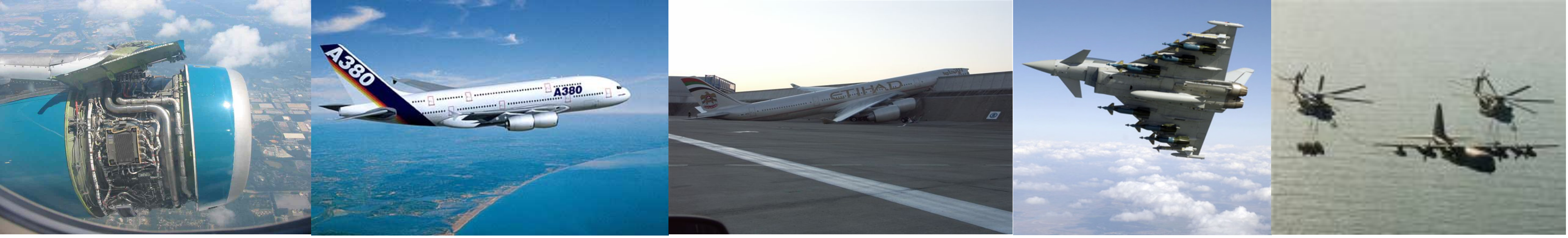


AENG 31200
Structures & Materials 3

Lecture: Creep

Supratik Mukhopadhyay

Learning Objectives

The student will be able to;

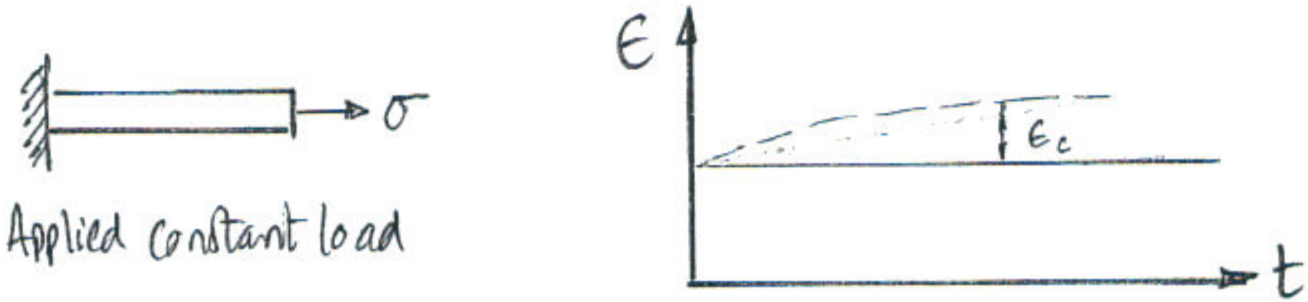
- Understand the basic phenomenon of creep in metals and polymers and their behaviour under sustained loads or displacements and temperature.
- Undertake a general analysis approach and be able to identify important design considerations.

Learning Resources

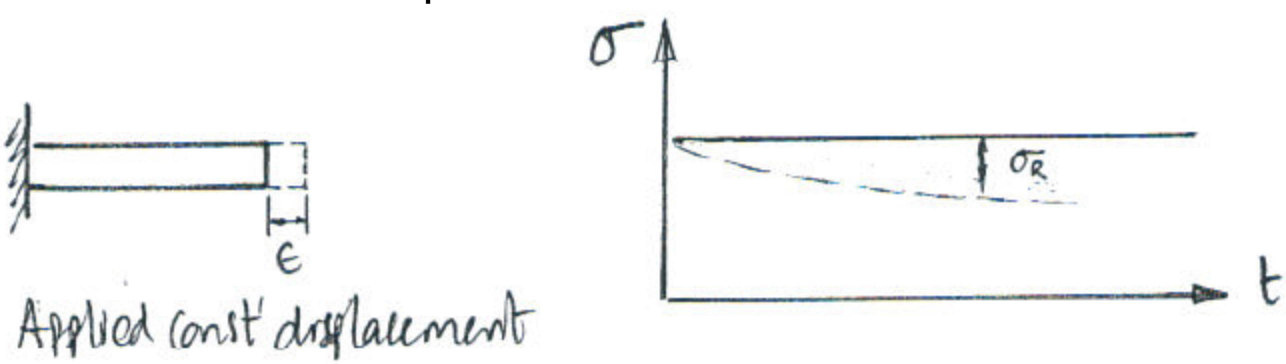
- WD Callister; "Materials Science & Engineering", Wiley. TA403
- Penny & Marriot; "Design for Creep" TA418.22
- Bernasconi & Piatti; "Creep of engineering materials and structures" TA418.22
- DWA Rees; "Mechanics of solids and structures" TA4048
- Boresi et al. "Advanced mechanics of materials" TA405

Introduction

- Definitions
  - Creep: the permanent elongation of a component under static load maintained for a period of time



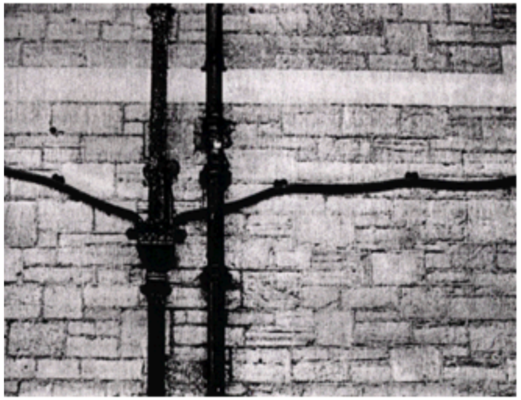
  - Stress Relaxation: the decrease in stress in a component under a constant strain over a period of time



Occurrence

- Phenomenon of metals and some non-metallic materials
  e.g. thermoplastics & rubbers
- Under load / time / temperature
- Creep deformation can occur at any temperature but is usually only significant at elevated temperatures for engineering materials:
  Metals: Above approximately 40% of T_m (in deg K)
    - High σ, High T

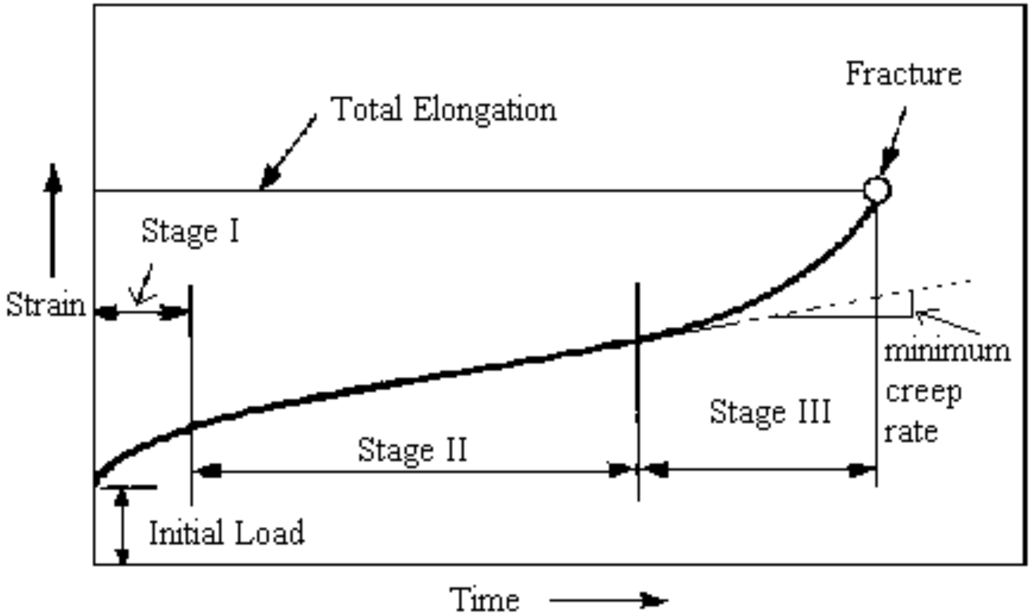
  Plastics: Above glass transition temperature, T_g (glassy ↔ rubbery)
    - Low σ, Low T


Lead pipes bend due to creep.

- Metal creep is especially important in applications subjected to high σ at elevated T:
  - Gas-turbine blades and similar components in jet engines and rocket motors
  - Supersonic airframes (e.g. Concorde)
  - High temperature steam lines, nuclear-fuel elements
  - Tools, dies during hot working operations such as forging and extrusion
  - Rivets and bolts

Mechanism

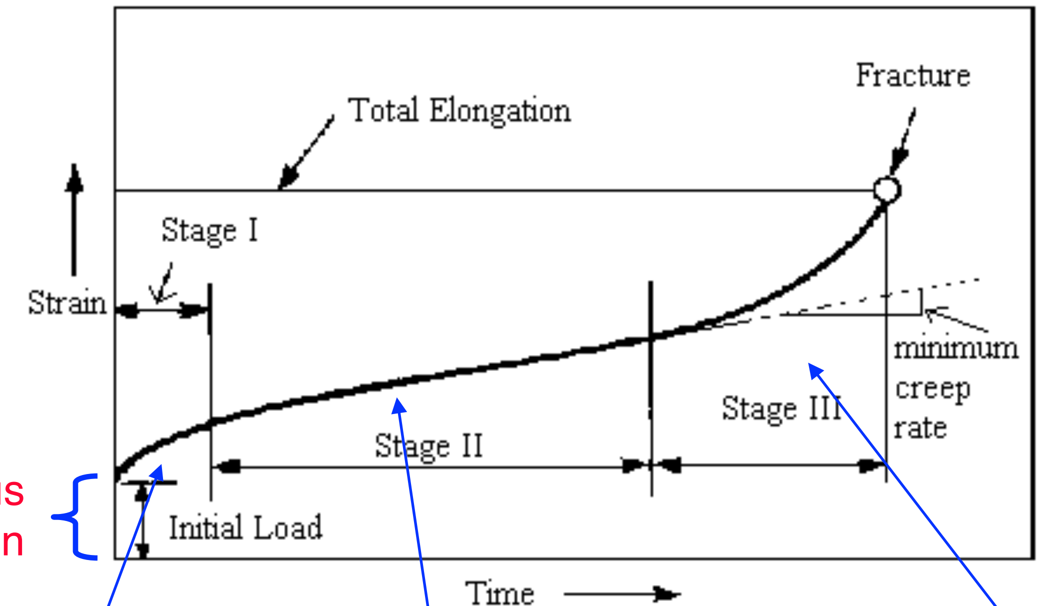
- For creep at elevated temperature;
  - Metals: Grain boundary sliding.
  - Plastics: Slip of polymer chains and alignment parallel to applied stress



- Primary and tertiary stages often referred to as <u>transient</u> creep
- Secondary creep also referred to as '*steady state creep*'

Behaviour

- Creep Deformation in **metals** (general trends, 3 stages)



Instantaneous elastic deformation

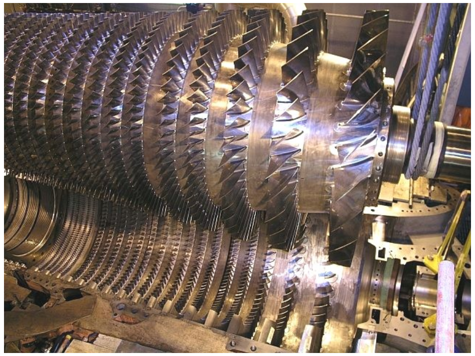
Primary (transient)
- Increasing dislocations
- Work hardening
- Reducing creep rate

Secondary (steady)
- Balanced
  work hardening vs. thermal softening
- Design region*

Tertiary (transient)
- Necking
- Cracking
- Increasing rate

Behaviour

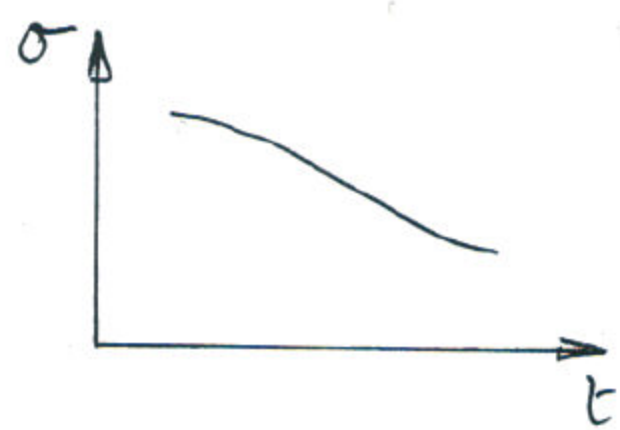
- Creep Failure
  - By excessive deformation, exceeding design allowable
  - By excessive deformation, leading to instability
  - By rupture i.e. creep fracture

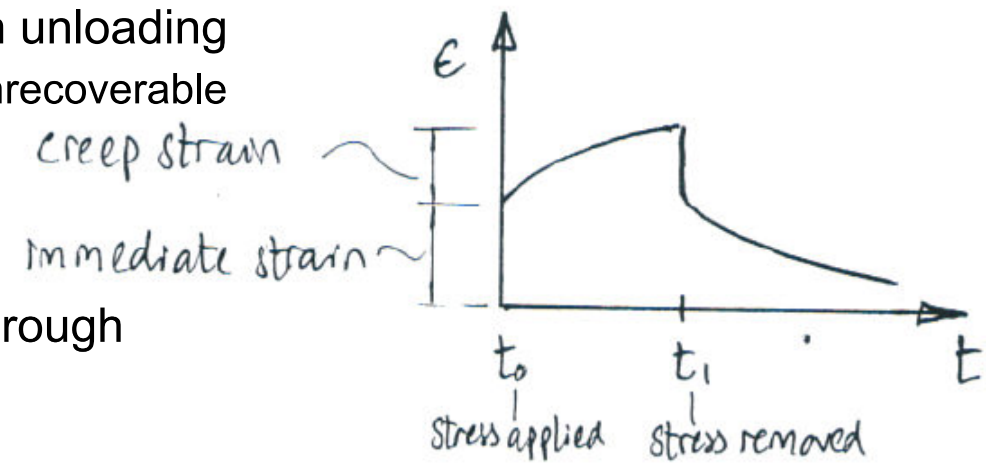


Behaviour

- Stress Relaxation
  - Relaxation of stress through creep at constant strain
- Viscoelasticity (polymers!)
  - Combined elastic (immediate)
    + viscous response (time dependent)
- Reverse Creep
  - The reversal of creep strain on unloading

    Note: creep in metals is usually unrecoverable
- Recovery
  - The loss of strain hardening through thermal softening





Analysis

- Creep strain functions

$$\varepsilon_c = f(\sigma, T, t)$$

Note: these parameters are usually interdependent with non-linear relationships

- Empirical functions – to describe one or all 3 creep stages w.r.t. σ, T & t.
  - e.g. considering time dependence only;

1. Low T (i.e. $<0.5T_m$) – primary creep dominates
   - With low σ, $\varepsilon_c = \alpha \ln t$ *i.e. logarithmic trend*
   - With high σ, $\varepsilon_c = \alpha t^m$ *i.e. power law trend*
2. High T (i.e. $>0.5T_m$) – secondary creep becomes significant
   - $\varepsilon_c = \alpha t^m + \beta t$

     (1ary) (2ary - linear) *where α & β = f(σ, T), empirically derived*

Useful generalised form;

$$\varepsilon_c = \alpha t^{1/3} + \beta t + \gamma t^3$$

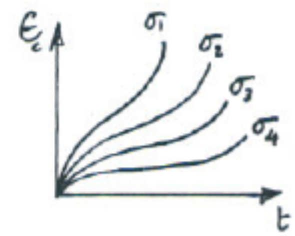
- good agreement with high temp alloys over wide range

Analysis

- Secondary creep is usual <u>design range</u>.
  - Designs nominally restricted to this region
  - Importance of secondary creep **<u>rate</u>** $d\varepsilon_s/dt$ modelling

- e.g. considering time dependence only;
  1. At low σ, $d\varepsilon_s/dt = A\,\sigma$
  2. At medium σ, $d\varepsilon_s/dt = A\,\sigma^n$ *(where $3 \le n \le 8$)*
  3. At high σ, $d\varepsilon_s/dt = A\,e^{B\sigma}$

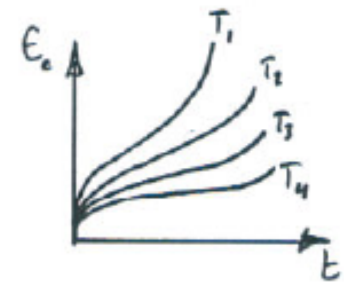
Const temp curves



$\sigma_1 > \sigma_2 > \sigma_3 > \sigma_4$

- e.g. considering temperature dependence only;
  1. Arrhenius equn. $d\varepsilon_s/dt = D\,e^{-Qc/RT}$
     (where D is constant,
     R is characteristic gas constant,
     Qc is creep activation energy)

Const stress curves



$T_1 > T_2 > T_3 > T_4$

Analysis

Creep strain rate functions

- Assuming that for a given creep time or creep strain; the creep rate is a function of the current σ and T only.

  (i.e. implying previous strain history does not influence creep rate)

- Two state equations:
  - "Time hardening" $d\varepsilon_c/dt = \acute{\varepsilon}_c\,(\sigma, T, t)$

    i.e. creep rate for σ & T @ particular accumulated creep **time**, t
  - "Strain hardening" $d\varepsilon_c/dt = \acute{\varepsilon}_c\,(\sigma, T, \varepsilon_c)$

    i.e. creep rate for σ & T @ particular accumulated creep **strain**, ε_c

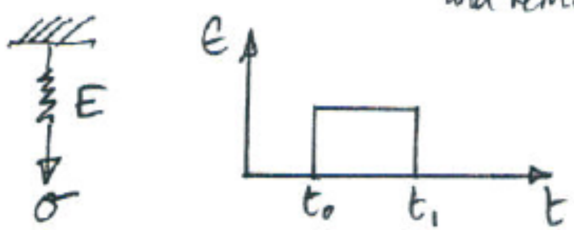
Analysis

- Viscoelasticity (**polymers!**)
  - Describes typical behaviour of <u>non-metallic materials</u> e.g. thermoplastics
  - Viscoelastic response is usually described by *rheological* (← relationship between σ and έ) models:

- For ideal elastic solid;
  - Hookean *spring* $\sigma = E\,\varepsilon$

    ⇨ $\varepsilon = \sigma / E$

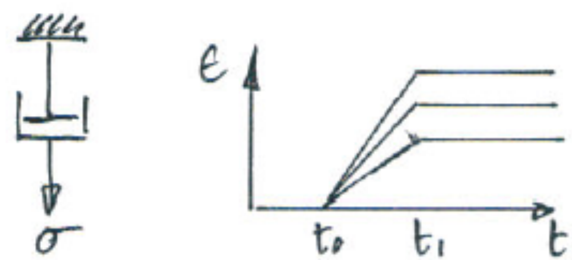
load applied at t_0 and removed at t_1



- For perfectly viscous fluid;
  - Newtonian *dashpot* $\sigma = \mu\, d\varepsilon/dt$

    ⇨ $\varepsilon = \int \sigma/\mu \, . \, dt$

μ = coefficient of viscosity



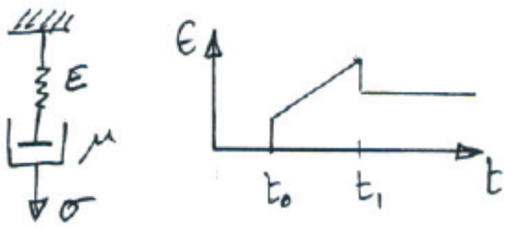
Analysis

- For viscoelastic behaviour;
  - Combined spring & dashpot models

1. Series "**M**axwell" model

$$\sigma = \sigma_s = \sigma_d$$

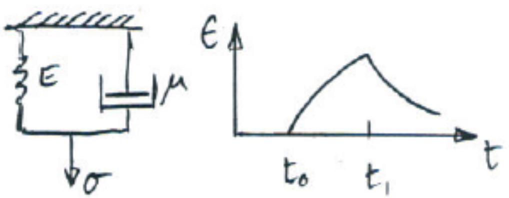
$$\varepsilon_m = \varepsilon_s + \varepsilon_d$$



2. Parallel "**V**oigt/Kelvin" model

$$\sigma = \sigma_s + \sigma_d$$

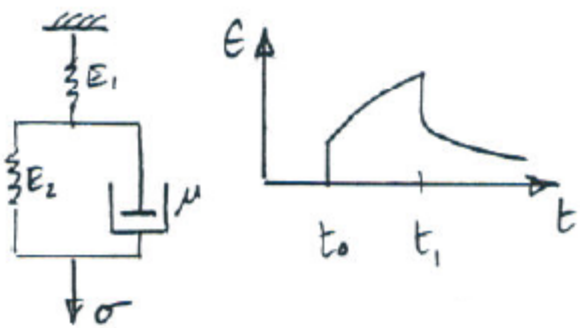
$$\varepsilon_v = \sigma/E\,[1 - \exp(-Et/\mu)]$$

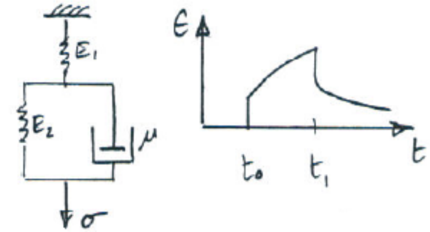


3. **S**tandard **L**inear **S**olid model

$$\sigma = E_1\,\varepsilon_1 = E_2\,\varepsilon_v + \mu\, d\varepsilon_v/dt$$

$$\varepsilon = \varepsilon_1 + \varepsilon_v$$





Analysis

- Note "**SLS**" model = simplest model providing good representation of observed creep + recovery in polymers
  - Combined spring & dashpot models
  - SLS creep ⇨ $\varepsilon = \sigma_0/E_1 + \sigma_0/E_2\ [1 - \exp(-E_2 t_2/\mu)]$

    instantaneous ε *time dependent creep strain*

    ↳ σ_0/E_2 as $t \rightarrow \infty$
  - SLS recovery after removal of σ_0 at time t_1, elastic strain σ_0/E_1 is immediately recovered and

    $$\varepsilon = \sigma_0/E_2 \exp(-E_2 t_2/\mu)\ [\exp(-E_2 t_2/\mu) - 1]$$

    $\varepsilon \rightarrow 0$ as $t \rightarrow \infty$
  - SLS relaxation

    $$\sigma = \varepsilon_0 E_1\ [E_1 \exp(-\{E_1 + E_2\}\ t / \mu) + E_2] / (E_1 + E_2)$$

    $\sigma \rightarrow (E_1\ E_2\ \varepsilon_0) / (E_1 + E_2)$ as $t \rightarrow \infty$ *i.e. asymptote*

Note: there are numerous other combinations of springs and dashpots of increasing complexity for modelling creep and relaxation with any required degree of accuracy

Design

- Criteria – design to avoid creep
  - Exceeding allowable deformation
  - Instability due to excessive deformation
  - Creep fracture “rupture”
- Typical design calcs:
  - σ for given life (t) and T
  - Life (time) for given σ and T

  For allowable strain

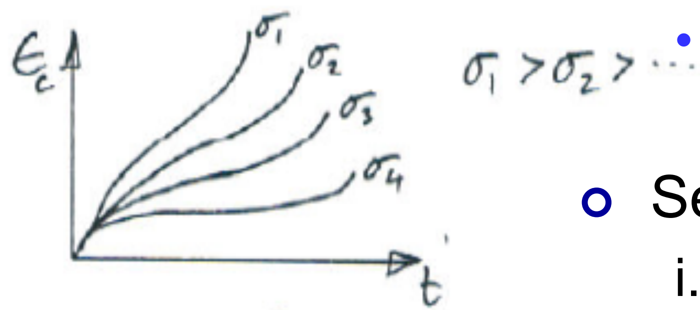
  - σ relaxation time i.e. time for σ to reduce to certain value for given T
  - Relaxed σ for a given t

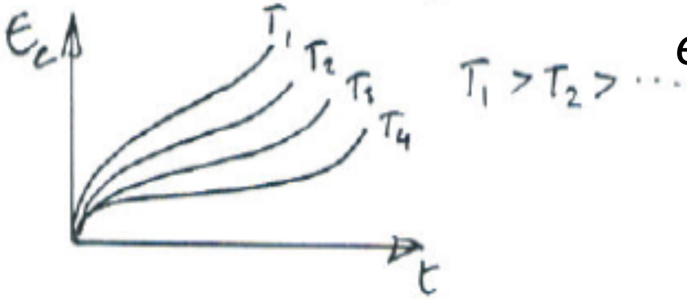
  e.g. bolt relaxation / retightening / creep life

Note: analysis procedures for real problems require computer based numerical techniques because the majority of important parameters have non-linear relationships with each other

Design

- Data – usually based on uniaxial load tests
  - Constant T creep curves for different σ
  - Constant σ creep curves for different T



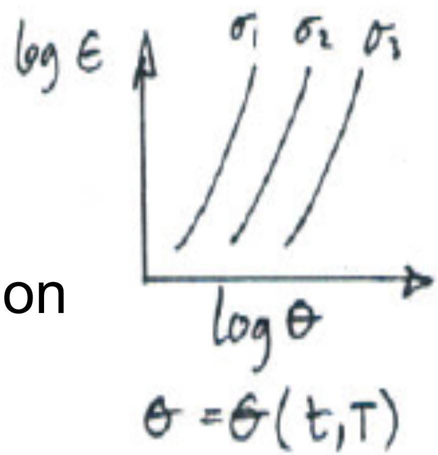


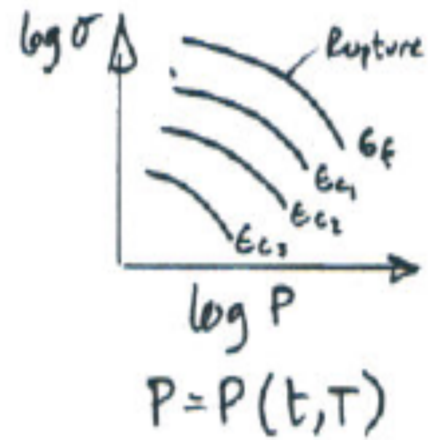
- Secondary creep ε rates

  i.e. ε per unit σ per hour at given T

  e.g. 10^{-9} */* Nmm^{-2} */ hr @ 150°C etc.*

- State equation parameters correlating creep deformation and rupture life





Design

- **Cross-plotted data**

  (Often used for **thermoplastic** creep design)

  1. Obtained from basic constant T creep data
  2. Isometric σ / t plots

     i.e. σ relaxation at given ε
  3. Isochronous σ / ε plots

     i.e. σ / ε behaviour at given times
  4. Tensile creep E / t plots

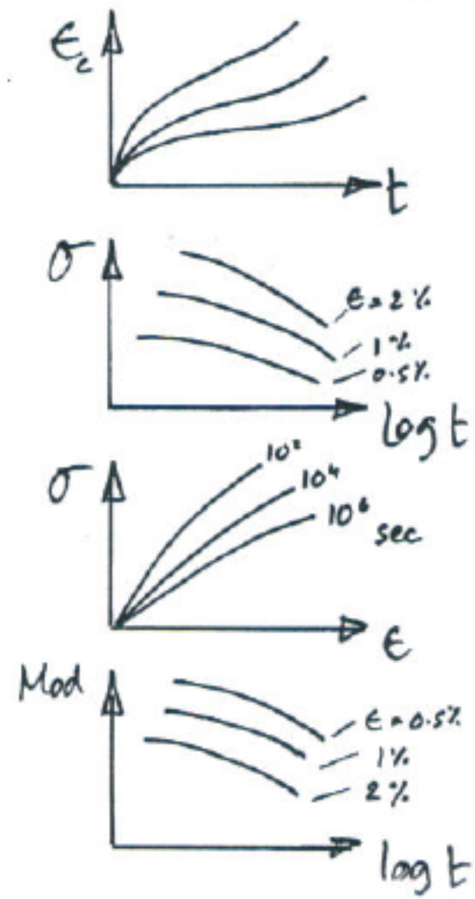
     i.e. creep modulus reduction at given ε

1

2

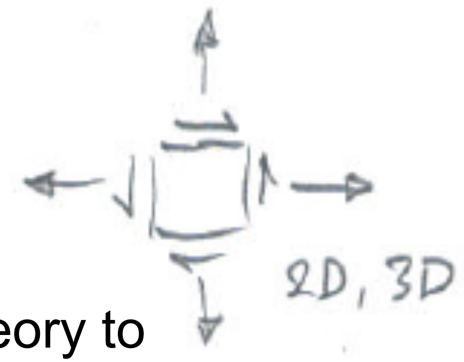
3

4



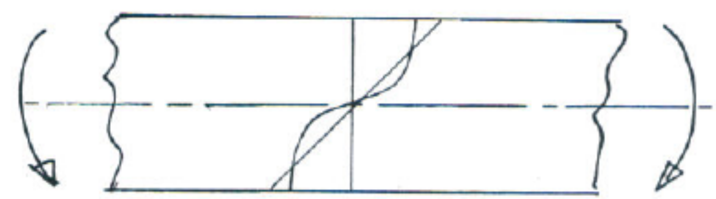
- Isothermal creep data for polymers is often presented in "Isochronous" form –
  - i.e. σ / ε curves associated with a particular creep time obtained from a family of creep curves
- For viscoelastic materials, a <u>single modulus</u> for each time may be identified with the slope of the σ / ε curve (from Fig. 3 above)

Design of Structures



- Multi-axial stress states (most structural members)
  - Creep is a shear deformation
  - Apply Von Mises shear (distortion) strain energy theory to obtain equivalent stress for comparison with uniaxial data
    - e.g. $\sigma_{vm} = f(\sigma_x, \sigma_y, \tau_{xy})$ as a scalar quantity

- Varying stress distribution (most structural members)
  - e.g. members in bending
  - Relaxation → redistribution of elastic stress [My/I] to a more uniform condition
  - Similarly for members in torsion, discontinuities,.etc...



Analysis

- Creep strain rate functions
  - Assuming that for a given creep time or creep strain; the creep rate is a function of the current σ and T only.

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  - Two state equations:
    - "Time hardening" $d\varepsilon_c/dt = \acute{\varepsilon}_c\,(\sigma, T, t)$

      i.e. creep rate for σ & T @ particular accumulated creep **time**, t
    - "Strain hardening" $d\varepsilon_c/dt = \acute{\varepsilon}_c\,(\sigma, T, \varepsilon_c)$

      i.e. creep rate for σ & T @ particular accumulated creep **strain**, ε_c

Design of Structures

- Changing stress states;

- "Time hardening"

$$d\varepsilon_c/dt = f(\sigma, T, t)$$

'Creep-time fraction rule' – defining creep w.r.t. accumulated creep time

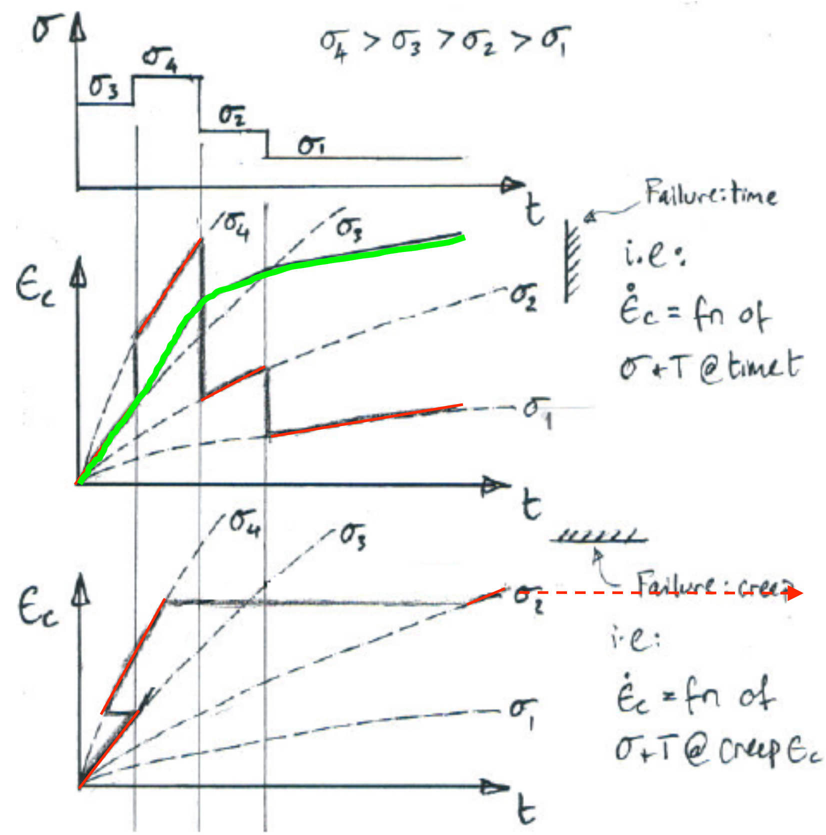
i.e. creep rupture when $\sum_i (t_{c\,i} / t_{cfi}) = 1$

- "Strain hardening"

$$d\varepsilon_c/dt = f(\sigma, T, \varepsilon_c)$$

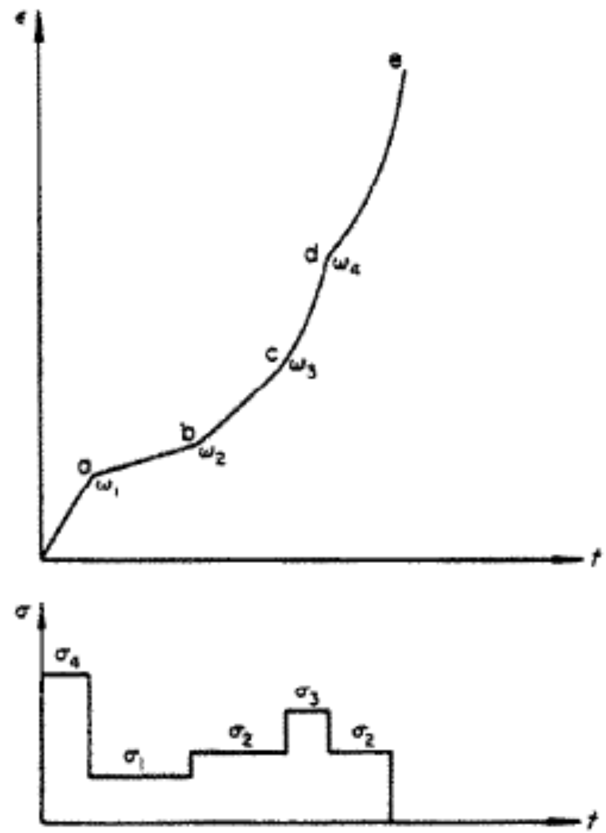
'Creep-strain fraction rule' – defining creep w.r.t. accumulated creep strain

i.e. creep rupture when $\sum_i (\varepsilon_{ci} / \varepsilon_{cfi}) = 1$



Note: for most practical applications, predictive methods must be capable of accounting for complex loadings which vary with time

Design of Structures



F.A. Leckie, D.R. Hayhurst Constitutive equations for creep rupture. *Acta Metallurgica*, 25(9), 1977, pp.1059-1070.

Note: for most practical applications, predictive methods must be capable of accounting for complex loadings which vary with time

Material Specification

- Generally, creep resistance increases with T_m (metals) or T_g (polymers)
  - Use stainless steels, superalloys, refractory metals for creep resistance under high σ, T
  - “Creep onset temperatures”

Metals

Al alloys	>200°C
Ti alloys	>315°C
Low alloy steels	>370°C
Stainless steels	>650°C
Super alloys	>1000°C
Refractories	>1500°C

Polymers (thermoplastics)

- Ambient or slightly above, typically >50°C

(thermosets)

- >50% Tg (Glass Transition Temperature)

Design Examples

- Aero gas turbine blades:
  - elongation + twist <<0.1% total creep
- Airframe subject to kinetic heating
  - Design for < 0.1% total creep in a/c life
  - e.g. W.M. Doyle, “The Development of Hiduminium-RR.58 Aluminium Alloy: The background to the choice of the main structural material for Concorde”, Aircraft Engineering & Aerospace Technology, 41(11),1969, (pp. 11-14)]
- Moving parts generally e.g. steam turbines
  - Design for < 1% total creep component life

  [10,000 hrs ~ 1 year, 100,000 hrs ~ 10 years]
- Avoid creep by:
  - Correct material selection
  - Lowering operational T and / or σ

Case Study