FITNET European Fitness-for-service Network

welded structures • design • fabrication • structural integrity

FITNET BASIC TRAINING PACKAGE

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I. TRAINING PACKAGE ON FRACTURE

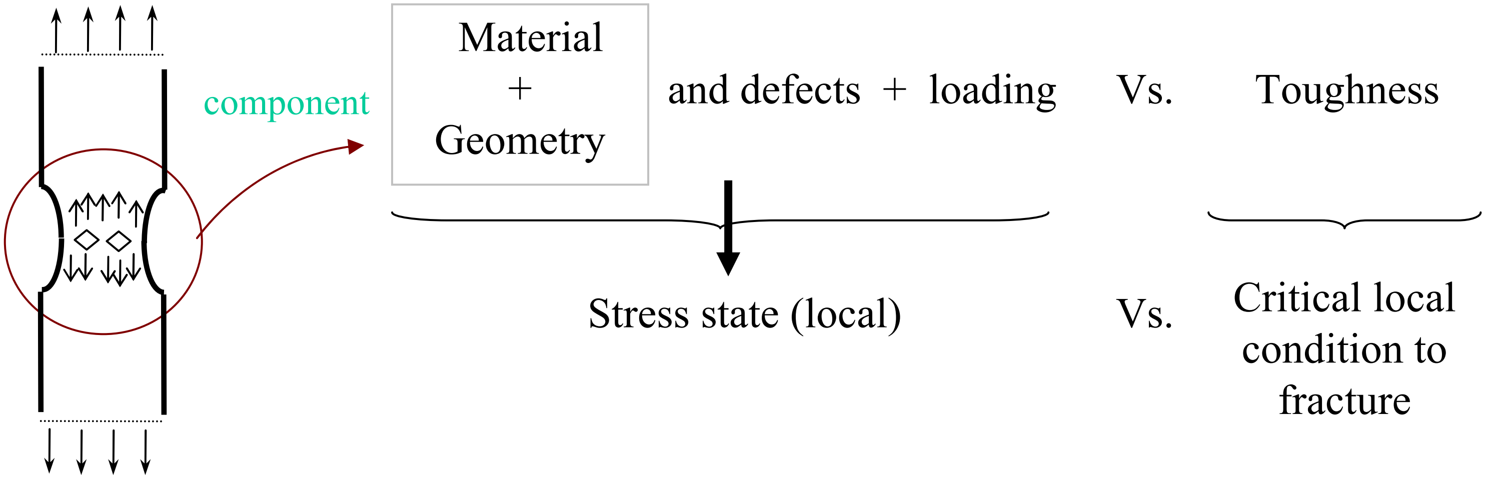
A. BASIC CONCEPTS

FRACTURE BEHAVIOUR

INTRODUCTION

The final fracture of structural components is associated with the presence of macro or microstructural defects that affect the stress state due to the loading conditions.

Fracture occurs when this state reaches at local level a critical condition.

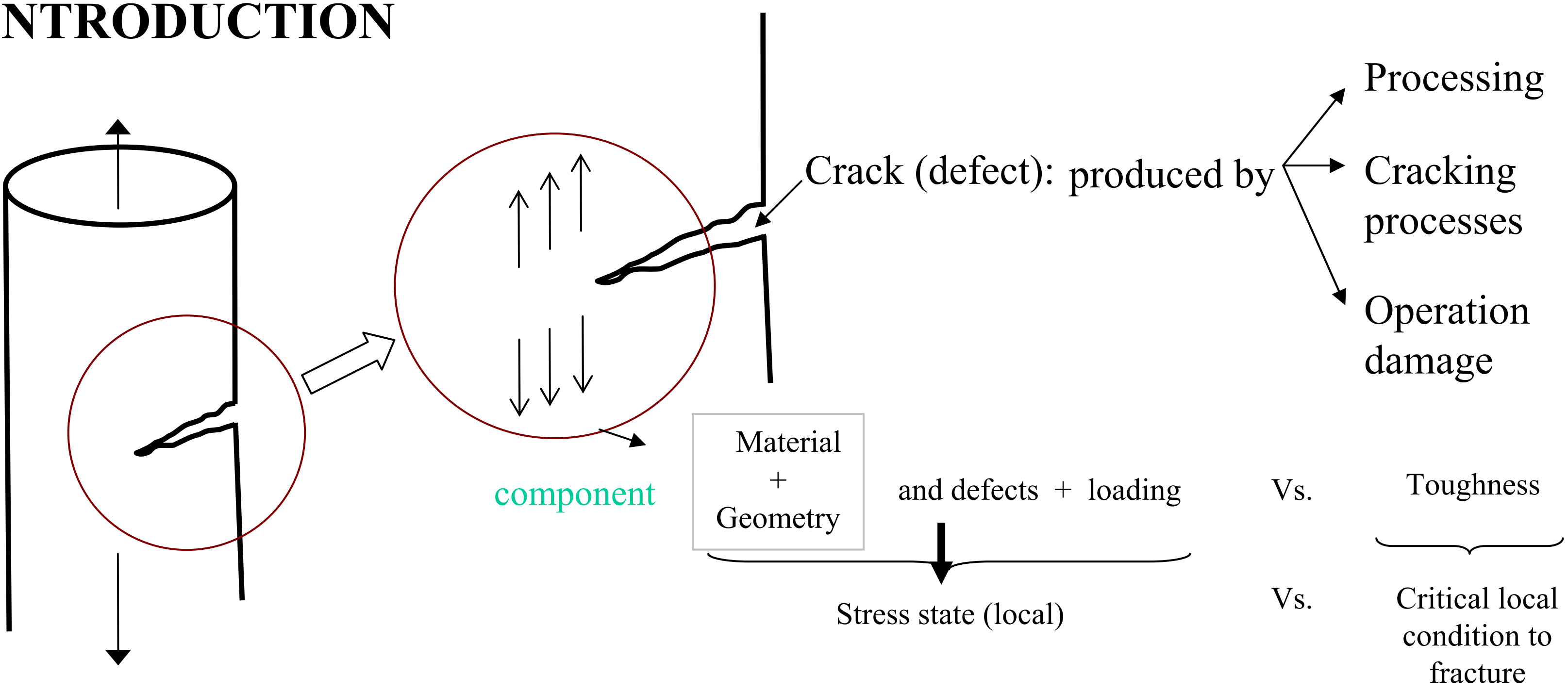


Material + Geometry and defects + loading Vs. Toughness

Stress state (local) Vs. Critical local condition to fracture

FRACTURE BEHAVIOUR

INTRODUCTION

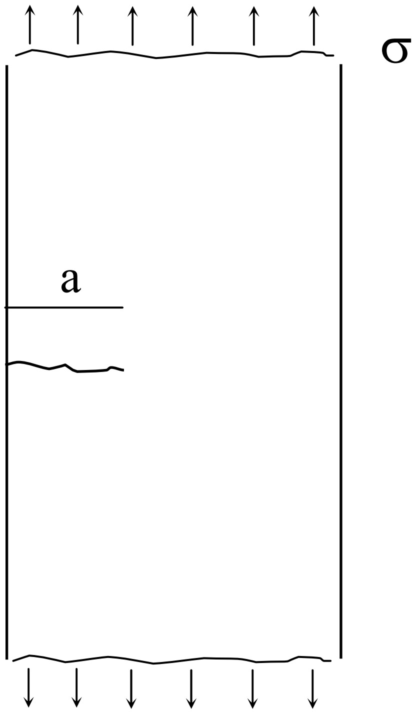


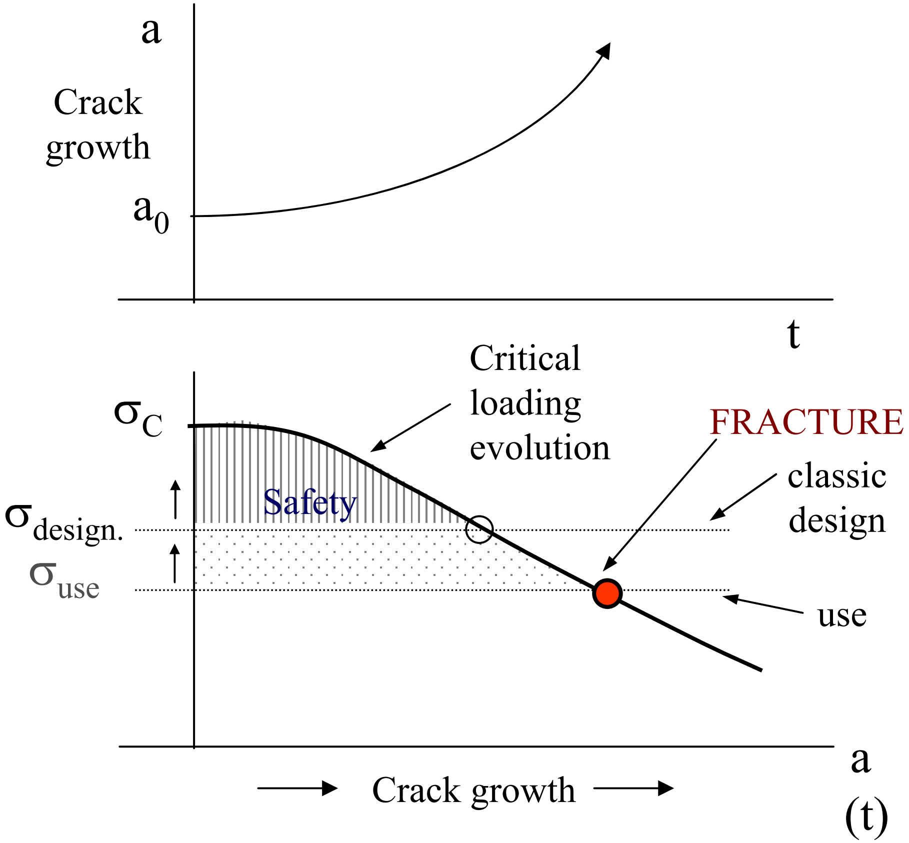
Fracture analysis → **FRACTURE MECHANICS**

FRACTURE BEHAVIOUR

INTRODUCTION

Fracture Mechanics





FRACTURE BEHAVIOUR

INTRODUCTION

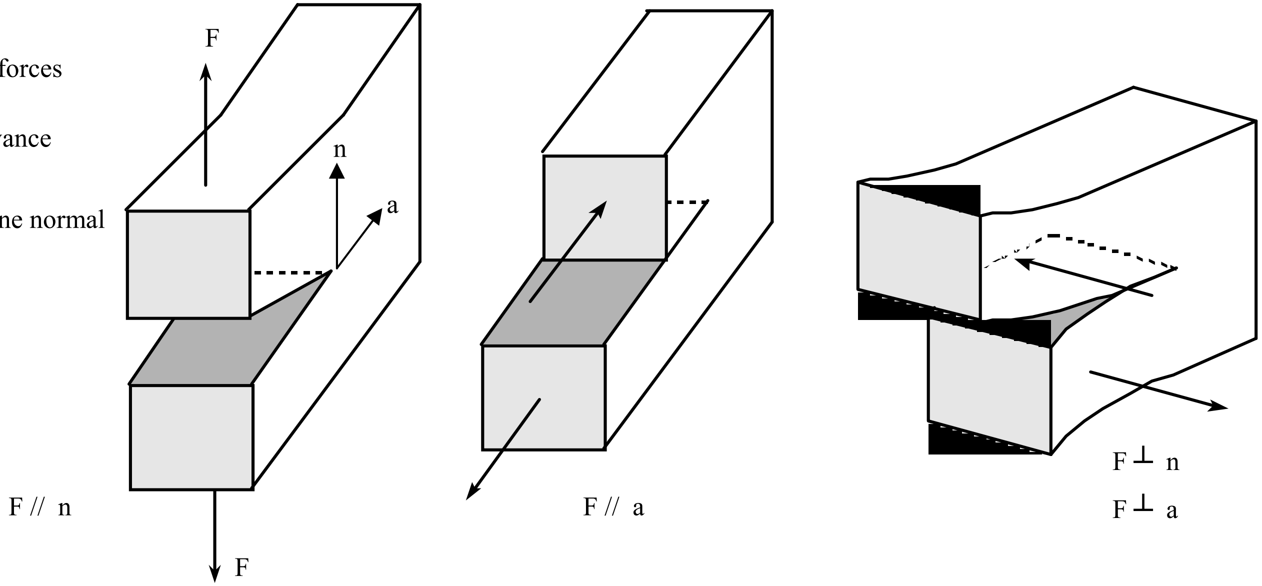
Fracture Modes

F: Loading forces

a: crack advance

n: crack plane normal

a ⊥ n



MODE I
Tensile

MODE II
Shear

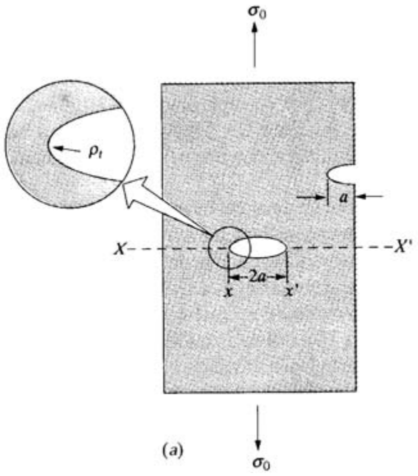
MODE III
Torsion

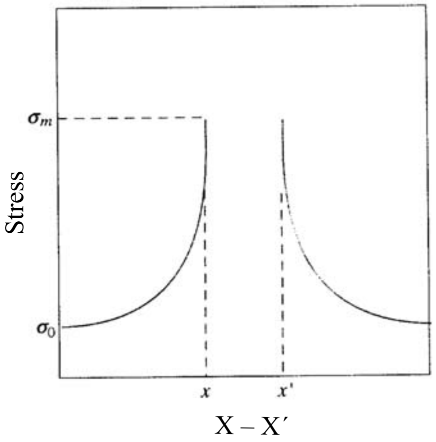
FRACTURE BEHAVIOUR

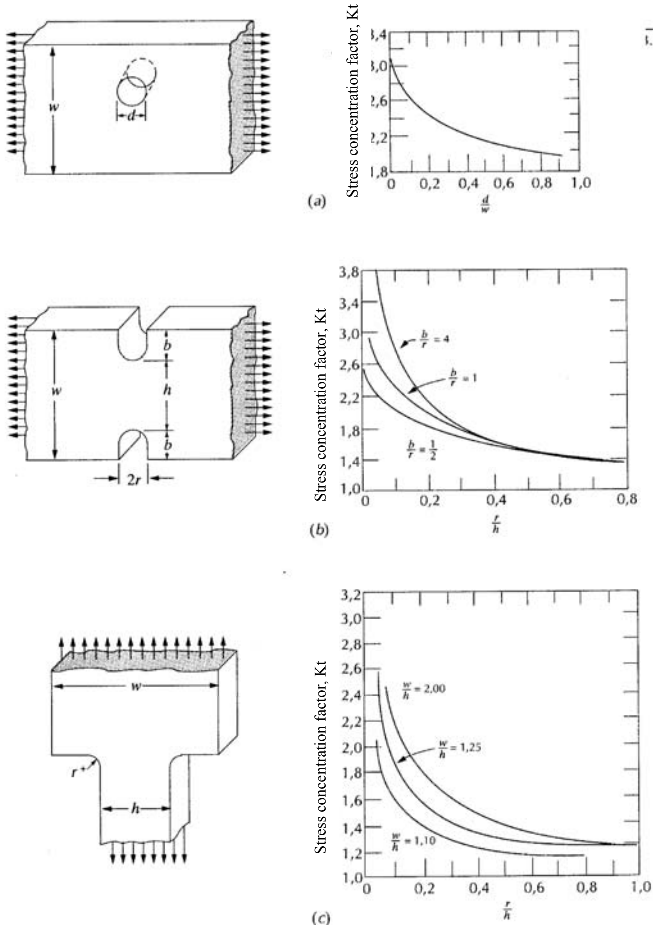
FRACTURE CRITERIA

Stress state in a crack front

Stress concentration







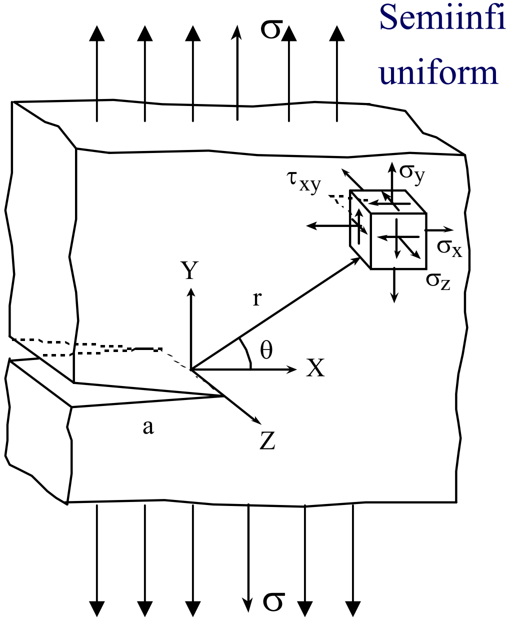
FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Local stress and strain states

in a crack front (Irwin)

Semiinfinite plate,
uniform stress (MODE I)



STRESSES

Plane solution

$$\sigma_x = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\left(1-\operatorname{sen}\frac{\theta}{2}\operatorname{sen}\frac{3\theta}{2}\right)\right]$$

$$\sigma_y = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\left(1+\operatorname{sen}\frac{\theta}{2}\operatorname{sen}\frac{3\theta}{2}\right)\right]$$

$$\tau_{xy} = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\operatorname{sen}\frac{\theta}{2}\cos\frac{3\theta}{2}\right]$$

$$\sigma_{ij}^{I} = \sigma\sqrt{\frac{a}{2r}}\,f_{ij}^{I}(\theta)$$

Plane stress (PSS)

$\sigma_z = 0$

Plane strain (PSN)

$\sigma_z = \nu\,(\sigma_x + \sigma_y)$

DISPLACEMENTS

$$u = \frac{\sigma}{2E}\sqrt{\frac{ar}{2}}(1+\nu)\left[(2\kappa-1)\cos\frac{\theta}{2}-\cos\frac{3\theta}{2}\right]$$

$$v = \frac{\sigma}{2E}\sqrt{\frac{ar}{2}}(1+\nu)\left[(2\kappa+1)\operatorname{sen}\frac{\theta}{2}-\operatorname{sen}\frac{3\theta}{2}\right]$$

$\kappa = 3-4\nu$ (PSS) $\kappa = \frac{3-\nu}{1+\nu}$ (PSN)

$$w = -\frac{\nu}{E}\int(\sigma_x+\sigma_y)\,dz$$

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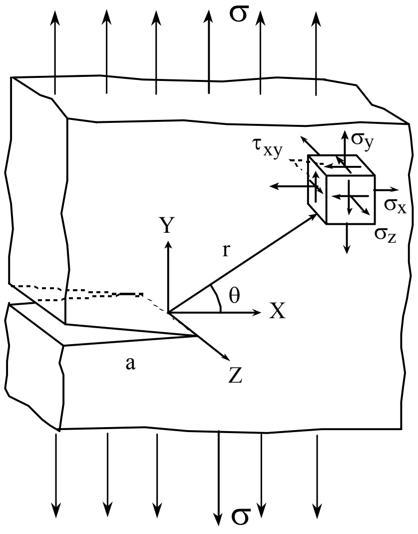
FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Stress state in a crack front. Stress Intensity Factor



$$\sigma^I_{ij} = \sigma\sqrt{\frac{a}{2r}}\, f^I_{ij}(\theta) = \sigma\sqrt{\pi a}\,\frac{1}{\sqrt{2\pi r}}\, f^I_{ij}(\theta)$$

$$\sigma^I_{ij} = \underbrace{K_I}_{\text{Stress Intensity Factor}}\,\underbrace{\frac{1}{\sqrt{2\pi r}}\, f^I_{ij}(\theta)}_{\text{Position}}$$

$$\mathbf{K_I = \sigma\sqrt{\pi a}}$$

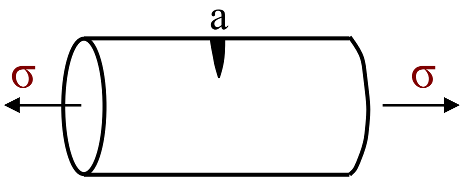
K_I defines the stress state in the crack front

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Stress state in a crack front ≡ Stress Intensity Factor

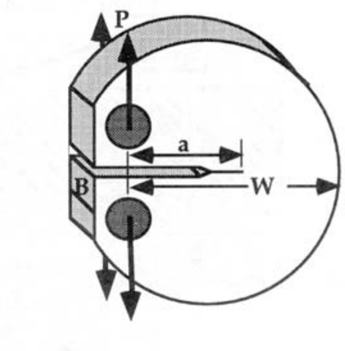
For any component
(geometry + defects)



$$K_I = f\sigma\sqrt{\pi a} \quad \text{or} \quad f\sigma\sqrt{\pi g(a)}$$

$$\downarrow$$

f: geometric factor



(b) Disk shaped compact specimen.

$$f\left(\frac{a}{W}\right) = \frac{K_I B \sqrt{W}}{P}$$

$$\downarrow$$

$$\frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}}\left[0.76+4.8\left(\frac{a}{W}\right)-11.58\left(\frac{a}{W}\right)^2+11.43\left(\frac{a}{W}\right)^3-4.08\left(\frac{a}{W}\right)^4\right]$$

For other modes
analogously ...

$$K_{II} = f_{II}\tau\sqrt{\pi g(a)}$$

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Stress fracture criterion

If $\sigma\uparrow \Rightarrow K_I \uparrow \Rightarrow \sigma_{ij}\ \text{(local)} \uparrow$

If $\sigma_{ij}\ \text{(local)} = \sigma_{ij}\ \text{(critical)}$ Local fracture criterion

$\downarrow$ $\downarrow$

$K_I = K_I^C$ Sress fracture criterion

- If fracture critical conditions (K_I^C) only depend on material

$\downarrow$

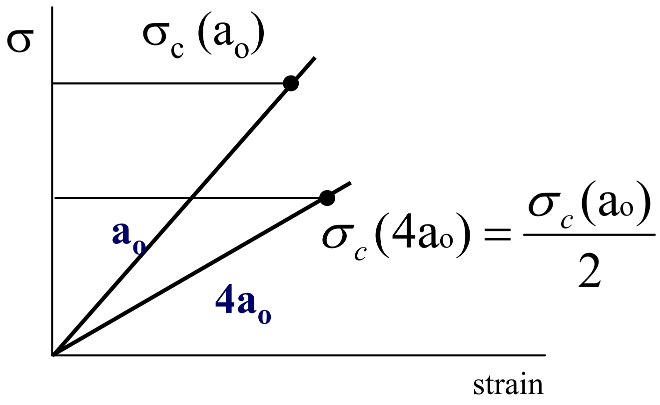
K_{Ic} (Fracture Toughness)

Stress Fracture Criterion $K_I = K_{Ic}$

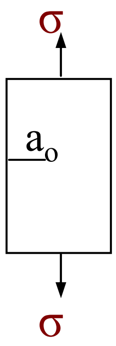
FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Stress fracture criterion



$$\sigma_c(4a_o) = \frac{\sigma_c(a_o)}{2}$$



$K_I = K_{Ic}$

↓

Fracture occurs with $\sigma_c\ (a)$

Another observation:

The compliance of the component increases with the length of the defects.

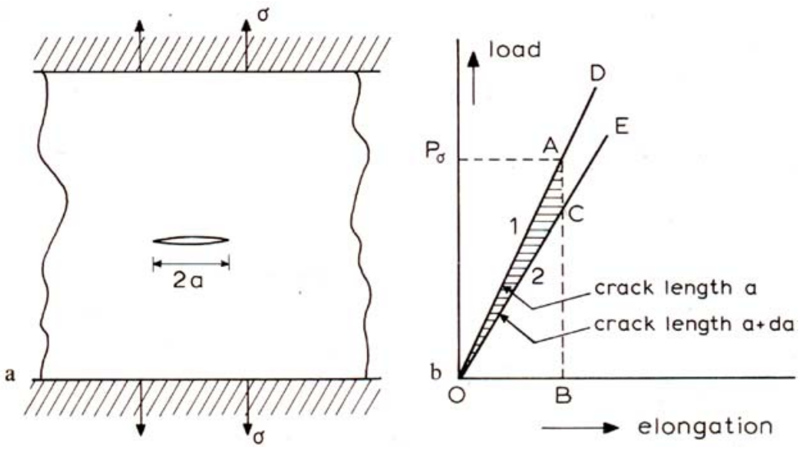
Compliance: Indicates the length of the defects.

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Energetic fracture criterion (Griffith)

Comparison between the energy that is released in crack extension and the energy that is necesary to generate new surfaces because of that extension.



$$\frac{d(U)}{da} \geq \frac{dE\gamma}{da} \longrightarrow$$ Crack grows (Fracture)

unitary thickness $$\frac{d(U)}{Bda} \geq \frac{dE\gamma}{Bda} = 2\gamma$$

γ: surface energy of the material

(Energy per unit of generated surface)

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Energetic fracture criterion (Griffith)

As a geometry function $f(\sigma, a, E) \geq 2\gamma$

Semiinfinite plate $G = \dfrac{\pi\sigma^2 a}{E} \geq G_c$

G: Energy release rate
G_c: Fracture Toughness

$\boxed{G = G_c}$ Fracture criterion

Where:

$$G = \alpha \frac{K_I^2}{\mathrm{E}} \quad \begin{cases} \alpha = 1 & \text{(Plane stress)} \\ \alpha = \left(1 - \upsilon^2\right) & \text{(Plane strain)} \end{cases}$$

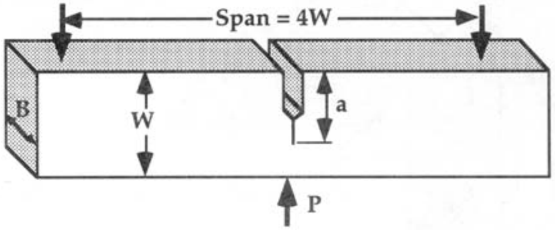
$$G_c = \begin{cases} 2\gamma \text{ in very brittle materials} \\ >> 2\gamma \text{ in materials with plasticity before fracture} \end{cases}$$

FRACTURE BEHAVIOUR

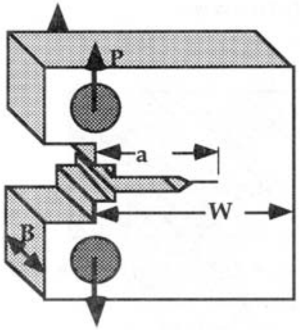
FRACTURE TOUGHNESS

Fracture Toughness Characterisation

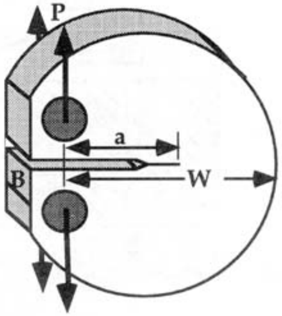
A) Standardised specimens



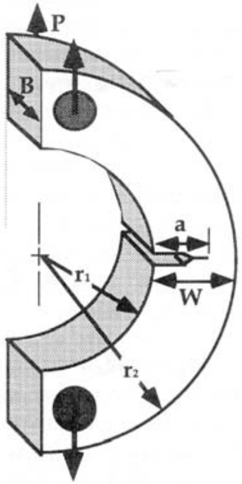
(c) Single edge notched bend (SENB) specimen.



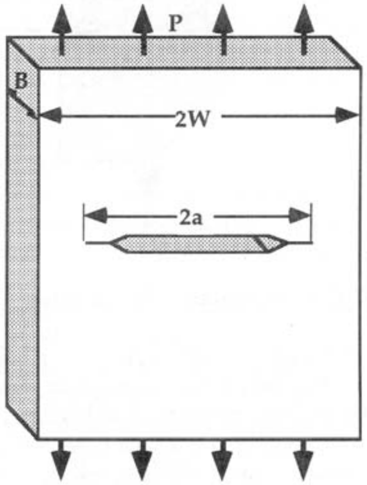
(a) Compact specimen.



(b) Disk shaped compact specimen.



(d) Arc shaped specimen



(e) Middle tension (MT) specimen.

B) Fatigue precracked specimens : a
(a as initial crack length)

FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

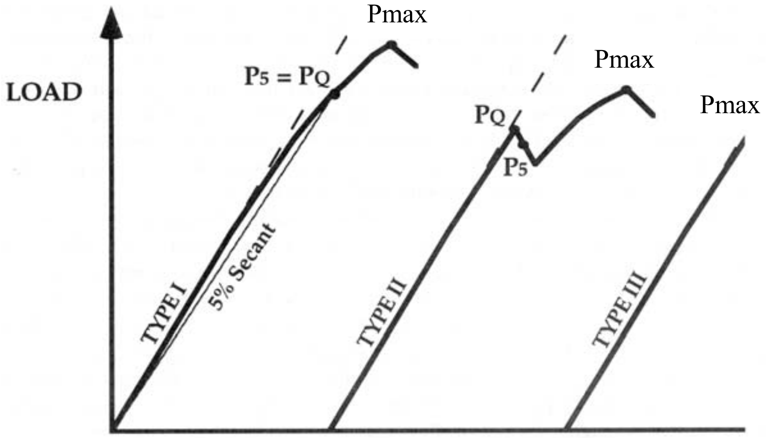
Fracture Toughness Characterisation

C) Mechanical Testing ⟶ P_Q (Load on Fracture initiation)

$$\Downarrow$$

$$K_Q = f\,(P_Q,\ a,\ \text{geometry})$$

$$K_Q = \left(\frac{P_Q}{B \cdot W^{\frac{1}{2}}} \right) \cdot f\left(\frac{a}{W} \right) \qquad \text{for CTs}$$



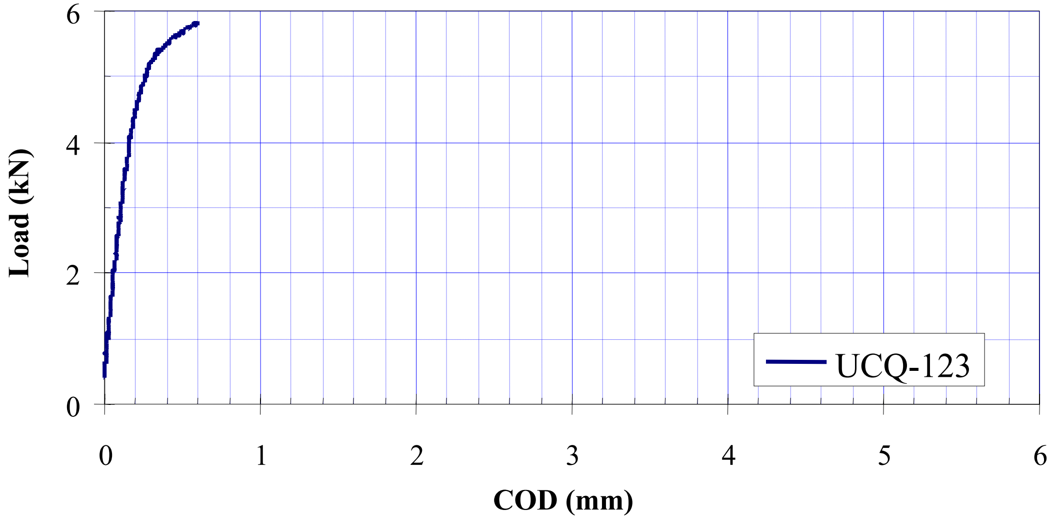
- **a** measured on fracture surface

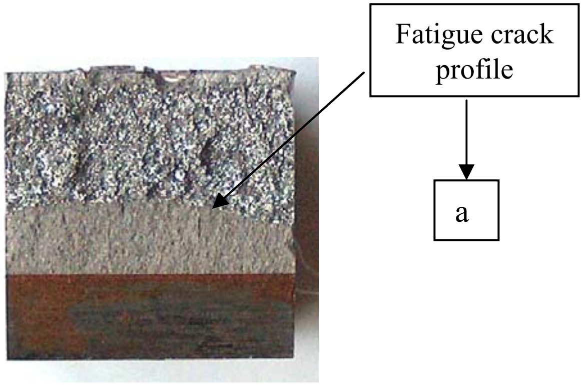
$K_Q = K_{Ic}$ (toughness), if some normalised conditions are fulfilled

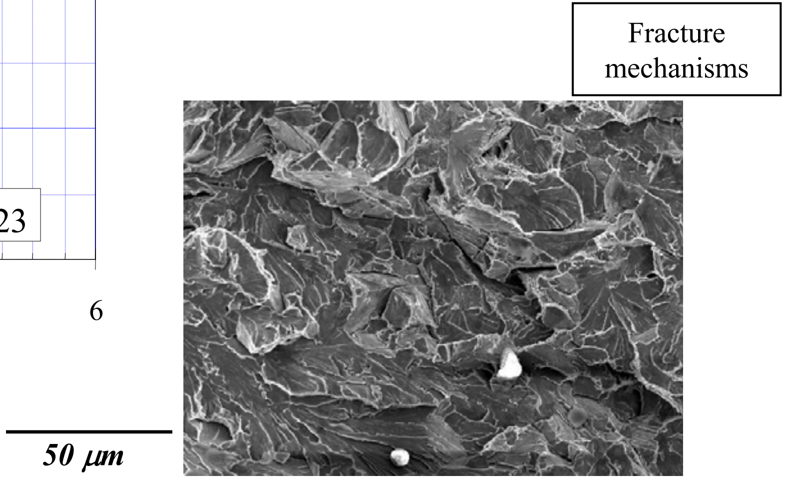
FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

Fracture Toughness Characterisation



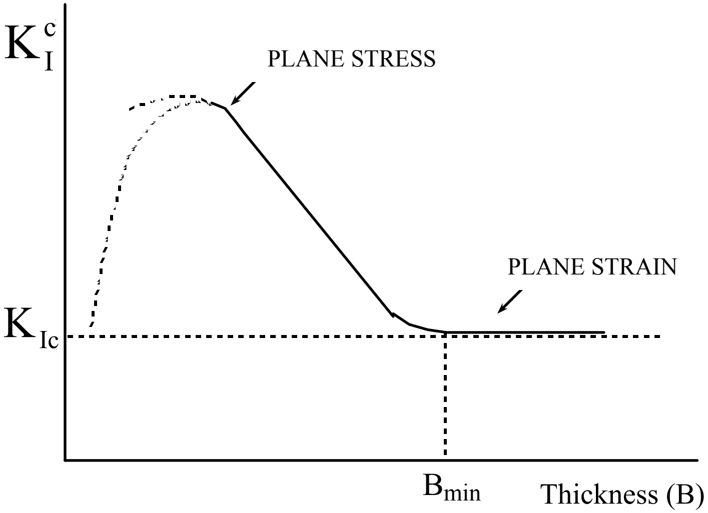




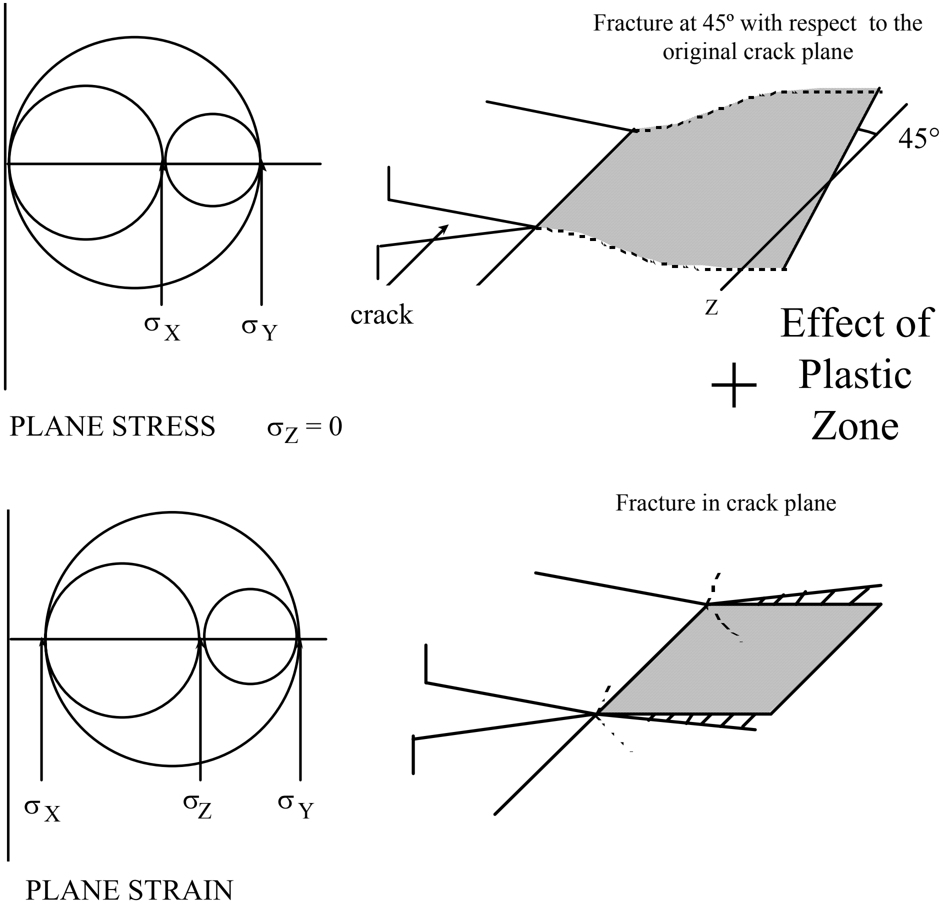
FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

Thickness effect



$$B_{min}\ (P.Strain) = 2.5\left[\frac{K_{Ic}^2}{\sigma_Y^2}\right]$$

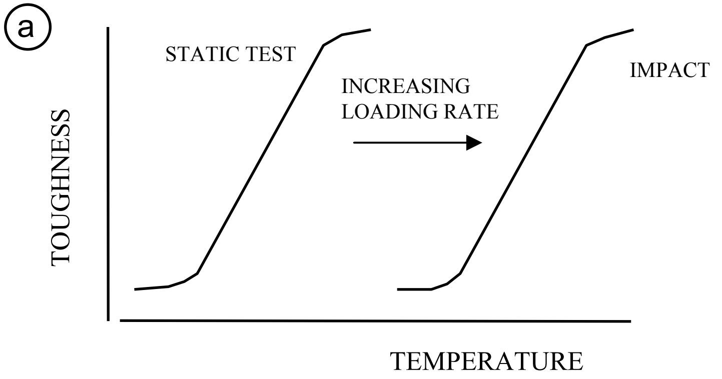


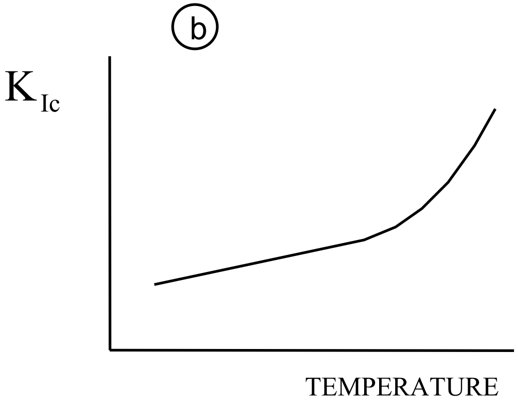
\+ Effect of Plastic Zone

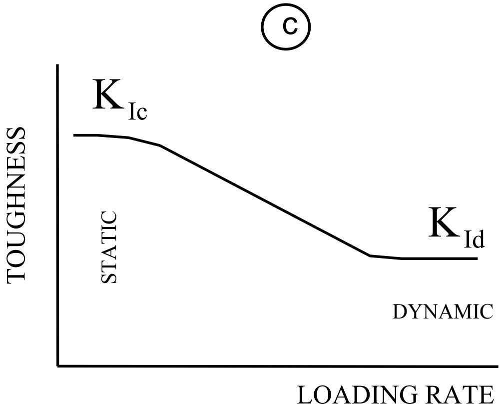
FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

Effect of temperature and loading rate





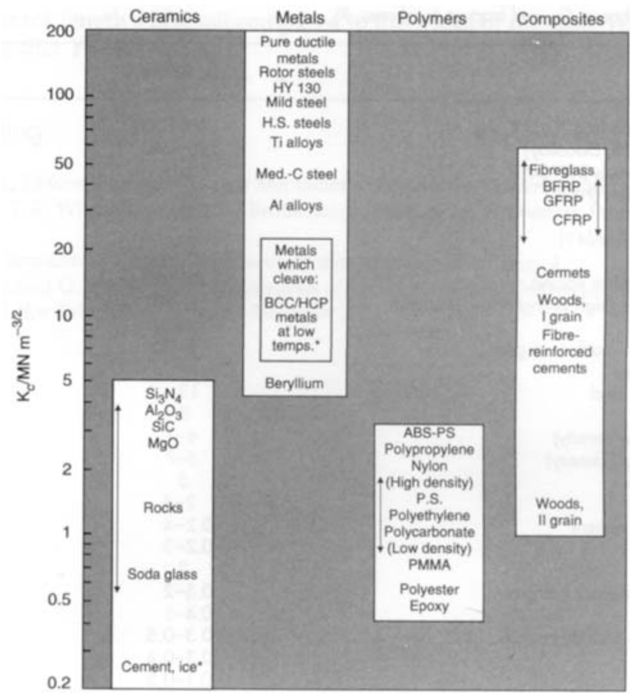


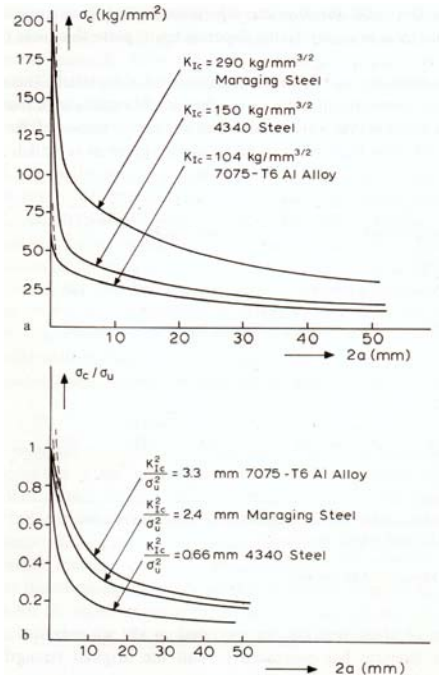
FRACTURE BEHAVIOUR

MATERIAL TOUGHNESS

Value

It depends on microstructure and external variables → Environment (temperature) (degradation) → Loading rate

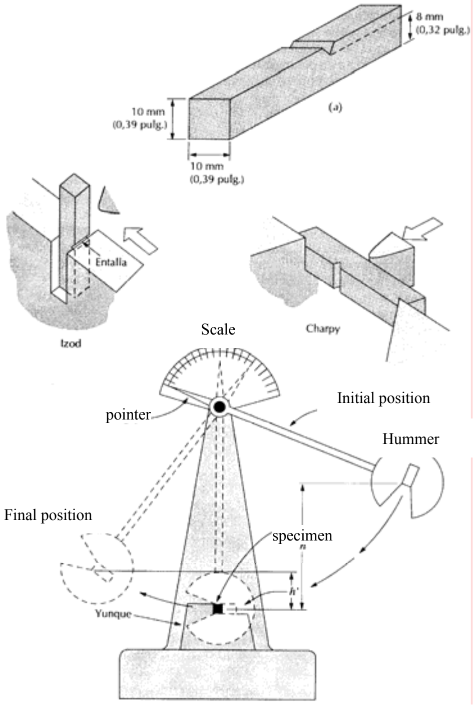


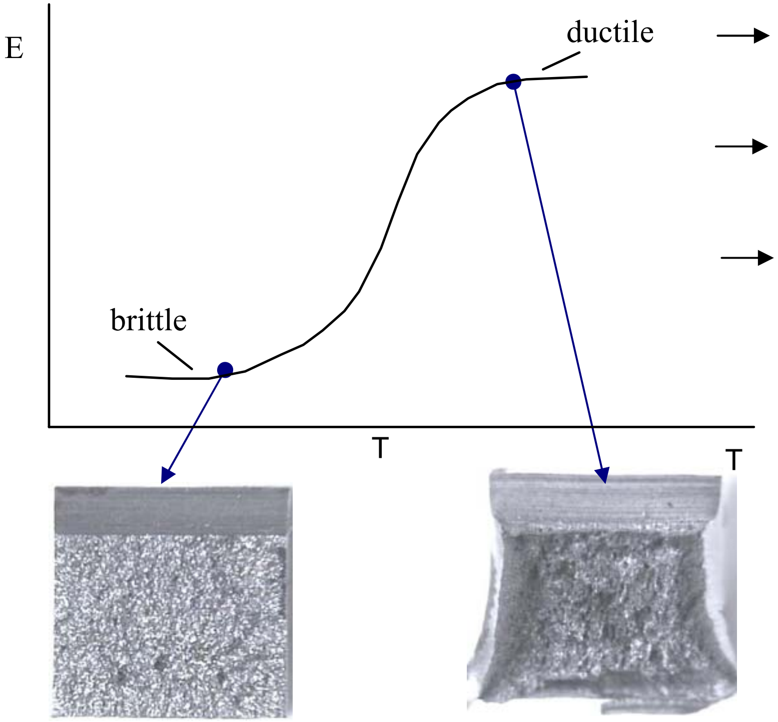


FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

Impact Toughness: Charpy Test





→ Absorbed Energy (E)

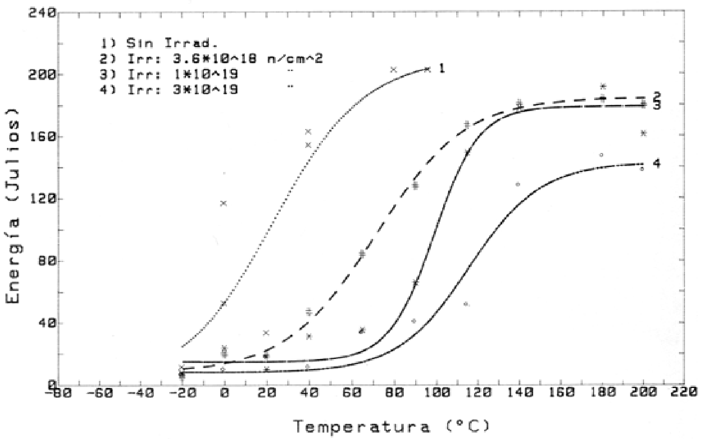
→ % Ductile fracture

→ % Lateral expansion

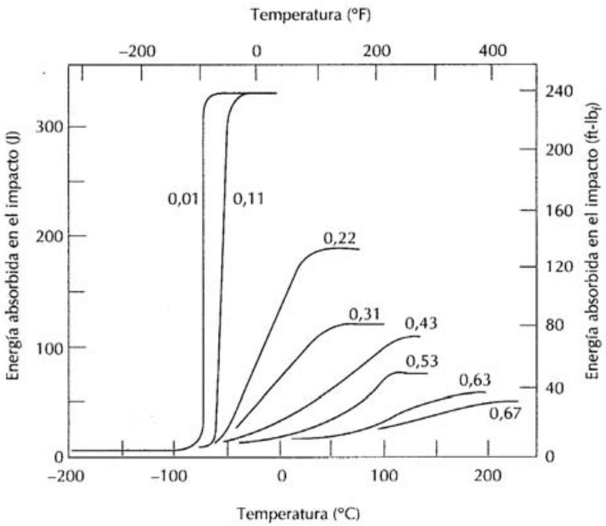
FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

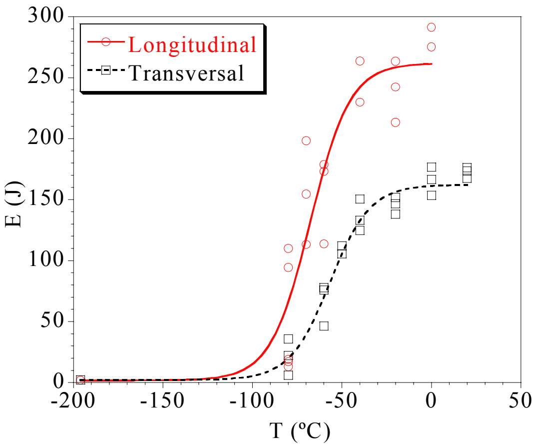
Impact Toughness: Examples of the effect of different variables



Influence of Irradiation



Influence of Carbon Content



Influence of microstructural orientation

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Plasticity in a crack front

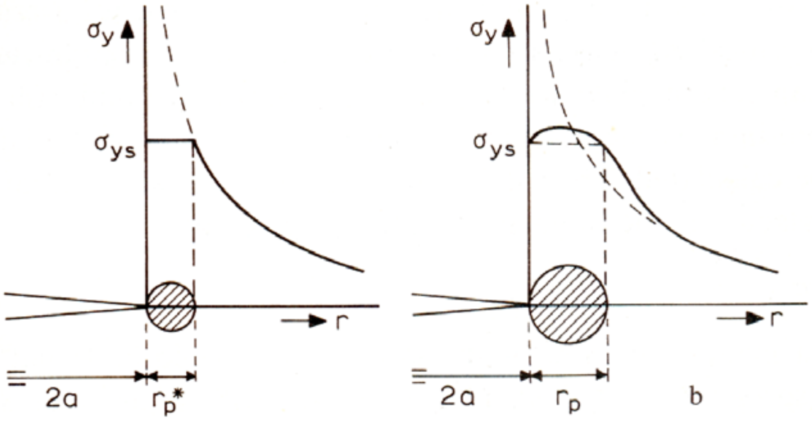
$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cdot \cos\left(\frac{\theta}{2}\right) \cdot \left[1 + sen\left(\frac{\theta}{2}\right) \cdot \cos\left(3\frac{\theta}{2}\right)\right]$$

Linear elastic solution

(LEFM)

For $\theta = 0$ (crack plane):

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}$$



1st plastic zone model

If $\sigma_y \geq \sigma_Y$ plastic zone: $\sigma_y = \sigma_Y$

$$r_Y = \frac{1}{2\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

(problem: there is no stress equilibrium)

2nd plastic zone model (Irwin correction)

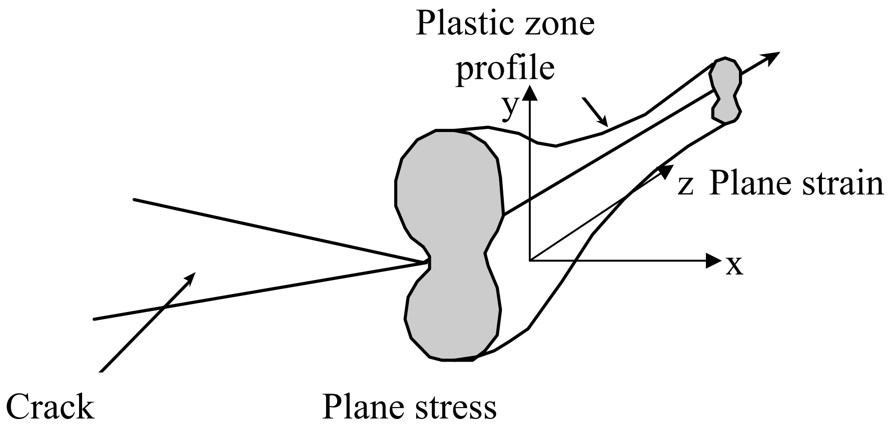
$$r_P = \frac{1}{\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

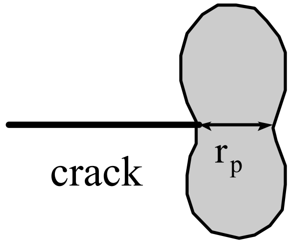
(stress redistribution)
(approximate solution)

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Plastic Zones on Plane Stress and Plane Strain





Plane Stress. Yield stress for $\sigma_y = \sigma_Y$

$$r_P = \frac{1}{\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

Plane Strain. Yield stress for $\sigma_y \cong 3\sigma_Y$

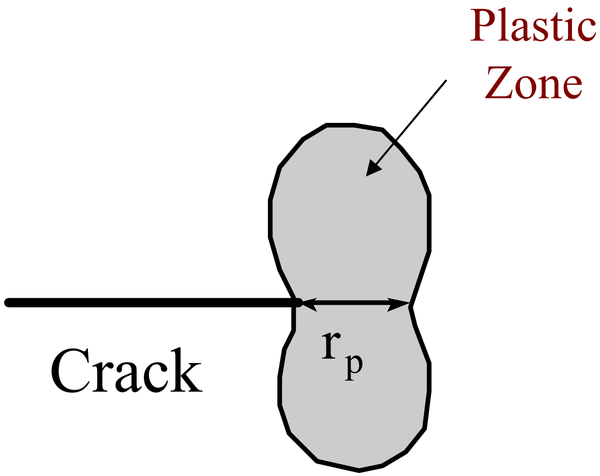
$$r_P = \frac{1}{9\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Corrections on Linear Elastic Fracture Mechanics (LEFM)

If the plastic zone is small and it is constrained:



r_P << a, defect
r_P << B, thickness
r_P << (W-a), residual ligament

$$K_I = K_I(a_{ef}) = K_I(a + \Delta a_P)$$

Effective defect = Real defect + Δa_P

Δa_P: plastic correction to crack length

$$\Delta a_P = f(r_P) = \frac{1}{n\pi}\cdot\frac{K_I^2}{\sigma_Y^2}$$

→ n = 6 Plane Strain
→ n = 2 Plane Stress

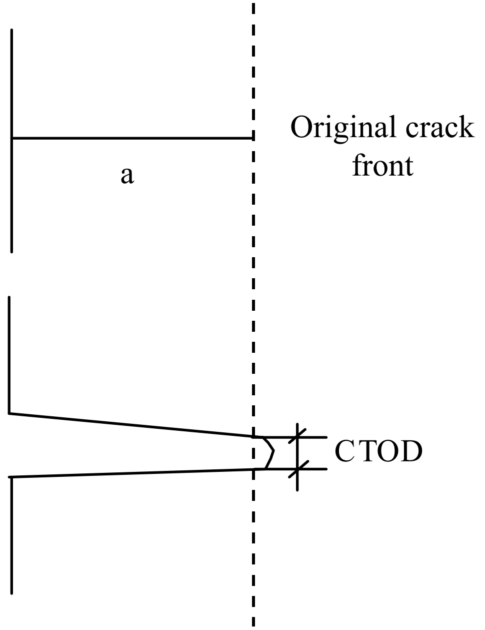
An iterative calculation is required to obtain K_I

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)

If plastic zone has important dimensions:



Parameters and fracture criteria change because of local condition changes

- Physical parameters and criteria

$CTOD = CTOD_c$

- Energetic parameters and criteria

J-Integral

$J = J_{Ic}$

(equivalent to G in linear elastic conditions)

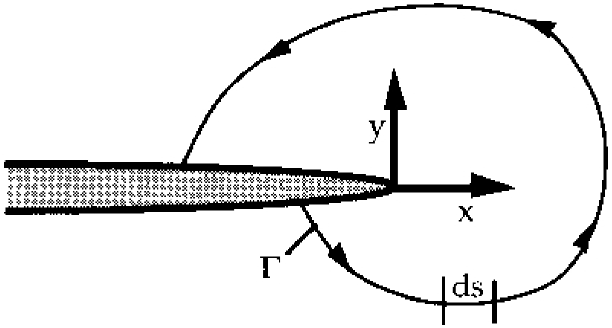
FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)

The non linear energy release rate , J, can be written as a path-independent line integral. Considering an arbitrary counter-clockwise path (Γ) arround the tip of the crack, the J integral is given by:

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$



Arbitrary contour around the tip of the crack

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)

J can also be seen as a Stress Intensity Parameter for Elastic-Plastic problems as long as the variation of stress and strain ahead of the crack tip can be expressed as:

$$\sigma_{ij} = k_1 \left(\frac{J}{r} \right)^{\frac{1}{n+1}}$$

$$\varepsilon_{ij} = k_2 \left(\frac{J}{r} \right)^{\frac{n}{n+1}}$$

Where k_1 and k_2 are proportionally constants and n is the strain hardening component.

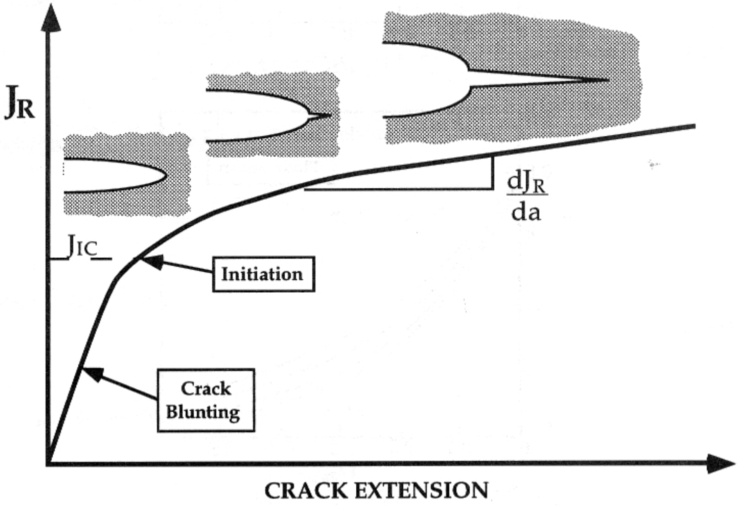
FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)

Many materials with high toughness do not fail catastrophically at a particular value of J or CTOD. In contrast, these materials exhibit a rising R curve, where J and CTOD increase with crack growth.

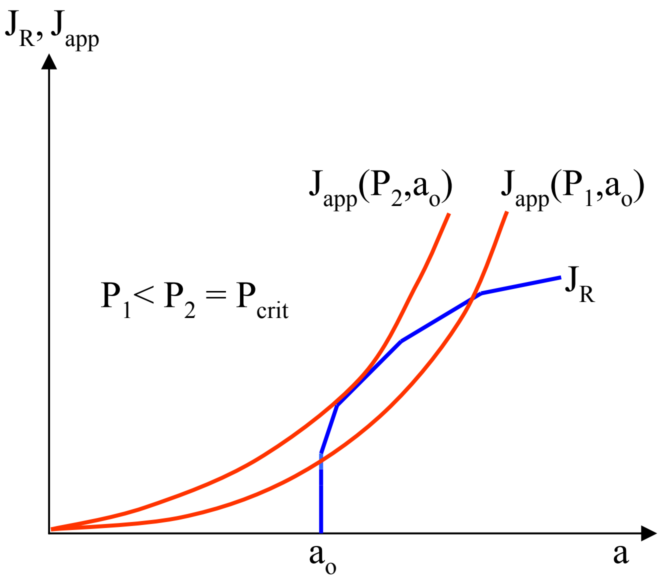
The figure illustrates a typical J resistance curve for a ductile material.



FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)



CRACK DRIVING FORCE DIAGRAM

Local conditions in the component

$J_{app}(P,a) = J_e(P,a) + J_p(P,a)$

Characterises the local state

Critical conditions in the material

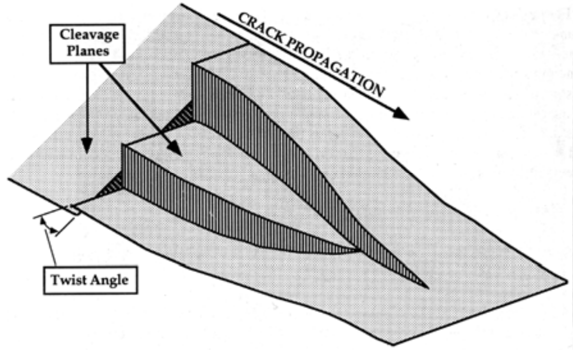
$J_R(\Delta a)$

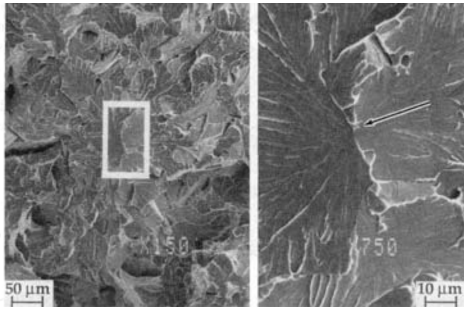
Characterises the strength of the material to cracking

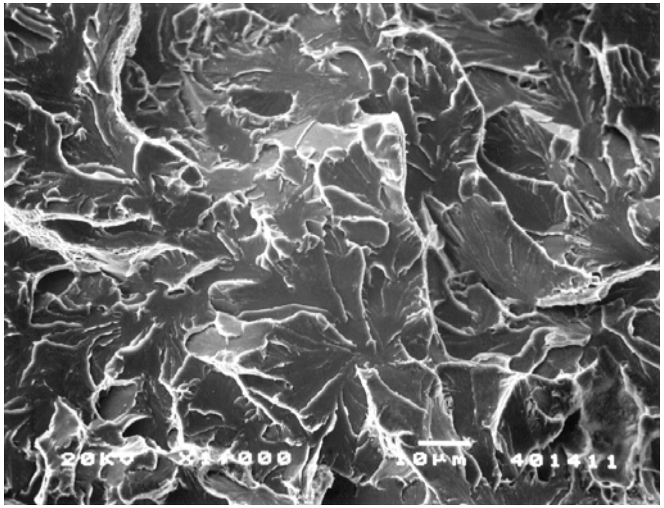
FRACTURE BEHAVIOUR

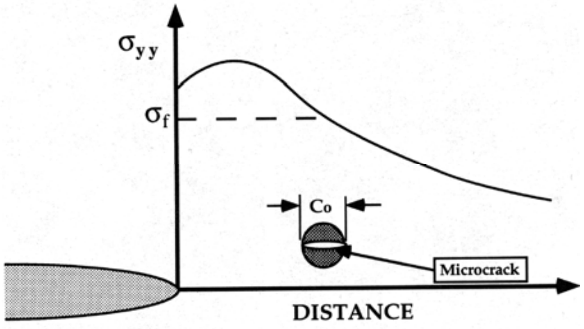
FRACTURE MICROMECHANISMS

Brittle Fracture: Cleavage









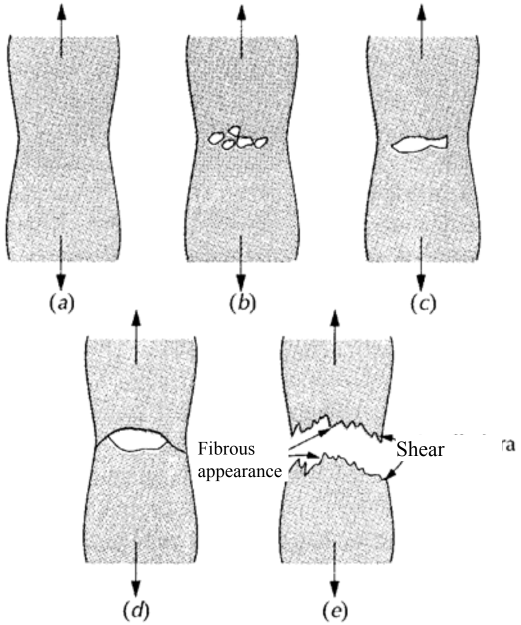
It occurs on metallic material with brittle behaviour

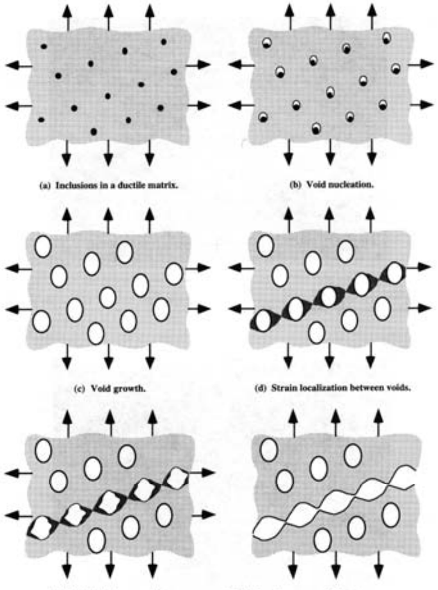
- favoured by low temperatures and high loading rates
- favoured in materials with high σ_Y

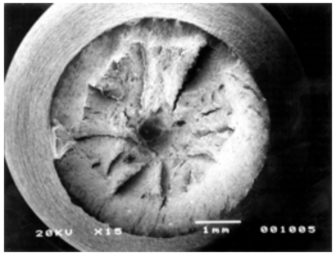
FRACTURE BEHAVIOUR

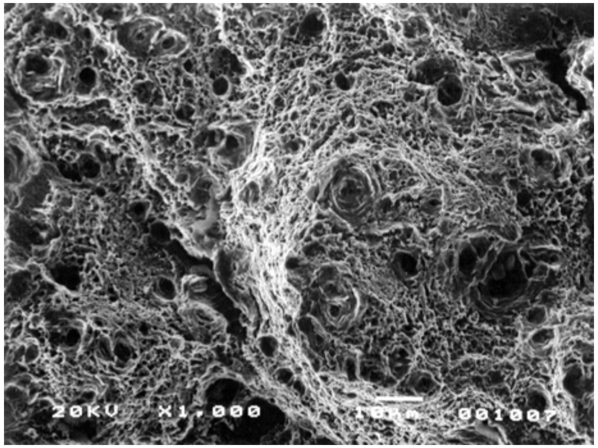
FRACTURE MICROMECHANISMS

Ductile Fracture: Void nucleation and coalescence




(a) Inclusions in a ductile matrix.
(b) Void nucleation.
(c) Void growth.
(d) Strain localization between voids.
(e) Necking between voids.
(f) Void coalescence and fracture.





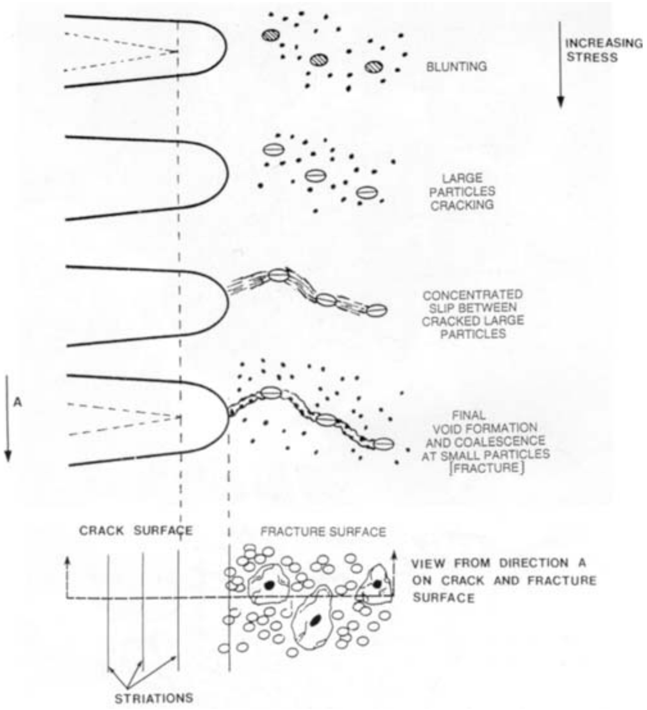
Metallic materials with plastic behaviour

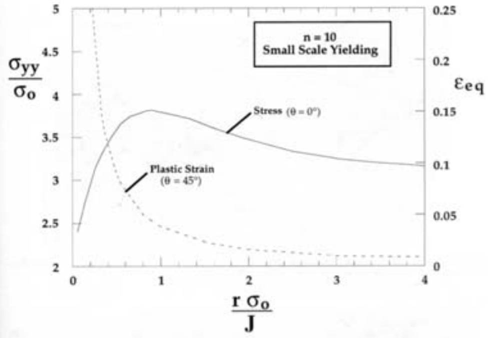
- favored by T ↑, σ_Y ↓, $\dot{\sigma}$ ↓

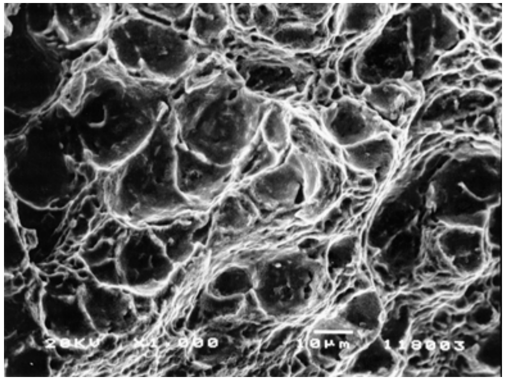
FRACTURE BEHAVIOUR

FRACTURE MICROMECHANISMS

Ductile Fracture: Void nucleation and coalescence



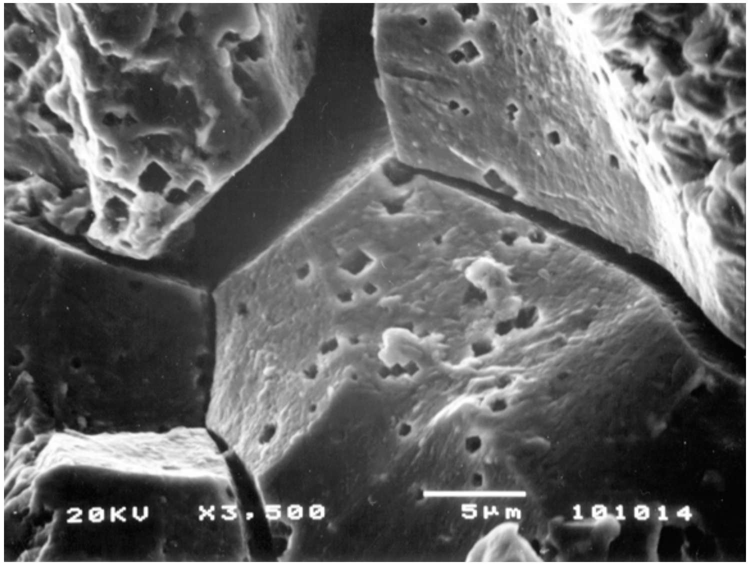




FRACTURE BEHAVIOUR

FRACTURE MICROMECHANISMS

Intergranular fractures



→ Because of the environment or grain boundary segragations

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B. INTRODUCTION TO ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

INTRODUCTION

HOW ARE INTEGRITY, SECURITY OR CRITICAL CONDITIONS ANALYSED IN A CRACKED STRUCTURE?

FRACTURE MECHANICS

Critical conditions

Local conditions in the component ≥ Critical conditions in the material

LEFM:

$K_I \geq K_{IC}$

LEFM with local plastic correction:

$K_I (a+r_y) \geq K_{IC}$

EPFM:

$J_I(a) \geq J_R(a)$

$\partial J_I(a)/\partial a \geq \partial J_R(a)/\partial a$

PLASTICITY

Critical conditions

Plastic collapse of the component

Plastification of the residual ligament

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

INTRODUCTION

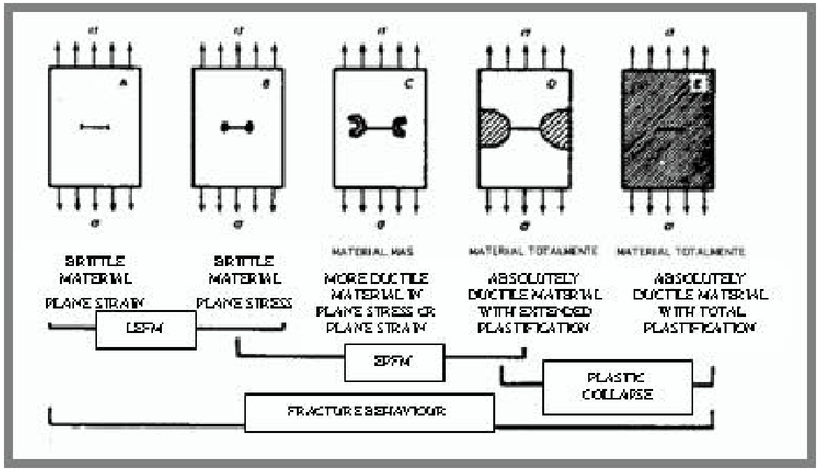
HOW ARE INTEGRITY, SECURITY OR CRITICAL CONDITIONS ANALYSED IN A CRACKED STRUCTURE?

In brittle materials or when conditions produce brittle behaviour:

LEFM

In other cases, when plasticity is present (with different extension):

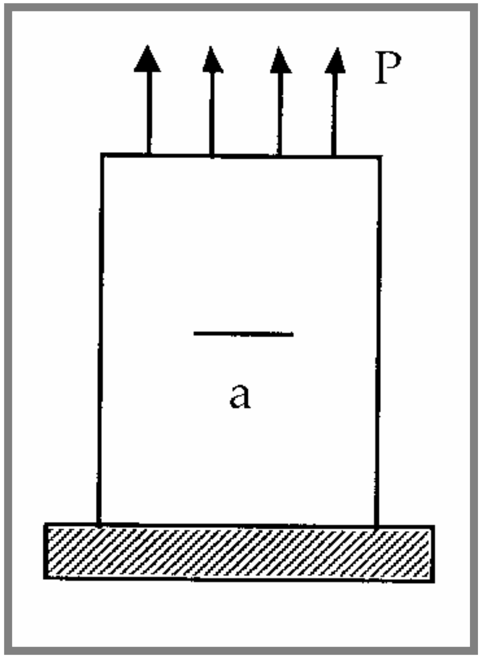
EPFM - PLASTICITY



ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

APPLICATION OF ELASTIC-PLASTIC CRITERIA COVERING LIMITED PLASTICITY CONDITIONS



Local conditions in the component

$J_{app}(P,a) = J_e(P,a) + J_p(P,a)$

Characterises the local state

Critical conditions in the material

$J_R(\Delta a)$

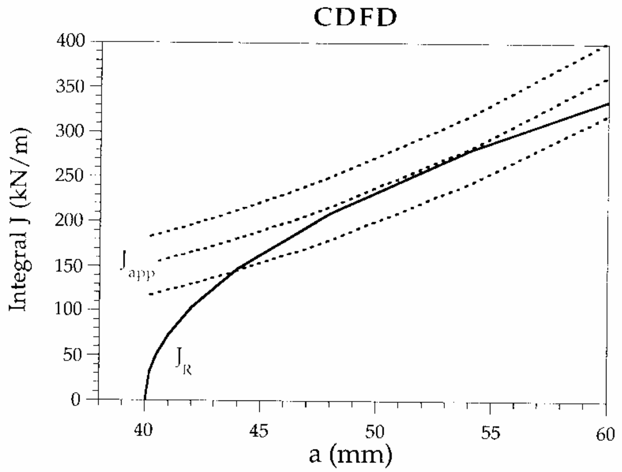
Characterises the strength of the material to cracking

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

APPLICATION OF ELASTIC-PLASTIC CRITERIONS WHICH COVERS LIMITED PLASTICITY CONDITIONS

Produces the Crack Driving Force Diagrams (CDFD)



CDFD have limitations:

-They do not take into account plastic collapse

- They need succcessive application:

LEFM + Plasticity

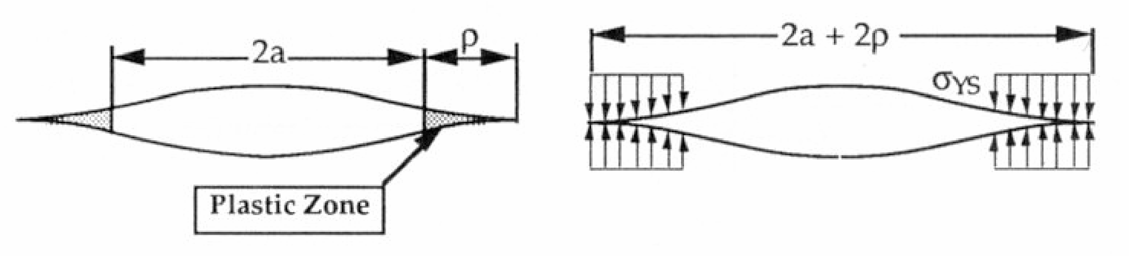
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

It starts with a solution for the effective stress intensity factor that considers the effect of the local yielding in the crack front.

Dugdale and Barenblatt proposed a model for limited plasticity (strip yield model). They supposed that a crack with a length of 2a and plastic zones of length ρ ahead the real crack tips, works as if its length was 2a+2ρ, being the crack tips, ρ, under a stress being equal to the yield stress.



ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

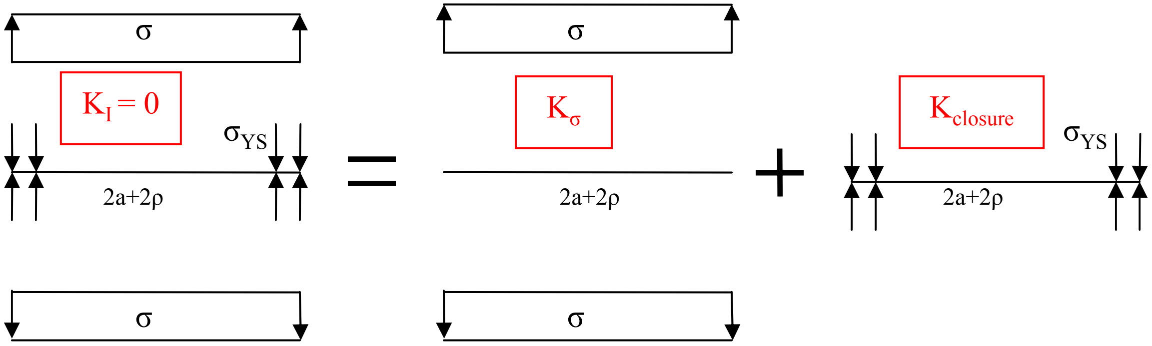
HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

The model is applied to a through thickness crack in an infinite plate and approaches the elastic-plastic behaviour superimposing two elastic solutions:

- a through thickness crack under remote tension

- a through thickness crack with closure stresses at the tip

The solution appears applying the Principle or Superposition



ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

Stresses are finite in the strip yield zone, so there cannot be a singularity at the crack tip. Therefore, the leading term in the crack tip field that varies with $1/r^{1/2}$ must be zero.

The plastic zone length, ρ, must be chosen such that the stress intensity factors from the remote tension and closure stress cancel one another.

$$K_I = K_\sigma + K_{closure} = 0$$

After some operations, the following can be obtained:

$$K_{closure} = -2 \cdot \sigma_{YS} \cdot [(a+\rho) / \pi]^{1/2} \cdot \cos^{-1}(a/(a+\rho))$$

$$K_\sigma = \sigma \cdot (\pi \cdot (a+ \rho))^{1/2}$$

From which we can obtain: $\rho = \pi^2 \cdot \sigma^2 \cdot a / 8 \cdot \sigma_{YS}^2 = \pi/8 \cdot (K_I/\sigma_{YS})^2$

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

Finally, we can obtain the effective stress intensity factor, K_I^{eff}, considering an effective crack length ($a_{eff} = a + \rho$) in the LEFM expression for K_I ($K_I^{eff} = \sigma \cdot (\pi \cdot a_{eff})^{1/2}$):

$$K_I^{eff} = \sigma \cdot (\pi \cdot a \cdot \sec(\pi \cdot \sigma / 2 \cdot \sigma_{YS}))^{1/2}$$

This equation tends to overestimate K_{eff}.

The actual a_{eff} is somewhat less than $a + \rho$ because the strip yield zone is rally loaded to σ_{ys}.

Buderkin and Stone obtained a more realistic estimate of K_{eff} for the strip yield model:

$$K_{1/2\,I}^{eff} = \sigma_{YS} \cdot (\pi \cdot a)^{1/2} \cdot [\ 8/\pi^2 \cdot \ln \sec(\pi \cdot \sigma / 2 \cdot \sigma_{YS})]$$

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

- **Relative stress intensity factors (with respect to the effective value) are taken:**

$$K_I / K_I^{eff} = [\sigma\cdot(\pi\cdot a)^{1/2} / \sigma_{YS}\cdot(\pi\cdot a)^{1/2}]\cdot[\,8/\pi^2\cdot \ln\sec(\pi\cdot\sigma / 2\cdot\sigma_{YS})]^{-1/2} = K_r^*$$

- **And taking (σ/σ_{YS}) = Lr as the value of the relative stress with respect to the one that causes plastic collapse, the result is:**

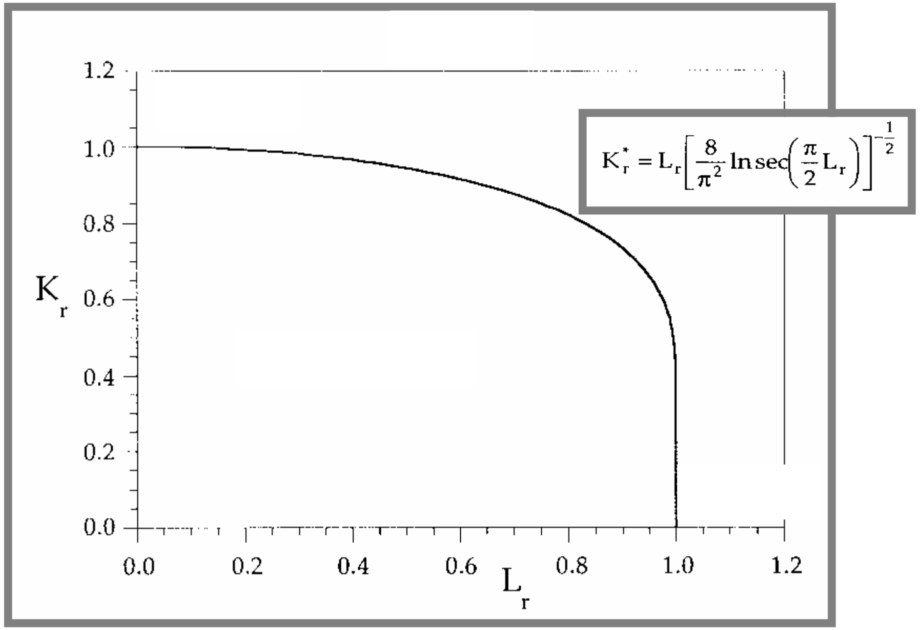
$$\boxed{K_r^* = L_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}L_r\right)\right]^{-\frac{1}{2}}}$$

- **This is the equation of a K_r^{line} in the space Lr, Kr* and eliminates the square root term that contains the half length of the through crack. Therefore, the geometry dependence of the strip yield model is removed.**

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?



$$K_r^* = L_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}L_r\right)\right]^{-\frac{1}{2}}$$

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

In the Lr, Kr space, and with those variables, critical conditions are established:

1. Fracture: $K_{ef} = K^{c}_{mat}$

or: $K_I/K_{ef} = K_I/K^{c}_{mat}$

The critical condition in a structure is defined by the K_r^{line}

$$Kr{,}structure = K_I/K^{c}_{mat} \leq K_I/K_{ef} = K_r^{line}$$

2. Plasticity: $\sigma = \sigma_c$

$$Kr{,}structure = K_I/K^{c}_{mat} > 0$$

$$Lr{,}\ structure = 1$$

$$K_r^{line}\ (Lr = 1) \longrightarrow 0$$

So, the Failure Assessment Diagram (FAD) is defined.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

SOLUTIONS

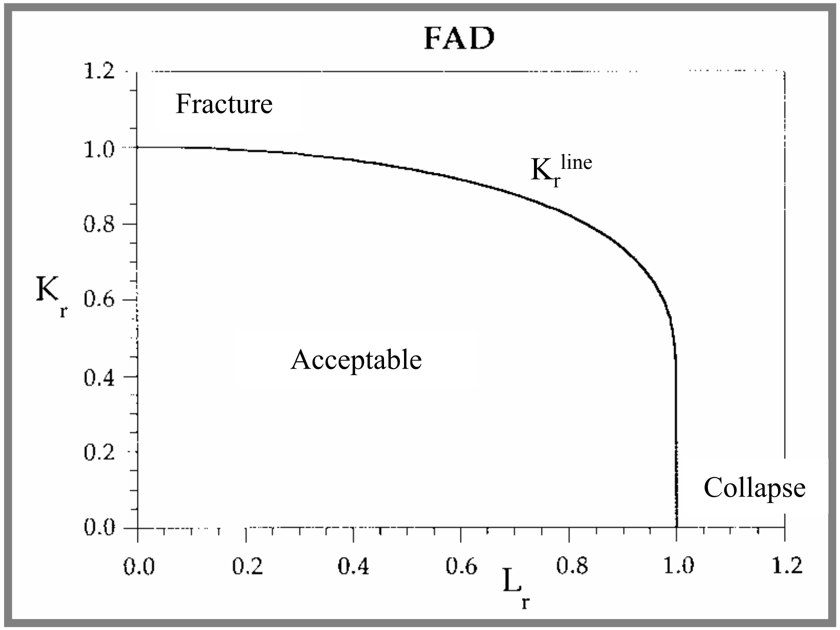
HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

The FAD is plotted in the space Kr, Lr.

The axes (Lr and Kr) and the line K_r^{line} (Lr) define the zone where the structure is safe and the zone where critical conditions are reached (the reasons can be brittle fracture, fracture with some plasticity or plastic collapse).

As a more general representation that encloses EPFM variables (which includes LEFM):

$$K_r^{line} = \frac{K_I}{K_{ef}} = \frac{(J_e E)^{\frac{1}{2}}}{(JE)^{\frac{1}{2}}} = \left(\frac{J_e}{J_e + J_p}\right)^{\frac{1}{2}} = \left(J_r^*\right)^{\frac{1}{2}}$$



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ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

DESCRIPTION

WHAT IS A STRUCTURAL INTEGRITY ASSESSMENT PROCEDURE?

It is a set of techniques which are used to demonstrate the fitness for service of structural components to transmit loads. They are applicable to:

- Design of new structures in order to guarantee their integrity during their life.

- Assess the integrity of in-service structures in control and supervision plans.

Therefore, these procedures provide considerable economic advantages because they optimise the design process and inspection and reparation conditions during the in-service period.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

DESCRIPTION

HOW MANY PROCEDURES EXIST?

WHICH ONE MUST WE USE?

- Based on FAD
  - R6
  - PD6493
  - ……
- Based on CDFD
  - GE-EPRI
  - ETM

Compatible: SINTAP

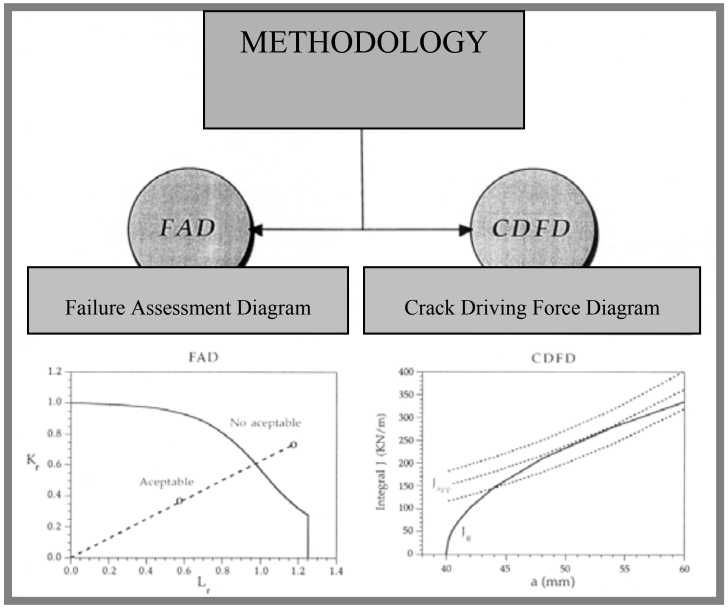
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

CLASSIFICATION ACCORDING TO THE METHODOLOGY USED

PROCEDURES ARE MAINLY GROUPED DEPENDING ON THE METHODOLOGY USED : FAD OR CDFD

- **<u>Simultaneous</u> assessment**
  - **Fracture**
  - **Plastic collapse**
- **Diagram**

  It <u>does not</u> compare <u>applied vs. resistant</u>
- **<u>Difficulties</u> to understand it physically**
- **<u>Easy</u> evaluation**



- **<u>Independent</u> assessment**
  - **Fracture**
  - **Plastic collapse**
- **Diagram**

  It compares <u>applied vs. resistant</u>
- **<u>Easy</u> to understand it physically**
- **<u>More complex</u> evaluation**

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ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

CONTENT

Procedures must define:

- **Methodological aspects**
  - General aspects
  - Material limitations
  - Methodology for structural analysis
  - Critical conditions
  - Fracture mechanics variables
  - Security factors and Risk assessment
- **Cases to which they can be applied**
  - Fracture mode
  - Joints

Also, in relation to the structure:

- **Definition of loading conditions**
  - Stresses
  - Library of solutions
  - Deliberations about the stress field
- **Definition of the material resistant properties**
  - Mechanical properties
  - Fracture toughness
- **Definition of the crack state**
  - Crack characteristics
  - Defect evolution and redefinition

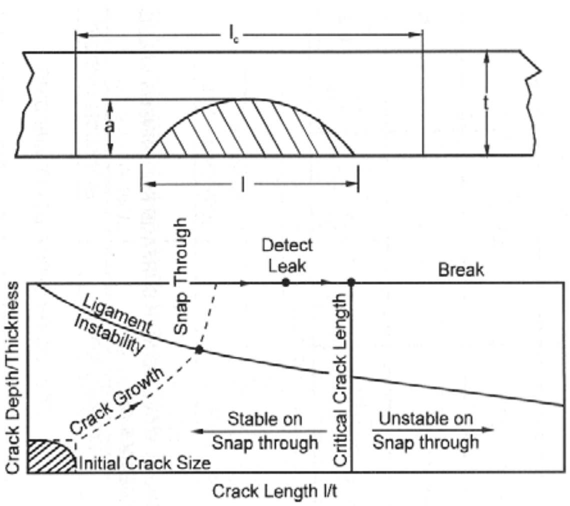
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ALTERNATIVE APPROACHES: LEAK-BEFORE-BREAK

LEAK-BEFORE-BREAK CONCEPT:

There are several options by which it may be possible to demonstrate the safety of a structure containing flaws when an initial analysis has failed to show that adequate margins exist.

For pressurised components one of these options is to make a leak-before-break case by demonstrating that a flaw will grow in such a way as to cause, in the first instance, a stable detectable leak of the pressure boundary rather than a sudden, disruptive break.



THE LEAK-BEFORE-BREAK DIAGRAM

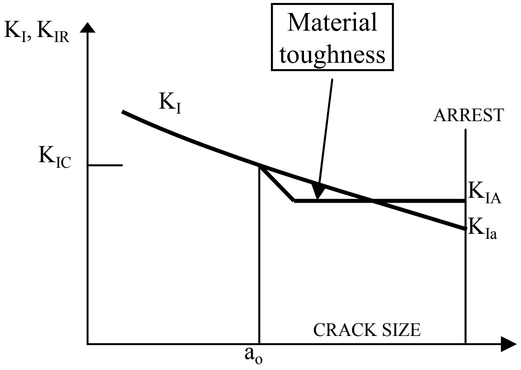
ℓ_c IS THE CRITICAL LENGTH OF A FULLY-PENETRATING THROUGH-WALL CRACK

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ALTERNATIVE APPROACHES: CRACK ARREST

CRACK ARREST CONCEPT:

When the energy available for an incremental extension of a propagating crack falls below the material resistance, the crack arrests



Crack arrest with a falling driving force curve. The apparent arrest toughness, Kia, is slighty below the true material resistance, K_{IA}, due to excess kinetic energy.

CRACK ARREST CONDITIONS (separately or in combination):

1) the crack front enters a region of increased toughness
2) the stress intensity factor reduces as a result of propagation

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ALTERNATIVE FRACTURE TOUGHNESS ESTIMATION: MASTER CURVE

- **LOW TEMPERATURES** → Cleavage failure (brittle failure)

  Low Fracture Toughness and low scattering

  Many triggering particles

- **TRANSITION REGION** → Fracture toughness increases rapidly with temperature

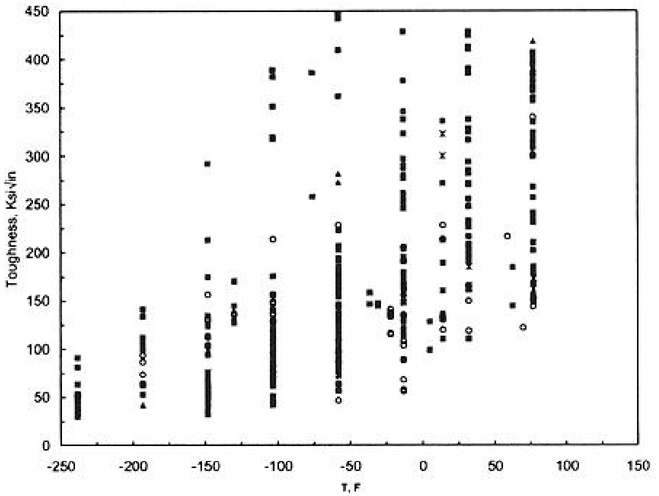
  Great scattering

  Few triggering particles

- **HIGH TEMPERATURES** → Ductile failure

  High Fracture Toughness and low scattering

  Microvoids



TRANSITION REGION

(ferritic steels)

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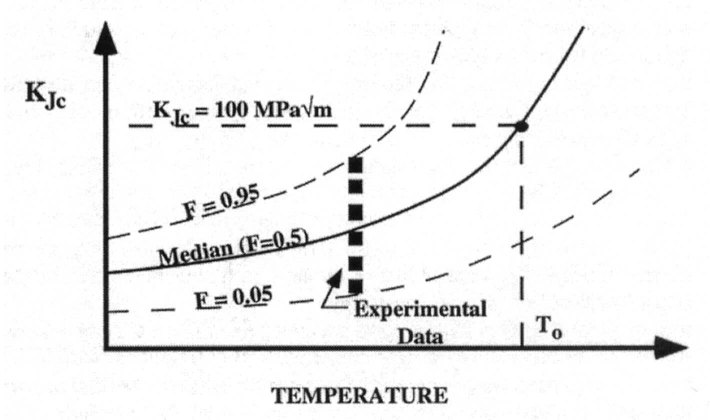
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ALTERNATIVE FRACTURE TOUGHNESS ESTIMATION: MASTER CURVE

The Master Curve hypothesis suggests that the distribution of toughness follows a 3 parameter Weibull distribution, where two of them are fixed a priori. Moreover, the mean fracture thoughness versus temperature (K_{JC}:T) curve will have the same shape for all ferritic steels. The only difference between steels is the position of the curve on the temperature axis.



$$K_{JC} = 30 + 70\, e^{(0.019(T-To))}$$

T_o = Reference Temperature

$$[K_{JC}(T_0) = 100\ \text{MPa}\cdot\text{m}^{1/2}]$$

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

ALTERNATIVE FRACTURE TOUGHNESS ESTIMATION: MASTER CURVE

The “Master Curve Approach” is based on correlation between a specific Charpy transition temperature (T_{27J}) and the Reference Temperature (T_o)

T_{27J} = 27J Charpy Transition Temperature (ºC)

T_0 correlates with T_{27J}

$$K_{mat} = 20 + \{11 + 77\, e^{(0{,}019(T - T_{27J} - 3^\circ C))}\}$$

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C. PROCEDURE APPLICATION (FITNET)

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

- **INTRODUCTION**
- **INPUTS**
- **ANALYSIS – FAD AND CDF ROUTES**
- **ANALYSIS OPTIONS**
- **GUIDANCE ON OPTION SELECTION**
- **SPECIAL OPTIONS**

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

INTRODUCTION:

The FITNET Fracture Module is based on fracture mechanics principles and is applicable to the assessment of metallic structures (with or without welds) containing actual or postulated flaws.

The purpose of the analysis in this Module is to determine the significance, in terms of fracture and plastic collapse, of flaws postulated or present in metallic structures and components.

The procedure is based on the principle that failure is deemed to occur when the applied driving force acting to extend a crack (the crack driving force) exceeds the material's ability to resist the extension of that crack. This material 'property' is called the material's fracture toughness or fracture resistance.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

The procedure can be applied during the design, fabrication or quality control as well as operational stages of the lifetime of a structure. Certainly, the procedure is also applicable for the Failure Analysis cases of the failed components.

a) FITNET at Design Phase

The method can be used for assessing hypothetical planar discontinuities at the design phase in order to specify the material properties needed, maximum applicable design stresses, inspection procedures, acceptance criteria and inspection intervals.

b) FITNET at Fabrication and Quality Control Phase

The method can be used for fitness-for-purpose assessment during the fabrication phase. However, this procedure shall not be used to justify shoddy workmanship and any flaws occurring should be considered on a case by case basis with respect to fabrication standards.

If non-conforming discontinuities are detected, which cannot be shown to be acceptable to the present procedure, the normal response shall be:

(i) correcting the fault in the fabrication process causing the discontinuities and (ii) repairing or replacing the faulty product.

c) Operational or In-Service Phase

The method can be used to decide whether continued use of a structure or component is possible and safe despite detected discontinuities or modified operational conditions.

If during in-service inspection discontinuities are found which have been induced by load fluctuations and/or environmental effects, these effects must be considered using suitable methods which may not be described in the present section (See sections 7, 8 and 9 in FITNET procedure).

The current procedure may be used to show that it is safe to continue operation until a repair can be carried out in a controlled manner. Further applications of the method described are the provision of a rationale for modifying potentially harmful practices and the justification of prolonged service life (life extension).

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

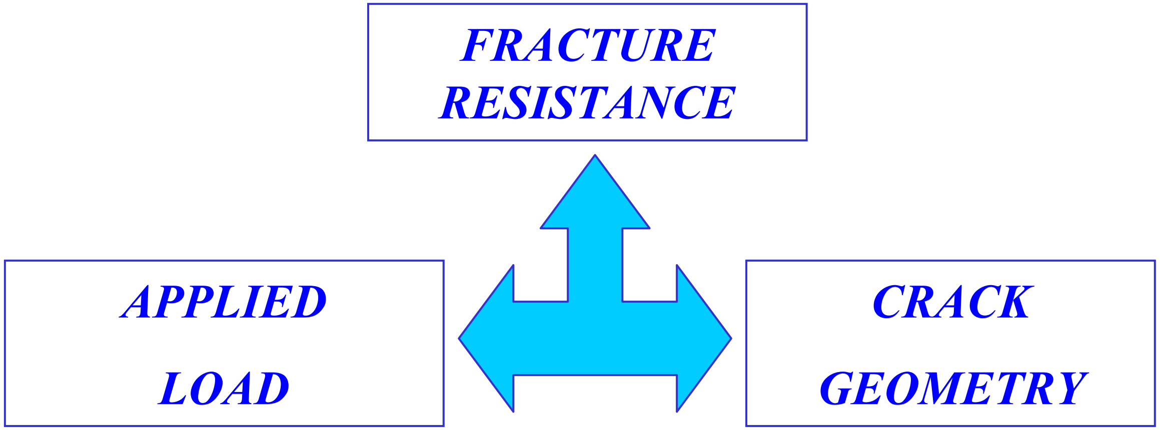
In order to cover previous described cases, the fracture analysis of the component containing a crack or crack-like flaw is expected to be controlled by the following three parameters:

1) the fracture resistance of the material,

2) the component and crack geometry, and

3) the applied load including secondary loads such as residual stresses.

If, as is usually the case, two of these parameters are known the third can be determined by using the relationships of fracture mechanics.



FRACTURE RESISTANCE

APPLIED LOAD

CRACK GEOMETRY

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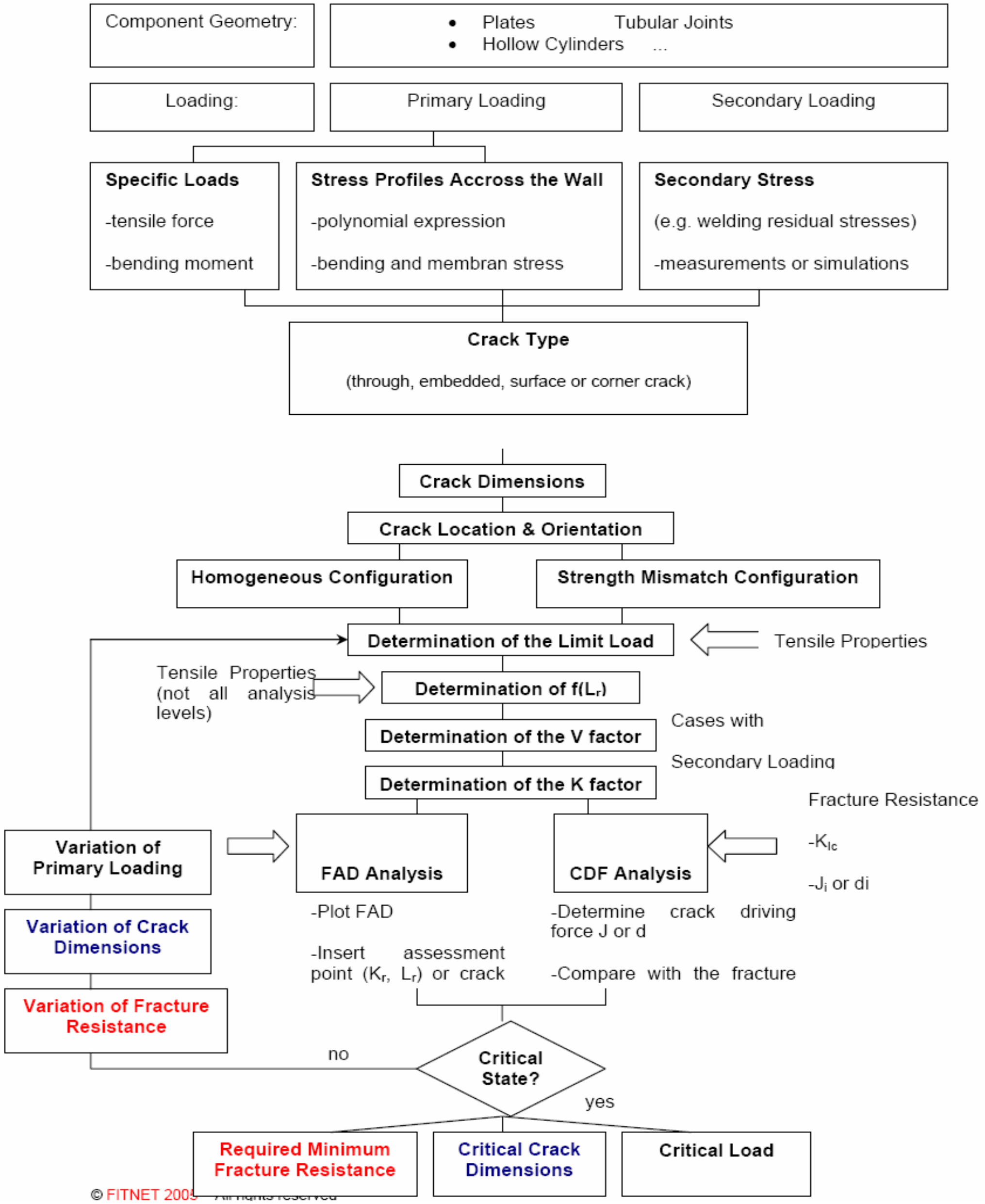
INTRODUCTION

The flowchart illustrates the determination of critical crack size, critical load and required minimum fracture resistance of the material using FITNET Fracture Module



Component Geometry:
- Plates Tubular Joints
- Hollow Cylinders ...

Loading: Primary Loading / Secondary Loading

Specific Loads
-tensile force
-bending moment

Stress Profiles Accross the Wall
-polynomial expression
-bending and membran stress

Secondary Stress
(e.g. welding residual stresses)
-measurements or simulations

Crack Type
(through, embedded, surface or corner crack)

Crack Dimensions

Crack Location & Orientation

Homogeneous Configuration / **Strength Mismatch Configuration**

Determination of the Limit Load ⇐ Tensile Properties

Tensile Properties (not all analysis levels) ⇒ **Determination of f(L_r)**

Determination of the V factor — Cases with Secondary Loading

Determination of the K factor

Variation of Primary Loading
Variation of Crack Dimensions
Variation of Fracture Resistance

FAD Analysis
-Plot FAD
-Insert assessment point (K_r, L_r) or crack

CDF Analysis ⇐ Fracture Resistance -K_{Ic} -J_i or di
-Determine crack driving force J or d
-Compare with the fracture

Critical State? no / yes

Required Minimum Fracture Resistance | **Critical Crack Dimensions** | **Critical Load**

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INTRODUCTION

Concerning cracks, the decisions that can be reached using this module are:

a) For design of a new component, structural significance of a postulated crack can be analysed. The dimensions of this crack shall be chosen such that it will probably be detected in quality control or in-service inspections.

If a crack of this size is demonstrated not to grow to a critical size over the projected lifetime of the component then no critical situation should be expected for the smaller undetected cracks.

Alternatively, a critical crack size can be determined in order to specify requirements on NDI in quality control and in-service inspections.

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INTRODUCTION

Concerning cracks, the decisions that can be reached using this module are:

b) If a crack is detected in-service, a decision can be made as to decide whether or not it is critical for the applied loading case. If necessary, the applied load can be reduced in order to avoid the critical state.

If the analysis is combined with a fatigue crack extension analysis (Fatigue Module, Section 7, Route 4) the residual lifetime of the component can be predicted and based on this non-destructive inspection (NDI) intervals can be specified which ensure a safe further service for a limited time.

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INTRODUCTION

An in-service inspection interval can be specified based on the residual lifetime that an assumed initial crack given by the NDE detection limit under service conditions requires to extend to its critical size.

In this case the present module will be part of a fatigue crack extension analysis (Fatigue Module, Section 7).

Finally, a minimum required fracture resistance of the material can be specified based on the critical crack size or the NDE detection limit under service conditions to avoid failure during the projected lifetime of the component.

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INPUTS

INPUTS

STRUCTURAL DATA AND CHARACTERISATION OF FLAWS

It is important to determine the detail and accuracy of the relevant aspects of the structural data. These include geometric details and tolerances, misalignments, details of welds, un-fused lands, and details of flaws and their locations, especially when associated with weld zones.

Although the procedure is aimed at establishing the integrity of a structure in the presence of planar flaws, the existence of non - planar (volumetric) flaws may also be of importance.

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INPUTS

STRUCTURAL DATA AND CHARACTERISATION OF FLAWS (cont.)

Defects treated as cracks must be characterised according to the rules given in the procedure, taking account of the local geometry of the structure and the proximity of any other flaw.

When determining the flaw tolerance of a structure, or determining or extending life, all possible locations of flaw should be assessed to ensure that the most critical region is covered. In the other cases, the actual location of the flaw must be assessed as realistically as possible.

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INPUTS

LOADS AND STRESSES ON THE STRUCTURE

Stresses need to be evaluated for all conceivable loading conditions, including non-operational situations, where relevant. Residual stresses due to welding, and thermal stresses arising from temperature differences or gradients must also be considered, as must fit-up stresses, and misalignment stresses. Guidance on these and other aspects and a compendium of weld residual stress profiles are given in the procedure.

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INPUTS

MATERIAL'S TENSILE PROPERTIES

Tensile data may come in a number of forms as follows:

(a) As specified in the design, or on the test certificates supplied with the material. One or more of the yield or proof stress, (ultimate) tensile stress and elongation may be available. These are unlikely to include data at temperatures other than ambient.

(b) As measured on samples of the material of interest. These data are likely to be specially collected, and where possible should include full stress strain curves, obtained on relevant materials, including weld metal, at relevant temperatures.

MATERIAL’S TENSILE PROPERTIES (cont.)

The quality and type of tensile data available determines the option of the analysis to be followed. Treatment of the tensile data is described in the procedure. In all cases, where scatter in the material’s tensile properties exist, the minimum value should be used to calculate L_r consistent with the option of analysis, while best estimates should be used to calculate $f(L_r)$ and L_r^{max} . Similarly, for mismatched cases, realistic values should be used to calculate the Mismatch Ratio, M and minimum values used for calculating L_r.

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INPUTS

MATERIAL’S FRACTURE PROPERTIES

All standard and advanced options of analysis require the material’s fracture properties to be in the form of fracture toughness data. In some circumstances these may be as specified, or from test certificates supplied with the material, but in most cases they will be from specially conducted tests.

The fracture data should relate to the material product form, microstructure (parent material, weld or heat affected zone) and temperatures of interest.

The fracture toughness data can come in different forms, depending on material type and temperature, and the test procedure adopted. Depending upon the extent and form of these data, they can be treated in different ways.

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INPUTS

MATERIAL'S FRACTURE PROPERTIES (cont.)

Characteristic values of the fracture toughness, K_{mat}, J_{mat}, or δ_{mat}, must be chosen by the user for the analysis. For assessing against the initiation of cracking a single value of fracture toughness is required, while for assessing in terms of ductile tearing, characteristic values will be a function of crack growth (Δa). The value chosen depends upon the confidence option or reliability required of the result. Appropriate procedures for determining characteristic values of toughness are given in the procedure.

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INPUTS

MATERIAL'S FRACTURE PROPERTIES (cont.)

Where it is not possible to obtain fracture toughness data, the analyst may use the default option for initiation where the characteristic value is based upon correlations with the material's Charpy impact data. Because this is a correlation, it is designed to provide a conservative estimate of fracture toughness.

The determination of fracture toughness from Charpy impact data is given in the Default Procedure (see Section 6.4.1. in FITNET procedure)

ANALYSIS: FAD AND CDF ROUTES

Two alternative approaches are proposed in the Fracture Module:

1) The Failure Assessment Diagram (FAD) approach
2) The Crack Driving Force Diagram (CDFD) Approach

A brief description of the alternative approaches follows.

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ANALYSIS: FAD AND CDF ROUTES

THE FAD APPROACH

The failure assessment diagram, FAD, is a plot of the failure envelope of the cracked structure, defined in terms of two parameters, K_r, and L_r. These parameters can be defined in several ways, as follows: -

K_r :- The ratio of the applied linear elastic stress intensity factor, K_I, to the materials fracture toughness, K_{mat}

L_r:- The ratio of the applied stress to the stress to cause plastic yielding of the cracked structure.

THE FAD APPROACH (cont.)

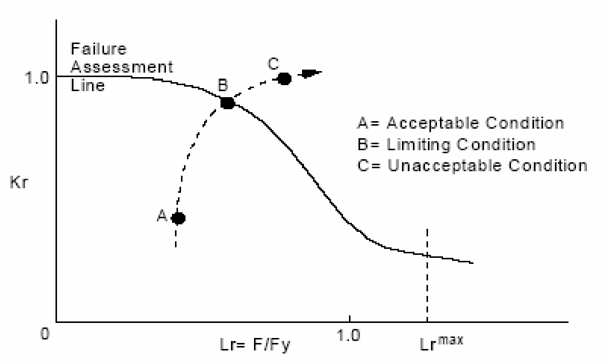
The failure envelope is called the Failure Assessment Line and for the basic and standard options of the procedure is dependent only on the material's tensile properties, through the equation:

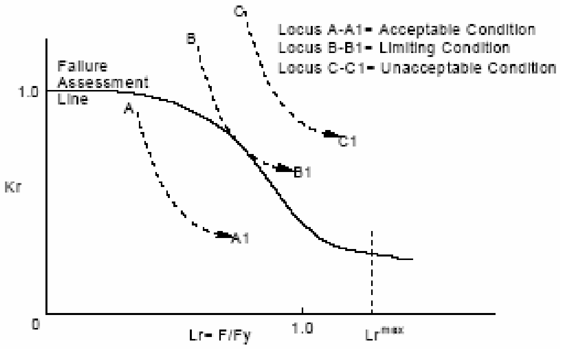
$$K_r = f(L_r)$$

It incorporates a cut-off at $L_r = L_{rmax}$, which defines the plastic collapse limit of the structure. *f(Lr)* functions are provided in the procedure (see Section 6 in FITNET procedure).

THE FAD APPROACH (cont.)

To use the FAD approach, it is necessary to plot an assessment point, or a set of assessment points, of co-ordinates (L_r-K_r), calculated under the loading conditions applicable (given by the loads, crack size, material properties). These points are then compared with the Failure Assessment Line. Figure on the left gives an example for a structure analysed using fracture initiation levels of analysis, and Figure on the right gives an example for a structure that may fail by ductile tearing.





THE FAD APPROACH (cont.)

Used this way, the Failure Assessment Line defines the envelope for achievement of a limiting condition for the loading of the cracked structure, and assessment points lying on or within this envelope indicate that the structure, as assessed, is acceptable against this limiting condition. A point which lies outside this envelope indicates that the structure as assessed has failed to meet this limiting condition.

Margins and factors can be determined by comparing the assessed condition with the limiting condition.

THE CDF APPROACH

The CDF approach requires calculation of the crack driving force on the cracked structure as a function of L_r. The crack driving force may be calculated in units of J or in units of crack opening displacement. Both are derived from the same basic parameters used in the FAD approach, the linear elastic stress intensity factor, K_r and L_r. In their simplest forms J is given by:

$$J = J_e\left[f\left(L_r\right)\right]^2$$

where:

$$J_e = K_e^2 / E'$$

and E’ is Young's modulus. E for plane stress,

and $E/(1-\nu^2)$ for plane strain.

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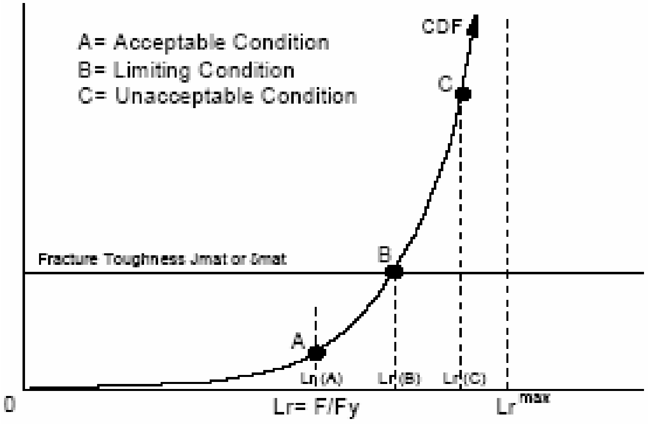
ANALYSIS: FAD AND CDF ROUTES

THE CDF APPROACH (cont.)

To use the CDF approach, for the basic option of analysis, the CDF is plotted as a function of L_r to values of $L_r \leq L_r^{max}$, and a horizontal line is drawn at the value of CDF equivalent to the material's fracture toughness. The point where this line intersects the CDF curve defines the limiting condition $L_r(B)$. A vertical line is then drawn at a value of L_r given by the loading condition being assessed.



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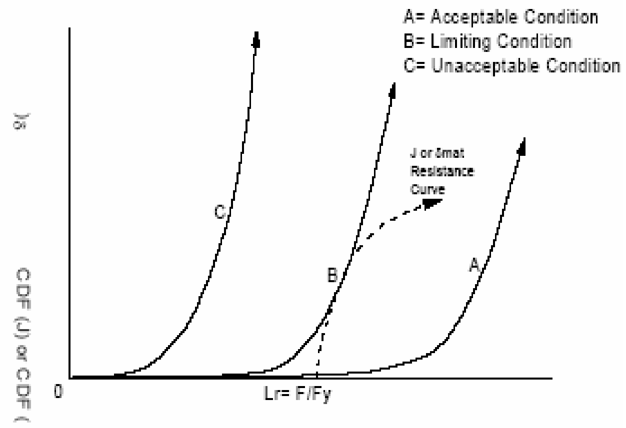
ANALYSIS: FAD AND CDF ROUTES

THE CDF APPROACH (cont.)

To use the CDF approach for the higher option of analysis required for ductile tearing, it is necessary to plot a CDF curve as a function of crack size at the load to be assessed.

The material's resistance curve is then plotted, as a function of crack size originating from the crack size being assessed. The limiting condition is defined when these two curves meet at one point only (tangent). The figure gives an example of this type of plot.



As for the FAD approach, margins and factors can be assessed, by comparing the assessed condition with the limiting condition.

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ANALYSIS OPTIONS

ANALYSIS OPTIONS

There are a number of different options of analysis available to the user, each being dependent on the quality and detail of the material's property data available.

The user should be aware that the higher the option of analysis, the higher is the quality required of the input data, and the more complex are the analysis routines. Conversely, the lower the option of analysis the more conservative the result, but the lowest option which gives an acceptable result implies satisfactory results at higher options.

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ANALYSIS OPTIONS

The option of analysis is characterised mainly by the detail of the material's tensile data used. There are three standardised options and three advanced options, including the special case of a leak before break analysis for pressurised systems. The different standardised options produce different expressions for $f(L_r)$ which define the FAD or CDF to be used in the analysis.

A subdivision of the option arises from the details of fracture toughness data used. There are two options for this, one characterising the initiation of fracture (whether by ductile or brittle mechanisms), the other characterising crack growth by ductile tearing. The value of fracture toughness to be used in the FITNET procedure is termed the characteristic value.

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ANALYSIS OPTIONS

Next table gives guidance on the selection of analysis option from tensile data

OPTION	DATA NEEDED	WHEN TO USE
BASIC OPTION		
OPTION 0 Basic	Yield or proof strength	When no other tensile data available
STANDARD OPTIONS		
OPTION 1 Standard	Yield or Proof Strength : Ultimate Tensile Strength	For quickest result. Mismatch in properties less than 10%
OPTION 2 Mismatch	Yield or Proof Strength : Ultimate Tensile Strength. Mismatch limit loads	Allows for mismatch in yield strengths of weld and base material. Use when mismatch is greater than 10% of yield or proof strength (optional).
OPTION 3 SS(Stress-strain defined)	Full Stress-Strain Curves.	More accurate and less conservative than options 1 and 2. Weld mismatch option included.
ADVANCED OPTIONS		
OPTION 4 Constraint	Estimates of fracture toughness for crack tip constraint conditions relevant to those of cracked structure.	Allows for loss of constraint in thin sections or predominantly tensile loadings
OPTION 5 *J*-Integral Analysis	Needs numerical cracked body analysis	

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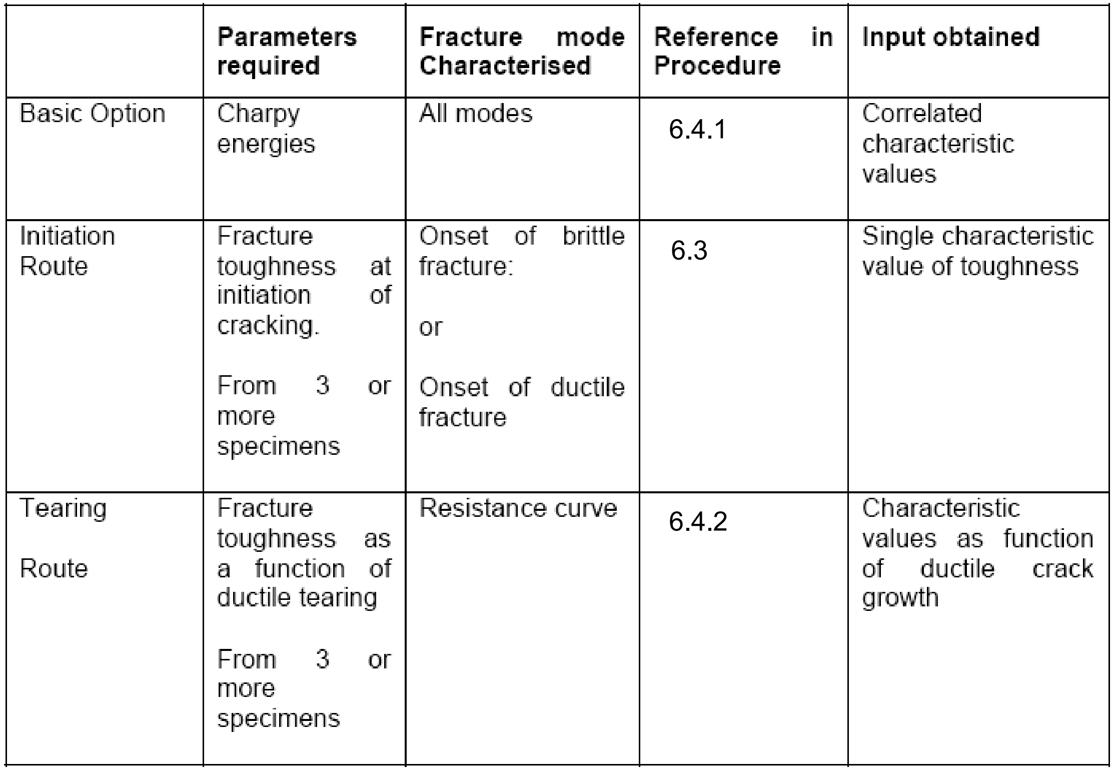
ANALYSIS OPTIONS

And this table gives guidance on the selection of analysis option from toughness data



	Parameters required	**Fracture mode Characterised**	**Reference in Procedure**	**Input obtained**
Basic Option	Charpy energies	All modes	6.4.1	Correlated characteristic values
Initiation Route	Fracture toughness at initiation of cracking. From 3 or more specimens	Onset of brittle fracture: or Onset of ductile fracture	6.3	Single characteristic value of toughness
Tearing Route	Fracture toughness as a function of ductile tearing From 3 or more specimens	Resistance curve	6.4.2	Characteristic values as function of ductile crack growth

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ANALYSIS OPTIONS

The OPTION 1, is the minimum recommended option. This requires measures of the material's yield or proof strengths and its tensile strength, and a value of fracture toughness, K_{mat}, obtained from at least three fracture toughness test results which characterise the initiation of brittle fracture or the initiation of ductile tearing.

For situations where data of this quality can not be obtained, there is a BASIC OPTION of analysis, which can be based on only the material's yield or proof strength and its Charpy data. The basic option uses correlations, and as such is very conservative. It should only be used where there is no alternative.

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ANALYSIS OPTIONS

In weldments where the difference in yield or proof strength between weld and parent material is smaller than 10%, the homogeneous procedure can be used for both under-matching and overmatching; in these cases the lower of the base or weld metal tensile properties shall be used.

For higher options of mismatch, and for $L_r > 0.75$, the option of using an OPTION 2 analysis, MISMATCH OPTION, can reduce conservatism. This method requires knowledge of the yield or proof strengths and tensile strengths of both the base and weld metals, and also an estimate of the mismatch yield limit load.

It is however, possible to use the procedures for homogeneous materials even when mismatch is greater than 10%; and provided that the lower of the yield or proof stress of the parent material or weld metal is used, the analysis will be conservative.

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ANALYSIS OPTIONS

The equations used to generate f(L_r) for OPTION 1 and 2 are based upon conservative estimates of the effects of the materials tensile properties for situations when complete stress strain curves are not known.

More accurate and less conservative results can be obtained by using the complete stress strain curve, and this approach is given in OPTION 3 as the SS (Stress-Strain) option. In this case every detail of the stress strain curve can be properly represented and where weldment mismatch effects are important these can also be allowed for.

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ANALYSIS OPTIONS

The fracture mechanics approach given here (Options up to 3), which is intended to result in a conservative outcome for the assessment, assumes that the section containing the flaw has a high level of constraint. In some instances, especially where the section is thin, or where the loading is predominantly tensile, this assumption can be over-conservative. In such cases it may be possible to reduce the conservatism by taking account of the lower constraint. OPTION 4 (Constraint) allows it.

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ANALYSIS OPTIONS

THE BASIC PROCEDURE

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Applicability

Only the simplest form of material properties data are required for this option of analysis. The tensile properties needed are yield or proof strength and ultimate tensile strength, and the characteristic value of the fracture toughness must be based upon data from at least three fracture toughness test results.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Procedure

1. Establish Yield or Proof Strength and Tensile Strength

Mean values of these define the equation for $f(L_r)$ for both the FAD and CDF approaches and minimum values define L_r for the loading on the structure. It is important to determine whether or not the material displays, or can be expected to display, a lower yield plateau or Luder’s strain.

2. Determine $f(L_r)$

The function $f(L_r)$ must be calculated for all values of $L_r \leq L_{r\ max}$. The Procedure provides formulation for different cases of stress-strain curves (see Section 6.3.2.2).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

3. Determine the Characteristic Value of the Material's Fracture Toughness

It is recommended that the characteristic value for fracture toughness is obtained from an analysis of as many test results as possible, taking appropriate account of the scatter in the data, and the reliability required on the result.

Where there is a large scatter in the data, the most representative values will be obtained for large data sets, but values can be obtained from as little as three results. Recommended methods for analysing the data are given in the Procedure (see Section 6.3.2.2).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Where the fracture mechanism is brittle the method uses maximum likelihood (MML) statistics.

For between 3 and 9 test results there are three stages in the statistical analysis, plus a correction for the number of specimens in the data set. This imposes a penalty on the use of small data sets, to make allowance for possible poor representation of the sample.

For 10 or more test results, only two stages need be performed. However, if it is known that the material is inhomogeneous, e.g, if it is taken from a weld or heat affected zone, it is advisable to perform the third stage for indicative purposes. The choice of characteristic value can then be made with more confidence.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Use of the MML method implies acceptance of the weakest link model for brittle fracture. This also implies crack size dependence. The characteristic value should be chosen with this in mind. Guidance and the equation for crack size adjustment is given in the Procedure (see Section 5.4.5.1.2).

Where the fracture mechanism is by ductile tearing, the data must relate to the onset of ductile tearing as described in the testing standards. The characteristic values may be obtained from the minimum of three test results or from a statistical analysis where more than three test results are available.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

4. Characterise The Crack

This is determined by the shape and size of the defect, or defects, and the geometry of the structure (see Annex E).

5. Determine Loads and Stresses

All potential forms of loading must be considered, including thermal loading and residual stresses due to welding, and test, fault and accidental loads. These must be classified into primary and secondary stresses.

For the purposes of this procedure, secondary stresses cannot affect the failure of the structure under plastic collapse conditions, and all other stresses must be classed as primary.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Plasticity effects due to primary stresses are evaluated automatically by means of the expression $f(L_r)$. However, further allowance has to be made for plasticity effects due to secondary stresses, and due to the combination of primary and secondary stresses. These are incorporated by means of a parameter defined as ρ and which is dependent on both L_r and the stress intensity factor due to the secondary stress. Guidance for stress characterisation and the calculation of ρ is given in the Procedure (see 5.3.1.12).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

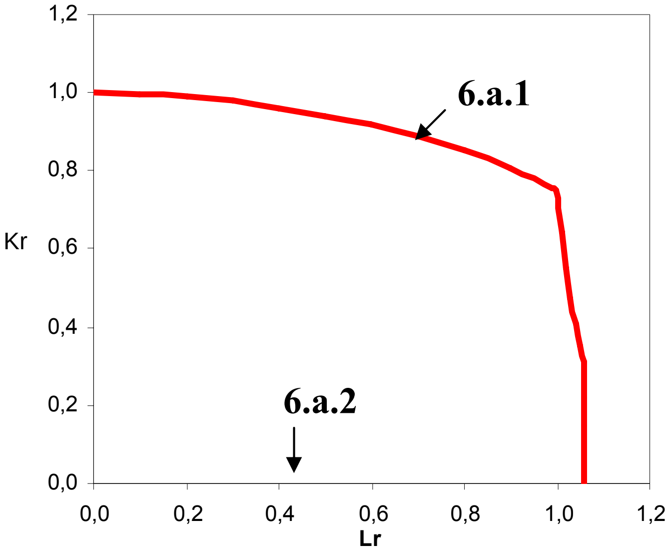
6. Analysis

Step 6 in the procedure has the following sub-steps, depending on the approach chosen:

(a) FAD Approach

6.a.1. Plot the FAD, using mean tensile properties and the appropriate expressions for $f(L_r)$, where the FAD is a plot of $K_r = f(L_r)$ on L_r and K_r axes.

6.a.2. Calculate L_r for the loading on the structure at the crack size of interest, using minimum values of tensile properties, taking into account only primary loads.



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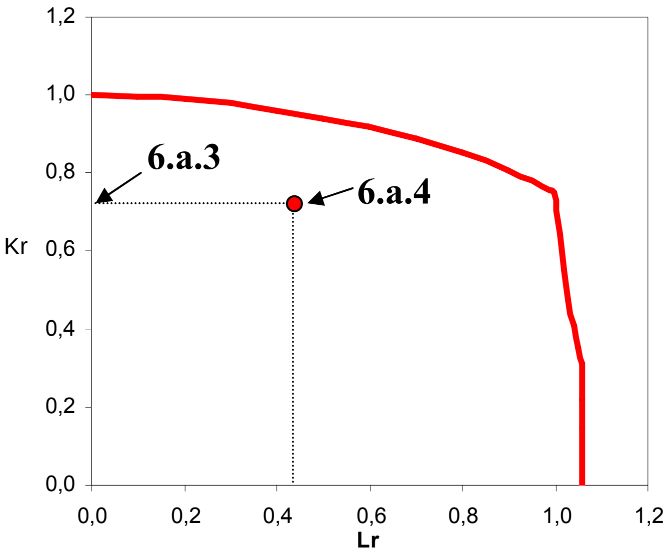
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.a.3. Calculate Kr for the loading on the structure at the crack size of interest. In the calculation of Kr, all primary and secondary loads need to be included, plus an allowance for plasticity effects due to secondary stresses by means of the parameter ρ.

6.a.4. With co-ordinates $\{L_r, K_r\}$ plot the Assessment Point on the FAD.



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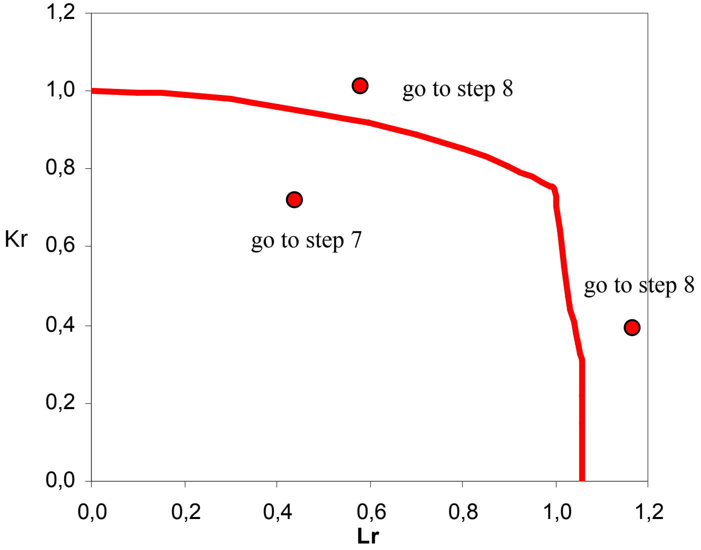
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.a.5. If the assessment point lies within the assessment line the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis option pursued. Go to Step 7 of the procedure. If the assessment point lies on or outside the assessment line, the structure is not acceptable in terms of the limiting conditions imposed. Go to step 8 of the procedure.



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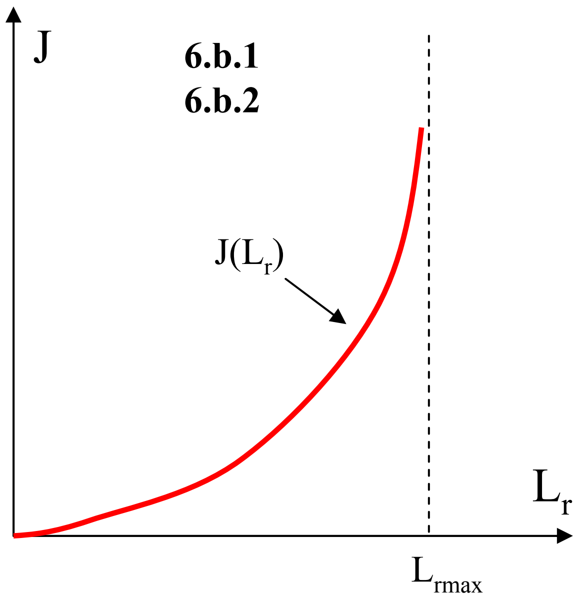
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(b) CDF Analysis using J

6.b.1. Calculate J_e as a function of the applied loads on the structure at the crack size of interest where $J_e = K^2/E'$, taking into account all primary and secondary loads. At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, ρ.

6.b.2. Plot the CDF (J) using mean tensile properties and the appropriate expression for $f(L_r)$ where the CDF(J) is a plot of $J = J_e[f(Lr)-\rho]^{-2}$ on L_r and J axes for values of $L_r \leq L_{r\,max}$. Draw a vertical line at $L_r = L_{r\,max}$.



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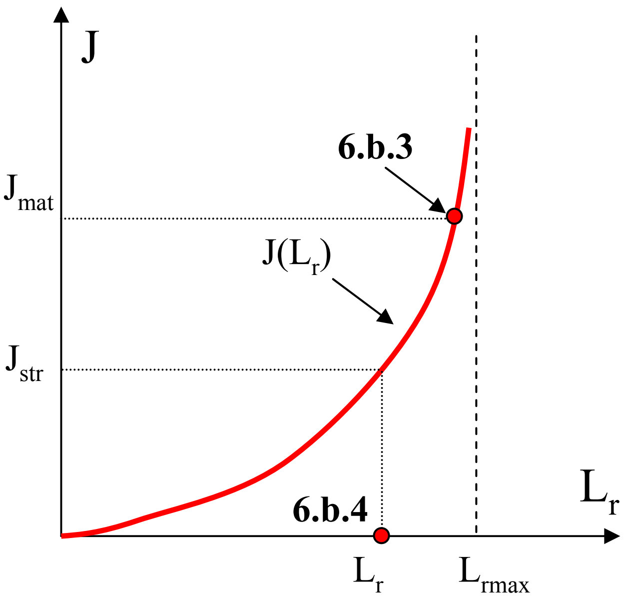
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.b.3. Identify the point on the CDF (J) curve where $J = J_{mat}$.

6.b.4. Calculate L_r for the loading on the structure at the crack size of interest using minimum values of tensile properties, and draw a vertical line at this value to intersect the CDF (J) curve at J_{str}.



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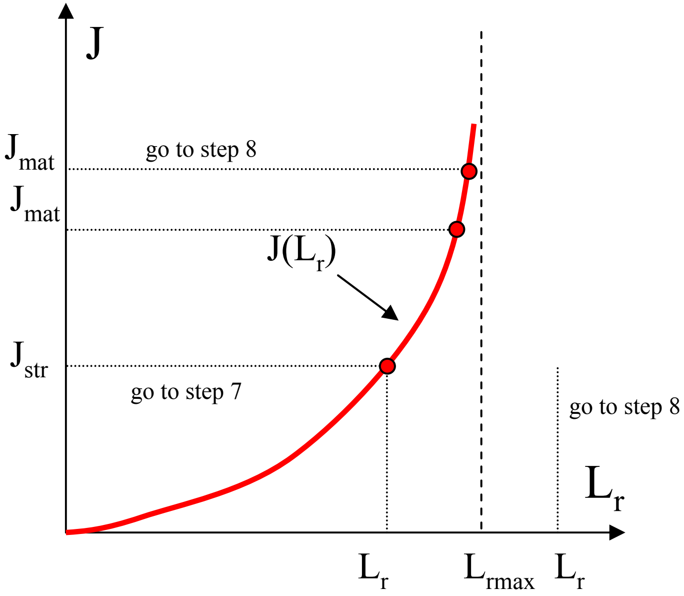
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.b.5. If J_{str} is less than J_{mat}, and L_r for the structure is less than $L_{r\ max}$, the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis option pursued. Go to step 7.

If either J_{str} is greater than J_{mat}, or L_r for the structure is greater than $L_{r\ max}$, the structure is not acceptable in terms of the limiting conditions. Go to step 8 in procedure.



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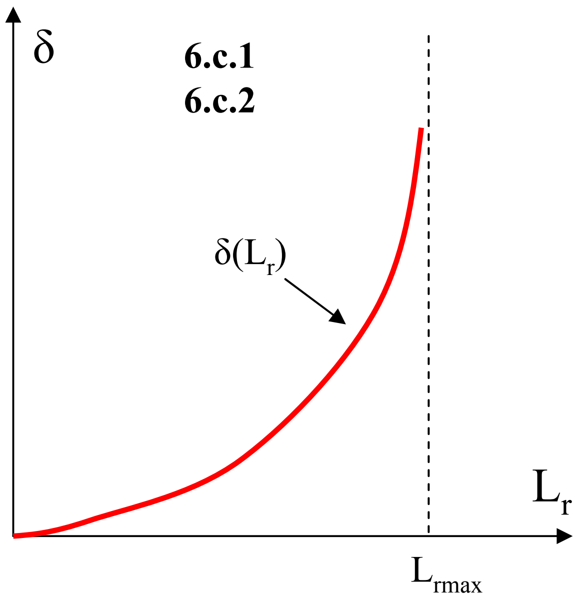
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(c) CDF Approach using δ

6.c.1. Calculate δ_e as a function of the applied loads on the structure at the crack size of interest, where $\delta_e = K^2/E'\cdot R_e$, taking into account all primary and secondary loads. At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, ρ.

6.c.2. Plot the CDF (δ) using mean tensile properties and the appropriate expression for L_r (step 2 Section I.4.2.2) where the CDF (δ) is a plot of $\delta = \delta_e[f(L_r)-\rho]^{-2}$ on L_r and δ axes for values of $L_r \leq L_{r\,max}$. Draw a vertical line at $L_r = L_{r\,max}$.



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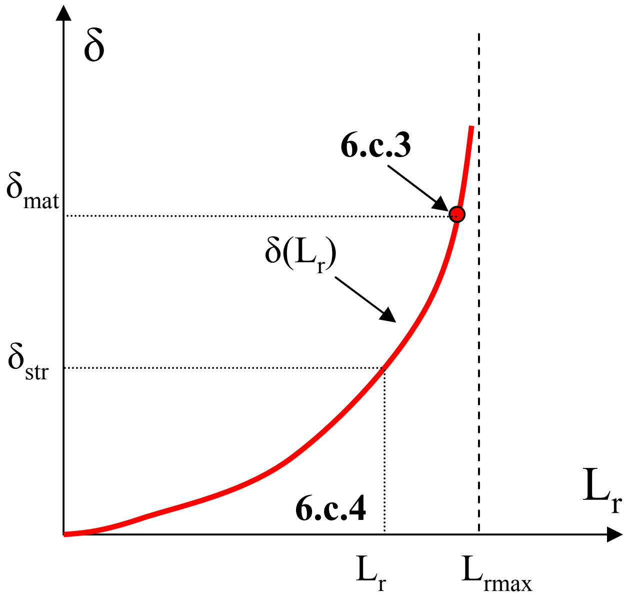
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.c.3. Identify the point on the CDF (δ) curve where $\delta = \delta_{mat}$.

6.c.4. Calculate L_r for the loading on the structure at the crack size of interest using minimum values of tensile properties and draw a vertical line at this value to intersect the CDF (δ) curve at δ_{str}.



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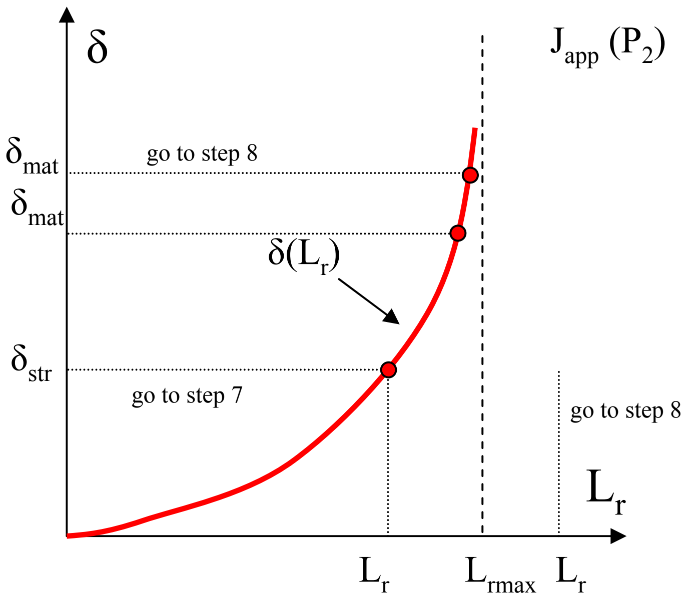
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.c.5. If δ_{str} is less than δ_{mat}, and L_r for the structure is less than $L_{r\ max}$, the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis option pursued. Go to step 7 in the procedure.

If either δ_{str} is greater than δ_{mat}, or L_r for the structure is greater than $L_{r\ max}$, the structure is not acceptable in terms of the limiting conditions. Go to step 8.



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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

7. Assess Result

The result must be assessed in terms of the reliability required taking into account the uncertainties in the input data. If the result is acceptable the analysis can be concluded and reported as appropriate.

8. Unacceptable result

If the result is unacceptable, it may be possible to proceed to a higher option of analysis. The Procedure gives guidelines to determine how best to proceed (see 6.3.2).

For a FAD analysis, the guidelines are based upon the ratio K_r/L_r defined under the loading conditions of the analysis.

For a CDF analysis, the guidelines are based upon the value of L_r obtained when defining a limiting load for the structure.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(a) If $K_r/L_r > 1.1$ or $L_r(L) < 0.8$, the result will be relatively insensitive to refinements in the tensile data. In this case, the result can be made acceptable only if K_r can be reduced. This may be done either by reducing the value of K_I by using a more accurate method of calculation, or by accepting a higher value of K_{mat}.

For materials failing by a brittle fracture mechanism K_{mat} may be raised by increasing the number of test results used in the MML analysis, which may necessitate the testing of more specimens.

For materials failing by ductile tearing, K_{mat} may be increased by performing a ductile tearing analysis which takes account of the increase in fracture toughness due to ductile tearing.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(b) If $K_r/L_r < 0.4$ or $L_r(L) > 1.2$, the result will be relatively insensitive to refinements in the fracture toughness data.

In this case, the result can only be made acceptable by refining the tensile data, thus changing the form of $f(L_r)$ and reducing the values of L_r calculated for the loading on the structure.

For situations of weld mismatch, where only yield and ultimate tensile data are known, employment of OPTION 2 may give more acceptable results.

For situations where the full stress strain curve is known, employment of the more accurate OPTION 3 analysis may provide the necessary improvements.

The analysis should be repeated, modifying steps 1 and 2 and details of step 6, as required.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

If $1.1 > K_r/L_r > 0.4$ or $1.2 > L_r(L) > 0.8$, the result can be affected by refinements in either or both fracture toughness data and tensile data (and/or refinements in K_I), following the guidelines given in steps 8(a) and 8(b) above.

The result may also be influenced by constraint, especially where $1.1 > K_r/L_r > 0.4$ or $1.2 > L_r(L) > 0.8$. An advanced method (OPTION 4), giving guidelines on how to allow for constraint effects is described in detail in the procedure that also provides for a further advanced option for situations where a numerical J-integral is preferred (OPTION 5).

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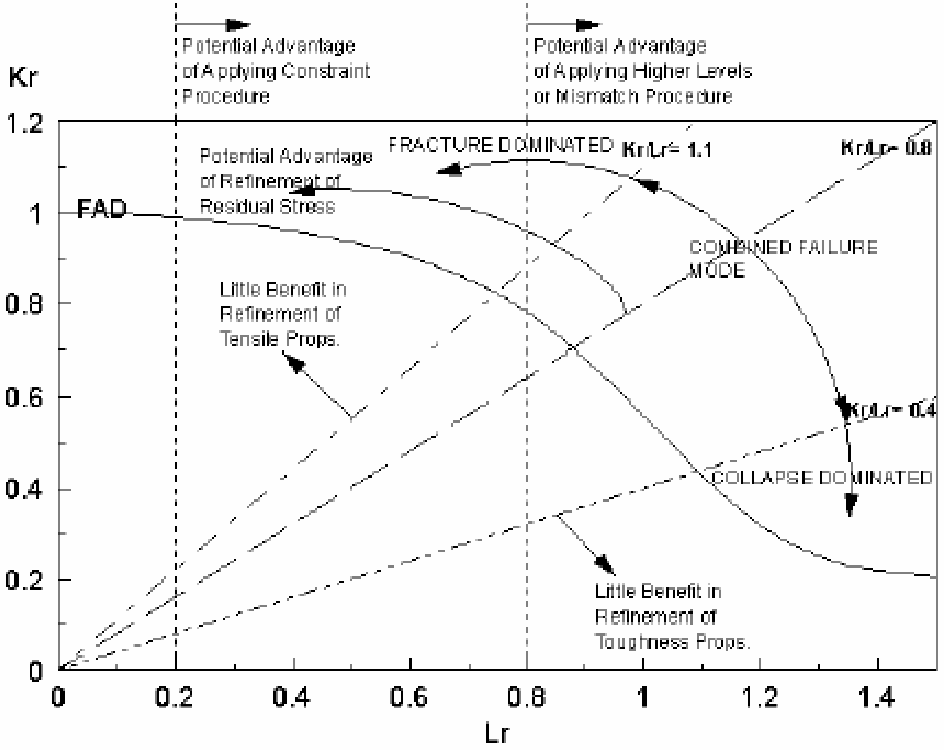
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

A summary of FAD regions for consideration of potential refinement of data or analysis option is shown in the figure.



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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

In certain circumstances, especially where data are extensive and very well documented, it may be possible to perform a full probability analysis. Suggestions for performing a probability analysis based upon the FAD approach are given in FITNET (see Section 11.10).

If none of these avenues can be followed, the integrity of the flawed structure cannot be demonstrated and appropriate action should be taken.

THE MISMATCH PROCEDURE

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

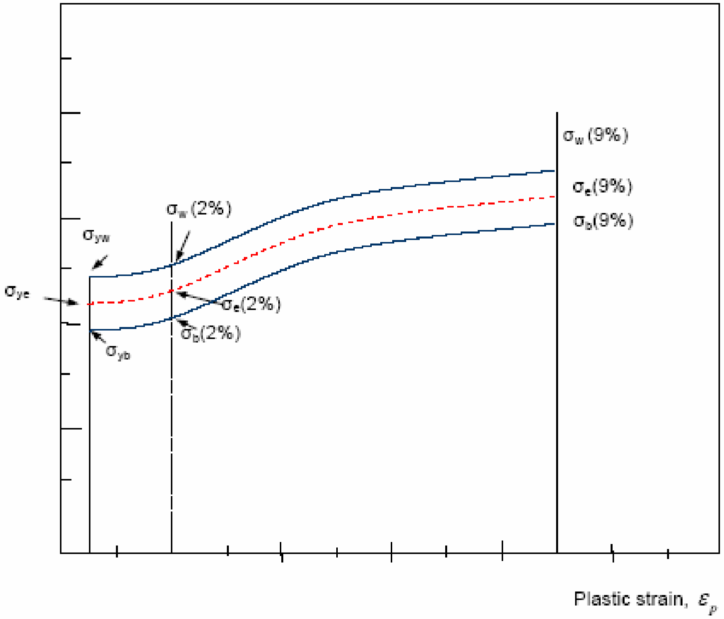
Applicability

In the case of weldments where the differences in yield strengths between the base material and the weld metal is greater than 10 %, the joint may behave as a heterogeneous bi-metallic joint. In such cases, use of minimum values of yield strength in the joint to define Lr may be over-conservative.

The mismatch option provides a method for reducing the conservatism by allowing for separate contributions of the base material (denoted B) and the weld material (denoted W).

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

The mis-match ratio is defined by the relation between yield or proof stress in weld material and yield or proof stress in base material



$M(0,2\%) = \sigma_{yw} \, / \, \sigma_{yb}$

$M(2\%) = \sigma_w \, (2\%) \, / \, \sigma_b \, (2\%)$

$M(9\%) = \sigma_w \, (9\%) \, / \, \sigma_b \, (9\%)$

$\sigma_e(2\%) \, / \, \sigma_b(2\%) = P_{1min} \, / \, P_{1b}$ [for M = M(2%)] etc

Definition of mis-match ratio M

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ANALYSIS OPTIONS

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

This option can only be used where there is available an estimate of the yield limit load under the mismatch conditions. This is dependent on the geometry of the joint and the flaw location within the joint. Solutions for some common geometries are given in the Procedure (see Annex B).

It should be recognised that weld tensile properties may vary through the thickness of a component and may be dependent on specimen orientation. The range of weld metal microstructures sampled can often lead to a high degree of scatter. The use of the lowest tensile properties irrespective of orientation and position is necessary to provide a conservative result.

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

Three combinations of stress strain behaviour are possible.

- Both base and weld metal exhibit continuous yielding behaviour
- Both base and weld metal exhibit a lower yield plateau
- One of the materials exhibits a lower yield plateau and the other has a continuous stress strain curve.

The Option 2 analysis is performed using FADs and CDFs derived using values of L_r and $f(L_r)$ for an equivalent material with tensile properties derived under the mismatch conditions (see 6.3.3).

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

In general, for all combinations of yield behaviour, this requires calculation of the mismatch ratio, M, a mismatch limit load, F_e^M, a value for $L_{r\ max}$ under the mismatch conditions, a value for N under the mismatch conditions and similar values for μ or λ, all of which are defined in the procedure (see Section 6.3.3).

Advice for calculating the mismatch limit load is given and this also contains solutions for some typical geometries (see Annex B).

Note that the mismatch limit load depends not only upon the mismatch ratio but also on the location of the flaw within the weldment.

FE BASED PROCEDURE

OPTION 3, KNOWN STRESS-STRAIN CURVES

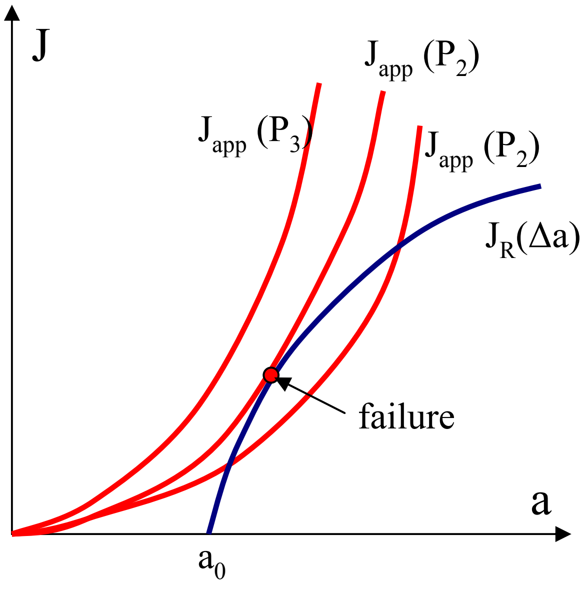
Applicability

This option of analysis can be used where the full stress strain curves are known. Where there is scatter in the data, a composite curve should be used to describe the best estimate for the calculation of $f(L_r)$ otherwise the lowest of all available stress strain curves should be used.

In situations where there is a mismatch in the weld and base material proof or yield strengths in excess of 10 % the mismatch option may be employed. This is based upon the concept of an equivalent mismatch material and requires an estimate of the yield limit load under the mismatch conditions.

ANALYSIS OPTION 4 (J-INTEGRAL ANALYSIS)

In some situations estimates of the J-integral may be available from a numerical stress analysis of the cracked body. In these cases an analysis may be performed using this value of the J-integral directly. If such an analysis provides enough information to make plots of J as a function of load, or as a function of crack size, these values of J may be used to construct a CDF J diagram from which an initiation or a tearing analysis may be performed. As this method requires numerical methods such as finite elements, further detail of this approach is not covered in this procedure.



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ANALYSIS OPTIONS

CONSTRAINT ANALYSIS

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

Associated with assessment procedures for analysis options 1 to 3, are reserve factors which indicate a proximity to a limiting condition. The limiting condition incorporates an element of conservatism so that, in general, the reserves in the structure are underestimated.

A particular conservatism implicit in the procedure arises from the value of K_{mat} being derived from deeply cracked bend or compact tension specimens recommended in the testing standards. These are designed to ensure plain strain conditions and/or high hydrostatic stresses near the crack tip to provide a minimum value, and then, a conservative estimate of the material's resistance to fracture which is relatively independent of geometry.

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

However, there is considerable experience that the material's resistance to fracture increases when the loading is predominantly tensile, and when the crack depths are shallow. These situations lead to lower hydrostatic stresses at the crack tip, referred to as lower constraint.

In order to claim benefit for a situation where the constraint is reduced over that in the test specimen, it is necessary to perform additional calculations and to have more information on fracture toughness properties.

Benefits are usually greatest for shallow cracks subject to tensile loads, but guidance on the cases where greatest benefit can be obtained is contained in the procedure. The methodology for determining the constraint benefit is also described in detail in the FITNET procedure (see Section 6.4.3).

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

When the FAD route is followed, two alternative procedures set out in Sections 6.4.3.3.1 and 6.4.3.3.2 can be used. The first involves a modification to the FAD but retains the definition of K_r. The second retains the FAD of Section 6.3.2 but modifies the definition of K_r. Guidance on how to perform these steps is contained in Section 6.4.3.3.4 along with guidance on assessing the significance of the results. This latter guidance, in Section 6.4.3.3.4.6, may be useful in deciding which of the two procedures to follow.

With the CDF approach, a modified toughness procedure is used. The procedure follows the steps in Section 6.3.2.3 apart from steps detailed in Section 6.4.3.3.3.

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GUIDANCE ON OPTION SELECTION

GUIDANCE ON OPTION SELECTION

Introduction

FITNET Procedure sets out a step-by-step procedure for assessing the integrity of structures containing defects.

To assist the user, the section provides guidance on selection of the various routes in the procedure. Additionally, the potential decisions necessary at the various options are briefly summarised and guidance on the benefits of consulting advice contained in the appropriate section is given.

Note, however, that the guidance on selection of routes is not meant to be prescriptive or to obviate the need for a sensitivity study, which may involve comparison of these alternative routes.

The recommendations given below refer in many cases to specific regions of the Failure Assessment Diagram (similar situations can be obtained in CDF analysis).

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GUIDANCE ON OPTION SELECTION

Selection of Failure Assessment Diagram

- The BASIC OPTION curve is the easiest to apply and requires only the yield stress to be known;
- OPTION 1 is applicable to homogeneous materials and requires a knowledge of the ultimate strength as well as the yield strength;
- OPTION 2 is a specific mis-match assessment option and requires knowledge of yield stress and ultimate tensile stress of base metal and weld metal.
- OPTION 3 requires additional information on the material stress-strain properties and can be applied to homogeneous materials or those cases where weld strength mis-match is an issue;

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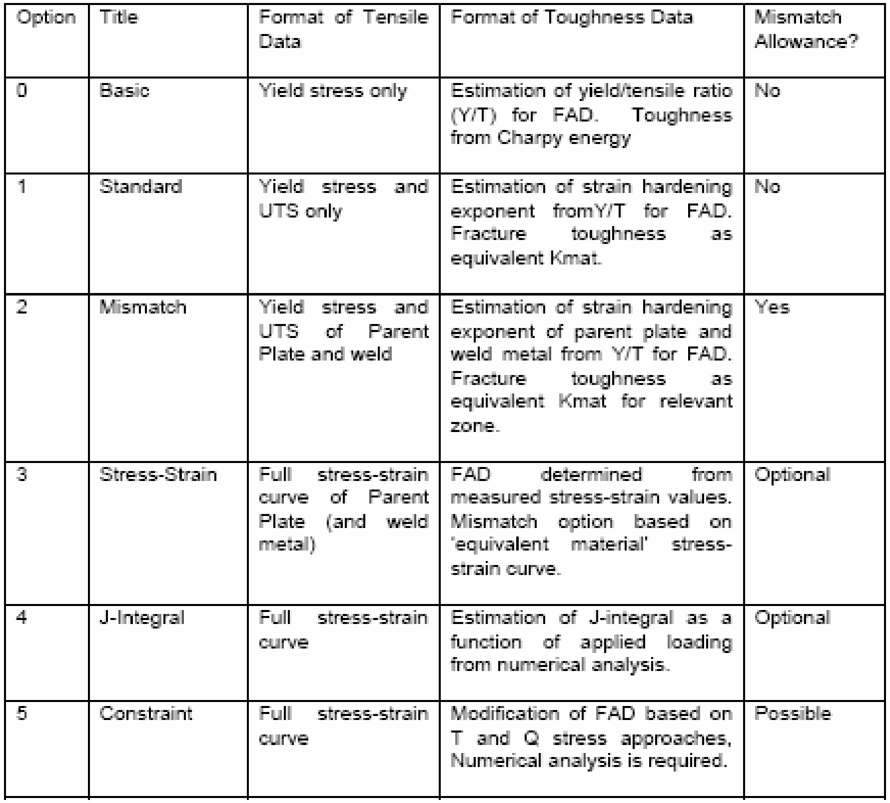
GUIDANCE ON OPTION SELECTION

Selection of Failure Assessment Diagram

- OPTION 4 requires results of detailed elastic-plastic analysis of the defective component while OPTION 5 invokes constraint treatment.



Option	Title	Format of Tensile Data	Format of Toughness Data	Mismatch Allowance?
0	Basic	Yield stress only	Estimation of yield/tensile ratio (Y/T) for FAD. Toughness from Charpy energy	No
1	Standard	Yield stress and UTS only	Estimation of strain hardening exponent fromY/T for FAD. Fracture toughness as equivalent Kmat.	No
2	Mismatch	Yield stress and UTS of Parent Plate and weld	Estimation of strain hardening exponent of parent plate and weld metal from Y/T for FAD. Fracture toughness as equivalent Kmat for relevant zone.	Yes
3	Stress-Strain	Full stress-strain curve of Parent Plate (and weld metal)	FAD determined from measured stress-strain values. Mismatch option based on 'equivalent material' stress-strain curve.	Optional
4	J-Integral	Full stress-strain curve	Estimation of J-integral as a function of applied loading from numerical analysis.	Optional
5	Constraint	Full stress-strain curve	Modification of FAD based on T and Q stress approaches, Numerical analysis is required.	Possible

Simplified Structure of the Fracture Assessment Procedure

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GUIDANCE ON OPTION SELECTION

To assist in deciding whether or not to choose one of the more complex Options, the following information may be noted.

•At low values of load, typically $L_r \leq 0.8$, the shape of the failure assessment curve is dominated by small-scale yielding corrections and all four Options are likely to produce similar curves. There is, therefore, likely to be little benefit in going to a higher Option for $L_r \leq 0.8$.

Note, however, that the relevant range of L_r values should include not only those at the load and crack size being assessed but also those at any limiting conditions used to derive margins or factors.

•For materials, which exhibit significant strain hardening beyond yield, such as austenitic stainless steels, Option 3 curves are close to Option 1.

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GUIDANCE ON OPTION SELECTION

- For materials with a Lüders strain, there is conservatism in the Option 1 and 3 curves for $L_r > 1$ for geometries not loaded in simple tension, i.e. where there is significant bending in the plane of the defect. Going to Option 4 may reduce this conservatism.

- For surface defects, significant conservatism can arise from the use of a local, rather than a global, limit load. Such conservatism can be quantified by detailed analysis leading to a Option 4 curve. In principle the Option 4 curve can be based on either the local or global limit load, but whichever is chosen must be used in the calculation of L_r. It is preferable to use the global limit load as otherwise the cut-off at $L_{r\,max}$ may be imposed at loads which correspond to only small plastic strains.

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GUIDANCE ON OPTION SELECTION

Selection of Analysis Methods: Initiation and Tearing

The use of initiation fracture toughness values is the usual approach. The following guidance is given for those cases where it may be appropriate to invoke ductile tearing.

- Greatest benefit arises from the use of ductile tearing for materials with a steep J_R fracture resistance (J-Δa) curve, i.e.. where toughness for small amounts of ductile tearing is significantly greater than the initiation toughness.
- Greatest benefit occurs when the component and defect dimensions, such as crack size, section thickness and remaining ligament, are much greater than the amount of ductile tearing being considered. This latter amount is usually about 1-2 mm as this is typically the limit of valid data collected on test specimens of standard size.
- When moving to a tearing analysis, care must be taken to account for any interactions between tearing and other modes of crack growth.

SPECIAL OPTIONS

The FITNET Procedure presents methodologies for the assessment of specific common technical problems:

- Basic Level of analysis, Option 0 (see Section 6.4.1)
- Ductile tearing analysis (see Section 6.4.2)
- Allowance for constraint effects (see Section 6.4.3)

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GUIDANCE ON OPTION SELECTION

SPECIAL OPTIONS

Also, the Procedure provides alternative and specific assessments for fracture:

- Leak before break (see Section 11.2)
- Crack arrest (see Section 11.3)
- Load history effect (see Section 11.4)
- Evaluation under Mode I, II and III loads (see Section 11.5)
- Master Curve (see Section 11.6)
- Probability and Reliability (see Section 11.7)

D. EXAMPLES

VALIDATION EXAMPLE

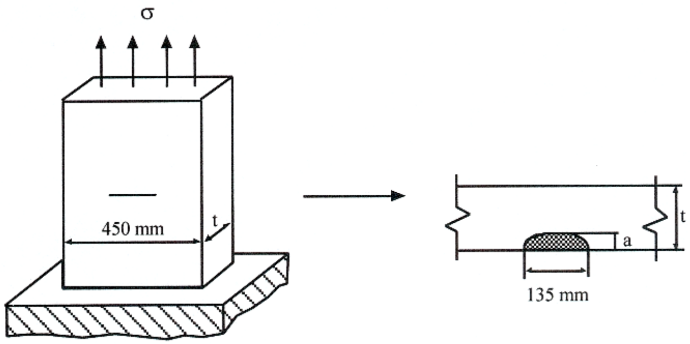
Planar Wide Plates

- **Introduction**
- **Geometry and Imput Data**
- **Materials**
- **Toughness**
- **Formulation and Calculus**
- **Diagrams**
- **Results**
- **Analysis**
- **Bibliography/References**

INTRODUCTION

- **Description: 7 wide plates with different Y/T ratio**
- **Defect: Semi-elliptical Finite Surface Crack**
- **Different Quality in Tensile Data**
- **Different Toughness Data: Charpy and CTOD**
- **Different Crack Sizes (Nominal and Real Values)**
- **Calculation of Critical Stress for a given Crack**
- **Total: 63 calculations**
- **Experimental Values Available. Evaluation of Reserve Factors**

GEOMETRY AND INPUT DATA



Geometry

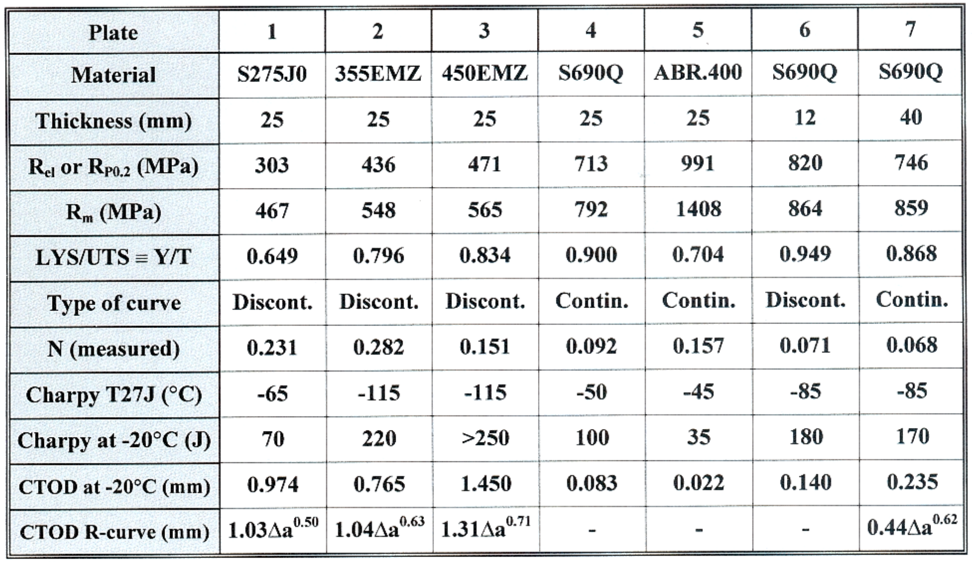
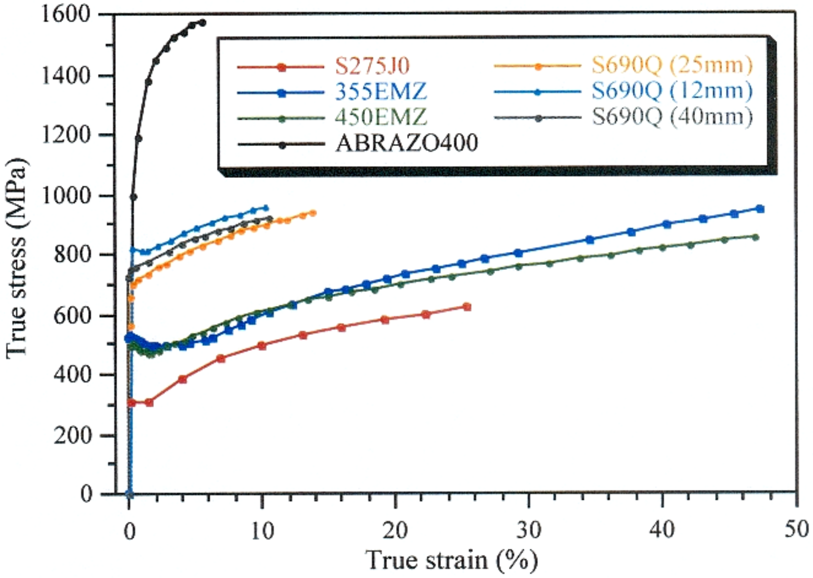


Plate	1	2	3	4	5	6	7
Material	S275J0	355EMZ	450EMZ	S690Q	ABR.400	S690Q	S690Q
Thickness (mm)	25	25	25	25	25	12	40
R_{el} or $R_{P0.2}$ (MPa)	303	436	471	713	991	820	746
R_m (MPa)	467	548	565	792	1408	864	859
LYS/UTS ≡ Y/T	0.649	0.796	0.834	0.900	0.704	0.949	0.868
Type of curve	Discont.	Discont.	Discont.	Contin.	Contin.	Discont.	Contin.
N (measured)	0.231	0.282	0.151	0.092	0.157	0.071	0.068
Charpy T27J (°C)	-65	-115	-115	-50	-45	-85	-85
Charpy at -20°C (J)	70	220	>250	100	35	180	170
CTOD at -20°C (mm)	0.974	0.765	1.450	0.083	0.022	0.140	0.235
CTOD R-curve (mm)	$1.03\Delta a^{0.50}$	$1.04\Delta a^{0.63}$	$1.31\Delta a^{0.71}$	-	-	-	$0.44\Delta a^{0.62}$

Input Data

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE

MATERIALS



Stress-Strain Curves

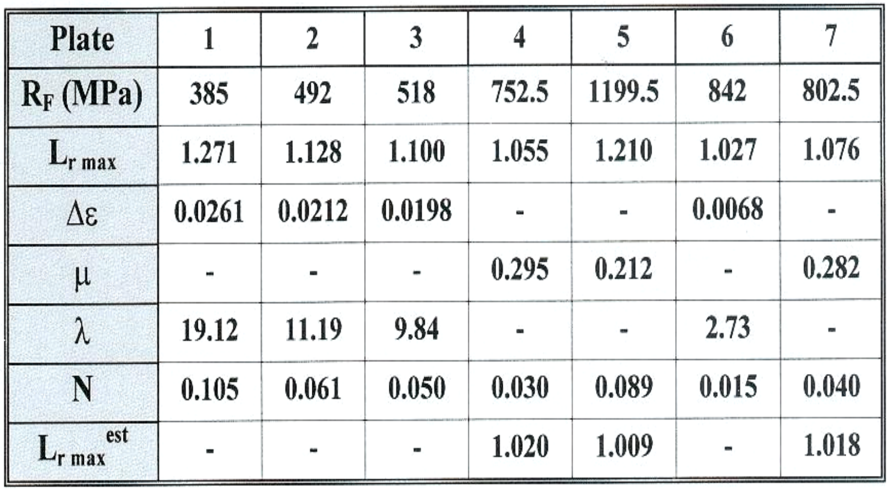


Plate	1	2	3	4	5	6	7
R_F (MPa)	385	492	518	752.5	1199.5	842	802.5
$L_{r\,max}$	1.271	1.128	1.100	1.055	1.210	1.027	1.076
$\Delta\varepsilon$	0.0261	0.0212	0.0198	-	-	0.0068	-
μ	-	-	-	0.295	0.212	-	0.282
λ	19.12	11.19	9.84	-	-	2.73	-
N	0.105	0.061	0.050	0.030	0.089	0.015	0.040
$L_{r\,max}^{est}$	-	-	-	1.020	1.009	-	1.018

Failure Assessment Diagram Parameters Derived from Tensile Data

TOUGHNESS

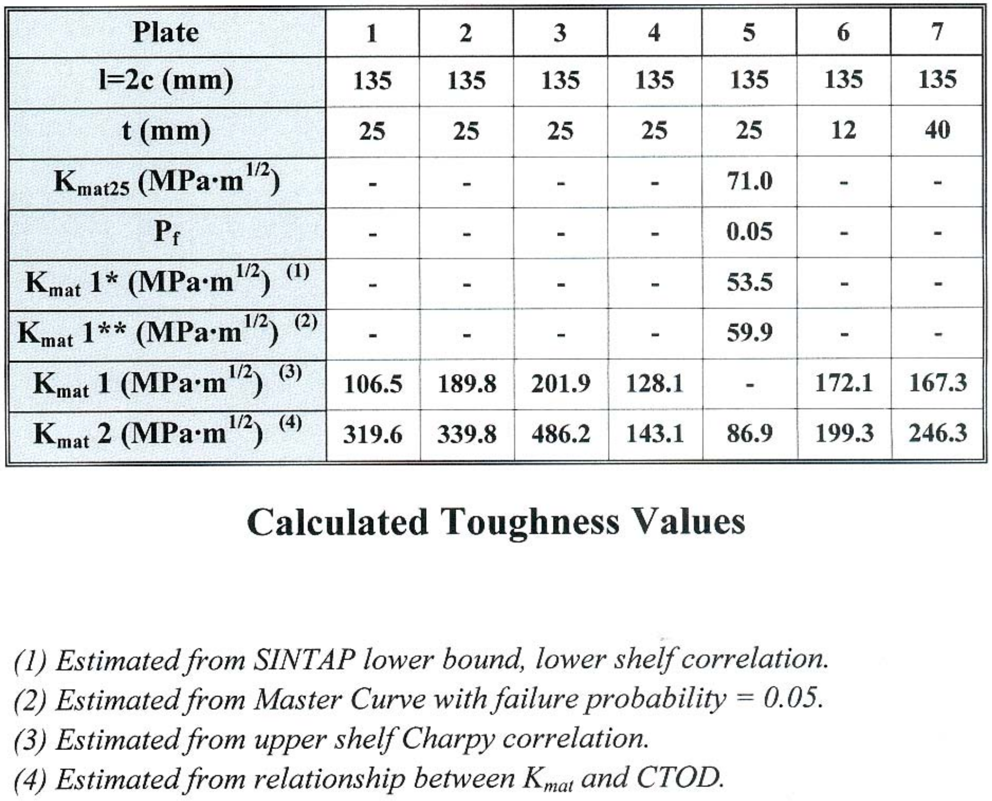


Plate	1	2	3	4	5	6	7
l=2c (mm)	135	135	135	135	135	135	135
t (mm)	25	25	25	25	25	12	40
K_{mat25} (MPa·m$^{1/2}$)	-	-	-	-	71.0	-	-
P_f	-	-	-	-	0.05	-	-
K_{mat} 1* (MPa·m$^{1/2}$) (1)	-	-	-	-	53.5	-	-
K_{mat} 1** (MPa·m$^{1/2}$) (2)	-	-	-	-	59.9	-	-
K_{mat} 1 (MPa·m$^{1/2}$) (3)	106.5	189.8	201.9	128.1	-	172.1	167.3
K_{mat} 2 (MPa·m$^{1/2}$) (4)	319.6	339.8	486.2	143.1	86.9	199.3	246.3

Calculated Toughness Values

(1) Estimated from SINTAP lower bound, lower shelf correlation.
(2) Estimated from Master Curve with failure probability = 0.05.
(3) Estimated from upper shelf Charpy correlation.
(4) Estimated from relationship between K_{mat} and CTOD.

FORMULATION AND CALCULUS

Plate	1	2	3	4	5	6	7
a real (mm)	5	6.5	6.8	5.5	5	3.1	8.4
a nominal (mm)	-	5	5	5	-	-	-

Crack Dimensions Considered

L_r (AII.42)

$$L_r = \frac{\sigma}{(1-\zeta)\sigma_Y}$$

where

$$\zeta = \frac{al}{t(l+2t)}$$

K_I (AI.3) -deepest point of the crack-

$$K_I = \sigma f_0 \sqrt{\pi a}$$

(Linear interpolation has been used for the determination of f_0)

Plate	1	2	3	4	5	6	7
ζ (real a)	0.1459	0.1897	0.1985	0.1605	0.1459	0.2193	0.1319
f_0 (real a)	1.2151	1.2904	1.3026	1.2421	1.2151	1.3991	1.1753
ζ (nominal a)	-	0.1459	0.1459	0.1459	-	-	-
f_0 (nominal a)	-	1.2151	1.2151	1.2151	-	-	-

ζ and f_0 Values for each Plate and Crack Combination

DIAGRAMS

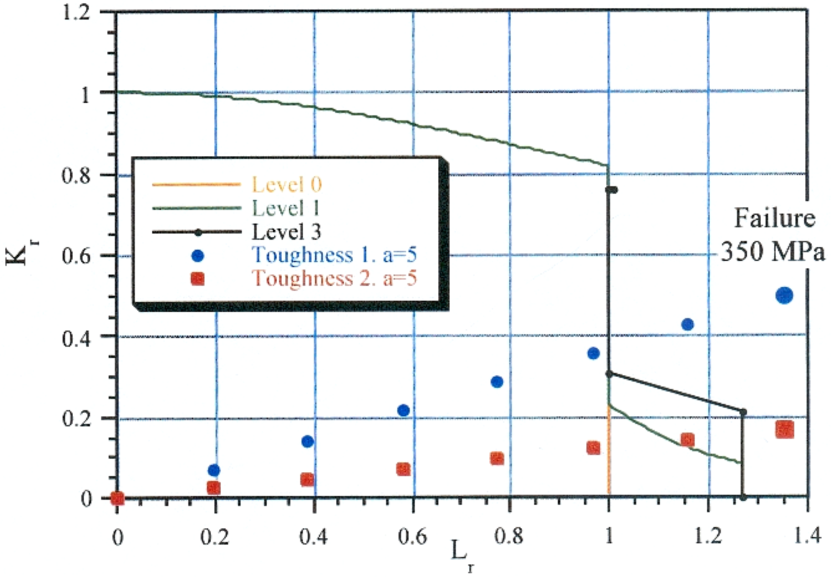


Plate 1

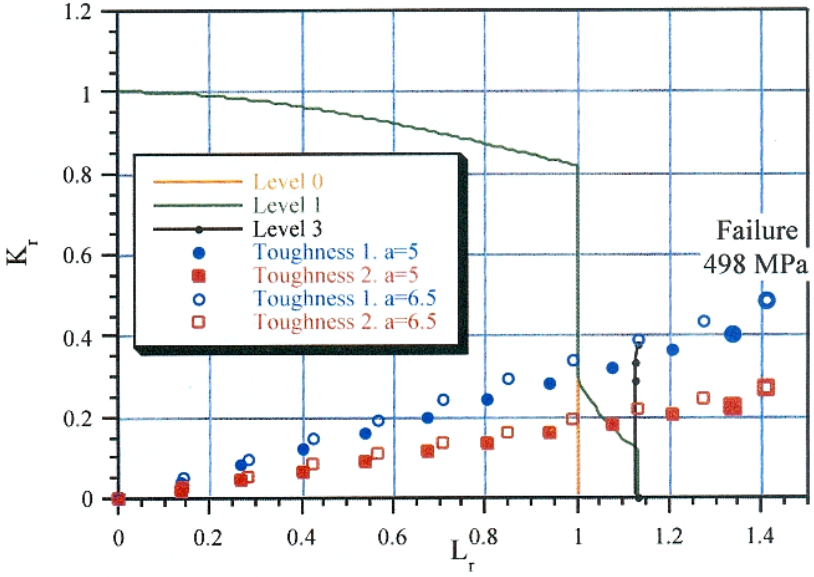


Plate 2

DIAGRAMS

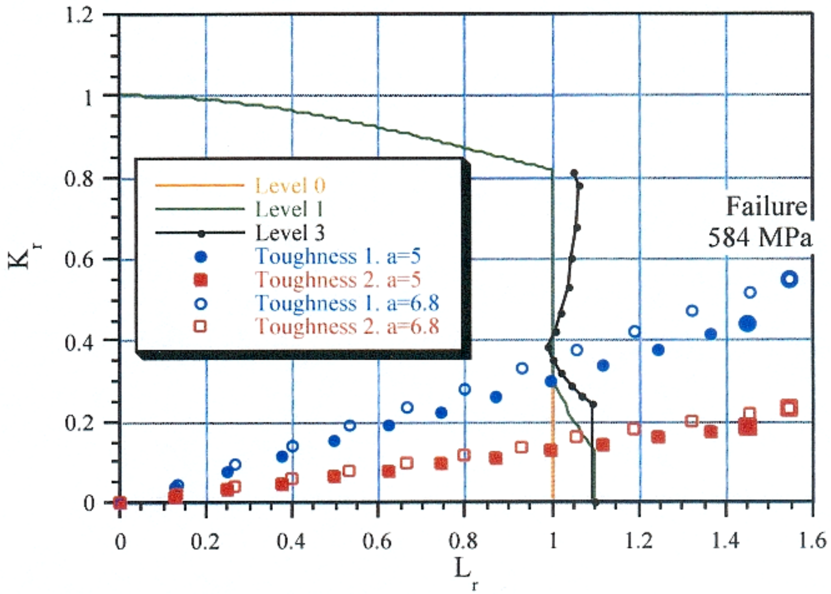


Plate 3

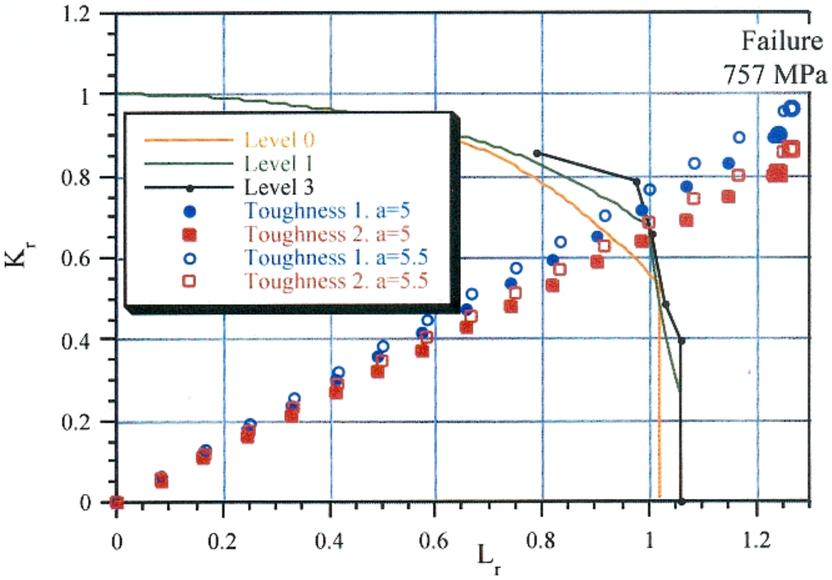


Plate 4

DIAGRAMS

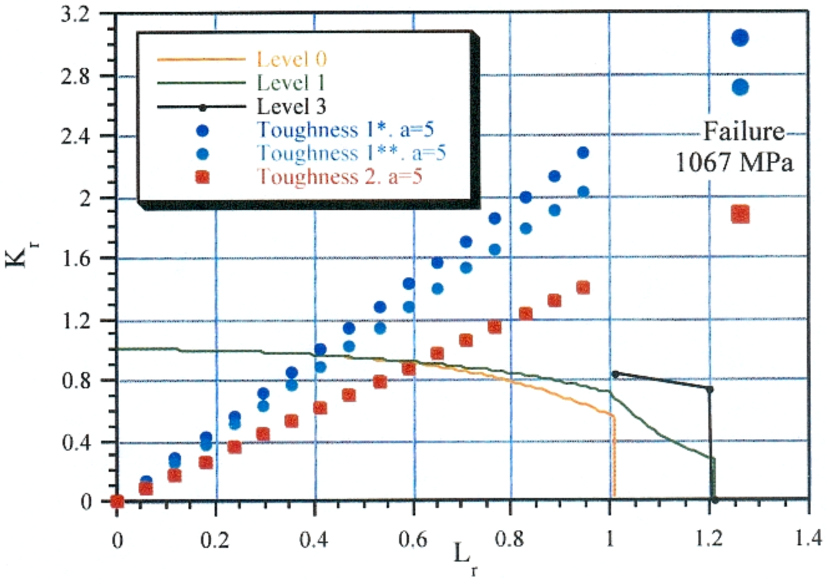


Plate 5

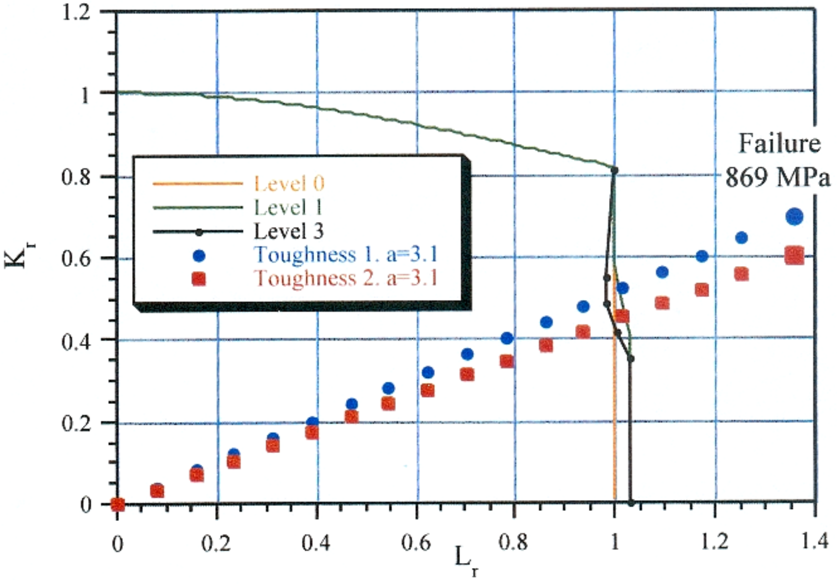


Plate 6

DIAGRAMS

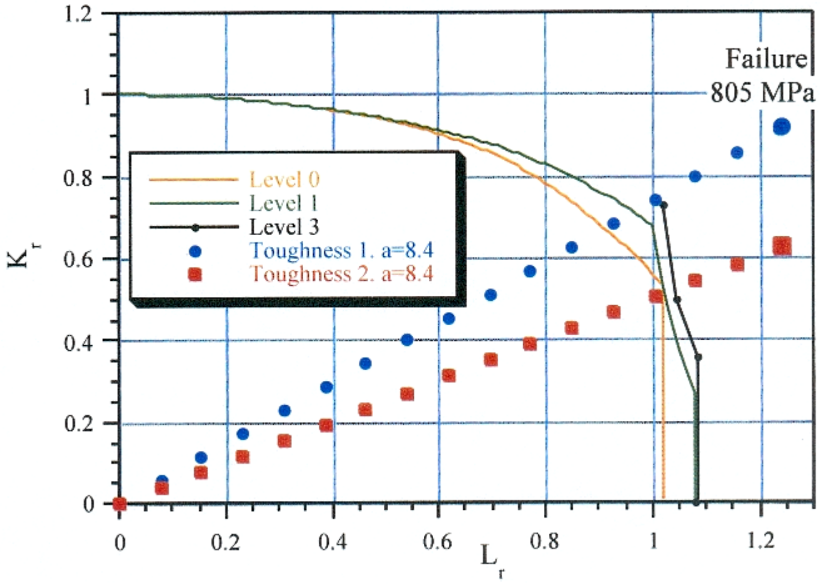
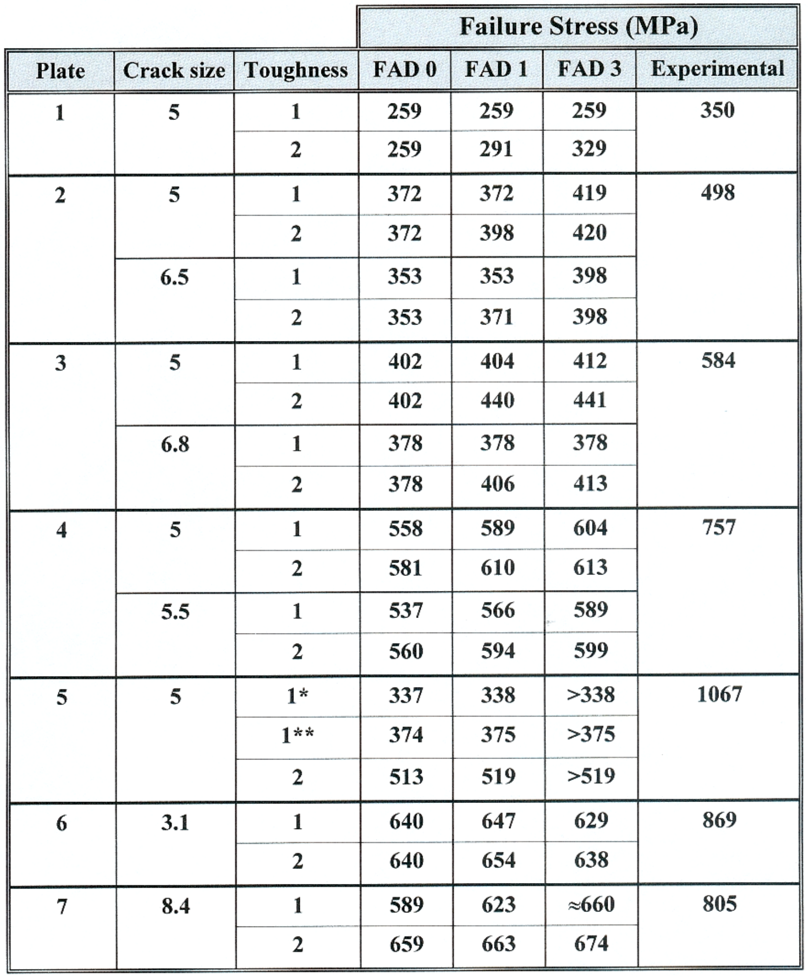


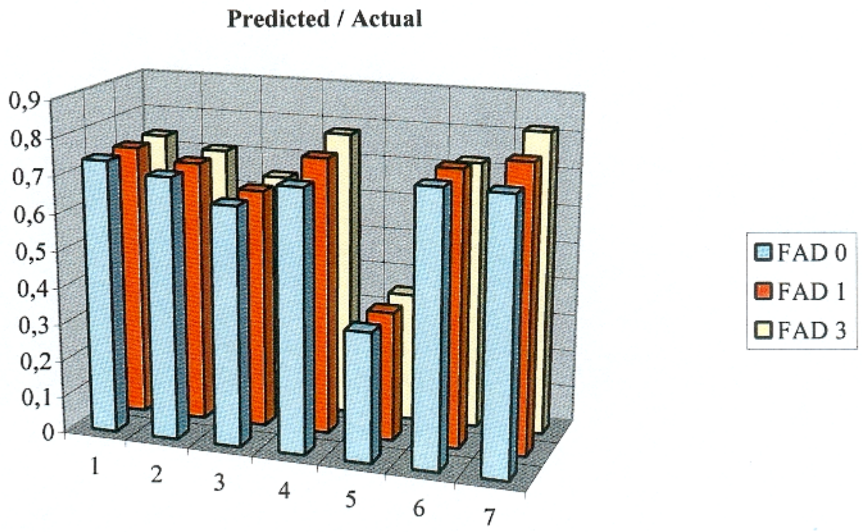
Plate 7

RESULTS

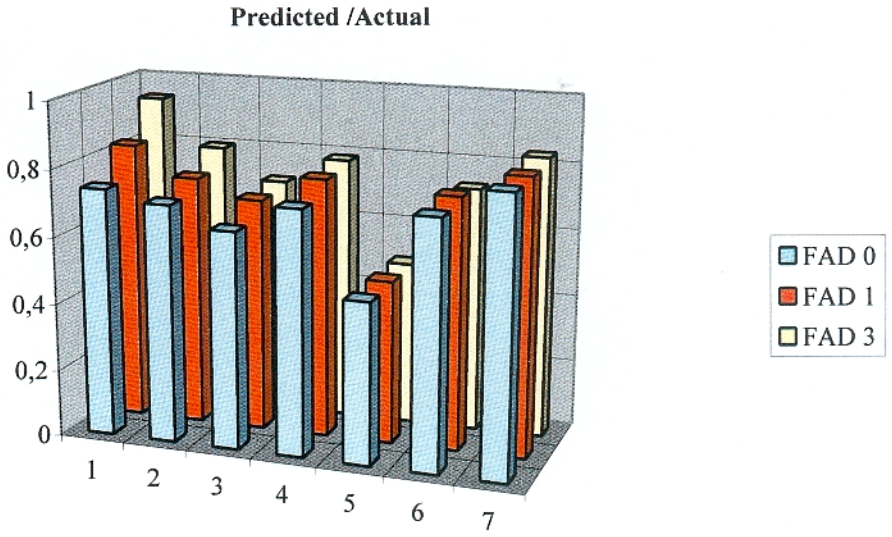


			Failure Stress (MPa)			
Plate	**Crack size**	**Toughness**	**FAD 0**	**FAD 1**	**FAD 3**	**Experimental**
1	5	1	259	259	259	350
		2	259	291	329	
2	5	1	372	372	419	498
		2	372	398	420	
	6.5	1	353	353	398	
		2	353	371	398	
3	5	1	402	404	412	584
		2	402	440	441	
	6.8	1	378	378	378	
		2	378	406	413	
4	5	1	558	589	604	757
		2	581	610	613	
	5.5	1	537	566	589	
		2	560	594	599	
5	5	1*	337	338	>338	1067
		1**	374	375	>375	
		2	513	519	>519	
6	3.1	1	640	647	629	869
		2	640	654	638	
7	8.4	1	589	623	≈660	805
		2	659	663	674	

ANALYSIS



Real Cracks, Charpy Toughness



Real Cracks, CTOD Toughness

BIBLIOGRAPHY / REFERENCES

- Ruiz Ocejo J. and Gutiérrez-Solana F., “SINTAP Validation Report”, June 1999

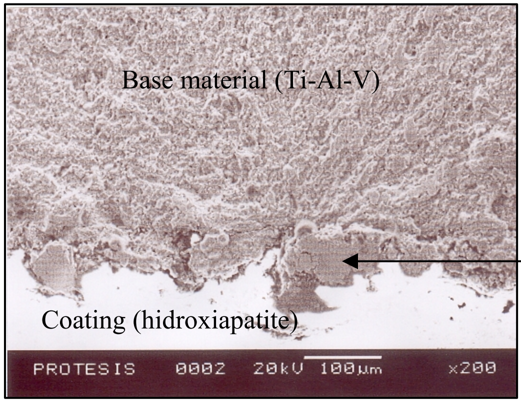
CASE STUDY EXAMPLE

Hip Implant

- **Introduction: The Case Study**
- **Geometry**
- **Material Properties**
- **Objectives**
- **Failure Analysis**
- **Summary**

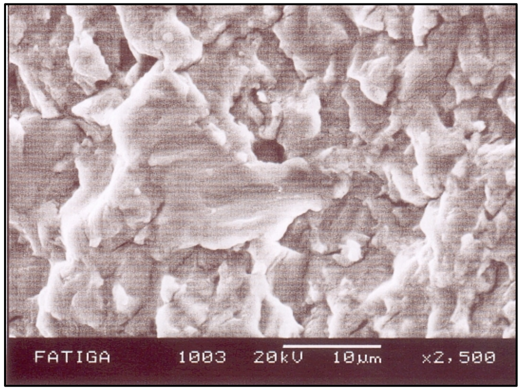
INTRODUCTION: THE CASE STUDY

Hip implant

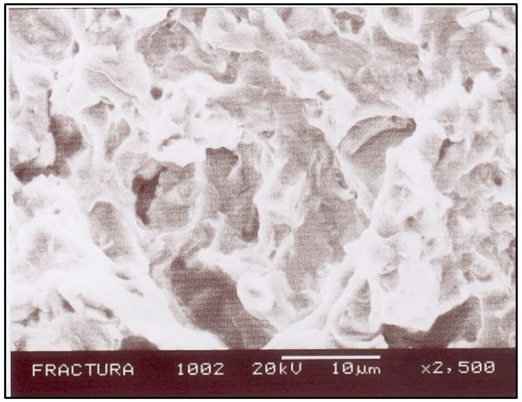


Fatigue initation at the Ti coating where some notches were observed

Irregular Ti coating

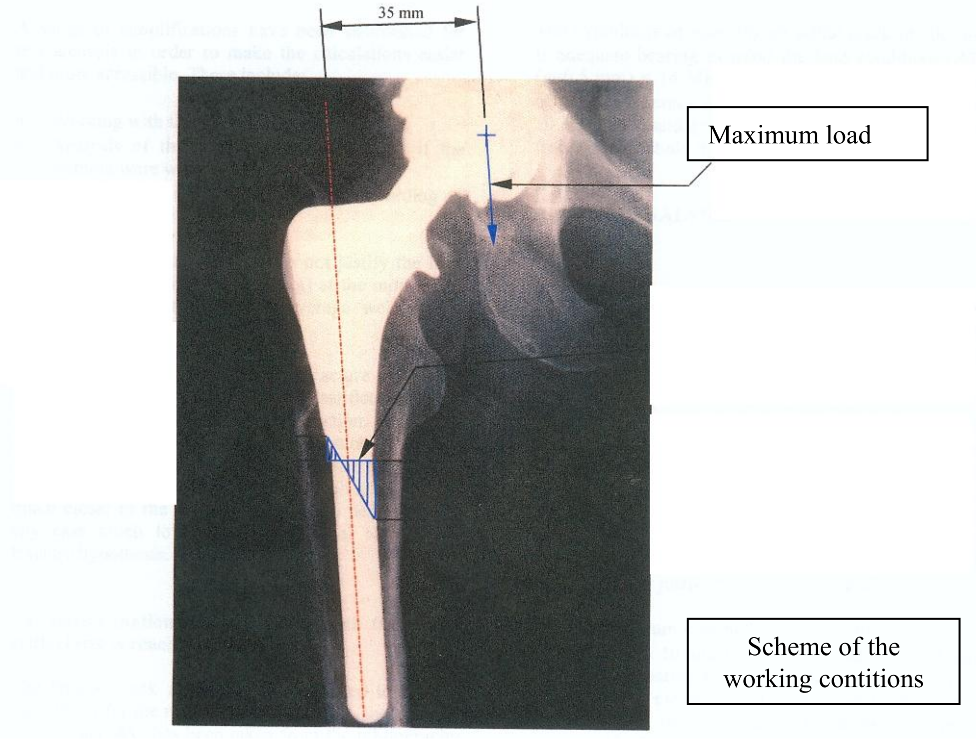


Fatigue propagation



Microvoids of the fracture surface

GEOMETRY

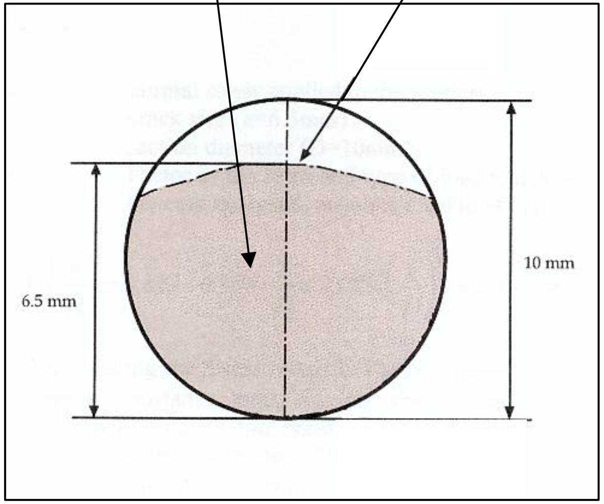


Maximum load

Scheme of the working contitions

Crack propagation by fatigue

Crack front at critical condition



a = 6.5 mm D = 10 mm

Schema of the fracture surface

MATERIAL PROPERTIES

K_{IC} = 110 MPa·m $^{1/2}$

σ_Y = 895 MPa

σ_u = 1000 MPa

E = 114 GPa

$da/dN = 3.54\ 10^{-14} * (\Delta K)^{4.19}$

when ΔK is given in MPa$m^{0.5}$ and da/dN in m/cycles

OBJECTIVES:

- FAILURE ANALYSIS
- NUMBER OF CYCLES BEFORE FAILURE CONSIDERING AN INITIAL DEFFECT OF O.1 mm.

FAILURE ANALYSIS:

DETERMINATION OF THE LOAD SUPPORTED AS A FUNCTION OF THE FRACTURE PARAMETERS:

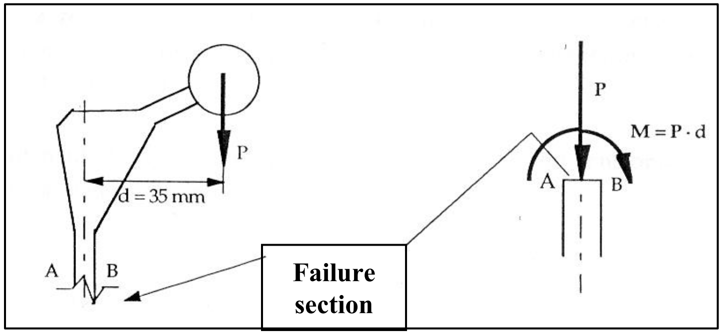
stress state = compression + pure bend

$$\sigma_{T,max} = \sigma_F - \sigma_C$$

where:

$$\sigma_F = 32 \cdot M / \pi \cdot D^3$$

$$\sigma_C = 4 \cdot P / \pi \cdot D^2$$



FAILURE ANALYSIS:

Many studies have been developed in order to know the peak forces that appear in a hip implant when the patient is walking. A value of 2.5 BW (Body Weight) seems to be reasonable.

Three different steps are distinguished during the process that starts with the operation and finishes with the failure of the hip implant:

- ***Crack nucleation*: It is considered very short, because there are defects at t = 0**
- ***Quick propagation*: We are going to consider that the patient has a "normal" activity. We will supose that he/she walks 2 hours per day with 1 step per second (0.5 cycles/second). Peak forces are 2.5 BW.**
- ***"Slow" propagation*: After the propagation of the second step, the patient starts to suffer pain. Therefore, he/she reduces his/her activity (1 hour/day) and uses crutches. Peak forces are now 1.0 BW. Failure occurs in this step, so if we want to obtain the load that produces it, no dynamic effect has to be considered.**

The whole process takes 9 months.

FAILURE ANALYSIS:

-The stress intensity factor, which characterises the stress state in the crack front, is defined by the expression:

$$K_I = \sigma \cdot Y_F(a/D) \cdot (\pi \cdot a)^{1/2}$$

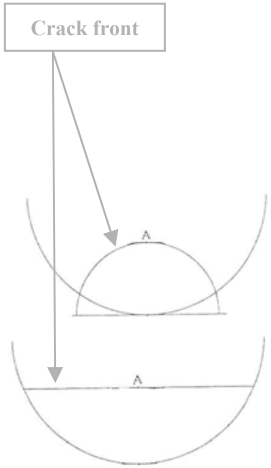
where:

σ : normal stress applied to the section

a : crack size (a = 6.5 mm)

D : section diameter (D = 10 mm)

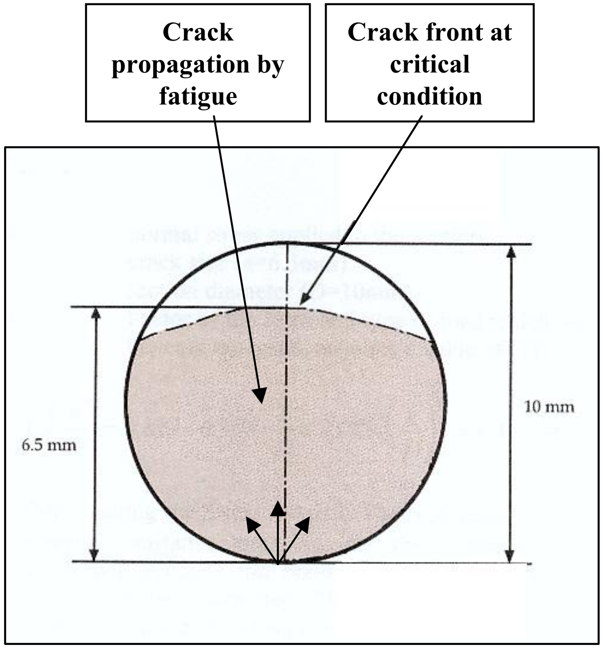
Y_F = geometric factor. In this case, this acquires a value of:



$$\left\{\begin{array}{l} Y_F(a/D) = g \cdot (0.953 + 0.199 \cdot (1 - \sin(\psi))^4) = 1.41 \\ g = 0.5857 \cdot (\tan\psi) / \psi)^{0.5} / \cos\psi \\ \psi = \pi \cdot a / 4 \cdot R \end{array}\right\} \quad \text{(API 579)}$$

$$\left\{ Y_F(a/D) = 1.04 - 3.64 \cdot (a/D) + 16.86 \cdot (a/D)^2 - 32.59 \cdot (a/D)^3 + 28.41 \cdot (a/D)^4 = 1.92 \right.$$

(API 579)


Crack propagation by fatigue

Crack front at critical condition

a = 6.5 mm D = 10 mm

Schema of the fracture surface

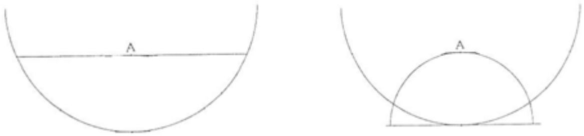
FAILURE ANALYSIS:

- CLASSIC LEFM.

Some simplifications have been established for this analysis in order to make the calculations easier and more accesible. These include:

- **Working with the piece in projection**
- **Analysis of the stress intensity factor as if the element were working in pure bend**
- **Fracture toughness of the material according to reference value**

$$K_I = K_{IC}$$



$\sigma \cdot Y(a/D) \cdot (\pi \cdot 0.0065)^{1/2} = 110 \longrightarrow$ $\sigma = 401$ MPa $\quad \sigma = 546$ MPa

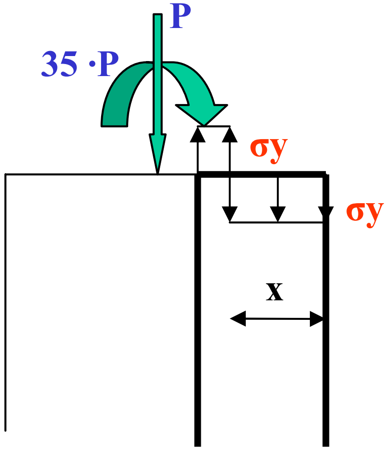
$\sigma = 32 \cdot M/\pi \cdot D^3 - 4 \cdot P/\pi \cdot D^2 \longrightarrow$ $P = 1.17$ kN $\quad P = 1.66$ kN

However, these simplifications do not justify the high value resulting from load P (1.66 kN / 1.17 kN) at the moment of fracture, with reference to the average weight of a person (0.75 kN).

FAILURE ANALYSIS:

- **LIMIT LOAD SOLUTION.**

A second hypothesis of fracture has been considered: the generalised plastification of the remaining ligament in the cracked section. Therefore a FAD will be used. Considering the yield stress 895 MPa, it is obtained that the limit load is 0.56 kN for a straight front crack and 0.89 kN for a semicircular crack, much closer to the average weight of a person and in any case much lower than the critical size of the fracture hypothesis.



$$\left.\begin{aligned}\Sigma M_{load} &= \Sigma M_{stress}\\ \Sigma F_{load} &= \Sigma F_{stress}\end{aligned}\right\}$$ **AT ANY POINT**

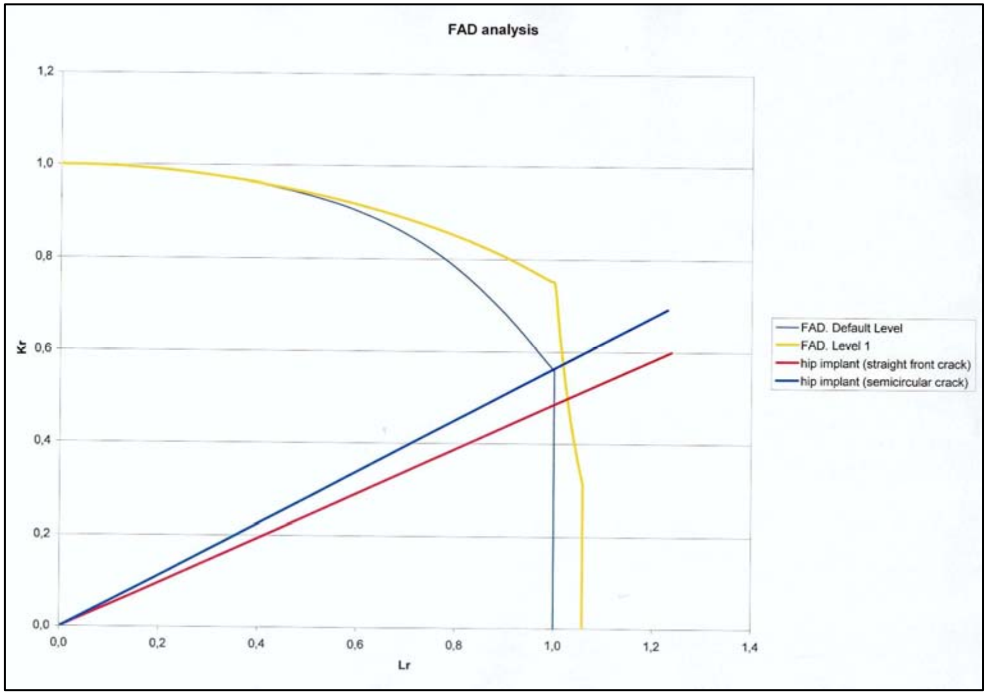
WE CAN OBTAIN P AND x.

P = 0.566 kN (straight front crack)

P = 0.895 kN (semicircular crack)

FAILURE ANALYSIS:

FAD:



Default level:	**P = 0,566 kN**	**P = 0.895 kN**
Level 1:	**P = 0,582 kN**	**P = 0.915 kN**

1) Loading critical conditions according to normal weight (real situation: 0.735 kN).

2) Final failure due to plastic collapse of residual ligament.

3) Good agreement with fractographic analisys and common sense.

FAILURE ANALYSIS:

DETERMINATION OF THE CRACK GROWTH TIME UNTIL CRITICAL SIZE IS REACHED:

-The fatigue crack growth time is adjusted to a Paris law, which has been taken from the bibliography and is given by equation:

$$da/dN = 3.54\ 10^{-14} * (\Delta K)^{4.19} \qquad (1)$$

when ΔK is given in $MPam^{0.5}$ and da/dN in m/cycle

- The load cycle to which the element is subjected varies from 0, support from the other leg or repose, up to 631.5 MPa, corresponding to the weight of 0.735 kN and peak forces of 2.5 BW. Thus the ΔK_I will have a value, depending on a, given by

$$\Delta K_I = Y_F(a/D) \cdot 631.5 \cdot (\pi \cdot a)^{1/2} \qquad (2)$$

-Taking as the initial crack length a_o = 0.1 mm, introducing expression (2) in (1) and integrating this, the number of cycles required for the crack to reach the critical size of 6.5 mm is obtained. The number is between 145.738 cycles (straight front crack) and 539.088 (semicircular crack).

FAILURE ANALYSIS:

DETERMINATION OF THE CRACK GROWTH TIME UNTIL CRITICAL SIZE IS REACHED:

a (mm)	a med (mm)	Y (straight)	Y (f.semic.)	ΔN (straight)	ΔN (semic.)	N (straight)	N (semic.)
0,1 - 0,5	0,30	0,945	0,660	108999	490750	108999	490750
0,5 - 1	0,75	0,849	0,644	18829	59855	127828	550605
1 - 1,5	1,25	0,792	0,635	7961	20040	135789	570645
1,5 - 2	1,75	0,771	0,635	4294	9709	140083	580354
2 - 2,5	2,25	0,776	0,643	2449	5377	142533	585731
2,5 - 3	2,75	0,799	0,661	1420	3139	143953	588870
3 - 3,5	3,25	0,836	0,689	824	1857	144777	590727
3,5 - 4	3,75	0,889	0,728	471	1089	145248	591816
4 - 4,5	4,25	0,963	0,781	259	623	145507	592438
4,5 - 5	4,75	1,069	0,852	133	343	145640	592781
5 - 5,5	5,25	1,218	0,945	62	180	145702	592961
5,5 - 6	5,75	1,431	1,071	26	88	145728	593049
6 - 6,5	6,25	1,729	1,242	10	40	**145738**	**593088**
BW = 2.5						**N TOTAL**	

FAILURE ANALYSIS:

DETERMINATION OF THE CRACK GROWTH TIME UNTIL CRITICAL SIZE IS REACHED:

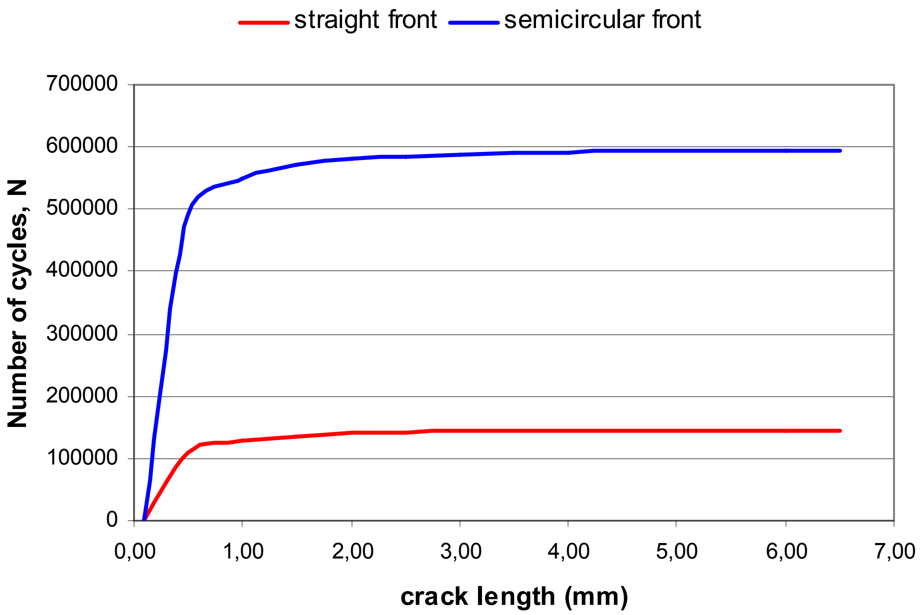
a (mm)	a med (mm)	Y (straight)	Y (f.semic.)	ΔN (straight)	Δ N (semic.)	N (straight)	N (semic.)
0,1 - 0,5	0,30	0,945	0,660	5067464	22815433	5067464	22815433
0,5 - 1	0,75	0,849	0,644	667745	2122708	5735208	24938140
1 - 1,5	1,25	0,792	0,635	291380	733428	6026589	25671568
1,5 - 2	1,75	0,771	0,635	158425	358205	6185014	26029773
2 - 2,5	2,25	0,776	0,643	90659	199035	6275672	26228808
2,5 - 3	2,75	0,799	0,661	52641	116360	6328313	26345168
3 - 3,5	3,25	0,836	0,689	30590	68903	6358903	26414071
3,5 - 4	3,75	0,889	0,728	17494	40417	6376397	26454488
4 - 4,5	4,25	0,963	0,781	9609	23124	6386006	26477612
4,5 - 5	4,75	1,069	0,852	4930	12740	6390936	26490352
5 - 5,5	5,25	1,218	0,945	2305	6673	6393241	26497025
5,5 - 6	5,75	1,431	1,071	970	3275	6394211	26500299
6 - 6,5	6,25	1,729	1,242	369	1478	**6394580**	**26501777**
BW = 1.0						**N TOTAL**	

FAILURE ANALYSIS:

DETERMINATION OF THE CRACK GROWTH TIME UNTIL CRITICAL SIZE IS REACHED.

INTERPRETATION OF RESULTS:

According with the conditions proposed for "normal" life (2.5 BW), the cycles obtained represent between 1.3 and 4.6 months of quick propagation before failure, depending on the crack front shape. However, the propagation under these conditions finished a few thousands of cycles before, when the patient starts to feel pain and, then, a new stage starts under new loading conditions (1.0 BW). The Figure shows that wherever the quick propagation finishes, it takes around 140000 cycles in case the crack front is straight or 500000 cycles in case the crack front is semicircular.



FAILURE ANALYSIS:

DETERMINATION OF THE CRACK GROWTH TIME UNTIL CRITICAL SIZE IS REACHED.

INTERPRETATION OF RESULTS:

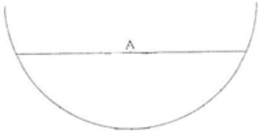
Considering that there is no nucleation time due to the notch effect and adding a quick propagation step of 1.3 months (equivalent to near 140.000 cycles) for a straight front crack and 4.6 months (equivalent to near 500.000 cycles) for a semicircular crack, the duration of the final stage (BW=1.0) can be obtained. This is 7.7 months for a straight front and 4.4 months for a semicircular front. This is equivalent to 415.800 and 237.600 cycles respectively. If we start to count the cycles from the end to the beginning of the process, we obtain that such numbers are the amount of cycles that are necessary for a growth from 1.5 mm to 6.5 mm (straight) or from 2.0 mm to 6.5 mm (semicircular). As a summary, a fatigue process can be suggested as follows:

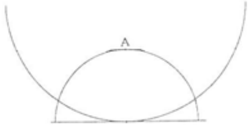
-No crack nucleation, as initial notches of 0.1 mm have been detected.

-STAGE 1: Propagation with dynamic effects, from 0.1 mm to a value between 1.5 and 2.0 mm. Taking mean values, this would take about 3 months (between 1.3 and 4.6).

-STAGE 2: Propagation without dynamic effects. This takes the rest of the implant life (an average of 6 months).

SUMMARY:





	Incubation	Quick propagation	Propagation without dynamic effect
STRAIGHT FRONT CRACK	**0 months**	**1.3 months/ 1.5 mm**	**7.7 months/ 6.5 mm**
SEMICIRCULAR CRACK	**0 months**	**4.5 months/ 2.0 mm**	**4.5 months/ 6.5 mm**

CASE STUDY EXAMPLE

Forklift

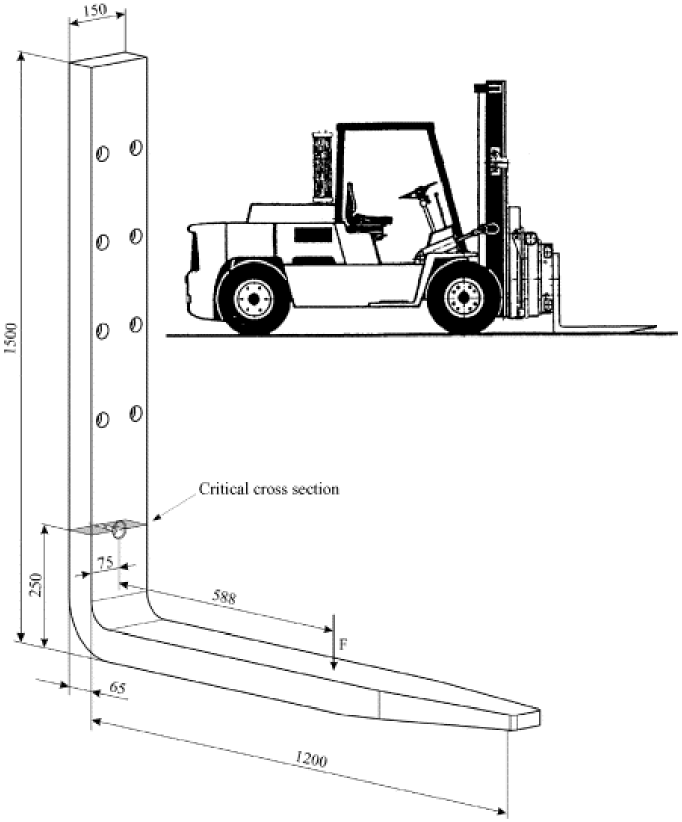
- **Introduction: The Case Study**
- **Geometry**
- **Material Properties**
- **Failure Analysis**
- **Conclusions**
- **Bibliography**

INTRODUCTION: THE CASE STUDY

A fork of a forklift broke in a brittle manner during transportation of an aluminium block of a weight of less than 3.5 tonnes, while the load carrying capacity the load was designed for is 3.5 tonnes.

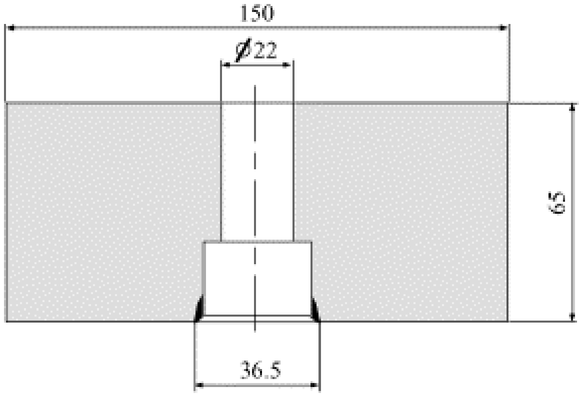
The failure happened at a temperature of 10ºC

The aim of the present investigation is to figure out whether failure had to be expected for nominal loading and material conditions or if any other reason such as overloading or deficient material properties were the reason of failure.



GEOMETRY

The dimensions of the relevant cross section where fracture occurred are shown in the figure.

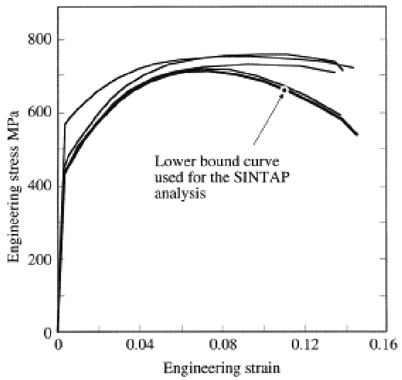


Failure analysis revealed that failure occurred at the bottom hole originating from small edge cracks at the front face at either side of the hole. The crack lengths at surface were 3 and 10 mm respectively.

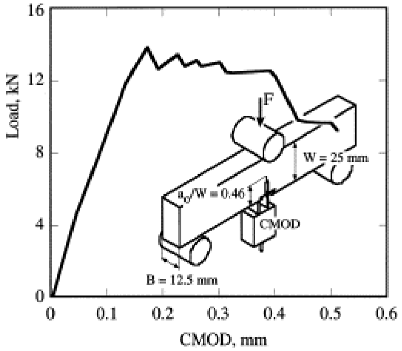
MATERIAL PROPERTIES

The engineering stress-strain curve of the material is shown in the figure. Five tests where carried out but only the lowest curve was used for the analysis. The true stress-strain curve are determined by:

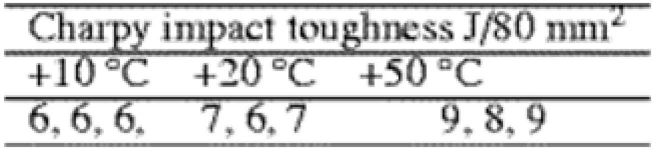
$$\varepsilon_{true} = \ln\ (1 + \varepsilon)\ \text{and}\ \sigma_{true} = \sigma\ (1 + \varepsilon)\,.$$



The fracture toughness was determined in terms of the CTOD according to the BS 7448. The result was δ_c =0.02 mm, corresponding to K_{mat} =49.7 MPam$^{1/2}$.



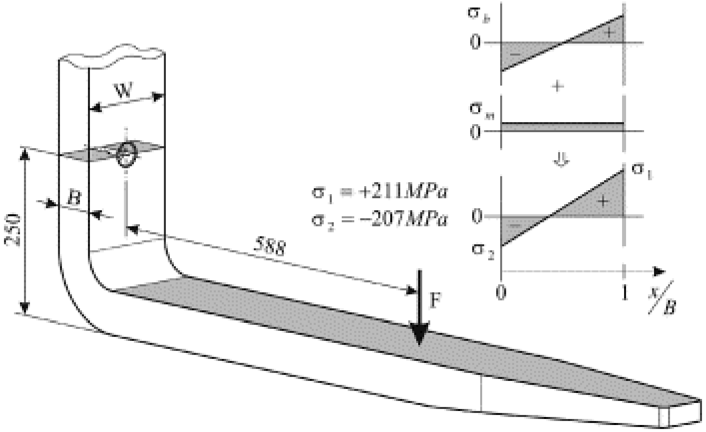
Charpy tests were performed as well. The results were:



Charpy impact toughness J/80 mm^2		
+10 °C	+20 °C	+50 °C
6, 6, 6.	7, 6, 7	9, 8, 9

FAILURE ANALYSIS (I)

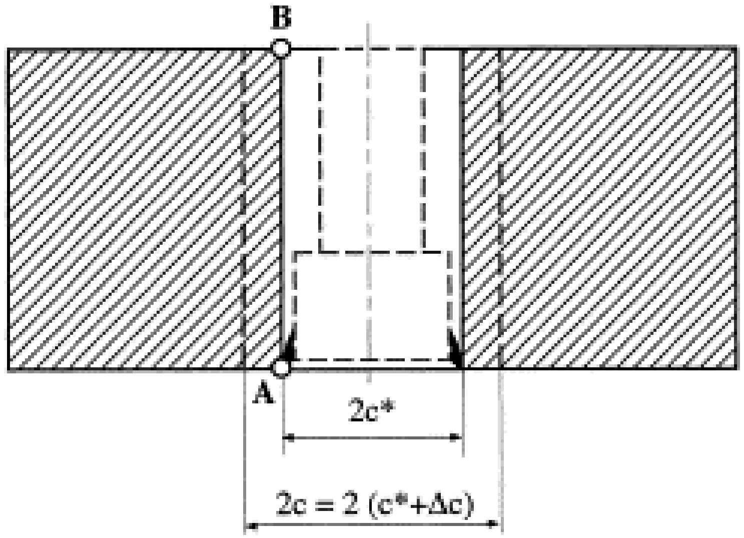
The loading type was predominantly bending, which would have allowed for the application of a simple analytical model for determining the bending stress. However, in order to consider also the membrane stress component, a finite element analysis was carried out, which gave the stress profile shown in the figure.



Based on this information σ_b =209 MPa and σ_m=2 MPa were determined. These values refer to one half of the nominal applied force of 35 KN, which the fork lift was designed for.

FAILURE ANALYSIS (II)

The two edge cracks are substituted by one through crack whose dimensions include the hole diameter as demonstrated in the figure. For simplicity the crack is assumed to be of constant length 2c over the wall thickness.



FAILURE ANALYSIS (III)

FAD analysis require the obtainment of parameters L_r and K_r. Here is the SINTAP formulation for the case studied:

$$L_r = F/F_Y = \sigma_{ref}/\sigma_Y$$

$$\sigma_{ref} = \frac{1}{1-(2c/W)}\left\{\frac{\sigma_b}{3}+\sqrt{\frac{\sigma_b^2}{9}+\sigma_m^2}\right\}$$

$$K_r = K_I/K_C$$

$$K_I(c,F) = \sqrt{\pi c}(\sigma_m \cdot f_m + \sigma_b \cdot f_b).$$

f^A_m=1 and f^A_b=1 for point A and f^B_m=1 and $f^B_b=-1$ *for point B*

FAILURE ANALYSIS (IV)

Default, Basic and Advanced level can be performed.

DEFAULT level formulation:

$$f(L_r) = \left[1+\frac{1}{2}L_r^2\right]^{-1/2} \times \left[0.3+0.7\exp\left(-0.6\,L_r^6\right)\right] \quad \text{for } 0 \leqslant L_r \leqslant L_{r\,\max}.$$

$$L_{r\,\max} = 1 + \left[\frac{150}{R_{p\,0.2}}\right]^{2.5}, \; R_{p0.2} \text{ in MPa.}$$

$$K_{mat} = \left[\left(12\sqrt{KV}-20\right)\times\left({}^{25}/_{B}\right)^{1/4}\right]+20$$

FAILURE ANALYSIS (V)

BASIC level formulation:

$$f(L_r) = \left[1 + \frac{1}{2}L_r^2\right]^{-1/2} \times \left[0.3 + 0.7\exp\left(-\mu L_r^6\right)\right] \quad \text{for } 0 \leqslant L_r \leqslant 1$$

$$\mu = \min \begin{bmatrix} 0.001\, E/R_{p0.2} \\ 0.6 \end{bmatrix}$$

$$f(L_r) = f(L_r = 1) \times L_r^{(N-1)/2N} \quad \text{for } 1 \leqslant L_r < L_{r\,max}$$

$$N = 0.3\left[1 - \frac{R_{p0.2}}{R_m}\right]$$

$$L_{r\,max} = \frac{1}{2}\left[\frac{R_{p0.2} + R_m}{R_{p0.2}}\right].$$

FAILURE ANALYSIS (VI)

ADVANCED level formulation:

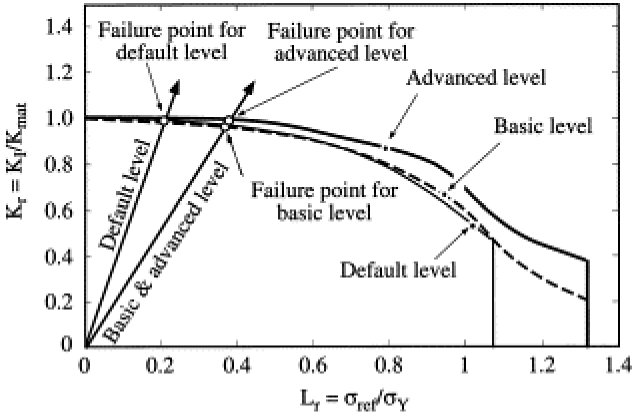
$$f(L_r) = \left[\frac{E\,\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\,\frac{L_r^2}{\left(E\,\varepsilon_{ref}/\sigma_{ref}\right)} \right]^{-1/2} \quad \text{for } 0 \leqslant L_r \leqslant L_{r\,max}$$

$$L_{r\,max} = \frac{\sigma_f}{\sigma_Y} \text{ with } \sigma_f = \frac{1}{2}\left(\sigma_Y + R_m\right).$$

FAILURE ANALYSIS (VII)

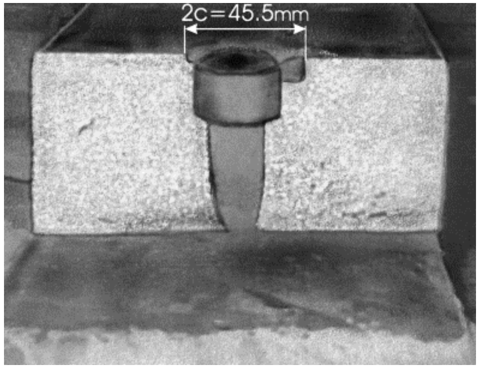
As the final result the critical crack size was determined to be

- **2c = 10.35 mm (default level analysis)**
- **2c = 33.2 mm (basic level analysis)**
- **2c = 35.6 mm (advanced level analysis).**



Compared to the real overall surface dimension of the edge cracks at failure of 45.5 mm the predictions were conservative by

- **77.28% (default level analysis)**
- **27.03% (basic level analysis)**
- **21.75% (advanced level analysis)**



CONCLUSIONS

In conclusion, it can be stated that the failure occurred as the consequence of inadequate design and not of inadmissible handling such as overloading. The failure could have been avoided by applying fracture mechanics in the design stage. The SINTAP algorithm was shown to be an easy but suitable tool for this purpose

BIBLIOGRAPHY

Gubeljak, N., Zerbst, U., Predan, J., and Oblak, M., "Application of the european SINTAP procedure to the failure analysis of a broken forklift", Engineering Failure Analysis, Vol. 11, pp. 33-47, 2004

II. TRAINING PACKAGE ON FATIGUE

A. BASIC CONCEPTS

FATIGUE

FATIGUE DEFINITION

- **Engineering :** type of failure in materials that implies initiation and propagation of cracks in components subjected to cyclic loading that, generally, do not exceed the yield stress of the material.

- **Science :** behaviour of a material subjected to cyclic loads that implies plastic deformations, crack nucleation and propagation and failure.

FATIGUE

FATIGUE IMPORTANCE

- **Basic idea:** Monotonous loads do not produce fatigue damage. Loads must be variable
- **Examples:** from 19th century (bridges in UK) to now (ships, planes,..) many registered accidents.
- **Design**: Fatigue design of structures and components supported by procedures, Eurocode, ASME, API,..

FATIGUE

FATIGUE ASSESSMENT

Focusing the problem

- Fatigue life assessment can be performed in two ways:
  I. Estimation of the **total life** of the component, including incubation period.
  II. Life determination through the **propagation**, supposing the presence of existing conditions (cracks and a stress intensity factor amplitude or variation) over the threshold ones.

FATIGUE

FATIGUE ASSESSMENT

Focusing the problem

I. Estimation of Total Life is the classical way (Wöhler, Basquin, Goodman).

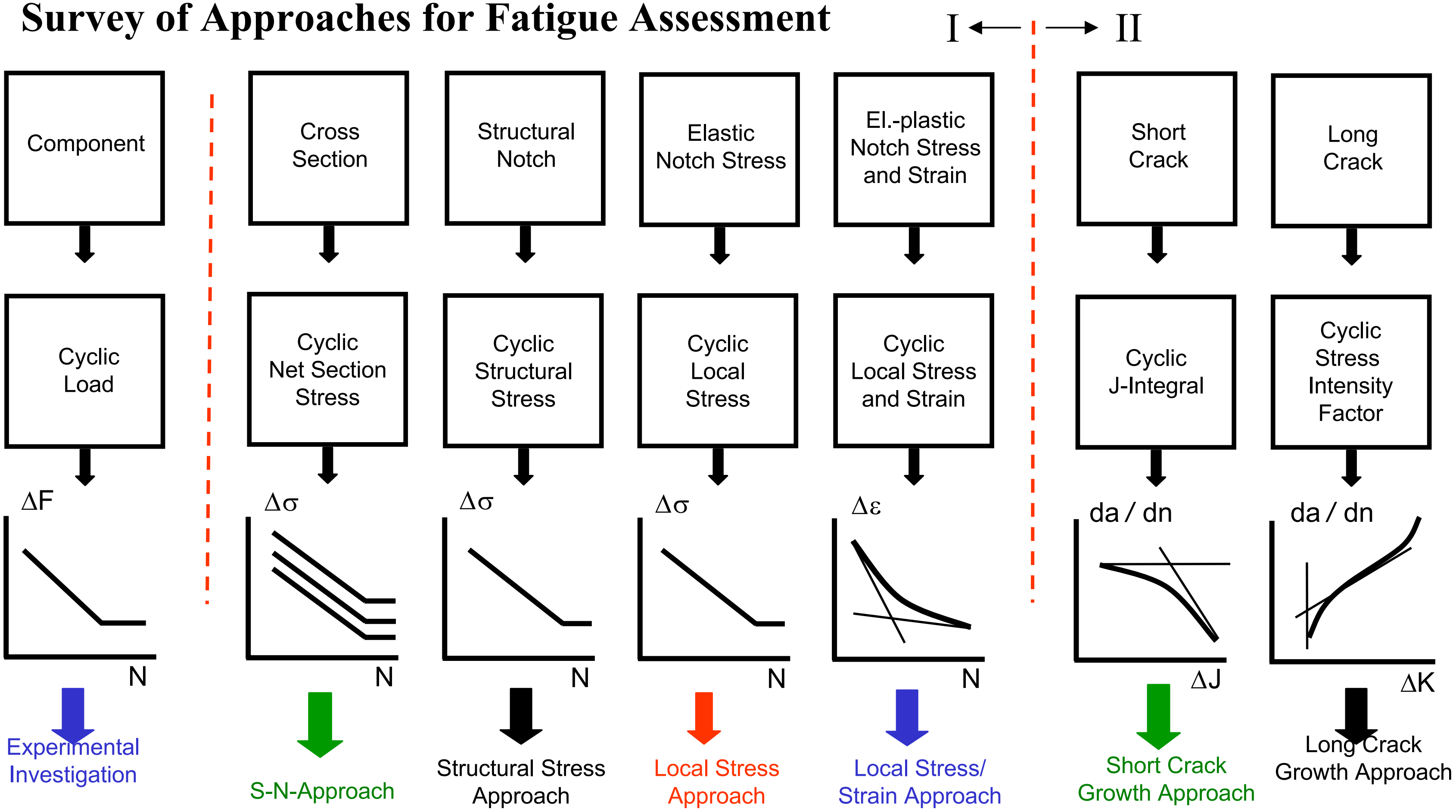
➢*Based on experimental and statistical studies, life can be determined from the knowledge of the applied stresses or the existent strains. The design parameter is the endurance*

➢*This approach distinguishes LCF (Low Cycling Fatigue) from HCF (High Cycling Fatigue). Also processes with no constant stresses can be assessed (Miner).*

II. Life determination based on crack propagation rate appears after the FM Paris works

FATIGUE FATIGUE ASSESSMENT

Survey of Approaches for Fatigue Assessment



Component → Cyclic Load → Experimental Investigation

Cross Section → Cyclic Net Section Stress → S-N-Approach

Structural Notch → Cyclic Structural Stress → Structural Stress Approach

Elastic Notch Stress → Cyclic Local Stress → Local Stress Approach

El.-plastic Notch Stress and Strain → Cyclic Local Stress and Strain → Local Stress/ Strain Approach

Short Crack → Cyclic J-Integral → Short Crack Growth Approach

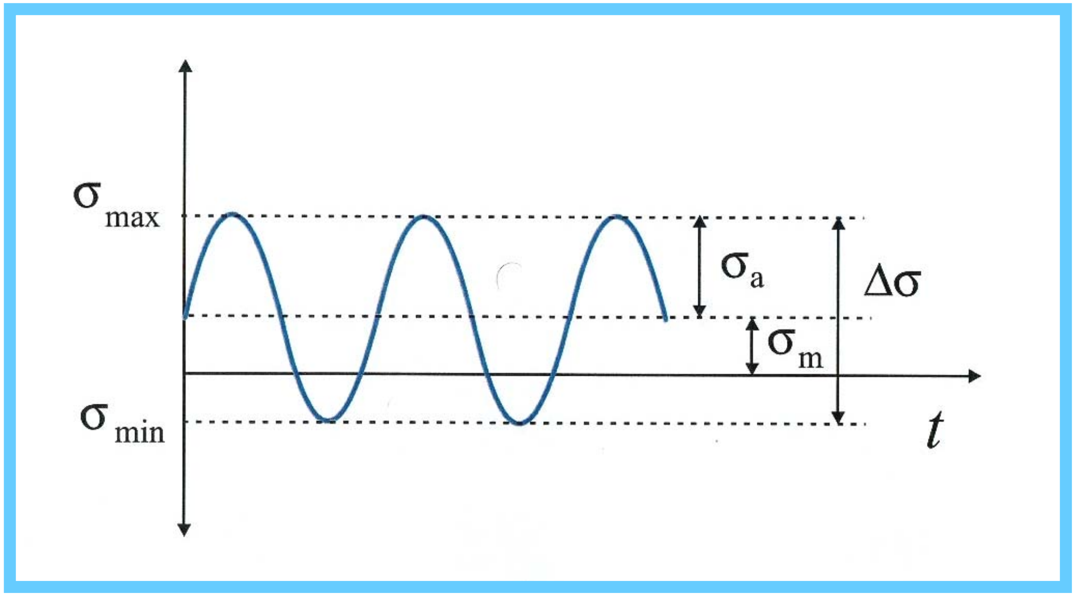
Long Crack → Cyclic Stress Intensity Factor → Long Crack Growth Approach

FATIGUE

CYCLIC LOADS

Definition and variables

- Evolution of the stresses during a constant cyclic loading process



FATIGUE

CYCLIC LOADS

Definition and variables

- Parameters characterising the fatigue process:

•**Stress amplitude:** $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$

•**Mean stress:** $\sigma_m = \frac{1}{2}\{\sigma_{\max} + \sigma_{\min}\}$

•**Stress Ratio:** $R = \frac{\sigma_{\min}}{\sigma_{\max}}$

•**Frecuency:** Measured in Hz (s^{-1})

- Generally, it only influences crack growth when it is accompanied by combined environmental effects (humidity, high temperatures, aggresive environments,…)

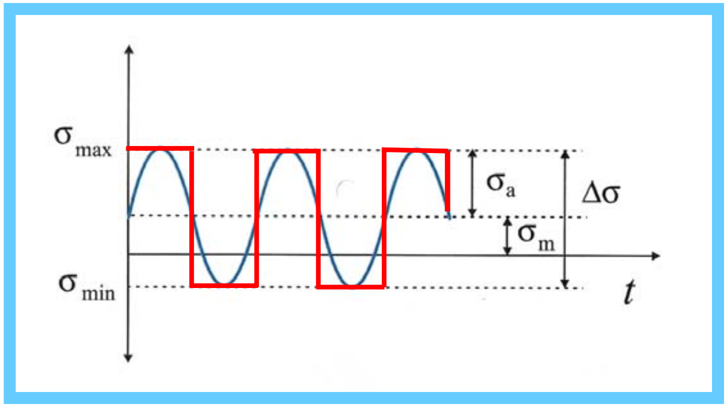
FATIGUE

CYCLIC LOADS

Definition and variables

- **Shape of the stress function:** Is it adjustable to a sine function, square,…

  - its influence on the crack growth is small, except when there is some environmental effect.



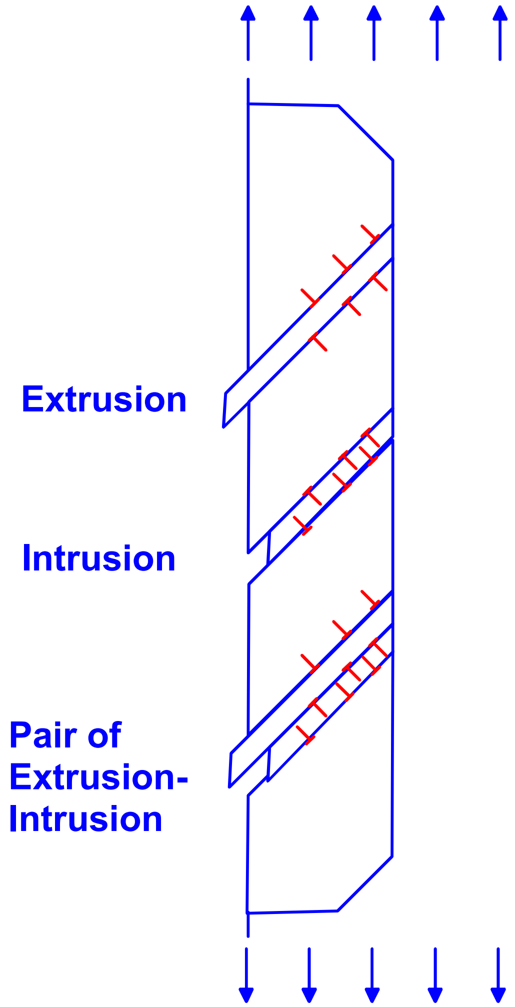
FATIGUE

REASONS

Cracks form due to cyclic plastic deformation.

In defect free material cracks form at slip bands, at intrusions and extrusions.

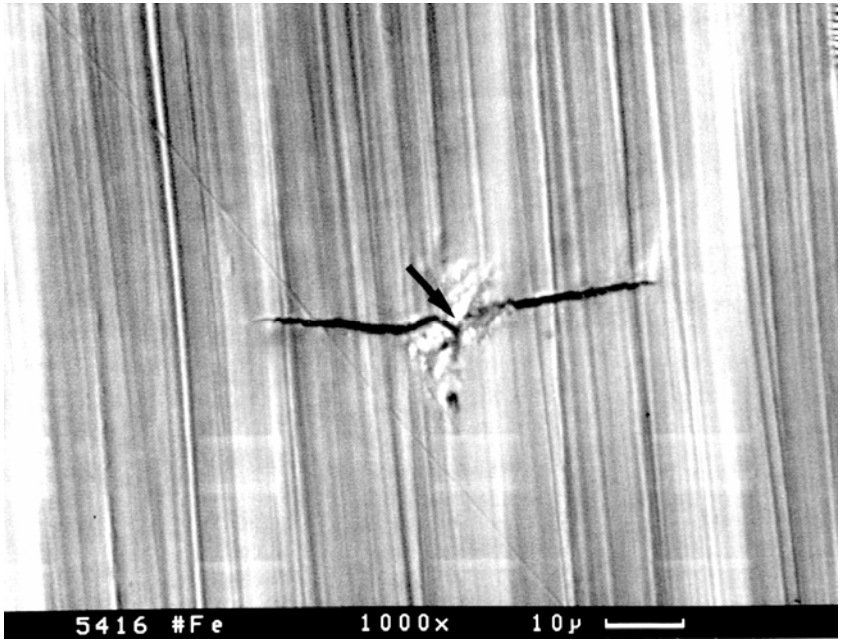
Plastic deformation starts in grains where slip planes are favorably oriented in the direction of alternating shear stresses.



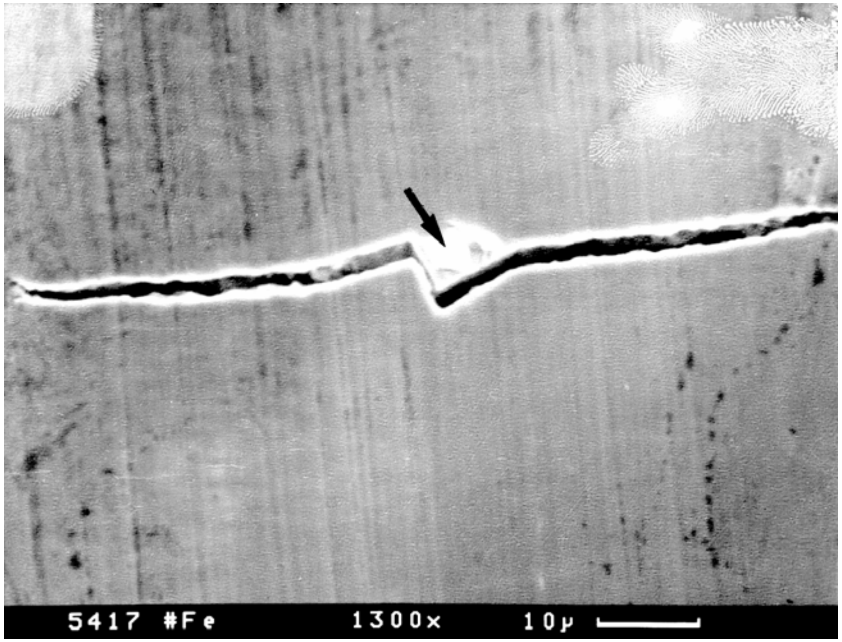
FATIGUE

The effect is enforced by stress raisers

(inclusions of Zirconium oxide in S690Q)



Broken Inclusion

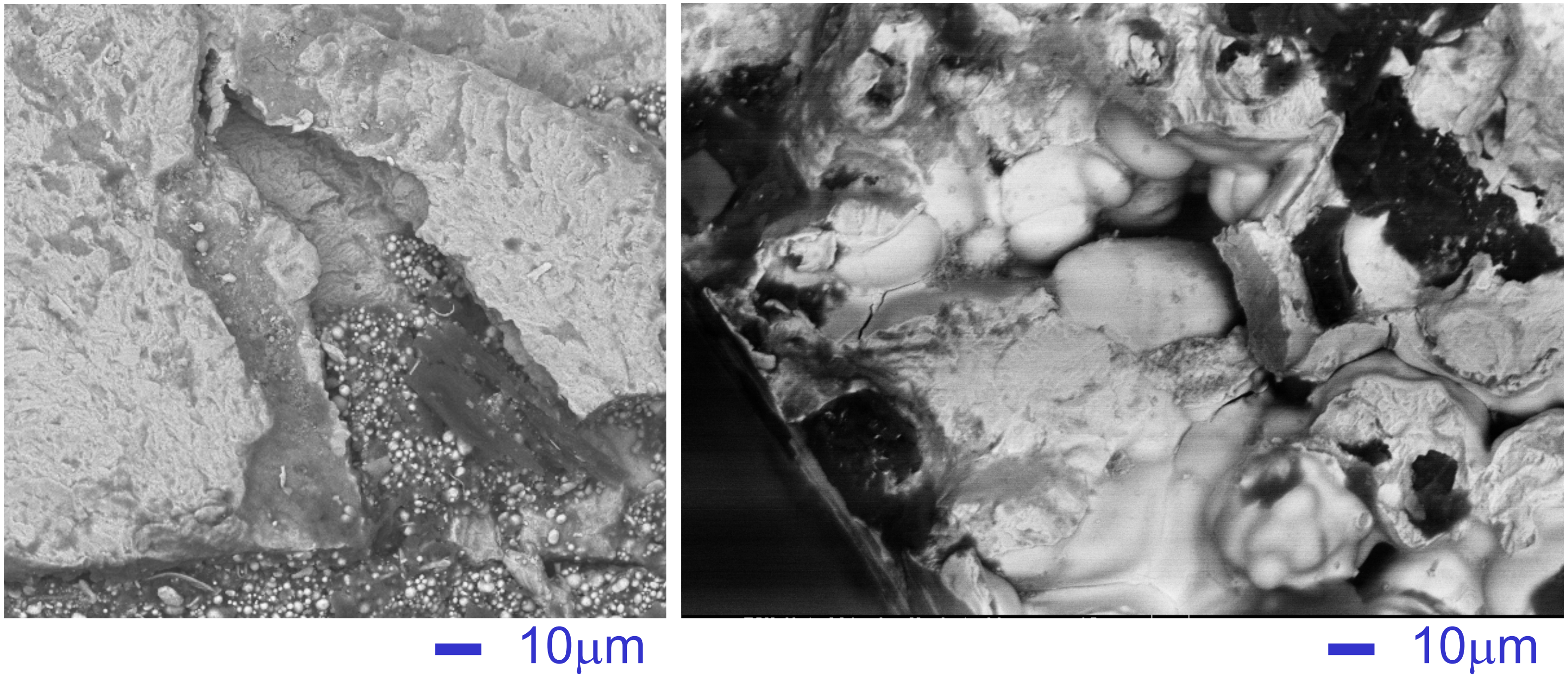


Broken Interface

FATIGUE

The effect is enforced by stress raisers

(Microscopical notches or pores)



Pore in a spring steel

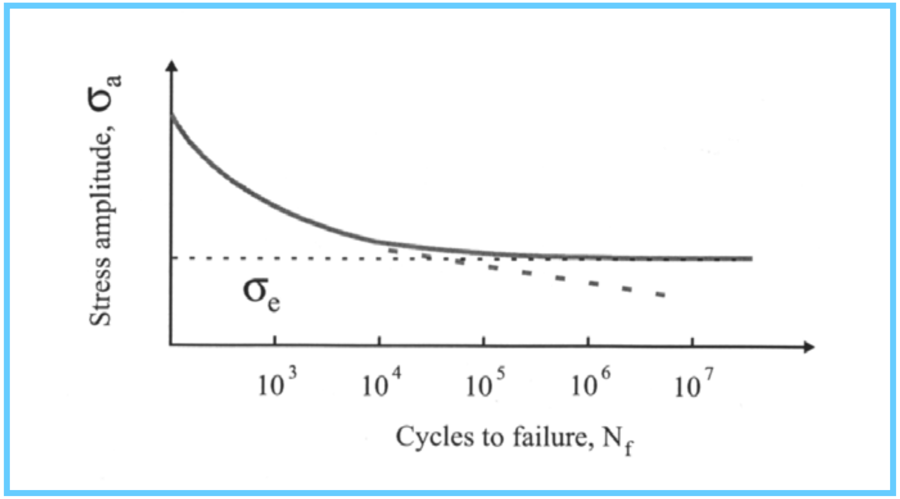
Pore in nodular graphite iron

FATIGUE

TOTAL LIFE ESTIMATION

Based on S-N Curves

•Stress amplitude σ_a vs Number of cycles before failure (N_f)



If $\sigma_a < \sigma_e$ (fatigue limit or endurance), life is considered infinite

- σ_e aprox. 0.35- 0.50 σ_u in steels and bronzes.
- Infinite life $N_f = 10^7$ cycles

FATIGUE

TOTAL LIFE EVALUATION

Stress approach I

Basquin 1910 ($\sigma_m = 0$; $\sigma_{max} = -\sigma_{min}$; $R = -1$)

$$\frac{\Delta\sigma}{2} = \sigma_a = \sigma'_f (2N_f)^{-b}$$

-Logarithmic relation between σ_a and $2N_f$

- σ'_f is, approximately, the tensile strength (σ_n)

- b varies between 0.05 y 0.12 σ_u in steels and bronzes

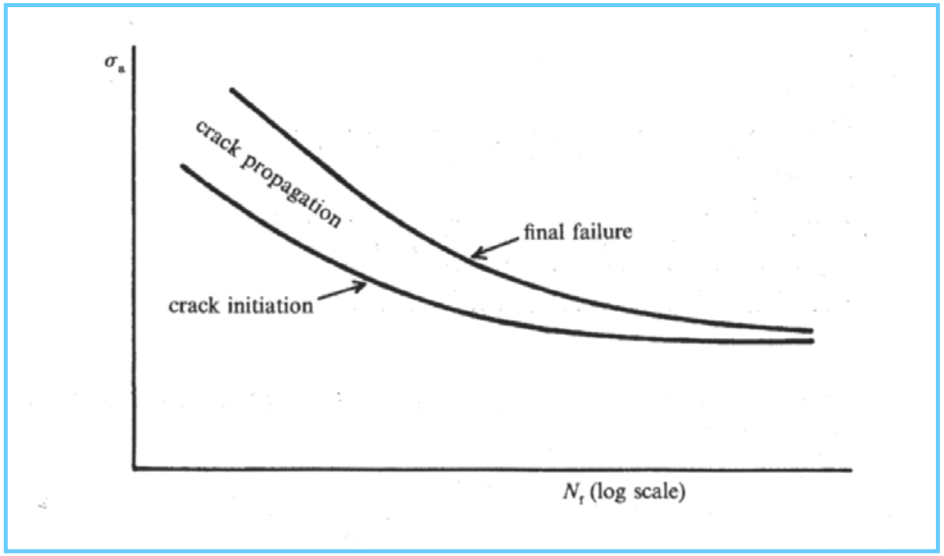
FATIGUE

TOTAL LIFE EVALUATION

Stress approach II

The whole life of a component has two periods:

- Crack Initiation period
- Crack Propagation period



FATIGUE

TOTAL LIFE EVALUATION

Stress approach III $(\sigma_m \neq 0)$

On previous considerations $\sigma_m = 0.$:

How can we design when σ_m is not equal to 0?

Corrections:

Soderberg

$$\sigma_a = \sigma_a\big|_{\sigma_m=0} \left\{1 - \frac{\sigma_m}{\sigma_y}\right\}$$

Goodman

$$\sigma_a = \sigma_a\big|_{\sigma_m=0} \left\{1 - \frac{\sigma_m}{\sigma_{TS}}\right\}$$

Gerber

$$\sigma_a = \sigma_a\big|_{\sigma_m=0} \left\{1 - \left(\frac{\sigma_m}{\sigma_{TS}}\right)^2\right\}$$

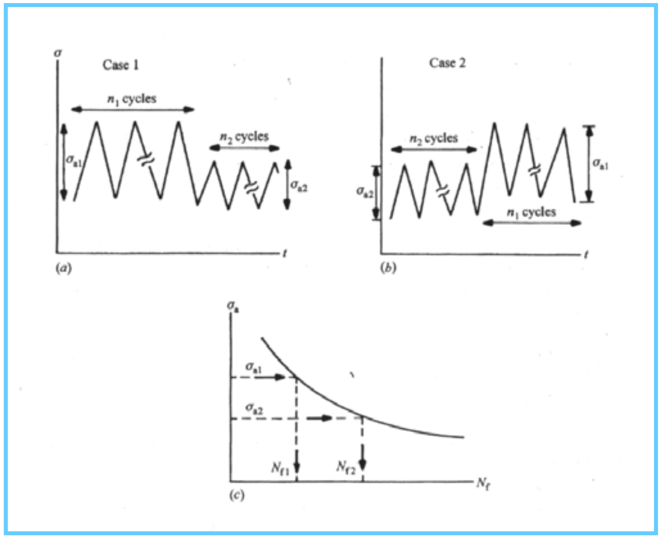
FATIGUE

TOTAL LIFE EVALUATION

Stress approach IV → **Amplitude**

On previous considerations σ_a is constant

If σ_a is not constant, define the damage due to each cyclic block.



$$d_i = \frac{n_i}{N_{fi}}$$ Damage

$$\sum_i \frac{n_i}{N_{fi}} = 1$$ Accumulated damage at life time (Miner´s rule)

FATIGUE

TOTAL LIFE EVALUATION

Strain approach I

The previous stress approach is useful with conditions which imply elastic strains (high N_f). This focus is known as High Cycling Fatigue (HCF).

In practice, there are some conditions in which fatigue is associated with high strains (high temperatures, stress concentration). Therefore, the number of cycles before failure is low.

This new focus, based on strains, is known as Low Cycling Fatigue (LCF)

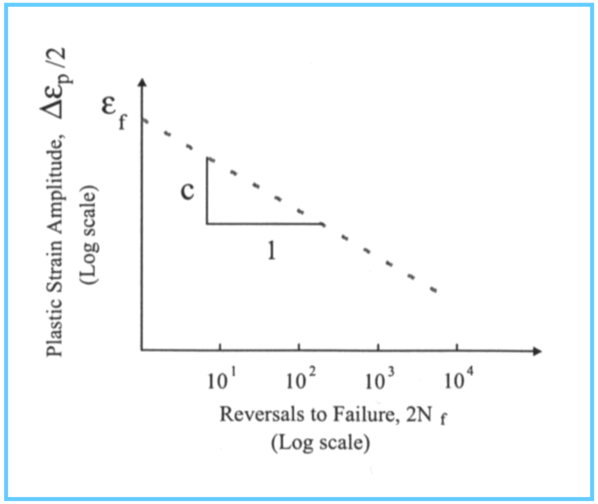
FATIGUE

APPROXIMATION TO TOTAL LIFE

Strain approach II

Coffin-Manson 1955

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^c$$



$\Delta\varepsilon_p/2$:Strain amplitude

ε'_f: tensile strain factor (aprox. ε_f)

c: fatigue coefficient (between 0.5 and 0.7)

FATIGUE

TOTAL LIFE EVALUATION

General approach: HCF/LCF

In a general case:

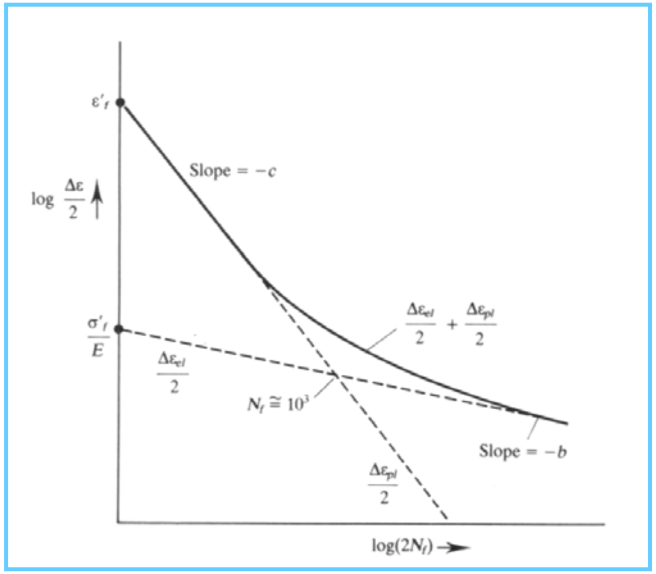
$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2}$$

HCF $$\frac{\Delta\sigma}{2} = \sigma'_f (2N_f)^{b}$$

if $$\frac{\Delta\varepsilon_e}{2} = \frac{\Delta\sigma}{2E} = \frac{\sigma_a}{E}$$

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma'_f}{E} (2N_f)^{b}$$

HCF/LCF $$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^{b} + \varepsilon'_f (2N_f)^{c}$$



FATIGUE

FATIGUE CRACK GROWTH

LEFM APPROACH

•In 1963 LEFM concepts were applied for first time to crack growth by Paris, Gómez and Anderson.

•For a given cyclic loading, ΔK is defined as $K_{máx}$- $K_{mín}$, which can be obtained from Δσ and the geometry of the cracked element, including crack extension.

•Paris, Gómez and Anderson established that crack propagation (Δa in N cycles) depends on ΔK :

$$\frac{\Delta a}{\Delta N} \rightarrow \frac{da}{dN} = C(\Delta K)^{m} \qquad \text{(Paris Law)}$$

FATIGUE

FATIGUE CRACK GROWTH

LEFM APPROACH

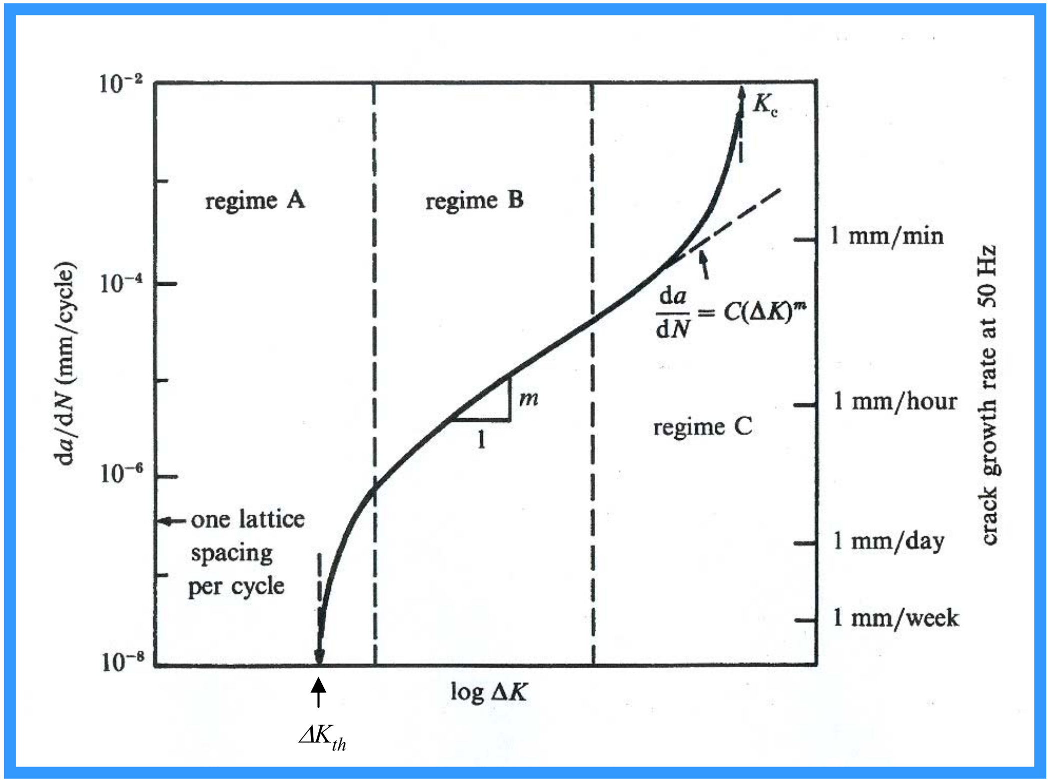
$$\frac{da}{dN} = C(\Delta K)^m$$

- Thus, the representation (da/dN) vs. Log (ΔK) must be a straight line with a slope equal to m.
- The relation between crack growth rate and ΔK defines three regions for the fatigue behaviour:
  - A: Slow growth (near the threshold) → Region I or Regime A
  - B: Growth at a medium rate (Paris regime) → Region II or Regime B
  - C: Growth at a high rate (near to fracture) → Region III or Regime C

FATIGUE

FATIGUE CRACK GROWTH

Three states



State I (Regime A)

$$\Delta K_{th}$$

State II (Regime B)

$$\frac{da}{dN_{II}} = C(\Delta K)^m$$

State III (Regime C)

near failure, where K_c is achieved

FATIGUE

FATIGUE CHARACTERISATION

Obtaining the Paris law

Methodology: Based on the LEFM, the crack propagation rate is determined as a function of ΔK.

1. Selection of specimen (FM type as CT, SENB,...)
2. Loading application system (Constant amplitude.)
3. Follow Crack propagation as a function of time or N.
4. Obtain crack propagation rate in zone II (mean value).
5. Determine the threshold, ΔKth
6. Represent da/dN-logΔK and adjust with Paris parameters

Standard: ASTM E-647

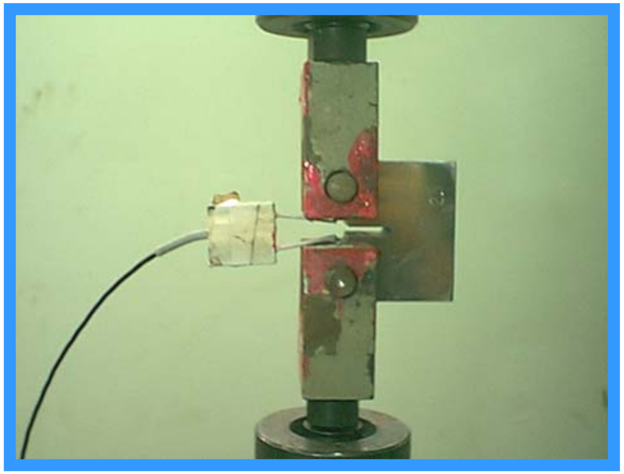
FATIGUE

FATIGUE CHARACTERISATION

Obtaining the Paris law

- *Example: Obtaining da/dN and Paris law*

1. Selection of the specimens in (FM type, such as CT,SENB,...)
2. Loading application system (Constant amplitude)



$$\Delta K = \frac{\Delta P}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$

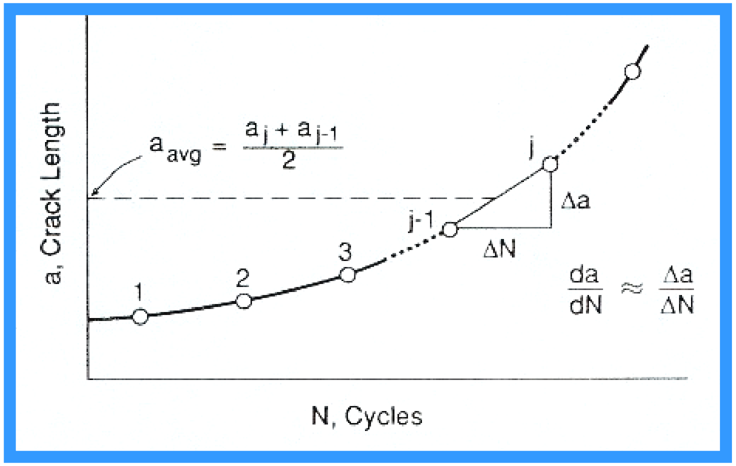
FATIGUE

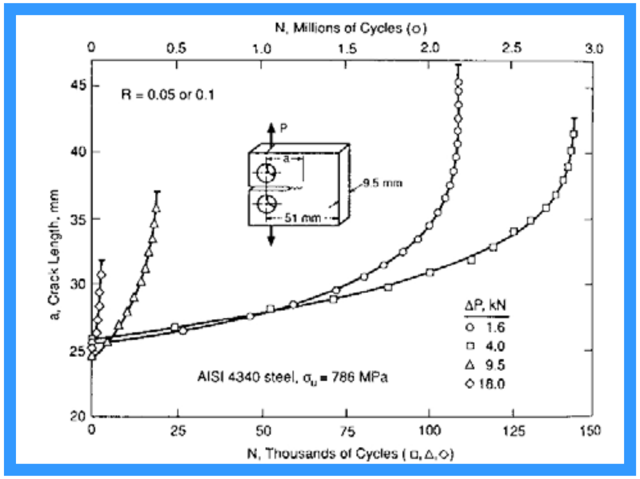
FATIGUE CHARACTERISATION

Obtaining the Paris law

- *Example: Obtaining da/dN and Paris law*

3. Determining crack propagation as a function of time or N cycles: by optical microscope or any other method





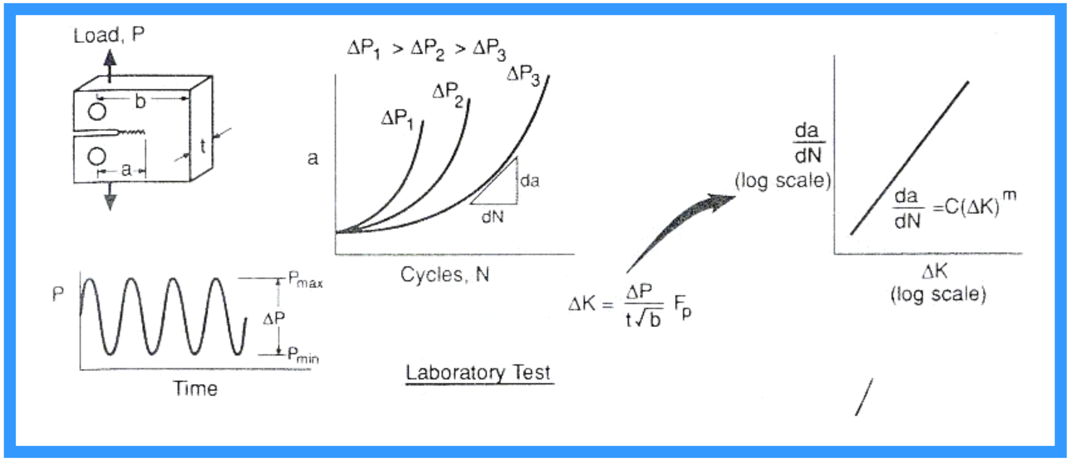
FATIGUE

FATIGUE CHARACTERISATION

Obtaining the Paris law

- *Example: Obtaining da/dN and Paris law*

4. Obtaining crack propagation rate law in zone II (Paris law).
5. Threshold determination, ΔK_{th} (i.e ASTM E647,…)

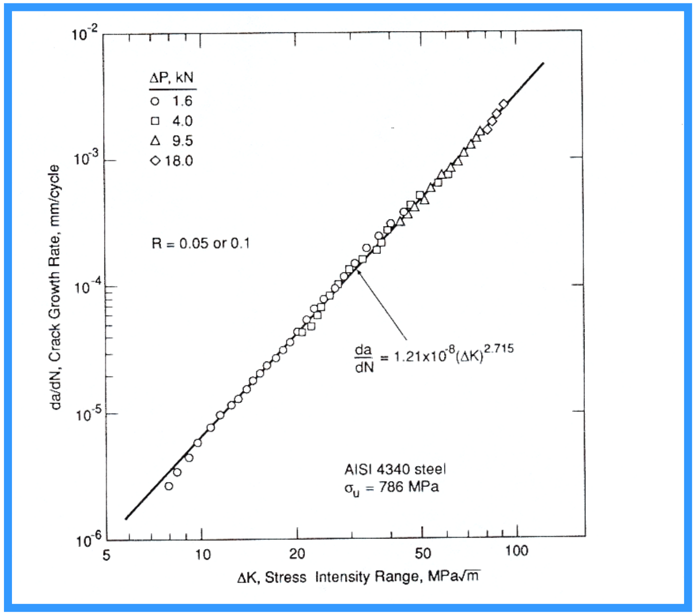


FATIGUE

FATIGUE CHARACTERISATION

Obtaining the Paris law

- Example: Determination of da/dN_{II}, m and C on AISI4130 steels



FATIGUE

FATIGUE CHARACTERISATION

Variables affecting $(da/dN)_{II}$:

- **Environmental effects**
  - –Corrosion – fatigue
  - –Temperature
- **Loading effects**
  - –Stress ratio $R = \sigma_{min}/\sigma_{max}$
  - –Variable amplitude. (Miner´s rule).
  - –Frequency
- **Limitations : LEFM**
  - –Short cracks
  - –Thickness
  - –Plastic zone extension

FATIGUE

FATIGUE CRACK GROWTH

Three regimes

Regime	A Slow growth	B Paris zone	C Quick growth
Fracture Microscopy	Mode II (Shear) Brittle facets	Striations (mode I) Beach Marks	Cleavages, Microvoids (failure)
Influence of microestructure	High	Low	High
R effect	High	Low	High
Environment effect	High	*	Low
Plastic zone	$r_y < d_g$ (grain size)	$r_y > d_g$	$r_y >> d_g$
*It depends on environment, frequency and material SCC,CF.			

FATIGUE

FATIGUE CRACK GROWTH

Regime A (I)

-Threshold concept, ΔK_{th}:

– When ΔK is equal or lower to ΔK_{th}, crack popagation rate is extremely slow and so, it is considered that crack doesn´t propagate or that it propagates at non-detectable rates.

– **Practical definition**: When crack propagation rate is less than 10^{-8} mm/cycle, it is considered that propagation has stopped and ΔK is called ΔK_{th}.

FATIGUE

FATIGUE CRACK GROWTH

Regime A (II)

-This propagation rate is smaller than one interatomic distance per cycle. How is it possible?

- It is considered that there is a large amount of cycles on which there is no propagation. Crack grows one interatomic space in a cycle and then it stabilises for some cycles.

- There are experimental difficulties to determine crack propagation rates at these values.

FATIGUE

FATIGUE CRACK GROWTH

Regime B (I)

- In regime B (Paris Zone) the number of cycles before failure can be calculated using the Paris law:

$$\frac{da}{dN} = C(\Delta K)^m$$

ΔK is defined as a function of Δσ

$$\Delta K = Y \Delta \sigma \sqrt{\pi a}$$

Y is a geometric factor

m and C are characteristic parameters of the material and they are obtained experimentally. For metallic materials, m varies between 2 and 4 and for ceramics and polymers it can reach values up to 100.

FATIGUE

FATIGUE CRACK GROWTH

Regime B (II)

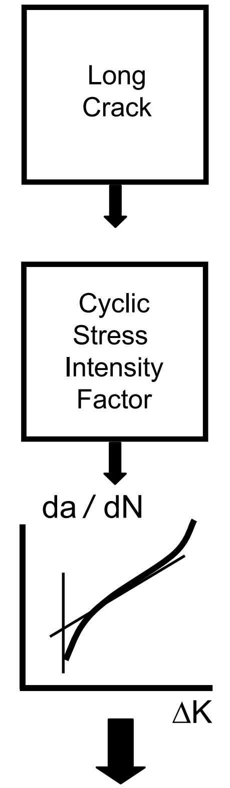
- Therefore, the Paris law can be written in this way:

$$\frac{da}{dN} = C\left(Y\Delta\sigma\sqrt{\pi a}\right)^m$$

- If Y is constant, both sides of the expression can be integrated:

$$\int_{a_0}^{a_f} \frac{da}{a^{m/2}} = C Y^m (\Delta\sigma)^m \pi^{m/2} \int_0^{N_f} dN$$

If Y depends on crack length, it is necessary to solve the problem numerically.


Long Crack

Cyclic Stress Intensity Factor

Long Crack Growth Approach

FATIGUE

FATIGUE CRACK GROWTH

Regime B (III)

If m > 2:

$$N_f = \frac{2}{(m-2) C Y^m (\Delta\sigma)^m \pi^{m/2}} \left[\frac{1}{a_0^{(m-2)/2}} - \frac{1}{a_f^{(m-2)/2}} \right]$$

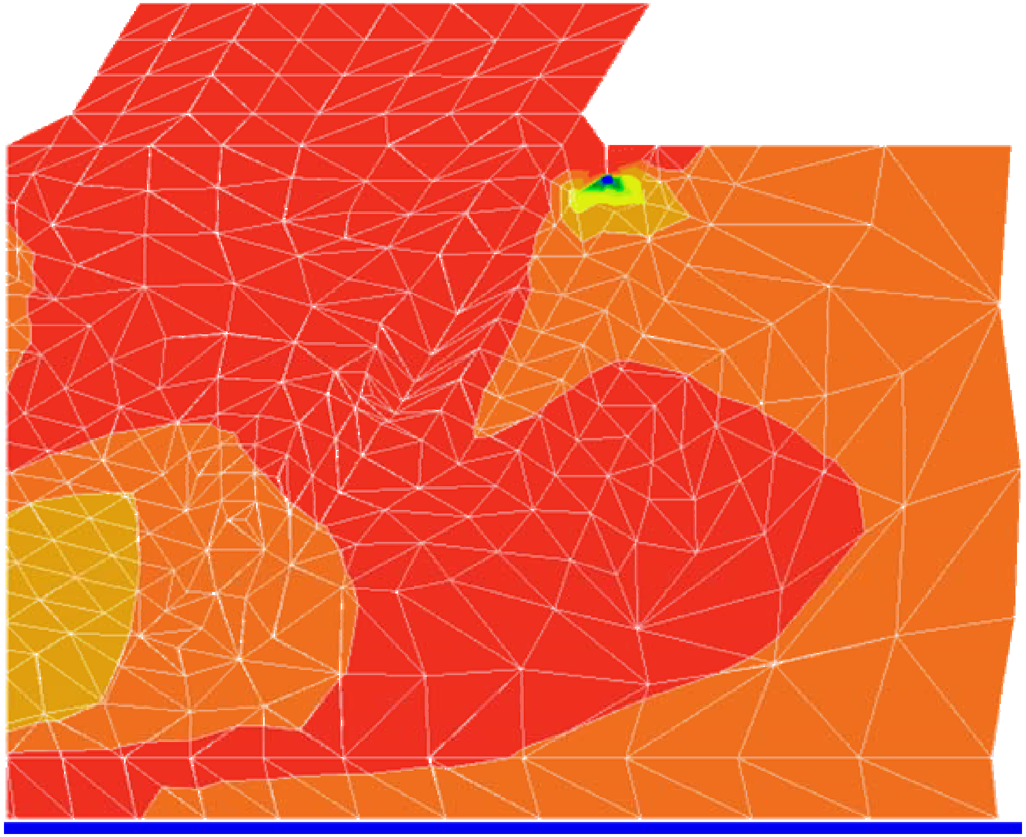
If m = 2:

$$N_f = \frac{1}{C Y^2 (\Delta\sigma)^2 \pi} Ln \frac{a_f}{a_0}$$

FATIGUE

FATIGUE CRACK GROWTH

Regime B (IV)



Determining Y:

- Search in handbooks (Tada, Rooke&Cartwright, Murakami)
- Perform (FE-) calculations

FATIGUE

FATIGUE CRACK GROWTH

Regime B (V)

-If $\Delta\sigma$ is not a constant value, the methods that are used to determine the number of cycles before failure are based on the application of Miner Rule (traditional method), considering the foreseen crack propagation rate law by Paris and following these steps :

- Reduce the load spectrum to blocks with constant amplitude (block_i)
- Estimate the foreseen N_f for each block (N_{fi})
- Apply Miner´s rule
- Previous plastification history of the material must be taken into account

FATIGUE

FATIGUE CRACK GROWTH

Regime B (VI)

- In order to solve the problem of life estimation (N_f), it is necessary to obtain the initial crack length, a_0, and the final crack length, a_f (usually called critical crack length).

How can we determine the initial crack length?

- There are various techniques, from visual inspection to ultrasonics or X rays. If no crack is detected with these methods, it is considered that crack length is equal to the resolution of inspection equipments.

FATIGUE

FATIGUE CRACK GROWTH

Regime B (VII)

How can we calculate the expected final crack length?

- Cracks grow until fracture occurs. Then, at failure:

$$K_{\max} = K_c$$

- In other terms:

From $Y\sigma_{\max}\sqrt{\pi a_f} = K_c$ we can estimate **a$_\mathbf{f}$** in this way: $a_f = \dfrac{1}{\pi}\dfrac{K_c^2}{Y^2\sigma_{\max}^2}$

FATIGUE

FATIGUE CRACK GROWTH

Regime B (VIII)

- Based on the previous analysis, a very important idea appears :

  Even when cracks are detected in a component or structure, it is not necessary to replace it!

- We must assess the remaining life. The component can be used if it is periodically inspected.

Then assessment concepts as

- ***Admissible crack - Admissible damage***
- ***Inspection period - Life time***

should be considered

FATIGUE

FATIGUE CRACK GROWTH

Regime C

The failure of a structure or component after a fatigue process can be produced in two different ways:

- For high ΔK, crack propagation rate increases a lot until sudden fracture occurs when fracture toughness is reached

  Ex: Brittle failure conditions at low temperatures

- Plastification and failure of the remaining section

  Ex: Plastic collapse ductile conditions

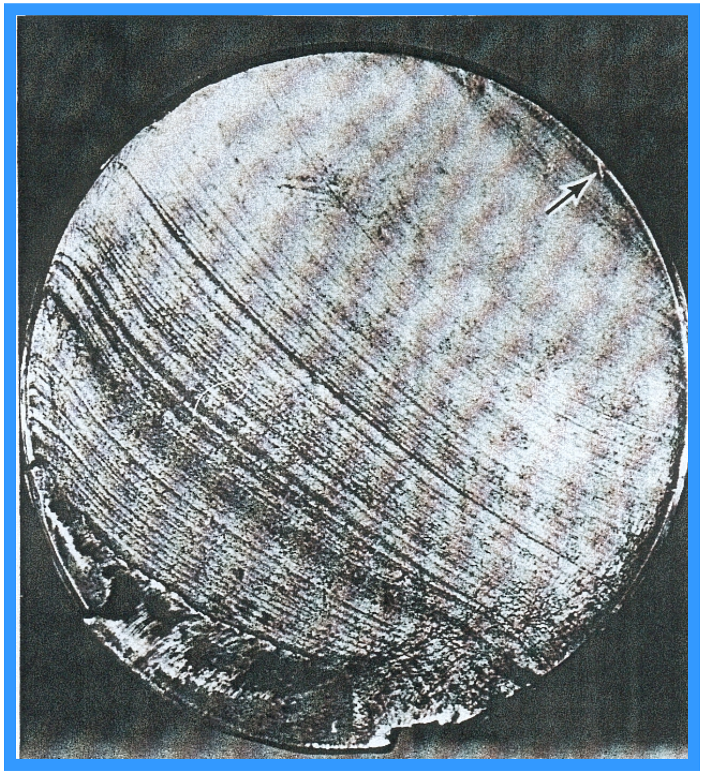
FATIGUE

FRACTOGRAPHIC ASPECTS

Regime B

- When a crack propagates because of a fatigue process, it produces marks which are known as **striations** or **beach marks**. These marks are usually the main proof of a failure caused by fatigue.

- Striations are the marks that crack propagation produces on the failure surface in various cycles.



FATIGUE

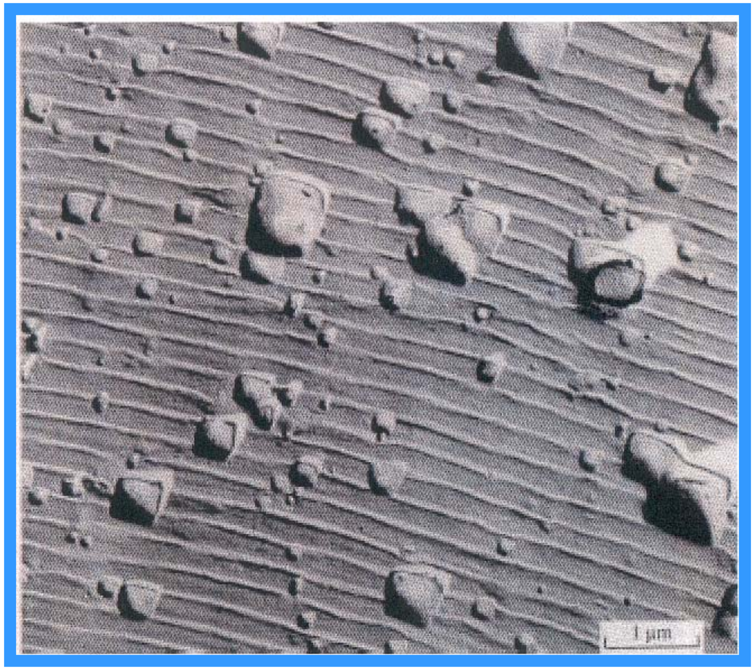
FRACTOGRAPHIC ASPECTS

Regime B

EXAMPLE:

Fatigue striations on the fracture surface of a 2024-T3Al alloy.

In some materials, each line is identified with the propagation Δa per cycle.



FATIGUE

FRACTOGRAPHIC ASPECTS

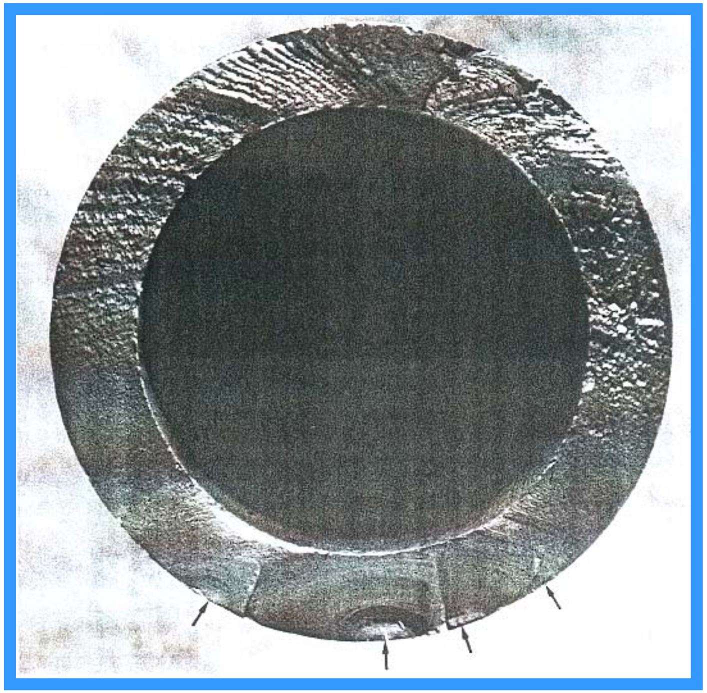
Regime C

Striations disappear in the final failure section and the following can appear:

1. Cleavage micromechanisms and tearing if fracture is brittle

or

2. Microvoids if fracture occurs because of the plastification process of the remaining section (ductile failure).



FATIGUE

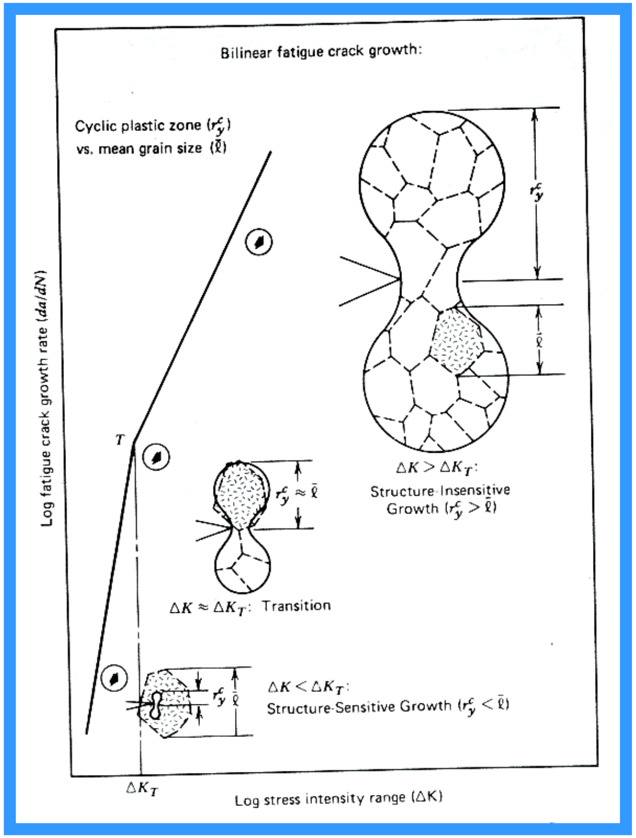
CRACK PROPAGATION MECHANISMS

Regimes A and B

Propagation models:

a) Plastic field extends inside a grain or occupies only a few grains ($r_y<d$). Propagation through sliding planes. (Regime A)

b) Plastic zone with a considerable size ($r_y>d$). Propagation occurs through a straight line (Regime B)



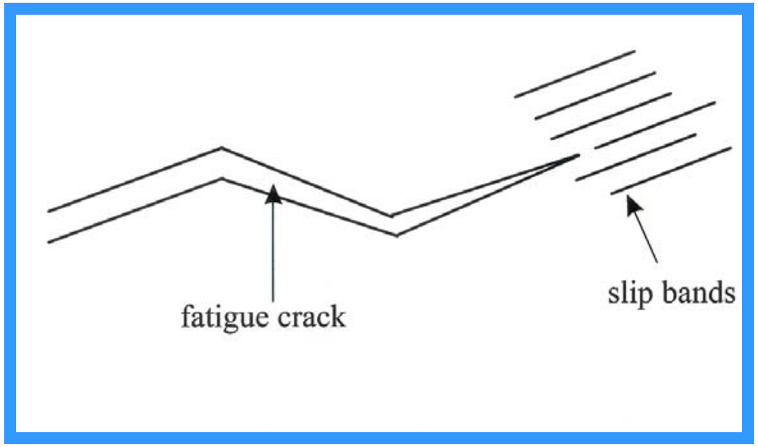
FATIGUE

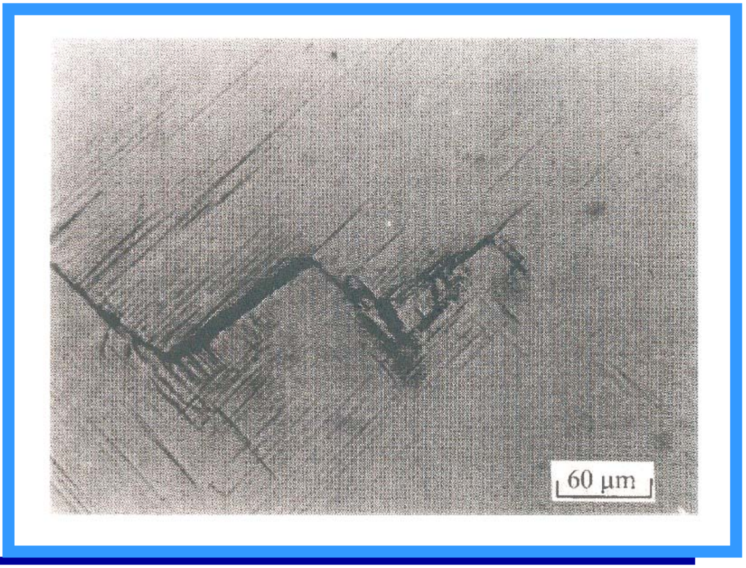
CRACK PROPAGATION MECHANISMS

Regime A: Threshold zone: $r_y < d$.

Propagation modes:

Propagation through sliding planes. Fracture Mode II (Shear)





FATIGUE

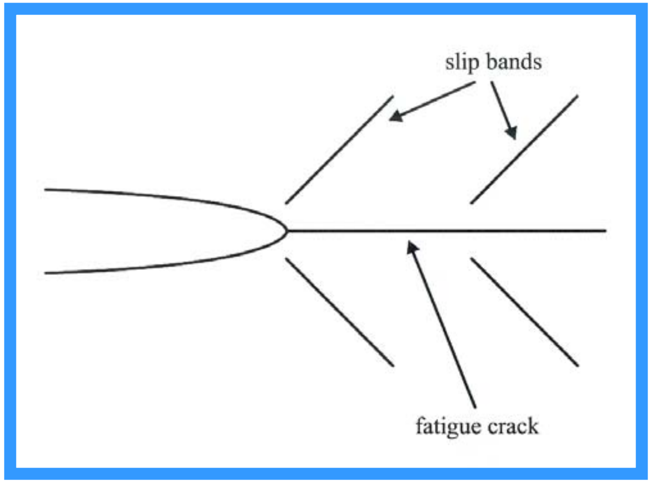
CRACK PROPAGATION MECHANISMS

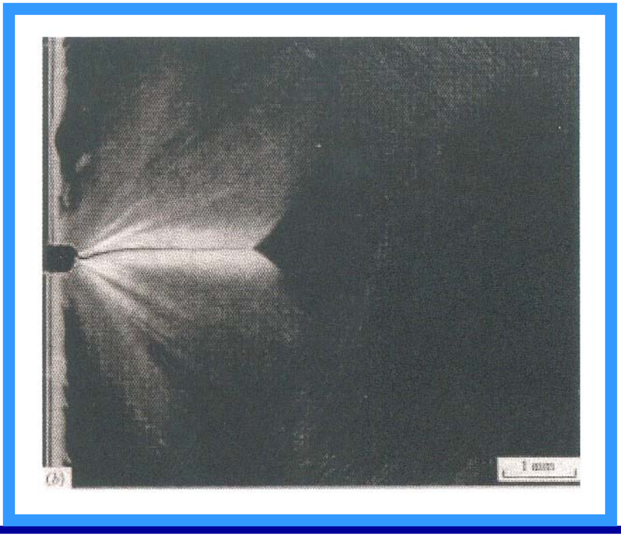
Regime B: State II Paris Law: $r_y > d$.

Propagation modes:

There are many sliding planes implied, so crack propagates through the intersection between them . Fracture Mode I (tension).

Sometimes striations are observed.





FATIGUE

CRACK PROPAGATION MECHANISMS

Regime B: State II Paris Law: $r_y>d$.

Physical models of crack propagation :

1 . Sliding irreversibility

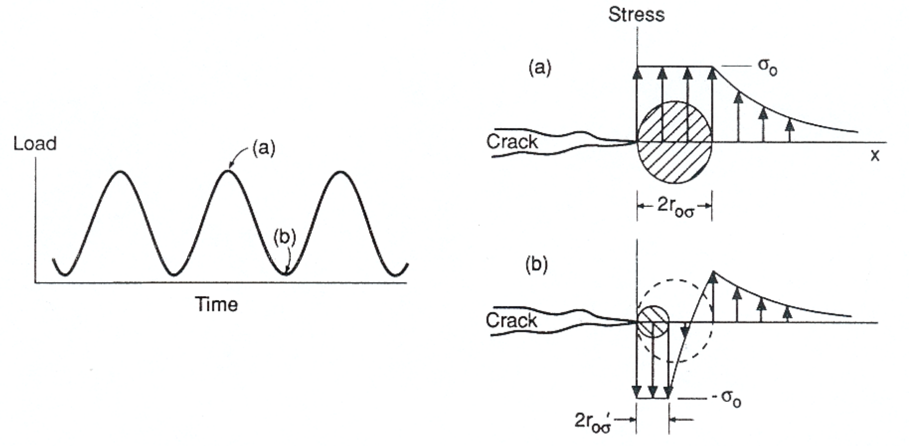


Figure 11.33 Monotonic (a) and cyclic (b) plastic zones. (Adapted from [Paris 64]; used with permission.)

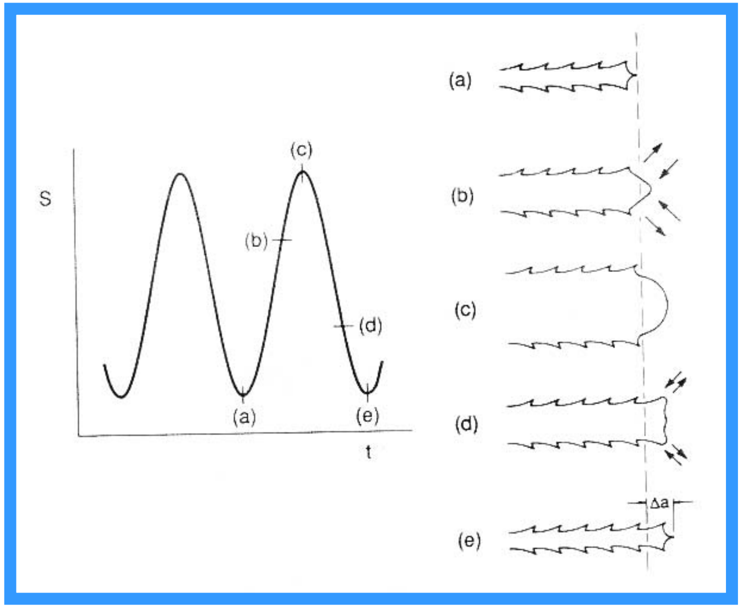
FATIGUE

CRACK PROPAGATION MECHANISMS

Regime B: State II Paris Law: $r_y > d$.

Physical models of crack propagation at Paris zone:

1 . Sliding irreversibility



Laird Model (1967)

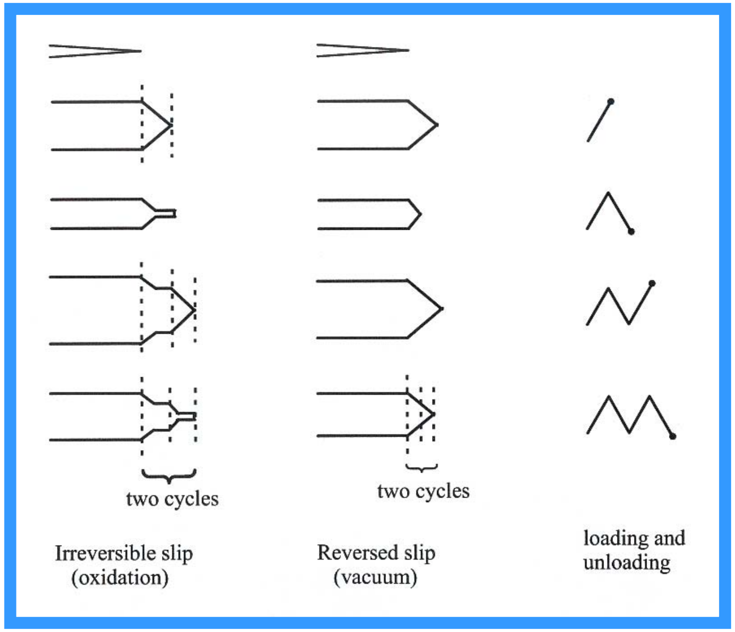
FATIGUE

CRACK PROPAGATION MECHANISMS

Regime B: State II Paris Law: $r_y>d$.

Physical models of crack propagation at Paris zone:

2. Environmental effects



FATIGUE

CRACK PROPAGATION MECHANISMS

Regime B. State II Paris Law

A model for the Paris law based on CTOD (δ_t)

$$da/dN = (\Delta a)_{1\ \mathrm{cycle}} \approx \delta_t = \beta \frac{(\Delta K)^2}{\sigma'_y E'}$$

Important: This implies m = 2 in the Paris law

Advantages of models based on CTOD:

1. Physical justification
2. Application to multiaxial fatigue.

FATIGUE

FATIGUE DESIGN

Safe-life

- **Philosophy**: Elements without cracks
- **Steps**:
  - Load spectrum determination.
  - Life estimation for the material through laboratory tests (from an initial crack size).
  - Application of a safety factor.
  - When estimated life finishes, the component is replaced, even though it could continue in service for a considerable time under safety conditions.
  - Periodic inspection
  - Ex: pressure vessels.

FATIGUE

FATIGUE DESIGN

Fail-safe

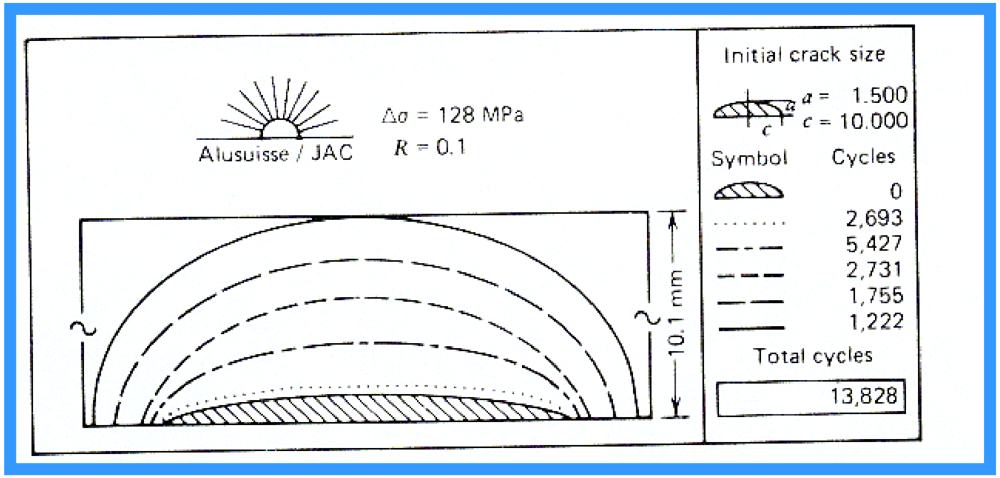
- **Philosophy**: Cracks acceptable until they reach a critical size.
- **Periodic inspections**: Inspection period design in order to detect cracks before they reach their critical size.
- **Steps**:
  - The component is replaced when its estimated life finishes: Detectable crack smaller than critical are allowed.
  - Ex: aeronautical industry.

FATIGUE

FATIGUE DESIGN

Leak before break

- Application to pipelines and pressure vessels
- Material and geometry selection in such a way that crack becames a through thickness crack before the component fails.



FATIGUE

SHORT CRACK GROWTH

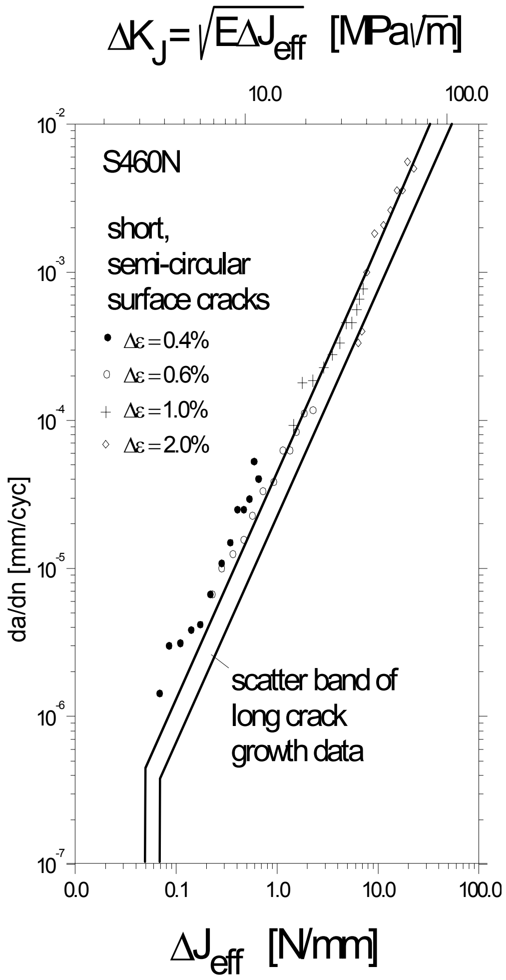
Short cracks can grow only under high stresses

Plastic zones are no longer much smaller than the crack size

The concepts of the Linear Elastic Fracture Mechanics are usually not applicable

Replace ΔK by ΔJ

$$\frac{da}{dN} = C\cdot\left(\Delta J_{eff}\right)^{m}$$



FATIGUE

SHORT CRACK GROWTH

Short crack’s closure behaviour differs from long crack behaviour. Approximation formulas:

$$\sigma_{op} = \begin{cases} \sigma_{\max} \cdot \left(A_0 + A_1 \cdot R + A_2 \cdot R^2 + A_3 \cdot R^3 \right) & \text{for } R > 0 \\ \sigma_{\max} \cdot \left(A_0 + A_1 \cdot R \right) & \text{for } R \leq 0 \end{cases}$$

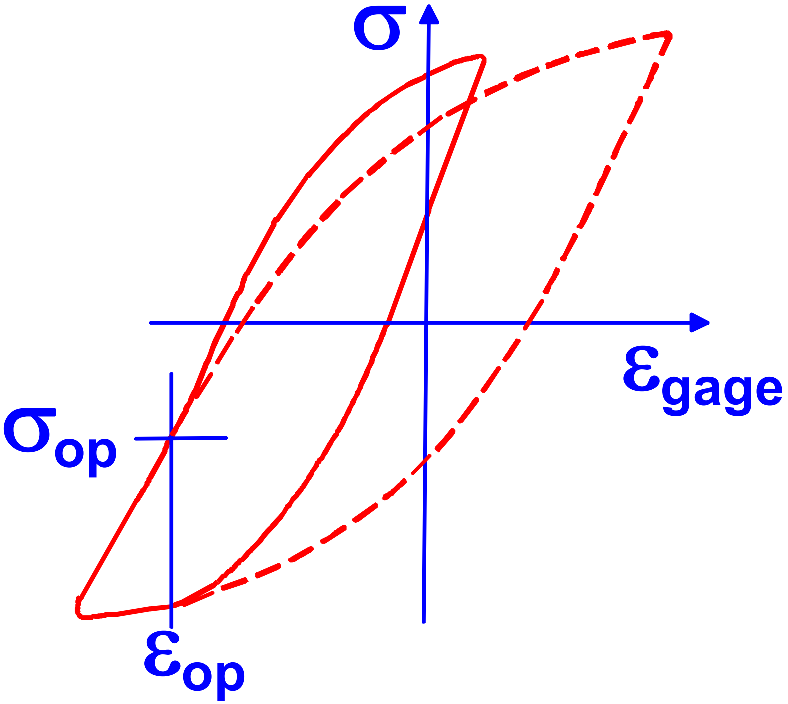
$$A_0 = 0.535 \cdot \cos\left(\frac{\pi}{2} \cdot \frac{\sigma_{\max}}{\sigma_F} \right) + a_{\text{mitt}}$$

$$A_1 = 0.344 \cdot \frac{\sigma_O}{\sigma_F} + a_{\text{mitt}}$$

$$A_3 = 2 \cdot A_0 + A_1 - 1$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$\sigma_Y = \frac{1}{2}\left(\sigma_{0.2}' + \sigma_{UTS} \right)$$

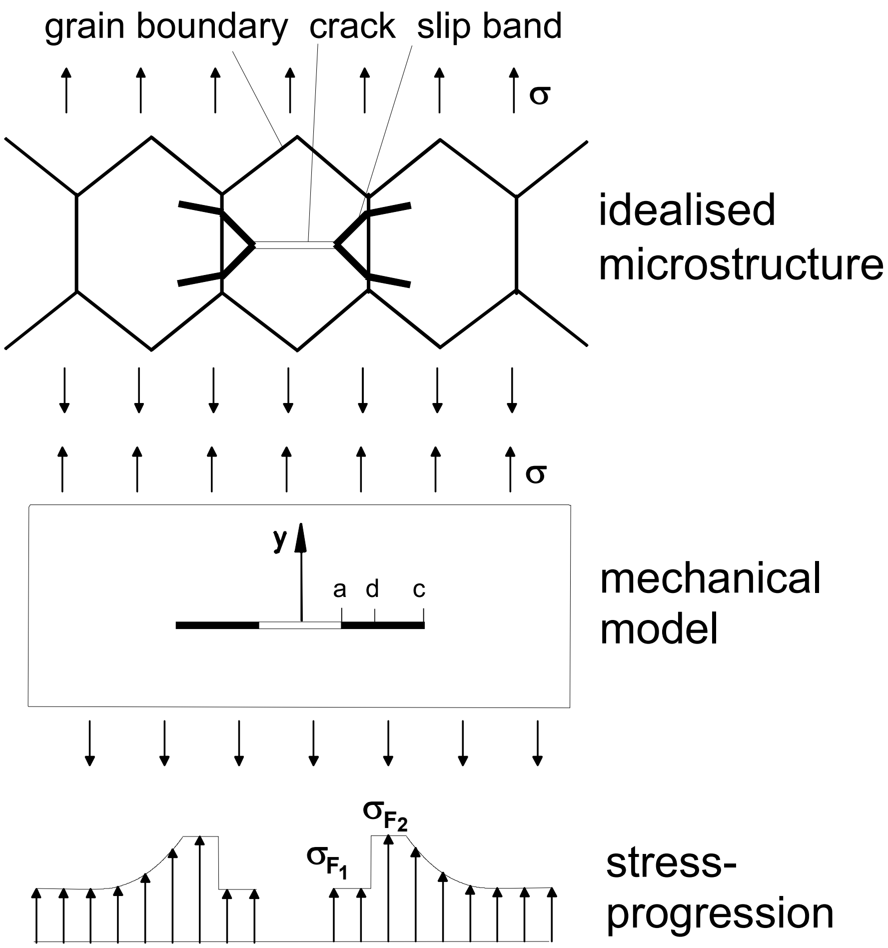


FATIGUE

SHORT CRACK GROWTH

Short crack growth is influenced by the microstructure

Principles can be studied using Tanaka’s model

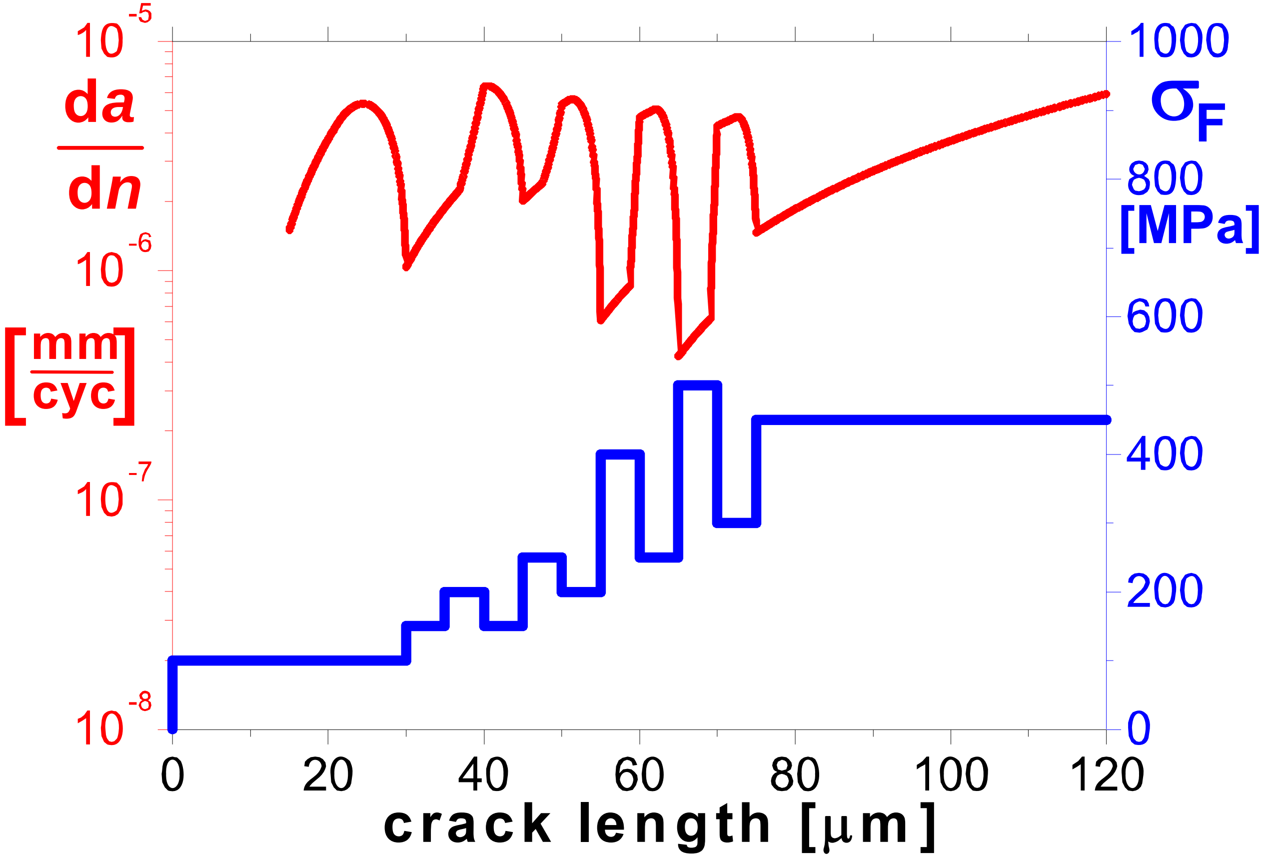


FATIGUE

SHORT CRACK GROWTH

$$\frac{da}{dN} = \left(0.63 \cdot \frac{CTOD}{mm} - 5.7 \cdot 10^{-5} \right)^{1.5}$$

Example of short crack growth through inhomogeneous microstructure calculated applying Tanaka's model



FATIGUE

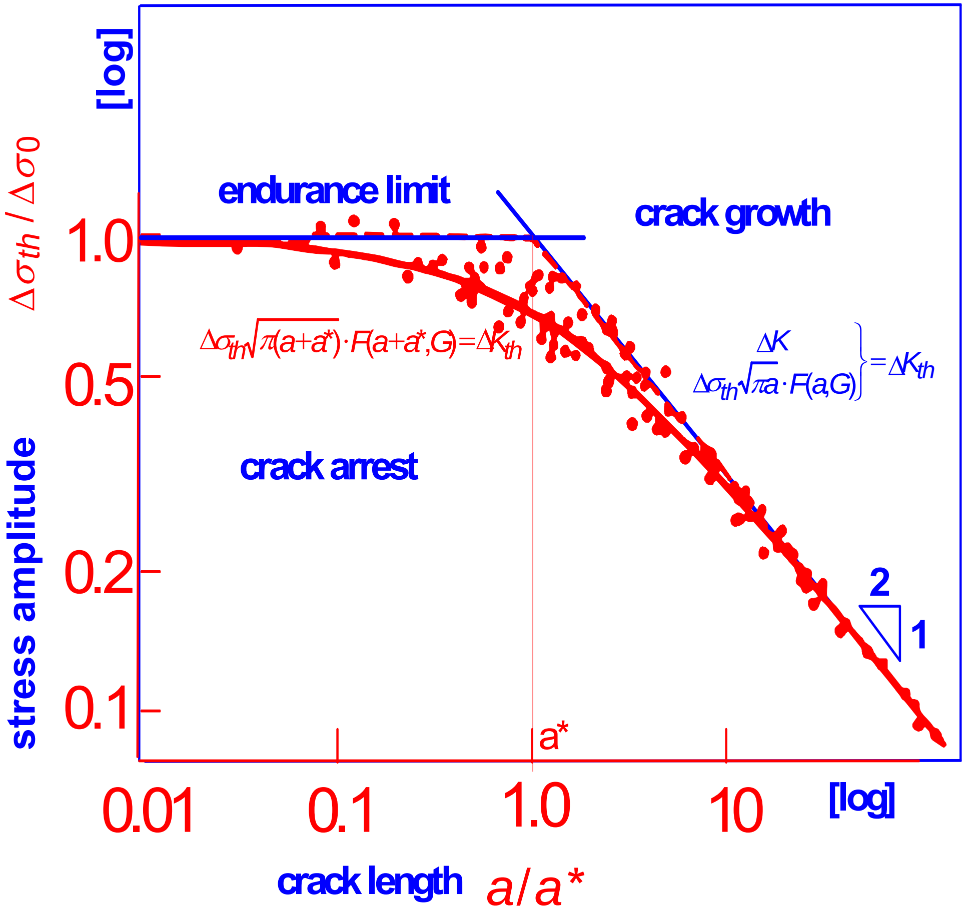
SHORT CRACK GROWTH

Microstructural influence dominates near the endurance limit.

Continuum mechanics based concepts need adjustment.

This leads to the introduction of an intrinsic crack length a*.

The crack length dependend endurance limit is often shown in a **Kitagawa** plot.



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FATIGUE

SHORT CRACK GROWTH

Short cracks are usually semi-circular surface cracks

There are approximation formulas to calculate J.

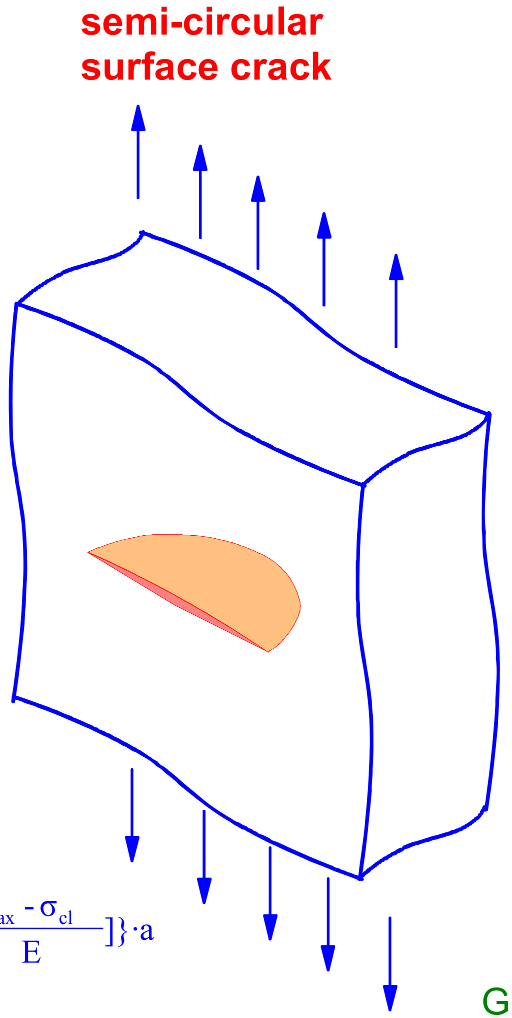
For

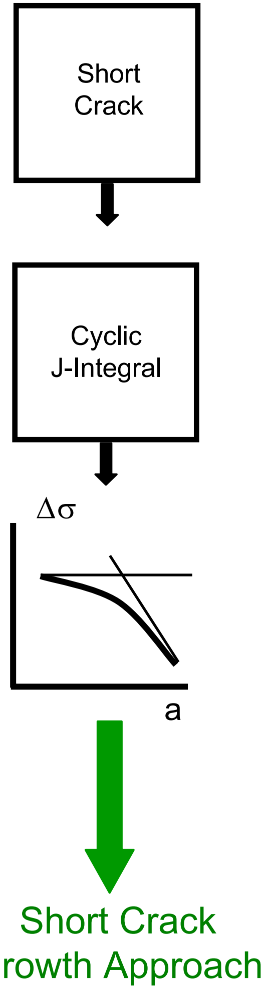
$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$

holds

$$J \approx \left(1.24 \cdot \frac{\sigma^2}{E} + \frac{1.02}{\sqrt{n'}} \cdot \sigma \cdot \varepsilon_p\right) \cdot a$$

$$\Delta J_{eff} = \left\{1.24 \cdot \frac{(\sigma_{max} - \sigma_{cl})^2}{E} + \frac{1.02}{\sqrt{n'}} \cdot (\sigma_{max} - \sigma_{cl})\left[(\varepsilon_{max} - \varepsilon_{cl}) - \frac{\sigma_{max} - \sigma_{cl}}{E}\right]\right\} \cdot a$$





Short Crack

Cyclic J-Integral

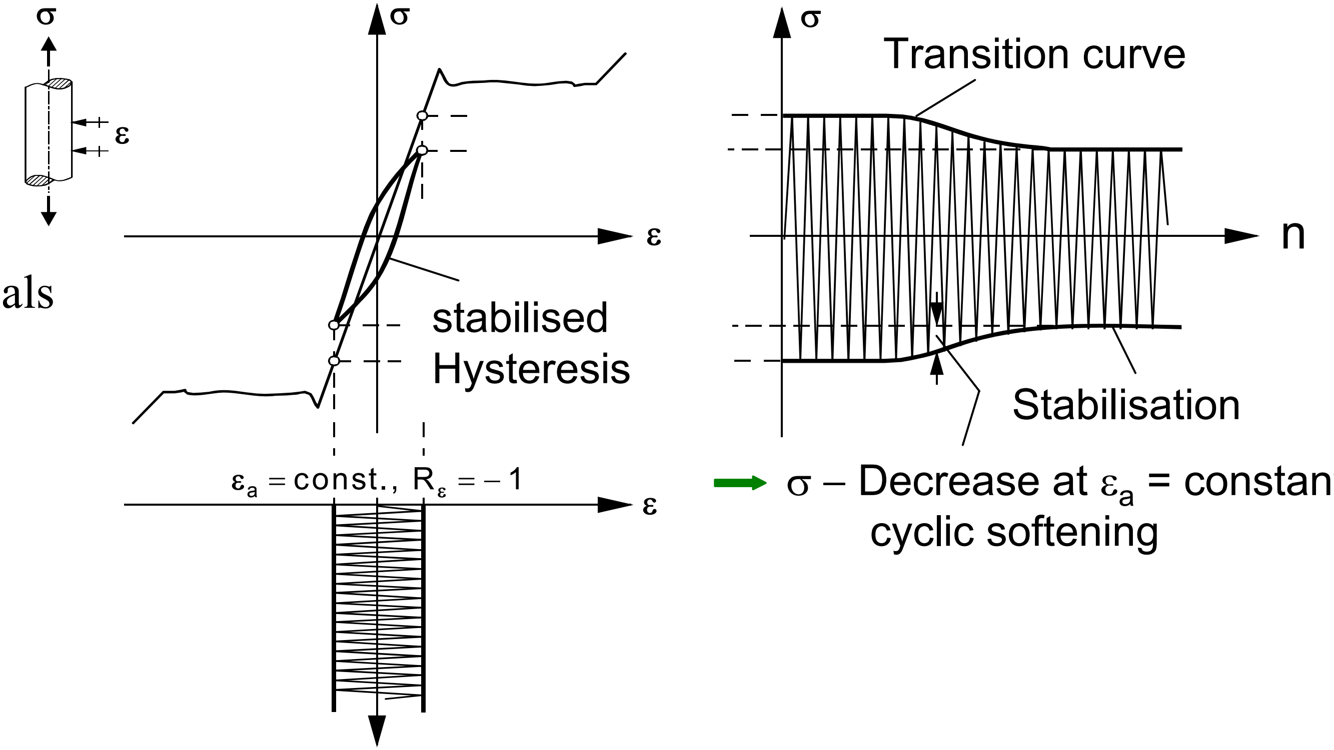
Short Crack Growth Approach

FATIGUE

CRACK INITIATION LIFE ESTIMATION

(without crack growth calculation)

Metallic materials show cyclic hardening or softening.



→ σ – Decrease at ε_a = constant cyclic softening

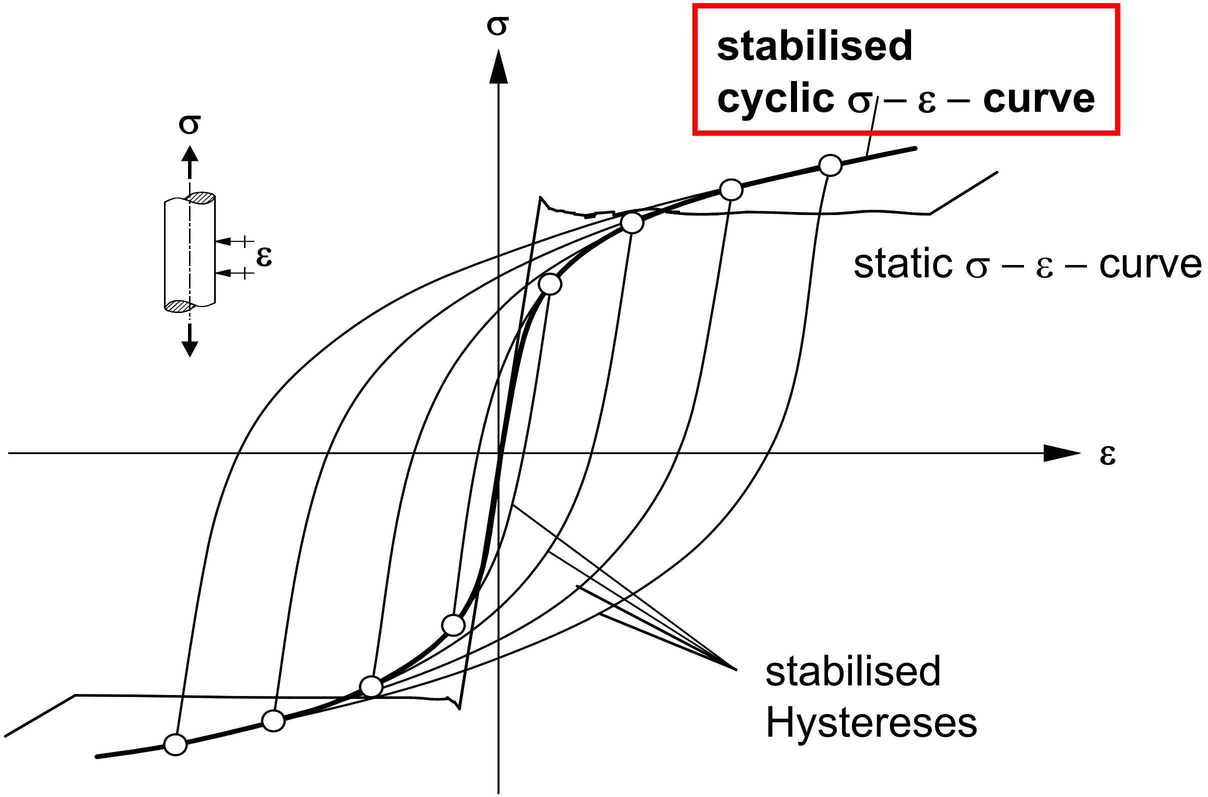
FATIGUE

CRACK INITIATION LIFE ESTIMATION

Until a stabilization is reached:

The stabilized cyclic stress-strain-curve can be used like usual static stress-strain curves.

However, amplitudes are calculated.



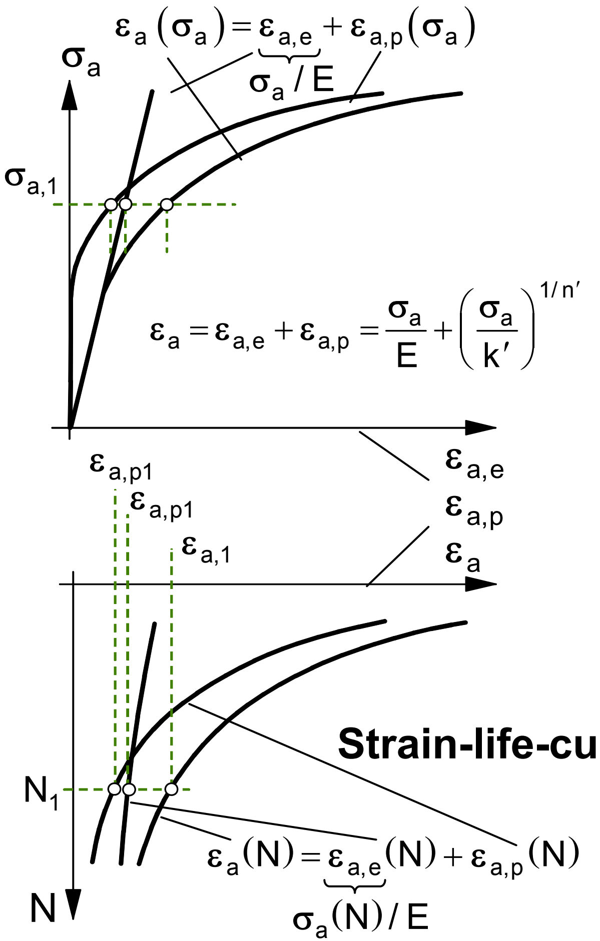
FATIGUE

CRACK INITIATION LIFE ESTIMATION

Stress- and strain-life curves give the number of cycles at the particular amplitudes.

Equations according to Coffin, Manson, Morrow, Basquin.

stabilised cyclic $\sigma-\varepsilon-$ curves



$$\varepsilon_a(\sigma_a)=\underbrace{\varepsilon_{a,e}}_{\sigma_a/E}+\varepsilon_{a,p}(\sigma_a)$$

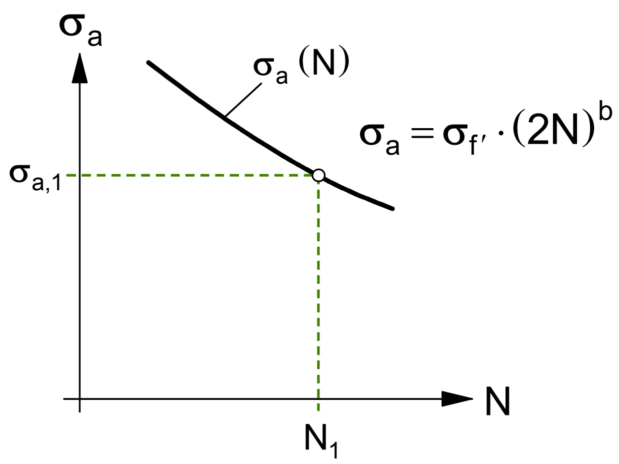
$$\varepsilon_a=\varepsilon_{a,e}+\varepsilon_{a,p}=\frac{\sigma_a}{E}+\left(\frac{\sigma_a}{k'}\right)^{1/n'}$$

Strain-life-curve

$$\varepsilon_a(N)=\underbrace{\varepsilon_{a,e}}_{\sigma_a(N)/E}(N)+\varepsilon_{a,p}(N)$$

$$\varepsilon_a=\frac{\sigma_{f'}}{E}\cdot(2N)^b+\varepsilon_{f'}\cdot(2N)^c$$

Stress-life-curve



$$\sigma_a=\sigma_{f'}\cdot(2N)^b$$

Compatibility among $\varepsilon_{a,p}(\sigma_a)$, $\sigma_a(N)$ and $\varepsilon_{a,p}(N)$

FATIGUE

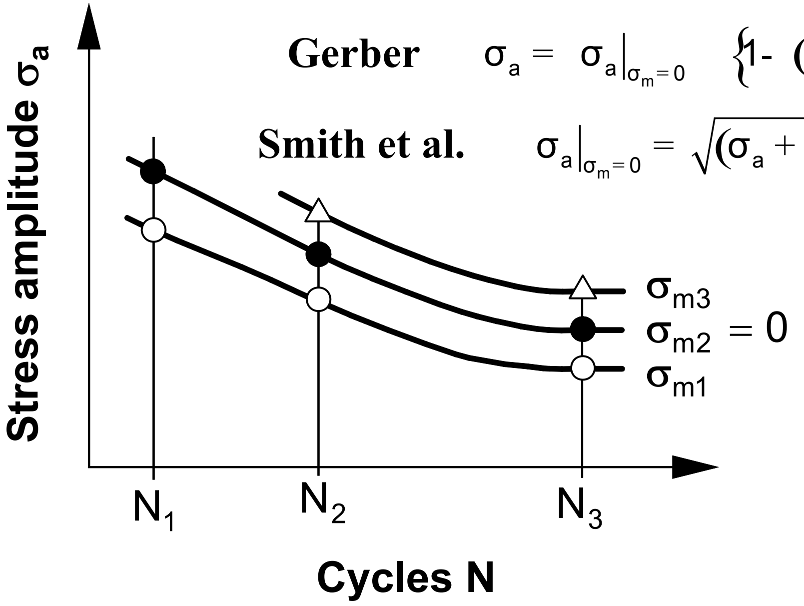
CRACK INITIATION LIFE ESTIMATION

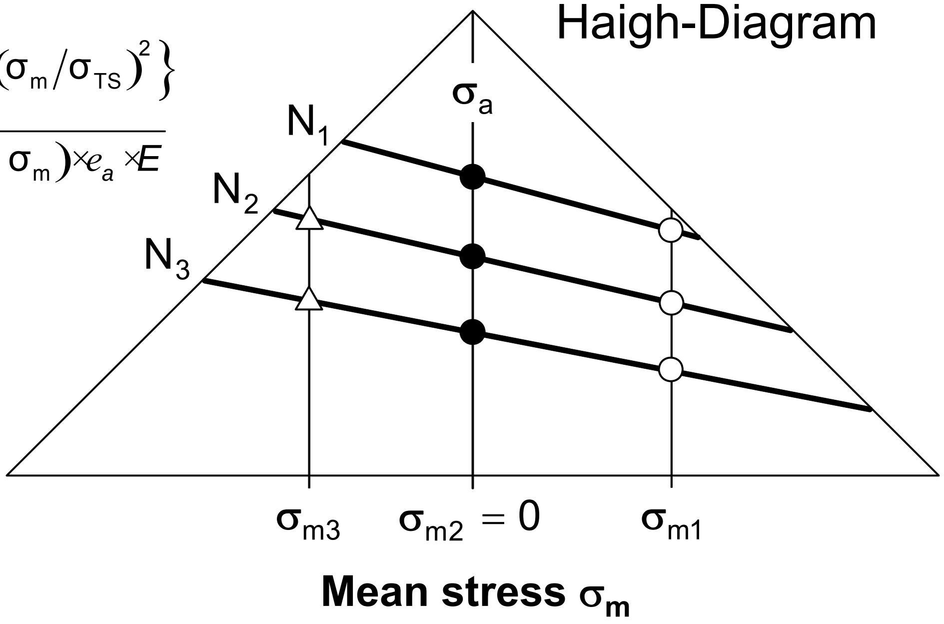
Tensile mean stresses decrease, compressive increase fatigue life. Often used approximation formulas are proposed by:

Goodman $\sigma_a = \sigma_a|_{\sigma_m=0}\{1-\sigma_m/\sigma_{UTS}\}$

Gerber $\sigma_a = \sigma_a|_{\sigma_m=0}\{1-(\sigma_m/\sigma_{TS})^2\}$

Smith et al. $\sigma_a|_{\sigma_m=0} = \sqrt{(\sigma_a+\sigma_m)\times\varepsilon_a\times E}$





FATIGUE

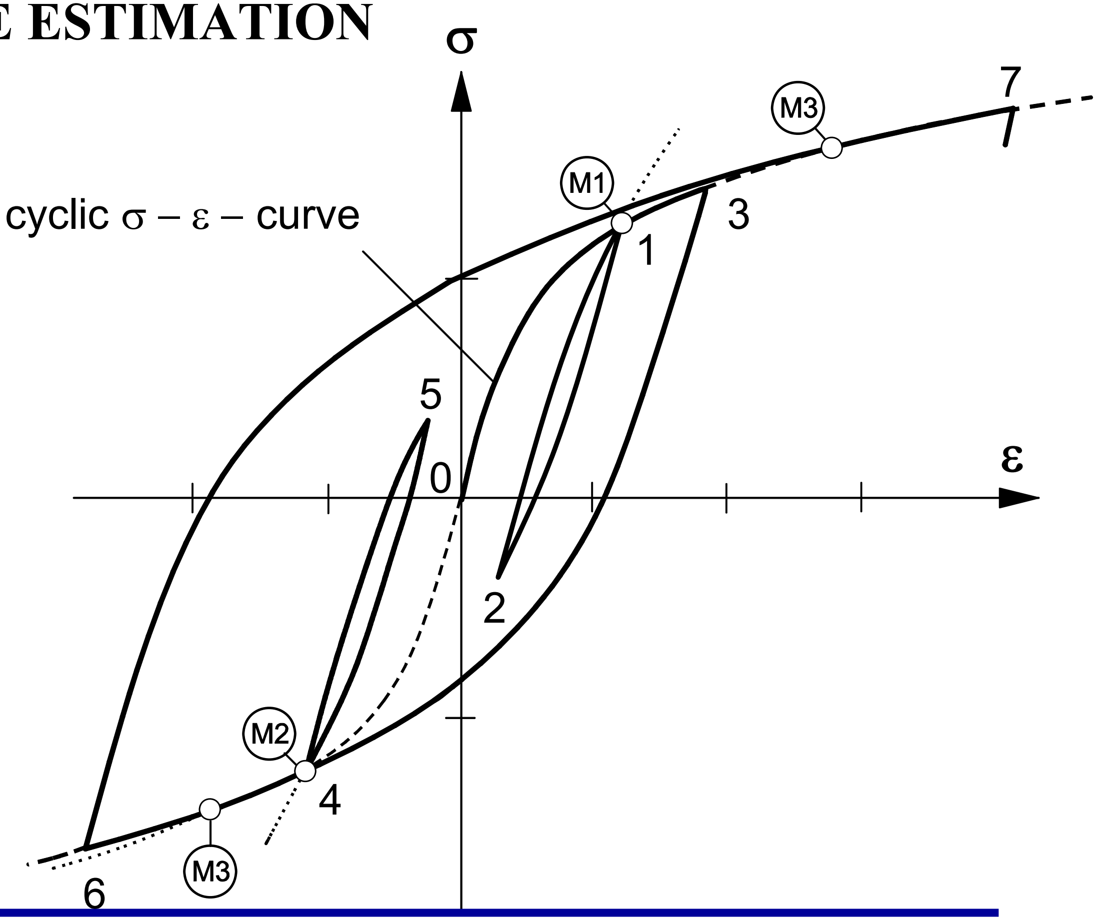
CRACK INITIATION LIFE ESTIMATION

Under variable amplitude loading closed hysteresis loops can be identified.

Doubling the cyclic σ–ε-curve describes the loop branches. The σ–ε–path of a branch kinks into a higher order path branch when both meet each other (Material Memory).

Counting closed loops is named **Rainflow Counting**.

The damage of individual cycles is summed according to Miner's rule.

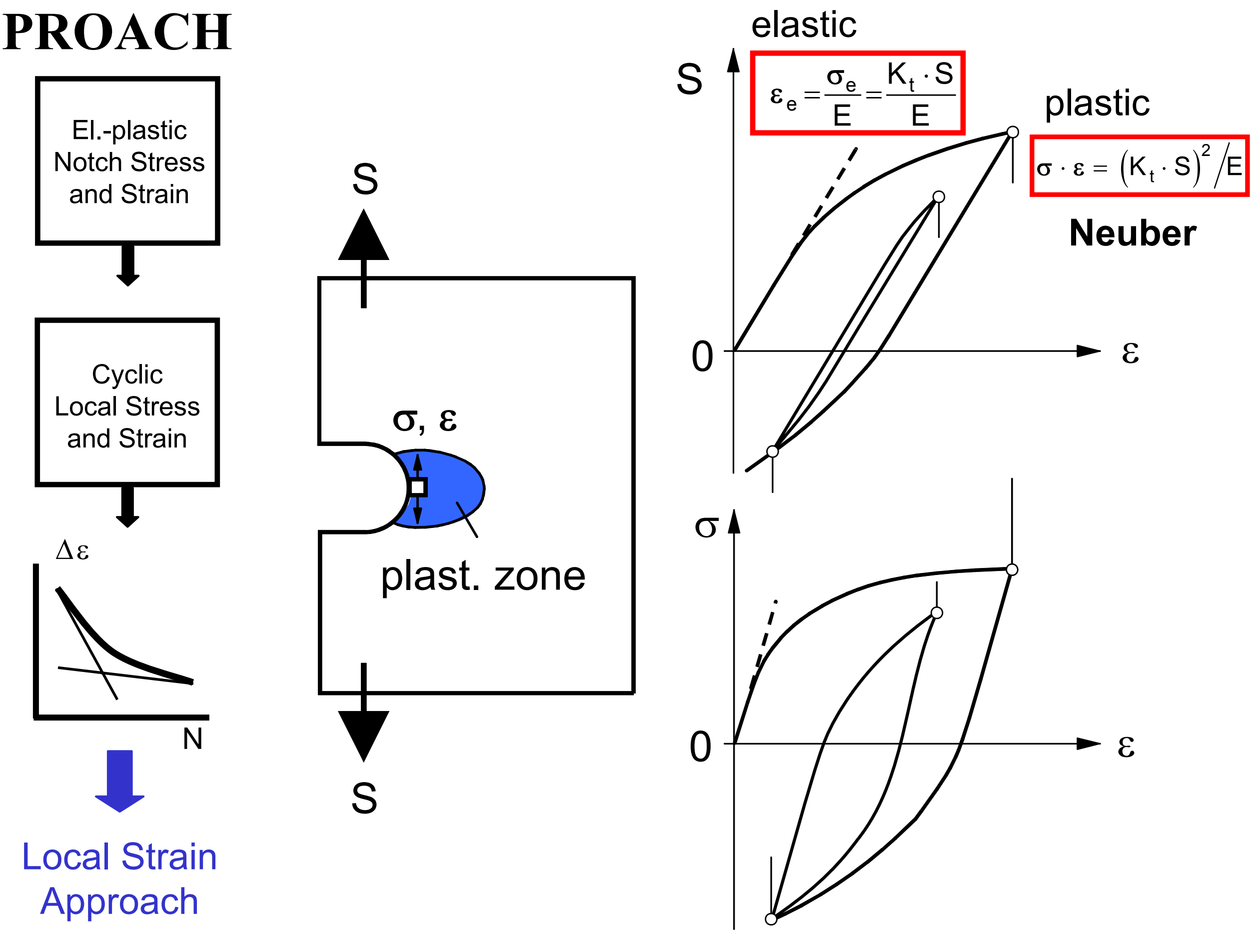


FATIGUE

LOCAL STRAIN APPROACH

For notched components the σ–ε path is calculated at the critical locations (notch roots). The elastic stress concentration factor K_t must be known.

Notch stresses and strains can be approximated using **Neuber's rule**.

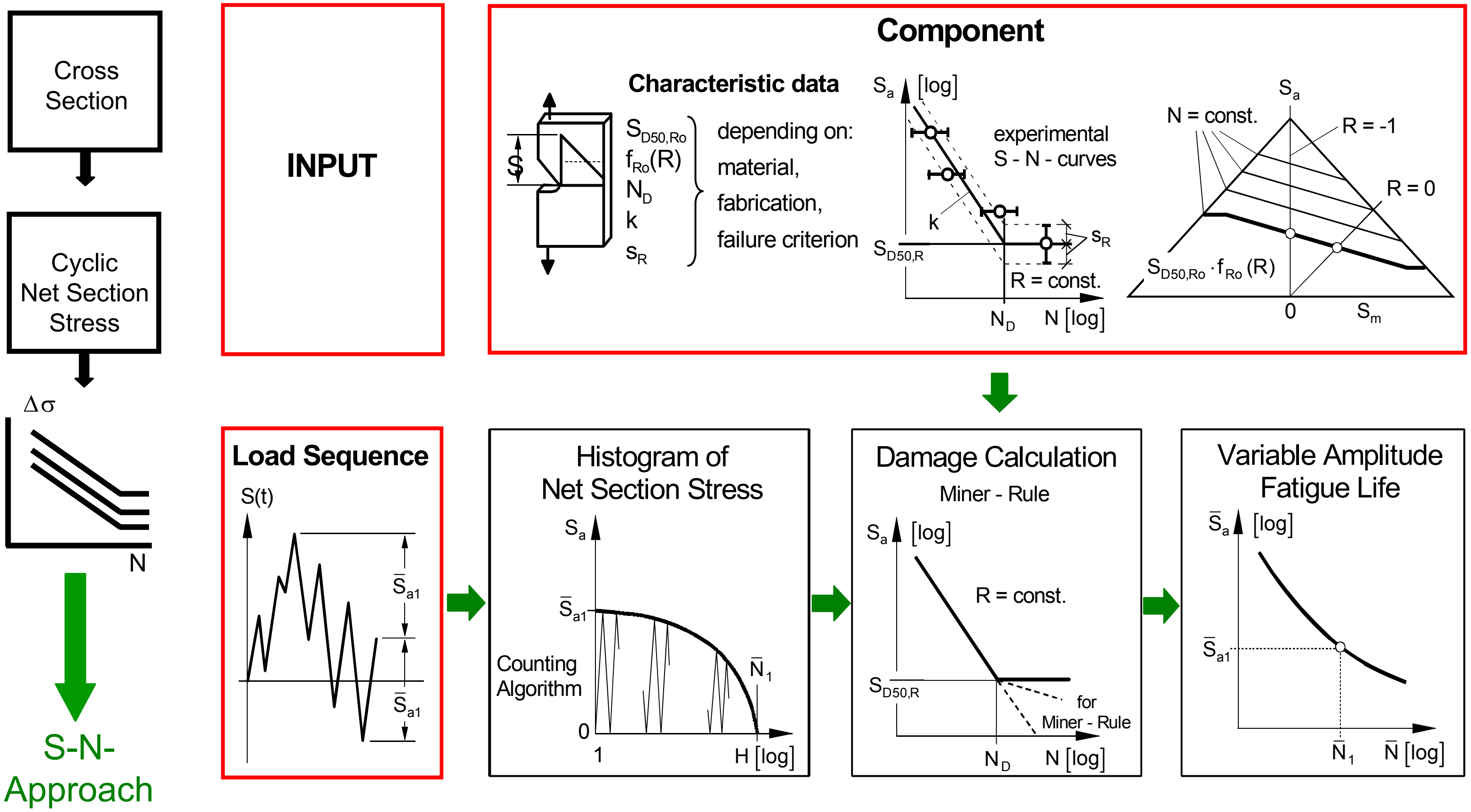


$$\varepsilon_e = \frac{\sigma_e}{E} = \frac{K_t \cdot S}{E}$$

$$\sigma \cdot \varepsilon = \left(K_t \cdot S\right)^2 / E$$

FATIGUE

S - N APPROACH



Cross Section

Cyclic Net Section Stress

INPUT

Component

Characteristic data

$S_{D50,Ro}$
$f_{Ro}(R)$
N_D
k
s_R

depending on:
material,
fabrication,
failure criterion

Load Sequence

Histogram of Net Section Stress

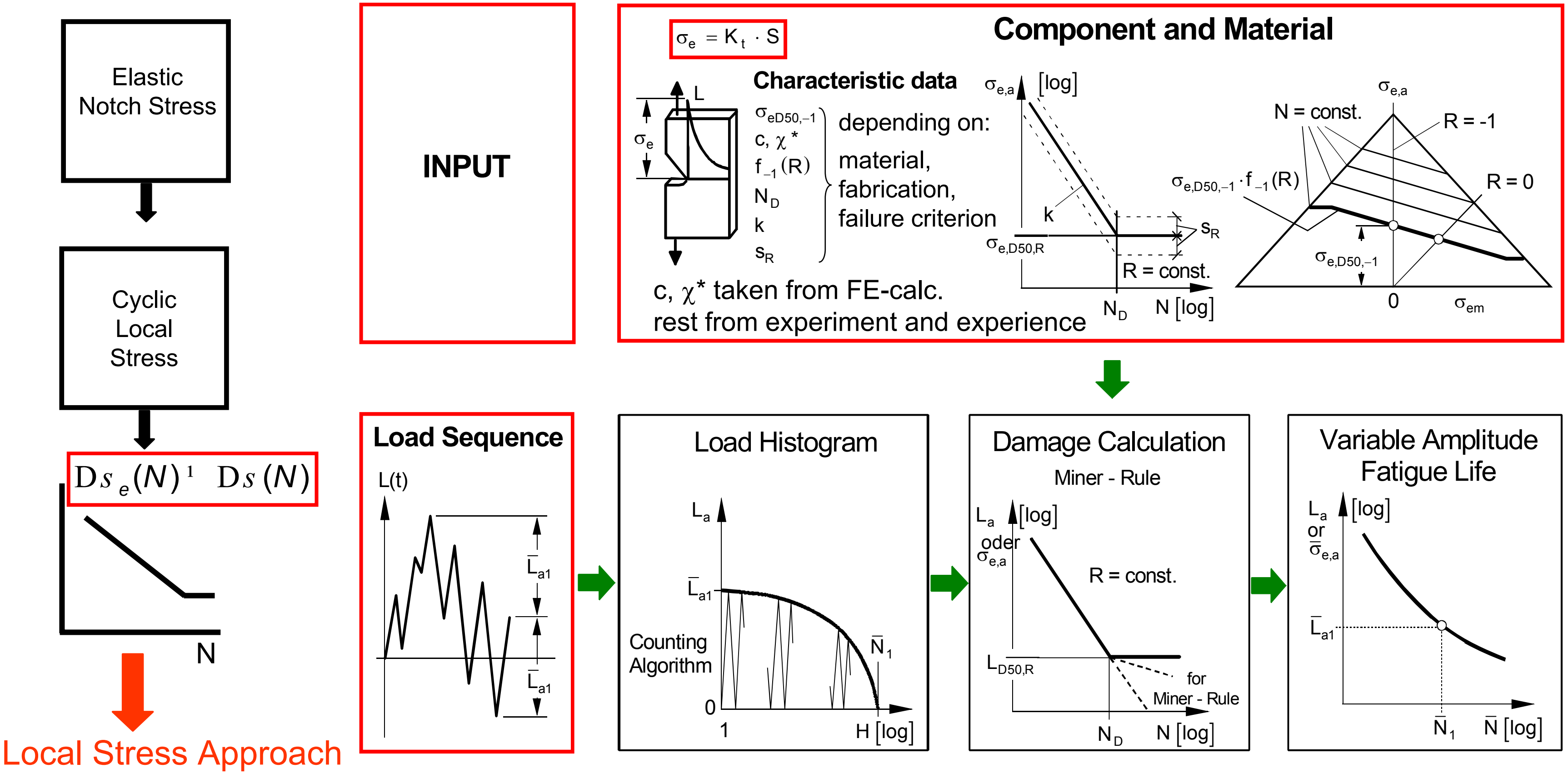
Damage Calculation
Miner - Rule

Variable Amplitude Fatigue Life

S-N-Approach

FATIGUE

LOCAL STRESS APPROACH



Elastic Notch Stress

Cyclic Local Stress

$\Delta\sigma_e(N) \neq \Delta\sigma(N)$

Local Stress Approach

INPUT

Component and Material

$\sigma_e = K_t \cdot S$

Characteristic data

$\sigma_{eD50,-1}$, c, χ^*, $f_{-1}(R)$, N_D, k, s_R depending on: material, fabrication, failure criterion

c, χ^* taken from FE-calc.
rest from experiment and experience

Load Sequence

Load Histogram

Damage Calculation

Miner - Rule

Variable Amplitude Fatigue Life

BIBLIOGRAPHY / REFERENCES

- Suresh S., *"Fatigue of Materials"*, Cambridge Solid State Science Series, Cambridge (1991).
- Anderson T.L., *"Fracture Mechanics. Fundamentals and Applications"*, 2nd Edition, CRC Press, Boca Raton (1995).

B. INTRODUCTION TO FATIGUE ASSESSMENT PROCEDURES

FATIGUE ASSESSMENT PROCEDURES

INTRODUCTION

Fatigue assessments involve comparison of the actions which the component or structure will be required to sustain during its design life with its resistance to fatigue.

Obviously, the resistance must be sufficient to resist the actions without failure occurring. The form and source of the resistance data depend on the type of assessment being performed.

FATIGUE ASSESSMENT PROCEDURES

INTRODUCTION

There are two main methods for assessing the fatigue life of structures or components:

- S-N curves
- The fracture mechanics approach, whereby fatigue crack growth data are used in conjunction with the stress intensity factor variation due to the spectrum of applied loading to calculate the progress of a known flaw.

The first is intended for application at the design stage and the second one is not generally used for design but for assessing known or assumed flaws. Thus, it would be applicable in an assessment of residual fatigue life.

FATIGUE ASSESSMENT PROCEDURES

DESIGN OF NEW STRUCTURES OR COMPONENTS

Fatigue resistance data for design are usually expressed in terms of S-N curves, relating nominal applied cyclic stress range S and the corresponding number of cycles N needed to cause failure.

The simplest situation is one in which the designer would ensure that the number of applied load fluctuations, n, in the design life that resulted in stress range S did not exceed N.

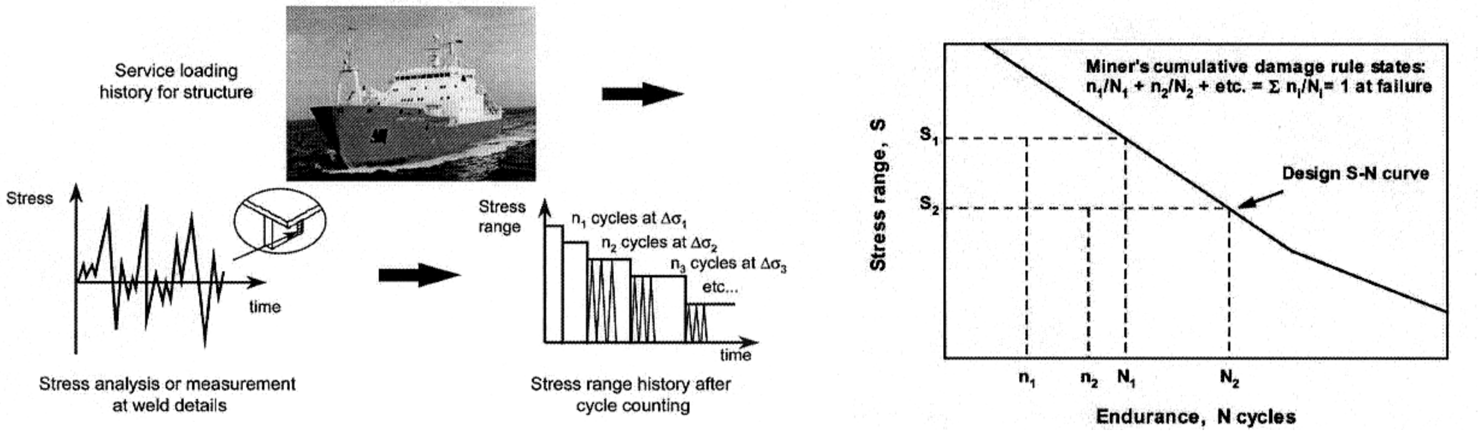
In the more general case there is a spectrum of applied loads and the cumulative damage due to individual load cycles need to be determined. The usual method is to apply Miner´s rule.

FATIGUE ASSESSMENT PROCEDURES

DESIGN OF NEW STRUCTURES OR COMPONENTS

This involves:

- identification of the loading history
- conversion from loads to stresses
- extraction of recognisable stress cycles from the stress spectrum (cycle counting) to provide input to Miner´s rule



Miner´s rule for estimating fatigue lives under variable amplitude loading and analysis of fatigue loading for cumulative damage calculations

FATIGUE ASSESSMENT PROCEDURES

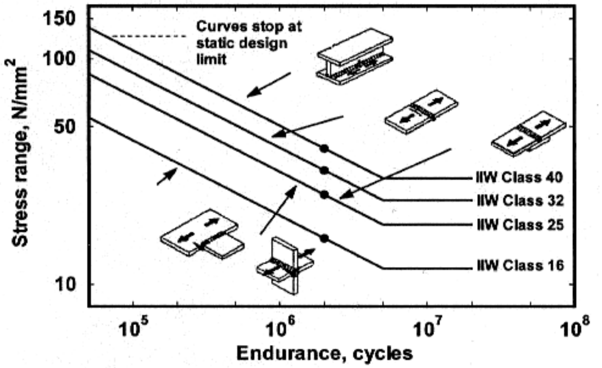
DESIGN OF NEW STRUCTURES OR COMPONENTS

The S-N curves used in fatigue design depend on the procedure being used. The most common approach is to use S-N curves obtained from fatigue tests.

Example: welded structures

S-N curves from fatigue tests on specimens containing the weld detail of interest are used. The design curve is usually some statistical lower bound to published experimental data (i.e, mean – 2·standard deviations of logN).

Since S-N curves refer to particular weld details, there is no need for the user to attempt to quantify the local stress concentration effect of the weld detail itself.



Examples of design S-N curves for welded joints (from IIW recommendarions)

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

Three approaches can be distinguished for the fatigue assessment of existing structures which have experienced some service:

- Fatigue design assessment
- Fatigue design reviews
- Fracture mechanics approach

The approach used will depend on the circumstances:

- Whether or not the structure was designed for fatigue loading
- The time in service
- What measures will be taken to assess its current condition with respect to potential fatigue damage already introduced during previous service.

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

FATIGUE DESIGN ASSESSMENT

This method follows the procedure outlined previously for original design.

If the structure was designed for fatigue loading, the same action can be assumed after any modification to allow for changes such as reduced severity of the stress history from reinforcement or a change in operating conditions. If repairs are introduced, a safety factor could be introduced.

Miner´s rule is used to calculate the fatigue damage introduced before and after the time of the assessment, on the basis that:

$$\left(\sum \frac{n}{N}\right)_{\mathrm{before}} + \left(\sum \frac{n}{N}\right)_{\mathrm{after}} \angle \quad 1$$

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

FATIGUE DESIGN REVIEW

Its aim is to improve the accuracy of the original design process to provide a better estimate of the proportions of fatigue life used and remaining at the time of assessment.

When assessing an existing structure, there may be scope for improving the accuracy of some of the assumptions made during the original design process.

Then the Miner´s rule should be applied.

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

FRACTURE MECHANICS APPROACH

This method addresses circumstances in which it has been found (or it must be assumed) that flaws have been introduced during the service life endured so far.

The fracture mechanics assessment uses the same actions as those determined for design calculations. However, fatigue resistance is represented by fatigue crack growth rate data for the material under consideration, expressed in terms of the fracture mechanics stress intensity factor parameter ΔK:

$$\Delta K = Y \cdot S \cdot (\pi \cdot a)^{1/2}$$

$$Y = Y(\text{geometry, loading})$$

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

FRACTURE MECHANICS APPROACH

A relationship between ΔK and crack growth rate is established through different equations. One of the most widely used is the Paris law:

$$\frac{da}{dN} = C \cdot (\Delta K)^n$$

For a flaw size a_0 and a critical fatigue crack size of a_f, the remining life N under stress range S is obtained by integrating the Paris law:

$$\int_{a_0}^{a_f} \frac{da}{\left(Y \cdot S \cdot \sqrt{\pi \cdot a}\right)^n} = C \cdot N$$

FATIGUE ASSESSMENT PROCEDURES

REMAINING LIFE OF EXISTING STRUCTURES

FRACTURE MECHANICS APPROACH

For variable amplitude loading the integration will be performed for each individual cycle or block of equal stress cycles, to give:

$$\int_{a_0}^{a_1} \frac{da}{\left(Y \cdot S_1 \cdot \sqrt{\pi \cdot a}\right)^n} + \int_{a_1}^{a_2} \frac{da}{\left(Y \cdot S_2 \cdot \sqrt{\pi \cdot a}\right)^n} + \ldots = C \cdot N$$

$$\sum_i \int_{a_{i-1}}^{a_i} \frac{da}{\left(Y \cdot S_i \cdot \sqrt{\pi \cdot a}\right)^n} = C \cdot N$$

BIBLIOGRAPHY / REFERENCES

- Maddox S.J., *"Review of fatigue assessment procedures for welded aluminium structures",* International Journal of Fatigue, December 2003, pages 1359-1378

C. PROCEDURE APPLICATION (FITNET)

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

- **INTRODUCTION**
- **INPUTS**
- **ASSESSMENT ROUTES**
- **SPECIAL OPTIONS**

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

INTRODUCTION

The FITNET fatigue module provides a series of assessment procedures or routes for evaluating the effect of cyclic or fluctuating loads. Two basic scenarios are foreseen:

a) There is no pre-existing flaw or defect, and the goal of the analysis is to determine the accumulation of fatigue damage at a critical location (fatigue damage analysis). In this case the basic approach is to determine the fluctuating stress range at the location in question and to relate this to appropriate fatigue life curves. Three different routes are proposed (Routes 1, 2 and 3), depending on the complexity of the loading.

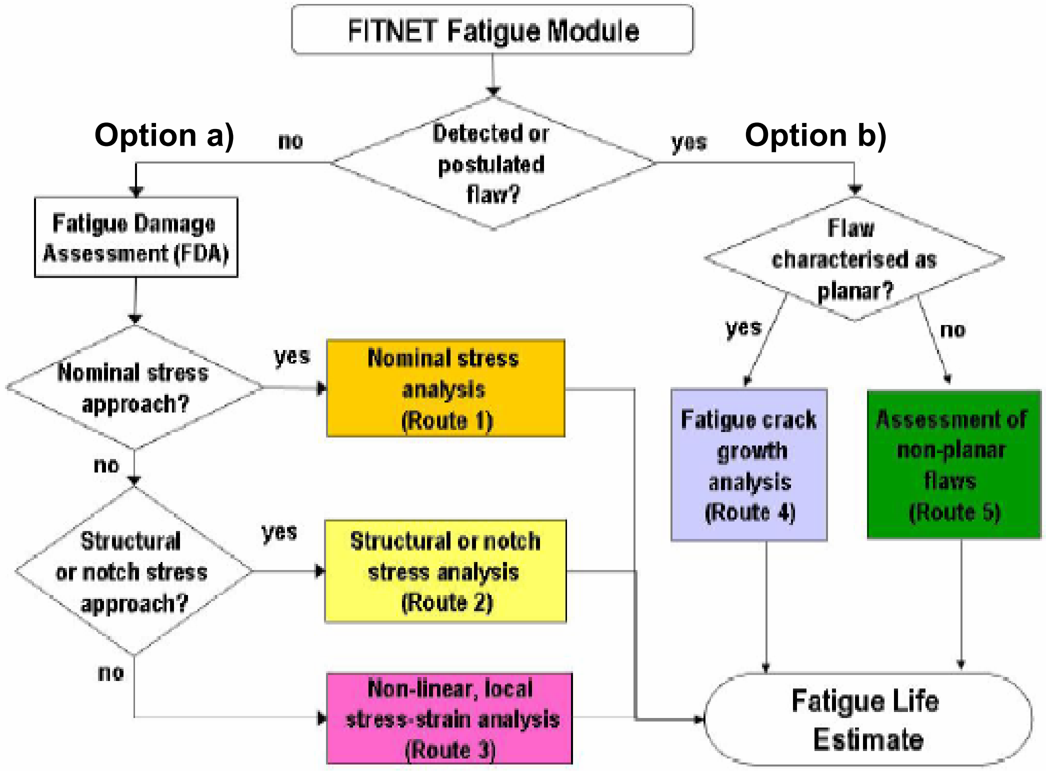
b) A real or postulated defect or flaw is present, and the goal of the analysis is to determine the growth of that flaw to a certain critical size. Two different routes are considered: The case of planar flaw in Route 4 and the case of non planar defects in Route 5.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

Both option a) and b) can be applied to either welded or non-welded structures. The overall scheme is shown in the figure.

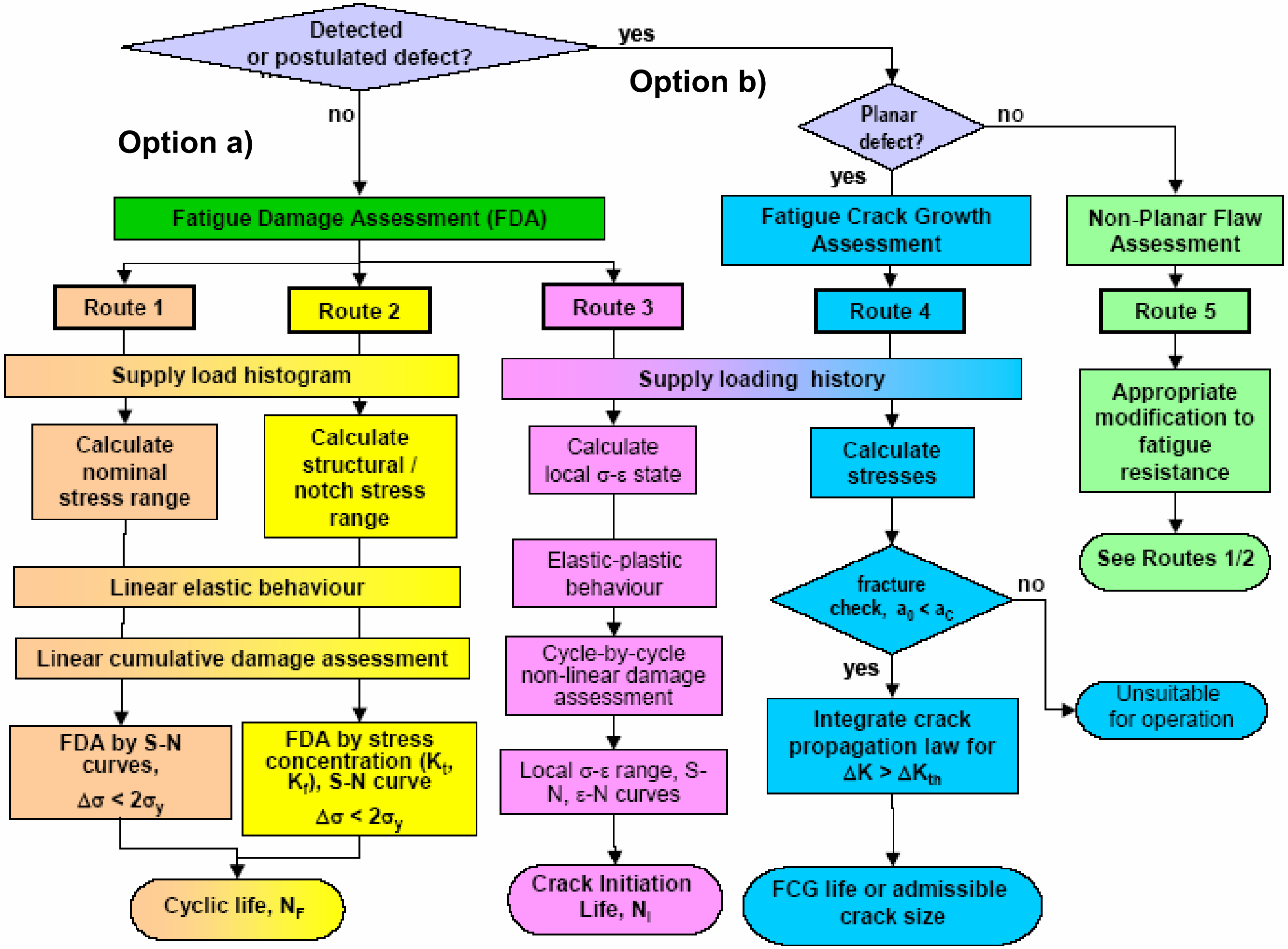


FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

The scope and background to the five assessment routes are briefly described in the following, while this figure shows the basic steps used in applying these.



Detected or postulated defect?

yes

no

Option a)

Option b)

Planar defect?

no

yes

Fatigue Damage Assessment (FDA)

Fatigue Crack Growth Assessment

Non-Planar Flaw Assessment

Route 1

Route 2

Route 3

Route 4

Route 5

Supply load histogram

Supply loading history

Appropriate modification to fatigue resistance

Calculate nominal stress range

Calculate structural / notch stress range

Calculate local σ-ε state

Calculate stresses

See Routes 1/2

Linear elastic behaviour

Elastic-plastic behaviour

fracture check, $a_0 < a_c$

no

Linear cumulative damage assessment

Cycle-by-cycle non-linear damage assessment

yes

Unsuitable for operation

FDA by S-N curves, $\Delta\sigma < 2\sigma_y$

FDA by stress concentration (K_t, K_f), S-N curve $\Delta\sigma < 2\sigma_y$

Local σ-ε range, S-N, ε-N curves

Integrate crack propagation law for $\Delta K > \Delta K_{th}$

Cyclic life, N_F

Crack Initiation Life, N_I

FCG life or admissible crack size

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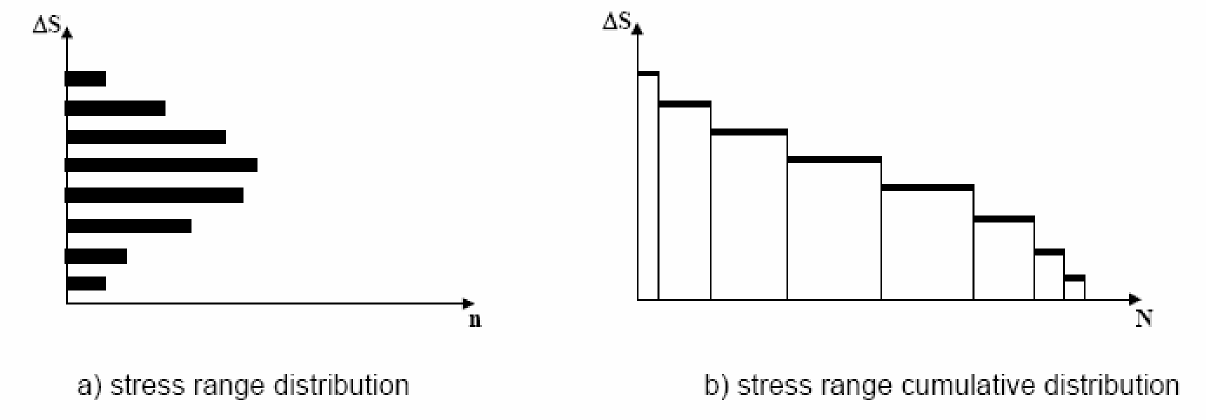
INPUTS

INPUTS: Description of variable loads

To assess fatigue risk it must be known the stress variation versus time.

In practice, the more commonly applied methods in design allow the use of the stress range distribution (histogram) versus the number of cycles.



a) stress range distribution

b) stress range cumulative distribution

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INPUTS

INPUTS: Partial Safety Factors

Depending on the level of safety built into the fatigue resistance data being used in the assessment, the confidence with which the fatigue actions can be estimated and possibly the consequences of fatigue failure, partial safety factors may need to be introduced. Those applied to the fatigue actions are termed γ_F while those applied to the resistance data are termed γ_M .

INPUTS: Fatigue Actions

Fatigue assessments are carried out using the design spectrum (histogram) of the fatigue actions in terms of stress ranges $\Delta\sigma_{i,s,d}$, which correspond to the stresses of the characteristic spectrum (histogram) $\Delta\sigma_{i,s,k}$ multiplied by the partial safety factor γ_F for fatigue actions.

For constant amplitude loading, the characteristic and design spectra are reduced to only one stress level, $\Delta\sigma_{s,d}=\Delta\sigma_{s,k}\cdot\gamma_F$

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INPUTS

INPUTS: Cumulative Fatigue Assessment

A cumulative fatigue assessment is applied in situations where it is considered that fatigue crack initiation and growth can be tolerated without the risk of failure during the required lifetime. The fatigue resistance is usually derived from constant or variable amplitude tests. The fatigue resistance data given in the Procedure are based on published results from constant amplitude tests.

The fatigue resistance data must be expressed in terms of the same stress (Nominal, Hot spot, Notch) or strain as that controlled or determined during the generation of those data.

INPUTS: Cumulative Fatigue Assessment (cont.)

The fatigue resistance data are based on the number of cycles N to failure. The data are represented in S-N curves (see Section 5).

$$N = \frac{C}{\Delta\sigma^m} \quad \text{or} \quad N = \frac{C}{\Delta\tau^m}$$

where:

$\Delta\sigma$	normal stress range
$\Delta\tau$	shear stress range
N	number of cycles to failure
C, m	material and assessed detail constants

INPUTS: Cumulative Fatigue Assessment (cont.)

The fatigue resistance is defined by the mean curve (50% probability of survival) and the Log (C) standard deviation.

The conventional fatigue resistance data can be given as characteristic values, $\Delta\sigma_{R,k}$ or $\Delta\tau_{R,k}$, which are assumed to have a survival probability of at least 95%, calculated from a mean value of a two-sided 75% confidence level.

In practice these characteristic values may be reduced further by dividing them by a partial safety factor γ_M to give the design resistance values, $\Delta\sigma_{R,d}$ and , $\Delta\tau_{R,d}$ used in the fatigue assessment. The design resistance S-N curve may be modified further according to the needs of the damage calculation procedure.

INPUTS: Cumulative Fatigue Assessment (cont.)

For constant amplitude loading, the characteristic stress range , $\Delta\sigma_{R,k}$ at the required number of stress cycles is firstly determined. Secondly, the fatigue design criterion is checked:

$$\Delta\sigma_{s,d} = \Delta\sigma_{s,k}\gamma_F < \Delta\sigma_{R,d} = \frac{\Delta\sigma_{R,k}}{\gamma_M}$$

For variable amplitude loading, the fatigue damage due to the applied load spectrum is assessed using a linear cumulative damage summation rule. Thus in a fatigue damage assessment has to be shown that:

$$\Sigma \frac{n_i}{N_i} < D$$

D : specified allowable damage sum
i Index for block number in load spectrum of required design life
n_i number of cycles of design load stress range $\Delta\sigma_{i,s,d}$ in load spectrum block i
N_i: number of cycles at which design stress range $\Delta\sigma_{i,s,d}$ causes failure in modified design fatigue resistance S-N curve.

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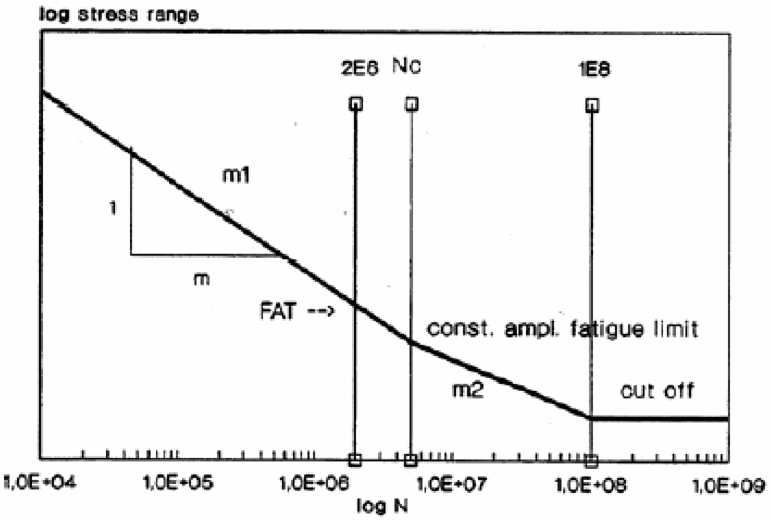
INPUTS

INPUTS: Cumulative Fatigue Assessment (cont.)

The order of the sequence of the blocks has no effect on the results of this calculation. Note that it will rarely be valid to assume that applied stresses lower than the constant amplitude fatigue limits are non-damaging. In practice the fatigue damage induced by higher stresses in the spectrum will have the effect of gradually lowering the effective fatigue limit. As a result, stresses below the original fatigue limit become increasingly damaging as the fatigue life progresses. To allow for this it is common to assume that the design S-N curve from which i values are obtained the form shown in the figure.



Generic S-N curve for welded joints used in cumulative damage calculations

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INPUTS

INPUTS: Fatigue Limit Assessment

A fatigue limit assessment is one that is applied to cases where no significant fatigue crack growth can be tolerated, for example because there is a risk of failure from a small crack or a very high number of stress cycles, typically greater than 10^9 cycles, are to be endured.

The fatigue limit resistance is defined by the stress range, $\Delta\sigma_{L,R}$, below which the lifetime is considered to be infinite from an engineering point of view. Again, characteristic values ,$\Delta\sigma_{L,R,k}$, are reduced to design values $\Delta\sigma_{L,R,d}=\Delta\sigma_{L,R,k}/\gamma_M$.

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INPUTS

INPUTS: Fatigue Limit Assessment (cont.)

When the fatigue limit assessment is applied for constant amplitude loading, the design verification criterion is:

$$\Delta\sigma_{M,s,d} < \Delta\sigma_{L,R,d}$$

where $\Delta\sigma_{M,s,d}$ is the maximum applied stress range and $\Delta\sigma_{L,R,d}$ is the design acceptable fatigue limit stress range.

For variable amplitude loading, if the maximum design stress range $\Delta\sigma_{M,s,d}$ of the load spectrum is lower than the design fatigue limit $\Delta\sigma_{L,R,d}$ of the design fatigue resistance S-N curve, or if it is lower than the design cut-off limit $\Delta\sigma_{cut,R,d}$ in cases where no fatigue limit is given, the life of the assessed detail can be assumed to be infinite and no further damage calculation is necessary.

INPUTS: Environmental Issues

The fatigue resistance data given here refer to non-corrosive environments (air) and for structures with normal protection against atmospheric corrosion. For free atmospheric corrosion, in particular sea environment, the SN curve to be applied can be derived from the standard curve applying the following conditions:

- the curve has no fatigue limit nor cut-off and no change of slope
- the life time is divided by 2

Concerning service temperature, unless stated otherwise the fatigue resistance data refer to temperatures lower than 100°C; a fatigue reduction factor has to be considered beyond this temperature level.

If the effect of environment cannot be excluded, then the assessment should be made using the creep or corrosion modules (see sections 8 and 9 respectively).

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INPUTS

INPUTS: Exemption for Fatigue Assessment

The Procedure provides criteria to determine when fatigue assessment is not required (see Section 7.2.3)

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FATIGUE ASSESSMENT ROUTES

ROUTE 1 – Fatigue Damage Assessment Using Nominal Stresses

This route considers **nominal elastic stress** values for the location of interest and the fatigue life N_f is determined from a **set of S-N curves** classified according to different classes or levels of fatigue resistance i.e. the effects of local geometric, weld or microstructural details and, if relevant, residual stress are accounted for in the S-N curve itself.

It is based on currently used procedures (e.g. IIW guidelines for welded joints).

The linear cumulative damage law is used to deal with variable load spectra is **based on Miner rules**.

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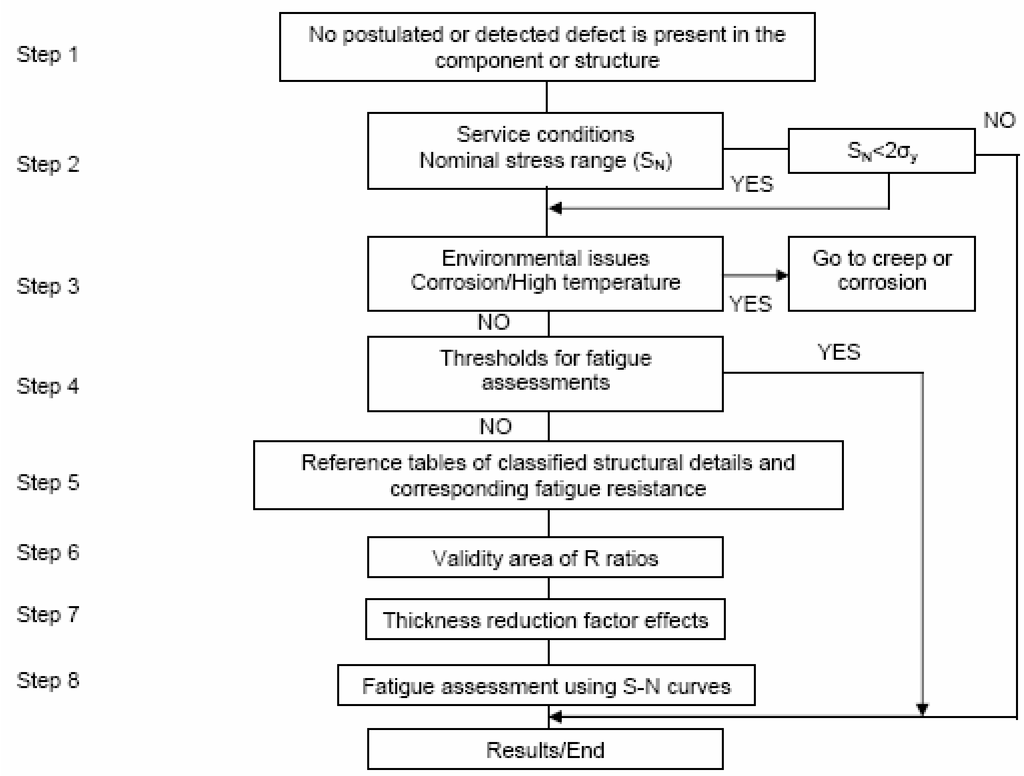
ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

WELDED COMPONENTS



Step 1: No postulated or detected defect is present in the component or structure

Step 2: Service conditions
Nominal stress range (S_N)

$S_N<2\sigma_y$ — YES → Step 3; NO → Results/End

Step 3: Environmental issues
Corrosion/High temperature

YES → Go to creep or corrosion; NO → Step 4

Step 4: Thresholds for fatigue assessments

YES → Results/End; NO → Step 5

Step 5: Reference tables of classified structural details and corresponding fatigue resistance

Step 6: Validity area of R ratios

Step 7: Thickness reduction factor effects

Step 8: Fatigue assessment using S-N curves

Results/End

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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

WELDED COMPONENTS

Step 1 No postulated or detected defect is present in the structure

The route 1 assumed that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue. Annexe D in the Procedure is providing guideline on NDE detection.

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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 2 Service condition

Nominal stress range SN. Guide on this is given in the Procedure (see Section 7.3)

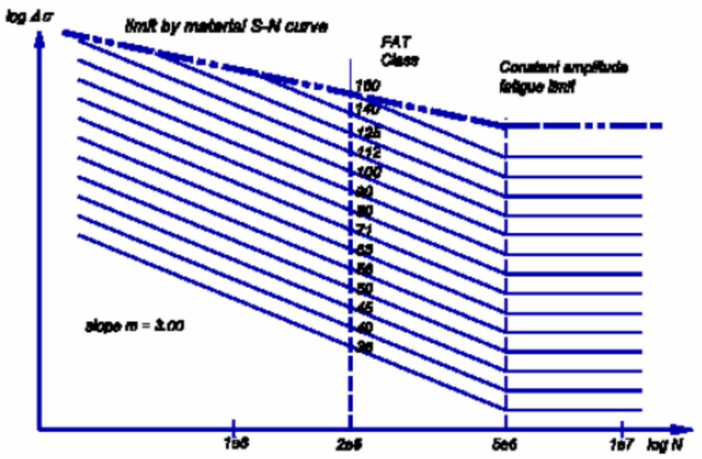
Step 3 Environmental issues (see 7.2.2)

Step 4 Thresholds for fatigue assessment (see 7.2.3)

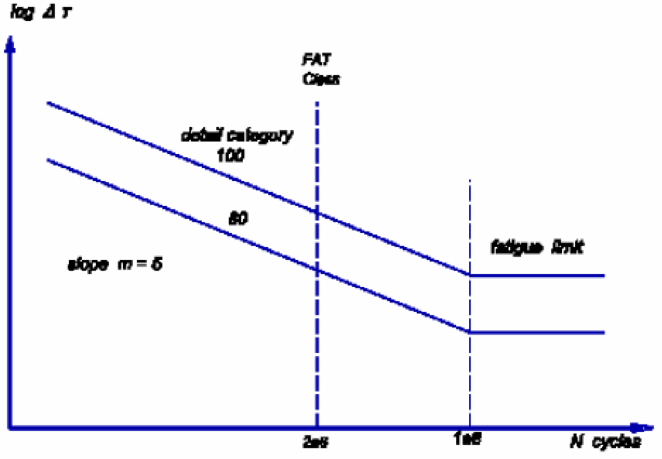
ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 5 Fatigue Resistance Data Specification

Separate S-N curves are provided for consideration of normal and shear stresses:



Fatigue resistance S-N curves for m=3, normal stress (steel)



Fatigue resistance S-N curves for shear stress (steel)

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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 6 Validity area of R ratios

For stress ratios R<0.5 a fatigue enhancement factor f(R) may be considered by multiplying the fatigue class of classified details by f(R). Values of f(R) are given in the Procedure (see Section 7.3.1.1.6).

Step 7 Thickness reduction factor effects

The influence of the plate thickness on fatigue strength should be taken into account in cases where cracks start from the weld toe on plates thicker than 25 mm and lower than 5 mm (see Section 7.3.1.1.7)

Step 8 Fatigue assessment using S-N Curves (see 7.3.1.1.8)

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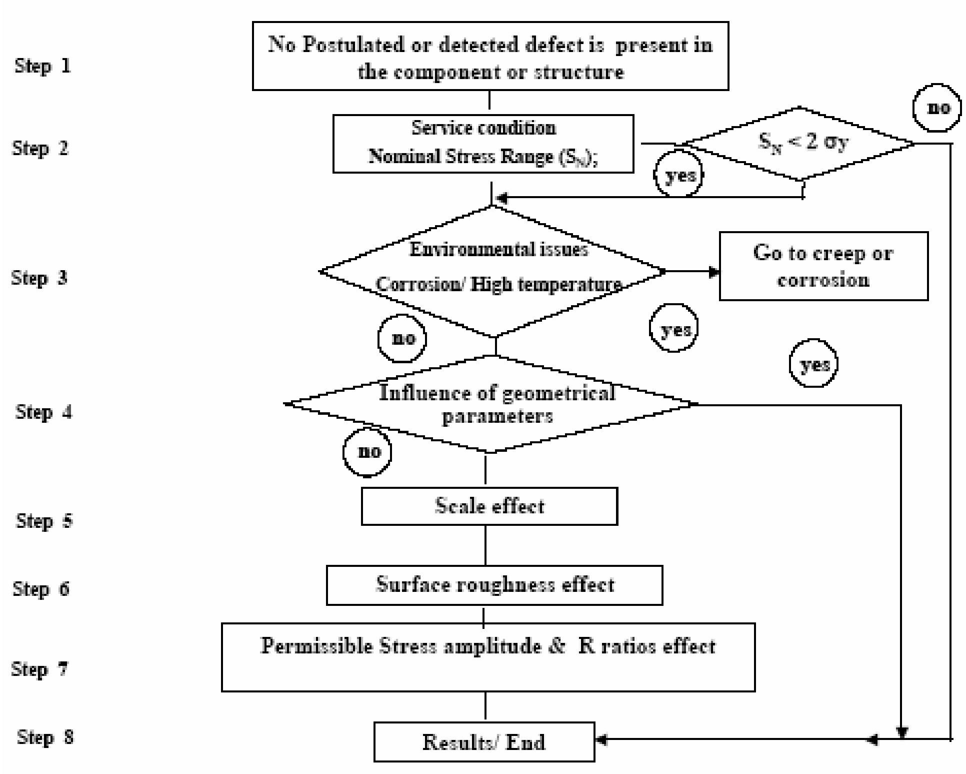
ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

NON-WELDED COMPONENTS



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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

The conventional approach starts from the knowledge of the fatigue resistance of the base material submitted to fatigue cycles.

This approach leads to modify this « intrinsic » endurance or reliability limit, σ_D, by taking into account of influencing parameters such as :

- the geometrical discontinuities of the components (notch effect, Step 4, see 7.3.1.2.4.1)
- its size (step 5, scale effect, see 7.3.1.2.4.2)
- the surface roughness (step 6, surface effect, see 7.3.1.2.4.3)
- the mean stress σ_m (step 7, mean stress effect, see 7.3.1.2.5)

Finally, the permissible nominal stress σ_a , is derived and compared to the actual (nominal) stress, σ_e applied to the component.

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FATIGUE ASSESSMENT ROUTES

ROUTE 2 – Fatigue damage assessment using structural or notch stresses

This route considers that the appropriate structural stress in a critical area of a component could be calculated by FEA or by formula. In some case it could also be measured by following specific methods. Two approaches are possible:

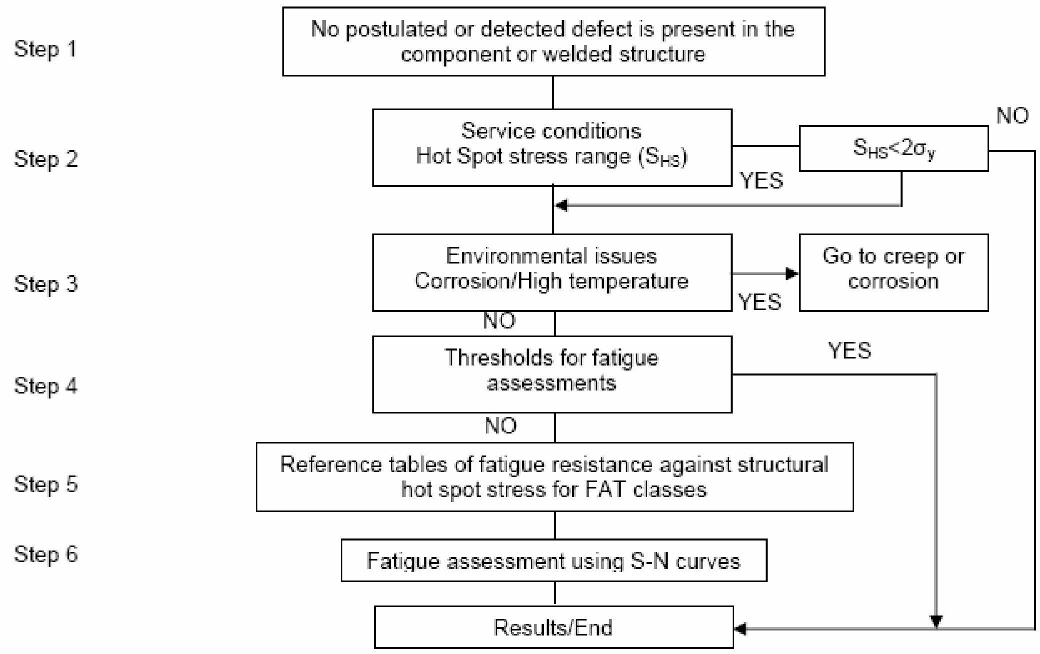
a)calculate the structural stress and apply with appropriate class S-N curves

b)calculate a notch stress via stress concentration factors such as K_t or K_f. and apply with appropriate S-N curves

The Palmgren-Miner linear cumulative damage rule is used to deal with variable loads.

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

WELD COMPONENTS



Step 1: No postulated or detected defect is present in the component or welded structure

Step 2: Service conditions Hot Spot stress range (S_{HS}) → $S_{HS}<2\sigma_y$ — YES / NO

Step 3: Environmental issues Corrosion/High temperature — YES → Go to creep or corrosion; NO

Step 4: Thresholds for fatigue assessments — YES / NO

Step 5: Reference tables of fatigue resistance against structural hot spot stress for FAT classes

Step 6: Fatigue assessment using S-N curves

Results/End

Stepwise flowchart for Route 2. Weld components.

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ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

WELD COMPONENTS

Step 1: No postulated or detected flaw is present in the structure

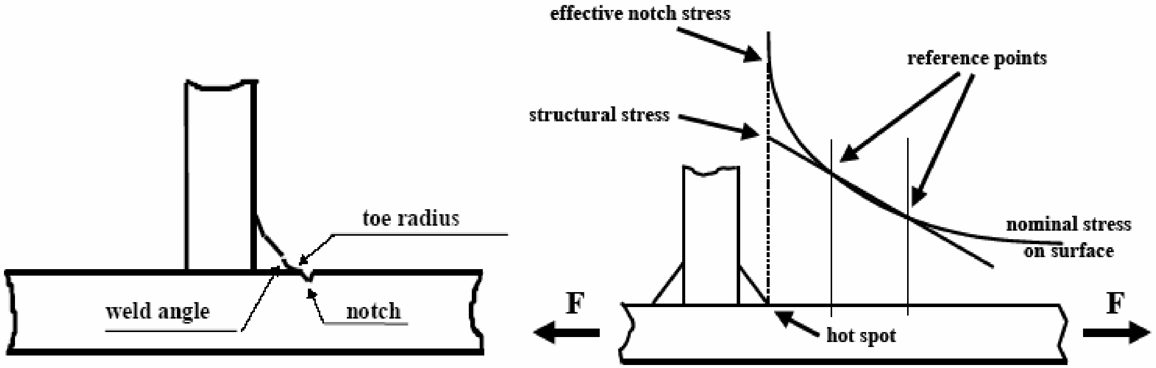
The route 2 assumed that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue. The fatigue assessment is based on fatigue linear damage analysis. FITNET procedure provides guideline on NDE detection (see Annex D).

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 2: Service condition

Fatigue resistance will be calculated in route 2 by using Hot spot stress range S_{HS} or Notch Stress range ($\Delta\sigma_{notch}$) calculation.

The structural hot spot stress and effective notch stress are defined versus the nominal stress by means of two stress coefficient factors: structural hot spot stress SCF_{HS} and notch effect SCF_{NS}. The procedure provides guidance for the calculation of these coefficients in 7.3.2.1.2.



Hot spot and notch stress in a welded joint.

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 3 Environmental issues (see Section 7.2.2)

Step 4 Thresholds for fatigue assessment (see Section 7.2.3)

Step 5 Fatigue Data Specifications (see Section 7.3.2.1.5)

Step 6 Fatigue assessment using S-N Curves (see 7.3.2.1.6)

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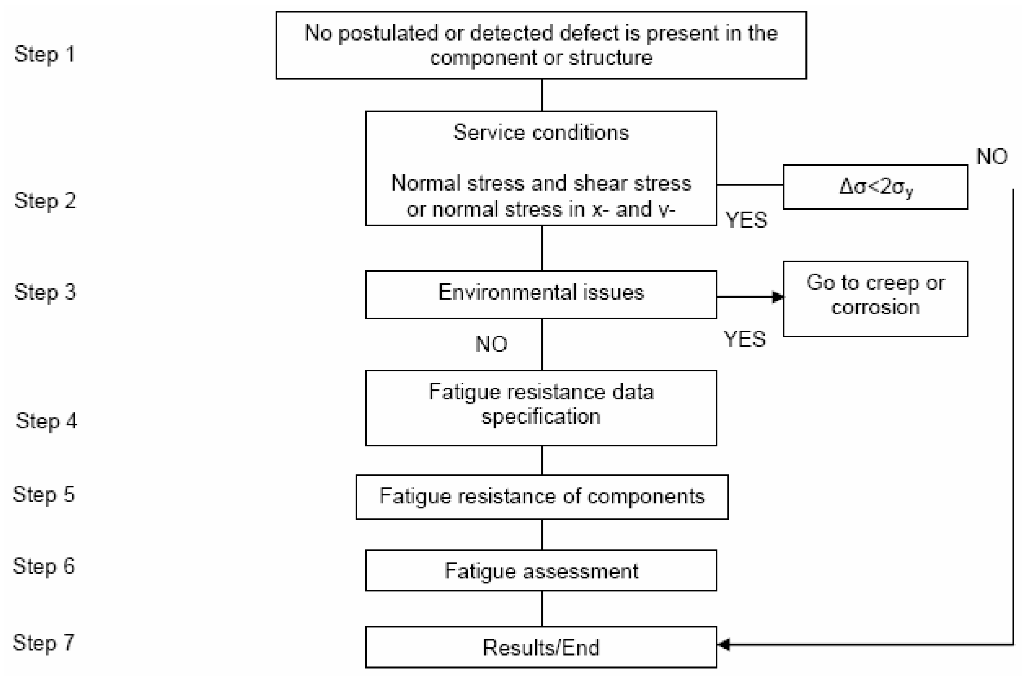
ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

NON-WELDED COMPONENTS



Stepwise flowchart for Route 2. Non-welded components.

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

NON-WELDED COMPONENTS

Step 1: No Postulated or detected defect is present in the component or structure

The Route 2 assumes that no detect is postulated or is detected by NDE in the component which is assessed in fatigue.

Step 2: Service condition

FITNET FFS provides guidance for the definition of Service Condition in non-welded components (see 7.3.2.2.2).

Step 3 Environmental issues, corrosion and high temperatures.

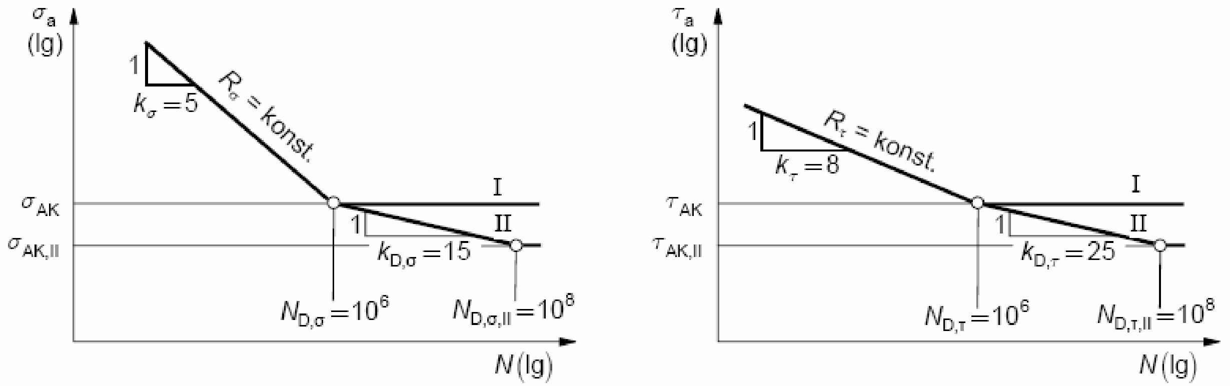
The procedure provides temperature limits for applying the fatigue module (see Section 7.3.2.2.3).

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 4 Thresholds for fatigue assessment (see Section 7.2.3)

Step 5: Fatigue resistance data specification

The constant amplitude resistance curves in terms of amplitudes of local elastic stresses, σ_a, are given as specified in the figure (see 7.3.2.2.5)



Step 6: Fatigue Assessment (see Section 7.3.2.2.6)

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FATIGUE ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

This route is mainly directed at non-welded applications and foresees direct calculation of strains at a critical location using an appropriate elastic or elasto-plastic description of the material behaviour.

The fatigue life is then determined from a strain range vs. cycles to initiation curve or relation such as the Manson-Coffin law.

It is also noted that the analysis can be taken further by considering subsequent crack growth using fracture mechanics (route 4).

The summation of life consumption is performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary.

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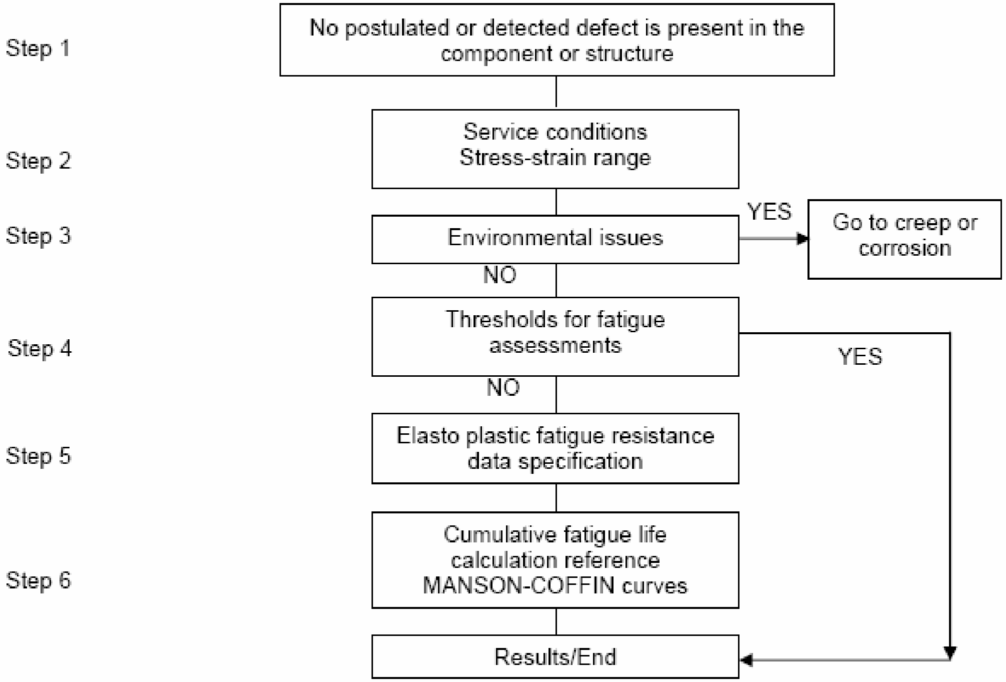
ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses



Step 1
No postulated or detected defect is present in the component or structure

Step 2
Service conditions
Stress-strain range

Step 3
Environmental issues
YES
Go to creep or corrosion
NO

Step 4
Thresholds for fatigue assessments
YES
NO

Step 5
Elasto plastic fatigue resistance data specification

Step 6
Cumulative fatigue life calculation reference MANSON-COFFIN curves

Results/End

Stepwise flowchart for Route 3

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ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

Step 1 No postulated or no detected defect is present in the component or structure

The route 3 assumes that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue.

Step 2 - Service Condition

The approach concerns the fatigue life assessment of a component with a high local stress concentration such as a groove or a notch, where the local surface roughness at the bottom of such features cannot be measured. For medium local stress concentrations such as shaft shoulders and grooves with medium to large radii (for which the local surface roughness can be measured) Route 1 can be applied. These analyses can be performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary. For further details, see 7.3.3.2.

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ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

Step 3 Environmental issues (see 7.2.2)

Step 4 Thresholds for fatigue assessment (see 7.2.3)

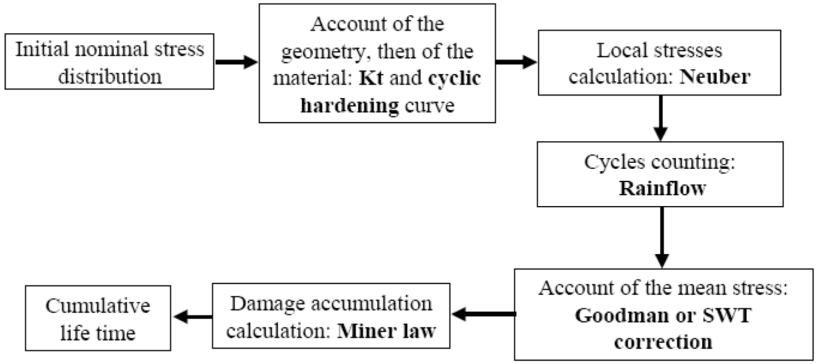
Step 5 Fatigue resistance data for elasto-plastic loading

- Material elastoplastic behaviour, Neuber-rule (see Section 7.3.3.5.1)

Step 6 Cumulative Fatigue life calculation

The Procedure provides guidance for this purpose.

The figure provides a scheme of such calculations.



ROUTE 4 – Fatigue crack growth assessment

This route addresses the assessment of detected or postulated planar flaws that can be considered as macrocracks. The initial flaw position, size and orientation can be determined in two ways: either based on the reported or detected size from non-destructive inspection results or from a postulated flaw, based on consideration of service experience, the manufacturing process, resolution limits of a non destructive technique, from the threshold stress intensity factor etc.

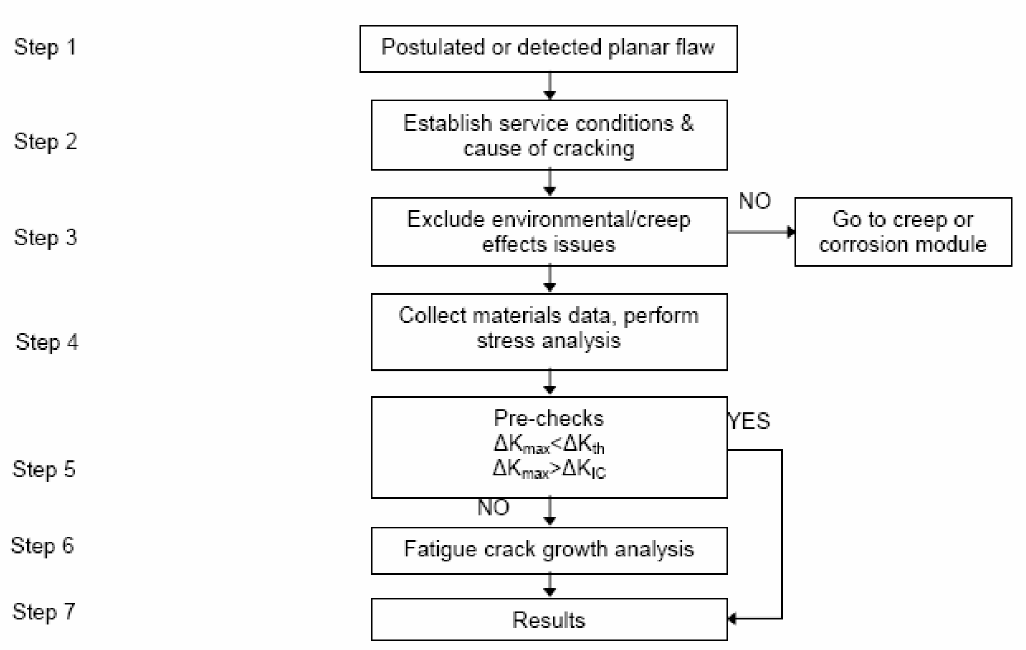
The basic approach foreseen for calculating fatigue crack growth is via the standard Paris law. A more sophisticated approach is also provided, based on the Forman-Mettu equation (see Reference 7.4 in the Procedure).

ROUTE 4 – Fatigue crack growth assessment

The procedure is based on a **fracture mechanics analysis**, which assumes that a **flaw may be idealized as a sharp tipped crack** which **propagates in accordance with the law relating the crack growth rate**, da/dN, **and the range of stress intensity factor**, ΔK, for the material containing the flaw.

ROUTE 4 – Fatigue crack growth assessment

The basic steps of the procedure are shown in the flowchart in the figure:



Step 1 Postulated or detected planar flaw

Step 2 Establish service conditions & cause of cracking

Step 3 Exclude environmental/creep effects issues — NO → Go to creep or corrosion module

Step 4 Collect materials data, perform stress analysis

Step 5 Pre-checks $\Delta K_{max}<\Delta K_{th}$ $\Delta K_{max}>\Delta K_{IC}$ — YES → Results; NO ↓

Step 6 Fatigue crack growth analysis

Step 7 Results

Stepwise flowchart for Route 4

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Step 1: Detected or Postulated Planar Flaw.

The defect type, position and size should be identified.

Step 2: Establish Service Conditions and Cause of Cracking.

The service life to date and the desired future service life should be defined. The cause of the cracking should be established to ensure that the fatigue crack growth procedure is applicable.

ROUTE 4 – Fatigue crack growth assessment

Step 3: Exclude Environmental or Creep Effects

If the flaw is characterised as surface breaking, the effects of the environment shall be considered on the fracture and fatigue properties. This requires it to be demonstrated that the environment in question does not influence these properties or that any effects are accounted for in the materials data used in the analysis.

If the temperature during operating in the vicinity of the flaw exceeds $0.4T_m$, where T_m is melting point of the material in ºK, time-dependent effects may need to be considered and the user is referred to the creep module (Section 8).

Step 4: Collect Materials Data and Perform Stress Analysis.

The materials relevant to the assessed feature including, in the case of weldments, the weld metal and heat-affected zone structures, shall be defined.

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Step 5: Pre-Checks Stability of the Flaw for the Maximum Foreseen Load (see 7.3.4.5)

Step 6: Calculate Crack Growth

The crack size at the end of the assessed period of operation is calculated by integrating the appropriate fatigue crack growth expression. This involves three sub-steps, which are repeated for pre-set cyclic increments:

- update the stress intensity factor as a function of the current flaw dimensions;
- compute the increment in crack size from the crack growth rate law;
- check its stability at fault or overload load levels using the fracture procedure.

The Procedure describes these for the Paris Law and Forman-Mettu approaches.(see Section 7.3.4.6)

ROUTE 4 – Fatigue crack growth assessment

Paris Equation:

The relevant equation is as follows:

$$\frac{da}{dN} = A.\Delta K^{m}$$

where A and m are constants which depend on the material and the applied conditions, including environment and cyclic frequency.

ROUTE 4 – Fatigue crack growth assessment

Forman-Mettu Approach:

This method follows a similar cycle-by-cycle integration method as discussed above using the sigmoidal crack growth rate relationship::

$$\frac{da}{dN} = C\left[((1-f)/(1-R))\cdot\Delta K\right]^{n} \frac{\left(1-\frac{\Delta \mathrm{K}_{\mathrm{th}}}{\Delta K}\right)^{p}}{\left(1-\frac{\mathrm{K}_{\max}}{\mathrm{K}_{\mathrm{c}}}\right)^{q}}$$

where N is the number of applied fatigue cycles, a is the crack length, and C, n, p, and q are empirically derived constants. For further information see Section 7.3.4.6.2.

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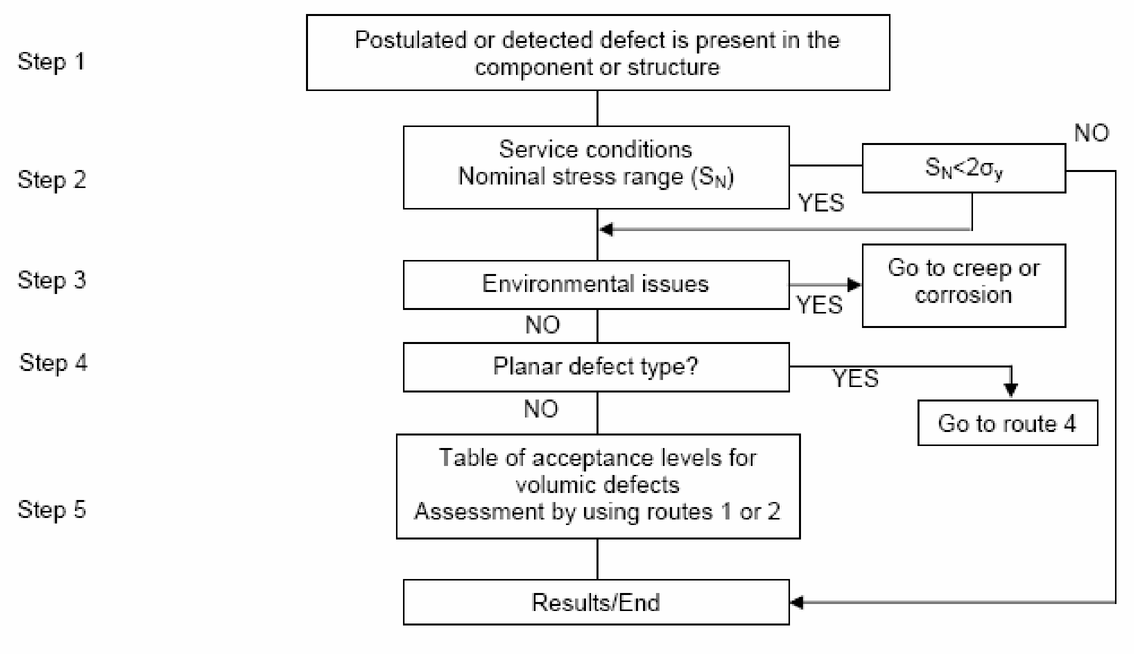
FATIGUE ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Non-planar flaws can be assessed in the same way as planar flaws using route 4. Since they are not crack-like, this will be conservative. However, it may be the only option if it is necessary to quantify the growth of the flaw under fatigue loading and to ensure the margin against unstable fracture at a specific crack size.

Otherwise, Route 1 using S-N curves for welded joints can be applied directly, in cases for which the equivalent fatigue strength are established for the non-planar flaw under consideration. At present, this approach is only available for assessing slag inclusions or porosity in steel or aluminium alloy butt welds

ROUTE 5 – Non-planar flaw assessment



Stepwise flowchart for Route 5

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ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Step 1 Postulated or detected non planar defect is present in the component or structure

The route 5 assumed that a non planar defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue.

Step 2 Service condition

Fatigue resistance will be calculated in route 5 by using nominal stress range S_N or Hot spot stress range calculation as defined in routes 1 and 2.

Step 3 Environmental issues (see 7.2.2)

ROUTE 5 – Non-planar flaw assessment

Step 4 Types of imperfections

A -Imperfect shape : Undercut

B- Volumetric discontinuities

- Gas pores and cavities of any shape
- Solid inclusions such as isolated slag, slag lines, flux, oxides and metallic inclusions

C- Planar discontinuities

If a volumetric discontinuity is surface breaking or near the surface, or there is any doubt about the type of an embedded discontinuity, it shall be assessed like a planar discontinuity.

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ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Step 5 Effects and assessment of imperfections

At geometrical imperfections, two effects affecting fatigue resistance can be distinguished:

1- *Nominal stress and Local notch effect* (Route 1)

2- *Crack like imperfection* (Route 4)

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SPECIAL OPTIONS

SPECIAL OPTIONS

FITNET Procedure provides guidance for the analysis of common industrial fatigue problems, such us the following:

- Dang Van criterion (see 7.5.1)
- Multi axial analysis (see 7.5.2)
- Rolling contact fatigue (see 7.5.3)
- Fatigue- creep (see 7.5.4)
- Fatigue- corrosion (see 7.5.5)
- Growth of Short crack (see 7.5.6)

D. EXAMPLES

WORKED EXAMPLE I

Infinite Plate under fatigue

- **Introduction and Objectives**
- **Data**
- **Analysis**

INTRODUCTION AND OBJECTIVES

One structural component of big dimensions is subjected to variable loading conditions everyday: 200 MPa during 12 hours and 20 MPa the rest of the day. During the maximum loading conditions other variable stresses appear, with a variation of 30 MPa (because of vibrations with a frequency 50 Hz).

Some NDT are performed, with equipment whose sensitivity is 0.2 mm and no cracks are detected.

Considering the component as an infinite plate:

a) Determine the crack length which is necessary to crack propagation because of vibrations

b) Critical crack length for final failure

c) Life time for the component

d) Evolution of the crack length with time in order to determine inspection periods

DATA

Material properties:

$K_{IC} = 100$ MPa·m$^{1/2}$

ΔK_{th} (or ΔK_0) = 3 MPa·m$^{1/2}$ if $R = P_{min}/P_{max} = 0.1$

$\Delta K_{th} = 1.5$ MPa·m$^{1/2}$ if $R = P_{min}/P_{max} = 0.85$

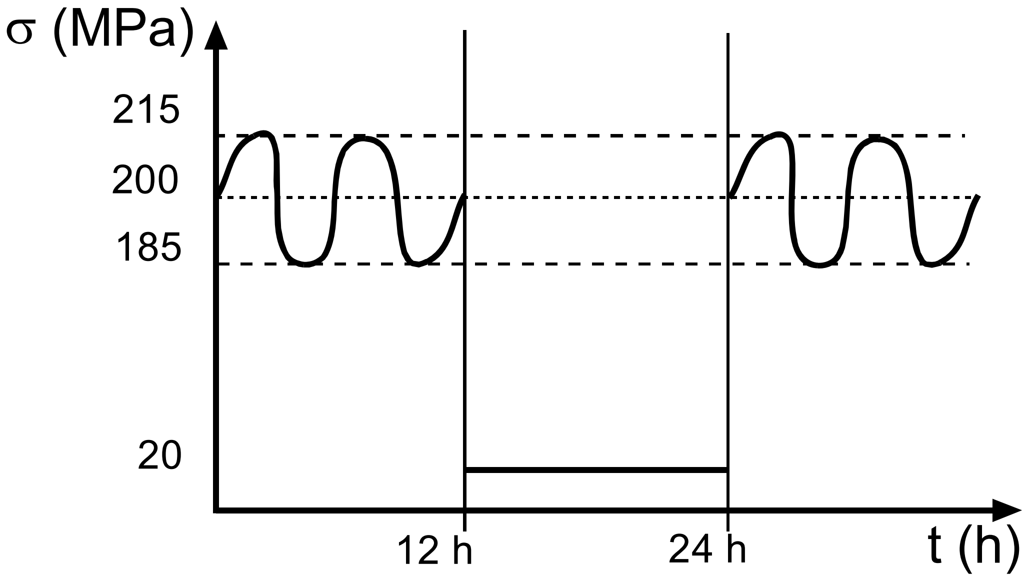
Paris Law:

$$\frac{da}{dN} = 1\cdot 10^{\;8}\cdot(\Delta K)^2$$

da/dN in m/cycle when ΔK in MPa·m$^{1/2}$

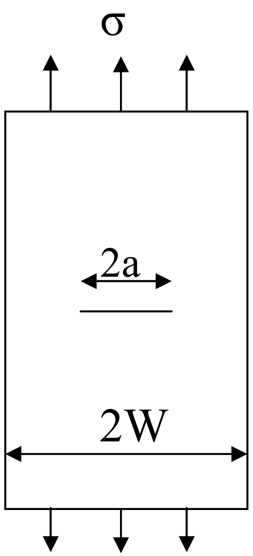
ANALYSIS

Working conditions are plotted in the next figure:



ANALYSIS

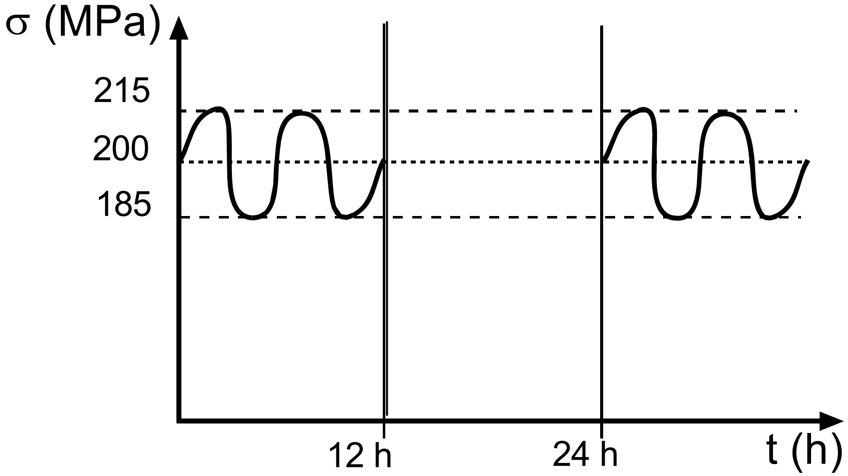
The component geometry can be simplified as:



The equipment sensitivity is 0.2 mm and no crack has been detected.
So, in the worst possible situation 2a = 0.2 mm.

ANALYSIS

State I: VIBRATIONS



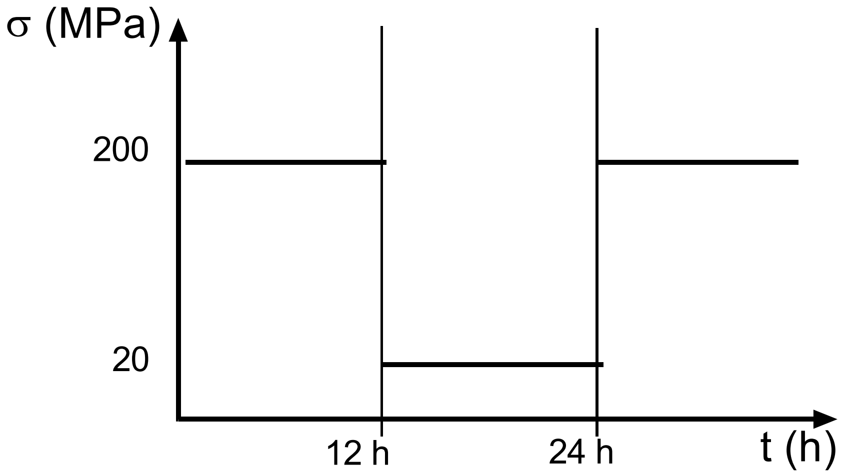
$R = P_{max}/P_{min} = 0.8$ $\Delta K_{th} = 1.5\ \mathrm{MPa{\cdot}m}^{1/2}$

$\Delta K = \Delta\sigma\cdot(\pi\cdot a)^{1/2} = 30\cdot(\pi\cdot 0.0001)^{1/2} = 0.53\ \mathrm{MPa{\cdot}m}^{1/2} < \Delta K_{th}$

Existing cracks don´t propagate

ANALYSIS

State II: MAIN LOADING CONDITIONS



As $R = 0.10$ $\Delta K_{th} = 3.0\ \mathrm{MPa\cdot m^{1/2}}$

$\Delta K = \Delta\sigma\cdot(\pi\cdot a)^{1/2} = 180\cdot(\pi\cdot 0.0001)^{1/2} = 3.19\ \mathrm{MPa\cdot m^{1/2}} > \Delta K_{th}$

Existing cracks could propagate

ANALYSIS

As existing cracks could propagate, it is necessary to determine the crack length for crack propagation because of vibrations:

$$\Delta K_{th} = 1.5 MPa \cdot m^{1/2} = 30 \cdot \sqrt{\pi \cdot a_v} \rightarrow a_v = 0.80 \text{ mm}$$

For shorter cracks propagation is only due to main loading variation ($\Delta\sigma = 180$ MPa, f = 1/86400 Hz)

The critical crack length determined at failure is:

$$K_{I\max} = \sigma_{\max} \cdot \sqrt{\pi \cdot a_c} = 215 \cdot \sqrt{\pi \cdot a_f} = 100 MPa \cdot m^{1/2}$$

$$a_f = 68 \text{ mm}$$

For crack length over 0.80 mm propagation is due to both main loading variation and vibrations ($\Delta\sigma = 30$ MPa, f = 5 Hz)

ANALYSIS

LIFE TIME:

The time necessary to initiate the effects of vibrations to cause crack propagation is determined through the Paris law:

$$N = \frac{1}{C \cdot Y^2 \cdot (\Delta\sigma)^2 \cdot \pi} \cdot \mathrm{Ln}\frac{a_f}{a_0} = \frac{1}{1 \cdot 10^{-8} \cdot (180)^2 \cdot \pi} \cdot Ln\frac{0.0008}{0.0001} = 2042 \text{ cycles}$$

2042 cycles is equivalent to 2042 days or 5.59 years

Once this crack length is reached, propagation is due to vibrations (mainly):

$a_0 = 0.8$ mm $\qquad$ $a_f = 68$ mm

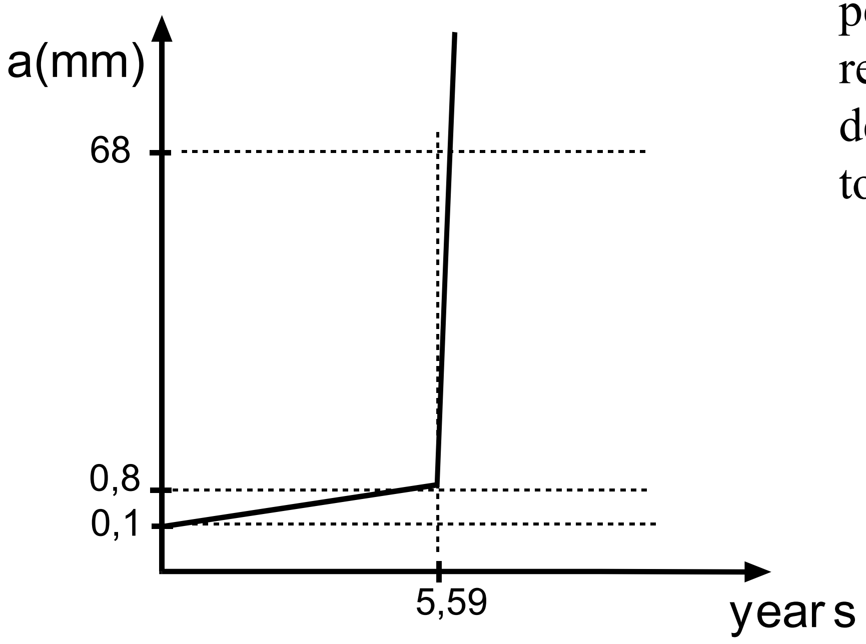
$$N = \frac{1}{C \cdot Y^2 \cdot (\Delta\sigma)^2 \cdot \pi} \cdot \mathrm{Ln}\frac{a_f}{a_0} = \frac{1}{1 \cdot 10^{-8} \cdot (30)^2 \cdot \pi} \cdot Ln\frac{68}{0.8} = 157126 \text{ cycles}$$

157126 cycles is equivalent to 0.73 days

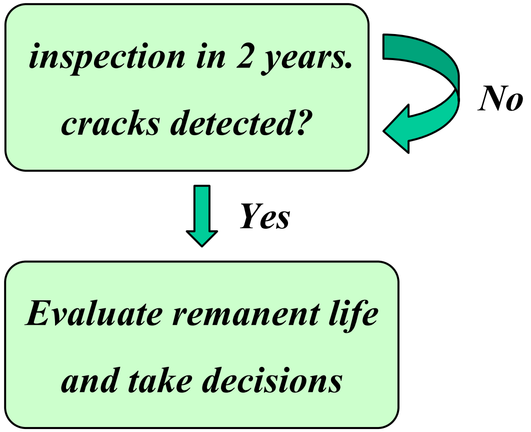
The same day that cracks achive length to propagate due to vibration amplitude, the component fails. SO, LIFE TIME IS 5.59 YEARS.

ANALYSIS

The evolution of semicrack length with time is (question d)):



It is reasonable to define periodical inspections to check if really cracks propagate over the detectable value of 0.2 mm in total length (i.e. every two years)



inspection in 2 years. cracks detected?

No

Yes

Evaluate remanent life and take decisions

WORKED EXAMPLE II

Fatigue test

- **Introduction and data**
- **Objectives**
- **Analysis**

INTRODUCTION AND DATA

A fatigue test on a seven wire strand was performed. The maximum applied stress is $0.8 \cdot \sigma_u$ and the amplitude is 390 MPa.

The strand is one meter long and the diameter of the wires is 5 mm.

The test finished with three broken wires, the central one and two external (which were together), after 320.000 fatigue cycles (f = 8 Hz).

The SEM observation of the failure surfaces gave the following information about crack lengths:

- *Central wire*: 0.25 mm (depth) elliptical crack from non propagated initial defect.
- *External wire A*: 1.32 mm from a non differentiated initial defect.
- *External wire B*: 1.20 mm proceeding from a 0.30 mm in depth initial defect.

From a previous tension test, the mechanical behaviour of the strand was obtained:

- E = 195 GPa
- Failure Load = 256.2 kN   Strain for Failure Load = 4.7 % (gauge base 500 mm)

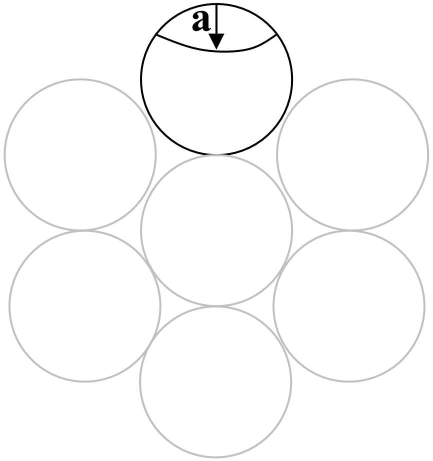
OBJECTIVES

From the testing results and the behaviour of the material, determine:

a) The failure sequence of the wires as well as their form of failure and the fracture toughness of the material.

b) Fatigue behaviour of the material considering a Paris exponent of 2.4 and the depth of the initial defect of wire A.

Consider for the wire geometry that $K_I = 2.12 \cdot \sigma \cdot a^{0.5}$



ANALYSIS

The area of each wire is:

$$A_w = \pi \cdot r^2 = \pi \cdot 2.5^2 = 19.635\ \text{mm}^2$$

Therefore, the area of the strand is

$$A = 7 \cdot A_w = 7 \cdot 19.635 = 137.44\ \text{mm}^2$$

The failure load is 256.2 kN, so the failure stress can be calculated:

$$\sigma_f = 256200/137.44 = 1864\ \text{MPa}$$

The maximum and minimum stresses are:

$$\sigma_{max} = 0.8 \cdot \sigma_f = 0.8 \cdot 1864 = 1491.2\ \text{MPa}$$

$$\sigma_{min} = 0.8 \cdot \sigma_f - 390 = 1491.2 - 390 = 1101.2\ \text{MPa}$$

ANALYSIS

Under these conditions, the first failure occurs in the external wire A because it has the bigger propagated defect. After that, the external wire B breaks and finally, the central one.

The external wire A breaks because of a fracture failure as a consequence of a fatigue process. Then:

$K_I = 2.12 \cdot \sigma \cdot a_c^{0.5} = 2.12 \cdot 1491.2 \cdot (0.00132)^{0.5} = 114.9\ \text{MPa} \cdot \text{m}^{1/2}$

$\underline{K_{IC} = 114.9\ \text{MPa} \cdot \text{m}^{1/2}}$

ANALYSIS

The external wire B also fails because of fracture, but with a smaller defect because the decrease of the section once the external wire A is broken. The new supported σ_{max} is:

$$\sigma_{max} = 7/6 \cdot 1491.2 = 1739.7 \text{ MPa}$$

This stress is smaller than the failure strength of the strand (1864 MPa). Therefore, failure happens as a consequence of sudden fracture or plastic collapse. This later as the applied stress (1739.7 MPa) is close to yield stress (even non considering a possible strain hardening effect, then $\sigma_{ymax} = \sigma_u = 1864$ MPa)

ANALYSIS

We can calculate the stress intensity factor:

$$K_I = 2.12 \cdot \sigma \cdot a_c^{\,0.5} = 2.12 \cdot 1739.7 \cdot (0.0012)^{0.5} \longrightarrow K_I = 127.76 \text{ MPa} \cdot \text{m}^{1/2}$$

This value is bigger than K_{IC} and it justifies the sudden failure of the external wire B. Now, there are only five wires in the section of the strand, so:

$$\sigma_{max} = 6/5 \cdot 1739.7 = 2087.6 \text{ MPa}$$

This stress is bigger than the failure stress of the cord (1864 MPa). Therefore, it is possible to affirm that the latest is the maximum stress in the strand, and the central wire fails because of tension. In effect, the necessary stress for fracture to occur would be:

$$114.9 = 2.12 \cdot \sigma \cdot 0.00025^{\,0.5} \longrightarrow \sigma = 3428 \text{ MPa}$$

Such a value is not reached at any time.

ANALYSIS

Let´s now determine the fatigue properties of the material. We know that the central wire had a defect of 0.25 mm which did not produce crack propagation under $\Delta\sigma = 390$ MPa. So:

$$\Delta K_{th} > 2.12 \cdot \Delta\sigma \cdot a^{0.5} = 2.12 \cdot 390 \cdot 0.00025^{0.5} = 13.07 \text{ MPa} \cdot \text{m}^{1/2}$$

We also know that an initial defect of 0.3 mm propagates in the external wire B and that the unknown initial defect of wire A should be higher than 0.3 because it reached a bigger final crack. So:

$$\Delta K_{th} < 2.12 \cdot \Delta\sigma \cdot a^{0.5} = 2.12 \cdot 390 \cdot 0.0003^{0.5} = 14.32 \text{ MPa} \cdot \text{m}^{1/2}$$

From both expressions the threshold SIF is limited from the following values:

$$\underline{13.07 < \Delta K_{th} < 14.32 \text{ MPa} \cdot \text{m}^{1/2}}$$

ANALYSIS

The Paris law is:

$$\frac{da}{dN} = C\cdot(\Delta K)^{2.4} = C\cdot(2.12\cdot\Delta\sigma\cdot\sqrt{a})^{2.4}$$ where C has to be defined

We know: $\Delta\sigma = 390$ MPa

So: $$\frac{da}{dN} = C\cdot(\Delta K)^{2.4} = C\cdot(2.12\cdot 390\cdot\sqrt{a})^{2.4}$$

$$\frac{da}{a^{1.2}} = C\cdot(2.12\cdot 390)^{2.4}\cdot dN$$

$$a_i^{-0.2} - a_f^{-0.2} = C\cdot 2.008\cdot 10^6\cdot N \quad \left\{ \begin{array}{l} a_i = 0.3\ \text{mm} \\ a_f = 1.2\ \text{mm} \\ N = 320000\ \text{cycles} \end{array} \right\}$$ conditions at wire B

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ANALYSIS

$$C = \frac{0.0003^{-0.2} - 0.0012^{-0.2}}{2.008\cdot10^{6}\cdot320000} = 1.909\cdot10^{-12}$$

Therefore, the Paris law is:

$$\boxed{\frac{da}{dN} = 1.909\cdot10^{6}\cdot(\Delta K)^{2.4}}$$

To calculate the initial defect in the external wire A, we will integrate the Paris law:

$$a_i^{-0.2} - a_f^{-0.2} = C\cdot2.008\cdot10^{6}\cdot N \quad \left\{ \begin{array}{l} C = 1.909\cdot10^{\ 12} \\ a_f = 1.32\ \text{mm} \\ N = 320000\ \text{cycles} \end{array} \right.$$

$$a_i^{-0.2} - 0.00132^{-0.2} = C\cdot2.008\cdot10^{6}\cdot N = 1.22665 \quad \xrightarrow{\qquad} \quad \underline{a_i = 0.3223\ \text{mm}}$$

III. TRAINING PACKAGE ON CREEP

A. BASIC CONCEPTS

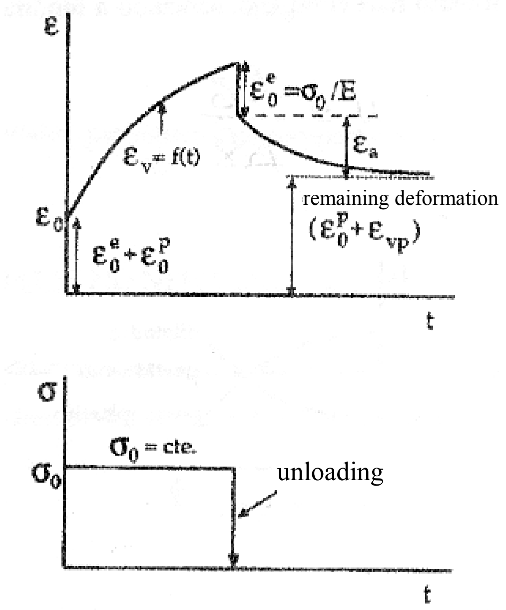
CREEP BEHAVIOUR

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:

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

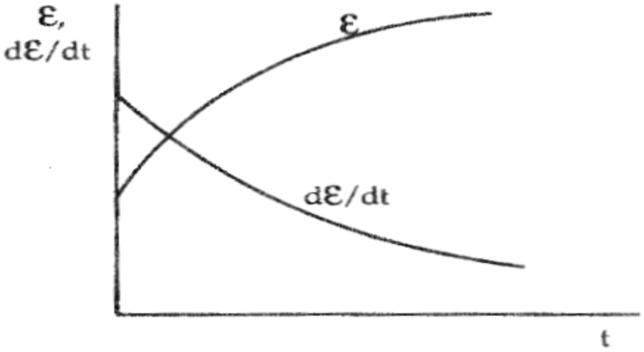
where ν varies from 10^{10} to 10^{13} s^{-1} and A=A(σ,T, material)

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.



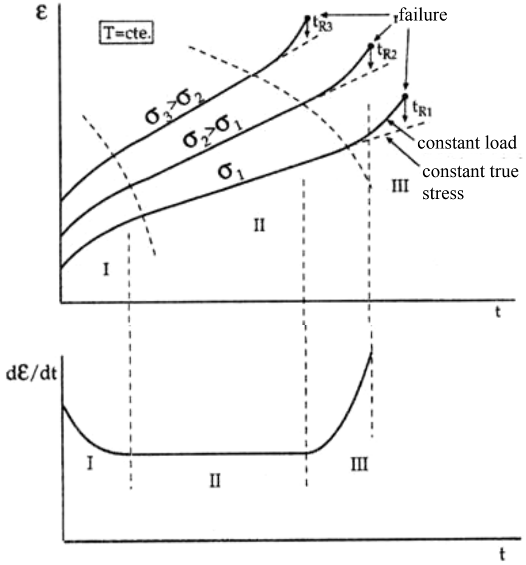
CREEP BEHAVIOUR

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.



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CREEP BEHAVIOUR

INTRODUCTION: DEFECT-FREE STRUCTURES

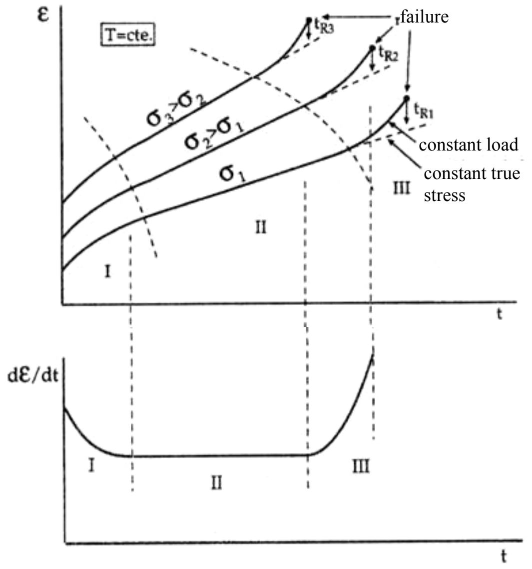
CREEP AT HIGH TEMPERATURES: $T/T_m > 0.5$

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

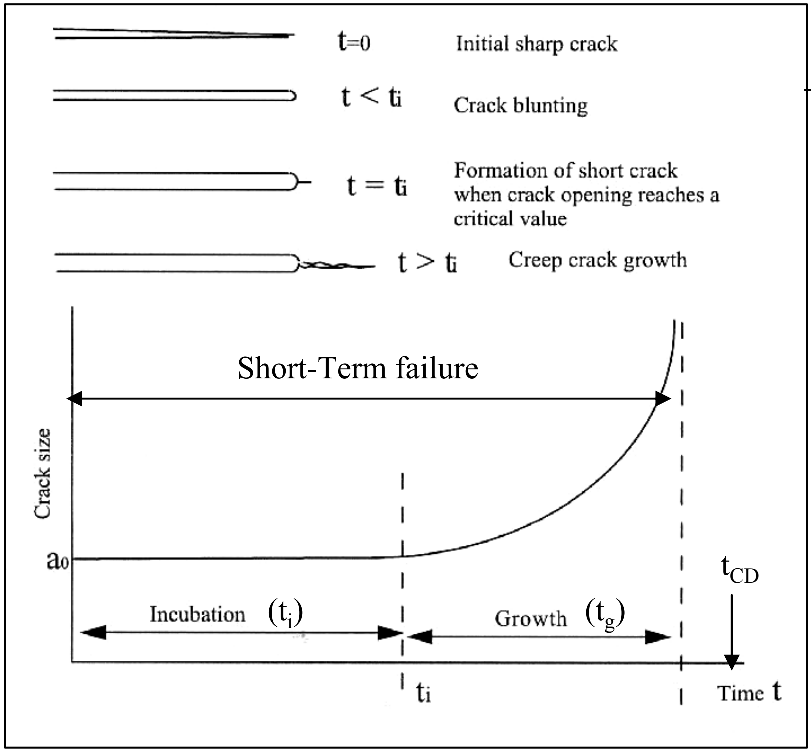
3a) FRACTURE: The crack may grow to a size at which short-term fracture (ductile or brittle) occurs

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

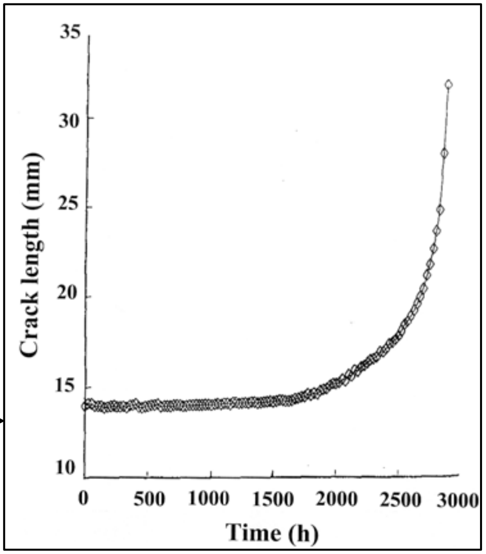


Lifetime = lower{$(t_i + t_g), t_{CD}$}

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

$\boldsymbol{\sigma_{ref}}$: 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)

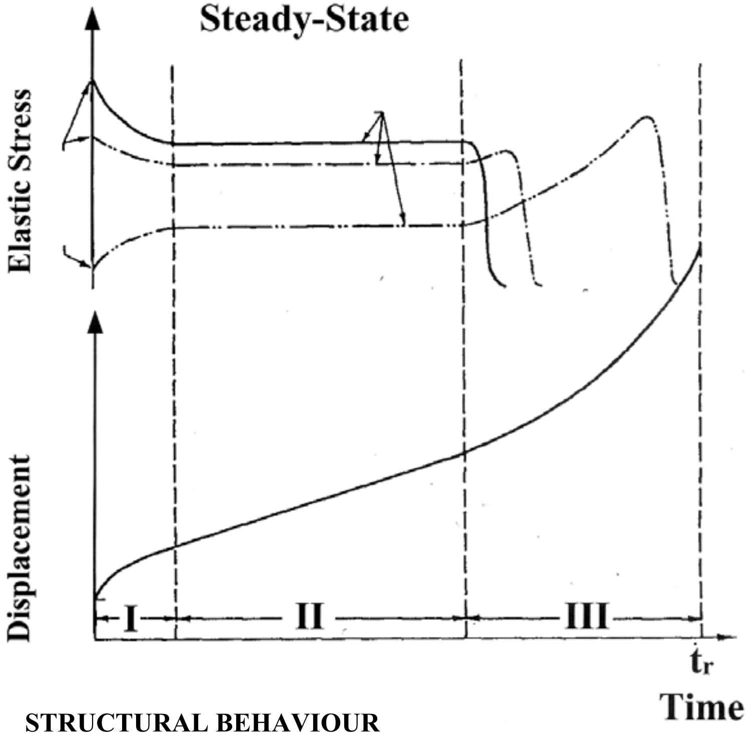
Following initial elastic (or elastic-plastic) behaviour on loading, structures at high temperature can exhibit various stages of response:

- **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

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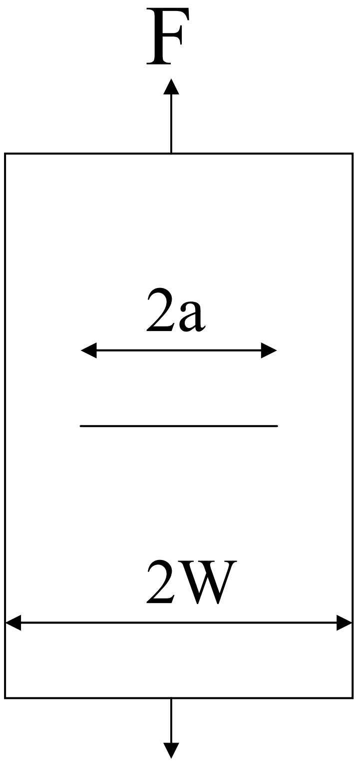
CREEP BEHAVIOUR

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

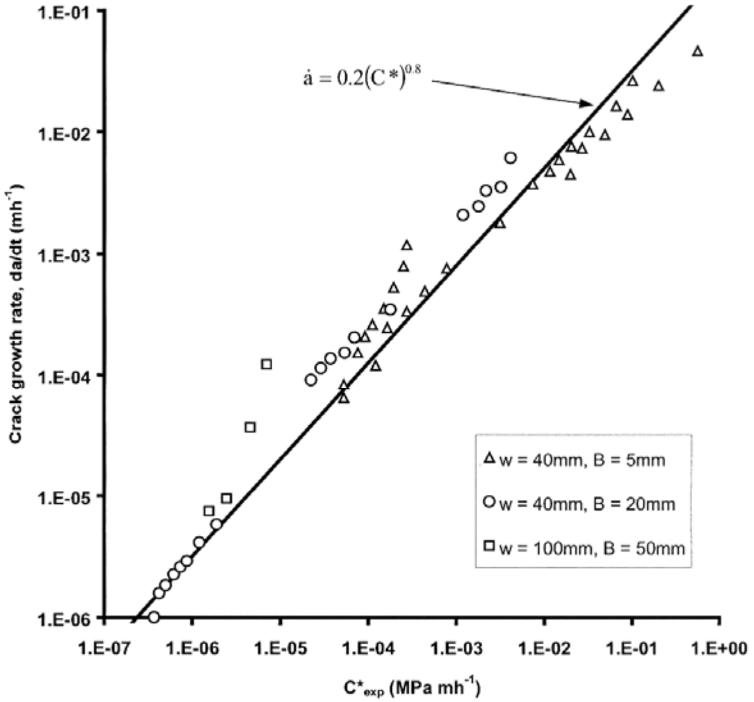
$q \approx n / (n+1)$

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:

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

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

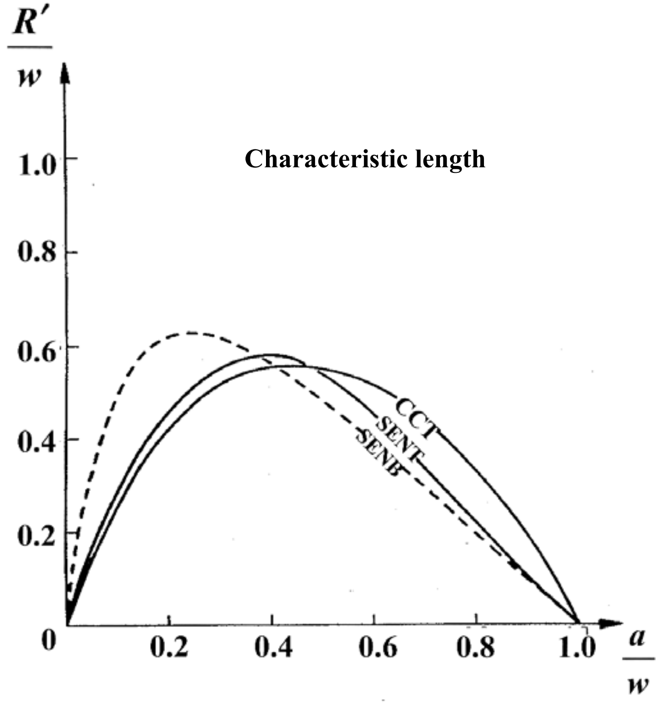
$h_1 = f$ (n, geometry, a/W, loading type)

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}

$R' =$ 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

$$C(t) = K^2/(n+1)Et \qquad t \rightarrow 0$$

$$C(t) = C^* \qquad t \rightarrow \infty$$

- 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·$m^{1/2}$

(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 + Δa.

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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B. INTRODUCTION TO ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

INTRODUCTION

The early approaches to high temperature life assessment show methodologies that were based on defect-free assessment codes, i.e. ASME Code Case N-47 and the French RCC-MR, which have many similarities and are based on lifetime assessment of un-cracked structures.

More recent methods make life assessment based on the presence of defects in the components.

The more advanced codes dealing with defects over the range of creep and creep-fatigue interaction in initiation and growth defects are the British Energy R5, the French A16 and BS7910 which have clear similarities in terms of methodology.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

INTRODUCTION

The available procedures are implemented in a series of well-defined steps, often shown as flow charts. The individual steps can refer to

- a component before it enters service, containing either a postulated defect or one discovered during inspection.
- a defect, which has been discovered after a component has been in service for a period of time.

The flow charts contain variations and choices available to the user in accordance with their level of expertise and the level of information available on the component under consideration.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

Some typical steps in an assessment are listed here:

1) Establish the cause of cracking
2) Define previous plant history, future operational requirements and relevant stresses
3) Characterise defects
4) Establish material properties
5) Check the fatigue component
6) *Perform defect assessment*
7) *Define Fatigue Crack Propagation Rates*
8) *Creep Crack Propagation Rate*
9) *Incubation Period*
10) *Assessment to Include Creep-Fatigue Loading*
11) *Others*

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

6) PERFORM DEFECT ASSESSMENT:

6.1) Determine margin against fast fracture assuming an initial defect or a measured defect dimension using various levels of FAD.

6.2) Evaluate ΔK_{th} and fatigue crack propagation rates.

6.3) Determine the creep rupture life of the component, using initial defect dimensions.

6.4) Evaluate crack propagation rates and estimate the amount of creep crack growth at intervals

6.5) Check the steady creep conditions applied at the crack tip; if not, revise crack growth estimates

6.6) Determine crack dimensions at the end of each interval.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

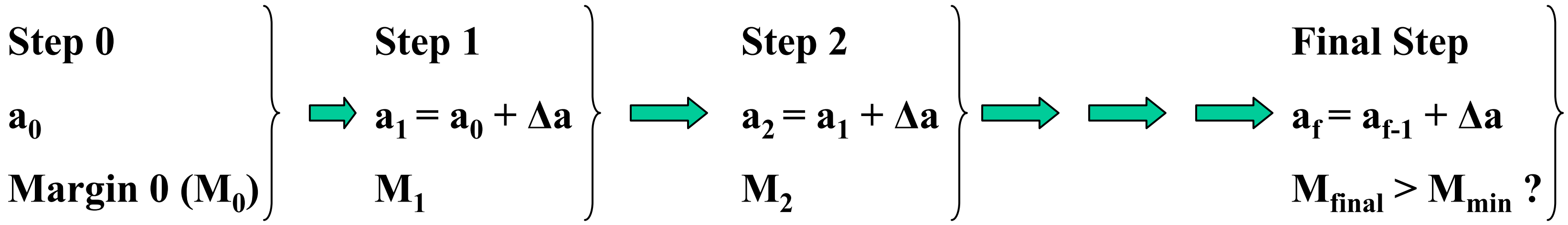
GENERAL STRUCTURE

6) PERFORM DEFECT ASSESSMENT:

6.7) Repeat calculation against fast fracture at the end of each interval.

6.8) If the end of life margin is satisfactory, no remedial action is needed.

6.9) If the end of life margin against fast fracture is unsatisfactory, the intermediate calculations can be used to establish the time at which this margin ceases to be acceptable and to define when a remedial action is necessary.



Step 0
$\mathbf{a_0}$
Margin 0 ($\mathbf{M_0}$)

Step 1
$\mathbf{a_1 = a_0 + \Delta a}$
$\mathbf{M_1}$

Step 2
$\mathbf{a_2 = a_1 + \Delta a}$
$\mathbf{M_2}$

Final Step
$\mathbf{a_f = a_{f\text{-}1} + \Delta a}$
$\mathbf{M_{final} > M_{min}}$ **?**

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

7) DEFINE FATIGUE CRACK PROPAGATION RATES:

The fatigue crack propagation rate is generally defined by the Paris equation:

$$\left(\frac{da}{dN}\right)_f = C \cdot (\Delta K)^m$$

C, m: material constants

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

8) CREEP CRACK PROPAGATION RATE:

Creep crack propagation rate is usually defined in the form:

$$\left(\frac{da}{dt}\right)_c = A \cdot \left(C^*\right)^q$$

A, q: constants.

Where the creep ductility of the material is known: $A = \dfrac{0.003}{\varepsilon_f}$ for $\left(\dfrac{da}{dt}\right)_c$ in m/h

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

8) CREEP CRACK PROPAGATION RATE:

Where the creep ductility of the material is not known, crack propagation rates can be obtained from:

$$\left(\frac{da}{dt}\right)_c = 0.005 \cdot \left(\frac{\left(K_a{}^p\right)^2}{\sigma_{ref} \cdot t_R\left(ref\right)}\right)^{0.85}$$

K_a^p : SIF at maximum depth for a crack of diminsions a and *l*.

$t_R(\sigma_{ref})$: time to rupture at the reference stress.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

8) CREEP CRACK PROPAGATION RATE:

The driving force C* is calculated from:

$$C^* = \sigma_0 \cdot \dot{\varepsilon}_{ref} \cdot \left(\frac{K^p}{\sigma_{ref}} \right)^2$$

$\dot{\varepsilon}_{ref}$: creep strain rate from uniaxial deformation data at σ_{ref}

The formulation covers primary creep

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

9) INCUBATION PERIOD:

Where incubation time data are available from test specimens, the incubation time for the component can be correlated with C^* provided both specimen and component are in the secondary stage of creep. Then, the incubation time t_I can be deduced from:

$$t_{i,component} = t_{i,specimen} \; {\frac{C^*_{specimen}}{C^*_{component}}}^{\frac{n}{n+1}}$$

Where data are not available for the material used in the component, procedures provide equations to estimate t_I.

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

GENERAL STRUCTURE

10) ASSESSMENT TO INCLUDE CREEP-FATIGUE LOADING:

In most cases, linear summarition of the time dependent creep and the time independent fatigue portions of crack growth adequately describes high temperature failure under cyclic loading:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_c + \left(\frac{da}{dN}\right)_f = \left(\frac{da}{dt}\right) \cdot \frac{1}{3600 \cdot \mathrm{f}} + \left(\frac{da}{dN}\right)_f = A \cdot \left(C^*\right)^q \cdot \frac{1}{3600 \cdot \mathrm{f}} + C \cdot \left(\Delta K\right)^m$$

f: frecuency

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS AT HIGH TEMPERATURES

SENSITIVITY ANALYSIS

Assuming the final defect size gives an acceptable end-of-life safety margin, a sensitivity analysis is recomended. Different procedures (BS7910, R5, R6...) describe the principles.

The sensitivity analysis considers the effects of different assumptions, such as stress levels, material properties, defect sizes, etc.

BIBLIOGRAPHY / REFERENCES

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- British Energy, *"R5, Assessment Procedure for the High Temperature Response of Structures"*. Issue 3, Gloucester: British Energy; June 2003

C. PROCEDURE APPLICATION (FITNET)

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- **INTRODUCTION**
- **ANALYSIS STEPS**
- **MATERIALS DATA**
- **BASIC CALCULATIONS**
- **ASSESSMENT CALCULATIONS**
- **ASSESS SIGNIFICANCE OF RESULTS**

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INTRODUCTION

Overall Procedure

In this section, a step-by-step procedure is set out for assessing a component containing a known or postulated defect under creep-fatigue loading. Flowcharts for the procedure are given in next pages.

Continuum damage accumulation and crack growth are addressed.

The cases of insignificant creep and insignificant fatigue are included as special cases.

The procedure may be applied to a component that has not yet seen operation at creep temperatures, or one that has already operated at high temperature. In the latter case, advice is given additionally on the effect of the time at which the defect is assumed to form.

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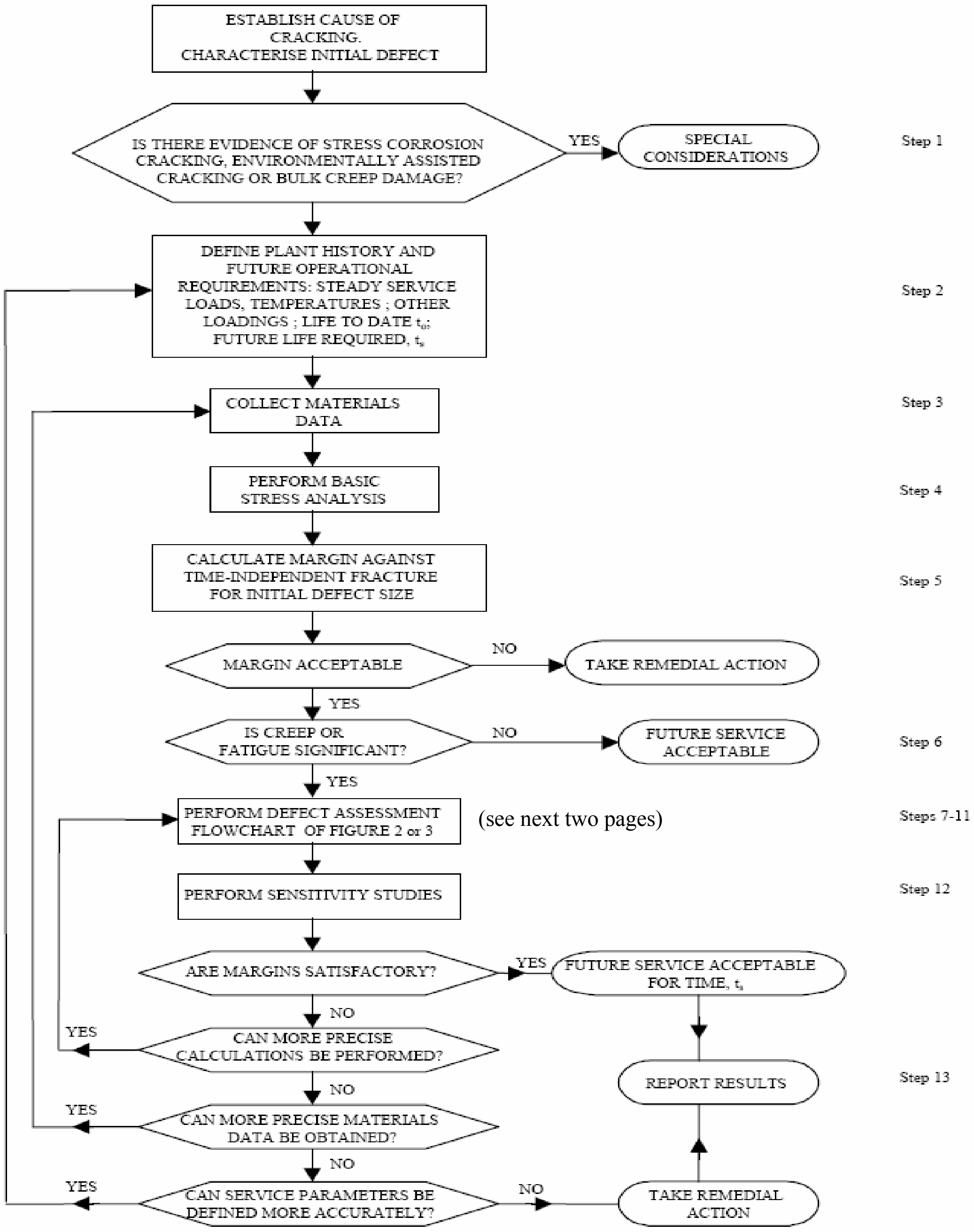
INTRODUCTION

Flowchart for Overall Creep Assessment Procedure



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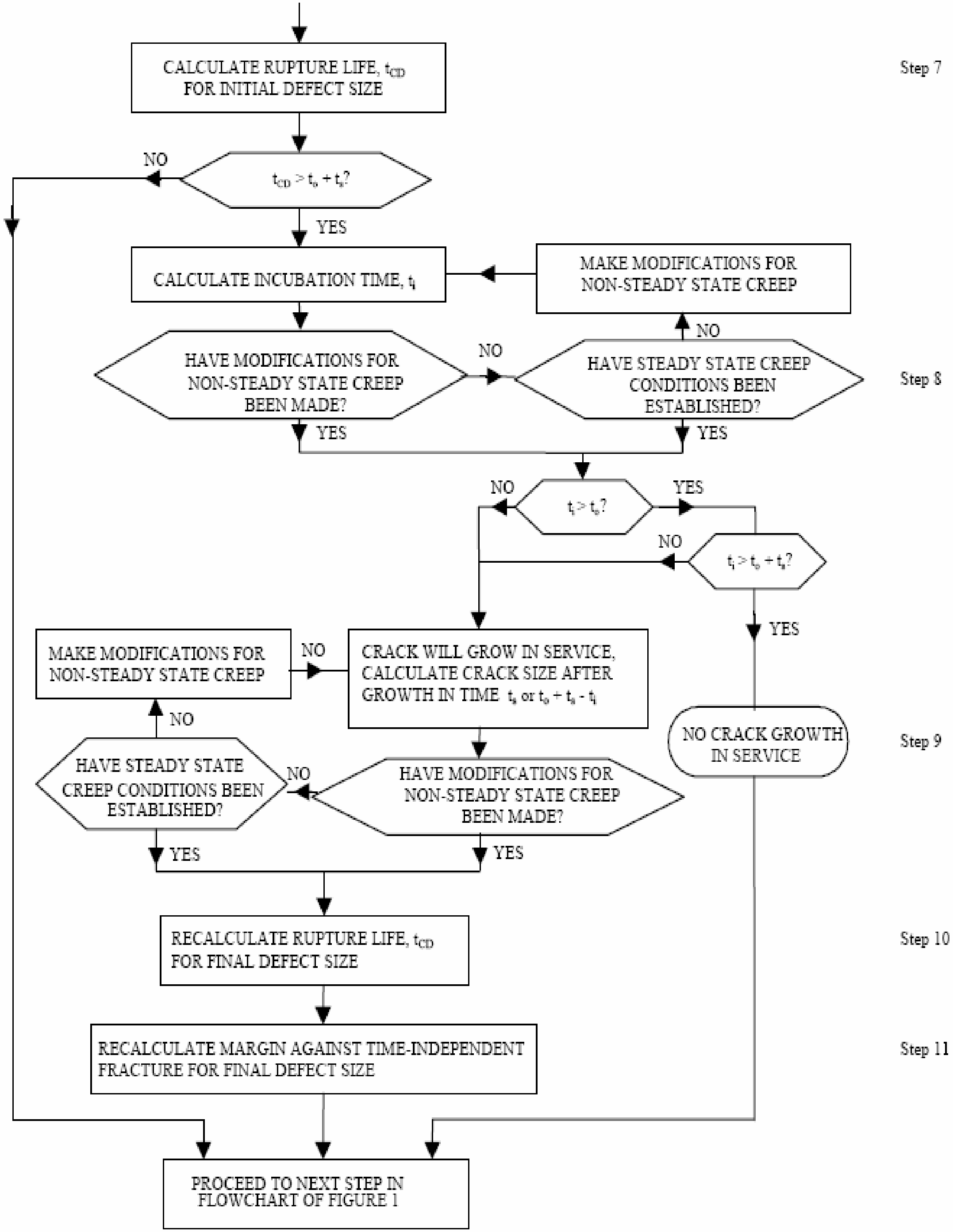
INTRODUCTION

Defect Assessment Flowchart for Insignificant Fatigue



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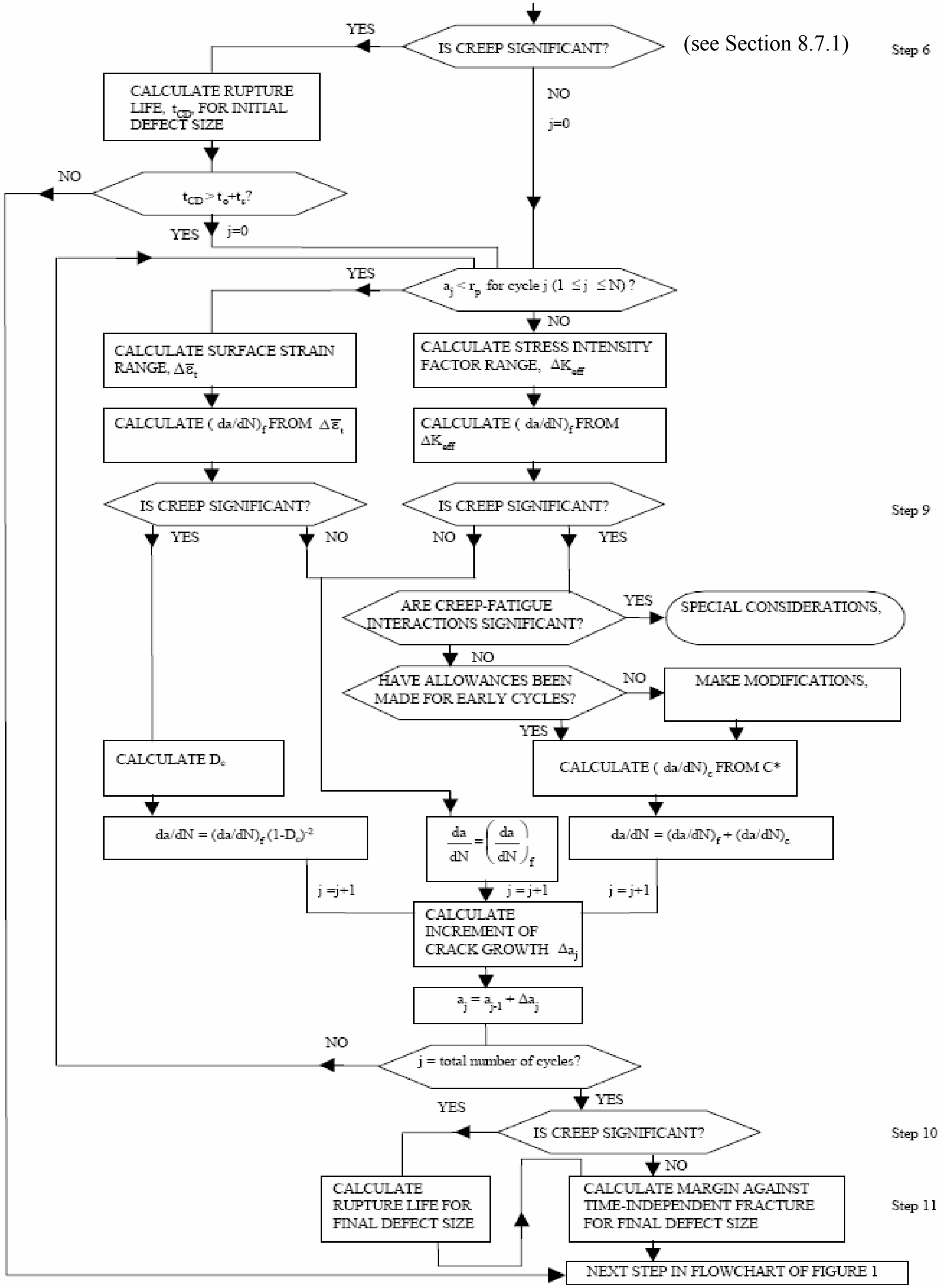
INTRODUCTION

Defect Assessment Flowchart for Significant Fatigue



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ANALYSIS STEPS

STEP 1. Establish Cause of Cracking and Characterise Initial Defect (see Section 8.3)

STEP 2. Define Service Conditions (see Section 8.4)

STEP 3. Collect Materials Data (see Section 8.5)

STEP 4. Perform Basic Calculations (see Section 8.6)

STEP 5. Check Stability under Time-Independent Loads

STEP 6. Check Significance of Creep and Fatigue (see Section 8.7)

STEP 7. Calculate Rupture Life based on the Initial Defect Size (see Section 8.8.1)

STEP 8. Calculate Initiation Time (see Section 8.8.2)

STEP 9. Calculate Crack Size after Growth (see Section 8.8.3)

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ANALYSIS STEPS

STEP 10. Re-Calculate Rupture Life after Crack Growth

STEP 11. Check Stability under Time-Independent Loads after Crack Growth

STEP 12. Assess Significance of Results (see Section 8.9)

STEP 13. Report Results (see Section 8.9.3)

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ESTABLISH CAUSE OF CRACKING (STEP 1)

STEP 1- Establish Cause of Cracking

Before performing calculations, an investigation should be carried out to determine the most likely cause of cracking.

When a defect has been discovered in a component that has been in service, the conservative assumption for the calculation of continuum damage is that the crack initiated early in life. This should be assumed unless there is evidence to the contrary.

Significant creep damage, away from the crack tip, probably indicates that there has been local over-heating or over-stressing. In these circumstances, all crack growth calculations should take account of the material in its damaged state.

For further information see Section 8.3.

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DEFINE SERVICE CONDITIONS (STEP 2)

STEP 2- Define Service Conditions

The Procedure is applicable to components which operate for long periods at steady or steady cyclic conditions of load (stress), or displacement, and temperature. Each loading and temperature must be defined for the locations of interest. In making an assessment, it is conservative to assume that all the loading is load-controlled and ignore stress relaxation; it may also be assumed that infrequent short-term overloads will not modify the crack tip conditions significantly.

For further information see Section 8.4.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data

Next pages outline the material properties data required to follow the steps in the procedure. Some of these properties may be inter-related and it is necessary to use consistent material properties data in different steps of the procedure. This is of particular importance when material properties data are obtained from a number of different source references.

Creep Rupture Data

Creep rupture data are required to calculate the rupture life of the remaining ligament and to estimate the current continuum damage level in the ligament as the defect grows.

STEP 3- Collect Materials Data (cont.)

Creep Deformation Data

Creep deformation data are required for steady loadings to estimate the creep crack incubation time and subsequent creep crack growth rates using reference stress techniques.

For cases with steady primary load or large elastic follow-up, forward creep data collected under constant load conditions are appropriate.

For essentially strain-controlled conditions, in the absence of follow-up, stress relaxation data may be more appropriate than forward creep data.

Reliable constitutive equations are needed to provide a smooth transition between these extremes.

For creep-fatigue loadings, a description is required of the creep deformation of the material in the relevant cyclic condition in order to estimate creep crack growth rates during the dwell periods.

STEP 3- Collect Materials Data (cont.)

Creep Deformation Data (cont.)

Creep deformation data may also be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface for use in a creep-fatigue crack growth law. Often a simple power law expression

$$\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_0} = \left(\sigma / \sigma_0\right)^n$$

$\dot{\varepsilon}_c$	creep strain rate
$\dot{\varepsilon}_0$	creep strain rate at stress σ_0
σ_0	initial stress
n	exponent of stress in creep strain equation

is used to describe creep strain rate.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Creep Ductility Data

Creep ductility data may be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface. In addition, creep ductility data may be used to estimate creep crack growth rates for situations in which explicit crack growth data are not available.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Creep Crack Initiation/Incubation Data

For situations where fatigue is insignificant, it may be possible to take account of an incubation period prior to crack extension. Creep crack incubation data may be expressed in terms of a critical crack tip opening displacement, δ_i, or for widespread creep conditions, by a relationship of the form:

$$t_i \left(C^*\right)^{\beta} = \gamma$$

where t_i is the incubation time and β and γ are material constants.
In situations where explicit incubation data are not available, it is possible to estimate the incubation time for widespread creep conditions using approximate expressions given later.
In addition, two alternative approaches for predicting incubation times are given in the procedure (see Section 8.10).

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Creep Crack Growth Data

Creep crack growth data are required to calculate crack growth under steady loading conditions or to estimate the crack extension during dwell periods for creep-fatigue conditions. Creep crack growth data are generally presented as a simple relationship of the form:

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

where *A* and *q* are material constants. The procedure gives some typical values of these constants for a number of materials (see Annex N).

STEP 3- Collect Materials Data (cont.)

Cyclic Crack Growth Data

Method I

The cyclic component of creep-fatigue crack growth required for a Method I crack growth rate law is described by

$$(da/dN)_f = C\Delta K_{eff}^{l}$$

where C and l are material and temperature dependent constants. ΔK_{eff} is the stress intensity factor range for which the crack is judged to be open.
In situations where cyclic crack growth data have been obtained from tests with significant plasticity, it is preferable to evaluate from experimental estimates of ΔJ . However, it will be pessimistic to use data which have been correlated with elastically calculated values.

STEP 3- Collect Materials Data (cont.)

Cyclic Crack Growth Data (cont)

Method II

The cyclic component of creep-fatigue crack growth required for a Method II crack growth rate law is described by a high strain fatigue crack growth law of the form

$$(da/dN)_f = B' a^Q \qquad a_{\min} \leqslant a \leqslant r_p$$

where $a_{\min} = 0.2$ mm is the crack depth below which the crack growth rate is assumed to be constant, B' and Q depend on material, strain range and environment and can be determined experimentally.

These laws apply for a total surface strain range $\Delta\bar{\varepsilon}_t$, while the defect is embedded in the cyclic plastic zone of size r_p at the surface of the component.

STEP 3- Collect Materials Data (cont.)

Other Data

In addition to the creep data described previously, it may be necessary to have other data to perform an assessment:

- Elastic and Physical Constants (see Section 8.5.7.1)
- Stress-strain Data (see Section 8.5.7.2)
- Fracture Toughness Data (see Section 8.5.7.3)

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations

Stress Intensity Factors

The linear elastic stress intensity factor, K, depends on the loading and the crack size and may vary with position around a crack front.

For cyclic loading, it is necessary to evaluate the stress intensity factor range and the ratio of minimum to maximum stress intensity factor, R.

The value of R should be calculated from a shakedown analysis rather than a simple elastic analysis. This is because creep during a cycle tends to lead to a cyclic stress state which gives a lower value of R than the initial elastic response. The shakedown analysis only affects the value of R and not the total stress intensity factor range, as the residual stress is independent of position in the cycle.

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations

Reference Stress

For creep crack growth evaluation, it is necessary to evaluate the reference stress at the start of the dwell. The reference stress for simple primary loading is determined by the methods of limit analysis and is defined by:

$$\sigma_{ref}^{p} = P\sigma_{y} / P_{L}\left(\sigma_{y}, a\right)$$

In cases where cyclic loading is present the load P is evaluated from the stress, produced by the shakedown analysis, at the time in the cycle corresponding to the creep dwell. It should be noted that this is not necessarily at the peak stress in the cycle.

P_L is the value of P corresponding to plastic collapse assuming a yield stress .

STEPS 4-5- Basic Calculations

C* Parameter

For steady state creep, the crack tip stress and strain rate fields (and hence creep crack growth rates) may be characterised by the C* parameter.

It may be evaluated by finite element analysis but a reference stress based estimate of is often used. This is

$$C^* = \sigma^p_{ref}\,\dot{\varepsilon}_c\left[\sigma^p_{ref}(a),\varepsilon_c\right]R'$$

Here, $\dot{\varepsilon}_c$ is the creep strain rate at the current reference stress and creep strain, ε_c, accumulated under the reference stress history up to time t.

The characteristic length, R′ is defined by: $R' = (K^p / \sigma^p_{ref})^2$

where K^p is the stress intensity factor due to primary load only.

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations (cont.)

Redistribution Time, t_{red}

This calculation is only required when cyclic loading is insignificant.

Time is required for stress redistribution due to creep from the initial elastic state at the start of a creep dwell.

The requirement for the stress redistribution to be complete and widespread creep conditions to be established may be expressed in terms of a redistribution time, t_{red}. This may be expressed conveniently in terms of the reference stress for cases of primary load only as

$$\varepsilon_c[\sigma_{ref}^p(a), t_{red}] = \sigma_{ref}^p(a)/E$$

where $\varepsilon_c[\sigma_{ref}^p(a), t]$ is the accumulated creep strain at the reference stress for time, t, and crack length, a, from uniaxial creep data.

STEPS 4-5- Basic Calculations (cont.)

C(t) Parameter

For times less than the redistribution time, it may be necessary to calculate the transient crack tip parameter C(t). An interpolation formula for C(t) during the transition between initial elastic loading and steady state secondary creep is

$$\frac{C(t)}{C^*} = \frac{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)}}{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)-1}}$$

where ε_c is the accumulated creep strain at time t, ε_e is the elastic strain and q is the exponent in the creep crack growth law with q~n/(n+1) where n is the exponent in the equation obtained from the creep deformation data. For times in excess of the redistribution time, C(t) approaches C*

STEPS 6- Check Significance of Creep and Fatigue

In many cases the complexity of a creep-fatigue crack growth assessment can be avoided by performing simple calculations to demonstrate the insignificance of creep and/or fatigue. In the event of both creep and fatigue being shown to be significant, simple tests can also be used to demonstrate insignificant creep-fatigue interactions, and thus remove the onerous requirement to generate material fatigue data incorporating the effects of creep holds.

The test for insignificant creep applies when both Method I and Method II data of Sections 8.5.6.1 and 8.5.6.2 are used.

The tests for insignificant fatigue and creep-fatigue interaction only apply to Method I.

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

Insignificant Creep

The significance of creep strains should be determined for the assessed loading and temperature history. Creep may be significant for some types of loading history but not for others.

The effects of creep may be neglected if the sum of the ratios of the hold time t to the maximum allowable time t_m , at the reference temperature, T_{ref}, for the total number of cycles is less than one:

$$\sum_{j=1}^{N}\left[t / t_m\left(T_{ref}\right)\right] < 1$$

For further information see Section 8.7.1

STEPS 6- Check Significance of Creep and Fatigue (cont.)

Insignificant Fatigue

It should first be determined whether or not creep behaviour is unperturbed by cyclic behaviour. This test should be performed both for the overall structural response and for stresses local to the crack tip.

Since Step 4 of the procedure of Section 8.2 requires that the crack depth is such that the compliance of the structure is not significantly affected, the test for the overall structural response may be demonstrated by showing that the elastic stress range does not exceed the sum of the steady state creep stress and the stress to cause yield at the other extreme of the cycle. For further information the Procedure refers to the R5 Procedure.

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

Insignificant Fatigue (cont.)

The test for stresses local to the crack tip may be made by demonstrating that, for the most severe fatigue cycle, the cyclic plastic zone at the crack tip is small.

Under cyclic loading, the allowable elastic stress range is $2\sigma_y$ in the absence of cyclic hardening or softening, and the cyclic plastic zone size at the crack tip, $r_p^{crack}=\beta(\Delta K/2\sigma_y)^2$, where β is typically $1/2\pi$ in plane stress and $1/6\pi$ in plane strain.

More generally, the cyclic plastic zone size at the crack tip should be calculated using the cyclic yield or 0.2% offset stress. This cyclic plastic zone size should be shown to be much less than the crack size or any other dimension characteristic of the structure, such as section thickness or remaining ligament ahead of the crack.

For further information see Section 8.7.2.

STEPS 6- Check Significance of Creep and Fatigue (cont.)

Insignificant Creep-Fatigue Interactions

When both creep and cyclic loading are shown to be significant, the significance of creep-fatigue interaction should be determined. In general, the effect of creep damage on fatigue crack growth rates has little influence on the total crack growth per cycle provided the latter includes an explicit calculation of creep crack growth. Hence, creep-fatigue interaction is insignificant and material data that allow for interactions, which lead to enhanced fatigue crack growth rates, are not required. It is adequate, therefore, in Step 9 of Section 8.2 to sum creep crack growth with continuous cycle fatigue crack growth estimates.

Two exceptions to this general rule are provided in Section 8.7.3.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 7- Calculate Rupture Life, t_{CD}

Both stress-based and ductility-based approaches may be used for assessing creep damage.

For loadings which are predominantly constant and primary, the stress is well known and it is appropriate to use stress/time-to-rupture relationships for assessment.

For damage due to cyclic relaxation, the strain accumulated is limited in each cycle and ductility methods are appropriate. For predominately primary loading the time, t_{CD}, for creep damage to propagate through a structure and lead to failure is taken as

$$t_{CD} = t_r \left\lfloor \sigma_{ref}^{p}(a) \right\rfloor$$

where $t_r(\sigma)$ is the rupture time at stress, σ, from conventional stress/time-to-rupture data and the reference stress is calculated for the primary loads only for the current crack size, a.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 7- Calculate Rupture Life, t_{CD} (cont.)

Prior to crack growth the rupture time is calculated for the initial defect size, a_0 . If t_{CD} is less than the remaining assessment time then remedial action must be taken.

For combined and cyclic loading, it may be necessary to evaluate t_{CD} from a ductility exhaustion approach; further details are given in Section 8.10.

FITNET

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 8- Calculate Crack Incubation Time, t_i

The method for representing incubation data depends on observed specimen response. For steady state creep conditions with an essentially constant displacement rate, the incubation time in test specimens is correlated with experimental estimates of the crack tip parameter by:

$$t_i\left(C^*\right)^\beta = \gamma$$

More generally, incubation times can be related to measurements of a critical crack opening displacement, δ_i, which can then be used to calculate a critical reference strain as

$$\varepsilon_c\left\lfloor\sigma_{ref}^p\left(a_0\right),t_i\right\rfloor = \left\lfloor\delta_i / R'\left(a_0\right)\right\rfloor^{n/(n+1)} - \sigma_{\mathrm{ref}}^p\left(a_0\right)/E$$

If fatigue is significant it is conservative to set the incubation time to zero. However, a creep-fatigue crack incubation time (or cycles) may be calculated using the FAD or sigma-d approaches outlined in the Procedure (Section 8.10).

STEP 9- Calculate Crack Size After Growth, a_g

The extent to which crack growth calculations are required depends on the relative magnitudes of the service life to date, t_0, the desired future service life, t_s and the incubation time, t_i; this may be summarised as follows

- If $t_0+t_s<t_i$, the crack will not incubate and $a_g=a_0$.
- If the crack incubates during the assessment time, then it is necessary to calculate the crack size, a_g, after growth in time $t_0+t_s-t_i$.
- If the crack has incubated prior to the assessment, then it is necessary to calculate the crack size, a_g, after growth in time t_s.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 9- Calculate Crack Size After Growth, a_g (cont.)

The time required for the crack to propagate by an amount Δa_g is denoted t_g. For the load controlled case and the attainment of steady state creep conditions this is obtained from creep crack growth data.

The creep crack extension per cycle, $(da/dN)_c$, is evaluated as follows:

$$\frac{da}{dN_c} = \int_0^{t_h} A(C^*)^q \, dt$$

t_h hold time at high temperature

To allow for the increased amplitude of the crack tip fields at short times, it is assumed that for times less than the redistribution time ($t<t_{red}$), equation for crack propagation may be generalised to

$$\dot{a} = A[C(t)]^q$$

STEP 9- Calculate Crack Size After Growth, a_g (cont.)

For situations where $t_i+t_g>t_{red}$, the effects of the redistribution period can be allowed for by using the crack growth rates previously seen multiplied by a factor of 2 for $t<t_{red}$, i.e.

$$\dot{a} = 2A\left(C^*\right)^q \qquad \text{for } t_i \le t < t_{red}$$

$$\dot{a} = A\left(C^*\right)^q \qquad \text{for } t \ge t_{red}$$

If the total time for the assessment does not exceed t_{red}, then this simplified treatment of transient creep is not adequate and it is necessary to use the parameter C(t) explicitly in estimating creep crack growth.

The creep crack extension per cycle, $(da/dN)_c$, including transient effects is then evaluated over the dwell period, t_h, as:

$$\frac{da}{dN_c} = \int_0^{t_h} A\left[C(t)\right]^q dt$$

FITNET

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ASSESS SIGNIFICANCE OF RESULTS (STEP 12)

STEP 12- Assess Significance Of Results

Application of the assessment procedures will lead to one of the following results:

i) The final defect size leads to an acceptable end-of-life safety margin. In this case, a sensitivity analysis should be carried out to ensure that the safety margin is not overly sensitive to variations in the input parameters of the assessment.

ii) Failure or excessive crack growth is indicated within the required service life. In these circumstances, the assessment may be revisited with a view to reducing the assumed pessimisms. In the event that acceptable end-of-life safety margins still cannot be demonstrated, remedial action should be taken.

These scenarios are both discussed in further detail in the Procedure (see Section 8.9).

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REPORT RESULTS (STEP 13)

STEP 13- Report Results

When reporting the results of a structural integrity assessment, the information listed below should be presented.

1.LOADING CONDITIONS
2.MATERIAL PROPERTIES
3. DEFINITION OF FLAW.
4. REFERENCE STRESS
5. STRESS INTENSITY FACTOR SOLUTION
6. SIGNIFICANCE OF CREEP AND FATIGUE.
7. TIME INDEPENDENT ASSESSMENT
8. CYCLE DEPENDENT ASSESSMENT
9. TIME DEPENDENT ASSESSMENT
10. SENSITIVITY ANALYSIS
11. REPORTING

ADDITIONAL INFORMATION

FITNET Procedure provides methodologies for the analysis of specific industrial/technical problems:

- Treatment of Defects in Weldments (see Section 8.10.1)
- Treatment of Secondary Loading (see Section 8.10.2)
- Failure Assessment Diagram Methods (see Section 8.10.3)
    - TDFAD Approach (see 8.10.3.2.1)
    - Two Criteria Diagram (see 8.10.3.2.2)
- Probabilistic Approach to Lifetime Assessment in Creep Regime (see Section 8.10.4)

D. EXAMPLES

WORKED EXAMPLE I

Flat Plate Under Constant Load

- **Introduction and objectives**
- **Data**
- **Analysis**
- **Bibliography/References**

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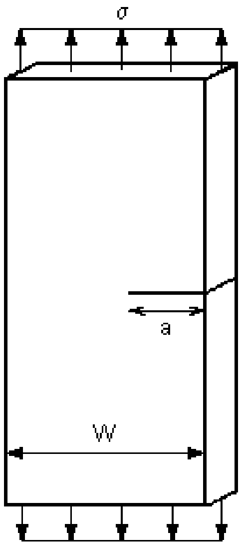
INTRODUCTION AND OBJECTIVES

During a visual inspection of a C-Mn flat plate of width 100mm, a single edge notch of depth 20 mm is detected.

The plate operates at 380 ºC under constant tension, P, corresponding to a nominal stress P/Bw = 100 MPa and the defect is assumed to have been present from the start of high temperature operation.

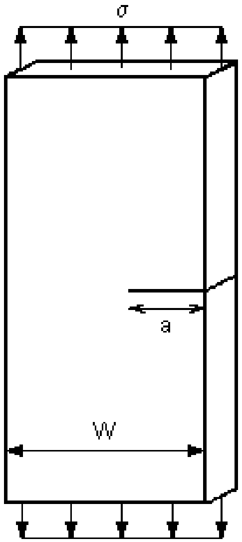
The objective is to assess the response of the component to the described conditions.



W = 100 mm

A = 20 mm

DATA



- *Geometry*:

W = 100 mm

a = 20 mm

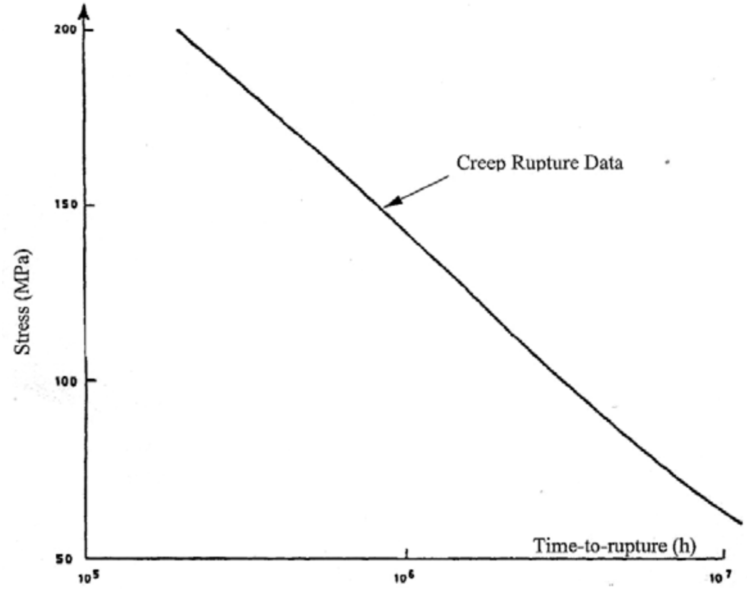
- *Material properties (I)*:

Young´s Modulus = 185000 MPa

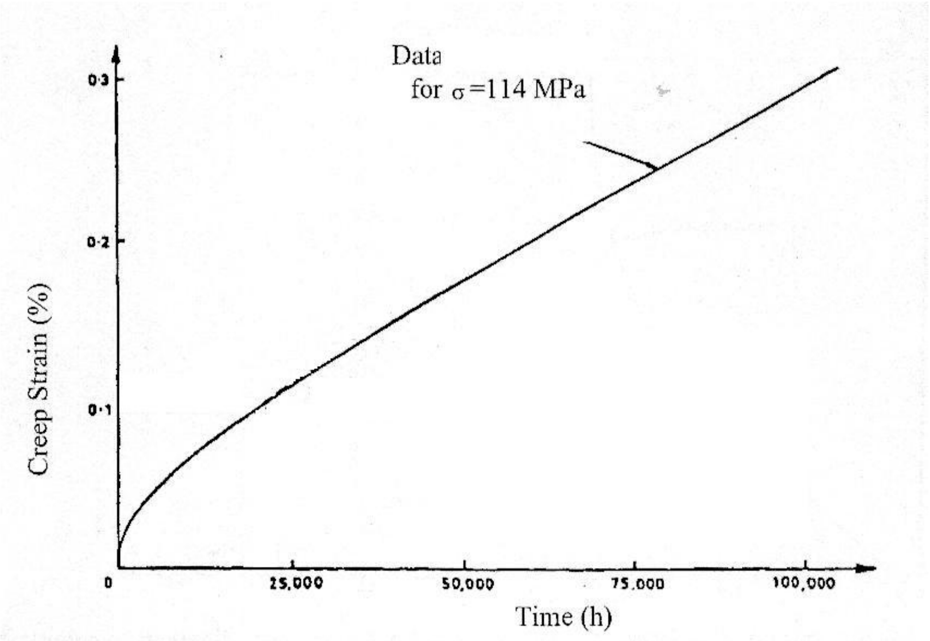
Some tests have been performed in order to obtain data to develop the assessment. The results are given in the next pages:

DATA

- Material properties (II):



Uniaxial stress/time to rupture data



Creep strain/time data

$$\text{Log}_{10}t_r = 10.68 + 153.2\cdot(-1.26 + 2.62x - 2.06x^2 + 0.72x^3 - 0.094x^4)$$

$$x = \log_{10}\sigma$$

$$\varepsilon_c(\sigma,t) = A'\left\{\frac{\sigma}{\sigma_R + B'}\right\}^{C'} \qquad \begin{cases} A' = 0.526 \\ B' = 23.0 \\ C' = 6.9 \end{cases}$$

DATA

- *Material properties (III):*

$da/dt = 0.006 \cdot (C^*)^{0.85}$ ((da/dt) in mh^{-1}, C* in $MPa \cdot mh^{-1}$)

Incubation COD (mm) = 0.06

- *Limit load for the geometry of the example:*

$P_L = 1.155 \sigma_y Bw \{1 - a/w - 1.232(a/w)^2 + (a/w)^3\}$

- *Stress Intensity Factor:* $\mathrm{K} = \sigma(\pi a)^{0.5} \mathrm{F}(a/w)$

$$F = \left\{\frac{\tan\Theta}{\Theta}\right\}^{0.5} \frac{0.752 + 2.02 \cdot \left(\frac{a}{w}\right) + 0.37 \cdot (1 - \sin\Theta)^3}{\cos\Theta}$$

$$\Theta = \frac{\pi a}{2w}$$

ANALYSIS

- BASIC STRESS ANALYSIS:

The reference stress is calculated according to the limit load for this geometry:

$$\sigma_{ref} = (P/P_L)\sigma_y = 0.866(P/Bw) / \{1\text{-}a/w\text{-}1.232(a/w)^2+(a/w)^3\} = 114 \text{ MPa}$$

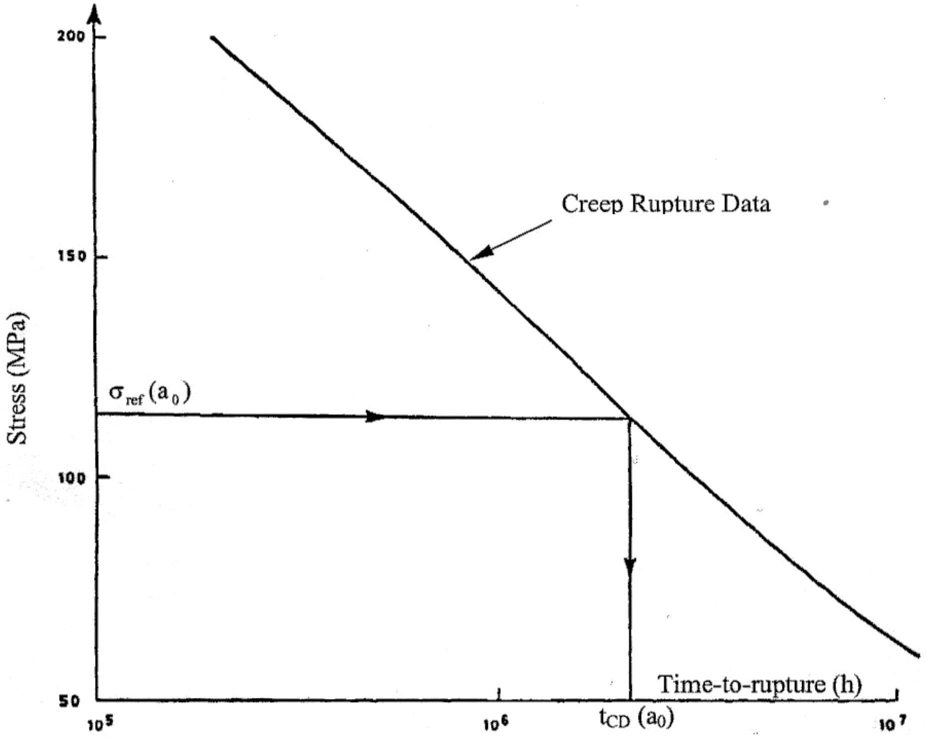
$a/w = 0.2$
$\sigma = P/Bw = 100 \text{ MPa}$

And the stress intensity factor is:

$$K_I = F(a/w)\cdot\sigma(\pi a)^{0.5} = 34.3 \text{ MPa}\cdot\text{m}^{0.5}$$

ANALYSIS

- RUPTURE LIFE: $t_{CD} = t_r [\sigma^p_{ref}(a)] = 2.17 \cdot 10^6$ h



ANALYSIS

- INCUBATION TIME:

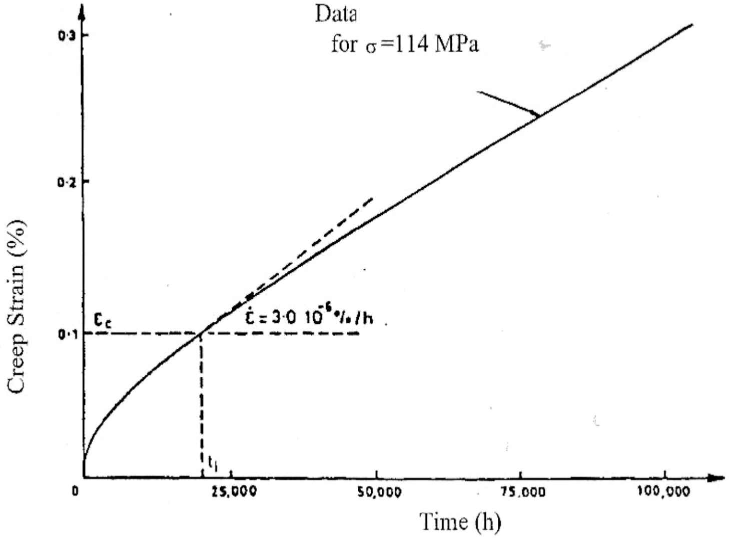
The creep strain that produces the critical crack opening displacement is:

$\varepsilon_c = 0.5(\delta_i/R')^{n/n+1} = 0.5(0.06/90)^{n/n+1} = 0.001$

$R' = (K^2/\sigma_{ref})^2$ m = 90 mm

A value of n is not available and hence n/(n+1) is set equal to the exponent q in the crack growth law (q = 0.85), as suggested in Section A2.6 of the R5 procedure.

As depicted in the figure, t_i = 20000 h



It may be noted that the elastic strain at the reference stress is $\sigma_{ref}/E = 0.0006$, which is less than the creep strain at incubation. Thus, the incubation time exceeds the redistribution time and the conservative expression used for ε_c is valid.

ANALYSIS

- CRACK SIZE AFTER GROWTH (I):

$$C^* = \sigma_{ref} \cdot \overset{\circ}{\varepsilon}{}^{c}_{ref} \cdot R'$$

The reference stress and the length parameter R´ have already been calculated. From the figure on the previous page, the creep strain rate at the incubation time is:

$$\overset{\circ}{\varepsilon}{}^{c}_{ref} = 3 \cdot 10^{-8} h^{-1}$$

Thus:

$$C^* = 3 \cdot 10^{-7} \text{MPa m h}^{-1}$$

at the incubation time

ANALYSIS

- CRACK SIZE AFTER GROWTH (II):

The corresponding crack growth rate growth rate using the crack growth law is

$$da/dt = 0.006 \cdot (3 \cdot 10^{-7})^{0.85} = 1.8 \cdot 10^{-5} \text{ mm h}^{-1}$$

By assuming that the crack growth and creep strain rates are constant for a short time, Δt, the crack size and accumulated creep strain can be updated, and new values for reference stress and creep strain rate can be obtained. The value of C* can then be obtained with R´ evaluated for the new crack size, leading to a new value for da/dt.

The process is explained in the next three pages.

ANALYSIS

- CRACK SIZE AFTER GROWTH (III):

The crack growth process is divided into different steps with a crack length increment. For the initial crack length on each step, the reference stress and the stress intensity factor are calculated. Then, we can obtain the figure ε_c-t from the formulas:

$$\varepsilon_c(\sigma_{ref}, t) = A'\left\{\frac{\sigma_{ref}}{\sigma_R + B'}\right\}^{C'}$$

$$\mathrm{Log}_{10} t_r = 10.68 + 153.2 \cdot (-1.26 + 2.62x - 2.06x^2 + 0.72x^3 - 0.094x^4)$$

$$x = \log_{10}\sigma$$

It is possible to consider different σ_R in the second formula and then, to obtain its t_r. Therefore, σ_{ref}, σ_R and t are known and ε_c can be obtained from the first formula. Finally, it is possible to plot the ε_c-t figure for the different σ_{ref}.

ANALYSIS

- CRACK SIZE AFTER GROWTH (IV):

So, for each step, the pocess is:

1) σ_{ref} and K

2) ε_c-t figure

3) $R' = (K^2/\sigma_{ref})^2$

4) $\varepsilon_c = 0.5(\delta_i/R')^{n/n+1}$ (creep strain that produces the critical crack opening displacement)

$$\left.\begin{array}{l}5)\ t_i\\ 6)\ \dot{\varepsilon}^{c}_{ref}\end{array}\right\}\ \text{from the } \varepsilon_c\text{-t figure}$$

7) C*

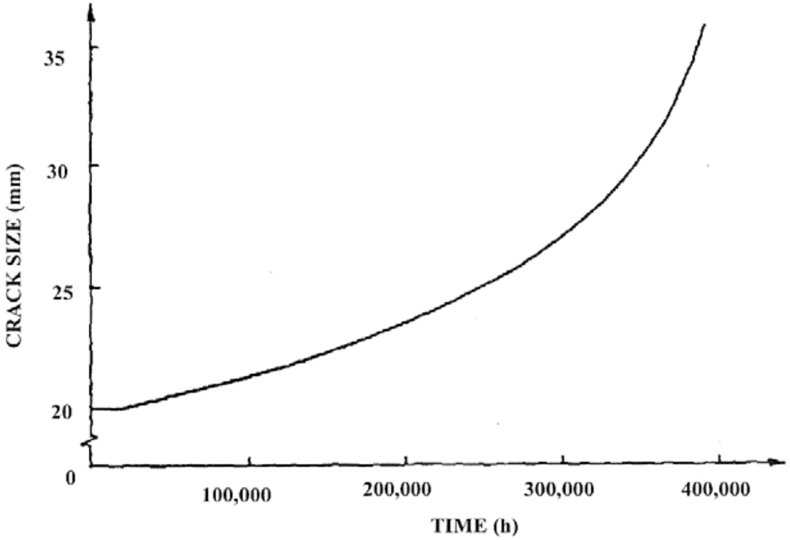
ANALYSIS

- CRACK SIZE AFTER GROWTH (V):

8) da/dt

9) Δt for each Δa

This process is easily developed with computer programs. The crack size as a function of time is shown in the next figure:



ANALYSIS

- RECALCULATE RUPTURE LIFE AFTER GROWTH

As the reference stress is calculated at each stage of the crack growth calculations, it is straightforward to recalculate t_{CD} from equation:

$$t_{CD}\,(a_g) = \mathrm{Min}\{t_r\,[\sigma_{ref}(a(t))]+t\} \quad \text{for } t \leq t_i + t_g$$

Even when the crack has grown to a depth of 35 mm, the reference stress is only 160 MPa and this corresponds to a remaining life of 650000 hours. It is clear from the timescale in the previous figure that in this example creep crack growth rather than creep rupture is the dominant failure mechanism.

ANALYSIS

- ASSESS SIGNIFICANCE OF RESULTS

The following conclusions can be drawn for this example:

- The remaining creep rupture life was found to be high at all stages of the assessment, showing that creep crack growth, rather than creep rupture, is the dominant failure mechanism.

- Widespread creep conditions are achieved prior to the incubation time.

- An incubation time of ti = 20000 h is predicted.

- The crack is predicted to grow by 15 mm over 380000 h.

BIBLIOGRAPHY / REFERENCES

- British Energy, *"R5, Assessment Procedure for the High Temperature Response of Structures"*. Issue 3, Volume 4/5, Appendix 8 Worked Examples, Example 1. Gloucester: British Energy; June 2003

WORKED EXAMPLE II

Cyclindrical Pipe Under Cyclic Loading

- Introduction
- Data
- Analysis
- Bibliography/References

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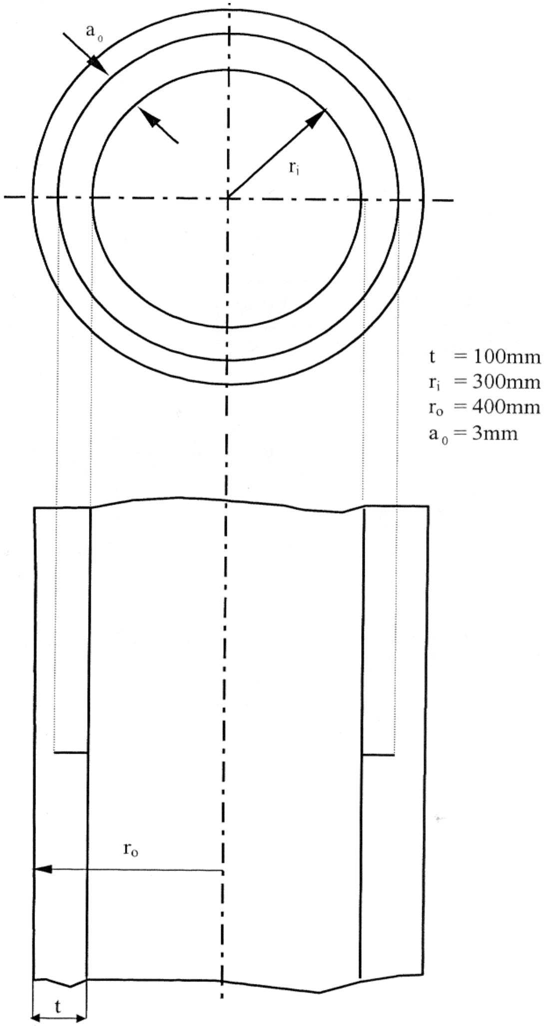
INTRODUCTION

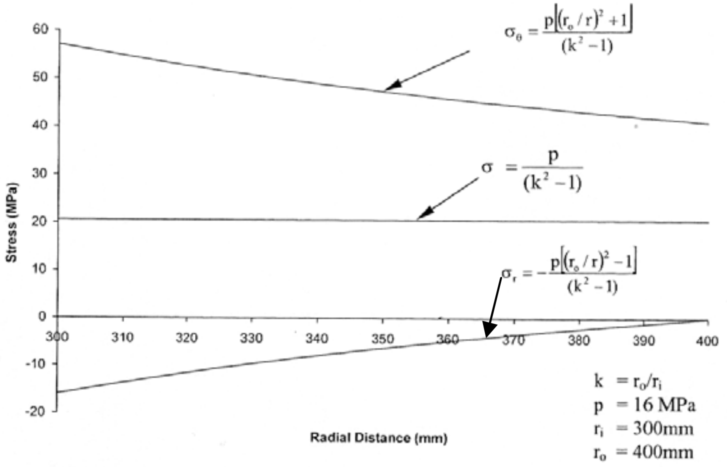
This example studies a cylindrical pipe with an internal, part-penetrating, fully circumferential defect under cyclic loading.

The idealised structural geometry is shown in the figure. It comprises a homogeneous Type 316 Stainless Steel pipe of internal radius, R_i = 300 mm and wall thickness, w = 100 mm. A defect is assumed to be present at the start of high temperature operation so that the life to date is taken as zero. The defect is assumed to be fully circumferential on the inside of the pipe with the initial depth, a_0, taken as 3 mm.

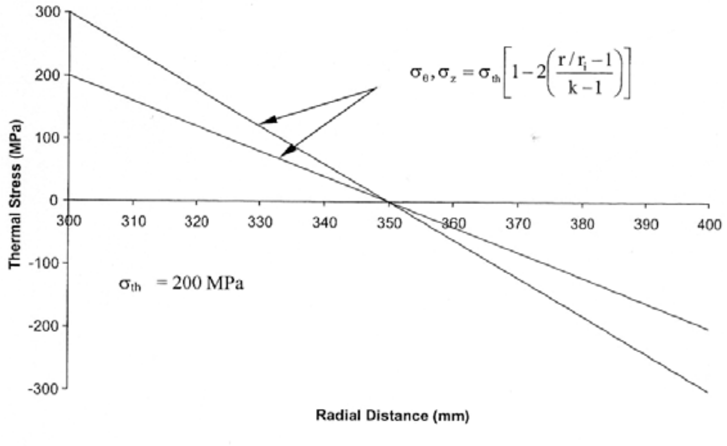


DATA

The pipe is subjected to repeated cyclic loading from an initially unstressed shutdown condition at ambient temperature (20°C) to an operating condition at 600°C , comprising an internal pressure of 16 MPa together with through wall axial and hoop thermal bending stresses of 200 MPa. The bending stresses are such that tensile stresses arise on the inside surface of the pipe as shown in the figure. 500 equal cycles, with 3000 hour dwells at operating conditions, are assumed to occur during the desired future service life of $1.5 \cdot 10^6$ hour.



a) Pressure Stresses



b) Thermal Stresses

DATA

Creep strain data are described by the following parametric expression proposed by White (see references):

$$\varepsilon = \varepsilon_p [1-\exp(-rt^{\mu})] + (d\varepsilon/dt)t$$

With the maximum primary strain, ε_p, given by

$$\varepsilon_p = A'\sigma^{m(\Phi)}\exp[-P/(\Phi+273)]$$

where $m(\Phi) = \alpha - \gamma\Phi$ and the secondary creep strain rate is given by

$$(d\varepsilon/dt)_s = B\sigma^n\exp[P/(\Phi+273)]$$

Where Φ is the temperature and σ the reference stress.

$r = 2.42\ 10^{-2}$
$\mu = 0.64$
$A' = 1.632\ 10^{35}$
$P = 9.292\ 10^{4}$
$\alpha = 16.32$
$\gamma = 0.02044$
$B = 1.065\ 10^{-5}$
$Q = 1.97\ 10^{4}$
$n = 4$

DATA

The creep strain rate may be obtained by differentiating the equation for the creep strain with respect to time as:

$$d\varepsilon/dt = \varepsilon_p r \mu t^{\mu-1} \exp(-rt^{\mu}) + (d\varepsilon/dt)$$

However, as $\mu < 1$, the creep strain rate given by the above analytical expression becomes infinite at time zero. For short times and low strains ($<10^{-4}$), the creep strain rate is approximated by dividing the strain of 10^{-4} by the time to reach this strain (obtained from the equation for ε).

The values of the coefficients A and q of the creep crack growth rate law (m/h) are:
$A = 0.0197$ and $q = 0.89$

The values of the coefficients C and l of the cyclic crack growth rate law (m/cycle) are:
$C = 2.0\ 10^{-9}$ and $l = 3$

ANALYSIS

- BASIC STRESS ANALYSIS:

For cyclic loading, the following are required:

- A shakedown analysis

- The depth of the cyclic plastic zone on the surface of the defective section.

- The elastic follow-up factor.

- The stress intensity factors, Kmin and Kmax and the associated R ratio, which permit the effective stress intensity factor range, ΔKeff, to be calculated.

- The reference stress for the creep dwell.

ANALYSIS

- SHAKEDOWN ANALYSIS (I):

Uncracked body elastic stresses are required as the starting point for the analysis. In this example, the pressure stresses are given by de Lamé thick cylinder equations with the thermal stresses taken as through wall bending stresses of equal magnitude in the hoop and axial directions (see the figure). The initial total operating elastic stresses are then the sum of the pressure and thermal contributions.

In order to determine whether the structure is operating within shakedown it is necessary to generate a residual stress field. For this example, it is convenient to select a residual stress field which is a factor, α, times the thermal stress field (i.e. axial and hoop bending stresses of 200α MPa). The shakedown stress field, σ^*_s, is then obtained by adding the residual stress field, ρ^*, to the elastically calculated stress field, σ^*_{el}. Thus:

$$\sigma^*_s = \sigma^*_{el} + \rho^*$$

ANALYSIS

- SHAKEDOWN ANALYSIS (II):

Shakedown stress fields are thereby determined for the cold (non-creep) and hot (creep) extremes of the loading cycle, denoted $(\sigma_s)_{nc}$ and $(\sigma_s)_c$ for shutdown and operating conditions, respectively.

For the structure to attain strict shakedown, the shakedown stress fields at the cold and hot extremes of the loading cycle must satisfy the following criteria:

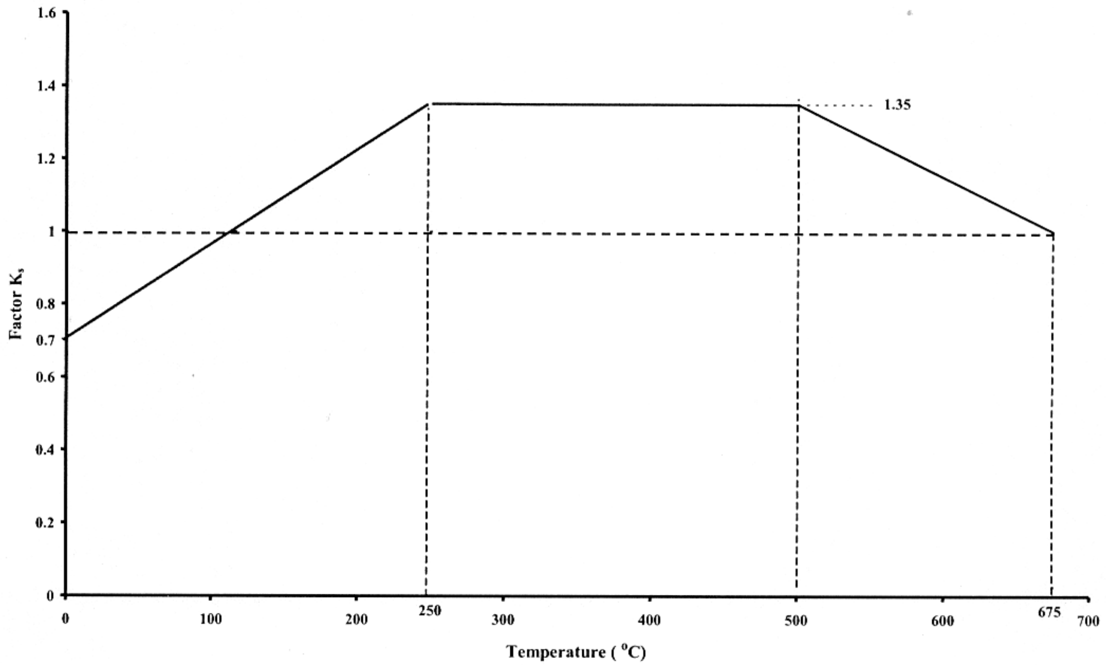
$$(\sigma_s)_{nc} \leq (K_s S_y)_{nc}$$
$$(\sigma_s)_c \leq (K_s S_y)_c$$

where S_y is the minimum 0.2% proof stress and $(\sigma_s)_{nc}$ and $(\sigma_s)_c$ are the shakedown equivalent stresses at shutdown and operating conditions respectively. The shakedown factor K_s is an experimentally derived factor which can be applied to S_y to give a level, $K_s S_y$, which is the largest semi-stress range for which the material has stable cyclic stress-strain behaviour.

ANALYSIS

- SHAKEDOWN ANALYSIS (III):

The variation of K_s with temperature for Type 316 steel is given in the next figure:



ANALYSIS

- SHAKEDOWN ANALYSIS (IV):

For the current example, which involves shutdown at 20°C, values of $(K_s)_{nc} = 0.752$ and $(S_y)_{nc} = 245$ MPa are assumed for the Type 316 Stainless Steel, leading to a shakedown criterion at shutdown of:

$$(\sigma_s)_{nc} \leq 184.2 \text{ MPa}$$

For operation at 600°C, assumed values of $(K_s)_c = 1.15$ and $(S_y)_c = 109.6$ MPa give a shakedown criterion at operation of:

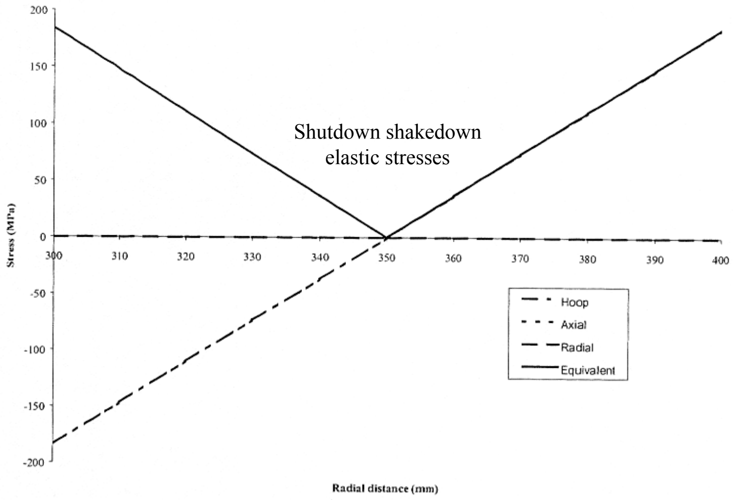
$$(\sigma_s)_c \leq 126.8 \text{ MPa}$$

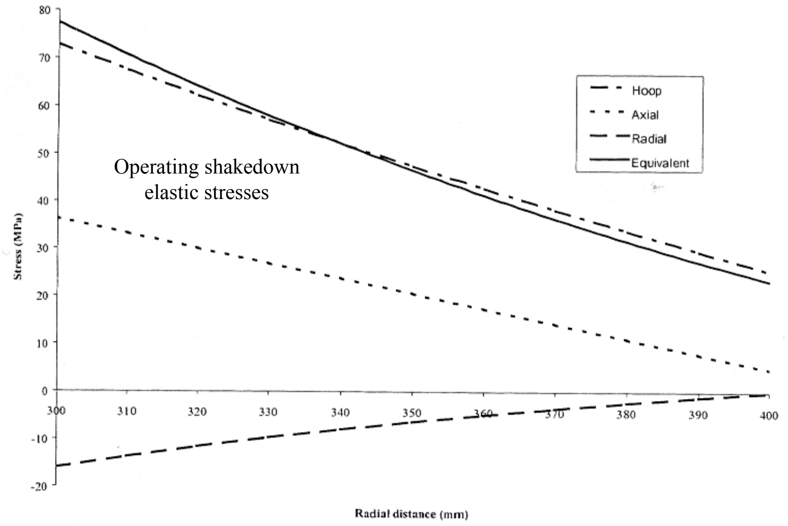
For this example, strict shakedown can be demonstrated for the pipe.

ANALYSIS

- SHAKEDOWN ANALYSIS (V):

Creep relaxation during early loading cycles reduces the stress at the hot extreme of the cycle until the cold extreme of the cycle reaches the limit of the shakedown criterion at shutdown. This situation is achieved using a residual stress field obtained by scaling the thermal stress field by α = -0.921. Resulting steady cyclic stress profiles for the uncracked pipe are shown in the next figures for shutdown and operating conditions, respectively:



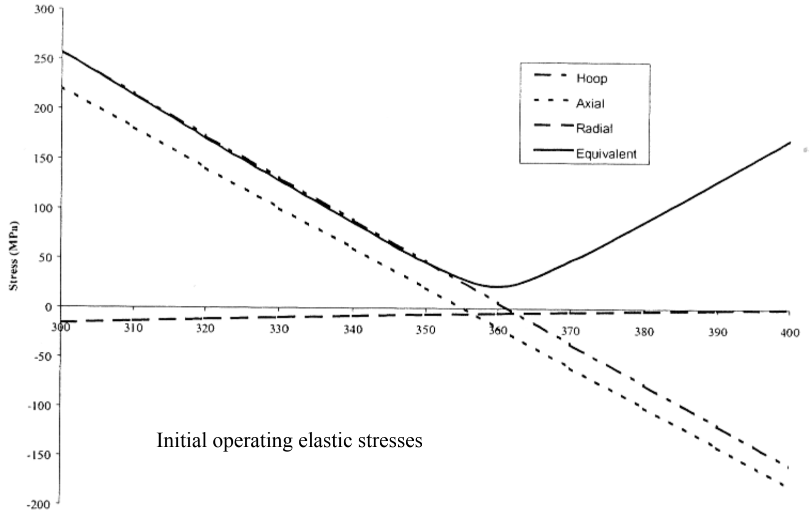


ANALYSIS

- SHAKEDOWN ANALYSIS (VI):

In order to take account of early cycles prior to attainment of the steady cyclic state, it is also necessary to determine the initial stress state. For this example, the initial stress state is obtained using a Neuber construction (see R5, Vol 2/3) for the most highly stressed inside surface point. The initial elastic operating stress profiles are shown in the figure and give an initial elastic equivalent stress at the inner surface of 256.8 MPa.

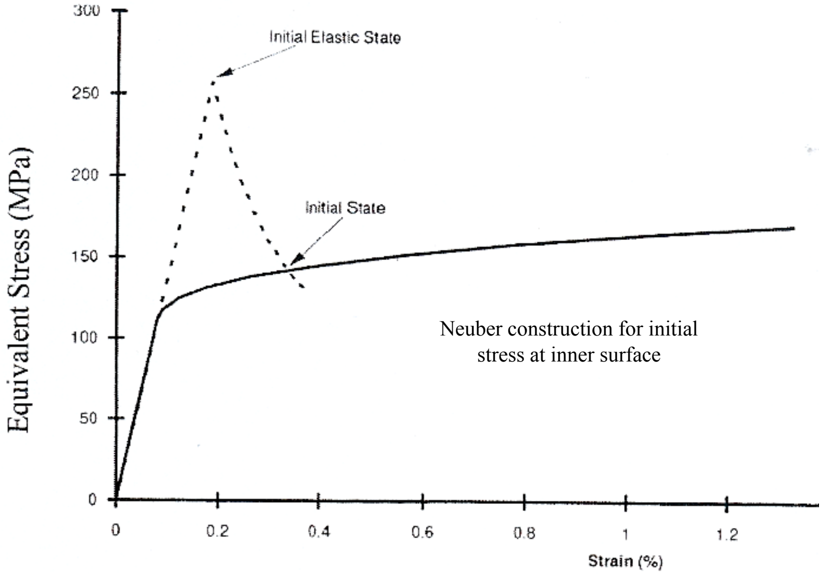
This elastic equivalent stress has then been used, together with isochronous data for Type 316 Stainless Steel at 600°C, to estimate the initial equivalent stress at the inner surface as shown on the next page.



Initial operating elastic stresses

ANALYSIS

- SHAKEDOWN ANALYSIS (VII):

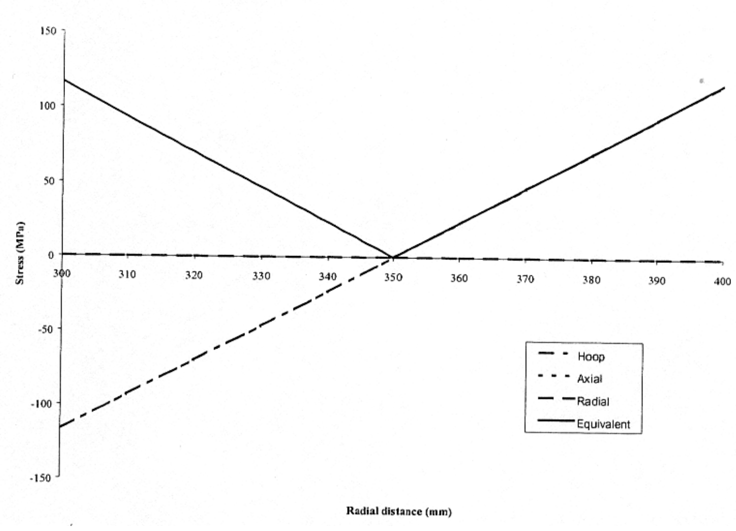


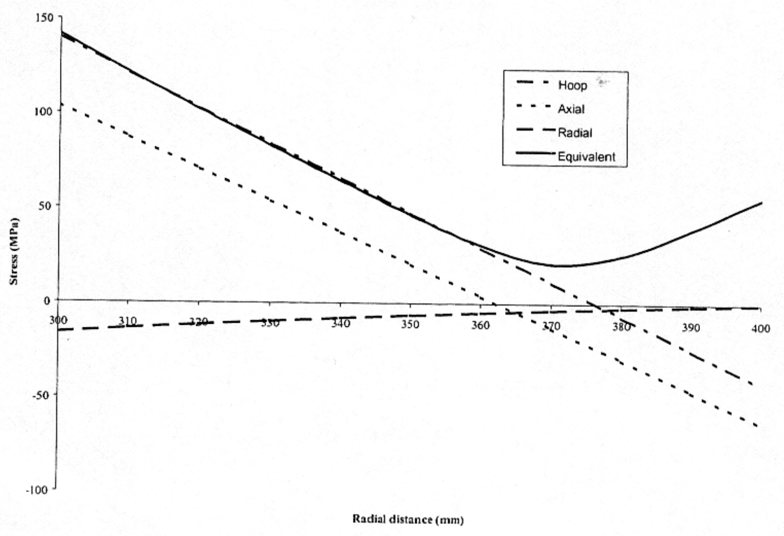
This initial equivalent stress at the inner surface (141.8 MPa) has then been used to infer an initial residual stress field, which when combined with the initial elastic stresses, gives the correct value of inner surface equivalent stress. The required initial residual stress field is obtained by scaling the thermal stress field by $\alpha = -0.583$.

ANALYSIS

- SHAKEDOWN ANALYSIS (VIII):

Resulting initial stress profiles are shown in the next figures for shutdown and operating conditions, respectively.





Strict shakedown has been demonstrated for this example. There is therefore no cyclic plastic deformation at the inner surface of the defective pipe section and the cyclic plastic zone, r_p, is set equal to zero.

ANALYSIS

- STRESS INTENSITY FACTORS (I):

$\Delta K_{eff} = K_{max} - K_{min}$

K_{max} → operation
K_{min} → shutdown

$K = (F_m \sigma_m + F_b \sigma_b) \cdot (\pi a)^{1/2}$

σ_m → membrane stress
σ_b → bending stress
F_m → membrane compliance function
F_b → bending compliance function

From the handbook of Tada, Paris and Irwin, (see references) and for $R_i/w = 3$:

$F_m = 1.123 - 0.103 \cdot (a/w) + 2.030 \cdot (a/w)^2 - 1.373 \cdot (a/w)^3 + 0.790 \cdot (a/w)^4$ for $0 < a/w < 0.6$

The corresponding bending compliance function has been derived using the computer program R-Code:

$F_b = 1.126 - 1.543 \cdot (a/w) + 2.613 \cdot (a/w)^2 - 3.986 \cdot (a/w)^3 + 2.123 \cdot (a/w)^4$ for $0 < a/w < 0.6$

ANALYSIS

- STRESS INTENSITY FACTORS (II):

The effective stress intensity factor range, ΔK_{eff}, has been evaluated as a function of crack depth from equations:

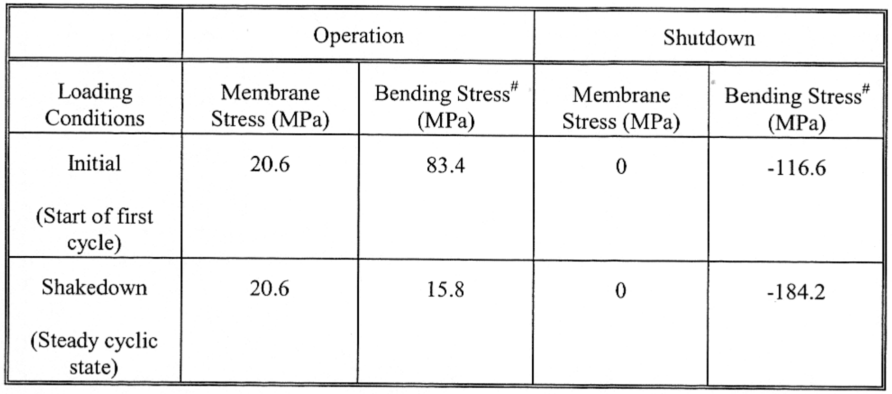
$$\Delta K_{eff} = q_0 \Delta K \qquad \Delta K = K_{max} - K_{min}$$

$$q_0 = 1 \qquad R \geq 0$$

$$q_0 = (1-0.5R)/(1-R) \qquad R < 0$$

$$\left.\begin{array}{l} R \geq 0 \\ R < 0 \end{array}\right\} R = K_{min}/K_{max}$$

from both initial and shakedown conditions using the compliance functions given previously together with the axial stresses given in the next table.



	Operation		Shutdown	
Loading Conditions	Membrane Stress (MPa)	Bending Stress# (MPa)	Membrane Stress (MPa)	Bending Stress# (MPa)
Initial (Start of first cycle)	20.6	83.4	0	-116.6
Shakedown (Steady cyclic state)	20.6	15.8	0	-184.2

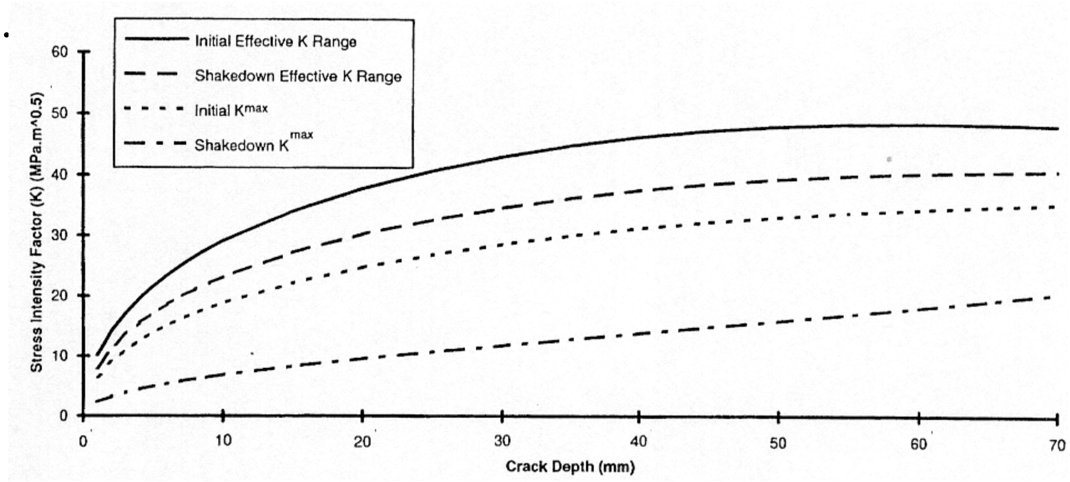
Positive values indicate tensile stress on the inside surface of the pipe

ANALYSIS

- STRESS INTENSITY FACTORS (III):

The effective stress intensity factor ranges (together with associated values of K_{max}) are shown as functions of crack depth in the figure for both the initial and shakedown conditions. Note that for the current example $R < 0$ and hence $q_0 < 1$ for both initial and shakedown conditions (for all crack depths).

For the period prior to the attainment of the steady cyclic state (i.e. $t < t_{cyc}$), the effective stress intensity factor range has been taken as the mean of the initial and shakedown values.



ANALYSIS

- REFERENCE STRESSES (I):

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

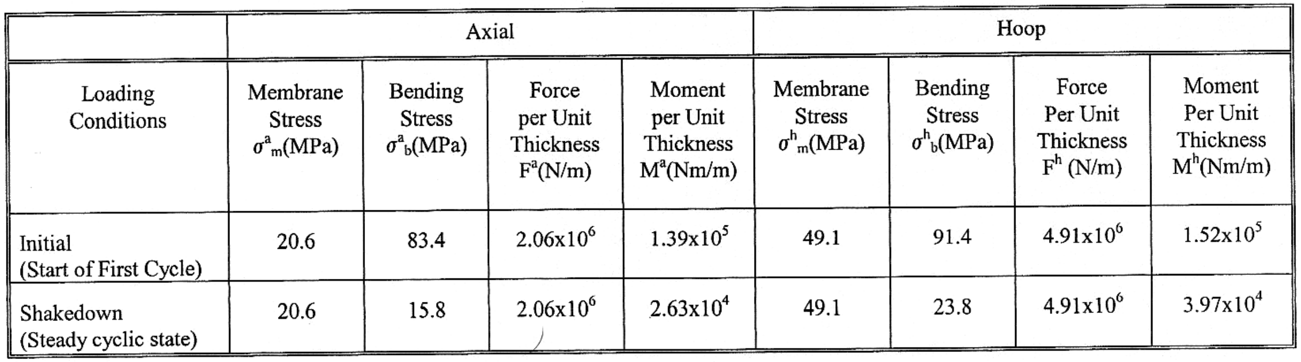
If proportional loading is assumed, the limit loads can be determined from:

$F_L/M_L = F/M$

The next table gives axial and hoop stresses appropriate to initial and shakedown conditions and associated forces and moments (per unit thickness) evaluated using:

$F = \sigma_m w$

$M = (\sigma_b w^2)/6$

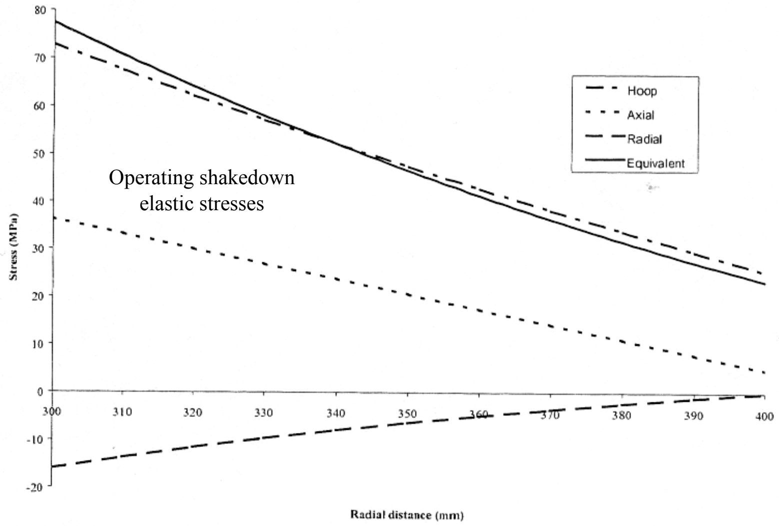


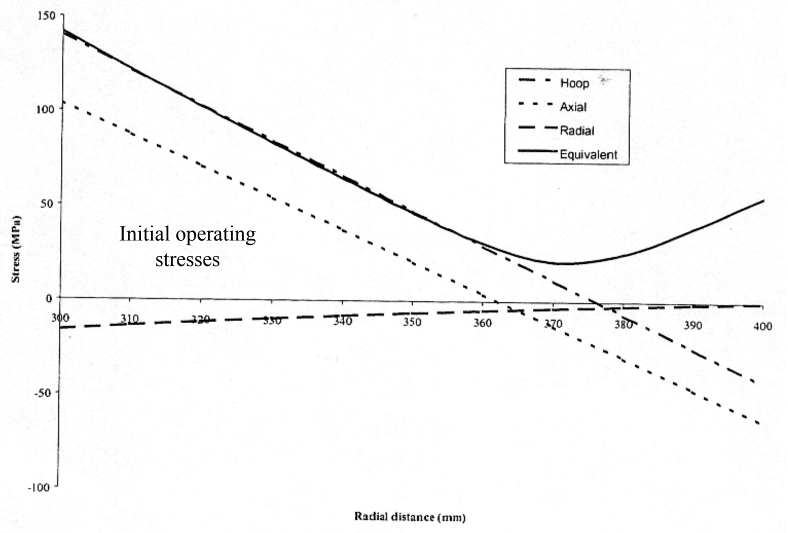
	Axial				Hoop			
Loading Conditions	Membrane Stress σ^a_m(MPa)	Bending Stress σ^a_b(MPa)	Force per Unit Thickness F^a(N/m)	Moment per Unit Thickness M^a(Nm/m)	Membrane Stress σ^h_m(MPa)	Bending Stress σ^h_b(MPa)	Force Per Unit Thickness F^h (N/m)	Moment Per Unit Thickness M^h(Nm/m)
Initial (Start of First Cycle)	20.6	83.4	$2.06\text{x}10^6$	$1.39\text{x}10^5$	49.1	91.4	$4.91\text{x}10^6$	$1.52\text{x}10^5$
Shakedown (Steady cyclic state)	20.6	15.8	$2.06\text{x}10^6$	$2.63\text{x}10^4$	49.1	23.8	$4.91\text{x}10^6$	$3.97\text{x}10^4$

ANALYSIS

- REFERENCE STRESSES (II):

Axial and hoop stresses have been evaluated for both steady cyclic and initial conditions (based on Neuber) using the stress profiles shown in the next figures:





In both cases, the axial and hoop stresses can be well represented by membrane and bending stresses, σ_m and σ_b, respectively.

ANALYSIS

- REFERENCE STRESSES (III):

The limit loads for axially dominated collapse have the form:

$$F^a_L = (2y-a)\sigma_y$$
$$M^a_L = \{(w^2/4) + (a^2/4) - (at/2) - x^2\}\sigma_y$$

where w is the pipe wall thickness and y is the distance between the plastic neutral axis and the mid-wall thickness. The value of y is found from the equation $F_L/M_L = F/M$ based on the values of F and M previously calculated and the expressions involving y for F^a_L an M^a_L. The resulting quadratic equation can then be easily solved.

For the hoop dominated collapse, the limit loads are:

$$F^h_L = 2y\sigma_y$$
$$M^h_L = \{(w^2/4) - y^2\}\sigma_y$$

ANALYSIS

- REFERENCE STRESSES (IV):

The maximum of the axial and hoop reference stress is then chosen. For both the initial and shakedown conditions, the reference stress is hoop dominated, and is therefore independent of crack depth.

For initial conditions the reference stress is

$$\sigma_{\mathrm{ref}}^{\mathrm{cyc}=1} = 88.1\,\mathrm{MPa}$$

while for steady cyclic conditions

$$\sigma_{\mathrm{ref}} = 57.6\,\mathrm{MPa}$$

is obtained.

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (I):

For the prupose of this example, it is assumed that both creep and fatigue are significant. The calculation of the incubation time is not considered in this example, although a conservative incubation time of zero is often assumed when creep and fatigue are significant.

Strict shakedown of the uncracked structure has been demonstrated for this example and so a Method I crack growth calculation is appropriate. The creep and fatigue crack growth contributions are separately calculated and added for each cycle.

The creep crack growth rate law takes the form:

$$da/dt = 0.0197 \cdot (C^*)^{0.89}$$

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (II):

In general, the parameter C^* is calculated by the reference stress approach. It is also necessary to calculate a mean value of C^* for use in calculating creep crack growth occurring in the dwell periods prior to the attainment of the steady state ($t < t_{cyc}$).

$$C^* = \frac{(\sigma_{ref}^{cyc=1} + \sigma_{ref})}{2} \cdot \overset{\circ}{\varepsilon} \cdot R' \qquad \text{where } d\varepsilon/dt \text{ is evaluated for } \frac{(\sigma_{ref}^{cyc=1} + \sigma_{ref})}{2}$$

An estimate of t_{cyc} can be expressed in terms of the reference stress for the first cycle, $\sigma_{ref\,(cyc=1)}$, and the reference stress under steady cyclic conditions, σ_{ref}, as:

$$\varepsilon_c\left[\left(\sigma_{ref}^{cyc=1} + \sigma_{ref}\right)/2,\ t_{cyc}\right] = Z \cdot \left(\sigma_{ref}^{cyc=1} - \sigma_{ref}\right)/E$$

where Z is the elastic follow-up factor defined in Appendix A3 of the R5 procedure.

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (III):

For the current example, the stresses acting during the dwell periods after the steady cyclic is reached are predominantly primary. Therefore, the small amount of stress relaxation that could occur during the dwell has been neglected and load-controlled loading has been assumed in calculating creep strain accumulation and crack growth during the dwell.

The stress intensity factor used for the calculation of R´ is evaluated using the stresses at the beginning of the dwell and is therefore equal to K_{max}. Prior to attainment of the steady cyclic state, a mean value of K_{max} has been used in the calculation of R´. This is given by:

$$\overline{K}_{max} = \frac{K_{max}^{cyc=1} + K_{max}}{2}$$

where $K_{max}^{cyc=1}$ and K_{max} are the maximum stress intensity factors at the start of the first cycle (using a Neuber construction) and the cycle in the steady cyclic state, respectively.

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (IV):

The cyclic crack growth rate law takes the form:

$$(da/dN) = 2\ 10^{-9}\cdot(\Delta K_{eff})^3$$

The total crack growth per cycle is obtained by adding the cyclic and creep contributions.

The crack extension over a desired future life of $1.5\cdot10^6$ hours is then calculated iteratively using a computer program. The main features of the iterative procedure are as follows:

i) Calculate creep crack growth for the dwell period in the first cycle. It should be noted that this itself involves an iterative procedure in which the creep crack growth and strain rates are assumed constant for a short time, Δt. The crack depth and accumulated creep strain are then updated and new values of reference stress and creep strain rate obtained assuming a strain hardening rule. The value of C*

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (V):

can then be obtained with R´ evaluated for the new crack depth, leading to a new value of creep crack growth rate. For the current example, these calculations have actually been implemented by incrementing crack depth.

ii) Calculate cyclic crack growth for the first cycle and increment crack depth.

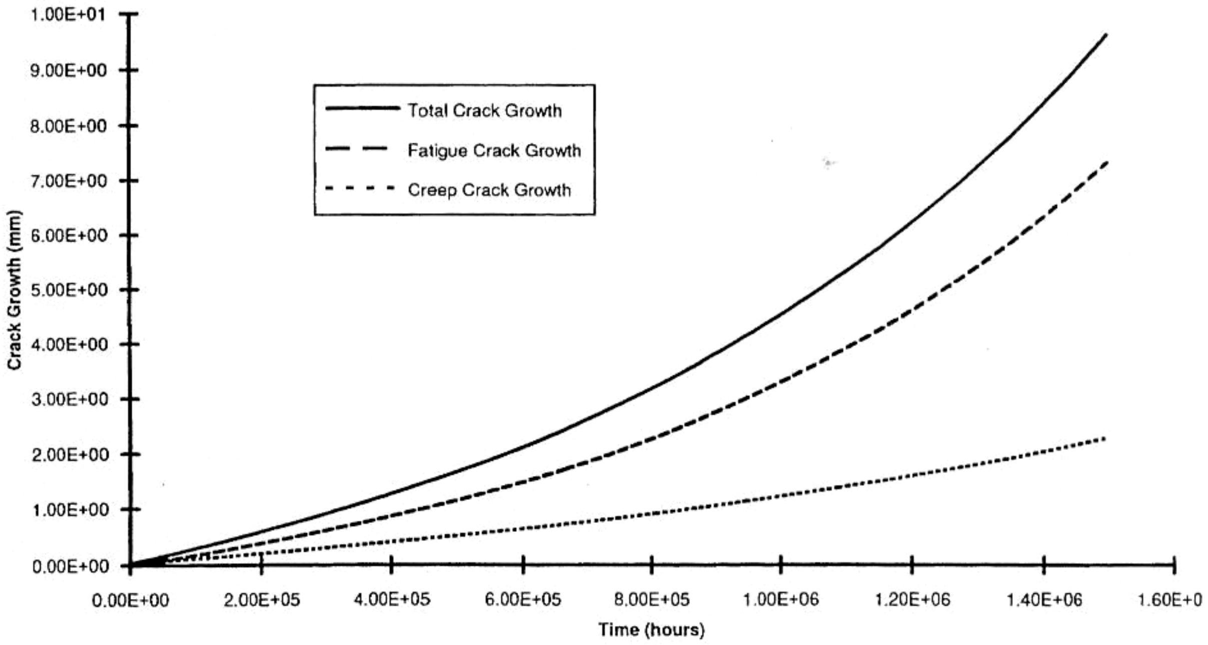
iii) Repeat calculations for subsequent cycles.

For the current example, it is also necessary to determine t_{cyc}, the time to redistribute to the steady cyclic state. A value of elastic follow up of Z=3 is arbitrarily assumed. With this assumption, the steady cyclic state is achieved after 1 cycle. Prior to attainment of the steady cyclic state, mean values of ΔK_{eff} and C^* are used to calculate cyclic and creep components of crack growth as described above. After steady cyclic state has been established, values of ΔK_{eff} and C^* appropriate to steady state conditions are used in the crack growth calculations.

ANALYSIS

- CALCULATE CRACK SIZE AFTER GROWTH (VI):

The results of these iterative calculations lead to the crack depth as a function of time shown in the figure:



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•White PS., "*SIWG recommendation on constitutive equations for Type 316 (CDFR) stainless steel*", GEC Report FDRC/SIWG/SASG/P(88)/183, 1998.

•Tada H., Paris PC. and Irwin GR., "*The Stress Analysis of Cracks Handbook*", Third Edition, ASME, New York, 2000.

IV. TRAINING PACKAGE ON ENVIRONMENTAL EFFECTS

A. BASIC CONCEPTS

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING PROCESSES

AGGRESSIVE ENVIRONMENT → **MATERIAL** ← MECHANIC LOADS

……

ENVIRONMENTAL ASSISTED CRACKING

LOADING RATE

Static or Quasi-Sstatic → **Stress corrosion cracking (SCC)**

Dynamic → **Corrosion – Fatigue (CF)**

ENVIRONMENT

Liquid or Gaseous Environments

Presence of damaging simple chemical elements or molecules

- Hydrogen: **Hydrogen assisted embrittlement**, **Hydrogen assisted cracking**
- Oxygen: **Intergranular corrosion cracking**

CORROSION BEHAVIOUR

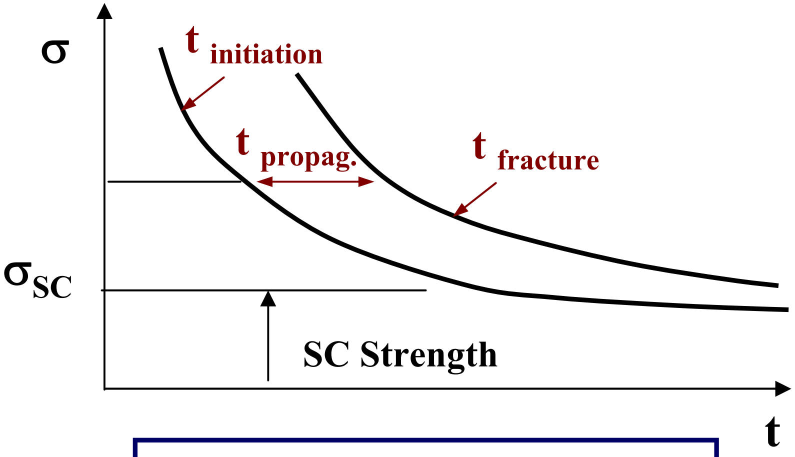
ENVIRONMENTAL ASSISTED CRACKING

Crack initiation processes

+

Propagation processes

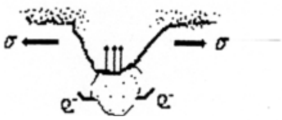
FRACTURE



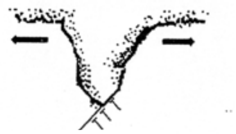
Safe Design: $\sigma \leqslant \sigma_{SC}$

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING



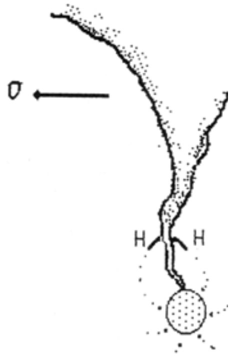
Anodic dissolution



Sliding σ>σ*)

Repasivation

Increase in deffect sharpening



Catodic reaction

$H^+ + e^- \rightarrow \frac{1}{2} H_2$

Hydrogen embrittlement

-Adsorption

-Absorption

-Diffusion

-Local damage and failure

-Crack advance

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

Life estimation (constant environment and stresses)

· Depends on initiation → material surface state
(roughness)
(surface defects) → inclusions ... / processing ... / recovering ...

· Depends on propagation → Local cracking mechanisms
(local fractures after restrained embrittlement)
(inherent mechanisms)

· If previous notches (stress concentration) or cracks exist → $t_{life} \equiv t_{propagation}$

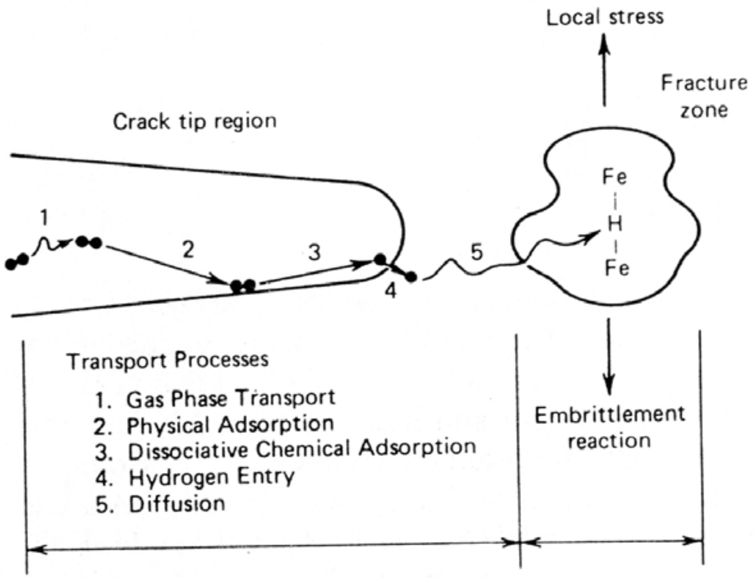
Design $\sigma \leqslant \sigma_{SCC}$

σ_{SCC} is not only material dependent, it also depends in processing (surface finishing) and design (notches, welds,…)

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

Crack propagation rate; $\left[\dfrac{da}{dt}\right]$ is a characteristic of the material (for a given environment and local conditions).



Local mechanisms of material transport and embrittlement

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

Material behaviour

- It defines the crack propagation process

- Stress state
+
Crack presence

↓

Application of Fracture Mechanics

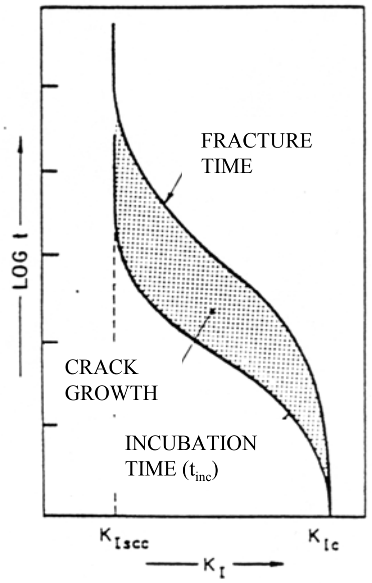
Crack propagation rate as a function of the local stress state (K_I), that establishes, together with the environment, the cracking mechanisms

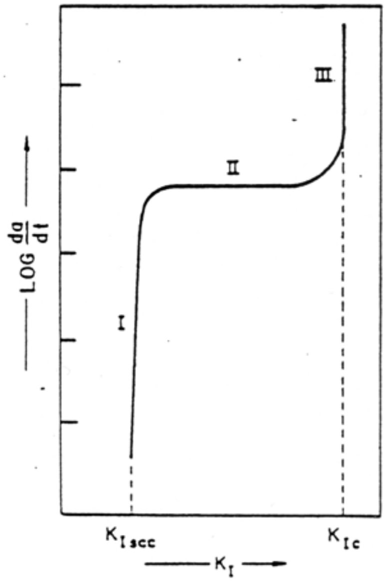
$$\frac{da}{dt} = f(K_I, \text{environment})$$

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

STRESS CORROSION





Crack propagation happens over some characteristic threshold conditions, defining K_{ISCC} ($da/dt = 0$ for $K_I<K_{ISCC}$, Stage I)

- at a quasi-constant rate (da/dt = cte for $K_I>K_{ISCC}$, Stage II)
- loading to final fracture at stage III ($K_I = K_{IC}$)

CORROSION BEHAVIOUR

DESIGN CONDITIONS AND INTEGRITY MAINTENANCE

- Guarantee maximum defect size ($a_0 \leqslant a_{\text{Lim}}$)

$a_{\text{Lim}} \longrightarrow$ observable on reception

- Determine crack evolution

$$\mathbf{a_{calc}(t) = a_{Lim} + \int_0^t \left[\frac{da}{dt} \right] dt}$$

$\uparrow$ **Material behaviour**

- Periodic and cyclic observations to guarantee

$$a_{\text{real}}(t) \leqslant a_{\text{calc}}(t)$$

when $K_I(a_{\text{calc}}) \leqslant K_{Ic} / F_{\text{safety}}$

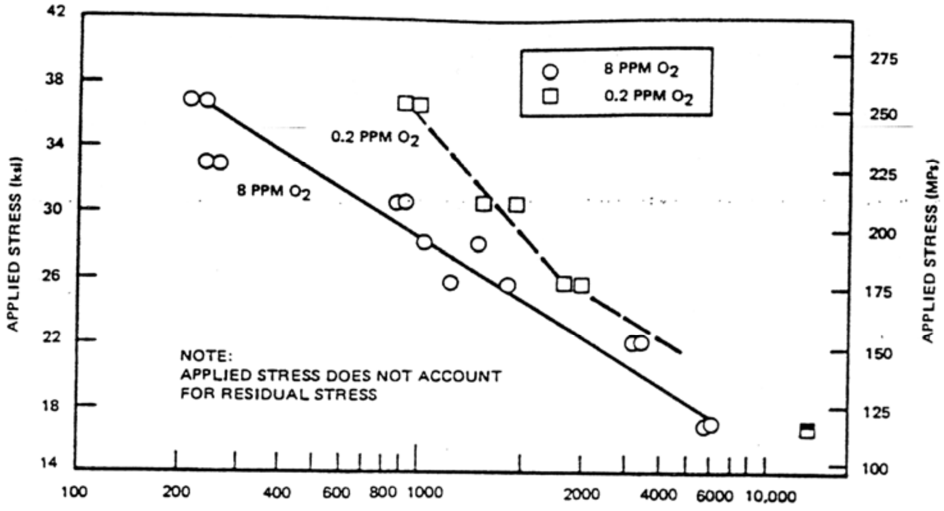
- Repair, substitute or leave when critical security conditions are reached.

CORROSION BEHAVIOUR

STRESS CORROSION

Example: Intergranular corrosion on stainless steels.

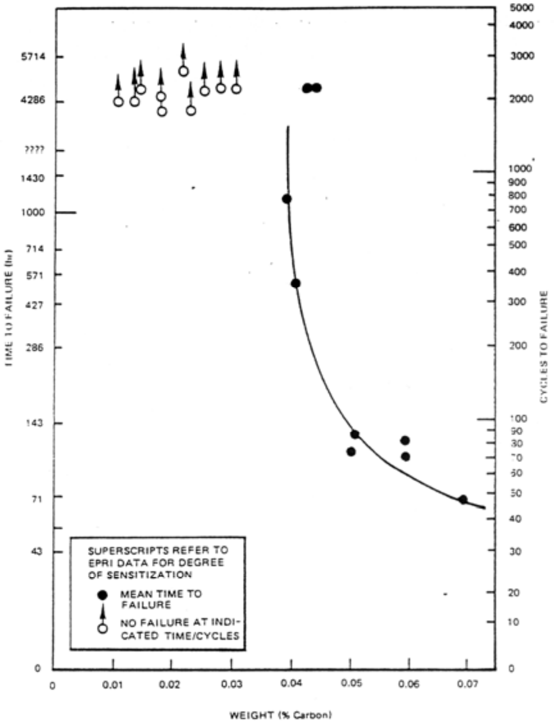
- Conditions:
  - Stress state greater than the threshold
  - Aggressive environment [dissolved oxygen]
  - Sensitized material



CORROSION BEHAVIOUR

STRESS CORROSION

Example: Intergranular corrosion on stainless steels.



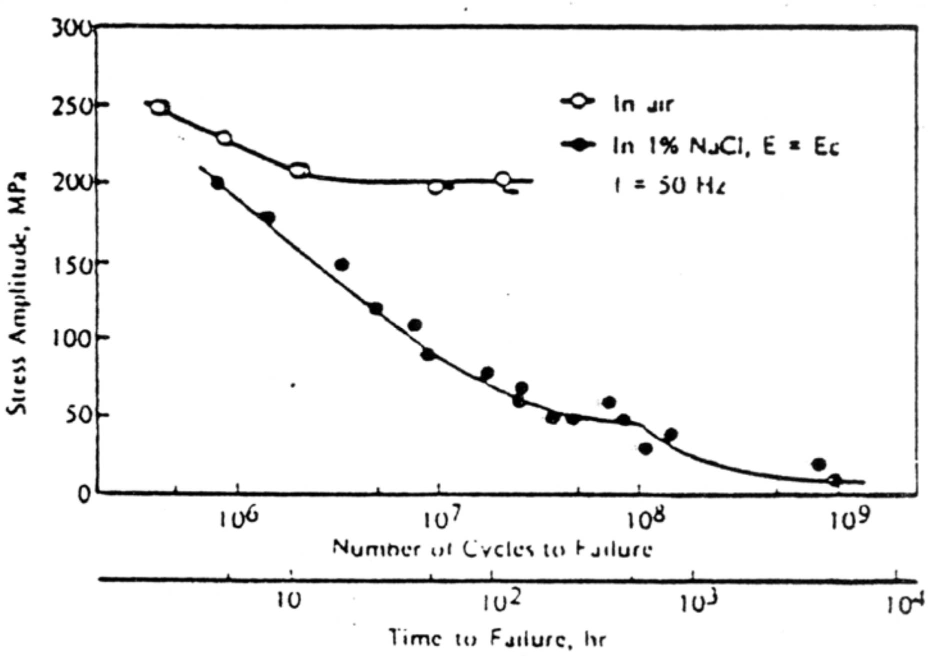
- Solution:
  - Reduction of aggresive element concentration (↓O_2)
  - Adequate material election
  - Not susceptible to be sensitized

% C ↓ to avoid chromium carbides formation at sensitive temperatures and then the IG loss of chromium

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

CORROSION - FATIGUE



Fatigue conditions

+

Aggressive environment

produce corrosion fatigue

CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

CORROSION-FATIGUE

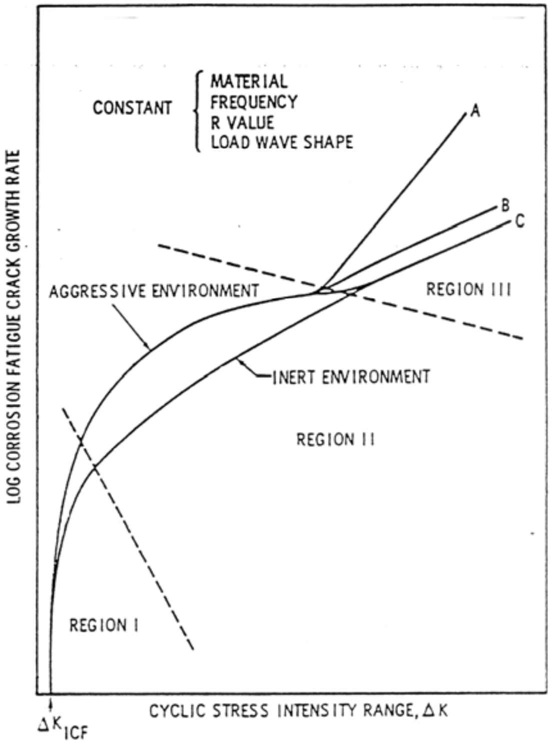
Similar behaviour than fatigue at inert environment

Threshold: ΔK_{ICF}

and crack propagation rate: $\frac{da}{dN} = f(\Delta K_I)$

The behaviour depends on:

→ Material (microstructure)
→ Stress condition (local)
→ Environment presence
+
Loading frequency
...

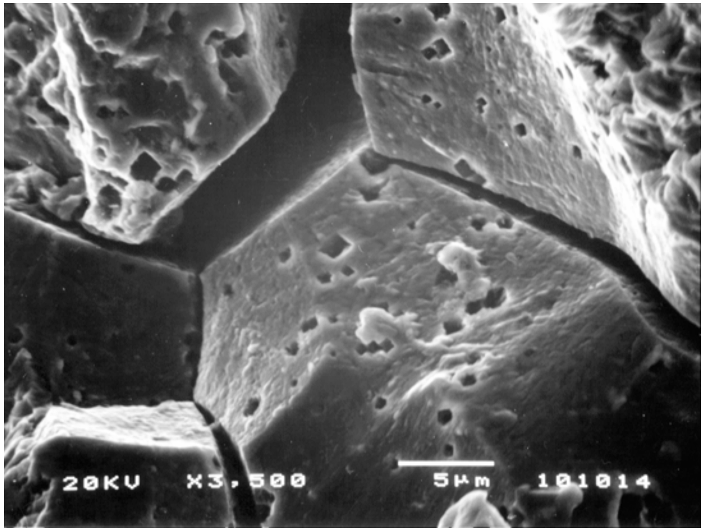


CORROSION BEHAVIOUR

ENVIRONMENTAL ASSISTED CRACKING

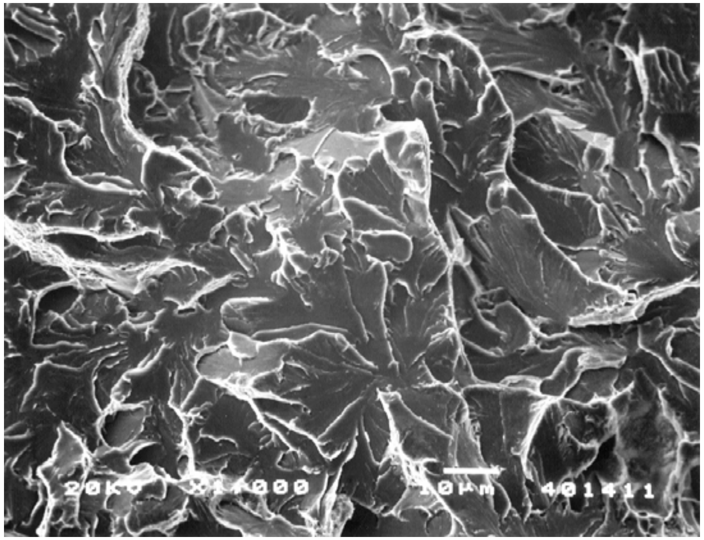
Mechanisms on metallic materials

SCC (metals) Crack advances generally by local fractures



Intergranular (IG)

or



Cleavages or tearing

Transgranular (TG)

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B. INTRODUCTION TO EAC ASSESSMENT PROCEDURES

Flaw in EAC should be treated with extreme caution. The following aspects should be considered:

1. If a material remains in aggressive environment in service, the cracks may growth by what is know subcritical crack growth if the applied K is above the threshold K_{TH}, the flaw will growth until the applied K exceed a value for the K_R curve, at which time unstable fracture will occur.

2. Long exposure to hydrogen or other damaging environment may produce irreversible damage in the material. The apparent toughness could fall below the K_R curve in such cases.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF CORROSION FATIGUE

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

SCC assessment: σ and K based approaches

The growth law should be derived to fit the relevant data but often take the form:

$$da/dt = f(K_I) \qquad \text{if } K_I \geq K_{ISCC}$$

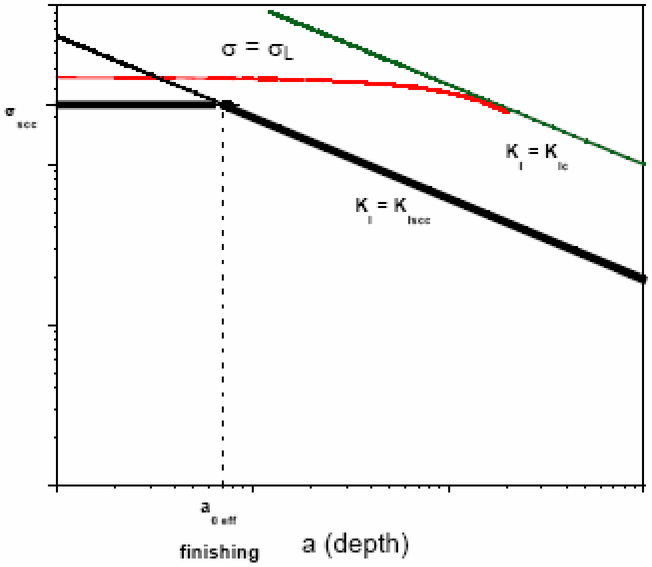
Contrarily, no crack propagation occurs if $K_I < K_{ISCC}$

The existence of a “maximum” effective initial defect (a_{0eff}) due to the surface finishing of the material or the design or fabrication conditions of the component, is associated to the existence of some threshold conditions σ_{scc} to avoid crack propagation due to SCC, related with the material and the geometrical conditions including surface finishing or maximum defect.

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

SCC assessment: σ and K based approaches (cont.)

The figure shows in a stress-crack depth (a) plot that the condition of σ_{scc} as a threshold stress could be linked to and effective crack like a_{0eff} value, from where a K_I approach can be done. Once the crack starts to grow (increasing *a* value), the local conditions in the material defining the threshold justify that lower stress values than σ_{scc} produce crack propagation. Therefore, the limit to define non growing conditions for existing cracks of any size a, is the K_I=K_{ISCC} line. For higher σ values than those defined by this line, cracks will grow until fracture (K_I=K_{IC}) or plastic collapse occur.



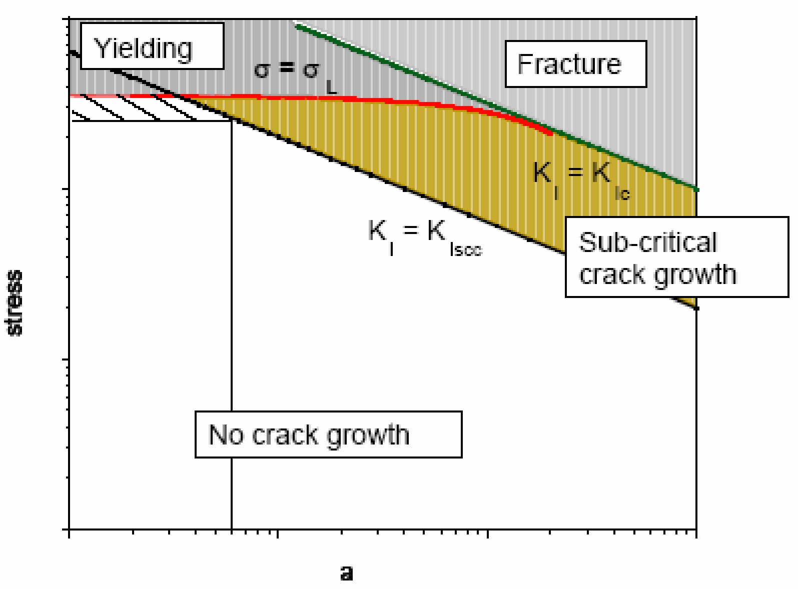
ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

SCC assessment: σ and K based approaches (cont.)

The following Figure shows in the same plot the different regimes related to the stress corrosion cracking in a particular component:

•No crack growth area under the threshold line (K_I-K_{ISCC});

•The sub-critical crack growth area over the threshold line, limited by the fracture region defined by the K_I=K_{IC} line and the plastic collapse one defined by the $\sigma = \sigma_{LL}$ line.



ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

SCC assessment: σ and K based approaches (cont.)

The two previous plots depend on the geometry of the component and the geometry and position of the defects. Therefore, it would be better to define an universal graphic assessment (valid for any component).

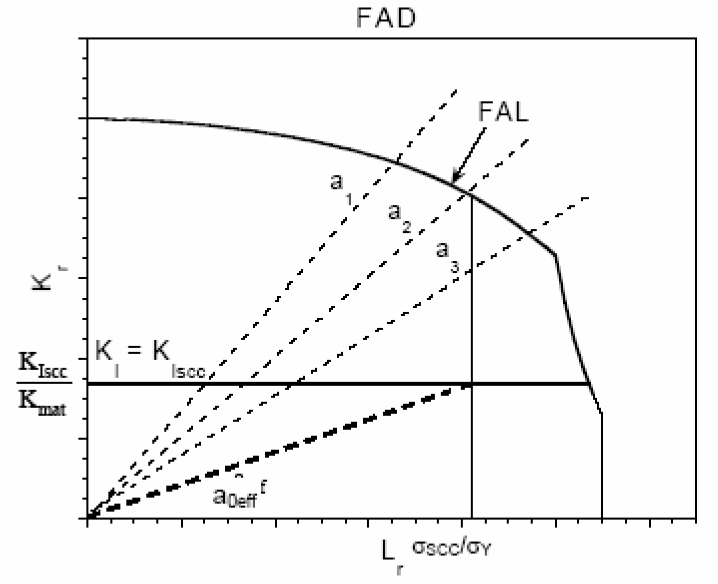
In such a case a K_I based analysis, instead of a σ based one, should be considered. Therefore, the same areas and conditions with regarding to cracking can be represented in a FAD, K_r-L_r plot.

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

SCC assessment: σ and K based approaches (cont.)

In the Figure, it can be observed that K_I-K_{ISCC} is a horizontal line. Above that line cracks will propagate due to environmental assisted cracking independently of the component geometry and crack conditions.

Each particular case, identified by its a_{0eff} defect condition and the corresponding σ_{scc} value is also plotted, but this value is only relevant for it, not for other component.



BIBLIOGRAPHY / REFERENCES

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- API Recommended Practice 579, Fitness-for-Service, API Publishing Services, First edition, January 2000

C. PROCEDURE APPLICATION (FITNET)

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

- **INTRODUCTION**
- **ASSESSMENT OF SCC**
- **ASSESSMENT OF CORROSION FATIGUE**
- **STRESS CORROSION AND CORROSION FATIGUE ANALYSIS**
- **ASSESSMENT OF LOCAL THINNED AREAS**

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

INTRODUCTION

The FITNET FSS Procedure provides guidelines on the appropriate steps to take when a stress corrosion or a corrosion fatigue crack as well as local thin area (LTA) has been detected in service and an assessment has to be one of the implications for structural integrity. Such an evaluation should be made in the context of the perceived consequences of failure using appropriate risk-based management methodologies. Since this is plant/component specific it is beyond the scope of this procedure.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

INTRODUCTION

Hence, this section deals primarily with the Fitness-for-Service assessments of damage types due to ;

a) Environmental assisted cracking (EAC)

- a1) Stress corrosion cracking,
- a2) Corrosion fatigue and

b) Local Thinned Area (LTA)

in metallic components with or without welds.

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ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

Introduction

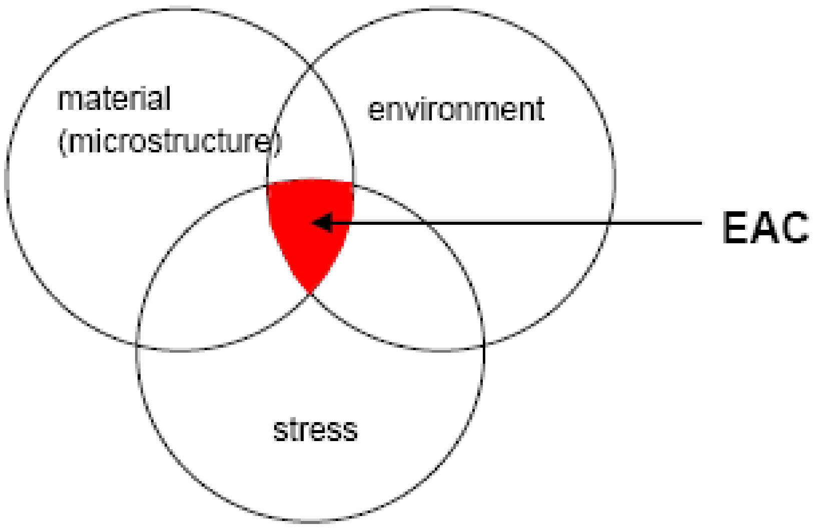
When assessing the integrity of structures with cracks or crack-like defects, it is necessary to consider whether sub-critical crack growth is a potential factor. If so, an estimate of the amount of tolerable growth during the design lifetime or between in-service inspections is required.

Therefore, structural integrity evaluations have to take into account the peculiarities of the damage processes when Environmental Assisted Cracking (EAC) is likely to occur. The basic tool for the characterization of EAC processes is the Fracture Mechanics, which has to be used with different criteria depending on the problem being assessed.

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

Introduction (cont.)

Three conditions are necessary in order EAC to occur, either at global or local level, as shown in the Figure: a susceptible material associated to the presence of an aggressive environment and loading conditions over a characteristic threshold level.



ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

Introduction (cont.)

In this section, subcritical crack growth due to stress corrosion cracking and corrosion fatigue (both of them EAC processes) is considered, with crack growth rate prediction in service based principally on the application of fracture mechanics in terms of either stress intensity factor (K) in the case of stress corrosion cracking, or the range of stress intensity factor (ΔK), in corrosion fatigue.

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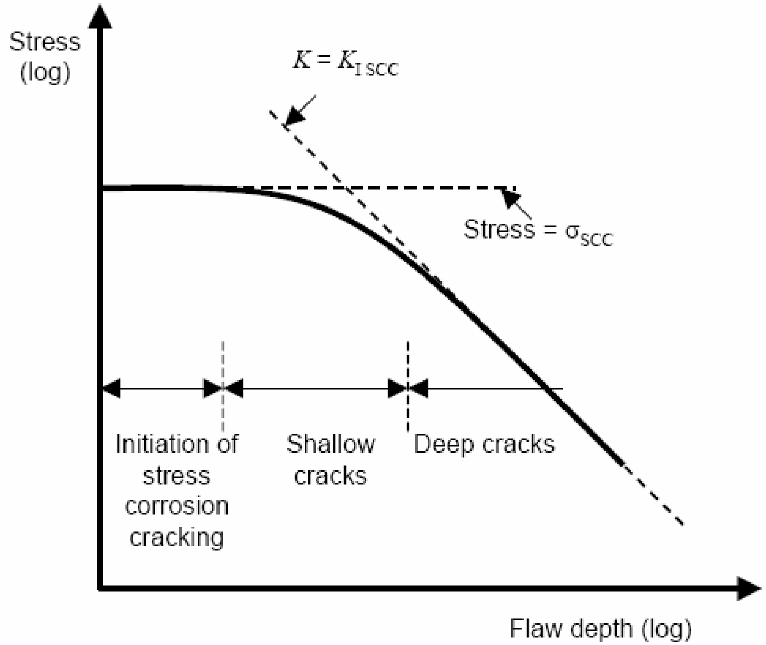
ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

Introduction (cont.)

Underlying that assumption is the presumption that the flaws or cracks are of a dimension that allows a description of the mechanical driving force by linear elastic fracture mechanics. In practice, for some systems, a significant amount of life may occur in the short crack regime. The figure illustrates the transition in mechanical driving force with flaw size for a stress corrosion crack; similar behaviour is observed for corrosion fatigue cracks.



Schematic diagram of the two parameter approach to stress corrosion cracking

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ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

Introduction (cont.)

Different uncertainties (loads, environment,…), allied to expert judgment, feed into the risk assessment when adopting a risk-based inspection methodology. In FITNET, a procedural approach to evaluating the evolution of damage due to environment assisted cracking is presented that includes:

- STEP 1- Characterise the nature of the crack
- STEP 2- Establish cause of cracking
- STEP 3- Define the material characteristics
- STEP 4- Establish data for stress-corrosion cracking assessment
- STEP 5- Undertake structural integrity assessment

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EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 1- Characterise the nature of the crack

Once a crack has been detected, a first step is to develop a complete physical evaluation in terms of its shape and dimensions, with any uncertainty in size from the particular detection method taken into account. This evaluation should include an assessment of the crack location in relation to local stress concentrators, welds, crevices (e.g. at fasteners, flanges), and also the details of the crack path and crack orientation, if feasible. If more than one crack is present, the crack density and the spacing between the cracks should be noted in view of possible future coalescence.

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 2- Establish cause of cracking

Identifying the cause of cracking in terms of the mechanistic process, i.e. stress corrosion or corrosion fatigue, may be challenging unless service conditions allow ready discrimination; for example, an absence of significant cyclic loading. Characterising the crack as a stress corrosion crack may be possible from visible observation, e.g. significant crack branching (although such branching would preclude simple stress analysis and warrant removal of the crack).

Where cyclic loading is apparent, corrosion fatigue should be considered to be the primary mechanism of crack growth. However, the loading frequency is a key factor with the influence of the environment on crack propagation decreasing in significance as the frequency increases and for many systems often being insignificant at frequencies greater than about 10 Hz.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 2- Establish cause of cracking (cont.)

The service conditions that need to be defined include the stress state and the environmental conditions:

- Stresses (see 9.1.2.2.1.1)
- Service environment (see 9.1.2.2.1.2)
  - Development of local environments (crevicing, hideout/evaporation, deposits) (see 9.1.2.2.1.2.1)
  - Excursions (see 9.1.2.2.1.2.2)
  - Corrosion (or system) monitoring (see 9.1.2.2.1.2.3)

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EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 3- Define the material characteristics

The first step is to ensure that the material of relevance actually corresponds to that specified at the design stage. In essence, this relates primarily to the quality control aspects of fabrication and installation and means assessing the traceability of the materials selection and welding process relative to the design specification. In some cases, in-situ measurement such as hardness may be undertaken. There are a number of factors that may subsequently affect the performance of the material.

For further information see Section 9.1.2.3 of the Procedure and the Basic Concepts on Environmental Effects provided on this Training Package.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for stress-corrosion cracking assessment: K_{ISCC} determination

The concept of K_{ISCC} is not trivial and the value is sensitive to the environmental conditions, temperature and loading characteristics. Accordingly, data obtained for one condition should not be transposed to another.

Initiation and growth can occur in the domain for which linear elastic fracture mechanics is inapplicable. The growth rate in the short crack domain and its relation to the relevant mechanical driving force is poorly characterised in stress corrosion cracking and needs further research.

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EUROPEAN FITNESS FOR SERVICE NETWORK

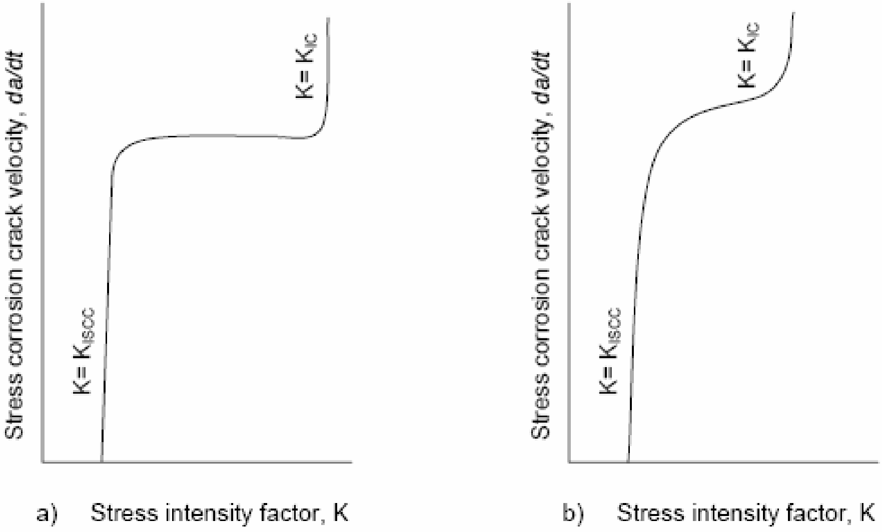
ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for stress-corrosion cracking assessment: K_{ISCC} determination

When the crack is of a length commensurate with the application of fracture mechanics, a threshold stress intensity factor for stress corrosion crack propagation, K_{ISCC}, is often defined. For long cracks, the behaviour is typically as represented in the Figure.

Further information is provided in Section 9.1.2.4.1



ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for stress-corrosion cracking assessment: Stress corrosion crack growth determination

The crack velocity during stress corrosion testing of pre-cracked fracture mechanics specimens can be measured using the procedures given in ISO 7539-6 and the crack monitoring methods given in BS7910. It is most relevant to obtain crack growth rate for the conditions of practical relevance and to fit the data with a growth law appropriate to the data. For example:

$$\frac{da}{dt} = C\left(K_I\right)^n \qquad K_{ISCC} \leq K \leq K_C$$

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EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for corrosion-fatigue assessment: ΔK_{th} determination

The threshold value of the stress intensity factor range (ΔK_{th}) in corrosion fatigue is influenced by crack size and by the stress ratio. FITNET provides reference for guidance on determination of ΔK_{th}.

In the short crack regime, where LEFM becomes invalid, cracks can grow at ΔK values seemingly below ΔK_{th}, because the latter is commonly determined from long crack measurement.

FITNET

EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for corrosion-fatigue assessment: ΔK_{th} determination (cont.)

Also, in the long crack regime, increasing the stress ratio, $R=\sigma_{min}/\sigma_{max}$, will usually reduce the threshold value because of diminished impact of crack closure. For that reason a high R value for the threshold is a sensible conservative assumption.

In the same context as stress corrosion cracking, it is important to simulate sensibly the service conditions in terms of the environment and loading conditions, particularly, frequency and waveform.

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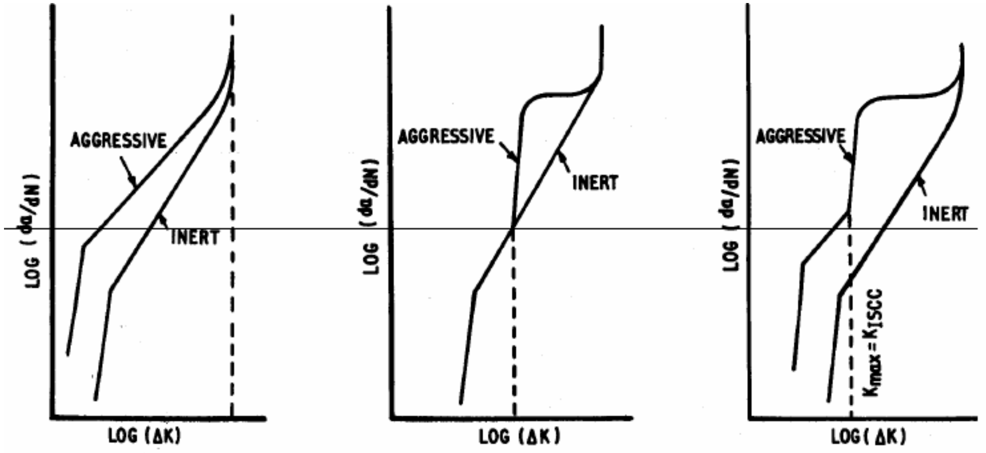
EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF EAC

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Establish data for corrosion-fatigue assessment: Crack growth determination

The form of the crack growth rate curves cannot be generalised as they are system specific. Some schematic examples for constant amplitude loading are shown in the Figure.



Basic types of corrosion-fatigue crack growth behaviour.

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 4- Corrosion fatigue crack growth data

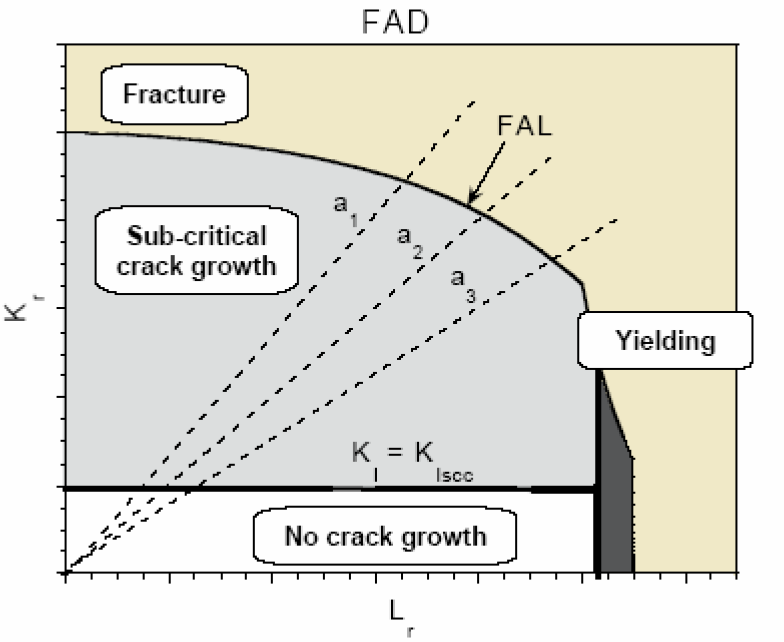
The procedure provides recommended fatigue crack growth laws for steels in marine environment, as well as recommended fatigue crack growth thresholds for assessing welded joints (see 9.1.2.4.3.3)

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 5: Undertake structural integrity assessment

This Figure shows the cracking related areas in the universal FAD plot.

The global FAD representation could be used to define areas related to different cracking micro-mechanisms (IG, TG by cleavage or tearing…) if the constitutive equation to differentiate them is known.



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ASSESSMENT OF CORROSION FATIGUE

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 5: Undertake structural integrity assessment

STEP 5a- Perform a fracture assessment for the initial crack size, based on the measured detected value or upon a maximum value reflecting the uncertainty in detection.

STEP 5b- If effective remedial measures are not possible and/or slow subcritical crack growth can be tolerated, then apply sections 9.1.2.1 9.1.2.3 to fully characterise the nature of the crack and the service conditions driving it.

STEP 5c- Compute the stress at the flaw, including any dynamic components, based on anticipated future operating conditions.

STEP 5d- Determine the evolution of the crack size based on the previous flaw size, or value and crack growth laws.

STEP 5e- Determine the time or number of stress cycles for the current crack size (a_0, c_0) to reach the limiting flaw size in relation to the FAD or LBB criteria.

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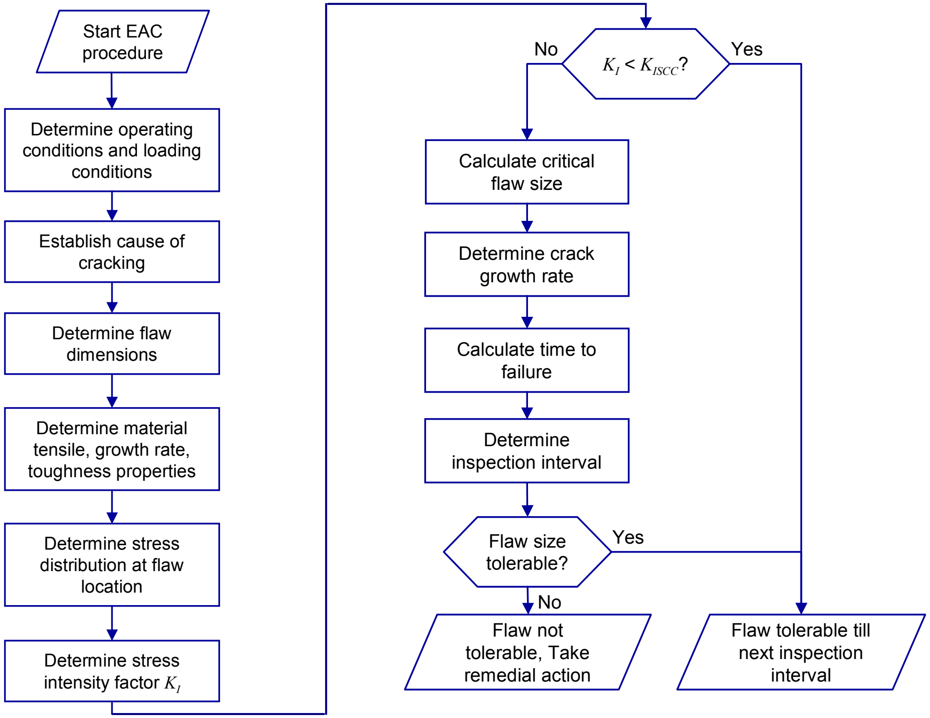
EUROPEAN FITNESS FOR SERVICE NETWORK

ASSESSMENT OF CORROSION FATIGUE

ASSESSMENT OF ENVIRONMENTAL ASSISTED CRACKING

STEP 5: Undertake structural integrity assessment

The methodology is summarised in the following flowchart:



Start EAC procedure

Determine operating conditions and loading conditions

Establish cause of cracking

Determine flaw dimensions

Determine material tensile, growth rate, toughness properties

Determine stress distribution at flaw location

Determine stress intensity factor K_I

$K_I < K_{ISCC}$?

No

Calculate critical flaw size

Determine crack growth rate

Calculate time to failure

Determine inspection interval

Flaw size tolerable?

No

Flaw not tolerable, Take remedial action

Yes

Flaw tolerable till next inspection interval

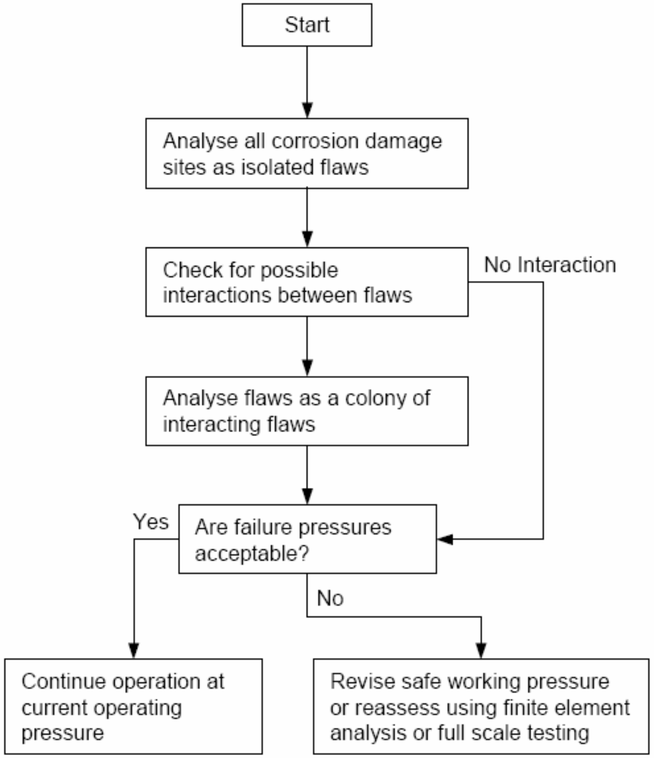
For further information see Section 9.1.2.5 in the Procedure.

ASSESSMENT OF LOCAL THINNED AREAS (LTA)

The methods specified in FITNET FFS procedure may be used to assess Local Thinned Area (LTA) flaws in pipes and pressure vessels that have been designed to a recognized design code.

The guidance does not cover every situation that requires a fitness for purpose assessment and further methods may be required.

A flowchart of the procedure is shown in the figure:



ASSESSMENT OF LOCAL THINNED AREAS (LTA)

The steps, as defined by the procedure, are the following:

STEP 1- Establish cause of wall thinning (corrosion, erosion, grinding damage…)

STEP 2- Define service condition

STEP 3- Collect material properties

STEP 4- Analysis

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ASSESSMENT OF LOCAL THINNED AREAS

ASSESSMENT OF LOCAL THINNED AREAS (LTA)

The procedure defines the type of defects to which the procedure can be applied and provides formulation for the assessment of specific geometries and loading conditions:

- Cylindrical body (Section 9.2.5.3)
- Sphere and vessel end (Section 9.2.5.4)
- Elbow (Section 9.2.5.5)
- Nozzles (Section 9.2.5.6)

The procedure provides guidance on the rules in order to take into account the interaction among adjacent LTA flaws (Section 9.2.5.7)

D. EXAMPLES

WORKED EXAMPLE I

Cracked ship hull

- **Introduction and objectives**
- **Data**
- **Analysis**

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INTRODUCTION AND OBJECTIVES

During a visual inspection of a ship hull, semi-elliptical surface cracks of 5 mm depth were observed. The working conditions cause a tensile state characterised by a stress of 110 MPa when the ship is unloaded and 350 MPa when the ship is loaded.

Knowing that in the marine environment, crack propagation can be provoked by stress corrosion cracking, and that in this steel this process takes place at a crack growth rate of $1.2.10^{-7}$ mm/s when the threshold of 20 $MPa.m^{-1/2}$ is passed:

a) Represent in a FAD the state of the security conditions as a function of time. The ship is under unloaded condition for 3 months and under loaded condition for 7 months.

b) Evaluate whether the critical conditions in the hull are produced by leak before break or brittle fracture in a plate of 20 mm in thickness.

c) Determine the total life of the component.

Hypotesis:

The cracks grow maintaining a constant relationship a/2c of 0.3 // General yielding is not considered

DATA

Material properties:

$\sigma_Y = 450$ MPa

$K_{IC} = 120$ MPa·m$^{1/2}$ $K_{Iscc} = 20$ MPa·m$^{1/2}$

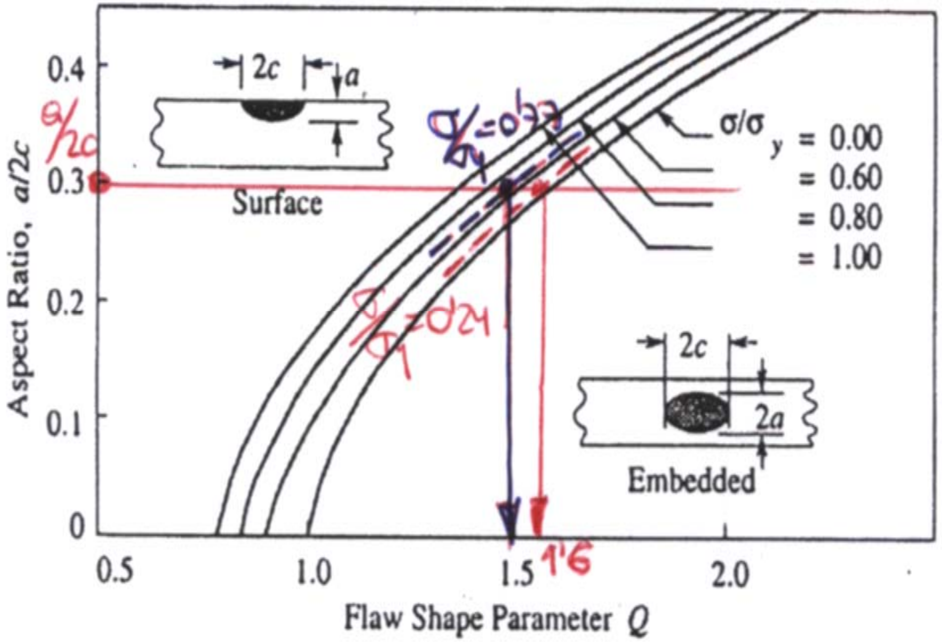
SCC conditions:

$da/dt = 1.2 \cdot 10^{-7}$ mm/s

$K_{ISCC} = 20$ MPa·m$^{1/2}$

ANALYSIS

$$K_I = \sqrt{\frac{1.21}{Q}} \cdot \sigma \sqrt{\pi a}$$



Unloaded ship: $\sigma = 110$ MPa $\quad \frac{\sigma}{\sigma_y} = 0.24 \quad$ in figure 1, Q = 1.6

Loaded ship: $\sigma = 350$ MPa $\quad \frac{\sigma}{\sigma_y} = 0.77 \quad$ in figure 1, Q = 1.5

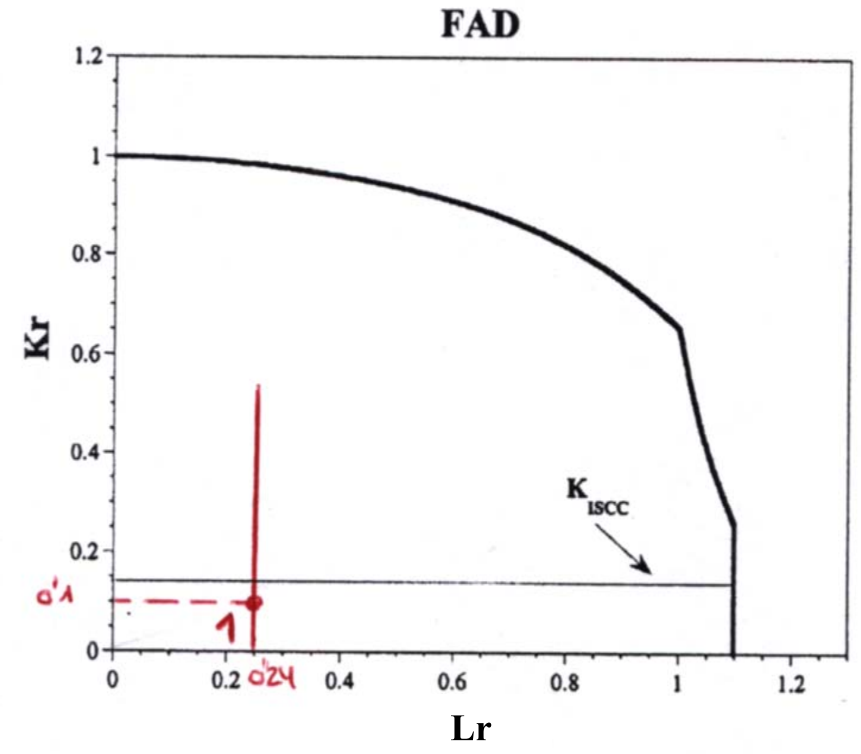
a) ANALYSIS

0 - 3 months:

$$K_I = \sqrt{\frac{1,21}{1,6}}.110.\sqrt{\pi.0,005} = 11.53\ MPa.m^{1/2} < K_{Iscc}$$

$$\left.\begin{array}{l} K_r = 0.1 \\ L_r = 0.24 \end{array}\right\}$$ **No Propagation**

(1)



ANALYSIS

3 – 10 months:

$$K_I = \sqrt{\frac{1.21}{1.5}} \cdot 350 \cdot \sqrt{\pi \cdot 0.005} = 37.90 \ \mathrm{MPa} \cdot \mathrm{m}^{1/2}$$

3 months

$$\left.\begin{array}{l} K_r = 0.31 \\ S_r = 0.77 \end{array}\right\} \ \textbf{Propagation}$$

$$\Delta a = \overset{o}{a}.t = 1.2 \cdot 10^{\ 7} \cdot 7 \cdot 30 \cdot 24 \cdot 3600 = 2.17 \ \mathrm{mm} \qquad a_f = 7.17 \ \mathrm{mm} \qquad K_{If} = 47.1 \ \mathrm{MPa.m}^{1/2}$$

10 months
(2)

$$\left.\begin{array}{l} K_r = 0.39 \\ L_r = 0.77 \end{array}\right\}$$

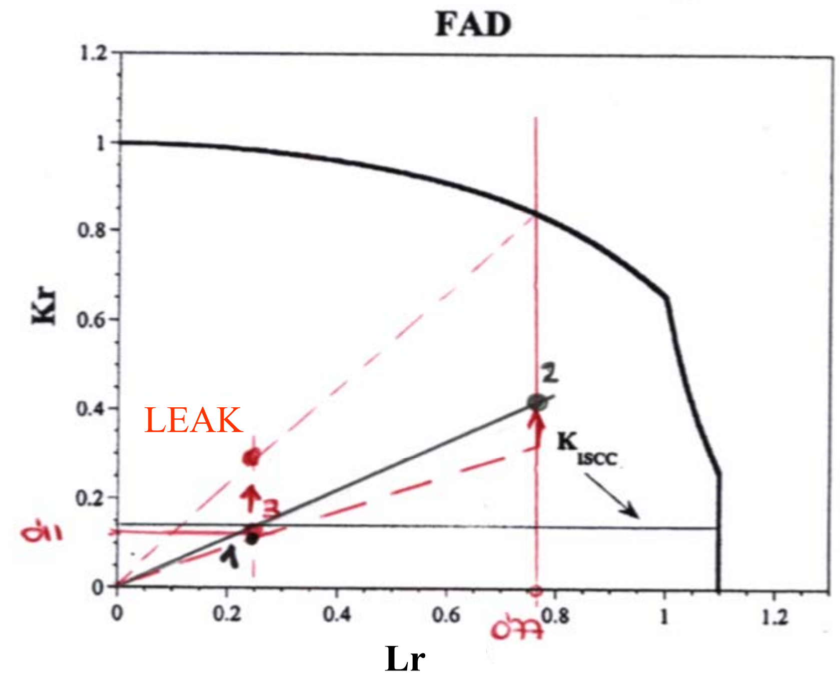
ANALYSIS

10 - 13 months: $K_I = \sqrt{\frac{1,21}{1,6}}.110.\sqrt{\pi.0,00717} = 14,30\ \text{MPa.m}^{1/2} < K_{Issc}$

$$\left.\begin{array}{l} K_r = 0.119 \\ L_r = 0.24 \end{array}\right\}$$

No Propagation

(3)



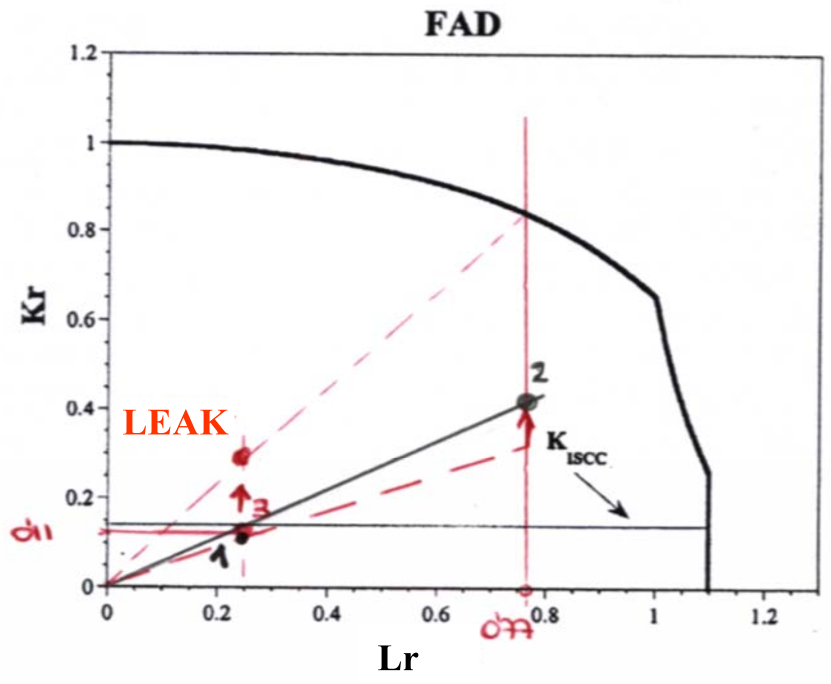
ANALYSIS

In order to have propagation while the ship is unloaded, a minimum a_{ul} is needed:

$$K_I = \sqrt{\frac{1,21}{1,6}}.110.\sqrt{\pi.a_{ul}} = 20\ \text{MPa.m}^{1/2}$$

$$a_{ul} = 13\ \text{mm}$$

Then, for $a<a_{ul}$ crack propagation is only produced during loading periods



ANALYSIS

13 - 20 months:

$a_f = 7.17 + 2.17 = 9.34$ mm

(4)

23 – 30 months:

$a_f = 9.34 + 2.17 = 11.51$ mm

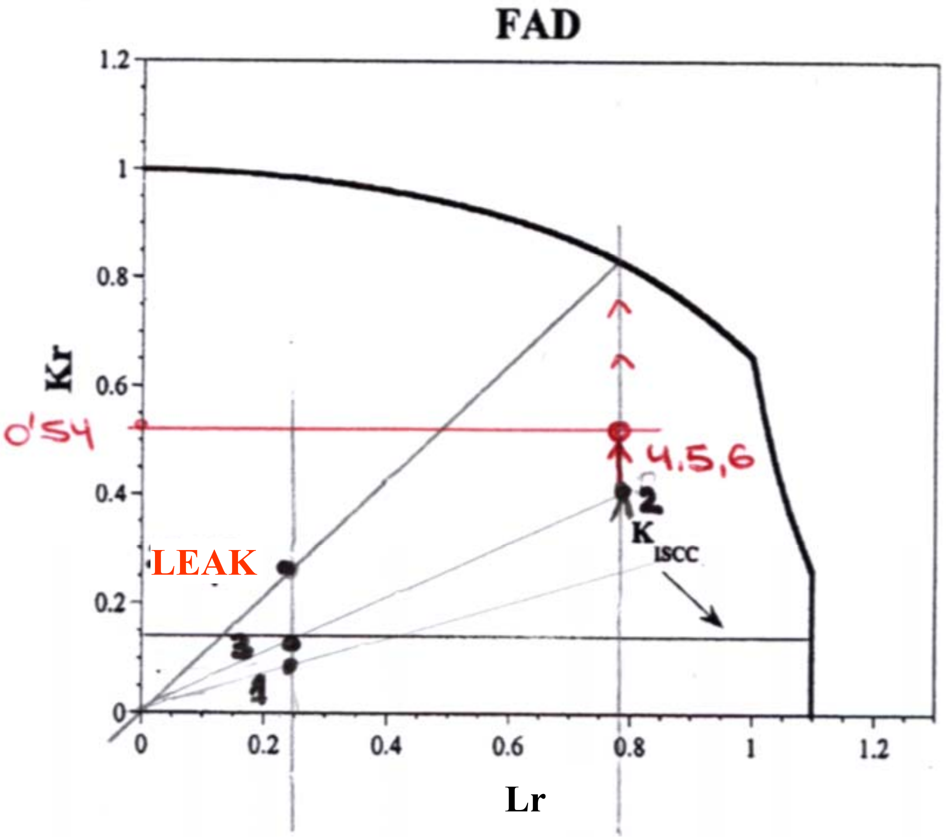
(5)

33 – 40 moths:

$a_f = 11.51 + 2.17 = 13.68$ mm

$$K_I = 65.15 \text{ MPa}\cdot\text{m}^{1/2}$$

$$\left.\begin{aligned} K_r &= 0.54 \\ S_r &= 0.77 \end{aligned}\right\} \quad \textbf{(6)}$$



From this moment, both loaded and unloaded conditions promote crack propagation cracking at the same time.

ANALYSIS

b)

The FAL is reached when: $K_r = 0.85$; then, $K_I = 0.85 \cdot 120 = 102\ \mathrm{MPa \cdot m^{1/2}}$

$$102 = \sqrt{\frac{1.21}{1.5}} \cdot 350 \cdot \sqrt{\pi \cdot a_c} \Rightarrow a_c = 0.034\ \mathrm{m} = 3.4\ \mathrm{mm} > 20\ \mathrm{mm}\ \text{(thickness)}$$

then leak before break will happen

Leak $a_{leak} = 20$ mm

In theory, after leak, another propagation occurs until critical length is reached

$$K_I = \sigma \cdot \sqrt{\pi \cdot c} = 350 \cdot \sqrt{\pi \cdot c_c} = 0.85 \cdot K_{IC} = 102 \Rightarrow c_c = 0.027\ \mathrm{m} = 27\ \mathrm{mm}$$

But for a_{leak}=20 mm, c = 33.3 mm, which is bigger than 27 mm. Therefore, once leak happens, the component fails.

ANALYSIS

c)

Knowing that Δa is 2.17 mm with the ship loaded and 0,93 mm with the ship unloaded:

Unloaded ship: 40-43 → $a_f = 14{,}61$ mm

Loaded ship: 43-50 → $a_f = 16{,}78$ mm

Unloaded ship: 50-53 → $a_f = 17{,}71$ mm

Loaded ship: 53-60 → $a_f = 19{,}88$ mm

Unloaded ship: 60-63 → $a_f = 20{,}81$ mm ⇒ LEAK AND FAILURE

WORKED EXAMPLE II

Plate under neutronic irradiation

- **Introduction**
- **Objectives**
- **Analysis**

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INTRODUCTION

This case is an example of how the environment can change the mechanical properties of the material.

A metallic plate of big dimensions has cracks of 2a = 20 mm. The working conditions causes a tensile state characterised by a stress of 50, 150, 250 or 350 MPa. Because of an irradiation process, the mechanical properties of the material change with time in this manner:

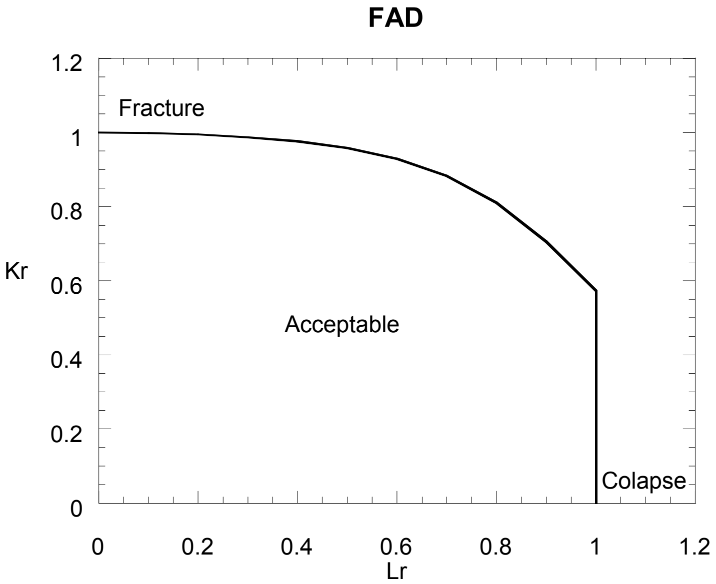
T (years)	0	5	10	15	20
σ_y (MPa)	500	510	540	565	585
K_{IC} (MPa· m$^{1/2}$)	150	135	120	100	85

OBJECTIVES

a) Represent in a FAD the state of the security conditions as a function of time (years 0, 10 and 20)

b) Which one is more critical?

c) Determine the period of time during which the safety factor is greater than 1.2.



ANALYSIS

The stress intensity factor for a big plate is:

$$K_I = \sigma\sqrt{\pi \cdot a}$$

The crack geometry is 2·a = 20 mm, so:

$$K_I = \sigma\sqrt{\pi \cdot 0.01} = 0.177 \cdot \sigma$$

Using the expresions K_r(K_r=K_I/K_{IC}) and L_r (L_r=σ/σ_Y) for the different working conditions, we can obtain for the years 0, 10 and 20:

ANALYSIS

Year 0

Working conditions	Kr	Lr
50 MPa	0.06	0.1
150 MPa	0.18	0.3
250 MPa	0.30	0.5
350 MPa	0.42	0.7

Year 10

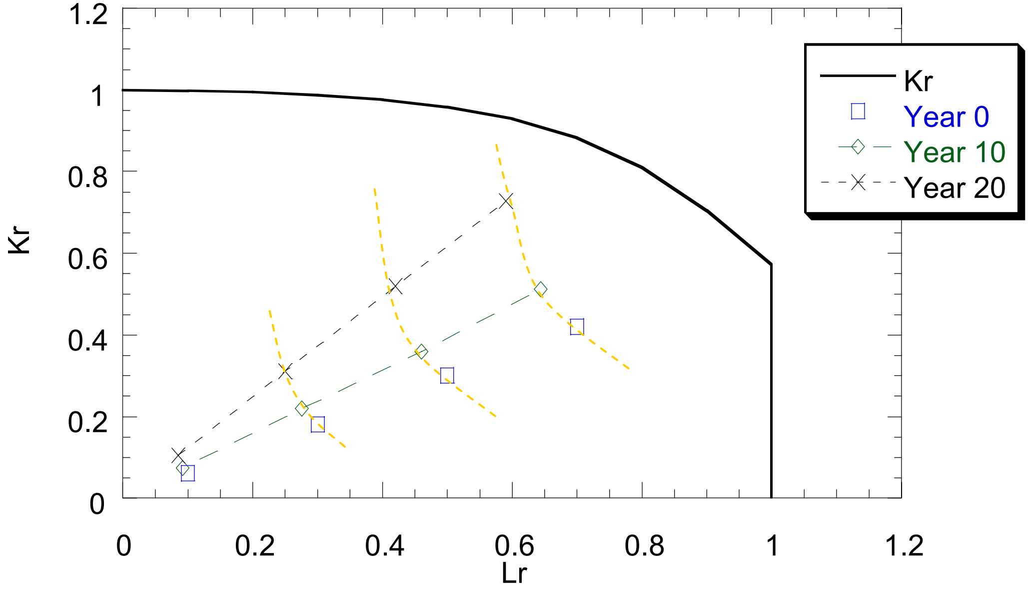
Working conditions	Kr	Lr
50 MPa	0.073	0.092
150 MPa	0.221	0.277
250 MPa	0.368	0.463
350 MPa	0.516	0.648

Year 20

Working conditions	Kr	Lr
50 MPa	0.104	0.085
150 MPa	0.312	0.25
250 MPa	0.520	0.42
350 MPa	0.728	0.59

ANALYSIS

It can be seen in the figure that the critical condition is reached in the year 20 when working conditions cause a tensile stress of 350 MPa. In this situation we have the lower safety factor.

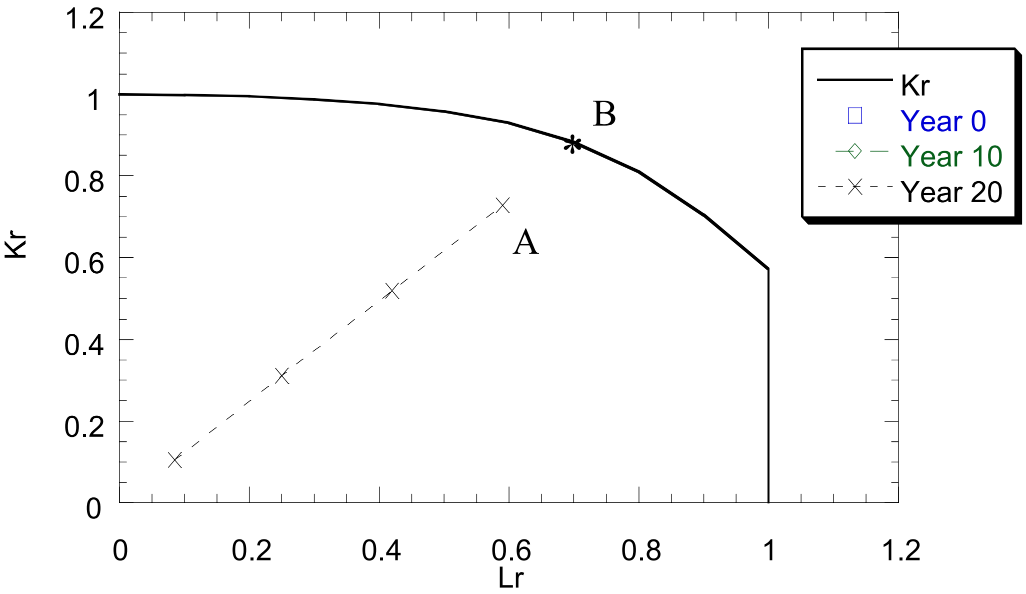


ANALYSIS

In the 20th year the safety factor can be obtained from the figure as:

$$S.F = \frac{OB}{OA} = 1.2$$

Therefore, the safety factor is greater than 1.2 during the first twenty years.



FITNET BASIC TRAINING PACKAGE

F.GUTIÉRREZ-SOLANA S.CICERO J.A.ÁLVAREZ R.LACALLE

THE END