Structural Integrity Assessment of Offshore Wind Turbine Foundations

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Offshore Wind Webinar, 10th July 2023

Timetable

- **Introduction 10:00-10:15**
- **Fatigue crack initiation and growth in offshore structures (followed by a tutorial) 10:15-11:25**
  - A brief introduction to S-N curves, Linear Elastic Fracture Mechanics, Stress intensity factor
- **Q & A 11:25-11:30**

Tea break 11:30-11:45

- **Fracture toughness testing and analysis of materials in offshore structures (followed by a tutorial) 11:45-12:55**
  - An introduction to Elastic-Plastic Fracture Mechanics, JIC fracture toughness testing and analysis for life prediction of ductile materials
- **Q & A 12:55-13:00**

Lunch break 13:00-14:00

- **Fracture mechanics based inspection (followed by a tutorial) 14:00-15:00**
  - Paris law, Fatigue crack length estimation and inspection using the Paris law
- **Defect assessment using failure assessment diagrams (followed by a tutorial) 15:00-15:40**
  - Life prediction of cracked components and structures using level I, II and III FADs
- **Q & A 15:40-15:45**

Tea break 15:45-16:00

- **Corrosion-fatigue testing and analysis of offshore monopile weldments (followed by a case study) 16:00-16:30**
  - An introduction to corrosion-fatigue testing and analysis, Environmental Reduction Factor, Estimation of crack growth acceleration in free-corrosion environment, Demonstration of a case study: SLIC Joint Industry Project
- **Welding residual stresses in offshore wind monopiles (followed by a case study) 16:30-16:55**
  - Residual stress measurement using destructive and non-destructive techniques, residual stress effects on fatigue crack initiation and propagation, demonstration of a case study: residual stress measurements in monopile weldments using neutron diffraction and contour techniques
- **Q & A 16:55-17:00**

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2- Fracture Toughness Testing and Analysis of Materials in Offshore Structures

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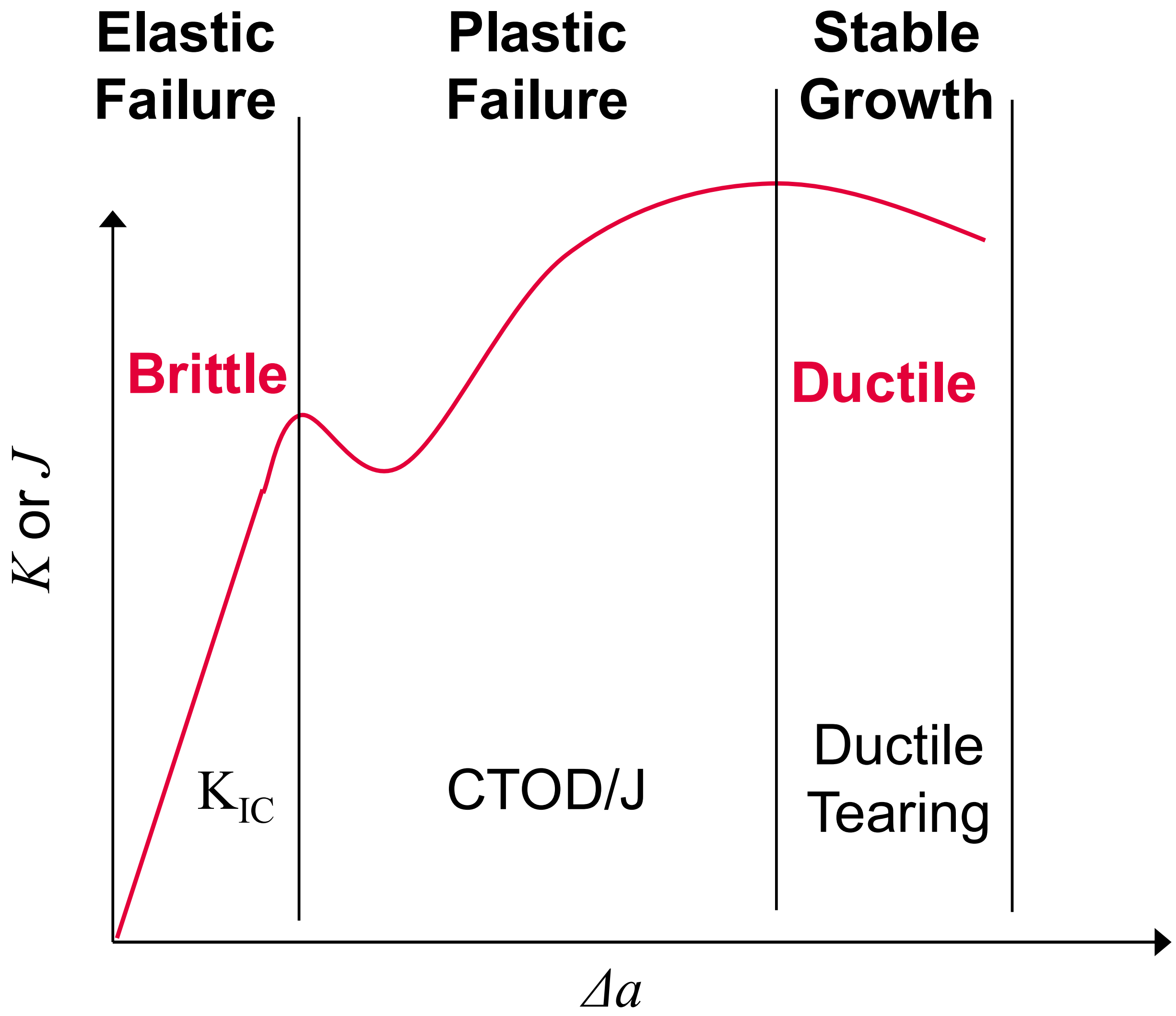
Overview

- Elastic-Plastic Fracture Mechanics
- Ramberg-Osgood Material Model
- HRR Stress and Strain Field Solutions
- Evaluation of J Parameter
- J_{IC} Fracture Toughness Testing and Analysis

Ductile Fracture vs. Brittle Fracture



Elastic-Plastic Fracture Mechanics

- **LEFM** is suitable for conditions that the plastic zone around the crack tip is sufficiently small.

- When the plastic zone size becomes significantly large, the stress intensity factor cannot characterise stress distribution at the crack tip under SSY conditions any longer.

- For an elastic-plastic material with relatively large plastic zone size, the **non-linear fracture mechanics parameter**, *J*, may describe the stress and strain distribution around the crack tip.

Ramberg-Osgood Material Model

- Many of the **non-linear fracture mechanics parameters solutions** are based on Ramberg-Osgood material model constants.

- The tensile behaviour of a strain hardening material may be described using Ramberg-Osgood material model (in uniaxial form) by

$$\varepsilon = \frac{\sigma}{E} + A_p \sigma^N$$

or in non-dimensional form by

$$\frac{\varepsilon}{\varepsilon_{p0}} = \frac{\sigma}{\sigma_{p0}} + \alpha \left(\frac{\sigma}{\sigma_{p0}} \right)^N$$

The first term on the RHS represents linear elastic deformation and the second term non-linear plastic deformation.

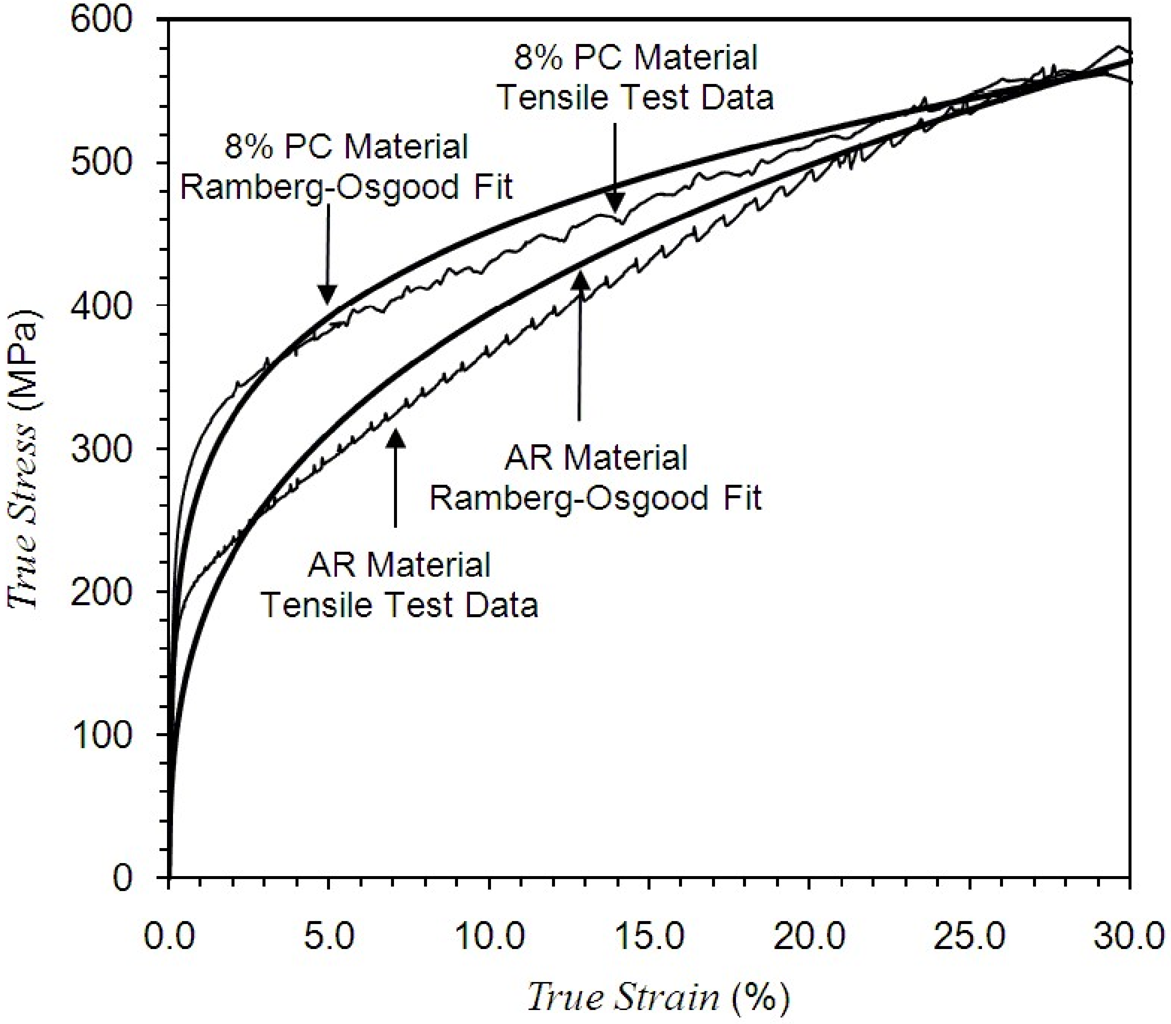
Ramberg-Osgood Material Model

- The normalising stress, σ_{p0}, in Ramberg-Osgood model is often taken as 0.2% proof stress of the material, $\sigma_{0.2}$.

$$\frac{\varepsilon}{\varepsilon_{p0}} = \frac{\sigma}{\sigma_{p0}} + \alpha\left(\frac{\sigma}{\sigma_{p0}}\right)^N$$

- **Non-linearity** is defined to exist from the beginning of the tensile response.
- Thus, **no absolute yield point** is considered in this material model.
- Under **small stresses** the non-linear term is almost negligible (hence linear relationship between stress and strain).
- As the **stress increases**, the linear component becomes negligible and the power law term is magnified.

Ramberg-Osgood Material Model



HRR Stress and Strain Distribution Fields

- For a **non-linear power law hardening** material, the stress and strain distribution fields near the crack tip can be defined in terms of *J*-integral by HRR (Hutchinson, Rosengren&Rice) equations as:

r is the radial distance from the crack tip

α, σ_{p0} and ε_{p0} are Ramberg-Osgood material model constants

$$\frac{\sigma_{ij}}{\sigma_{p0}} = \left[\frac{J}{\alpha\varepsilon_{p0}\sigma_{p0}I_N r}\right]^{\frac{1}{N+1}} \underbrace{\tilde{\sigma}_{ij}(\theta, N)}$$

$$\frac{\varepsilon_{ij}}{\varepsilon_{p0}} = \alpha\left[\frac{J}{\alpha\varepsilon_{p0}\sigma_{p0}I_N r}\right]^{\frac{N}{N+1}} \underbrace{\tilde{\varepsilon}_{ij}(\theta, N)}$$

Solutions for different values of θ and N are provided in a table by Shih

$$I_N = 7.2\sqrt{0.12 + \frac{1}{N}} - \frac{2.9}{N} \quad \text{Plane stress}$$

$$I_N = 10.3\sqrt{0.13 + \frac{1}{N}} - \frac{4.6}{N} \quad \text{Plane strain}$$

Evaluation of *J* Parameter

- For a **non-linear power law hardening** cracked body *J*-integral can be defined as

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

W is the strain energy density

- The non-linear fracture mechanics parameter, *J*, can be partitioned into **elastic** J_e and **plastic** J_p terms:

$$J = J_e + J_p$$

- The elastic term can be calculated using the stress intensity factor, *K*, and the effective Young's modulus, E' :

$$J_e = \frac{K^2}{E'}$$

$E' = E$ for plane stress

$E' = E/(1\text{-}\nu^2)$ for plane strain

- The existing methods to estimate the plastic J_p term are next described.

Evaluation of *J* Parameter- Experimental Displacement Method

$$J_p = \frac{A_p}{B_n(W-a)}\eta$$

- where B_n is the net thickness between the side grooves, W is the width, a is the crack lengthy, η is a geometry dependent function and A_p is the plastic area under load vs. displacement curve.

- J_p can be alternatively written as

$$J_p = \frac{P\Delta_p}{B_n(W-a)}H\eta$$

For a C(T) specimen:

$H = N/(N+1)$

$\eta = 2.2$

- where P is the applied load, Δ_p is the plastic load line displacement.

J_{IC} Testing

- For **ductile** materials, the fracture toughness is described by the J_{IC} parameter.

- For ductile materials with stable crack growth behaviour, the fracture toughness is quantified by generating a resistance curve (**R-curve**).

- There are two approached to generate the R-curve:

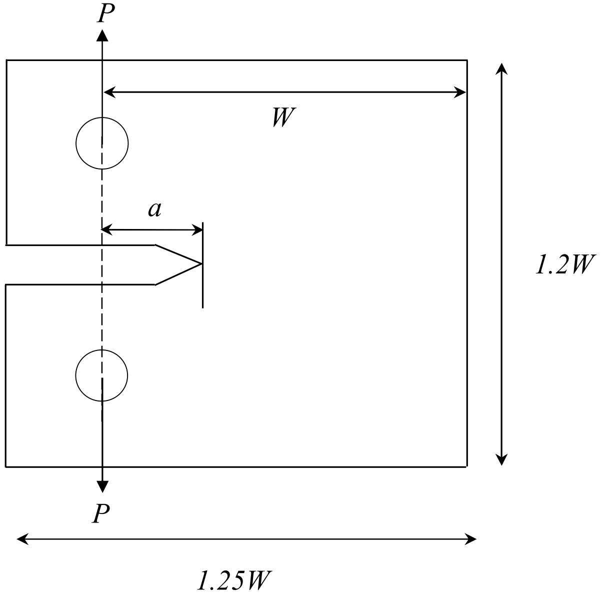
  - **A series of identical cracked specimens** are loaded to different load levels and then unloaded.

  - **A single cracked** specimen is frequently loaded and unloaded→ **Unloading compliance technique**.

- The latter approach is often used for J_{IC} testing.

J_{IC} Testing

- The fracture mechanics specimen geometries for J_{IC} testing are **C(T)** and **SEN(B).**



- The fracture specimens are **pre-fatigue cracked** (from a machined Chevron notch) before J_{IC} testing to introduce a **sharp crack tip** into the specimen.

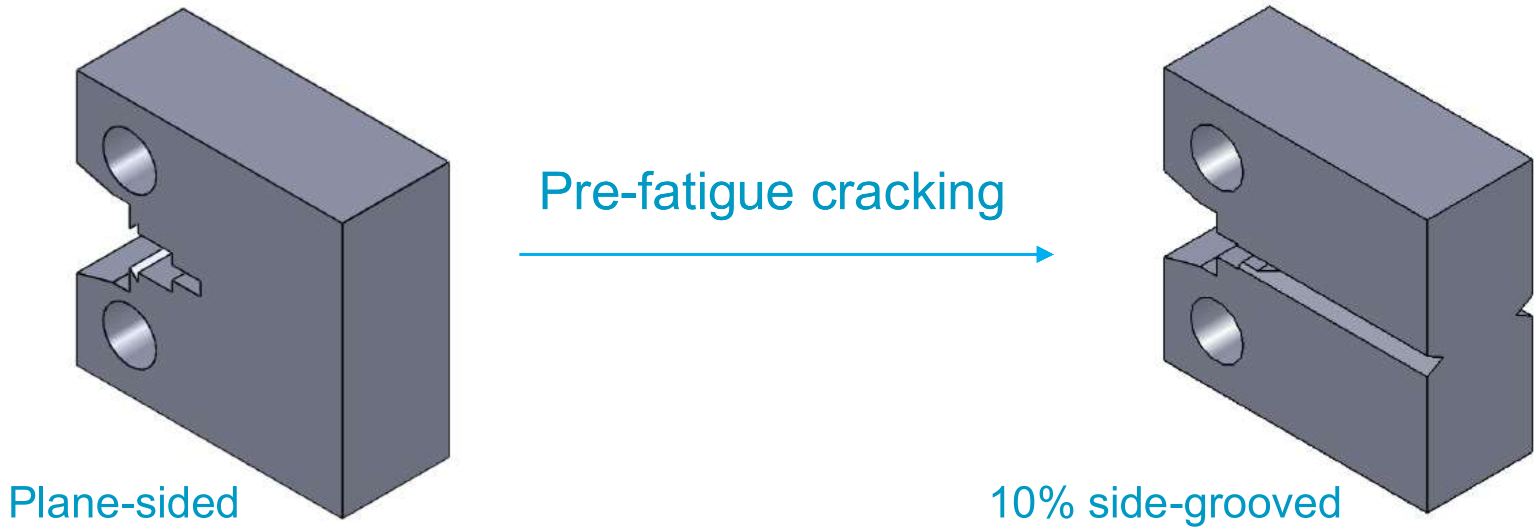
- The maximum pre-fatigue force must not exceed $0.6F_y$ to **limit the plasticity ahead of the pre-crack.**

$$F_y = \frac{B(W-a)^2}{(2W+a)}\sigma_{0.2}$$

J_{IC} Testing

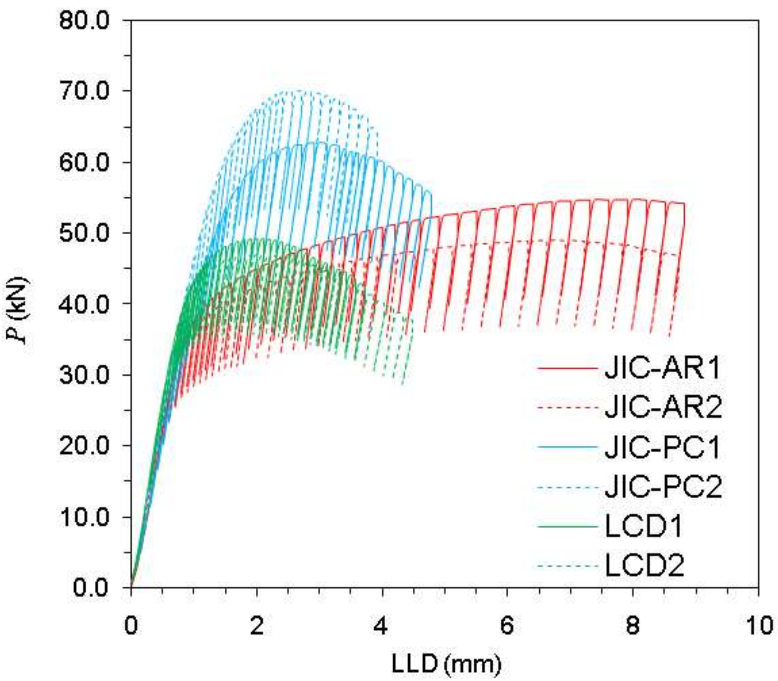
- When the test **specimen thickness is smaller than the component thickness**, specimens are recommended to be **side-grooved** subsequent to pre-fatigue cracking.

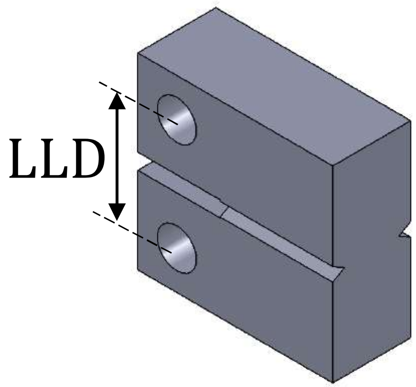
- This will introduce a higher constraint level into the specimen.



J_{IC} Testing

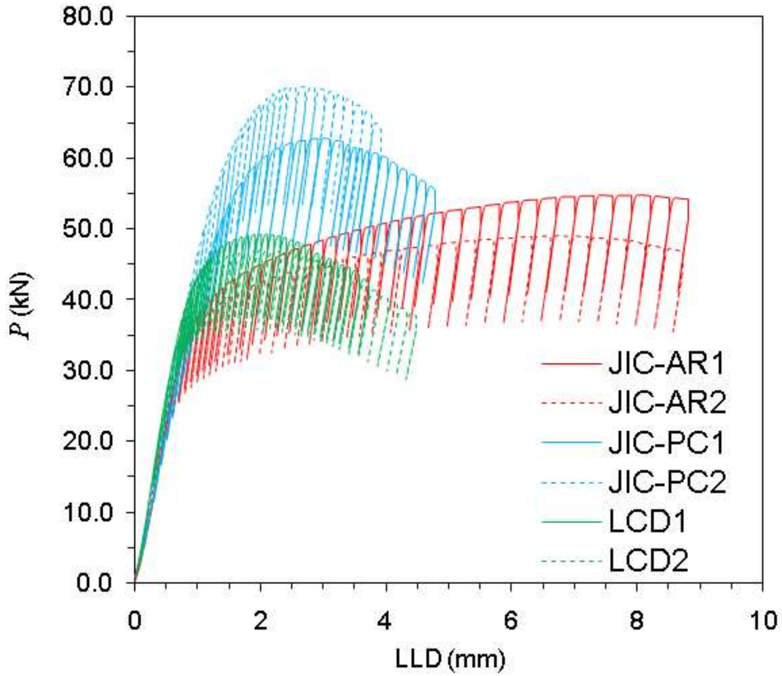
- Subsequent loading & unloading on a single C(T) specimen
- "Unloading force" **< "30% of the peak force"**, at each interval
- The load and load line displacement (LLD) are recorded during the test





J_{IC} Testing: Crack Length Measurement

- The **linear unloading compliance** at each interval provides an approximate measure of the **instantaneous crack length.**



$$a/W = \begin{pmatrix} 1.000196 - 4.06319\mu + 11.242\mu^2 \\ -106.043\mu^3 + 464.335\mu^4 - 650.677\mu^5 \end{pmatrix}$$

$$\mu = \frac{1}{\sqrt{B_e E C_e} + 1}$$

$$B_e = B - (B - B_n)^2 / B$$

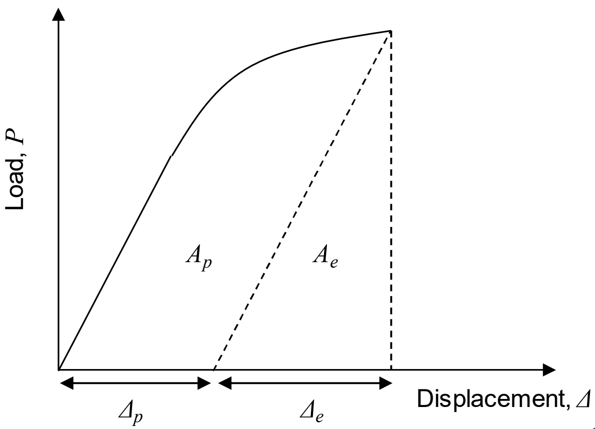
J_{IC} Testing: *J* Calculation

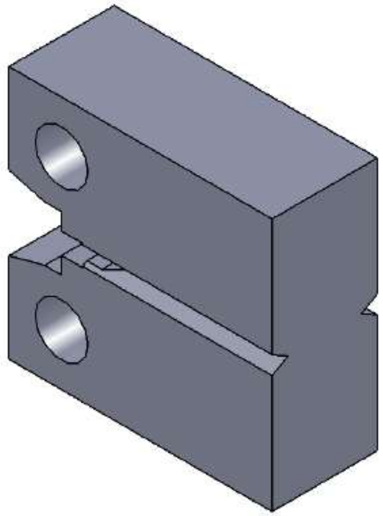
- **The fracture resistance, "*J*",** at the kth interval can be calculated by

$$J_{0,k} = \frac{\eta U_k}{B_n (W - a_0)}$$

$\eta = 2.2$ for a C(T) specimen

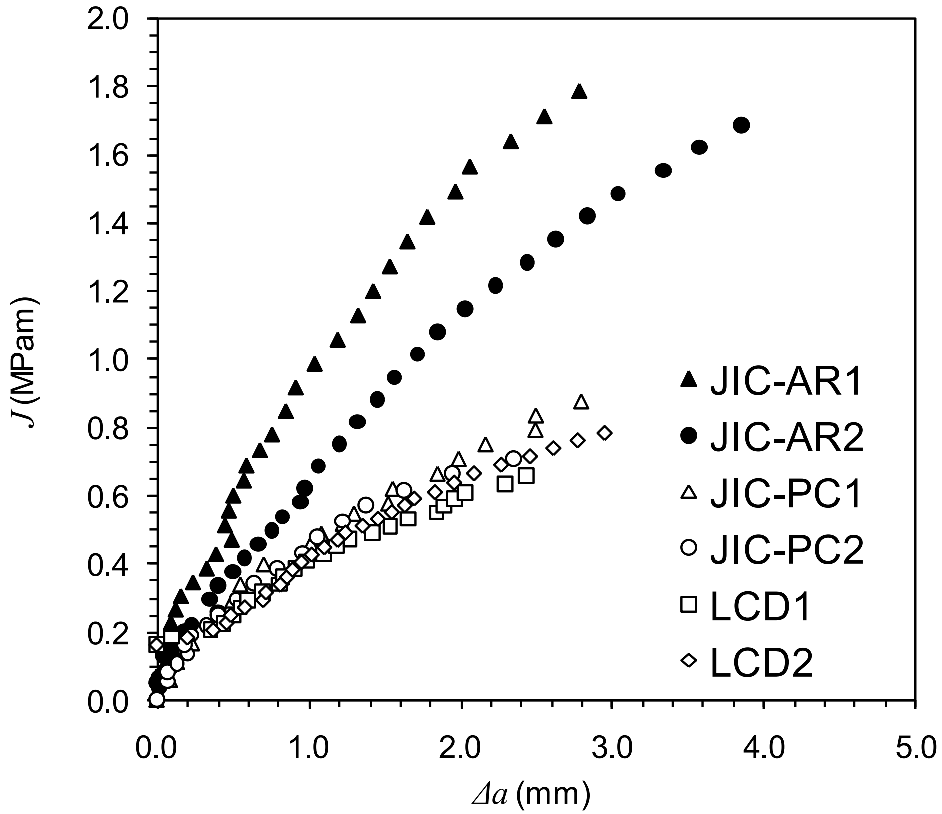
U_k is the area under the force *vs.* displacement curve up to the line of constant displacement at the *k*th interval.





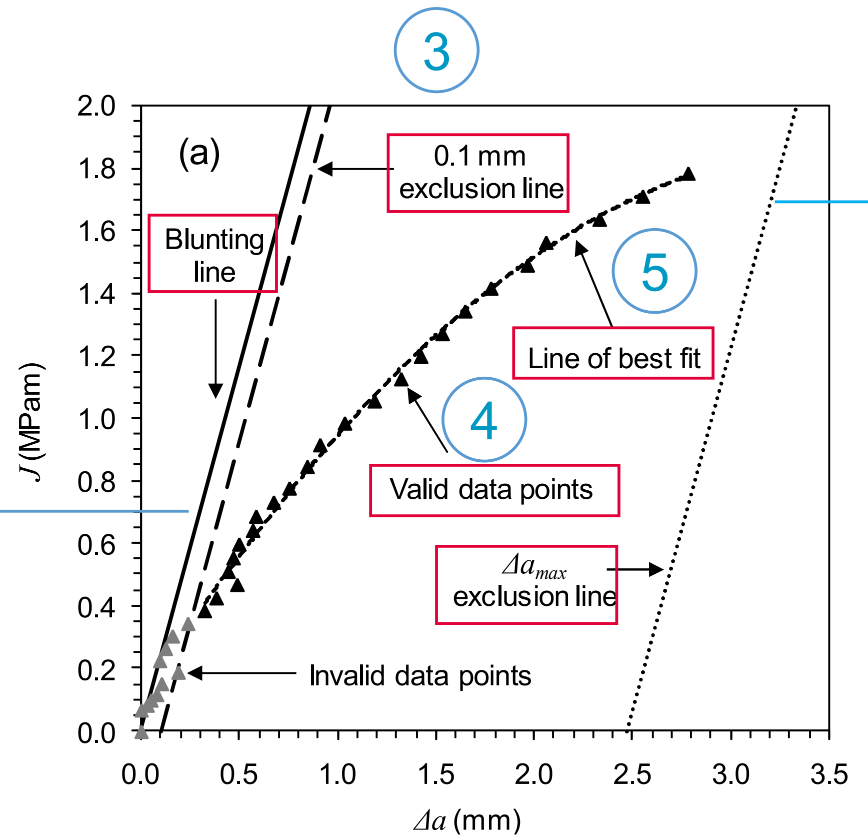
J_{IC} Testing: R-Curve

- The R-curve is generated by plotting ***J* vs. Crack Extension, *Δa*.**



J_{IC} Testing: R-Curve Validity Criteria

- In order to identify the **valid data points** for fracture toughness analysis the **exclusion lines are constructed**.



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$$\Delta a_{max} = 0.10(W - a_0)$$

1

$$J / \Delta a_B = E / (0.4 d_n^*)$$

$$d_n^* = \varepsilon_0^{n-1}(0.787 + 1.554n - 2.45n^2 + 16.952n^3 - 38.206n^4 + 33.13n^5)$$

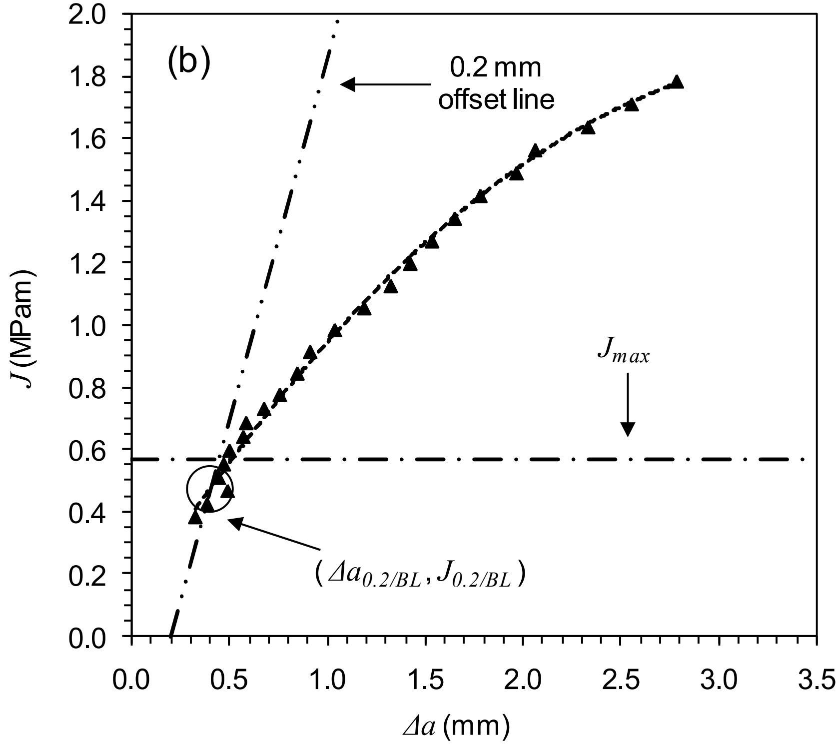
J_{IC} Testing: Quantification of J_{IC}

- A line parallel to the blunting line with **0.2 mm offset** is plotted.

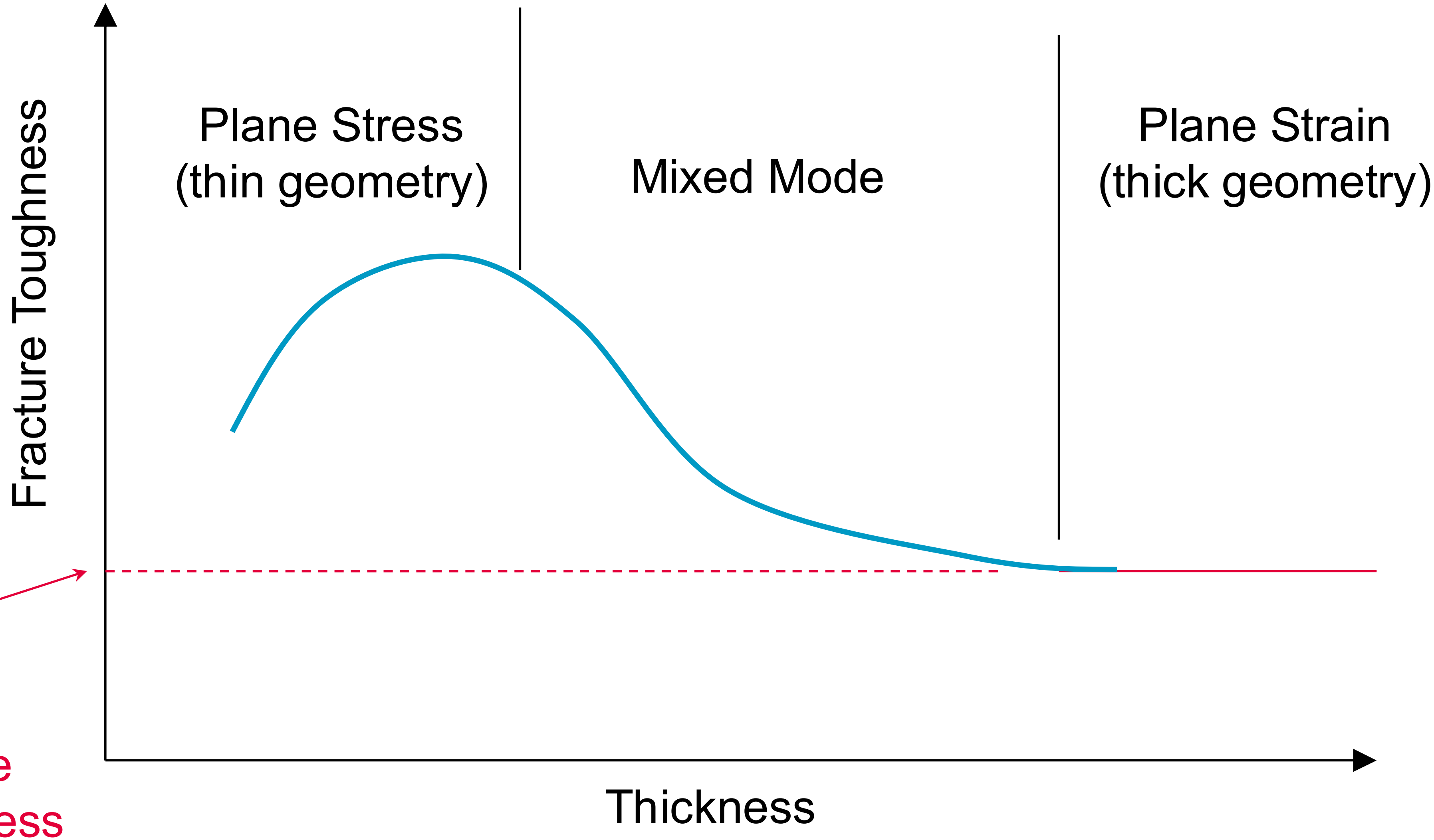
- The **intersection** between this line and the best fit curve is regarded as J_{IC}.

- J_{IC} must be smaller than J_{max}

$$J_{max} = Min\{(W - a_0)(\sigma_{0.2} + \sigma_{UTS})/40, B(\sigma_{0.2} + \sigma_{UTS})/40\}$$



Fracture Modes – Variation with Thickness



Plane Strain Fracture Toughness (**Material Property**)

Fracture Toughness Standard Test Methods

- **ESIS P2-92: ESIS Procedure for Determining the Fracture Behaviour of Materials**

- **ASTM E-1820: Standard Test Method for measurement of fracture toughness**.

- **ASTM E-399: Plane strain fracture toughness testing**.

- **ASTM E-813: Elastic-plastic fracture toughness testing using the J-Integral technique**. Both the compliance technique and potential drop method of crack measurement

- **ASTM E-561: Fracture resistance testing using the R-Curve (resistance curve) technique**. Testing is performed using the compliance technique as well as the potential drop method of crack measurement.

- **ASTM E-1290:** Fracture toughness testing using the Crack Tip Opening Displacement (CTOD) measurement method. Performed using the compliance technique on all the standard-geometry, fracture toughness specimens.

- **ASTM E-1304: Plain-strain fracture toughness testing using the short rod or short bar specimen design**. Specification sometimes used for brittle materials.

Tutorial