B. INTRODUCTION TO ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

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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

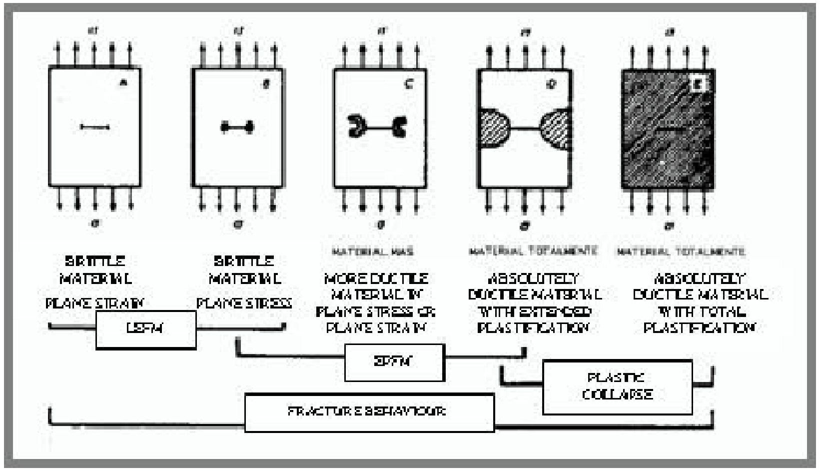
HOW ARE INTEGRITY, SECURITY OR CRITICAL CONDITIONS ANALYSED IN A CRACKED STRUCTURE?

In brittle materials or when conditions produce brittle behaviour:

LEFM

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

EPFM - PLASTICITY



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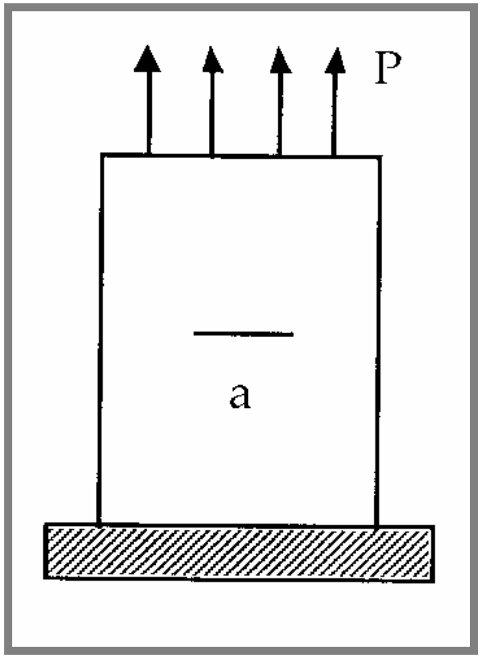
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

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

$J_R(\Delta a)$

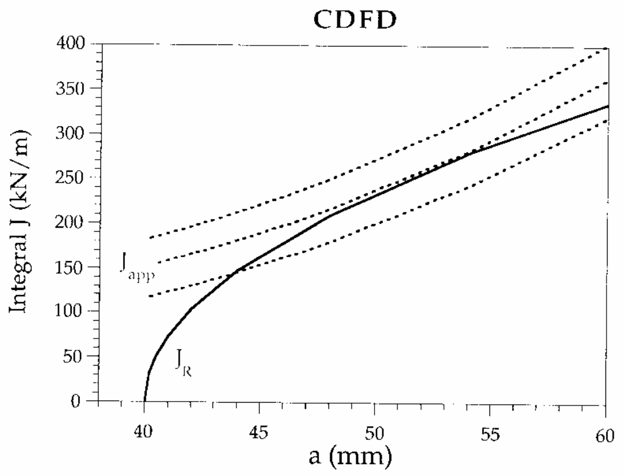
Characterises the strength of the material to cracking

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

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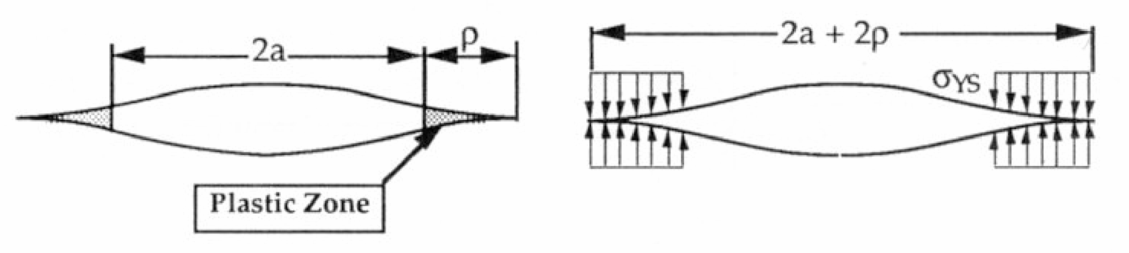
SOLUTIONS

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

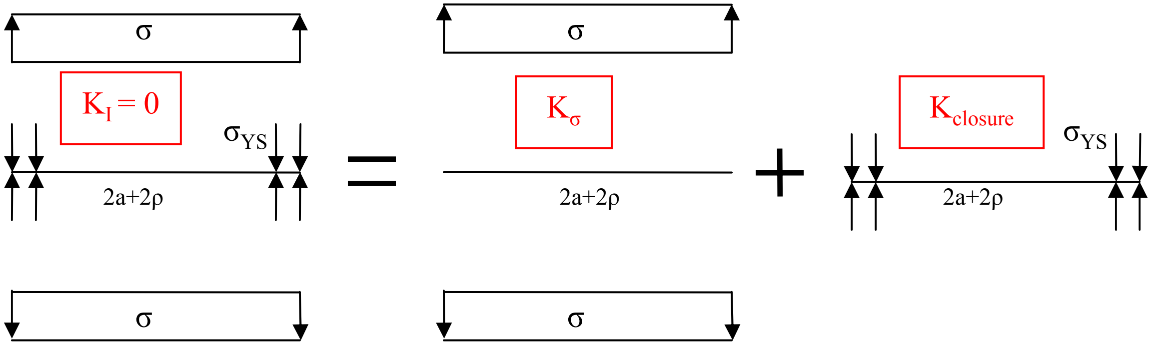
SOLUTIONS

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+ ρ 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:

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

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:**

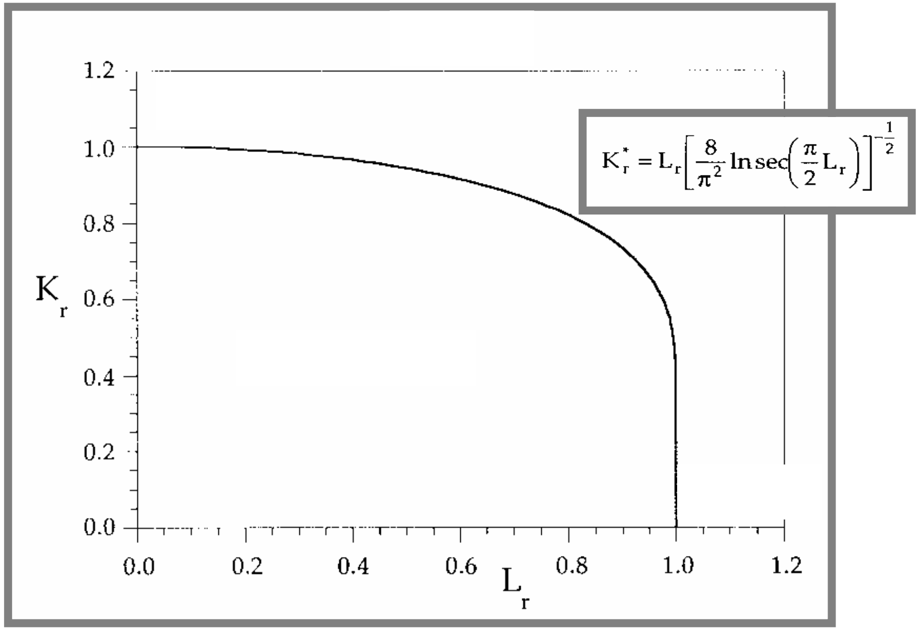
$$\boxed{K_r^* = L_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}L_r\right)\right]^{-\frac{1}{2}}}$$

- **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

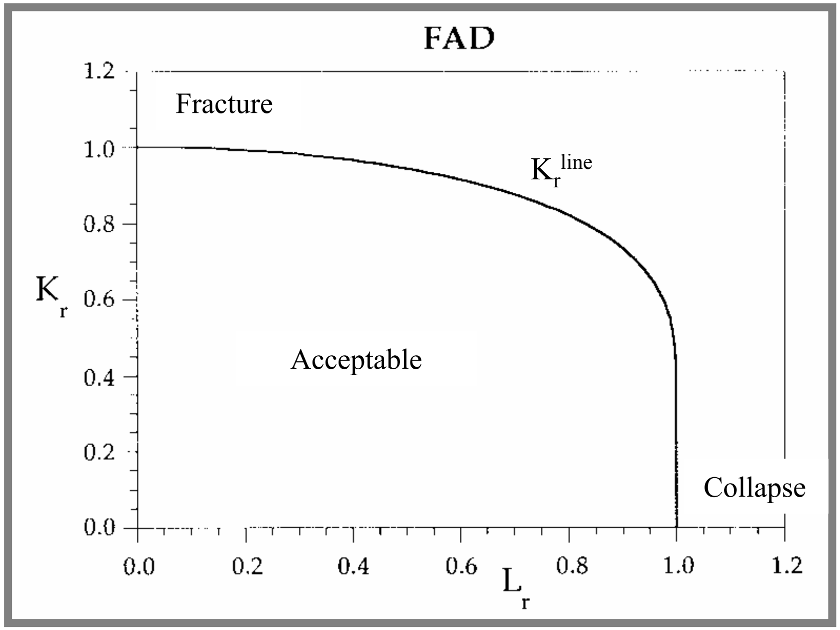
HOW CAN WE SOLVE THE GLOBAL PROBLEM: FRACTURE + PLASTIC COLLAPSE ?

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):

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



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.

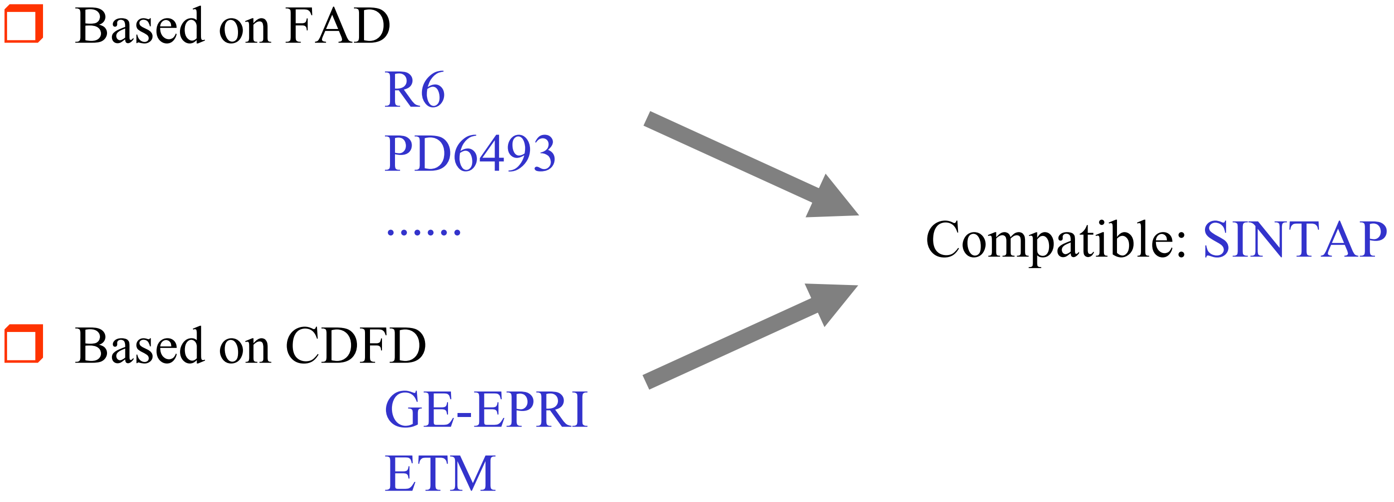
Therefore, these procedures provide considerable economic advantages because they optimise the design process and inspection and reparation conditions during the in-service period.

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

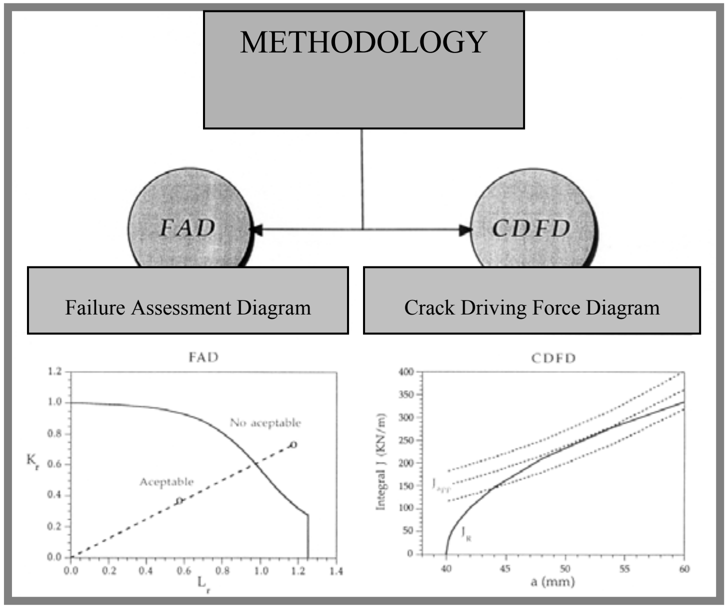
Compatible: SINTAP

ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

CLASSIFICATION ACCORDING TO THE METHODOLOGY USED

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

- **Simultaneous assessment**
  - **Fracture**
  - **Plastic collapse**
- **Diagram**
  - **It does not compare applied vs. resistant**
- **Difficulties to understand it physically**
- **Easy evaluation**



- **Independent assessment**
  - **Fracture**
  - **Plastic collapse**
- **Diagram**
  - **It compares applied vs. resistant**
- **Easy to understand it physically**
- **More complex evaluation**

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

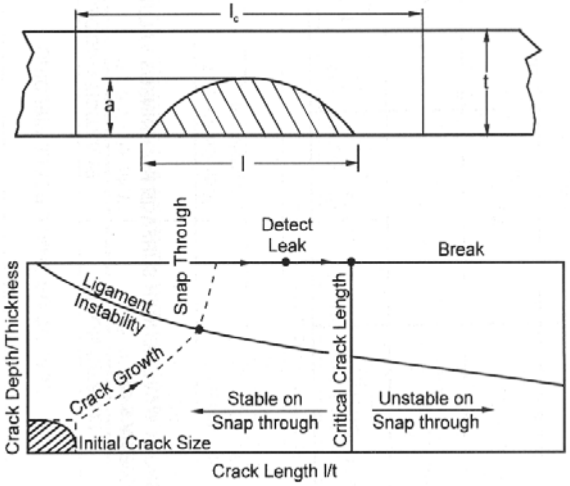
ASSESSMENT PROCEDURES FOR CRACKED COMPONENTS

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

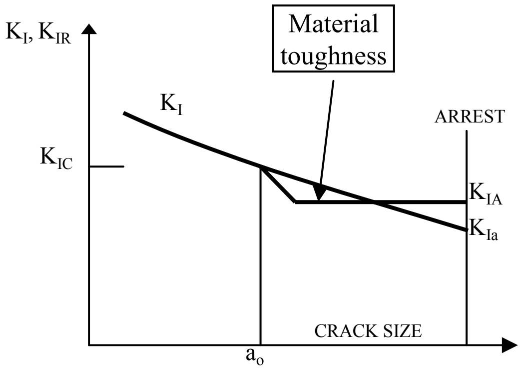
ℓ_c IS THE CRITICAL LENGTH OF A FULLY-PENETRATING THROUGH-WALL CRACK

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

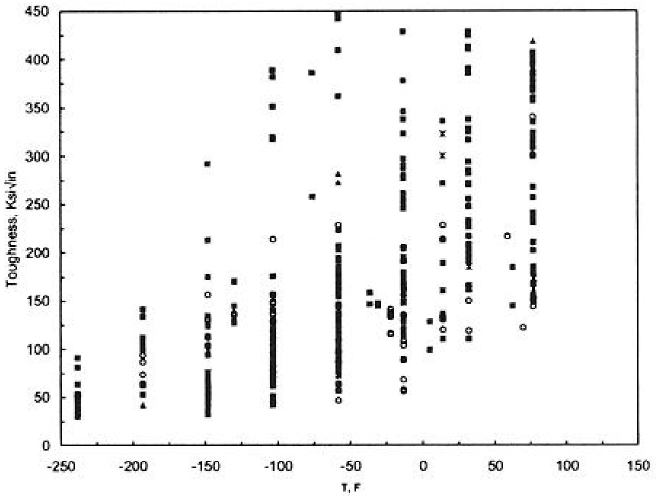
  Great scattering

  Few triggering particles

- **HIGH TEMPERATURES** → Ductile failure

  High Fracture Toughness and low scattering

  Microvoids



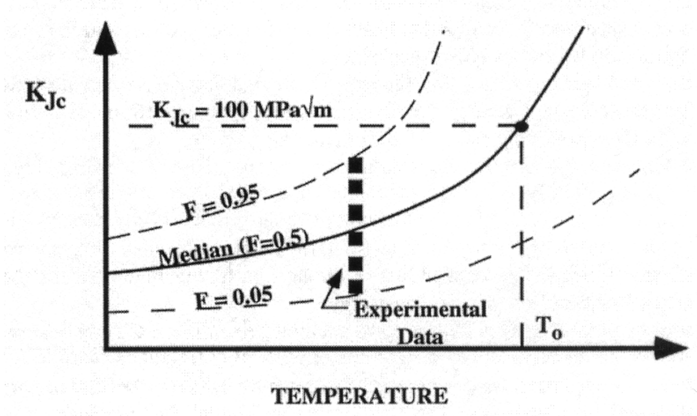
TRANSITION REGION

(ferritic steels)

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

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

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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