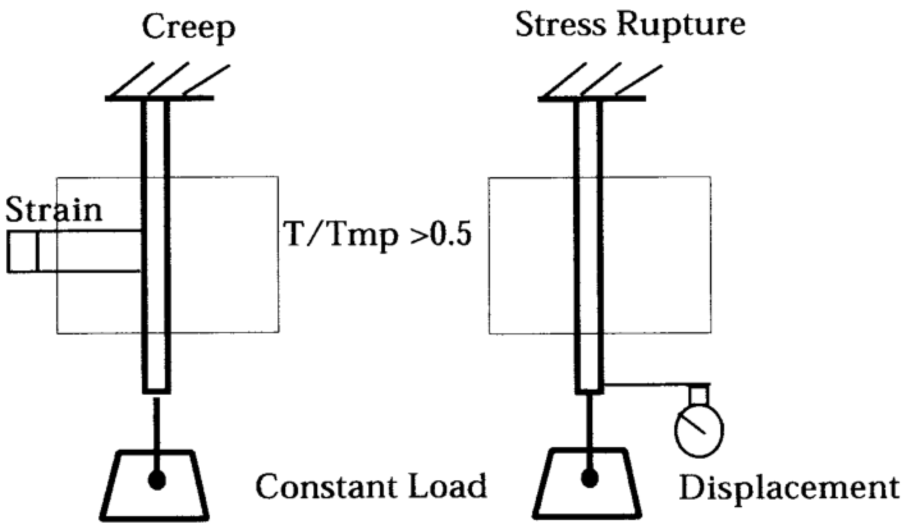


Image Courtesy- Pratt & Whitney

- Equiaxed
- Directionally solidified
- Single Crystal

Creep Tests



Creep

- Low Loads
- Precision Strain Measurement (ε_f<0.5%)
- Long term (2000-10,000 h)
- Expensive equipment

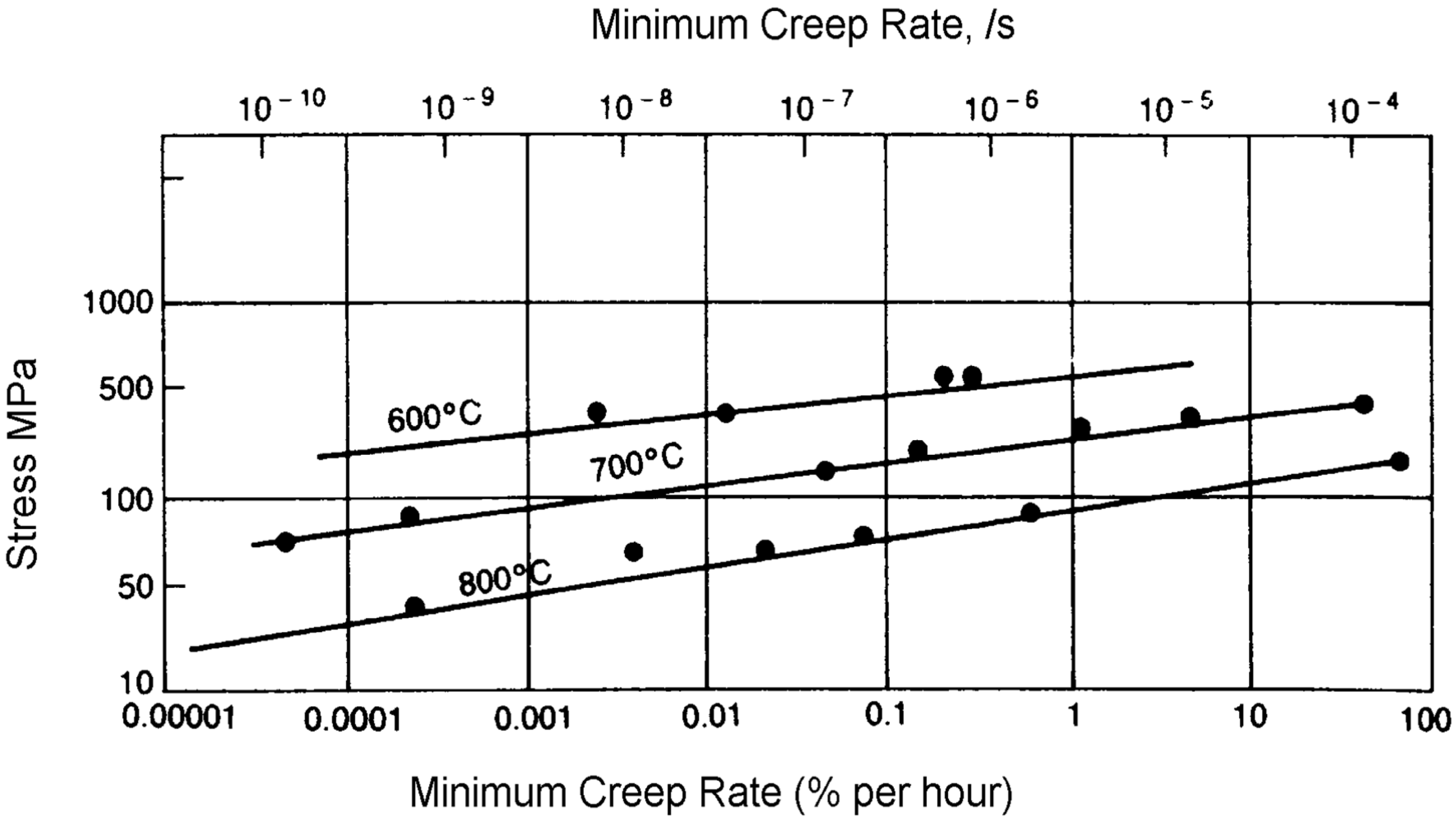
Emphasis on minimum strain rate at stress and temperature

Stress Rupture

- High Loads
- Gross Strain Measurement (ε_f up to 50%)
- Short term (<1000 h)
- Less expensive equipment

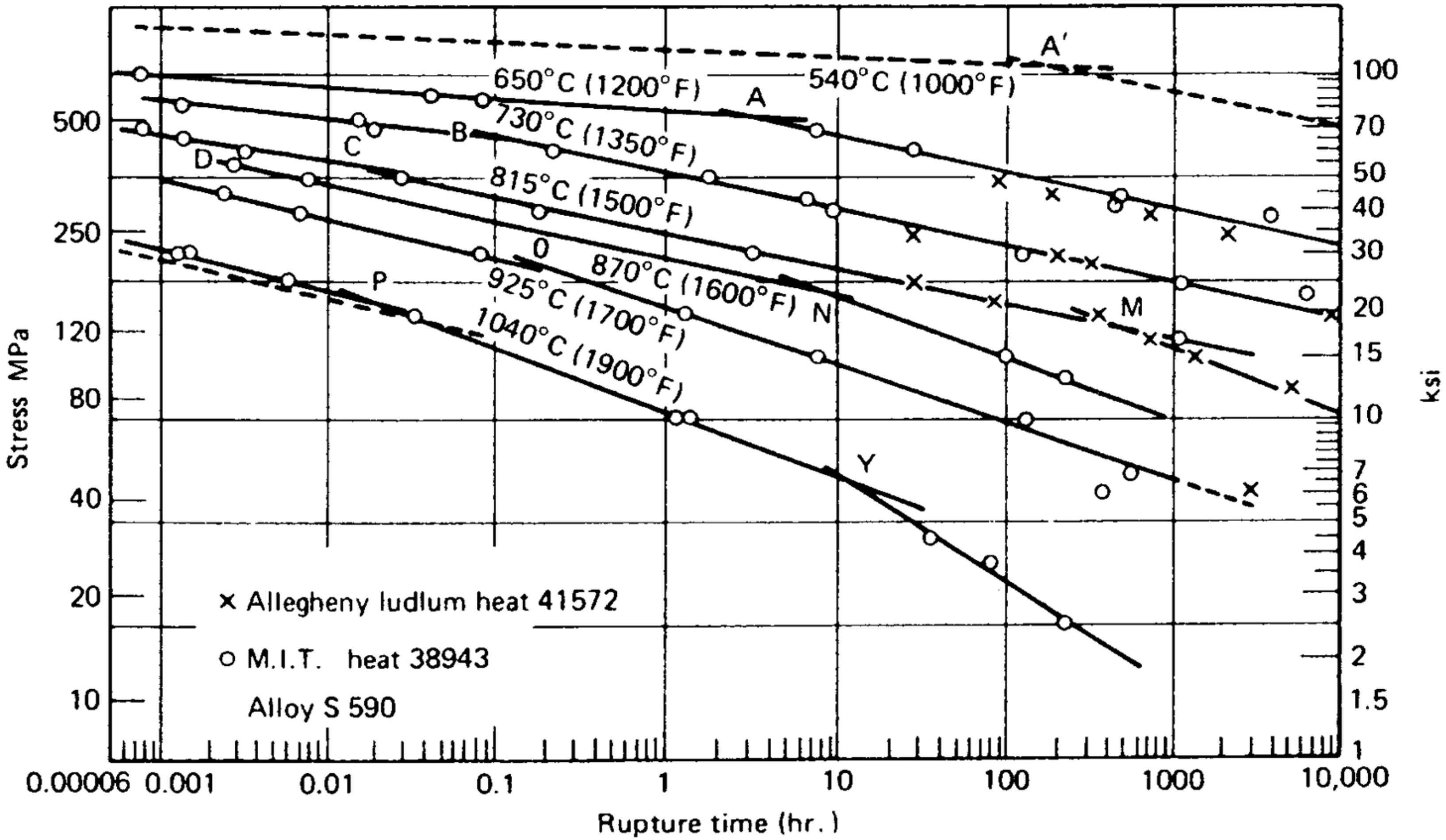
Emphasis on time to failure at at stress and temperature

Creep Design Data

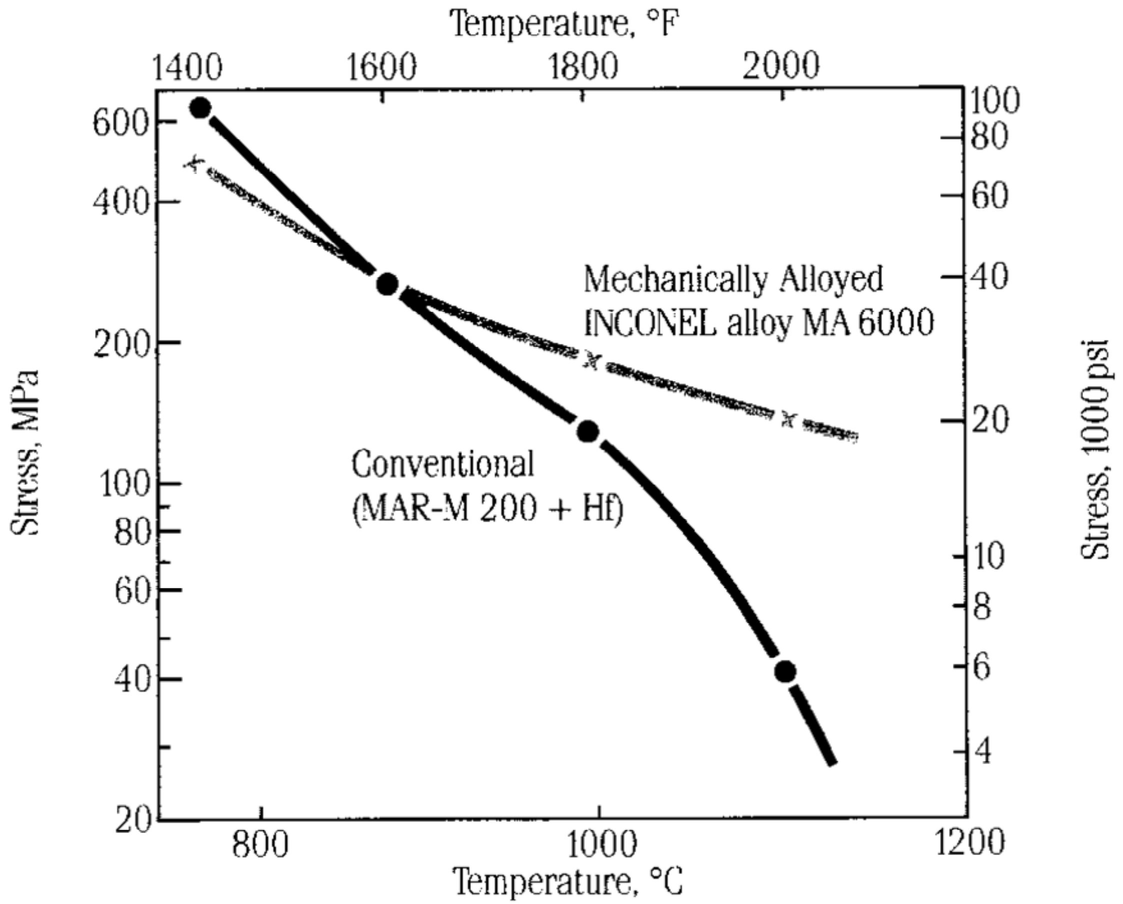


Creep Rupture Tests

Iron Based Alloy S590



Creep Data



1000-hour rupture strength of mechanically alloyed INCONEL alloy MA 6000 and conventionally melted MAR-M 200 + Hf.

(MAR-M is a trademark of Martin Marietta Corporation).

Time-Temperature Compensation

- Manufacturers may require creep strength or rupture strength at 100,000 hours (11years) when the material has only been around a few months – creep test is therefore impractical

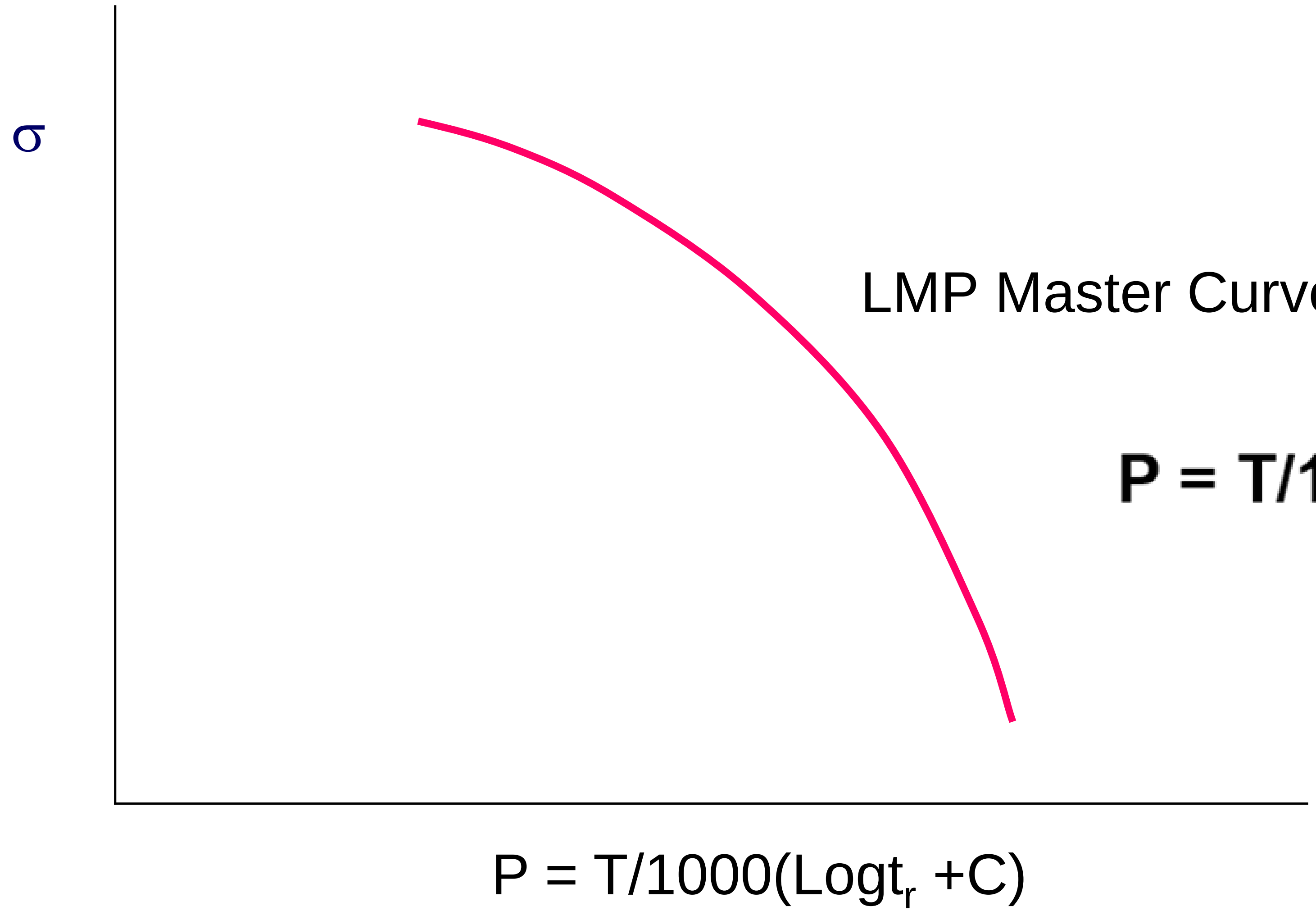
- One way forward is to extrapolate short-term data to longer terms – as with creep rupture testing

- Difficulty with extrapolation if there are changes in the material structure with time

- One method of extrapolation is to use **temperature compensated time** parameters

- Temperature compensated time parameters permit the prediction of long-term rupture behaviour from the results of shorter tests at higher temperatures at the same stress

Larson Miller Parameter



$$P = T/1000(20 + \log t_r)$$

Understanding Creep Life

	Time (min)
Take-off	1.5
Climb	15.0
Cruise	103.0
Low Ratings	30.0
Reverse Thrust	0.5
TOTAL	150.0

	T°K	Stress (MPa)	P	t_f (hours)
Take-off	1000	300	22.8	631
Climb	1100	200	23.9	53.4
Cruise	950	150	24.5	615848
Low Ratings	925	100	25.3	224569800
Reverse Thrust	1000	300	22.8	631

Understanding Creep Life

	T°K	Stress (MPa)	P	t_f (hours)
Take-off	1000	300	22.8	631
Climb	1100	200	23.9	53.4
Cruise	950	150	24.5	615848
Low Ratings	925	100	25.3	224569800
Reverse Thrust	1000	300	22.8	631

Understanding Creep Life

Operation	t/t_f
Take-off	0.00004
Climb	0.0047
Cruise	0.0000028
Low Ratings	2.22×10^{-9}
Reverse Thrust	0.0000132
Total creep life consumed	= 0.0048

$$\sum \frac{t}{t_f} = 210 \text{ cycles}$$

84

Thank You