国立大学法人 東京工業大学

Fundamental Concepts of Fracture Mechanics

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Introduction

During World War II

5000 ships built

over 1000 ships: cracks by 1946

200 ships: serious damage

9 T-2 tankers

7 Liberty ships

broken in two

What is Fracture Mechanics?

Strength of Materials

Yield $\sigma = \sigma_y$

Failure $\sigma = \sigma_B$

Fatigue $S - N$ *Diagram, Fatigue Limit*

Fracture Mechanics

Failure $K = K_C$

Stress Intensity Factor K

Fracture Toughness K_C

Fatigue $\frac{da}{dN} = C\left((\Delta K)^m - (\Delta K_{th})^m\right)K_C$

Fracture Mechanics is

Mechanics of Members with Cracks

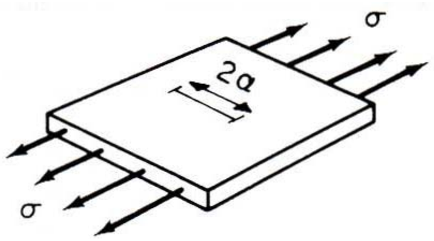
Stress Intensity Factor, K

Stress, σ

Crack Length, a

Fracture Toughness, Kc

Material Property



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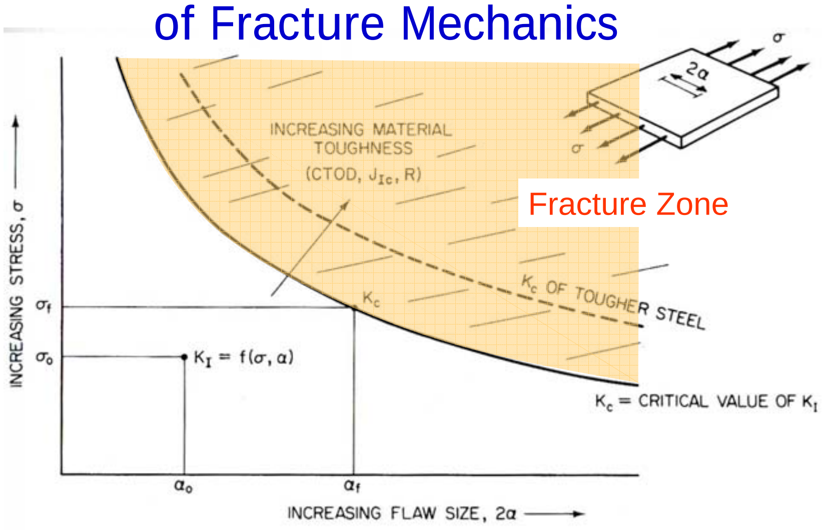
Fundamental Concepts of Fracture Mechanics



Relationship among a stress condition, a crack size and fracture toughness

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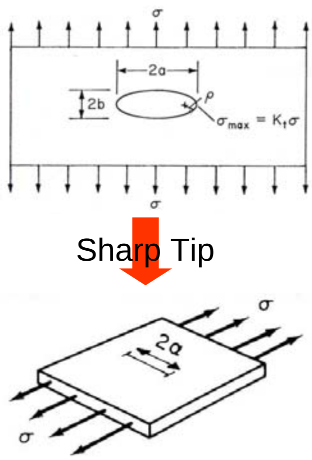
Types of Discontinuities

Notches

Imperfections

Cracks



History of Fracture Mechanics

1921 Griffith

Griffith’s Formula

1948 Irwin

1957 Irwin

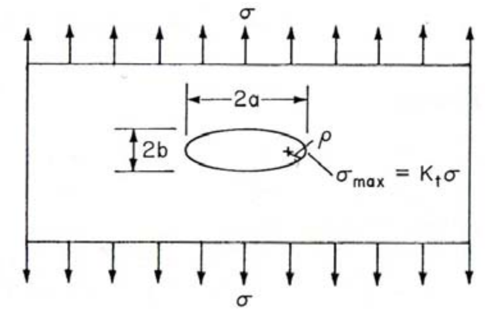
Stress Intensity Factor, K

.....

Stress Analysis of Members with Notches

Stress Concentration Factor, Kt

For An Elliptical Hole



$$K_T = \frac{\sigma_{\max}}{\sigma} = 1 + \frac{2a}{b}$$

$$\sigma_{\max} = \sigma\left(1 + \frac{2a}{b}\right)$$

$$\rho = \frac{b^2}{a} \Rightarrow b = \sqrt{a\rho}$$

$$\sigma_{\max} = \sigma\left(1 + 2\sqrt{\frac{a}{\rho}}\right) \Rightarrow = 2\sigma\sqrt{\frac{a}{\rho}}\ (\rho << a)$$

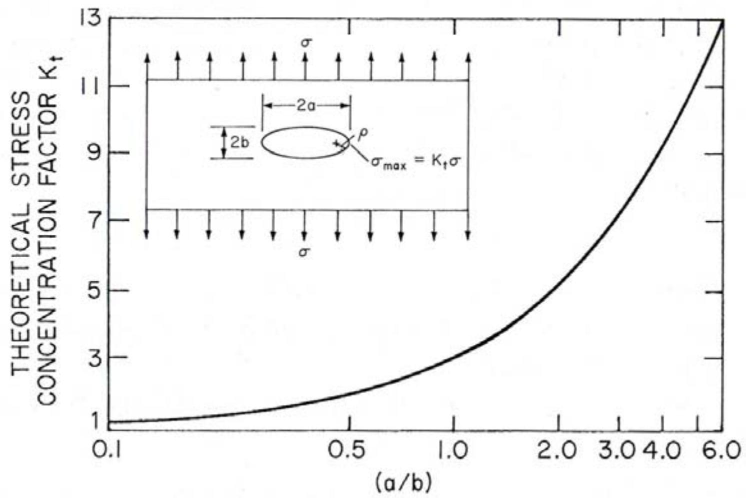
$$\sqrt{\frac{a}{\rho}} \to \infty\ (\rho \to 0)$$

$$K_t \to \infty$$

Stress Analysis of Members with Notches

Stress Concentration Factor, Kt

For An Elliptical Hole $K_t \rightarrow \infty$ Meaningless



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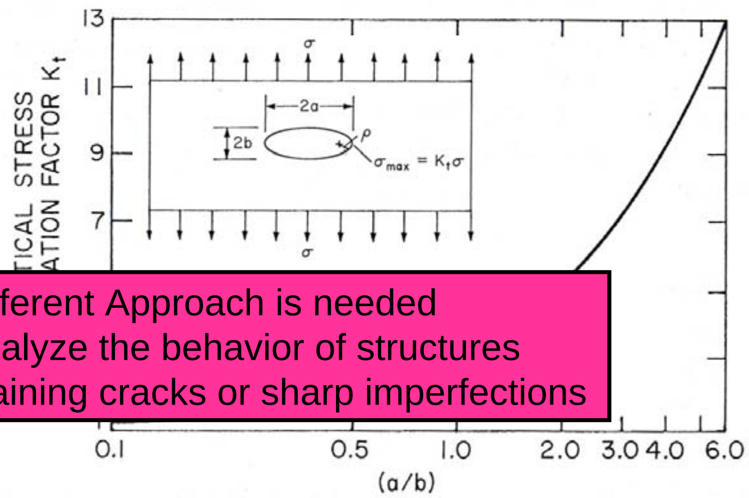
Stress Analysis of Members with Notches

Stress Concentration Factor, Kt

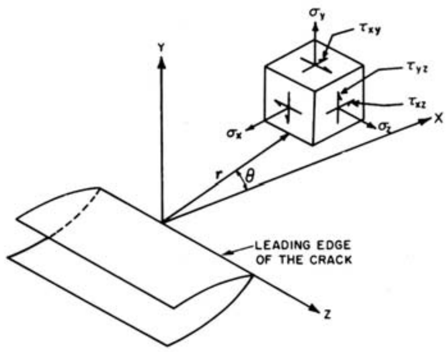
For An Elliptical Hole $K_t \rightarrow \infty$ Meaningless



A Different Approach is needed
to analyze the behavior of structures
containing cracks or sharp imperfections

Stress Analysis of Members with Notches

Stress Distribution
along X-axis
near the notch root



$$\frac{(\sigma_y)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}\left(1+\frac{\rho}{2r+\rho}\right)+\left(\frac{\rho}{2r+\rho}\right)$$

$$0 \le r \ll a\,,\ \rho \ll a$$

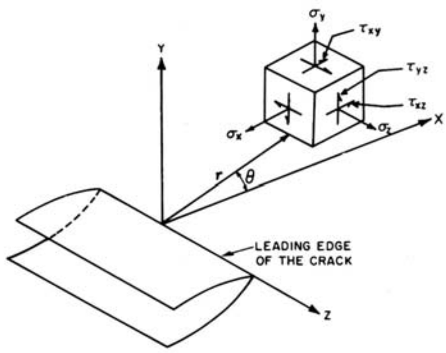
$$\frac{(\sigma_x)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}\left(1-\frac{\rho}{2r+\rho}\right)$$

Stress Analysis of Members with Notches

Stress Distribution
along X-axis
near the notch root

$$\frac{(\sigma_y)_{y=0}}{\sigma} = \frac{(\sigma_x)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}$$

$$\rho \to 0$$



$$\frac{(\sigma_y)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}\left(1+\frac{\rho}{2r+\rho}\right)+\left(\frac{\rho}{2r+\rho}\right)$$

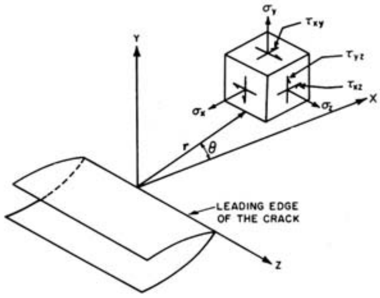
$$0 \le r \ll a\,,\ \rho \ll a$$

$$\frac{(\sigma_x)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}\left(1-\frac{\rho}{2r+\rho}\right)$$

Stress Analysis of Members with Cracks

$$\frac{(\sigma_y)_{y=0}}{\sigma} = \frac{(\sigma_x)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r+\rho}}$$

$$\rho \to 0$$

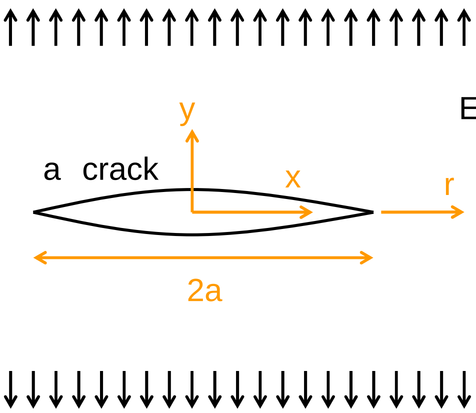


Stress near a crack tip

1. Singularity about $\dfrac{1}{\sqrt{r}}$
2. Intensity of Stress Singularity is Proportional to
   far field stress σ_∞
   square root of crack length a

Stress Analysis of Members with Cracks

σ_y^∞



σ_y^∞

Exact solution of stress near crack

$$\frac{(\sigma_y)_{y=0}}{\sigma} = \frac{|x|}{\sqrt{x^2-a^2}} = \frac{a+r}{\sqrt{r(2a+r)}}$$

$$\frac{(\sigma_x)_{y=0}}{\sigma} = \frac{|x|}{\sqrt{x^2-a^2}} - 1 = \frac{a+r}{\sqrt{r(2a+r)}} - 1$$

Stress Analysis of Members with Cracks

$$\frac{(\sigma_y)_{y=0}}{\sigma} = \frac{|x|}{\sqrt{x^2-a^2}} = \frac{a+r}{\sqrt{r(2a+r)}}$$

$$\frac{(\sigma_x)_{y=0}}{\sigma} = \frac{|x|}{\sqrt{x^2-a^2}} - 1 = \frac{a+r}{\sqrt{r(2a+r)}} - 1$$

r/a<1

Series Expansion

$$\frac{(\sigma_y)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r}} + \frac{3}{4}\sqrt{\frac{r}{2a}} - \frac{5}{32}\left(\sqrt{\frac{r}{2a}}\right)^3 + \cdots$$

$$\frac{(\sigma_x)_{y=0}}{\sigma} = \sqrt{\frac{a}{2r}} - 1 + \frac{3}{4}\sqrt{\frac{r}{2a}} - \frac{5}{32}\left(\sqrt{\frac{r}{2a}}\right)^3 + \cdots$$

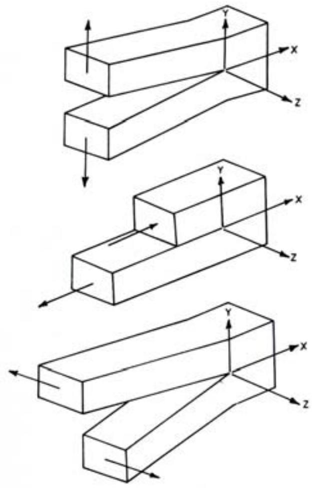
r/a>1

$$\frac{(\sigma_y)_{y=0}}{\sigma_y^\infty} \Rightarrow 1 + \frac{1}{2}\left(\frac{a}{r}\right)^2$$

$$\frac{(\sigma_x)_{y=0}}{\sigma_y^\infty} \Rightarrow \frac{1}{2}\left(\frac{a}{r}\right)^2$$

Stress Analysis for Cracks in Elastic Solids

Three Types of Relative Movements of Two Crack Surfaces



MODE I : Opening Mode

MODE II : Sliding/Shear Mode

MODE III : Tearing Mode

Basic Types of Stress Fields near Crack Tips

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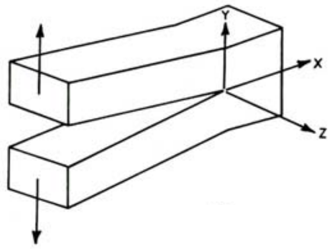
Important Basic Mode I

Most engineering situations corresponding to Mode I

$$\sigma_x = \frac{K_I}{(2\pi r)^{\frac{1}{2}}}\cos\frac{\theta}{2}\left[1-\sin\frac{\theta}{2}\cdot\sin\frac{3\theta}{2}\right]$$

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

$$\tau_{xy} = \frac{K_I}{(2\pi r)^{\frac{1}{2}}}\sin\frac{\theta}{2}\cdot\cos\frac{\theta}{2}\cdot\cos\frac{3\theta}{2}$$



$$u = \frac{K_I}{G}\left[\frac{r}{2\pi}\right]^{\frac{1}{2}}\cos\frac{\theta}{2}\left[1-2\nu+\sin^2\frac{\theta}{2}\right]$$

$$v = \frac{K_I}{G}\left[\frac{r}{2\pi}\right]^{\frac{1}{2}}\sin\frac{\theta}{2}\left[1-2\nu-\cos^2\frac{\theta}{2}\right]$$

$$w = 0$$

Target unit

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General Form of Stress Intensity Factor

The Applied Stress
The Crack Shape and Size
The Structural Configuration

Affect

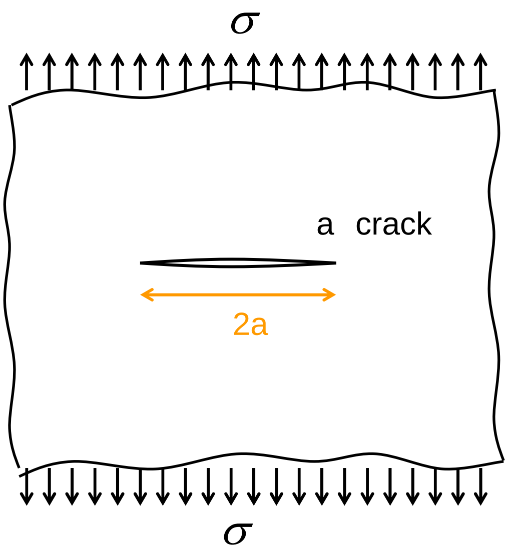
The Value of The Stress Intensity Factor, K

$$K = \sigma\sqrt{\pi a}\cdot f(g)$$

$f(g)$: Crack Geometry

Local Stress Field ⟷ Global Stress Field

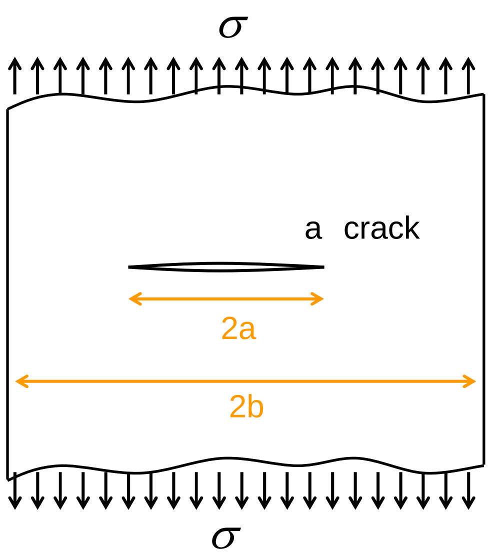
Stress Intensity Factor Equations (1)



A Through Thickness Crack
In an Infinite Plate subject
to Uniform Tensile Stress

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

Stress Intensity Factor Equations (2)

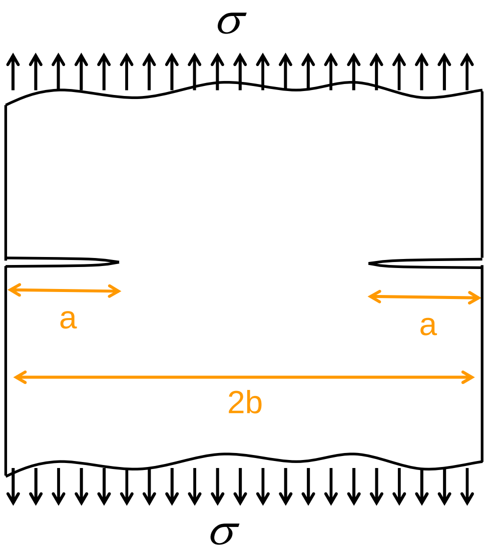


A Through Thickness Crack
In a Plate with Finite Width
Subject to
Uniform Tensile Stress

$$K = \sigma\sqrt{\pi a}\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{\frac{1}{2}}$$

$$= \sigma\sqrt{\pi a}\sqrt{\sec\left(\frac{\pi a}{2b}\right)}$$

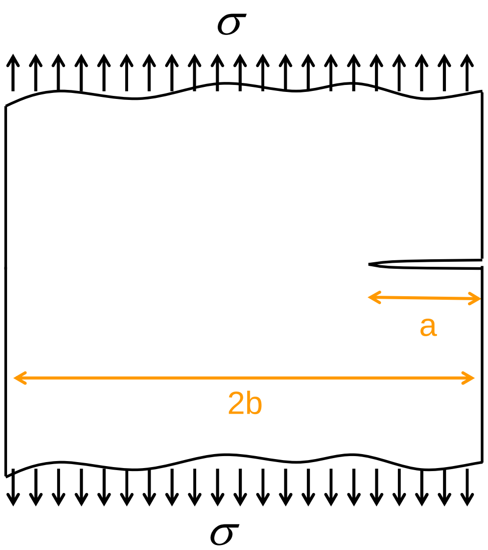
Stress Intensity Factor Equations (3)



Double-Edge Cracks
In a plate with finite width

$$K = \sigma\sqrt{\pi a}\cdot 1.12$$

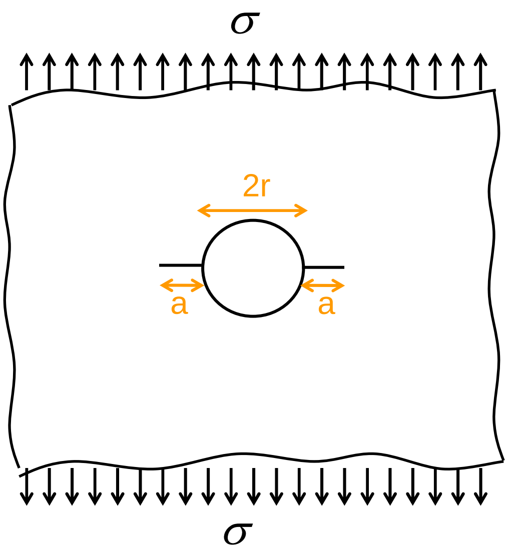
Stress Intensity Factor Equations (4)



Single-Edge Crack
In a plate with finite width

$$K = 1.12\cdot\sigma\sqrt{\pi a}\cdot f\left(\frac{a}{b}\right)$$

Stress Intensity Factor Equations (5)



Cracks growing
from a round hole

$$K = \sigma\sqrt{\pi a} \cdot f\left(\frac{a}{r}\right)$$

$$a \to 0 \quad f\left(\frac{a}{r}\right) \to 3$$

For short cracks

$$K = K_t \sigma\sqrt{\pi a}$$

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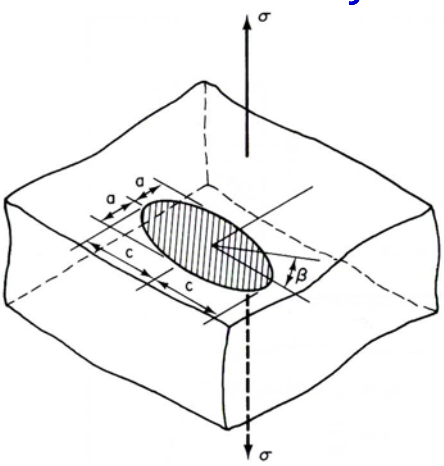
Stress Intensity Factor Equations (6)

An Embedded elliptical crack
or a circular crack
In an Infinite Plate



$$K = \frac{\sigma\sqrt{\pi a}}{\Phi_0}\left(\sin^2\beta + \frac{a^2}{c^2}\cos^2\beta\right)^{\frac{1}{4}}$$

$$\Phi_0 = \int_0^{\frac{\pi}{2}}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\theta\right]^{\frac{1}{2}} d\theta$$

$$K = \sigma\sqrt{\frac{\pi a}{Q}} \quad for \quad \beta = \frac{\pi}{2}$$

$$Q = \Phi_0^2$$

$$K = 0.65\sigma\sqrt{\pi a} = 1.15\sigma\sqrt{a}$$

$$for \quad \beta = \frac{\pi}{2}, a = c \quad (a\ circle)$$

$$\Leftrightarrow \quad K = \frac{2}{\sqrt{\pi}}\sigma\sqrt{a} = 1.13\sigma\sqrt{a}$$

Exact expression

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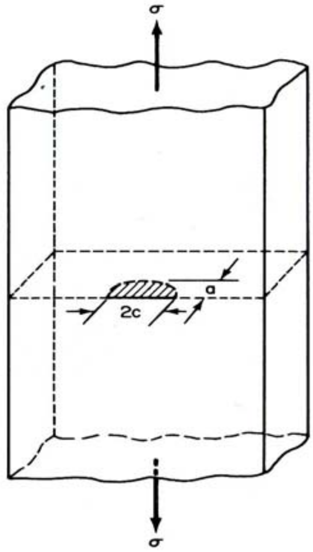
Stress Intensity Factor Equations (6)



A Surface crack
or a circular crack
In an Infinite Plate

$$K = 1.12\sigma\sqrt{\pi\frac{a}{Q}}\cdot M_k$$

$$M_k = 1.0 + 1.2\left(\frac{a}{t} - 0.5\right)$$

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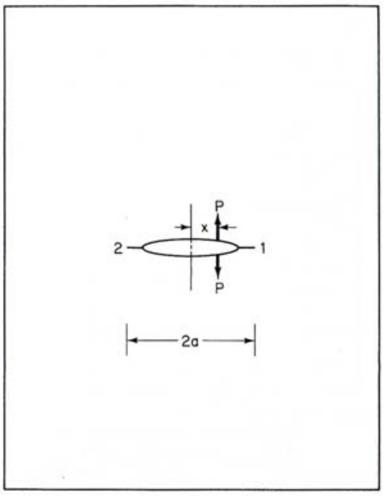
Stress Intensity Factor Equations (7)



Cracks with wedge forces
and internal pressure

Eccentric line forces, P,
per unit thickness

$$K_{@1} = \frac{P}{\sqrt{\pi a}}\left(\frac{a+x}{a-x}\right)^{\frac{1}{2}}$$

$$K_{@2} = \frac{P}{\sqrt{\pi a}}\left(\frac{a-x}{a+x}\right)^{\frac{1}{2}}$$

$$K_{@1} = K_{@2} = \frac{P}{\sqrt{\pi a}} \quad at\ x = 0$$

$K = p\sqrt{\pi a}$: internal pressure

Engineering Calculation of Stress Intensity Factor

Pedro Albrecht/ K. Yamada, ASCE, STR, Feb.1977

$$K = F(a)\sigma\sqrt{\pi a}$$

$$F(a) = F_e \cdot F_s \cdot F_w \cdot F_g$$

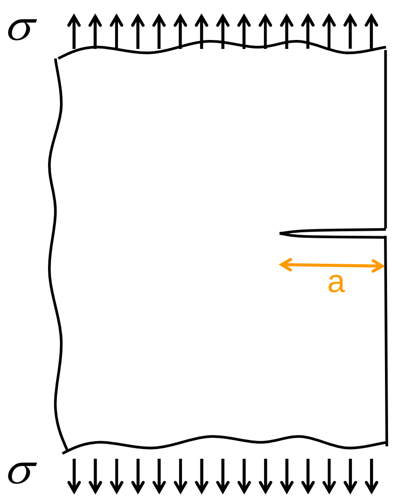
Fe: The Shape of Crack Front,
which is often assumed as an elliptical crack, correction

Fs: Effects of Free Surface, Front Free Surface Correction

Fw: Finite Width, The Back Surface Correction

Fg: Non-uniform Opening Stresses, Stress Gradient Correction

2 Dimensional Crack Problems(1)



The Edge Crack
in a semi-infinite plate

$$K = F(a)\sigma\sqrt{\pi a}$$

$$F(a) = F_s = 1.12$$

Front Free Surface Correction

$$K = 1.12\sigma\sqrt{\pi a}$$

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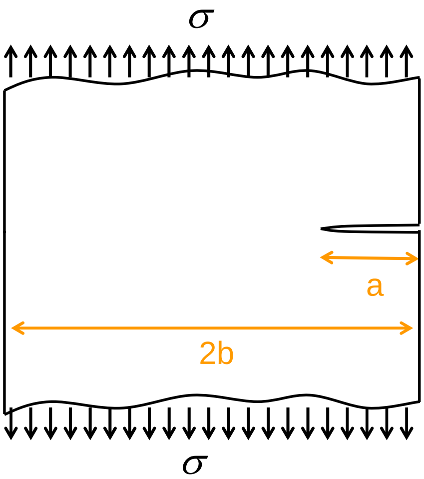
2 Dimensional Crack Problems(2)

Single-Edge Crack
In a plate with finite width



$$K = F(a)\sigma\sqrt{\pi a}$$

$$F(a) = F_s \cdot F_w$$

$$K = \underbrace{\boxed{1.12}}_{F_s} \cdot \sigma\sqrt{\pi a} \cdot \underbrace{\boxed{f\left(\frac{a}{b}\right)}}_{F_w}$$

F_s: Front Free Surface Correction

F_w: Finite Width

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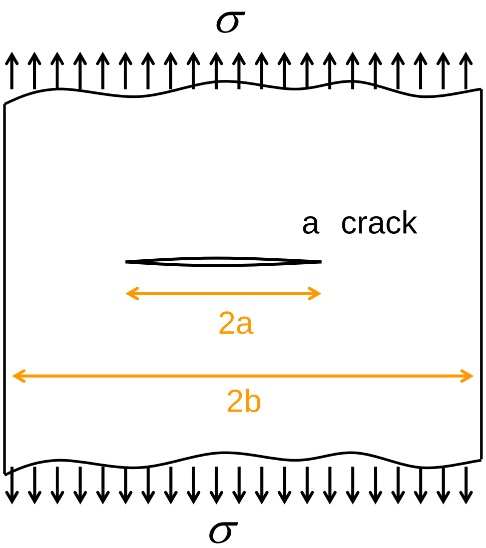
2 Dimensional Crack Problems (3)



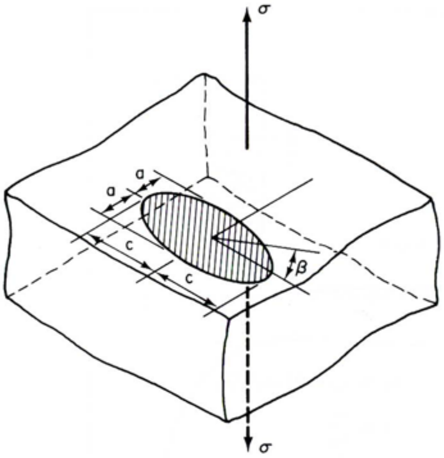
A Through Thickness Crack
In a Plate with Finite Width
Subject to
Uniform Tensile Stress

$$K = \sigma\sqrt{\pi a}\boxed{\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{\frac{1}{2}}}$$

$$= \sigma\sqrt{\pi a}\boxed{\sqrt{\sec\left(\frac{\pi a}{2b}\right)}}$$

Finite Width $F(a) = F_w$

3 Dimensional Crack Problems (1)



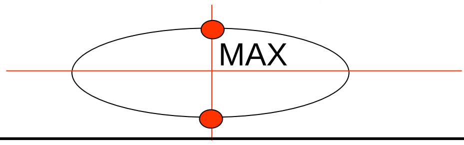
An Embedded elliptical crack
or a circular crack
In an Infinite Plate

$$K = \frac{1}{\Phi_0}\left(\sin^2\beta + \frac{a^2}{c^2}\cos^2\beta\right)^{\frac{1}{4}} \cdot \sigma\sqrt{\pi a}$$

$$\Phi_0 = \int_0^{\frac{\pi}{2}}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\theta\right]^{\frac{1}{2}} d\theta$$

$$K = \boxed{\frac{1}{\Phi_0}}\sigma\sqrt{\pi a} \quad for \quad \beta = \frac{\pi}{2}$$

$$F_e \qquad F(a) = F_e = \frac{1}{\Phi_0}$$



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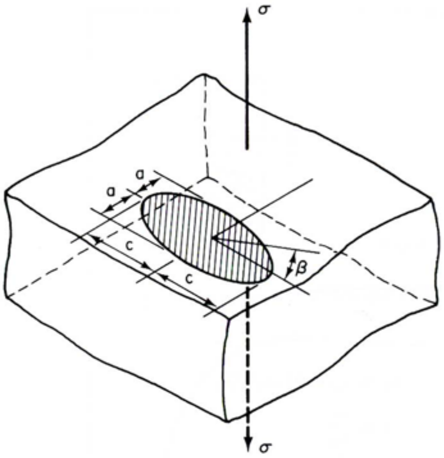
3 Dimensional Crack Problems (1)



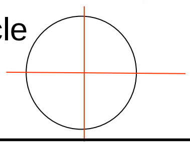
An Embedded elliptical crack
or a circular crack
In an Infinite Plate

$$K = \frac{1}{\Phi_0}\left(\sin^2\beta + \frac{a^2}{c^2}\cos^2\beta\right)^{\frac{1}{4}} \cdot \sigma\sqrt{\pi a}$$

$$\Phi_0 = \int_0^{\frac{\pi}{2}}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\theta\right]^{\frac{1}{2}} d\theta$$

$$K = \boxed{\frac{1}{\Phi_0}}\sigma\sqrt{\pi a} \quad for \quad \beta = \frac{\pi}{2}$$

Circle

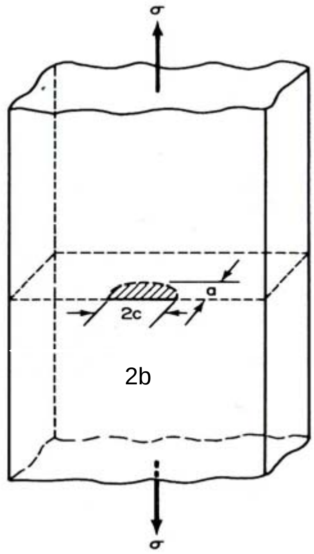


$$K = \frac{2}{\pi}\sigma\sqrt{\pi a}$$

$$F_e \qquad F(a) = F_e = \frac{1}{\Phi_0} = \frac{2}{\pi}$$

$$for \ a = c$$

3 Dimensional Crack Problems (2)



A Surface crack
or a circular crack
In a Plate with Finite Width

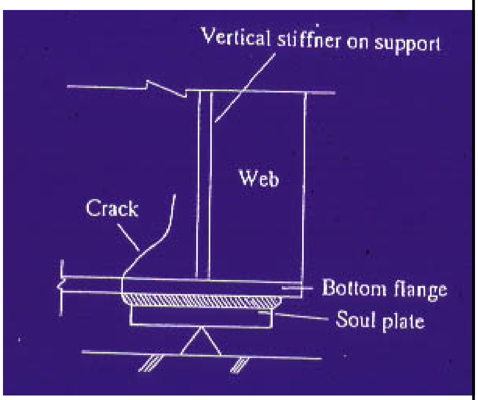
$$K = \underbrace{\boxed{M_k}}_{F_s} \cdot \underbrace{\boxed{\frac{1}{\Phi_0}}}_{F_e} \cdot \boxed{F_g}\, \sigma\sqrt{\pi a} \cdot \underbrace{\boxed{\sqrt{\frac{2b}{\pi a}\tan\frac{\pi a}{2b}}}}_{F_w}$$

$$M_k \begin{cases} = 1.0 + 1.2\left(\dfrac{a}{t} - 0.5\right) & \text{for surface cracks} \\ = 1.12 & \text{for through thickness cracks} \end{cases}$$

Stress Gradient Correction
Correction for Stress Concentration

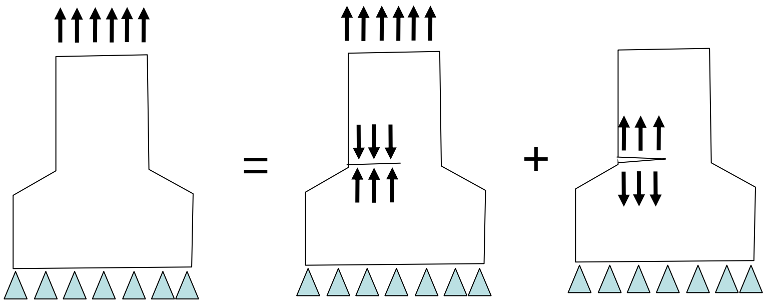
Geometry Correction Factor F_g

Cracks always occur at geometrical discontinuities as cover plate ends .....



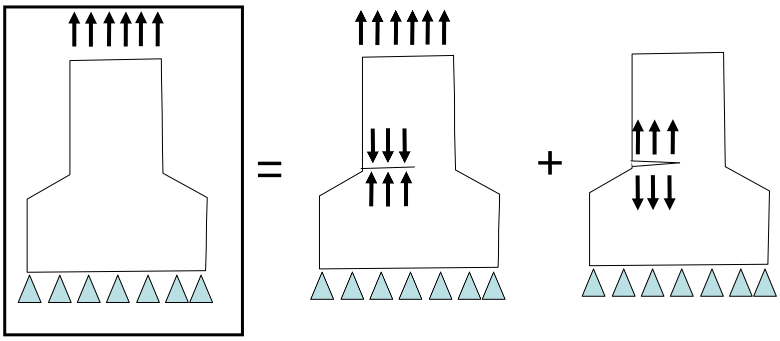
Calculation of F_g

Superimpose



Calculation of F_g

Superimpose



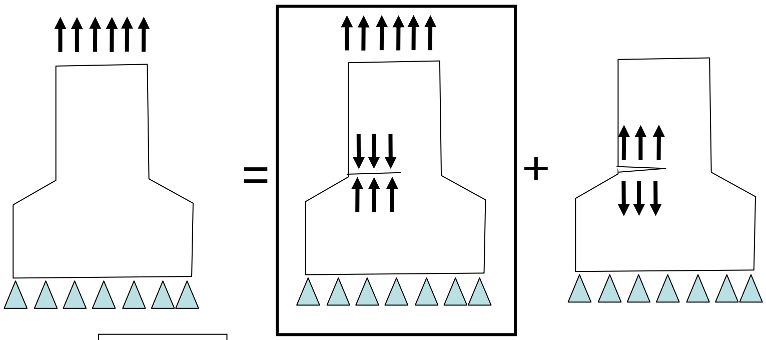
Step 1

Compute the actual stress
Along the line where the crack
Shall be inserted
By any suitable methods.

FEM

Calculation of F_g

Superimpose



Step 2

Insert a crack of given length
Along the same line

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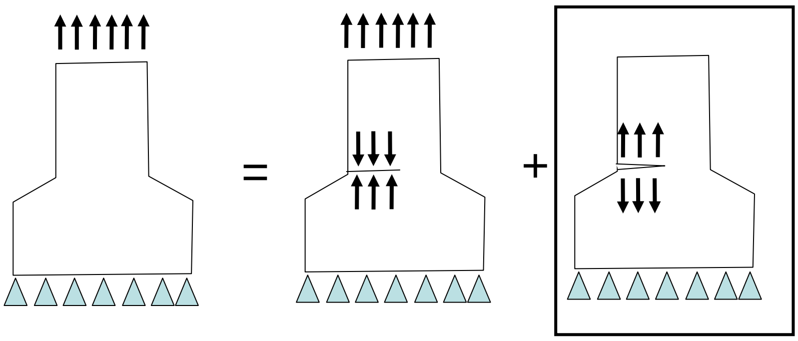
Calculation of F_g

Superimpose



Step 3

Compute K by integrating away
the normal, determined in Step 1
stresses applied over the length
of the crack

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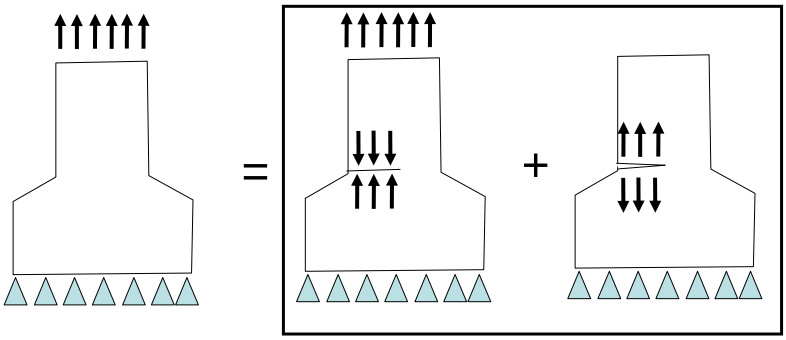
Calculation of F_g

Superimpose



Step 4

Repeat steps 2 and 3
for any desired crack size

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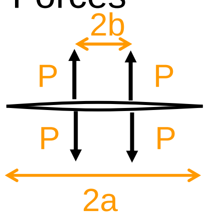
Calculation of F_g

Calculation of K in Step 3

Concentrated Forces

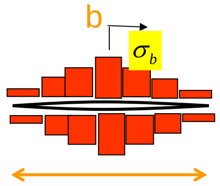
a crack



$$K = \frac{2P}{\sqrt{\pi a}} \frac{a}{\sqrt{a^2 - b^2}}$$

Distributed Forces

a crack



$$K = \sqrt{\pi a}\,\frac{2}{\pi}\int_0^a \frac{\sigma_b}{\sqrt{a^2 - b^2}}\,db$$

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Calculation of F_g

Stress Distribution in Step 1

Closed form expressions defining the stress distribution In the uncracked body are usually not available.

From FEM

$$K = \sqrt{\pi a}\,\frac{2}{\pi}\sum_{i=1}^{n}\sigma_{b_i}\int_{b_i}^{b_{i-1}}\frac{1}{\sqrt{a^2-b^2}}db$$

In which the discrete stress σ_{b_i} is applied over the element b_i and b_{i+1}

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Calculation of F_g

Stress Distribution in Step 1

After factoring out the mean stress

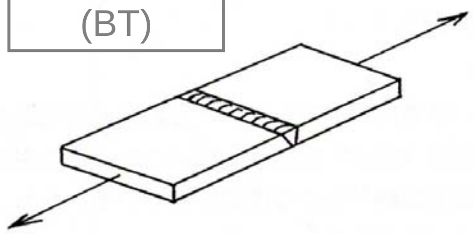
$$K = \sqrt{\pi a}\,\frac{2}{\pi}\sum_{i=1}^{n}\sigma_{b_i}\int_{b_i}^{b_{i-1}}\frac{1}{\sqrt{a^2-b^2}}db$$

$$\Downarrow$$

$$K = \sigma\sqrt{\pi a}\,\frac{2}{\pi}\sum_{i=1}^{n}\frac{\sigma_{b_i}}{\sigma}\left(\arcsin\frac{b_{i-1}}{a}-\arcsin\frac{b_i}{a}\right)$$

Examples of F_g

Butt Joint (BT)



$$F_g = 1$$

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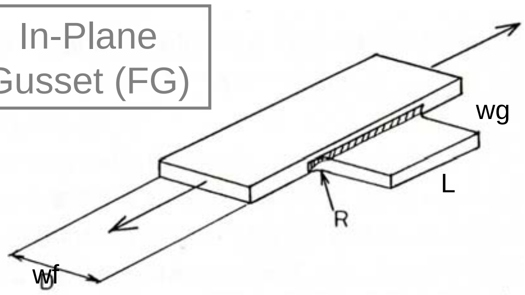
Examples of F_g

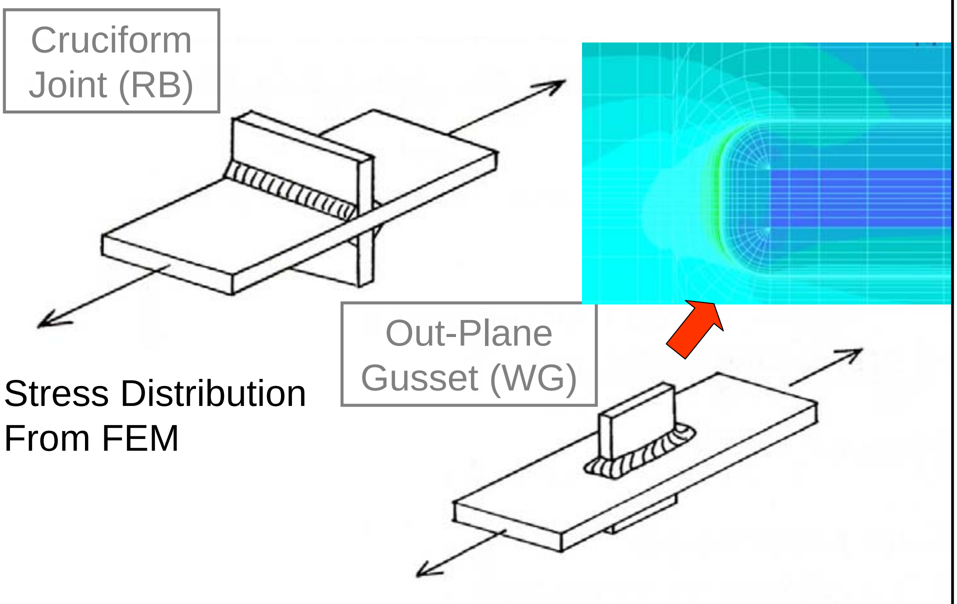
In-Plane Gusset (FG)

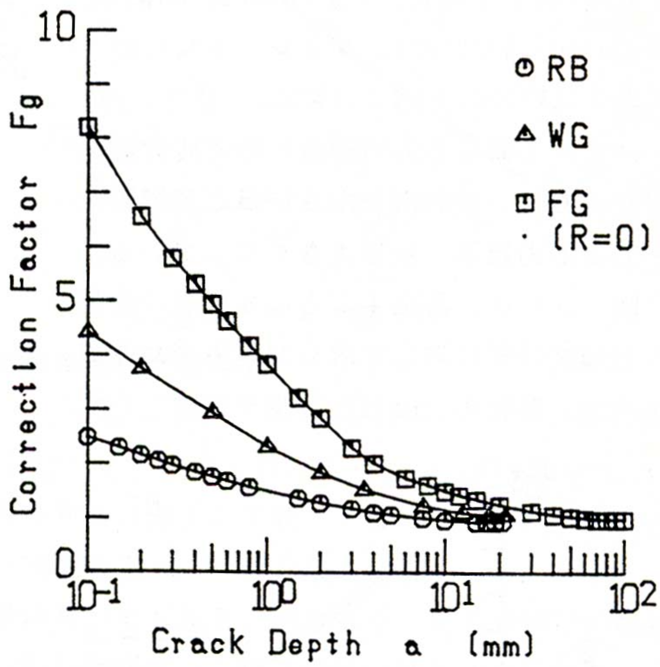


$$F_g = \frac{-1.115\log(\frac{R}{w_f}) + 0.537\log(\frac{L}{w_f}) + 0.1384\log(\frac{w_g}{w_f}) + 0.6801}{1 + \frac{1}{1.158}\cdot(\frac{a}{w_f})^{0.6051}}$$

By Zettlemoyer and Fisher

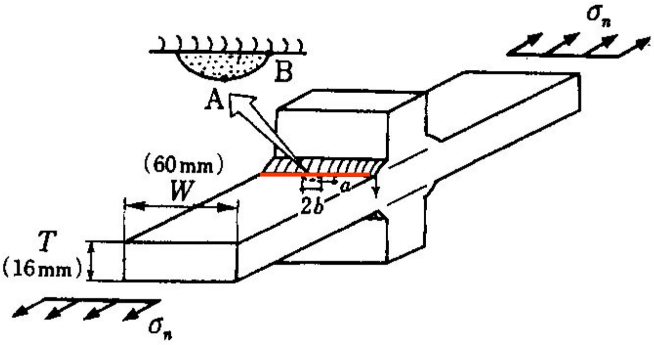
Examples of F_g





Examples of F_g

Cracks from Incomplete Penetration



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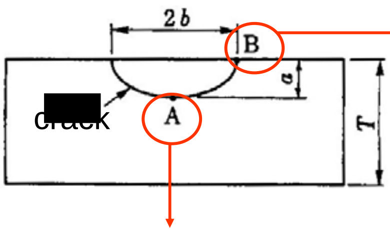
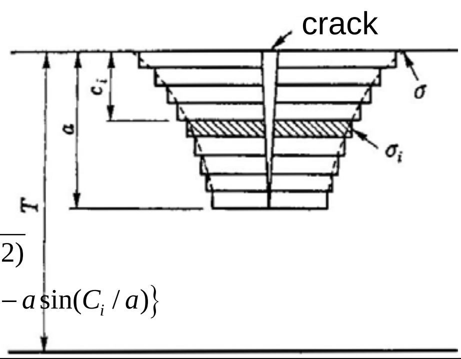
Model of Cracks



$$\Delta K_B = F_{eB} \cdot F_{tB} \cdot F_{gB} \cdot \Delta\sigma \cdot \sqrt{\pi a}$$

$$F_{eB} = F_{eA} \Big/ \sqrt{a/b}$$

$$F_{tB} = (1 - 0.025k^2 + 0.06k^4)\sqrt{\sec(\pi k/2)}$$



$$\Delta K_A = F_{eA} \cdot F_{sA} \cdot F_{tA} \cdot F_{gA} \cdot \Delta\sigma \cdot \sqrt{\pi a}$$

$$F_{eA} = 1 \Big/ \sqrt{1 + 1.464(a/b)^{1.65}}$$

$$F_{sA} = 1 + 0.12(1 - a/b)$$

$$F_{tA} = (1 - 0.025\lambda^2 + 0.06\lambda^4)\sqrt{\sec(\pi\lambda/2)}$$

$$F_{gA} = (2/\pi)\sum(\sigma_i/\sigma_n)\left\{a\sin(C_{i+1}/a) - a\sin(C_i/a)\right\}$$

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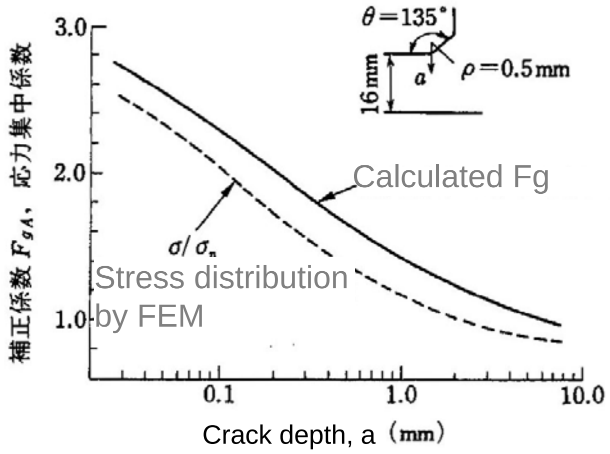
Calculation of Fg

Relationships of stress distribution and Fg



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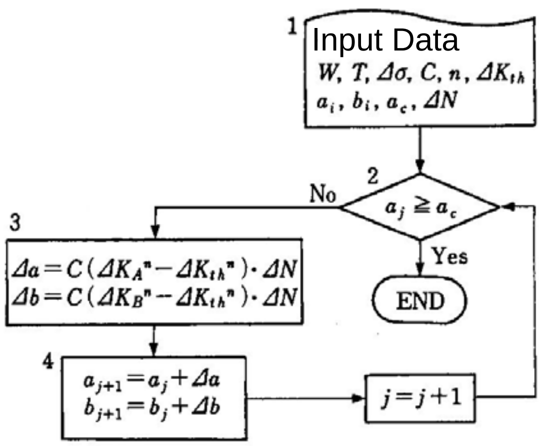
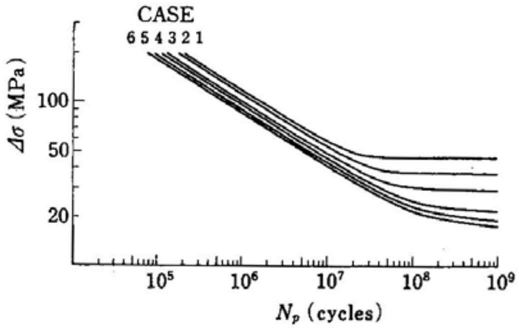
Calculation strategies



Results

Variation of initial crack width and height



Initial crack geometry

CASE	depth a (mm)	width $2b$ (mm)
1	0.1	0.4
2	0.2	0.8
3	0.5	2.0
4	1.0	4.0
5	1.5	6.0
6	2.0	8.0

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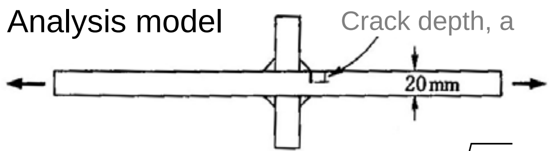
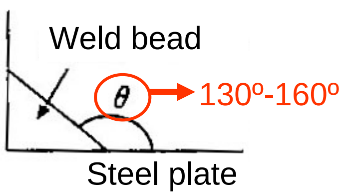
Effects of weld shape

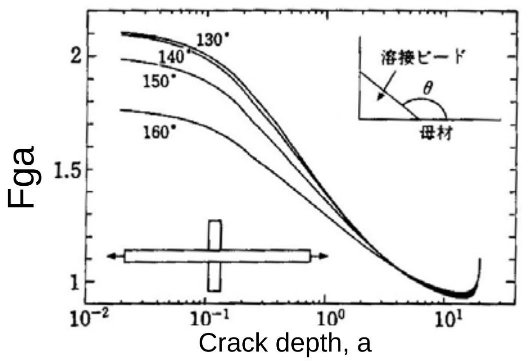
Analysis model



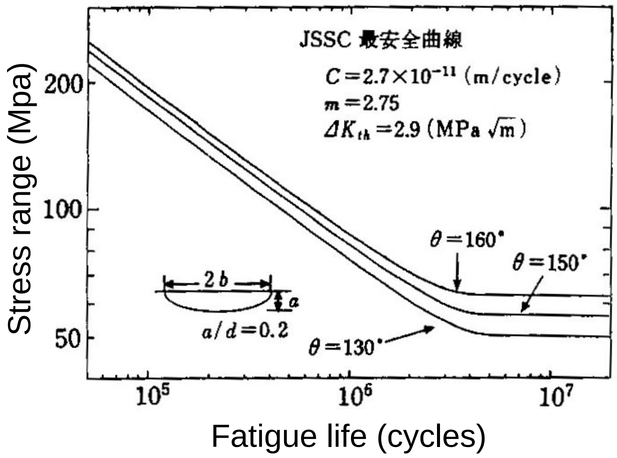
a_o = 0.1 mm
$2b_o$ = 1.0 mm

$$\Delta K_A = F_{eA} \cdot F_{sA} \cdot F_{tA} \cdot F_{gA} \cdot \Delta\sigma \cdot \sqrt{\pi a}$$

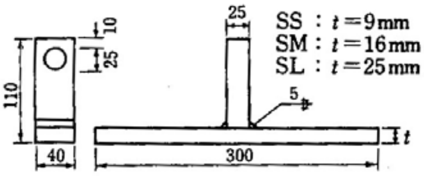




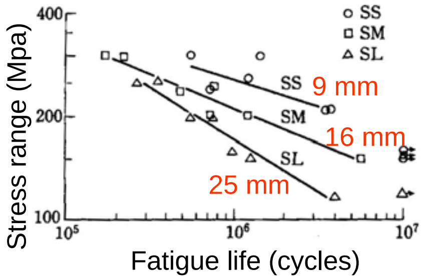
Effects of weld shape



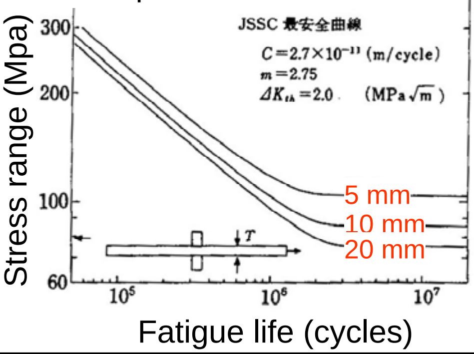
Effects of plate thickness



Experimental results



Computational results



Fracture Toughness

The Condition for Unstable Crack Growth

$$K = K_c$$

Fracture Toughness

The Critical Stress Intensity Factor for Unstable Crack Growth

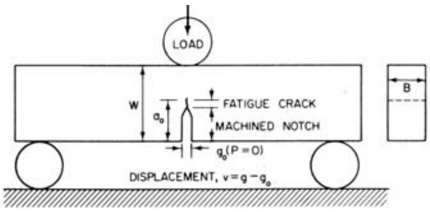
Mode I

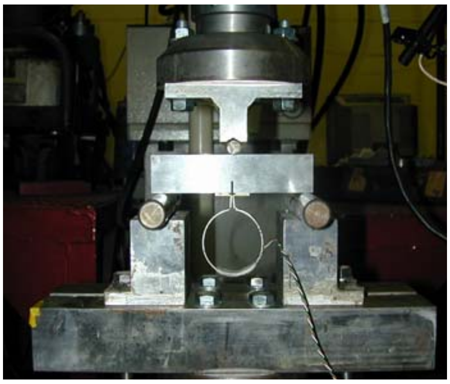
$$K_I = K_{Ic}$$

Test Methods to Evaluate K_{Ic}

ASTM E-399

A Bend Specimen

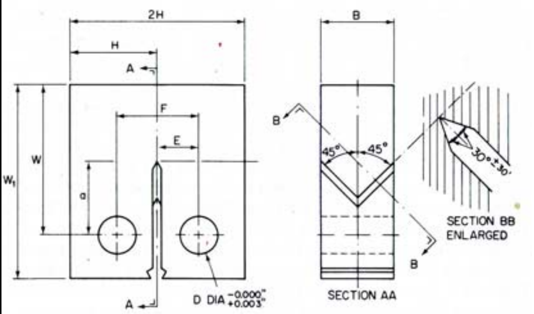


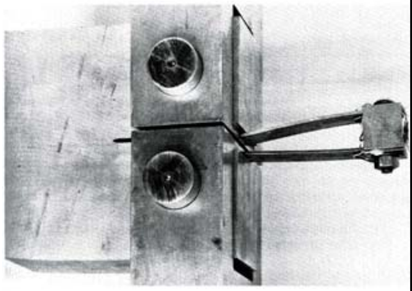


Test Methods to Evaluate K_{Ic}

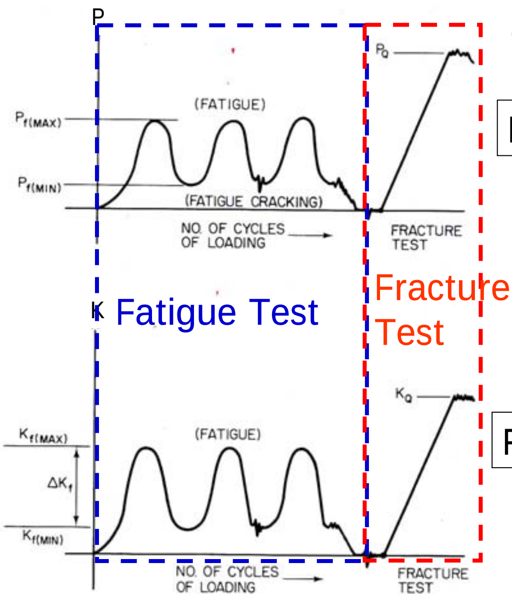
ASTM E-399

Compact Tension Specimen





Test Methods to Evaluate K_{Ic}



The Testing Program

Fatigue Cracking

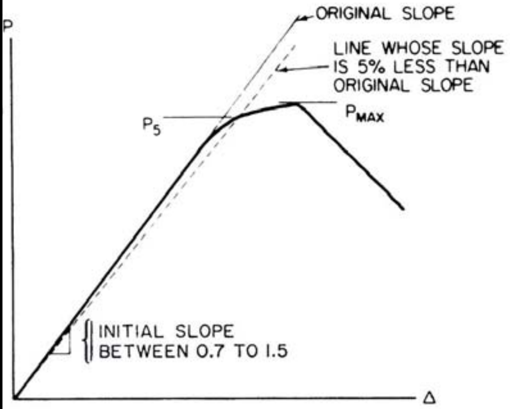
Small Scale Yielding Condition

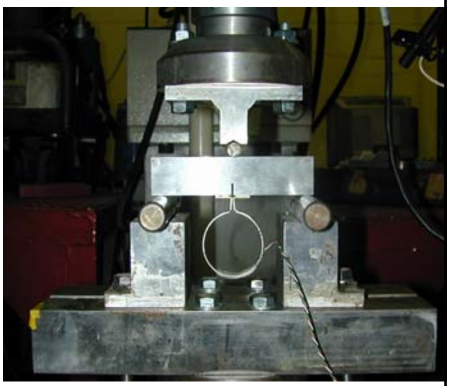
Fracture Test

Plane Strain Condition

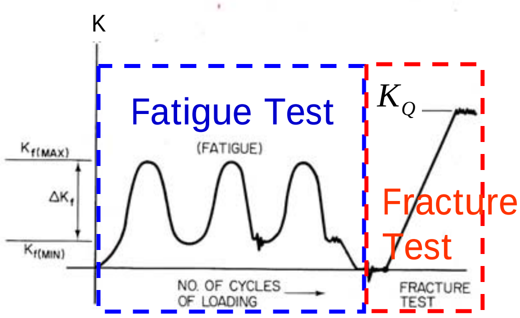
Test Methods to Evaluate K_{Ic}

Fracture Tests





Test Methods to Evaluate K_{Ic}



$$a \geq 2.5\left(\frac{K_Q}{\sigma_{Yield}}\right)^2, B \geq 2.5\left(\frac{K_Q}{\sigma_{Yield}}\right)^2, W \geq 5.0\left(\frac{K_Q}{\sigma_{Yield}}\right)^2$$

$$K_Q \Rightarrow K_{Ic}$$

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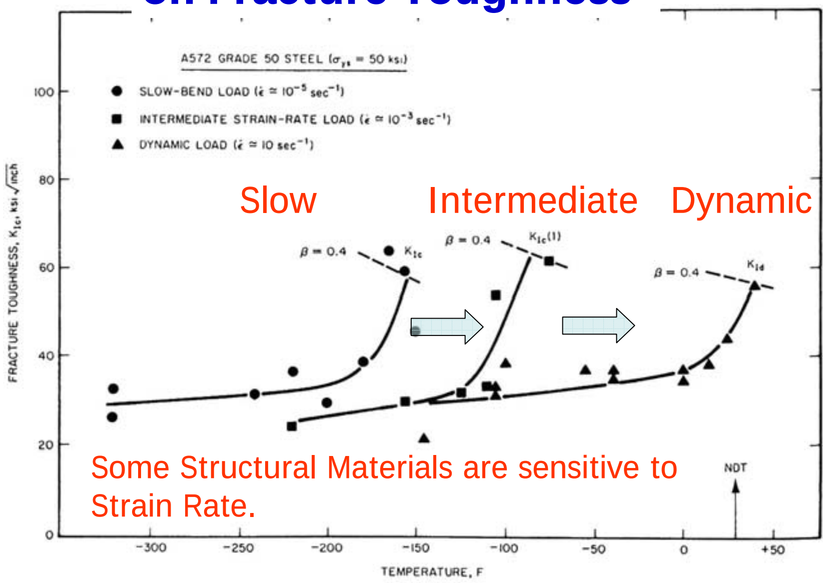
Effects of Loading Rate on Fracture Toughness



Some Structural Materials are sensitive to Strain Rate.

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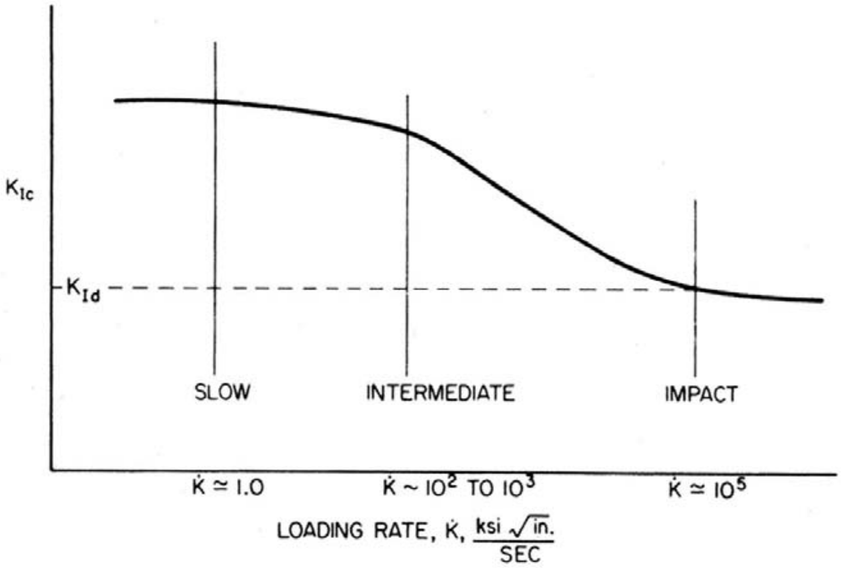
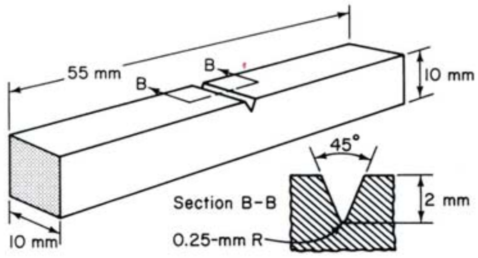
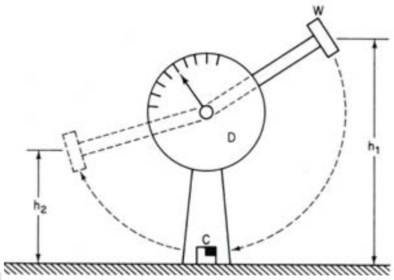
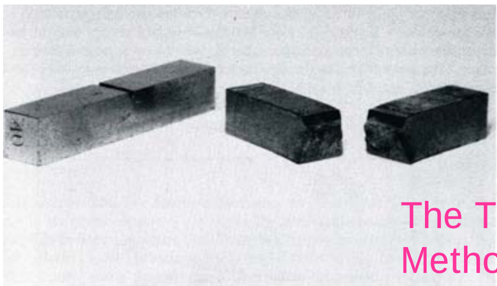
Effects of Loading Rate on Fracture Toughness



Charpy Impact Tests



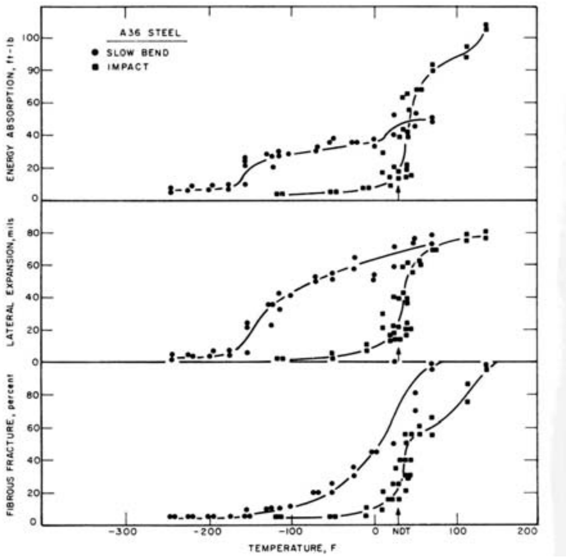




Charpy V-Notch (CVN) Impact Tests

The Traditional Evaluation Method of Fracture Toughness

Charpy Impact Tests



To Prevent Brittle Fracture

Absorbed Energy: Ev

Transition Temperature: Ttr

Absorbed Energy-Temperature

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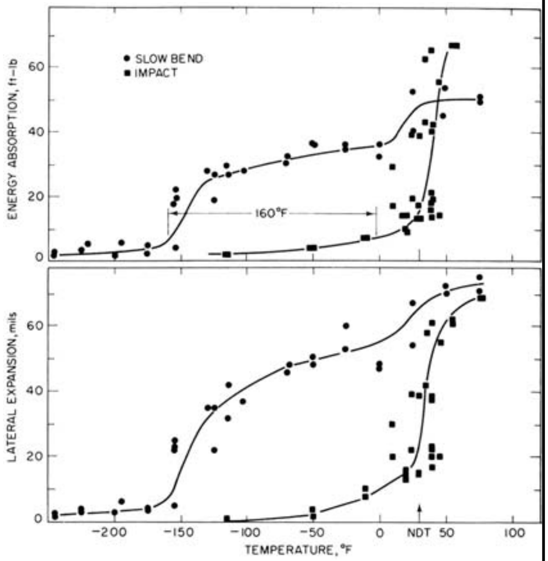
CVN Tests vs K1c Tests

CVN Tests:
Dynamic Condition
Crack Initiation
+ Propagation

K1c Tests:
Slow Bending
Crack Initiation



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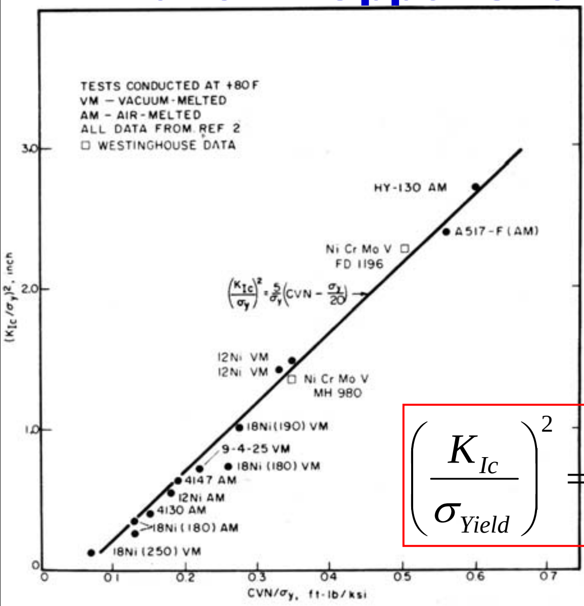
K1c- CVN Upper Shelf Correlation



Proposed by
Barsom and Rolf

$$\left(\frac{K_{Ic}}{\sigma_{Yield}}\right)^2 = 5\left(\frac{CVN}{\sigma_{Yield}} - 0.05\right)$$