A. BASIC CONCEPTS

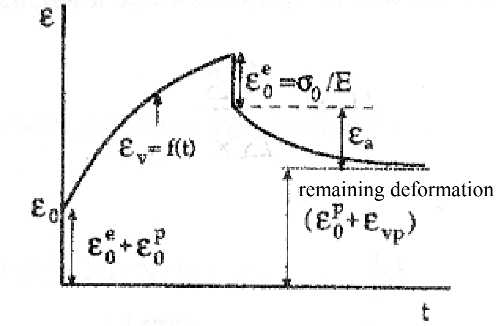
CREEP BEHAVIOUR

OVERVIEW: MATERIAL RESPONSE

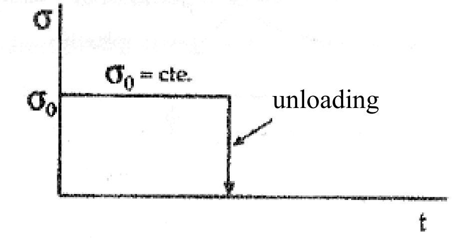
SLOW CREEP

It is the variation in time of the strain in a material which is subjected to constant load.

The more general response of materials is shown in the figure:



The microstructural mechanisms are described in the next pages depending on the temperature at which they happen in relation with the melting point, T_m.



CREEP BEHAVIOUR

OVERVIEW: MATERIAL RESPONSE

CREEP AT LOW TEMPERATURES: $T/T_m < 0.5$

In this case, the viscoelastic component of the strain predominates, and it has a small magnitude ($\varepsilon_v < 0.1$). In metallic materials, this process has importance for high stresses whereas in other materials (i.e, polymers) lower stresses are enough.

The stress condition for this process to be important is unified for all kind of materials through the relation:

$$\varepsilon_v = A \cdot \log(1 + \nu t)$$

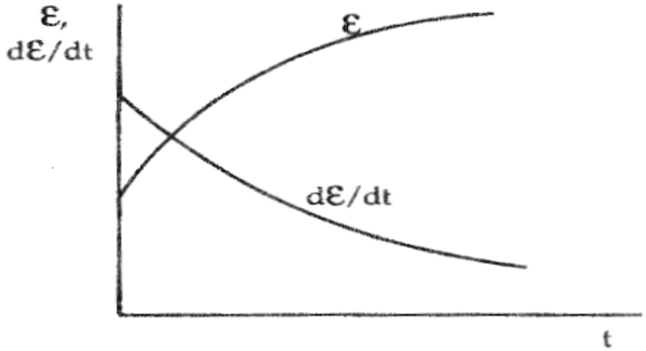
where ν varies from 10^{10} to 10^{13} s^{-1} and $A = A(\sigma, T, \text{material})$

CREEP BEHAVIOUR

OVERVIEW: MATERIAL RESPONSE

CREEP AT LOW TEMPERATURES: $T/T_m < 0.5$

The figure shows the behaviour of this kind of creep. It is explained from the movement of dislocations because of the applied stress and assisted by the thermal agitation. Dislocation go to more a more stable positions from where it is more difficult to move them and, because of that, the strain rate becomes lower.



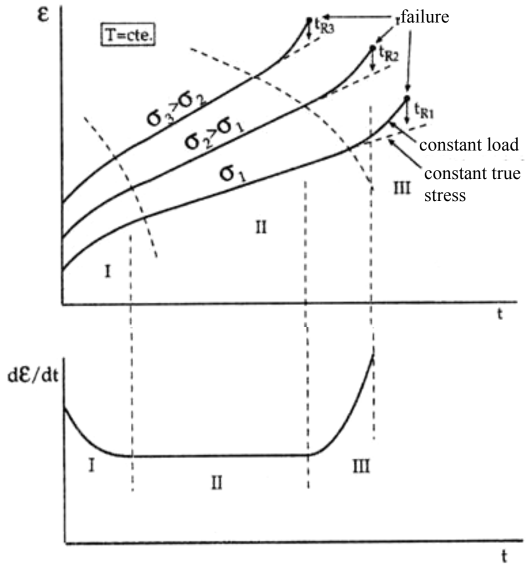
CREEP BEHAVIOUR

OVERVIEW: MATERIAL RESPONSE

CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$

This kind of creep has a predominant viscoplastic component in the strain and it has a big magnitude (ε_v can be even bigger than 100%). In metals an polymers, these strains appear from very low stresses ($\sigma/G = 10^{-3}$ to 10^{-4}) and limitations because of them are more decisive than strength limitations in service.

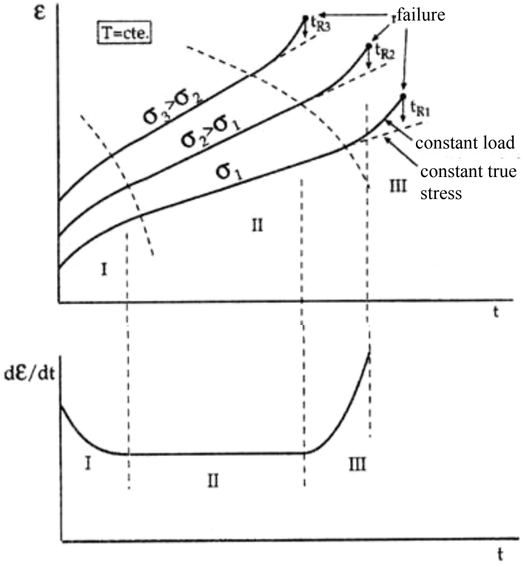
The figure shows the behaviour of a metallic material through ε-t curves and for different values of σ at a given temperature, T.



CREEP BEHAVIOUR

INTRODUCTION: DEFECT-FREE STRUCTURES

CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$



Three stages can be distinguished:

-*Stage I*: Primary creep with decreasing strain rate.

-*Stage II*: Secondary creep with constant strain rate.

-*Stage II*: Tertiary creep with increasing strain rate.

CREEP BEHAVIOUR

INTRODUCTION: DEFECT-FREE STRUCTURES

CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$

The behaviour at stages I and II can be described by relations such as Andrade´s equation:

$$\varepsilon_v = \varepsilon_0 + \beta \cdot t^n + K \cdot t$$

where

$$\varepsilon_0 = \varepsilon_0^e + \varepsilon_0^p$$

$$K = C\sigma^N \cdot e^{\frac{-Q}{kT}}$$

βt^n corresponds to transitory creep (n takes values from 1/4 to 2/3) and Kt corresponds to stationary creep. When t increases, the relation $\beta t^n/Kt$ decreases.

N is typically higher than 3

CREEP BEHAVIOUR

INTRODUCTION: DEFECT-FREE STRUCTURES

CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$

The deformation increases with time so the section of the structure decreases and, under constant load conditions, there is an increase of stresses that produces the acceleration of the deformations, which is characteristic of stage III.

There are some methods that allows to extrapolate the behaviour of a material under some given conditions to other conditions of σ or T. The most extended method is determined by the Larson-Miller equation:

$$T \cdot (\log t_R + C) = m$$

where C depends on the material and m depends on the stress. This correlation can be used to the rupture time t_R or to any other time when some given conditions are achieved, provided the microstructural mechanisms are similar.

CREEP BEHAVIOUR

INTRODUCTION: DEFECT-FREE STRUCTURES

CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$

The microstructural mechanisms that produces creep at high temperatures and that are associated with viscoplastic strains are:

-*Dislocation movement assisted by vacancies diffusion or interstitial diffusion*. It appears for $10^{-4} < \sigma/G < 10^{-2}$. These mechanisms justify the stationary creep as the equilibrium state between the strain hardening rate and the thermal recovery due to the reordenation and disappearance of dislocations.

-*Creep due to vacancies and interstitial diffusion assisted by stress* ($\sigma/G < 10^{-4}$). The stress generates a flow of vacancies from the grain boundaries in tension to those in compression and a flow of atoms in the opposite direction. It generates the enlargement of the grains and, then, strains.

-*Grain boundary slips*, which are necessary for the maintenance of the grains continuity, which justify the appearance of intergranular microvoids.

CREEP BEHAVIOUR

INTRODUCTION: STRUCTURES WITH DEFECTS

This chapter focuses on the concepts for predicting and characterising crack growth in structural materials at elevated temperatures:

-Components and structures that operate at high temperatures (relative to the melting point of the material) may fail through slow, stable extension of a macroscopic crack.

- Traditional approaches to design in the creep regime are applied only when creep and material damage are uniformly distributed.

- Time-dependent fracture mechanics approaches are required when creep failure is controlled by a dominant crack in the structure.

CREEP BEHAVIOUR

INTRODUCTION: STRUCTURES WITH DEFECTS

Creep failure occurs because of either widespread or localised creep damage:

WIDESPREAD DAMAGE: When the component is subjected to uniform stresses and temperatures, creep rupture can occur. This is mainly observed in thin section components.

LOCALISED CREEP DAMAGE: Components subjected to nonuniform stresses and temperatures. It is quite likely that failure occurs because of creep crack propagation. This is mainly observed in large structures.

CREEP BEHAVIOUR

INTRODUCTION: STRUCTURES WITH DEFECTS

It is possible to distingish two different creep behaviours:

CREEP-DUCTILE MATERIALS: These materials can develop considerable crack growth before failure. This growth is accompanied by creep strain at the crack front. Damage is usually in the form of grain boundary cavitation which is initiated at second phase particles or defects on the grain boundaries. Their nucleation and growth ends with their coalescence and, then the crack appears and grows.

Examples: Stainless steels, Cr-Mo steels, Cr-Mo-V steels,...

CREEP-BRITTLE MATERIALS: The main difference between these materials and creep-ductile materials is that creep crack growth is accompanied by small-scale creep deformation and by crack growth rates that are comparable to the rate at which creep deformation spreads in the cracked component.

Examples: Titanium and aluminium alloys, nickel-base superalloys, ceramic materials...

CREEP BEHAVIOUR

INTRODUCTION: STRUCTURES WITH DEFECTS

Four stages can appear in the behaviour of a pre-existing defect when it is subjected to load at high temperatures:

1) INITIATION: a period during which no growth occurs ($\Delta a \leq 0.2$ mm)

2) CRACK GROWTH: The crack extends in a stable manner as a result of creep processes

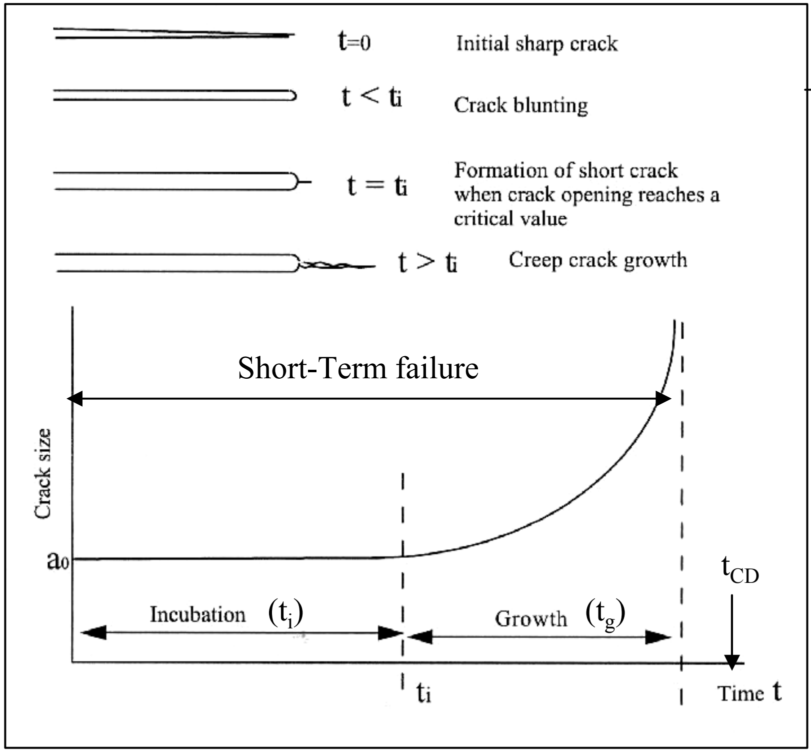
3a) FRACTURE: The crack may grow to a size at which short-term fracture (ductile or brittle) occurs

3b) CREEP RUPTURE: Failure may occur due to accumulation of creep damage in the ligament ahead of the crack (or elsewhere in the structure)

CREEP BEHAVIOUR

INTRODUCTION: STRUCTURES WITH DEFECTS

Schematic behaviour of failure due to crack growth at elevated temperature

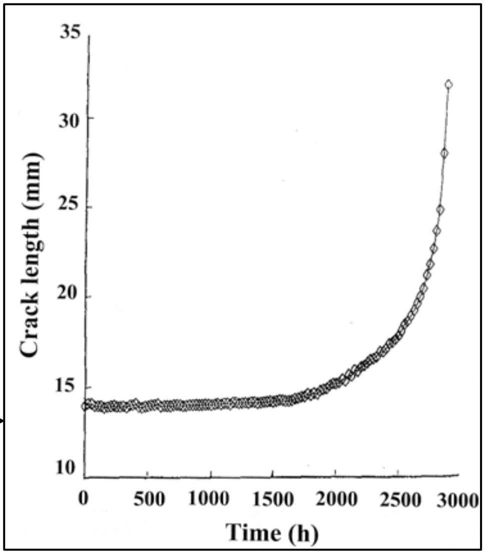


Lifetime = lower{$(t_i + t_g)$, t_{CD}}

t_{CD} : time for creep rupture

EXAMPLE:

Experimental crack growth in 2_CrMo weld at 565 ºC



CREEP BEHAVIOUR

KEY DEFINITIONS

•**STEADY CYCLE STATE**: It is defined as the condition in which repeated cycles of loading give rise to repeated cycles of stress and a constant increment of strain, which may be zero, per cycle.

•**DWELL PERIOD**: It is a part of the steady cycle during which the structure experiences continuous operation at temperatures in the creep range with only slight changes in loads and temperatures.

•**SHAKEDOWN**: The component is in strict shakedown if the behaviour is elastic at all points in the structure at all instants of time during operation in the steady cyclic state.

CREEP BEHAVIOUR

PARAMETERS USED TO DESCRIBE THE DEFECT BEHAVIOUR

K: Linear Elastic Stress Intensity Factor

J: J Integral value, useful under elastic-plastic conditions

$\boldsymbol{\sigma}_{\mathbf{ref}}$: Reference stress

$\mathbf{C}^*$: Crack Tip Parameter

C(t): Non steady crack parameter

CREEP BEHAVIOUR

PARAMETERS USED TO DESCRIBE THE DEFECT BEHAVIOUR

-The initial response of the body is elastic-plastic, and the crack-tip stress field is proportional to K if the scale of plasticity is small compared with crack size. If the plastic zone is not small, the J-integral characterises the instantaneous crack tip stresses and strains.

-With increasing time, creep deformation causes the relaxation of the stresses in the immediate vicinity of the crack tip, resulting in the formation of the creep zone, which continually increases in size with time. Because the parameters K and J are independent of time, they are not able to uniquely characterise the crack-tip stresses and strains within the creep zone.

CREEP BEHAVIOUR

PARAMETERS USED TO DESCRIBE THE DEFECT BEHAVIOUR

- The parameters C* and C(t) have been developed to describe the evolution of time-dependent creep strains in the crack-tip region.
- For a body undergoing creep, the uniaxial stress-strain-time response for a material that exhibits elastic, primary, secondary and tertiary creep is given by:

$$\frac{d\varepsilon}{dt} = \frac{\frac{d\sigma}{dt}}{E} + A_1 \cdot \varepsilon^{-p} \cdot \sigma^{n_1 \cdot (1+p)} + A \cdot \sigma^{n} + A_3 \cdot \sigma^{n_3} \cdot (\varepsilon - \mathrm{A} \cdot \sigma^{\mathrm{n}} \cdot t)^{p_3}$$

A, A_1, A_3, p, p_3, n, n_1 and n_3 are the creep regression constants derived from creep deformation data.

CREEP BEHAVIOUR

STRESS INTENSITY FACTOR

As K describes elastic behaviour, it is not generally relevant to the behaviour of defects at high temperature, except for:

- **Very brittle materials** which exhibit little creep deformation prior to failure
- **At very short times** when stresses have had little time to redistribute from the elastic field to the steady state creep field

CREEP BEHAVIOUR

REFERENCE STRESS (I)

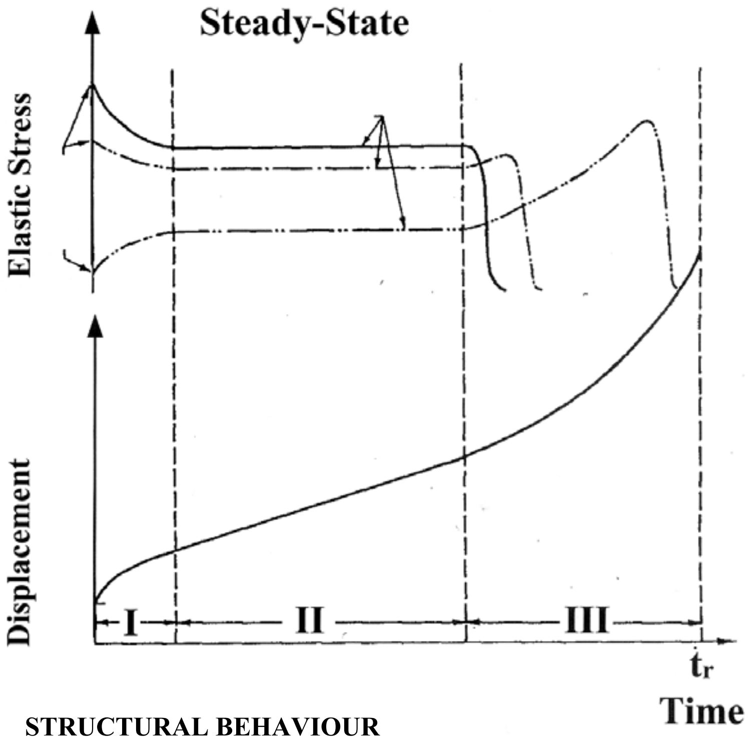
Following initial elastic (or elastic-plastic) behaviour on loading, structures at high temperature can exhibit various stages of response:

- **Stage I** : a period of stress redistribution in which stresses become more uniform. This usually involves a reducing displacement rate because of both the stress redistribution and primary creep. Primary creep dominates at short times after application of the load.
- **Stage II** : a steady state period when stresses are essentially constant. The displacement rate is also constant for steady state creep.

CREEP BEHAVIOUR

REFERENCE STRESS (II)

- **Stage III:** as local damage develops, further stress redistribution may occur. This involves an increasing displacement rate because of both the stress redistribution and tertiary creep. Microscopic failure mechanisms, such as grain boundary cavitation, nucleate at this final stage of creep.



STRUCTURAL BEHAVIOUR

CREEP BEHAVIOUR

REFERENCE STRESS (III)

- The steady state generates reasonably uniform stress fields which can be described by a single value of stress called the **reference stress, $\boldsymbol{\sigma}_{\mathbf{ref}}$.**

- Limit load solutions also tend to produce uniform stresses, so that the limit load (F_L) can be used to define σ_{ref}.

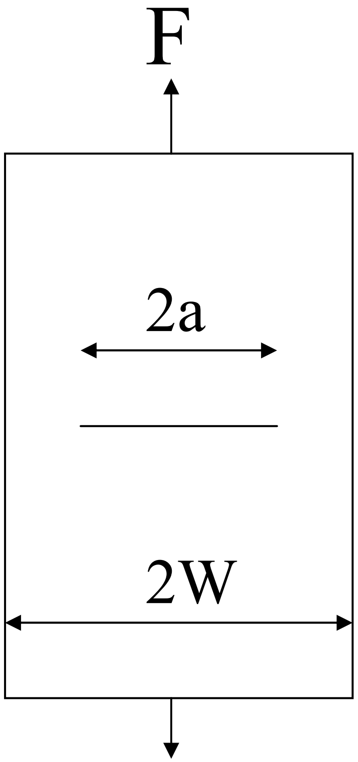
$$\boldsymbol{\sigma_{ref} = F\,\sigma_y / F_L(\sigma_y)}$$

F - applied load

F_L - limit load solution for yield stress

CREEP BEHAVIOUR

REFERENCE STRESS (IV)



Example: Centre cracked plate under tension

(t, thickness)

$$F_L = 2Wt\sigma_y(1- a/W)$$

$$\sigma_{ref} = F\sigma_y / F_L = F/ (2Wt(1- a/W))$$

CREEP BEHAVIOUR

REFERENCE STRESS (V)

The reference stress can be used for various purposes:

1) **Plastic Collapse:** $\sigma_{ref} \leq \sigma_y$ is equivalent to $F \leq F_L$

2) **Creep Rupture**: the time for creep rupture t_{cd} can be estimated as

$$t_{cd} \approx t_r(\sigma_{ref})$$

$t_r(\sigma)$ is the time-to-rupture in a standard specimen at stress σ for a given temperature

Even in cracked components, the time to failure can be governed by creep rupture if crack growth rates are low in creep ductile materials

3) **Estimating crack tip parameters**: J or C*

CREEP BEHAVIOUR

C* PARAMETER (I)

C* is the creep analogue of J in post-yield fracture.

Hoff´s analogy states that if there exists a nonlinear elastic body that obeys the relationship $\varepsilon_{ij}=f(\sigma_{ij})$ and a viscous body that is characterised by $d\varepsilon_{ij}/dt = f(\sigma_{ij})$, where f is the same for both, then both bodies develop identical stress distributions when the same load is applied. It can be applied to steady state creep because the creep rate is a function only of the applied stress.

The C* integral is defined by replacing strains with strain rates, and displacements with displacement rates in the J contour integral:

$$C^* = \int_{\Gamma} \left(\dot{w}\,dy - \sigma_{ij} n_j \frac{\partial \dot{u}_i}{\partial x} ds \right)$$

where $\dot{w}$ is the stress work rate (power) density

CREEP BEHAVIOUR

C* PARAMETER (I)

C* is the creep analogue of J in post-yield fracture.

Hoff´s analogy implies that C* integral is path-independent, because J is path-independent.

Just as the J integral characterises the crack tip fields in an elastic or elastic-plastic material, the C* integral uniquely defines crack tip conditions in a viscous material.

Thus, the time-dependent crack growth rate in a viscous material should depend only on C*.

Experimental studies have shown that creep crack growth rates correlate very well with C*, provided steady state creep is the dominant deformation mechanism in the specimen.

CREEP BEHAVIOUR

C* PARAMETER (II)

It characterises stress and strain-rate fields in steady state creep

$$\sigma_{ij} = (C^*/D \cdot I_n \cdot r)^{1/(n+1)}$$

for $d\varepsilon/dt = D \cdot \sigma_n$

It can be calculated from creep displacement rates, $(d\Delta/dt)^c$, in standard test specimens

$$C^* = [n/(n+1)] \cdot [\eta \cdot F \cdot (d\Delta/dt)^c]/[B \cdot (W-a)]$$

for CT specimens . $\eta = 2 + 0.522 \cdot (1-a/W)$

It generally characterises creep crack growth rates, da/dt:

$da/dt = A \cdot C^{*q}$ where A is a correlation constant depending on material

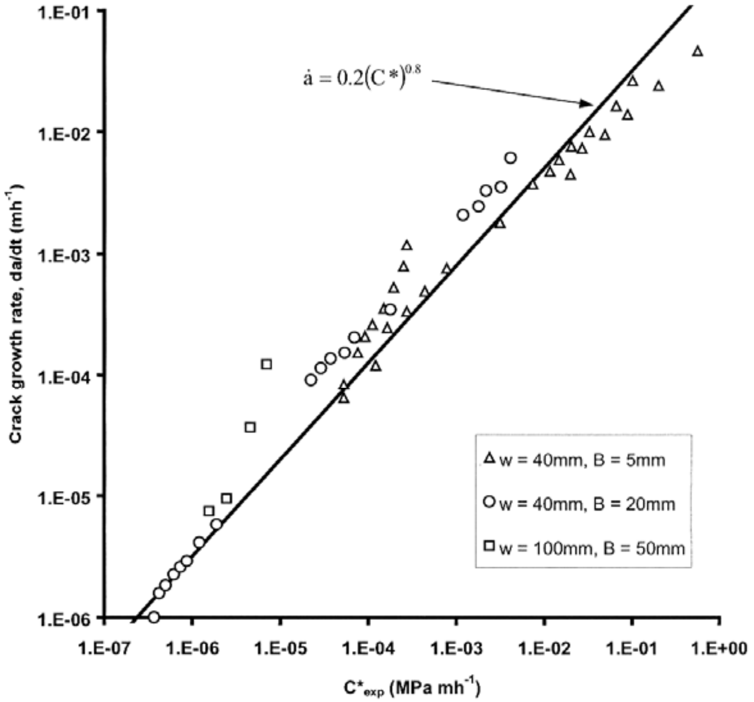
$q \approx n / (n+1)$

CREEP BEHAVIOUR

C* PARAMETER (III)

Typical creep crack growth data

$$da/dt = A \cdot C^{*\,q}$$



½CrMoV

CREEP BEHAVIOUR

C* PARAMETER (IV)

ESTIMATING C*

1) By analogy with J:

$C^* = \sigma_o \cdot (d\varepsilon/dt)_o \cdot c \cdot h_1 \cdot (P/Po)^{n+1}$

$(d\varepsilon/dt) = (d\varepsilon/dt)_o \cdot (\sigma/\sigma_o)^{\,n}$

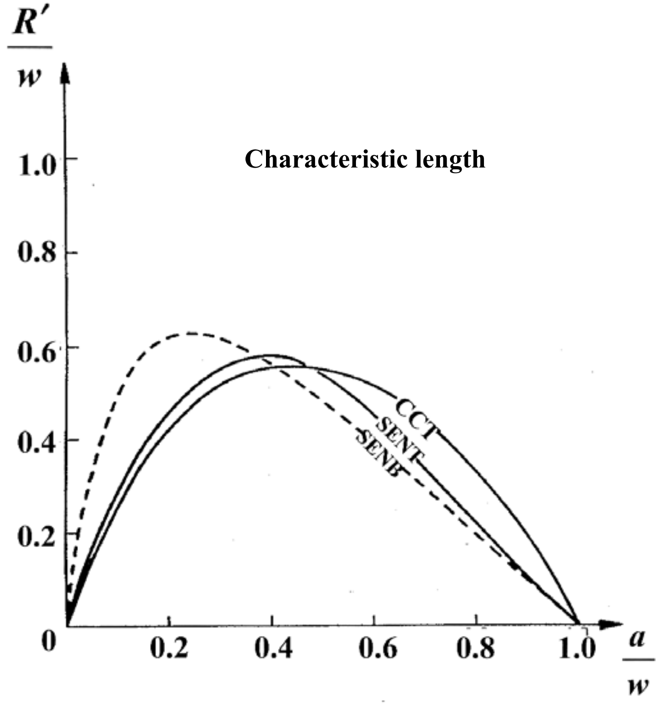
$h_1 = f\,(n, \text{geometry}, a/W, \text{loading type})$

2) For more general creep laws, aproximately:

$C^* = \sigma_{ref} \cdot (d\varepsilon/dt)_{ref} \cdot R'$

$(d\varepsilon/dt)_{ref}$ = creep strain rate at stress σ_{ref}

$R' = \text{length} \approx K^2/\sigma^2_{ref}$



Reference stress estimate validated by comparision with numerical solutions and experimental data.

CREEP BEHAVIOUR

C* PARAMETER (V)

REALISTIC CREEP LAWS

- Having written C* in terms of the strain rate at a reference stress, it is no longer necessary to retain a simple power law. The formula enables:

- Creep laws including primary, secondary and tertiary parts to be used
- Raw creep data to be used directly if an equation fitting the data is not avalaible
- Allowance to be made for creep strain accumulation under rising stress as the crack grows, via strain hardening rules.

CREEP BEHAVIOUR

NON-STEADY CREEP PARAMETER

$$\mathbf{C(t) = K^2/(n+1)Et \qquad t \to 0}$$

$$\mathbf{C(t) = C^* \qquad t \to \infty}$$

- The transition between these extremes may be described in terms of

$$t_T = K^2/(n+1)EC^*$$

or

$$t_{red} = K^2/EC^*$$

- The reference stress estimate of C* means

$$\varepsilon^c(\sigma_{ref}, t_{red}) = \sigma_{ref}/E$$

i.e. the steady state is reached when the creep strain equals the elastic strain (at the reference stress)

CREEP BEHAVIOUR

INCUBATION CALCULATIONS (I)

There are various routes for assessing when a crack starts to grow:

1) For steady state creep via data, t_I, correlated with C*: $\mathbf{t_i = constant \cdot (C^*)^{-m}}$

$m \approx n/(n+1)$

and C* calculated by various means.

2) With primary or transient creep via critical COD, δi. Then calculate a critical strain for initiation:

$$\varepsilon_i^c = (\delta_i/R')^{n/(n+1)} - \sigma_{ref}/E$$

(or 0 if less than zero)

Then $\boldsymbol{\varepsilon_c(\sigma_{ref}, t_i) = \varepsilon_i^c}$ **defines** $\mathbf{t_i}$

CREEP BEHAVIOUR

INCUBATION CALCULATIONS (II)

3) In the absence of initiation data from cracked specimens, an estimated value may obtained be made using rupture data:

3.1. $t_I = 0.0025 \cdot (\sigma_{ref} \cdot t_r(\sigma_{ref})/K^2)^{0.85}$

for t_r, t_I in h, σ_{ref} in MPa, K in $MPa \cdot m^{1/2}$

(from BS7910)

3.2 using the σ_d method

(from A16)

CREEP BEHAVIOUR

CRACK GROWTH CALCULATIONS

- These are generally performed using an estimate of C^* and crack growth data in the form:

$$\mathbf{da/dt = A \cdot C^{*q}}$$

- In the absence of crack growth data, an estimate can be made using
  - Ductility data, ε_f^*

$$\mathbf{da/dt = 3 \cdot C^{*0.85}/\varepsilon_f}$$

  - Creep rupture data, $t_r(\sigma)$

$$\mathbf{da/dt = (K^2/\sigma_{ref} \cdot t_r(\sigma_{ref}))^{0.85}}$$

- With all methods, $\Delta a = (da/dt) \cdot \Delta t$ and calculations of K, σ_{ref}, C^* and hence da/dt are updated as the crack extends to $a + \Delta a$.

CREEP BEHAVIOUR

CRACK GROWTH CALCULATIONS

- ASTM E 1457 (for collecting creep crack growth data only)
- BS 7910 (formely BS PD 6539)
- R5 (British Energy)
- A16
- API 579

Sample flow charts for structural assessment have been produced.

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