Fatigue of metals

Subjects of interest

- *Objectives / Introduction*
- *Stress cycles*
- *The S-N curve*
- *Cyclic stress-strain curve*
- *Low cycle fatigue*
- *Structural features of fatigue*
- *Fatigue crack propagation*
- *Factors influencing fatigue properties*
- *Design for fatigue*

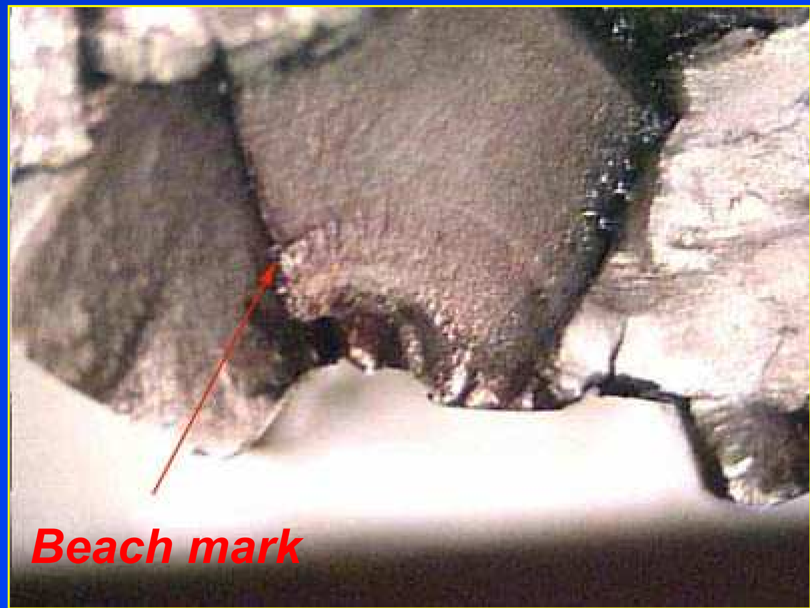
Objectives

- This chapter provides fundamental aspects of fatigue in metals and the significance of fatigue failure.
- Different approaches for the assessment of fatigue properties, i.e., fatigue S-N curve and fatigue crack growth resistance will be introduced.
- Discussion will be made on factors influencing fatigue properties of metals, for example, mean stress, stress concentration, temperature
- Finally design against fatigue failure will be highlighted.

Introduction

Fatigue failure in a bolt

Fatigue initiation



Introduction

Fatigue failure occurs at the outer rim of the wheel

Fatigue fracture area in a shaft caused by corroded inside area

Introduction

Fatigue failures are widely studies because it accounts for 90% of all service failures due to mechanical causes.

Failure of crankshaft journal

Characteristics

- Fatigue failures occur when metal is subjected to a ***repetitive or fluctuating stress*** and will fail at a ***stress much lower than its tensile strength***.
- Fatigue failures occur without any ***plastic deformation*** (no warning).
- Fatigue surface appears as a smooth region, showing ***beach mark*** or origin of fatigue crack.

Fatigue failure of a bolt

Factors causing fatigue failure

Basic factors

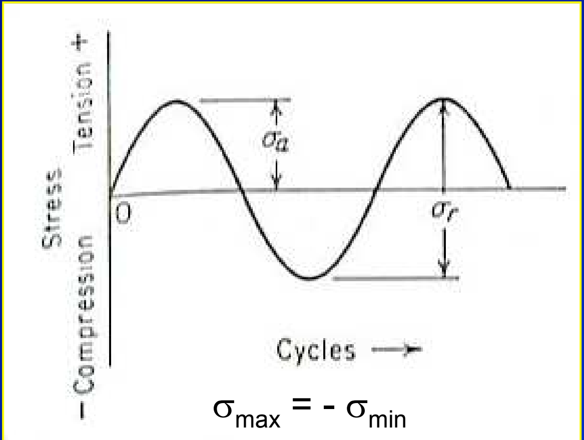
1) *A maximum tensile stress of sufficiently high value.*
2) *A large amount of variation or fluctuation in the applied stress.*
3) *A sufficiently large number of cycles of the applied stress.*

Additional factors

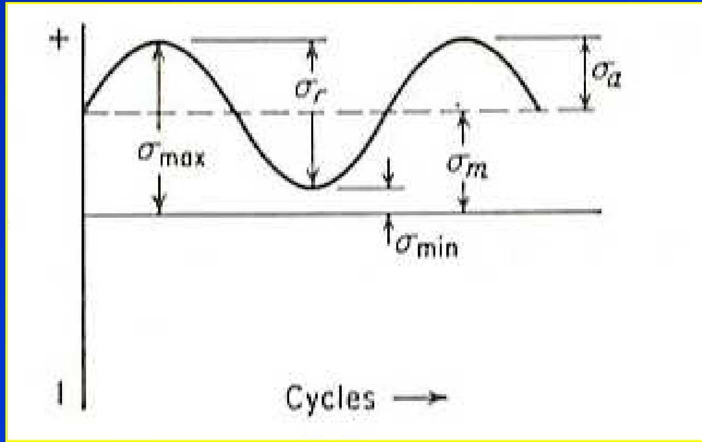
- Stress concentration
- Corrosion
- Temperature
- Overload
- Metallurgical structure
- Residual stress
- Combined stress

Stress cycles

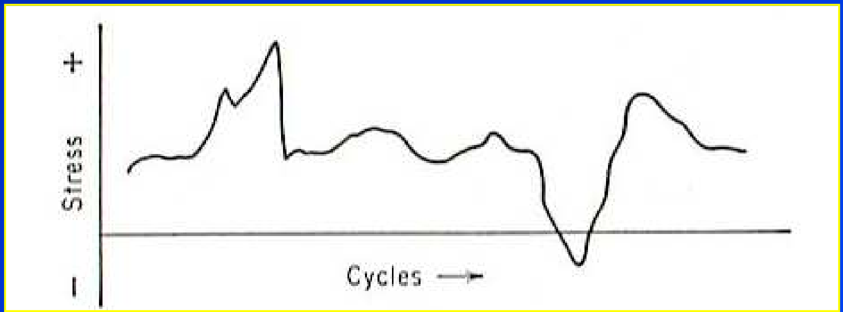
Different types of fluctuating stress



(a) Completely reversed cycle of stress (sinusoidal)



(b) Repeated stress cycle



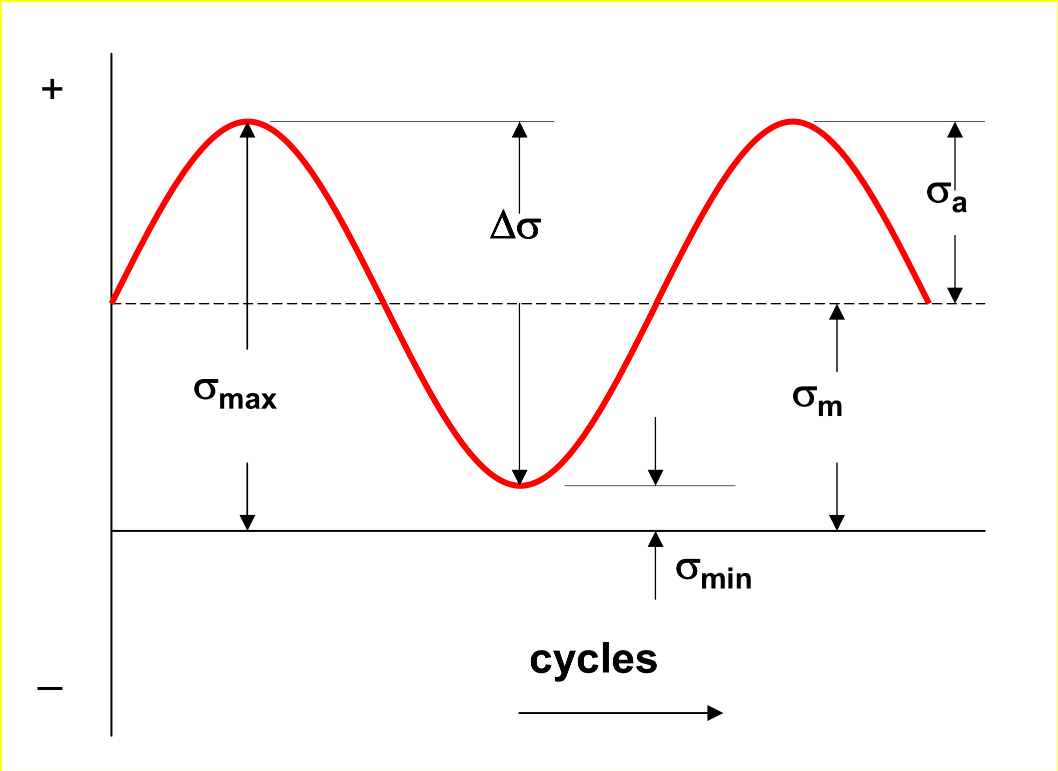
(c) Irregular or random stress cycle

Tensile stress +

Compressive stress -

Stress cycles

Nomenclature of stress parameter in fatigue loading



Fatigue stress cycle

Maximum stress, σ_{max}

Minimum stress, σ_{min}

Stress range

$$\Delta\sigma \ \ or \ \ \sigma_r = \sigma_{\max} - \sigma_{\min}$$ *Eq.1*

Alternating stress

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$ *Eq.2*

Mean stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$ *Eq.3*

Stress ratio

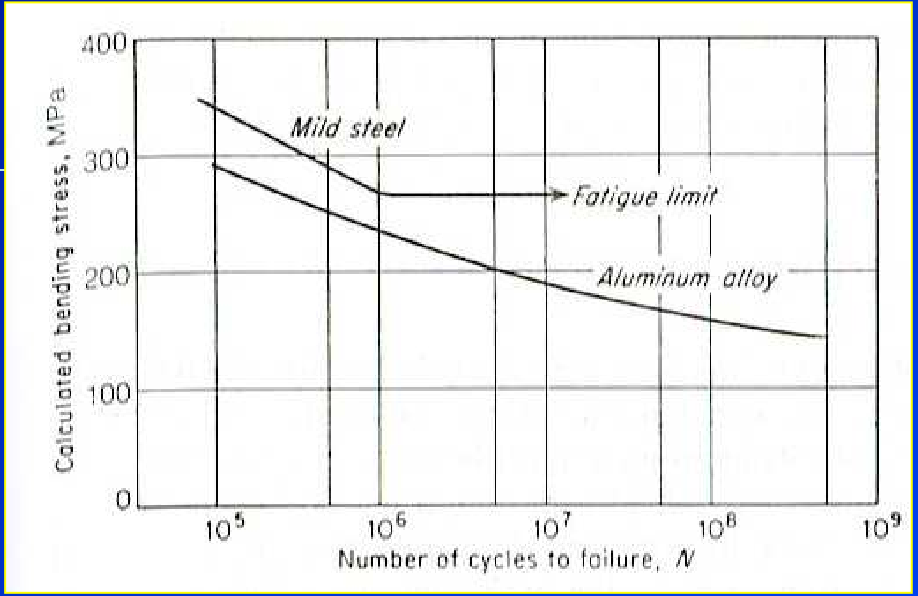
$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$ *Eq.4*

Amplitude ratio

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R}$$ *Eq.5*

The S-N curve

- ***Engineering fatigue data*** is normally represented by means of ***S-N curve***, a plot of ***stress S*** against the ***number of cycle***, ***N***.
- *Stress can be → σ_a, σ_{max}, σ_{min}*
- *σ_m , **R or A** should be mentioned.*



Typical fatigue curves

- ***S-N curve*** is concerned chiefly with ***fatigue failure at high numbers of cycles*** (N > 10^5 cycles) → high cycle fatigue (***HCF***).
- ***N*** < 10^4 or 10^5 cycles → low cycle fatigue (***LCF***).
- ***N*** increases with decreasing ***stress level***.
  - ***Fatigue limit or endurance limit*** is normally defined at 10^7 or 10^8 cycles. Below this limit, the material presumably can endure an infinite number of cycle before failure.
  - ***Nonferrous metal***, i.e., aluminium, do not have ***fatigue limit*** → fatigue strength is defined at ~ 10^8 cycles.

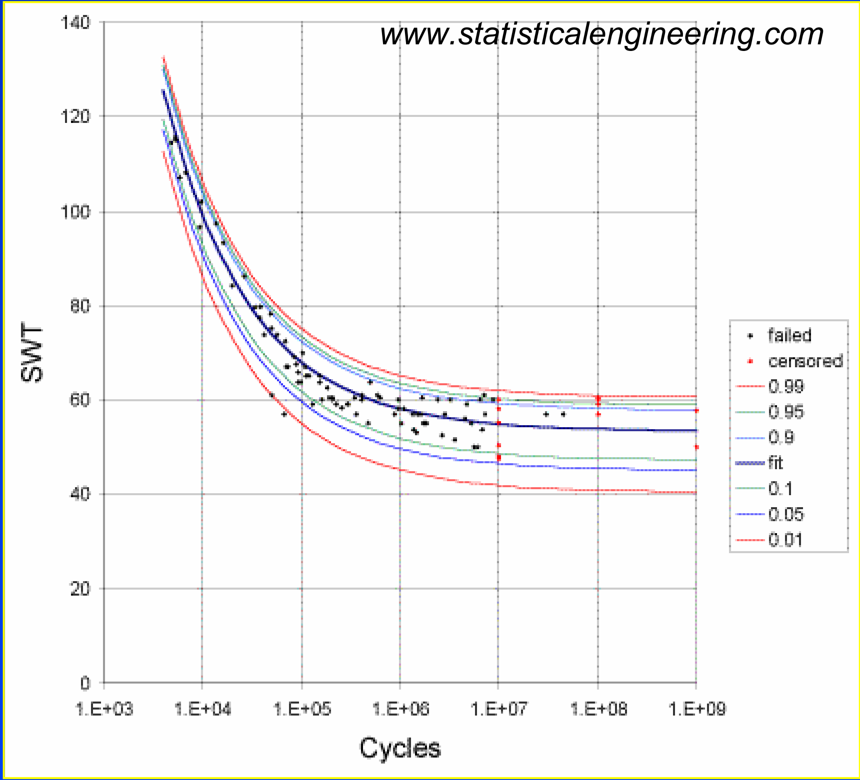
Construction of S-N curve

• The construction of ***S-N curve*** normally requires ~ 8-12 specimens by first testing at a high level of stress ~ 2/3 of the tensile strength of the material.

• The test is then carried out at lower levels of stress until ***runout***.

• The data obtained is normally ***scattered*** at the same stress level by using several specimens.

• This requires ***statistic approach*** to define the ***fatigue limit***.



S-N fatigue curve

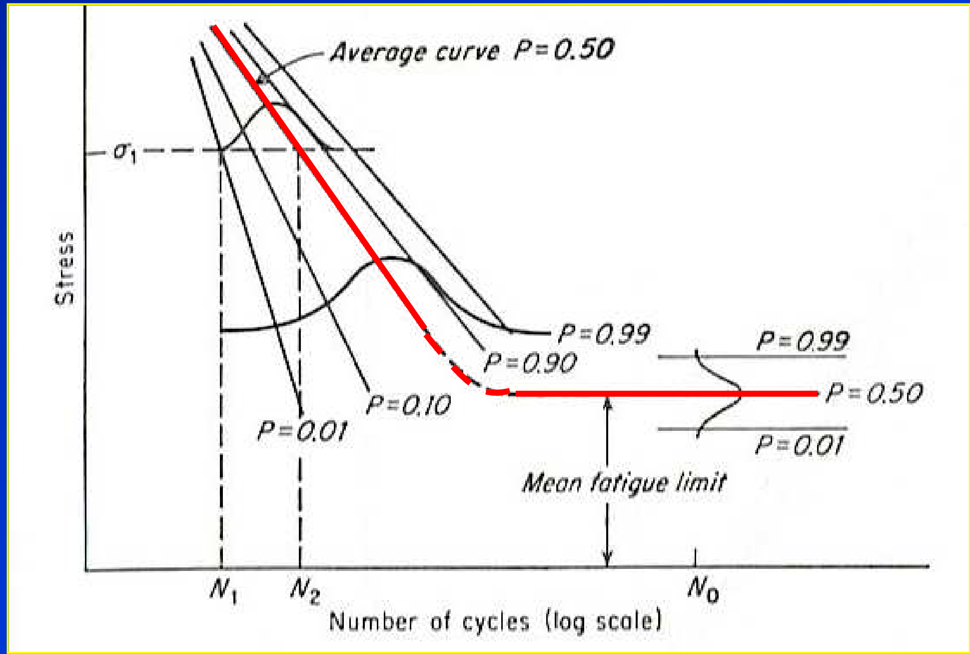
Statistical nature of fatigue

• Because the ***S-N fatigue data*** is normally scattered, it should be therefore represented on a ***probability basis***.

• Considerable number of specimens are used to obtain statistical parameters.

• At σ_1, 1% of specimens would be expected to fail at N_1 cycles.

• 50% of specimens would be expected to fail at N_2 cycles.



Fatigue data on a probability basis

<u>Note:</u> The S-N fatigue data is more scattered at lower stress levels. Each specimen has its own fatigue limit.

• For ***engineering purposes***, it is sufficiently accurate to assume ***a logarithmic normal distribution of fatigue life*** in the region of the probability of failure of ***P*** = 0.10 to ***P*** = 0.90.

Structural features of fatigue

The fatigue process can be divided into the following processes;

1) ***Crack initiation:*** the early development of fatigue damage (can be removed by a suitable thermal anneal).
2) ***Slip band crack growth:*** the deepening of the initial crack on plane of high shear stress (stage I crack growth)
3) ***Crack growth on planes of high tensile stress:*** growth of well-defined crack in direction normal to maximum tensile stress
4) ***Ultimate ductile failure:*** occurs when the crack reaches sufficient length so that the remaining cross section cannot support the applied load.

Factors influencing fatigue properties

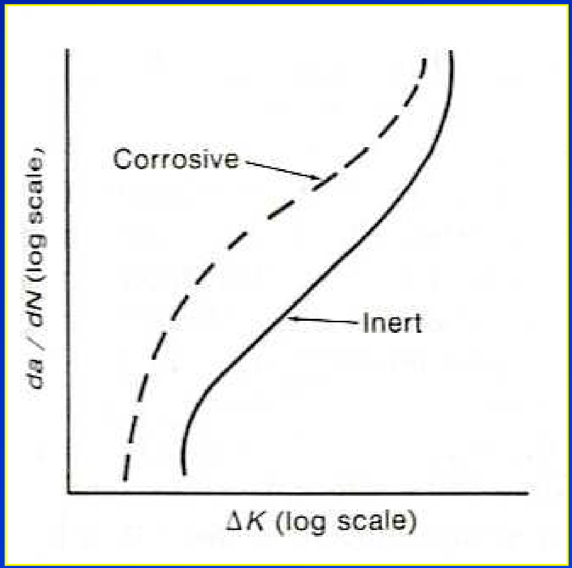
- *Stress concentration*
- *Size effect*
- *Surface effects*
- *Combined stresses*
- *Cumulative fatigue damage and sequence effects*
- *Metallurgical variables*
- *Corrosion*
- *Temperature*

Effect of corrosion on fatigue

- ***Fatigue corrosion*** occurs when material is subjected to ***cyclic stress*** in a ***corrosive condition***.

Corrosion fatigue of brass

- ***Corrosive attack*** produces ***pitting*** on metal surface. ***Pits*** act as notches → fatigue strength ⬇⬇.
- Chemical attack greatly ***accelerates*** the rate of fatigue crack propagation.



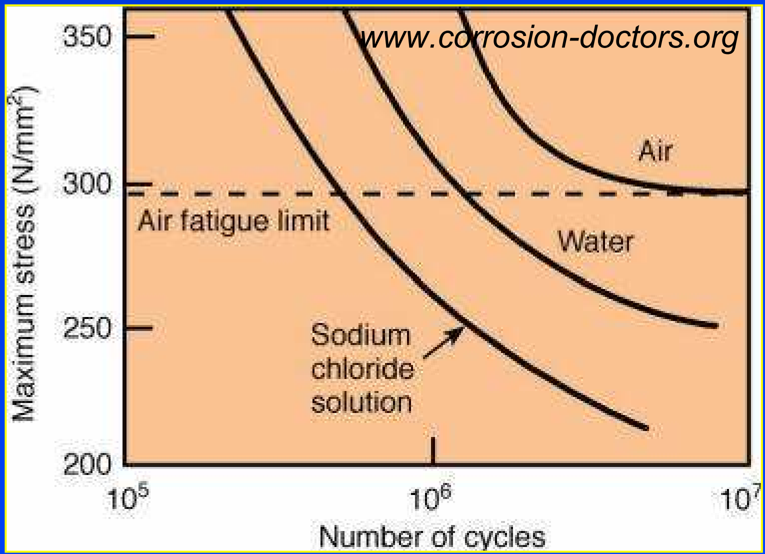
Role of a corrosive environment on fatigue crack propagation

Corrosion fatigue test

Corrosion fatigue test *can be carried out similar to fatigue test but in a controlled corrosive environment.*

- Since corrosion process is a ***time-dependent phenomenon***, the higher the ***testing speed*** (frequency), the smaller the ***damage due to corrosion***.

- The action of the cyclic stress causes ***localised breakdown of the surface oxide film*** → corrosion pits.



S-N curve in various condition

Minimization of corrosion fatigue

- ***Select corrosion-resistant materials*** for the desired application. ***Ex:*** stainless steel, bronze, would give better service than heat-treated steel.
- Protection of the metal from contact with the corrosive environment by ***protective metallic or non-metallic coatings***.
- ***Introducing compressive residual stresses*** by nitriding, shot peening → eliminating surface defects.

Effect of temperature on fatigue

Temperature ↓

(Increasing σ_{TS})

Fatigue strength ↑

If testing temp < ***RT*** → low temperature fatigue.

If testing temp > ***RT*** → high temperature fatigue.

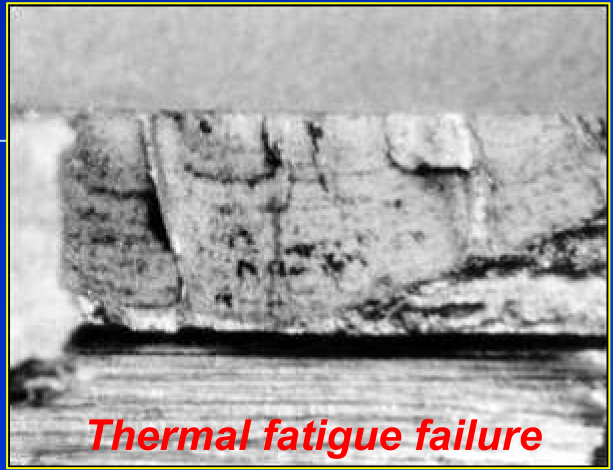
- In high temperature fatigue, there is a transition from ***fatigue failure*** to ***creep failure*** as the temperature increases (creep dominates at high temperatures).
- ***Coarse grained metal*** has higher fatigue strength – where creep dominates.
- **Fine grained metal** has higher fatigue strength at low temperatures.

Temp →

Fatigue failure	→	***Creep failure***
Transcrystalline fatigue failure		Intercrystalline creep failure

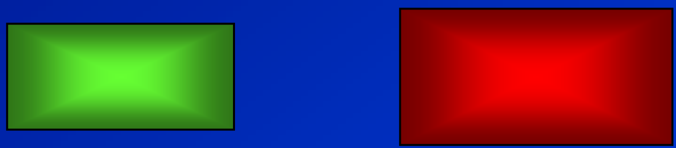
Thermal fatigue

Thermal fatigue occurs when metal is subjected to high and low temperature, producing fluctuating cyclic thermal stress.


Thermal fatigue failure

Thermal cycle → **Volume change**

Cold **Hot**



- Normally occurs in high temperature equipment.
- Low thermal conductivity and high thermal expansion properties are critical.

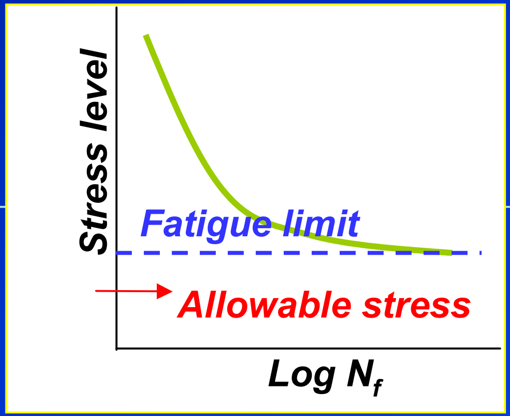
- The ***thermal stress*** developed by a temperature change ΔT is

$$\sigma = \alpha E \Delta T \qquad \textit{Eq.19}$$

Where α is linear thermal coefficient of expansion
E is elastic modulus

If failure occurs by one application of thermal stress, the condition is called ***thermal shock***.

Design for fatigue



There are several distinct philosophies concerning for design for fatigue

1) ***Infinite-life design:*** Keeping the stress at some fraction of the fatigue limit of the material.
2) ***Safe-life design:*** Based on the assumption that the material has flaws and has finite life. Safety factor is used to compensate for environmental effects, varieties in material production/manufacturing.
3) ***Fail-safe design***: The fatigue cracks will be detected and repaired before it actually causes failure. For aircraft industry.
4) ***Damage tolerant design:*** Use fracture mechanics to determine whether the existing crack will grow large enough to cause failure.