Task 6 - Safety Review and Licensing
On the Job Training on Stress Analysis

Fracture Mechanics experimental tests (ASTM standards and data) 1/2

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BEYOND THE RESEARCH

UNIVERSITÀ DI PISA

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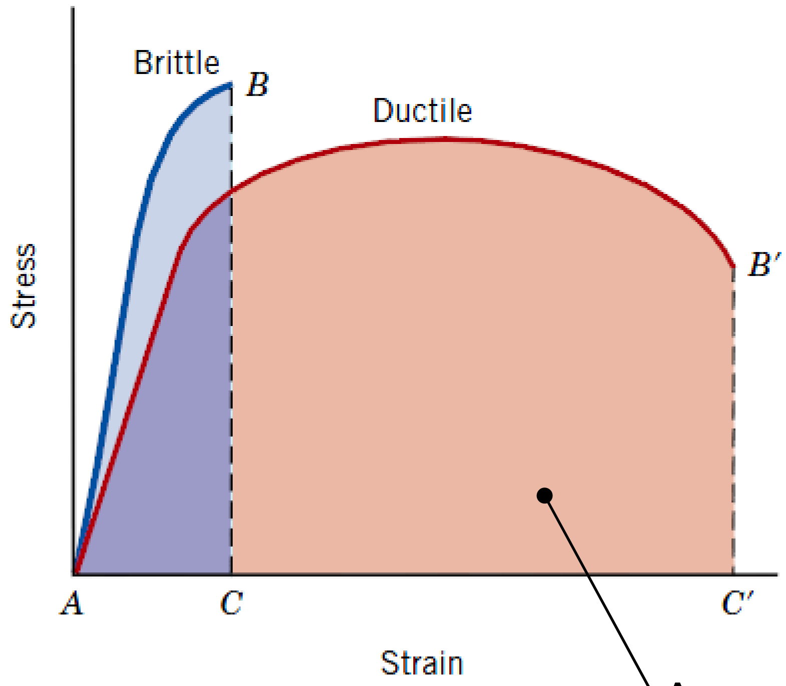
Content

- Fracture Toughness K_{Ic}
  - Plane strain condition
  - ASTM standard E399
- High Toughness J_{Ic}
  - Limitation of the K_{Ic}
  - ASTM standard E1820
- Measurement of Fatigue Crack Growth Rates
  - Paris curve experimental determination, ASTM standard E647

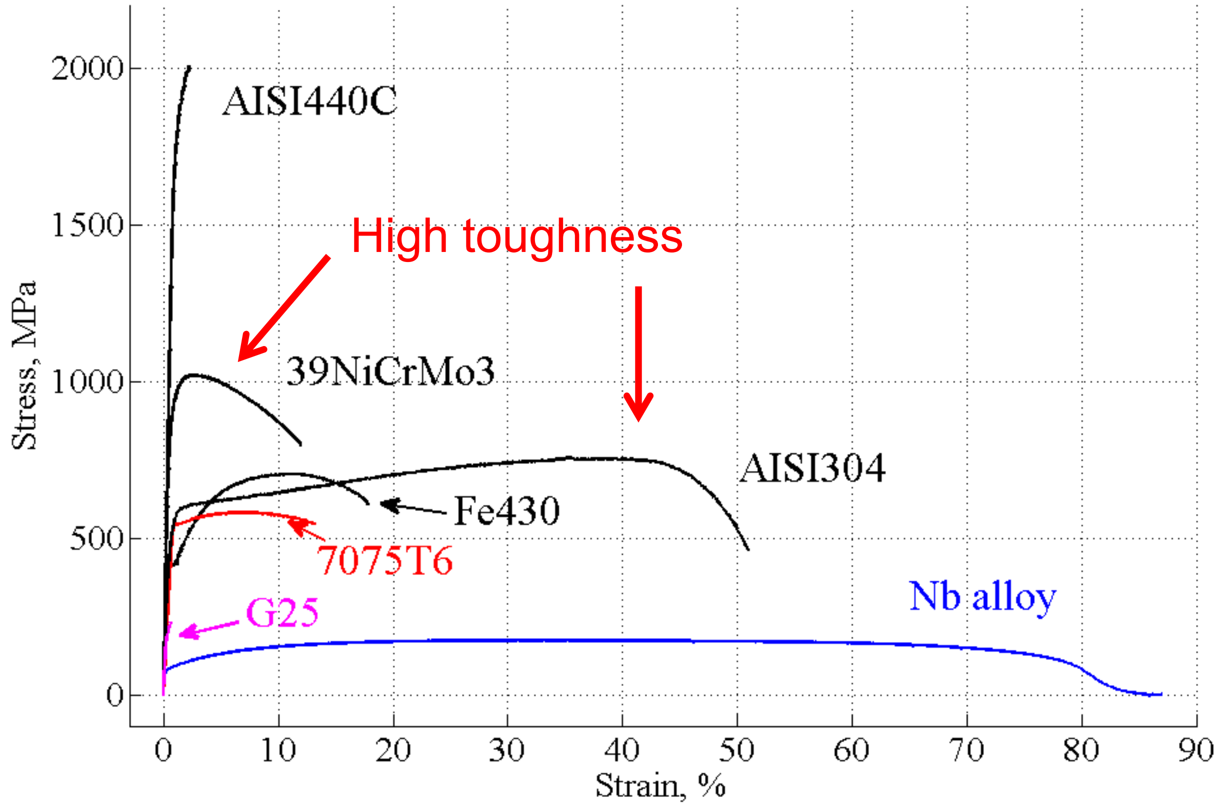
Toughness is NOT *Fracture* Toughness



Plain specimen:
Toughness is the energy (per unit volume) absorbed before final fracture:
- No notch
- No stress concentration

Area: $\sigma\,\varepsilon$ = Energy density

Toughness usually is a trade-off between Strength and Ductility



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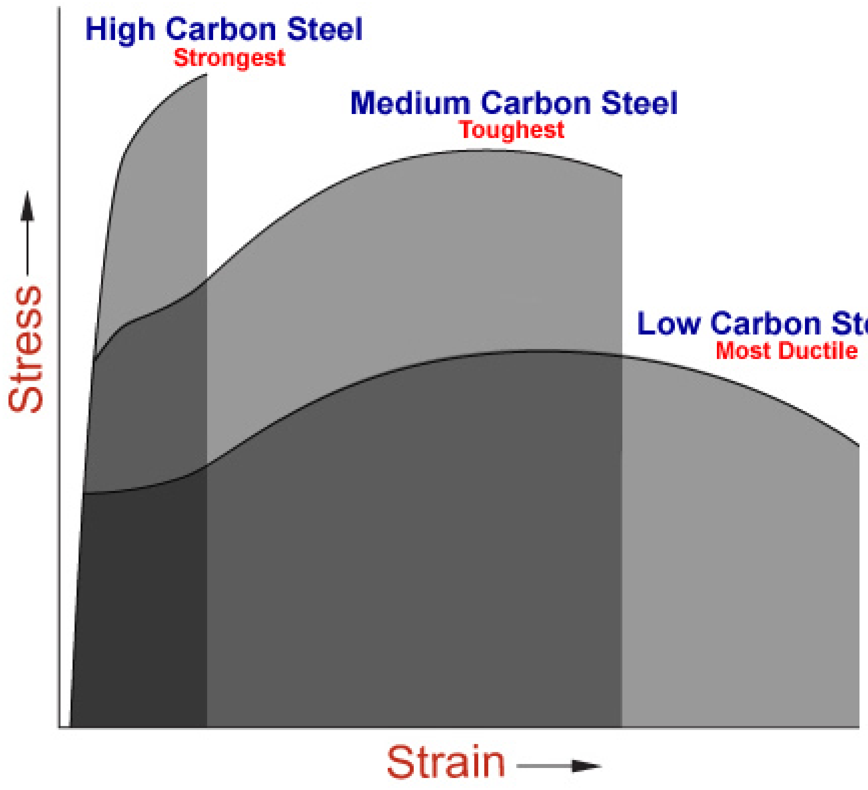


What is the Fracture Toughness

- It is a property indicative of the material resistance to fracture, relatively to a cracked body (high stress triaxiality and high stress concentration)

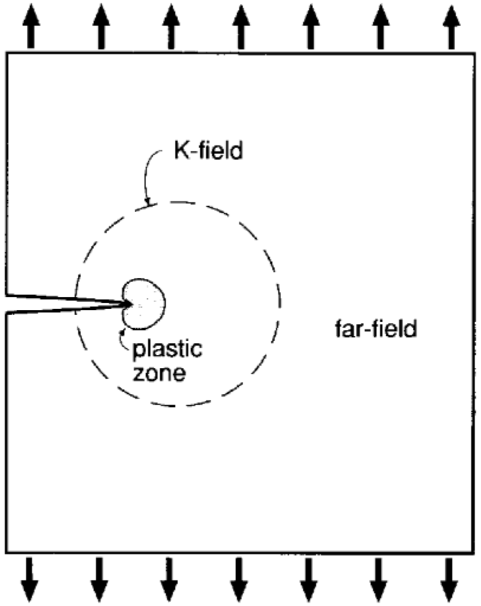
- It is a quantity to be compared to the Stress Intensity Factor

- Usually, just the First SIF is considered

$$K_c \quad \text{'c' stands for the Critical value}$$

Resistance criterion

The crack tip stress and strain distributions may not be well understood or well quantified. If the LEFM holds the K-field defines the actual loading at the crack tip.

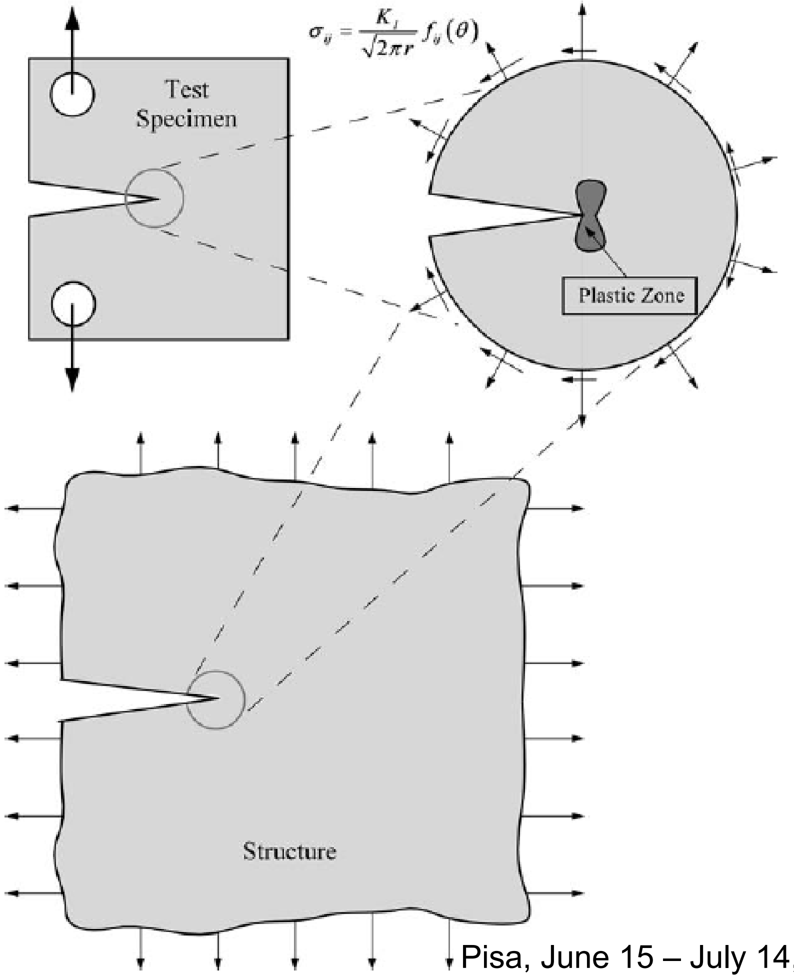


$$K_{\mathrm{I}} < K_{\mathrm{c}} \quad \rightarrow \text{Crack stable, no crack propagation}$$

$$K_{\mathrm{I}} > K_{\mathrm{c}} \quad \rightarrow \text{Unstable crack propagation (fracture)}$$

If the plastic zone is too large K-field concept is questionable and then LEFM is no more valid…

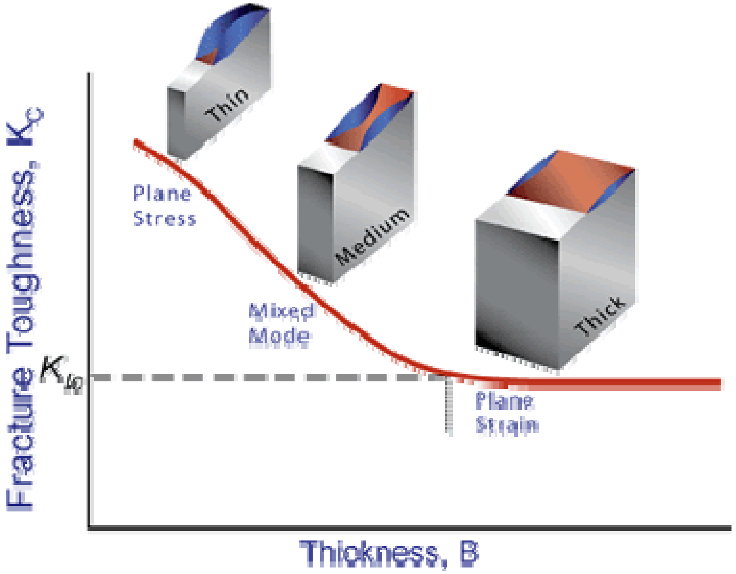
From specimen to component



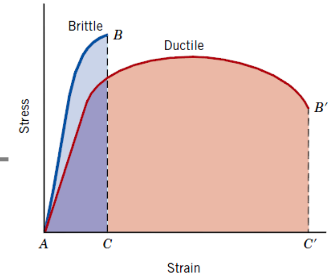
If the plastic zone is small, the K-field dominates the pl. zone and then the fracture zone

Is fracture toughness a purely material property?

It is a matter of fact that the Fracture Toughness depends on the specimen thickness. Apparently the explanation is: Pl. Stress/ Pl. Strain

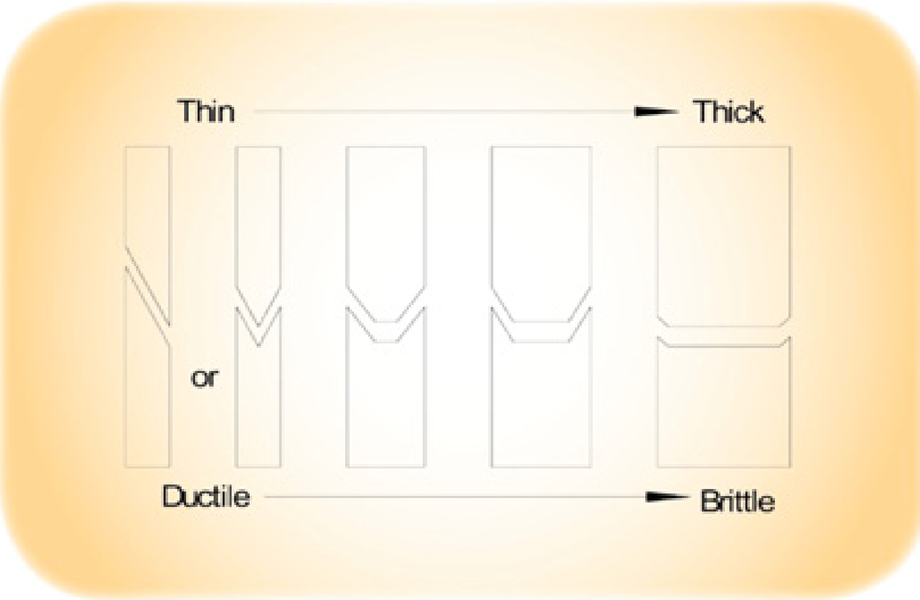


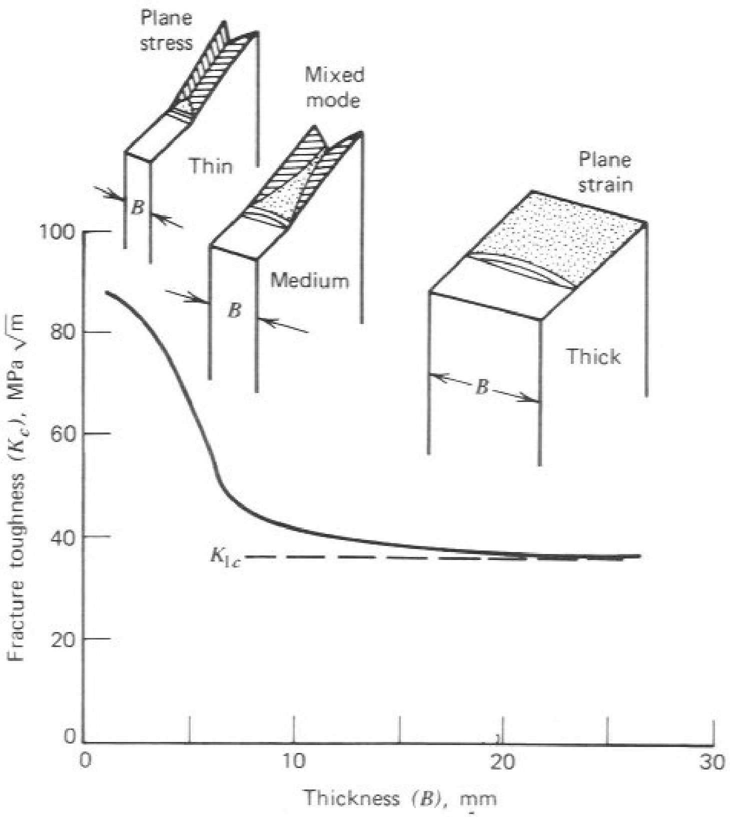
A thicker specimen shows lower Toughness (though the total force for fracture may be higher)
Under pl. strain conditions the plastic volume is less and then the absorbed energy.



Thickness dependence Pl. Stress/ Pl. Strain

45° fracture is usual under Pl. Stress
or at least not well developed Pl. Strain





Thickness dependence Pl. Stress/ Pl. Strain

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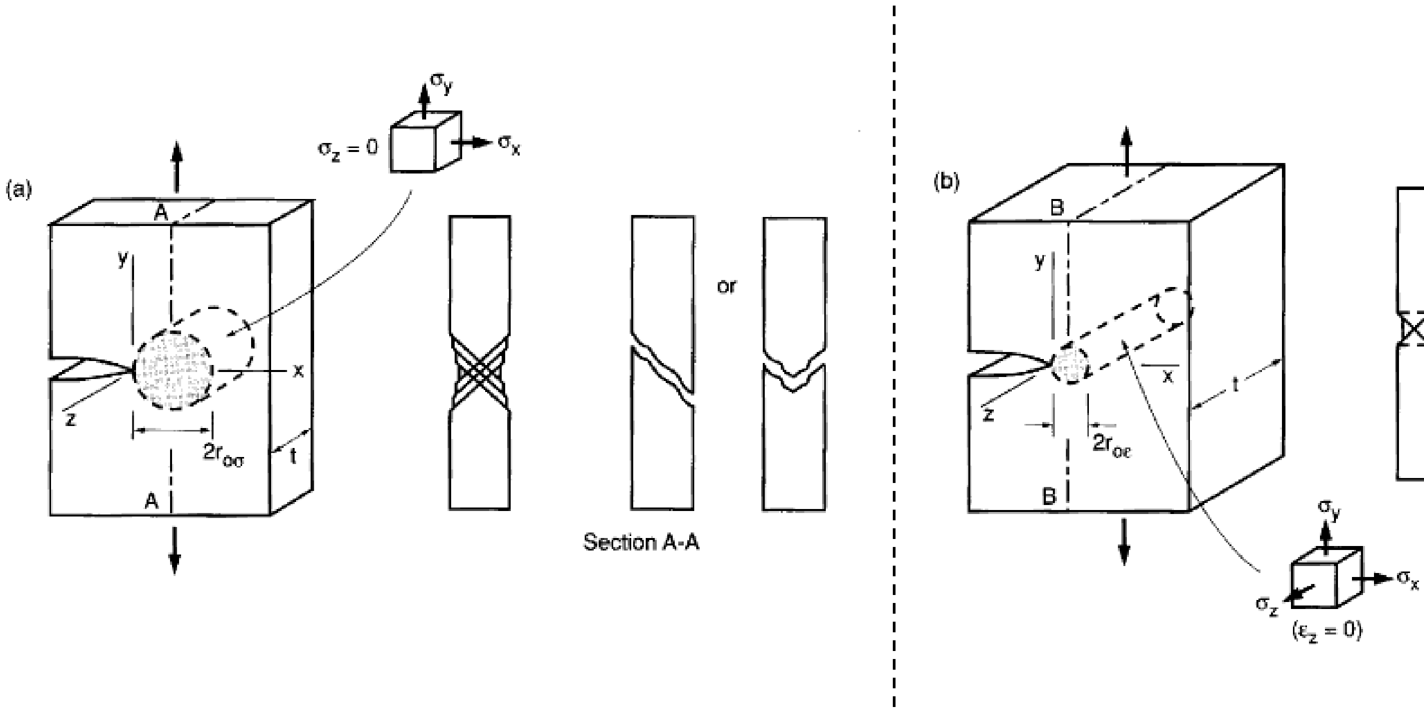
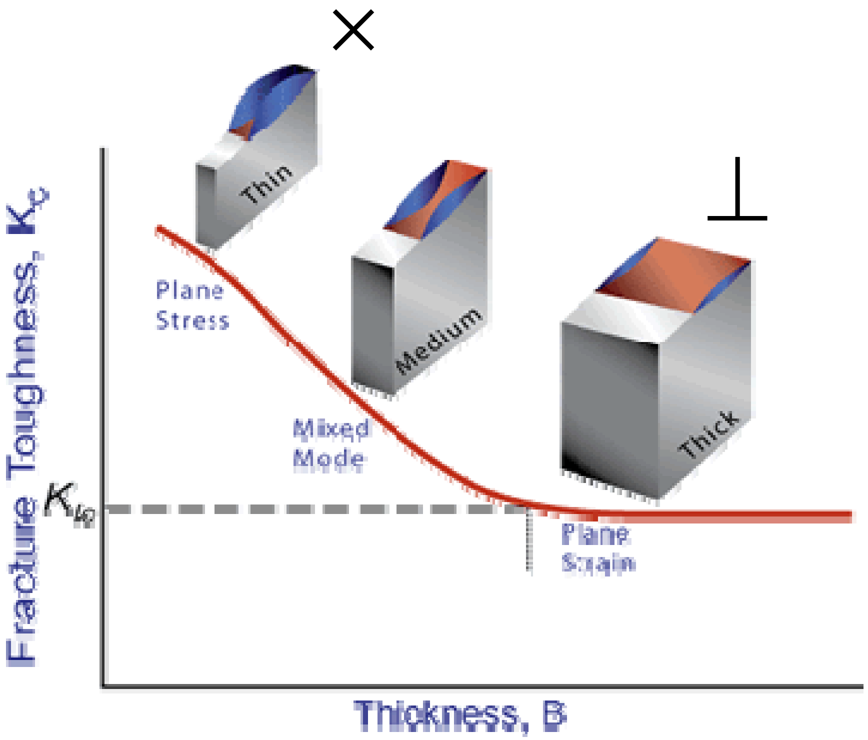


High thickness (Pl. Strain) Fracture Toughness



The high thickness fracture section is mainly perpendicular to the load, that's why the 'I' (first) is added to the fracture toughness symbol

Large thickness:

$K_c \rightarrow K_{Ic}$

K_{Ic} is a material property only!

no more dependent on thickness

or any other geometry parameter

Standard E399

Designation: E399 – 09$^{\varepsilon 2}$

Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials[1]

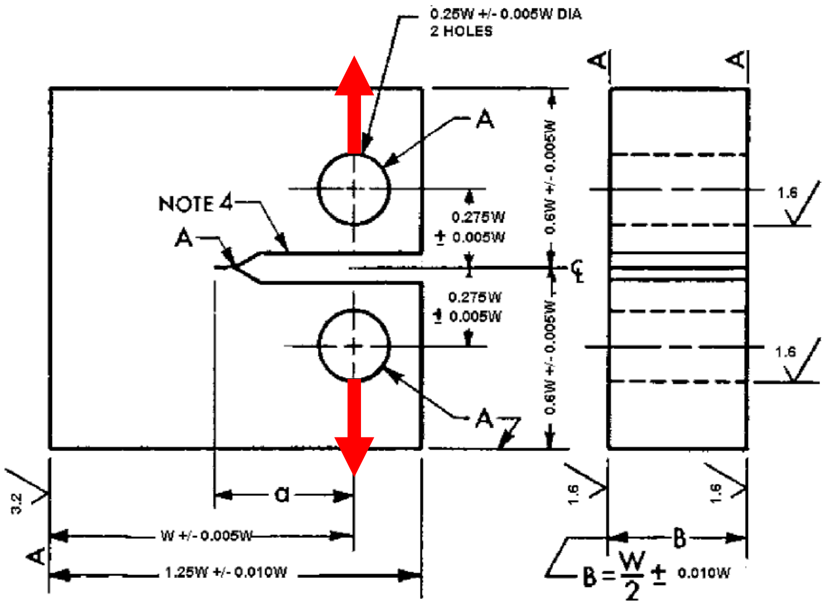
This standard is issued under the fixed designation E399; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

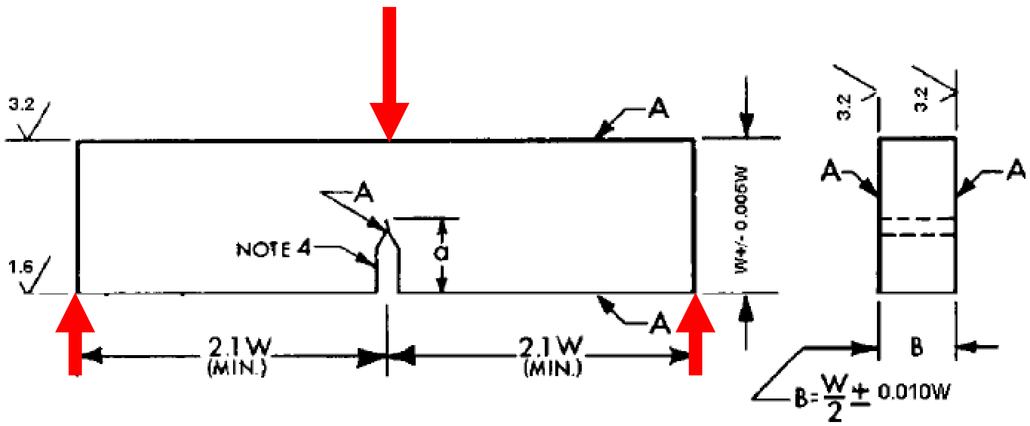
ε^1 NOTE—Eq A3.4, Eq A4.4, Eq A5.4, and Eq A6.11 were editorially corrected in May 2010.
ε^2 NOTE—11.2 and 11.4 were editorially corrected in December 2010.

ASTM Standard test for K_{Ic}

Specimen geometries



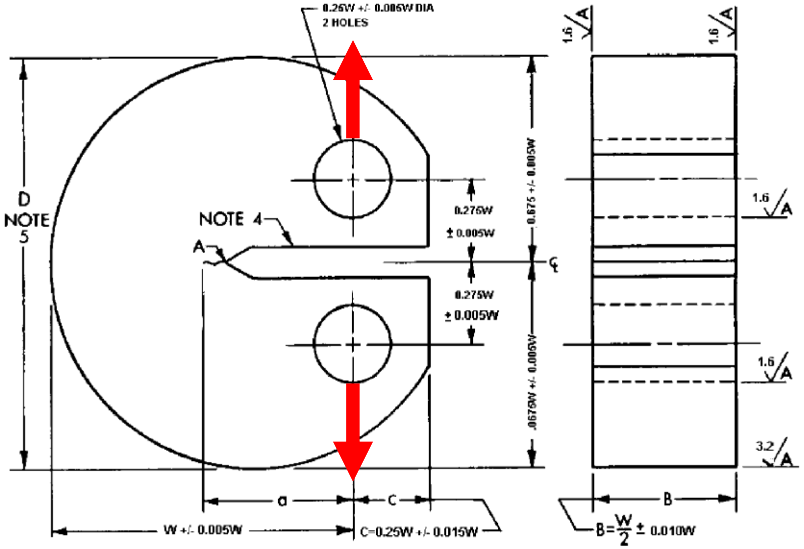
SEB specimen
Single Edge notched specimen
for three or four point Bending



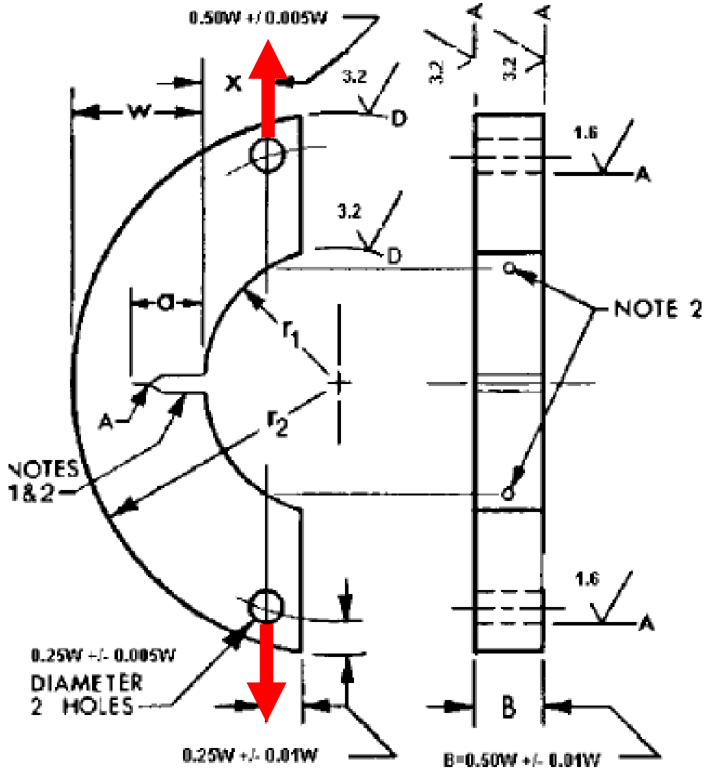
CT specimen
Compact Tension specimen,
tensile load applied at the holes
Mostly used and referenced

Specimen geometries

Disc shaped specimen
DCT specimen, similar to CT



Arc-Shaped Tension
AT specimen

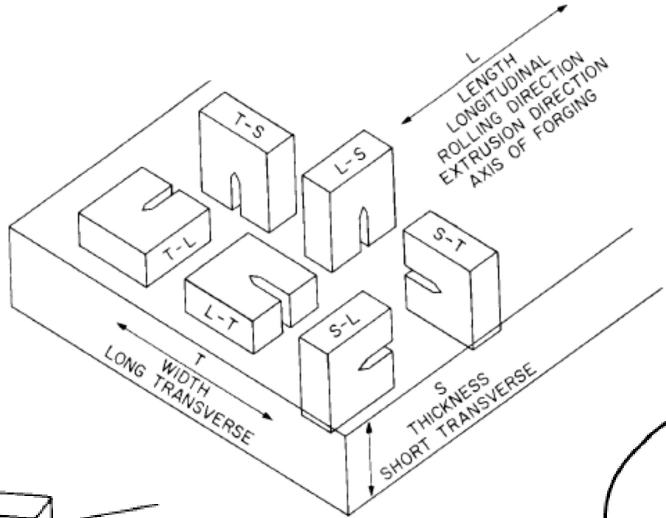


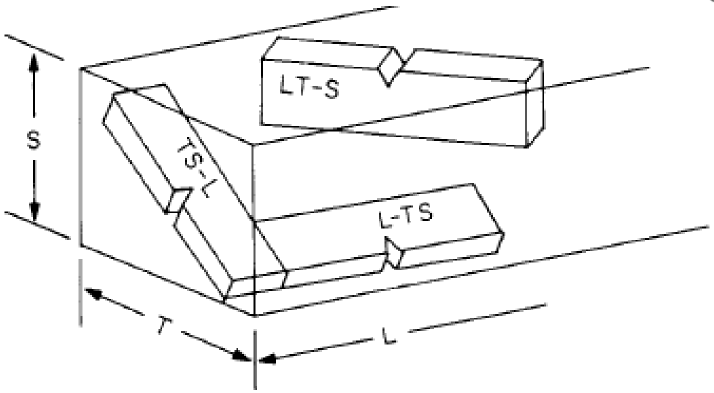
(a) $X/W = 0.5$

Specimen orientations

L = direction of principal deformation (maximum grain flow)
T = direction of least deformation
S = third orthogonal direction

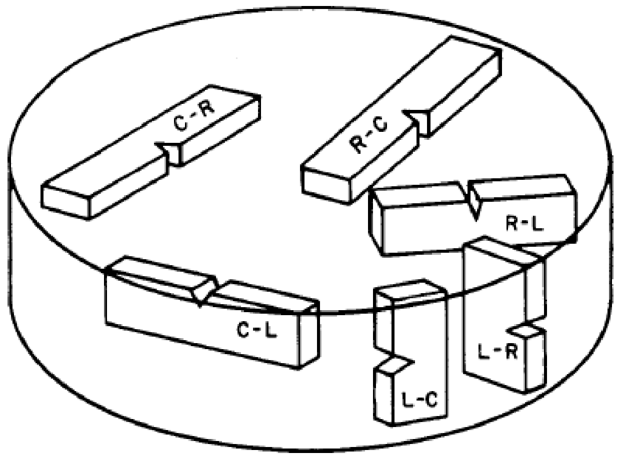
Plates



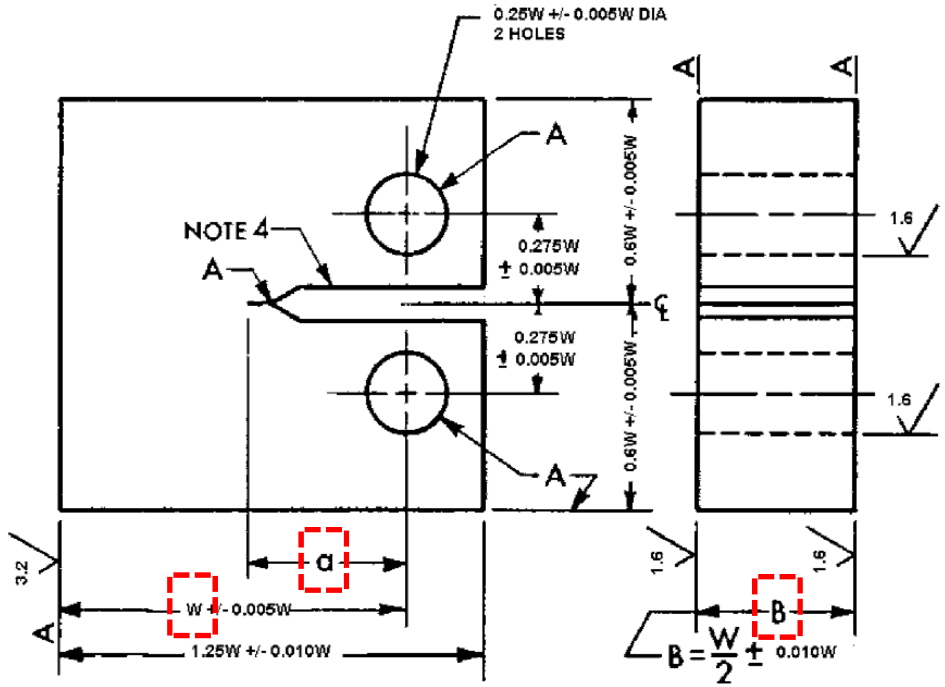


Cylindrical bars

L = direction of maximum grain flow
R = radial direction
C = circumferential or tangential direction



Specimen dimensions



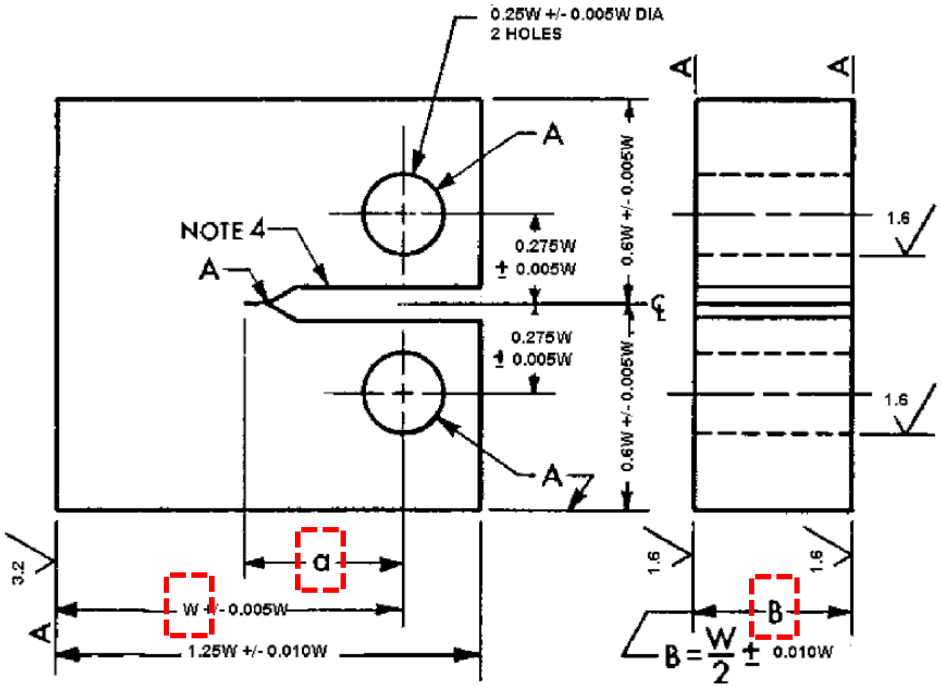
Main dimensions are:

a crack size

W specimen width

B specimen thickness

Specimen dimensions

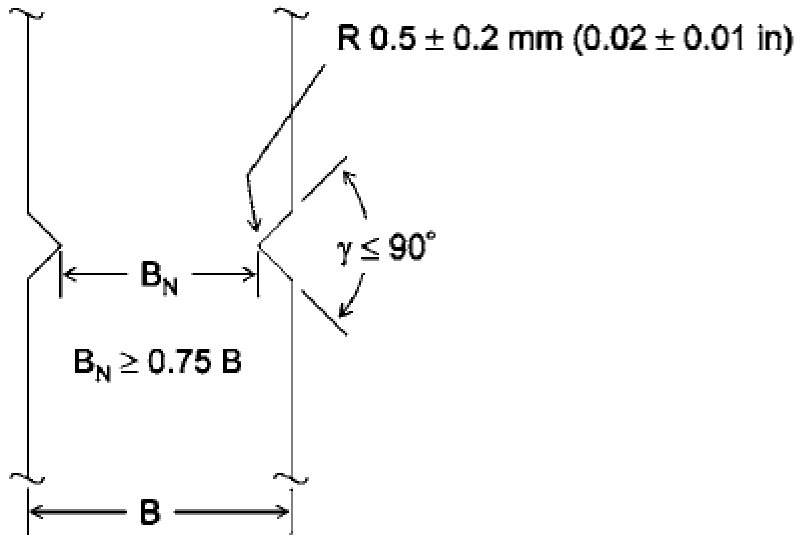


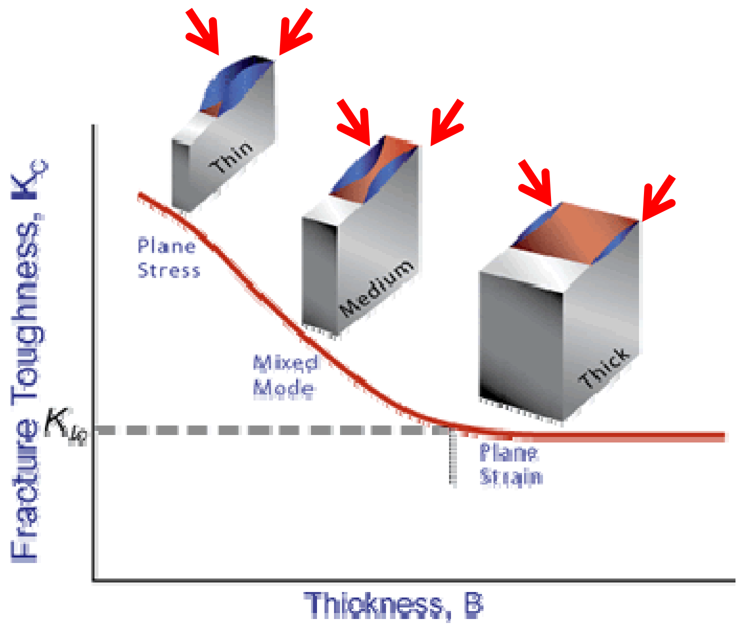
W is a free parameter that defines the specimen size

The specimen thickness *B* is imposed as half the width *W*

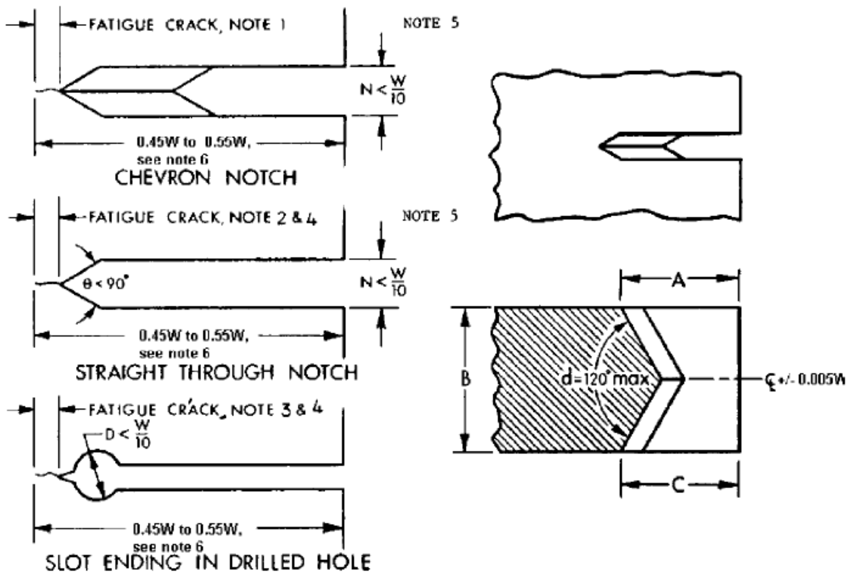
Side groove

To reduce the effect of the shear lips on the lateral edges





Specimen dimensions



(*a*) Starter Notches and Fatigue Cracks

(*b*) Detail of Chevron Notch

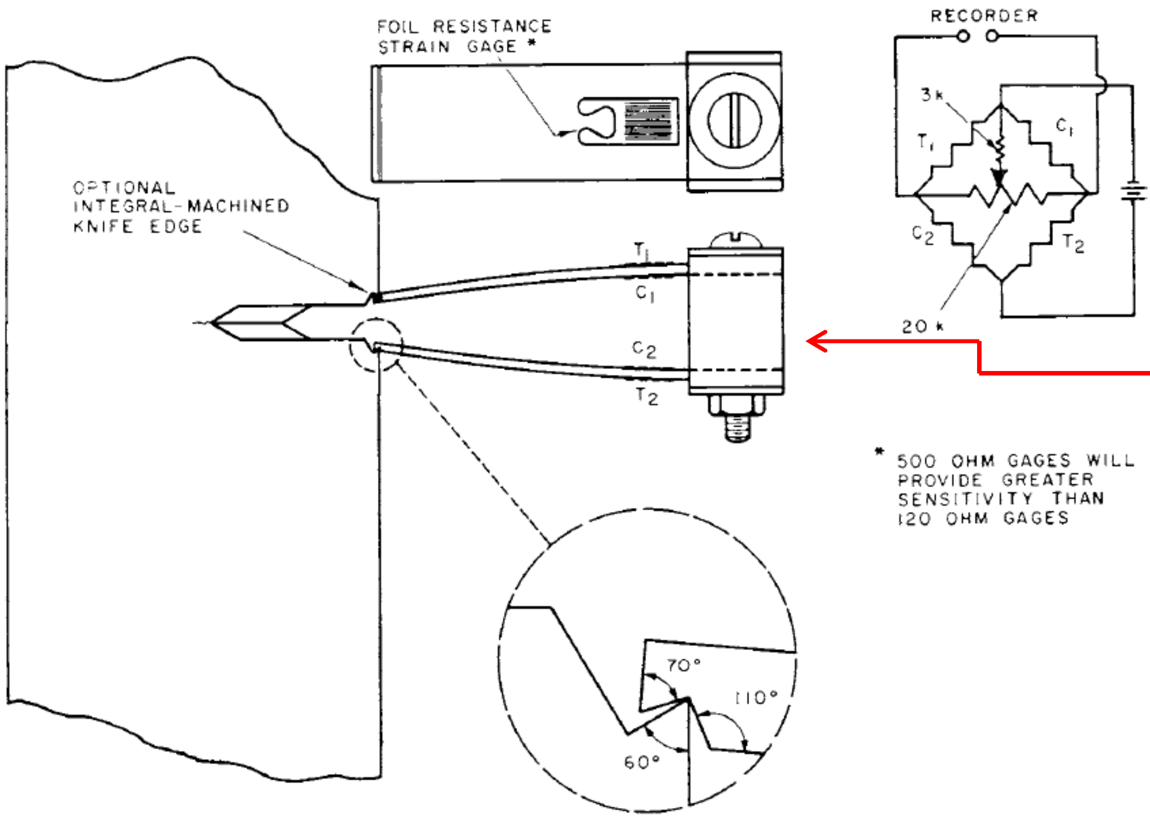
The crack size is from the load axis to the crack front.

The crack is generated by fatigue (precrack procedure)

Chevron Notch can help precracking

The crack size is recommended to be in the range 0.45-0.55 *W* so, again half the width

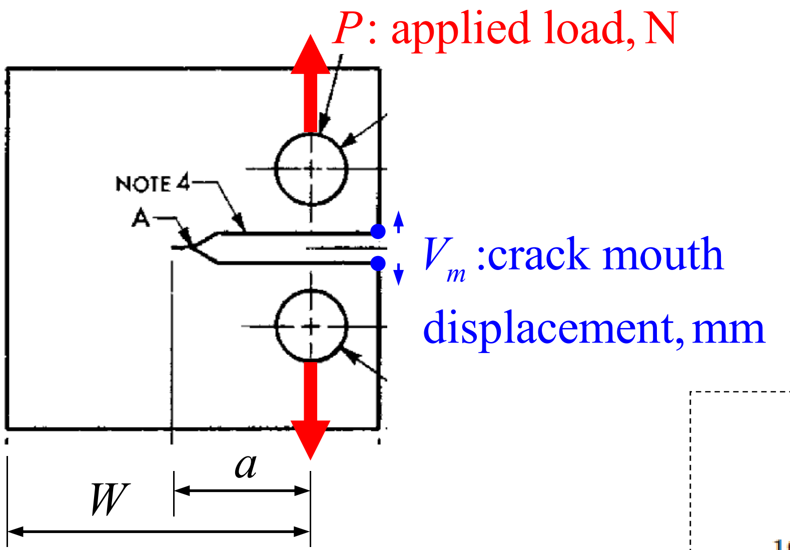
Compliance method to determine the crack size



Double–Cantilever Clip-In Displacement Gage

The crack size can be correlated to the specimen Compliance

A4. SPECIAL REQUIREMENTS FOR TESTING COMPACT SPECIMENS



$$\frac{V_m}{P} = \frac{1}{E'\,B_e} \cdot q\left(\frac{a}{W}\right)$$

E':Elastic constraint modulus

$E' = E$ plane stress

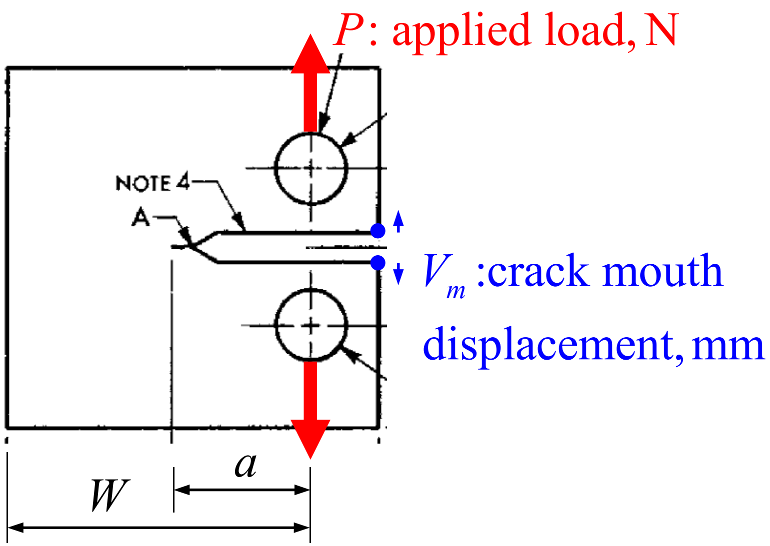
$E' = \frac{E}{1-\nu^2}$ plane strain

$Be = B - (B - B_N)^2 / B$

$$q\left(\frac{a}{W}\right) = \tag{A4.4}$$

$$\frac{19.75}{\left(1-\frac{a}{W}\right)^2}\left[0.5 + 0.192\frac{a}{W} + 1.385\left(\frac{a}{W}\right)^2 - 2.919\left(\frac{a}{W}\right)^3 + 1.842\left(\frac{a}{W}\right)^4\right]$$

Compliance inverse relationship is required to find the crack size



$$\frac{a}{W} = 1.000 - 4.500 \cdot U + 13.157 \cdot U^2 - 172.551 \cdot U^3 + 879.944 \cdot U^4 - 1514.671 \cdot U^5 \qquad (A4.5)$$

where:

$$U = \frac{1}{1 + \sqrt{\frac{E' B_e V_m}{P}}} \qquad (A4.6)$$

Step 1: Calculate U from the applied load and the crack mouth opening displacement (A 4.6)

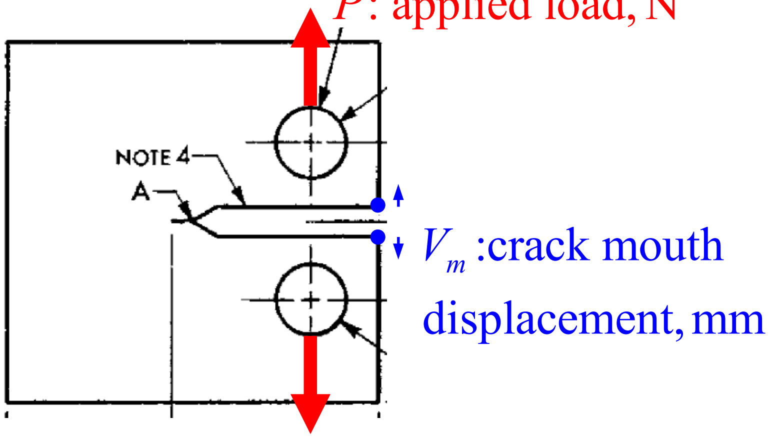
Step 2: Calculate the a / W ratio (A 4.5)

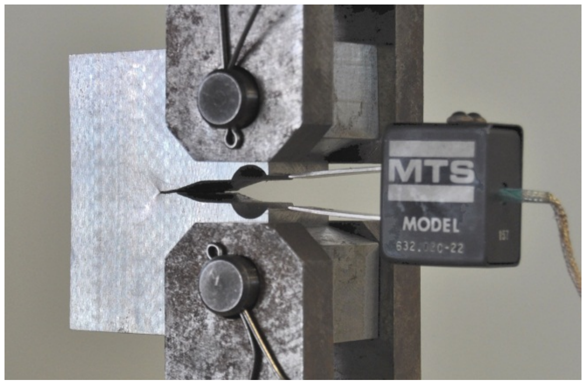
Step 3: Easily deduce a since W is obviously known

7.3.2.1 Crack size (total size of crack starter plus fatigue crack) shall be between 0.45W and 0.55W.

7.3.2.2 The size of the fatigue crack on each face of the specimen shall not be less than the larger of 0.025W or 1.3 mm (0.050 in.) for the straight-through crack starter configuration, not less than the larger of 0.5D or 1.3 mm (0.050 in.) for the slot ending in a hole (of diameter $D < W/10$), and need only emerge from the chevron starter configuration.

The Fracture Toughness test





Similarly to the Tensile Test,
a slow and monotonic displacement rate is imposed up to the specimen fracture.

The test should be under displacement control

The recorded displacement related to the load can be either the machine imposed or the crack mouth displacement

P_Q value

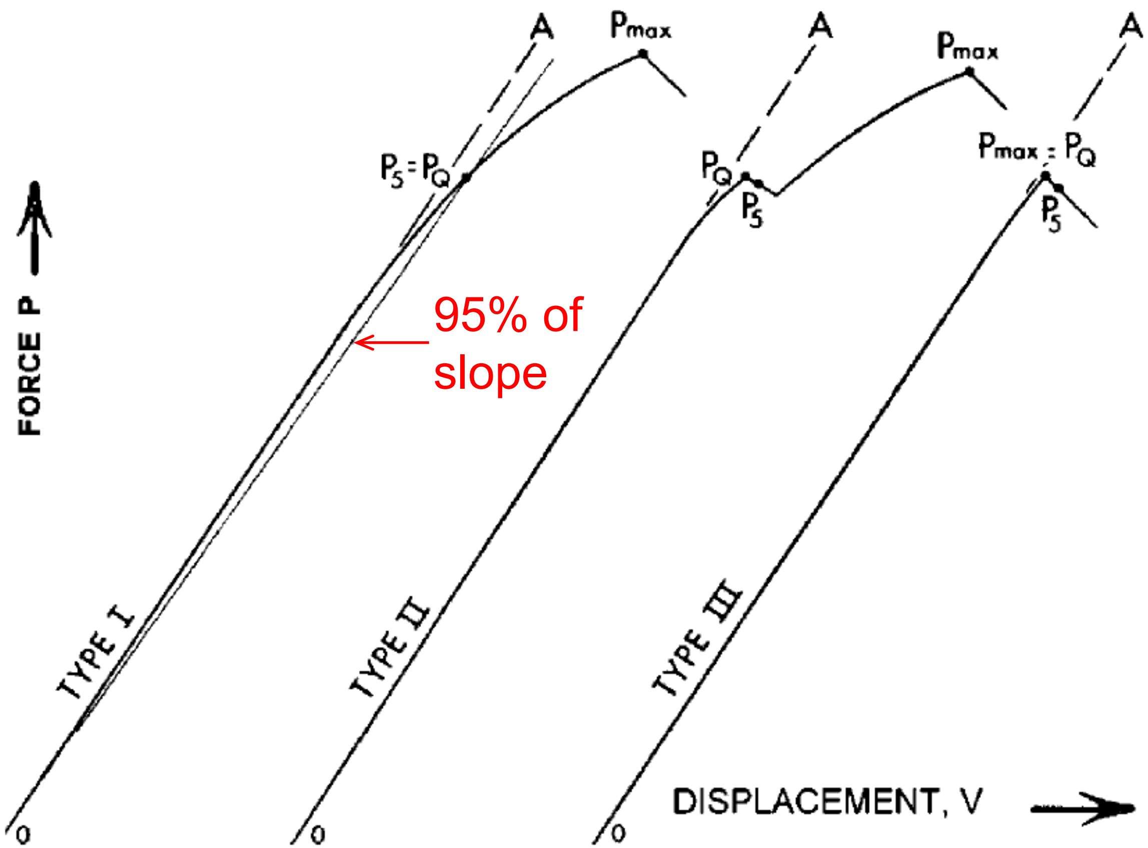


FIG. 7 Principal Types of Force-Displacement (CMOD) Records

Q stands for Conditional result
(initially it is evaluated,
then a condition is to be verified!)

P_5 is the 95% intersection, then
3 different possible behaviors:

Type I: No max. before P_5, $P_Q = P_5$

Type II: P_Q is the max.
before P_5 and $P_{max} > P_Q$

Type III: P_Q is the max.
before P_5 and no more max. after

P_{max}/P_Q

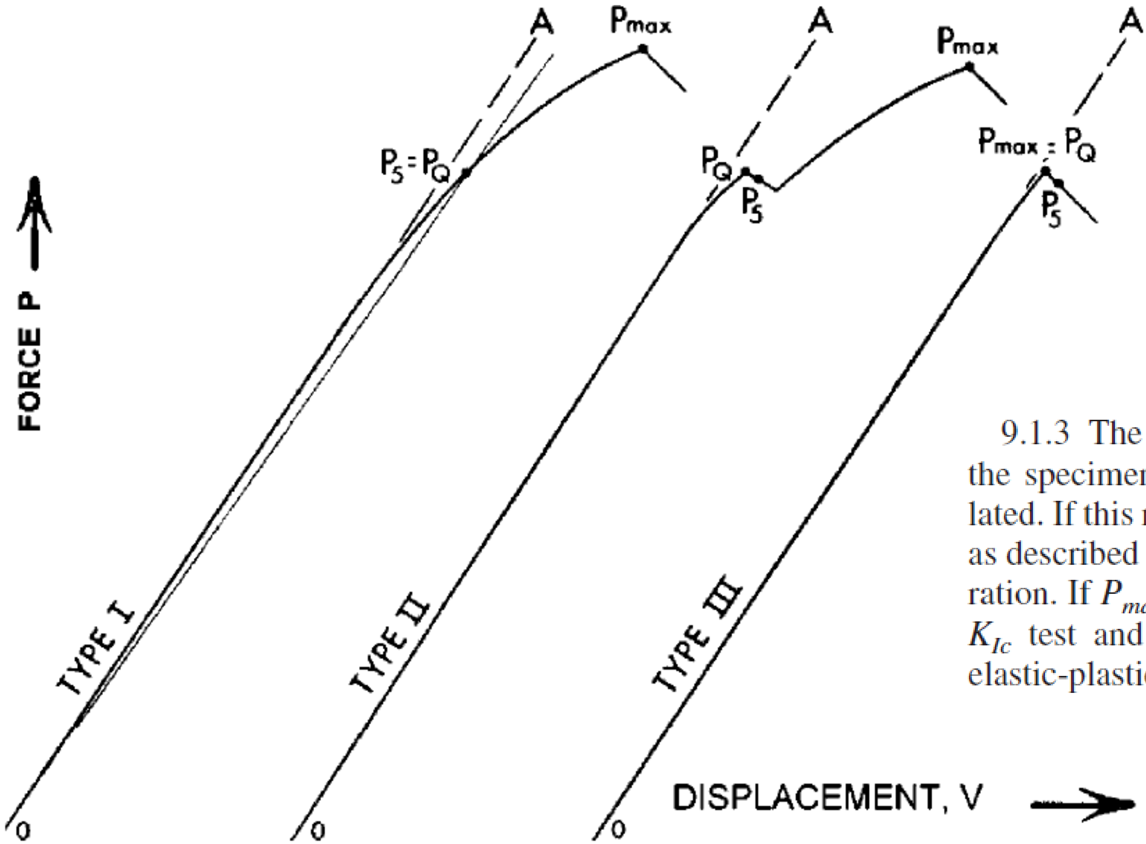


FIG. 7 Principal Types of Force-Displacement (CMOD) Records

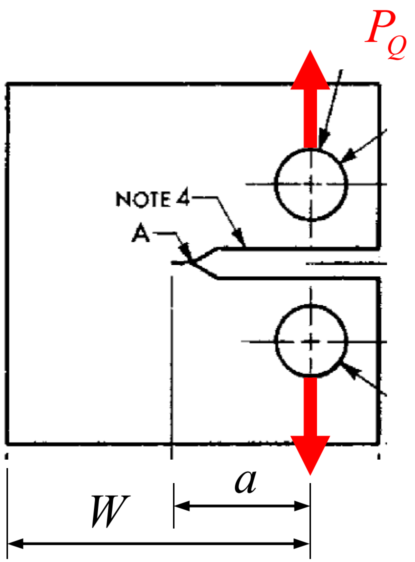
First condition to be fulfilled

9.1.3 The ratio P_{max}/P_Q, where P_{max} is the maximum force the specimen was able to sustain (see 8.4.1), shall be calculated. If this ratio does not exceed 1.10, proceed to calculate K_Q as described in the Annex appropriate to the specimen configuration. If P_{max}/P_Q does exceed 1.10, then the test is not a valid K_{Ic} test and the user is referred to Test Method E1820 on elastic-plastic fracture toughness.

This is the standard for J!

After crack test the SIF (Mode I) can be calculated at the load P_Q

a is known after compliance



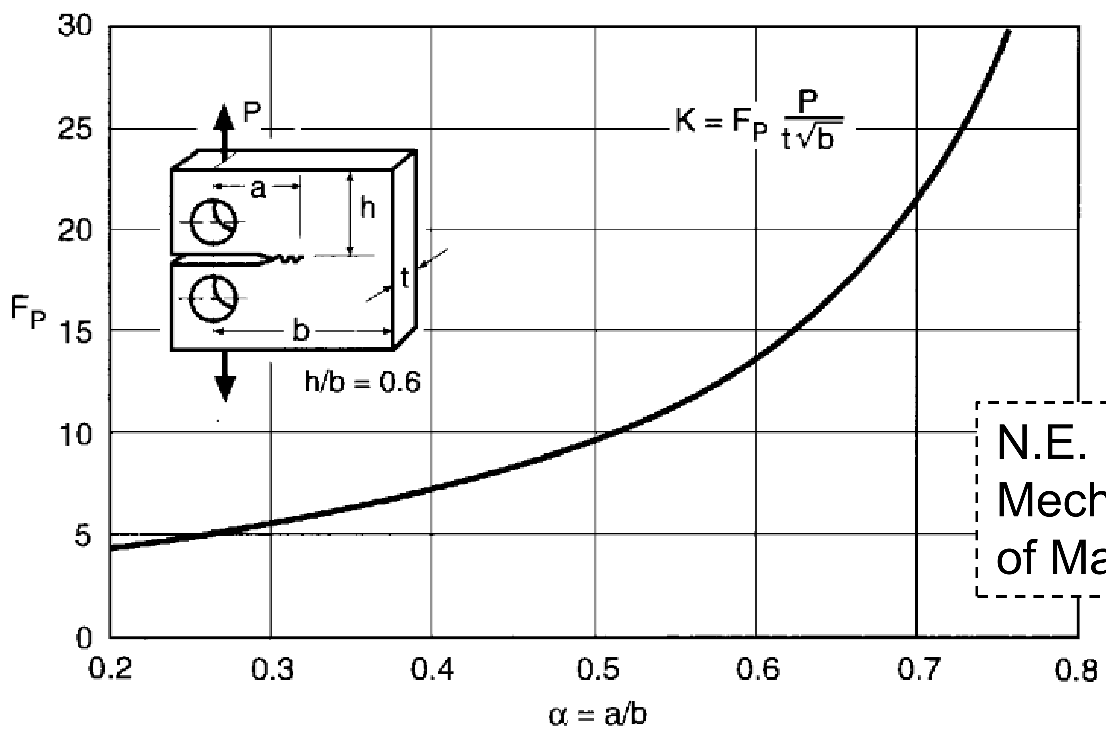
$$K_Q = \frac{P_Q}{\sqrt{BB_N}\sqrt{W}} \cdot f\left(\frac{a}{W}\right) \quad \text{(A4.1)}$$

$$f\left(\frac{a}{W}\right) = \quad \text{(A4.2)}$$

$$\frac{\left(2+\frac{a}{W}\right)\left[0.886+4.64\frac{a}{W}-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right]}{\left(1-\frac{a}{W}\right)^{3/2}}$$

Again K_Q stands for the Conditional result

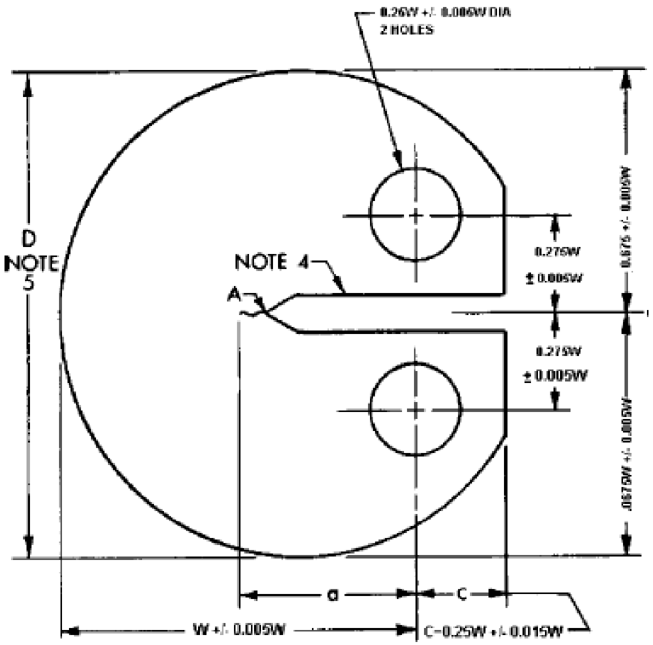
Same *f*(*a/W*) relationship is also available on textbooks



N.E. Dowling, Mechanical Behavior of Materials

$$F_P = \frac{2+\alpha}{(1-\alpha)^{3/2}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \qquad (a/b \geq 0.2)$$

Similar relationship for the other standard specimen shapes



$$K_Q = \frac{P_Q}{B\sqrt{W}} \cdot f\left(\frac{a}{W}\right) \qquad \text{(A5.1)}$$

where:

$$f\left(\frac{a}{W}\right) = \qquad \text{(A5.2)}$$

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

Just slightly different coefficients…

How to accept K_Q as the Plane Strain Fracture Toughness K_{Ic} ?

This is the Tensile Test standard

9.1.4 The value $2.5(K_Q/\sigma_{YS})^2$, where σ_{YS} is the 0.2 % offset yield strength in tension (see Test Methods E8/E8M), shall be calculated. If this quantity is less than the specimen ligament size, $W–a$ then K_Q is equal to K_{Ic}. Otherwise, the test is not a valid K_{Ic} test. Expressions for calculating K_Q are given in the Annexes for each specified specimen configuration.

How to accept K_Q as the Plane Strain Fracture Toughness K_{Ic} ?

9.1.4 The value $2.5(K_Q/\sigma_{YS})^2$, where σ_{YS} is the 0.2 % offset yield strength in tension (see Test Methods E8/E8M), shall be calculated. If this quantity is less than the specimen ligament size, $W–a$ then K_Q is equal to K_{Ic}.

$$\text{Being } (W-a) \approx \frac{W}{2} = B$$

$$(W-a), B > 2.5\left(\frac{K_\mathrm{I}}{S_\mathrm{Y}}\right)^2$$

→

Implies both:

- Plane strain (condition on B)
- Small Scale Yielding

and then LEFM validity

How to accept K_Q as the Plane Strain Fracture Toughness K_{Ic} ?

$$\text{Since } B > 2.5\left(\frac{K_\mathrm{I}}{S_\mathrm{Y}}\right)^2 \text{ then plane Strain follows.}$$

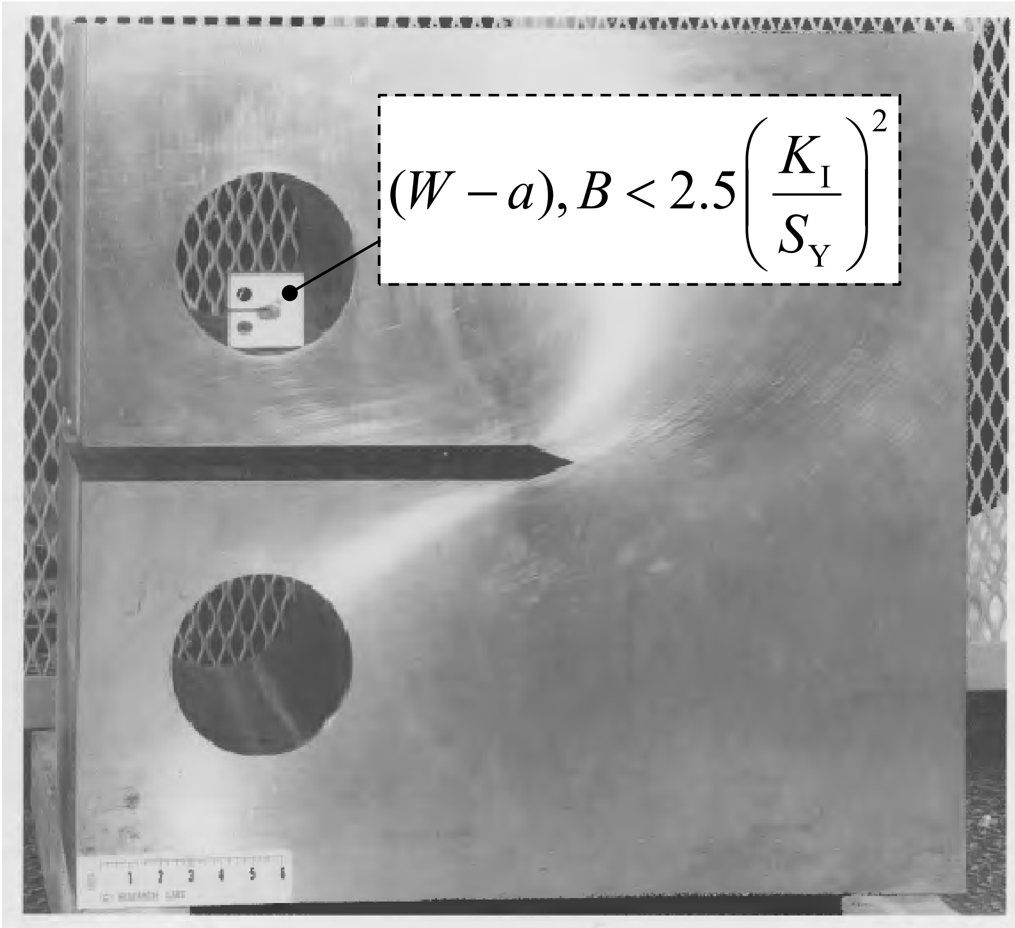
To have the (Small Scale Yielding) SSY

$$\text{in plane boundaries should be } > \frac{4}{3\pi}\left(\frac{K_\mathrm{I}}{S_\mathrm{Y}}\right)^2$$

$$\text{being } B \approx a, W-a \text{ and } 2.5 > 4/3\pi = 0.42$$

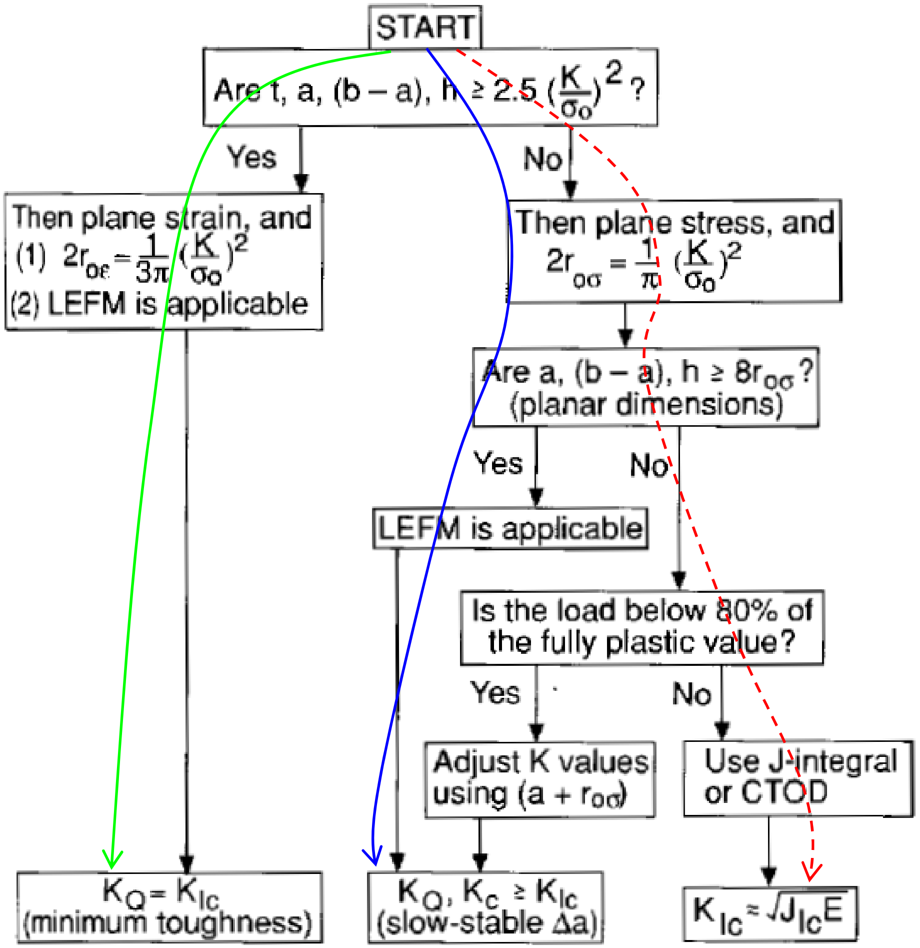
plane Strain easily implies the SSY and then LEFM validity

When this condition is not satisfied a larger specimen is needed

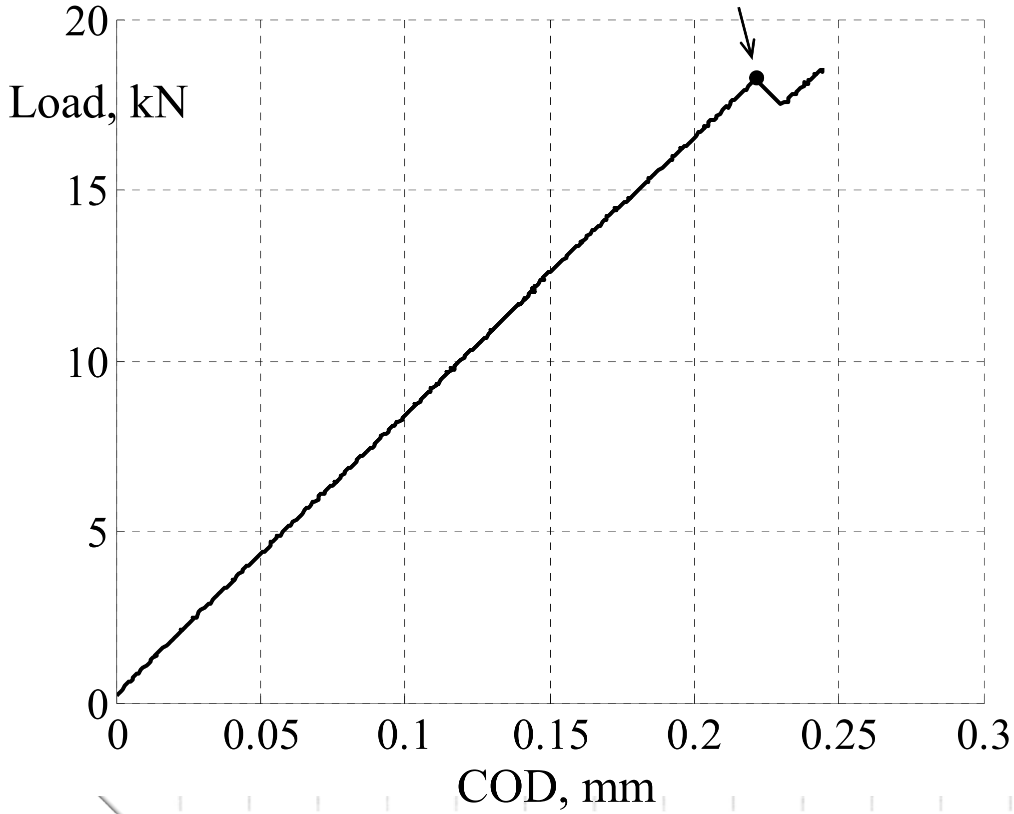


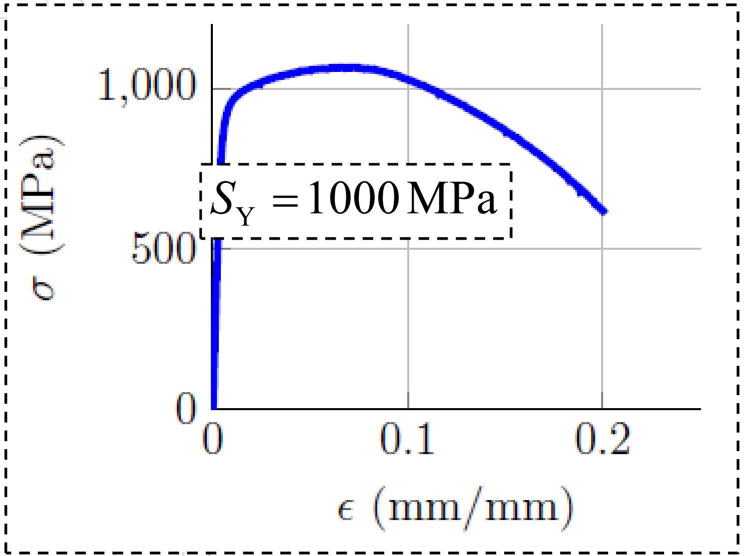
Huge testing machine would be required, otherwise J parameter is to be referred instead

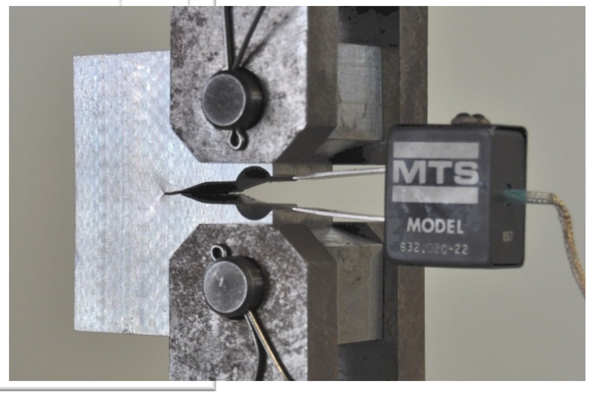
Summary


START
Are t, a, (b – a), h ≥ 2.5 $(\frac{K}{\sigma_o})^2$?
Yes
No
Then plane strain, and
(1) $2r_{o\varepsilon} \approx \frac{1}{3\pi}(\frac{K}{\sigma_o})^2$
(2) LEFM is applicable
Then plane stress, and
$2r_{o\sigma} = \frac{1}{\pi}(\frac{K}{\sigma_o})^2$
Are a, (b – a), h ≥ $8r_{o\sigma}$?
(planar dimensions)
Yes
No
LEFM is applicable
Is the load below 80% of
the fully plastic value?
Yes
No
Adjust K values
using $(a + r_{o\sigma})$
Use J-integral
or CTOD
$K_Q = K_{Ic}$
(minimum toughness)
$K_Q, K_c \geq K_{Ic}$
(slow-stable Δa)
$K_{Ic} \approx \sqrt{J_{Ic}E}$

Test example







Test example

$$P_Q = 18\,200\,N$$

$$a/W = 0.5$$

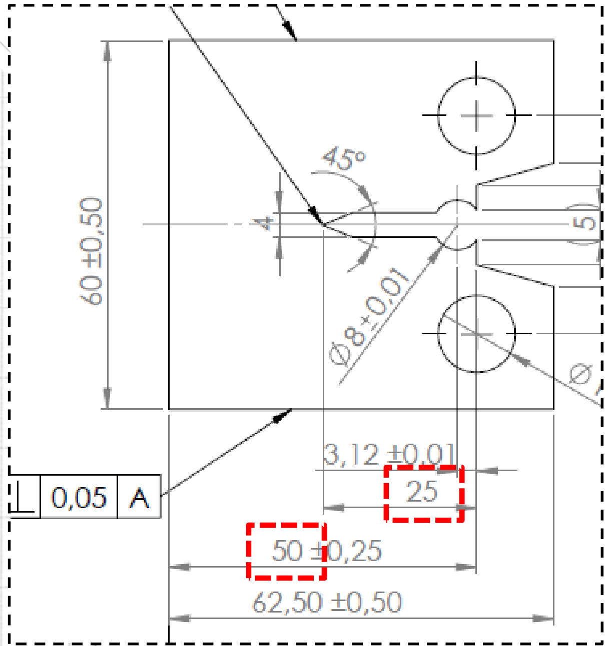
$$f(a/W) = 9.66$$

$$K_Q = \frac{P_Q}{B\sqrt{W}} f(a/W) = 994\,\text{MPa mm}^{1/2} = 31.4\,\text{MPa m}^{1/2}$$

$$S_Y = 1000\,\text{MPa}$$

$$B = 25\text{ mm} > 2.5\left(\frac{K_Q}{S_Y}\right)^2 = 2.47\,\text{mm}\quad \text{Ok!}$$

$$\rightarrow K_{Ic} = K_Q = 994\,\text{MPa mm}^{1/2} = 31.4\,\text{MPa m}^{1/2}$$



Fracture Toughness values

Dowling book

Material	Toughness K_{Ic} MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	Yield σ_o MPa (ksi)	Ultimate σ_u MPa (ksi)	Elong. $100\varepsilon_f$ %	Red. Area %RA %
(a) Steels					
AISI 1144	66 (60)	540 (78)	840 (122)	5	7
ASTM A470-8 (Cr-Mo-V)	60 (55)	620 (90)	780 (113)	17	45
ASTM A517-F	187 (170)	760 (110)	830 (121)	20	66
AISI 4130	110 (100)	1090 (158)	1150 (167)	14	49
18-Ni maraging air melted	123 (112)	1310 (190)	1350 (196)	12	54
18-Ni maraging vacuum melted	176 (160)	1290 (187)	1345 (195)	15	66
300-M 650°C temper	152 (138)	1070 (156)	1190 (172)	18	56
300-M 300°C temper	65 (59)	1740 (252)	2010 (291)	12	48
(b) Aluminum and Titanium Alloys (L-T Orientation)					
2014-T651	24 (22)	415 (60)	485 (70)	13	–
2024-T351	34 (31)	325 (47)	470 (68)	20	–
2219-T851	36 (33)	350 (51)	455 (66)	10	–
7075-T651	29 (26)	505 (73)	570 (83)	11	–
7475-T7351	52 (47)	435 (63)	505 (73)	14	–
Ti-6Al-4V annealed	66 (60)	925 (134)	1000 (145)	16	34

Sources: Data in [Barsom 87] p. 172, [Boyer 85] pp. 6.34, 6.35, and 9.8, [MILHDBK 94] pp. 3.10 to 3.12 and 5.3, and [Ritchie 77].

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TABLE 2 Precision Using C(T) Specimens (Nominal Crack Size-to-Specimen Width Ratio a/W = 0.5)

Parameter	Material and Yield Strength	Average	Repeatability Standard Deviation	Reproducibility Standard Deviation	Repeatability Limit	Reproducibility Limit
K_{Ic} (MPa$\sqrt{m}$)	2219–T851 (353 MPa)	35.61	1.91	2.17	5.36	6.07
	Maraging 18Ni (1903 MPa)	59.06	2.14	2.65	5.98	7.41
	4340–500 F (1641 MPa)	50.38	2.12	2.87	5.95	8.04
	4340–800 F (1420 MPa)	87.83	2.21	3.14	6.19	8.80

Minimum specimen size

$K_{Ic} = 66\,\text{MPa m}^{1/2}$

$S_Y = 540\,\text{MPa}$

$$B_{min} = 2.5\left(\frac{K_{Ic}}{S_Y}\right)^2 = 37.3\,\text{mm}$$

$$W_{min} = 2B_{min} = 74.7\,\text{mm}$$

E.g.: $W = 80\,\text{mm}$

Material	Toughness K_{Ic}	Yield σ_o	Ultimate σ_u	Elong. $100\varepsilon_f$	Red. Area $\%RA$
	MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	MPa (ksi)	MPa (ksi)	%	%
(a) Steels					
→ AISI 1144	66 (60)	540 (78)	840 (122)	5	7
ASTM A470-8 (Cr-Mo-V)	60 (55)	620 (90)	780 (113)	17	45
ASTM A517-F	187 (170)	760 (110)	830 (121)	20	66
AISI 4130	110 (100)	1090 (158)	1150 (167)	14	49
18-Ni maraging air melted	123 (112)	1310 (190)	1350 (196)	12	54
18-Ni maraging vacuum melted	176 (160)	1290 (187)	1345 (195)	15	66
300-M 650°C temper	152 (138)	1070 (156)	1190 (172)	18	56
300-M 300°C temper	65 (59)	1740 (252)	2010 (291)	12	48

Brittle fracture vs. Ductile plastic collapse

Possible independent failures

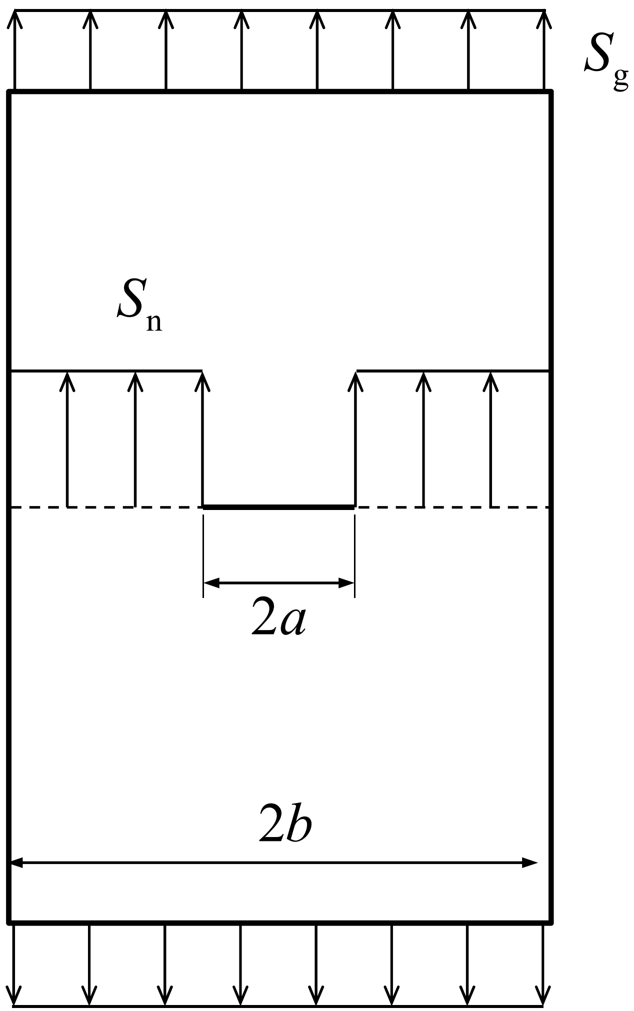
Fracture onset:

$$K_{\mathrm{I}} = F S_{\mathrm{g}} \sqrt{\pi a} = K_{\mathrm{Ic}}$$

$$F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1-\alpha}}$$

Plastic collapse onset:

$$S_{\mathrm{n}} = S_{\mathrm{g}} \frac{b}{b-a} = S_{\mathrm{Y}}$$



Brittle fracture vs. Ductile plastic collapse

The transition length a_t is the crack size for which both failures are at onset:

$$S_g = \frac{K_{Ic}}{F(a_t)\sqrt{\pi a_t}}$$

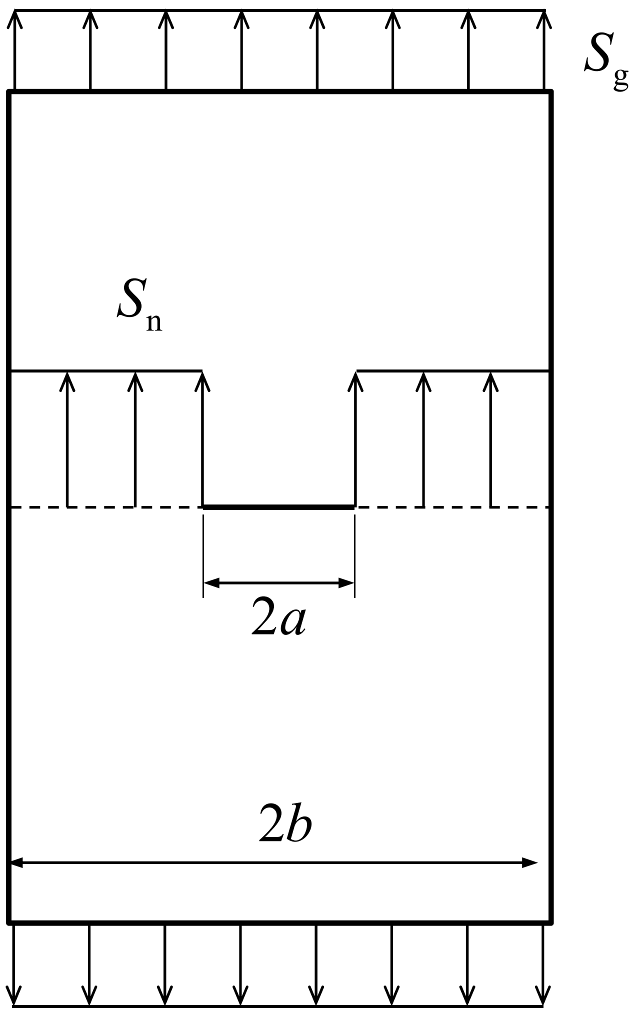
$$S_g = S_Y \frac{b-a_t}{b}$$

then:

$$\frac{K_{Ic}}{F(a_t)\sqrt{\pi a_t}} = S_Y \frac{b-a_t}{b}$$

this eq. can be solved numerically

$$a_t = \ldots$$



Brittle fracture vs. Ductile plastic collapse

by assuming $a_t << b$

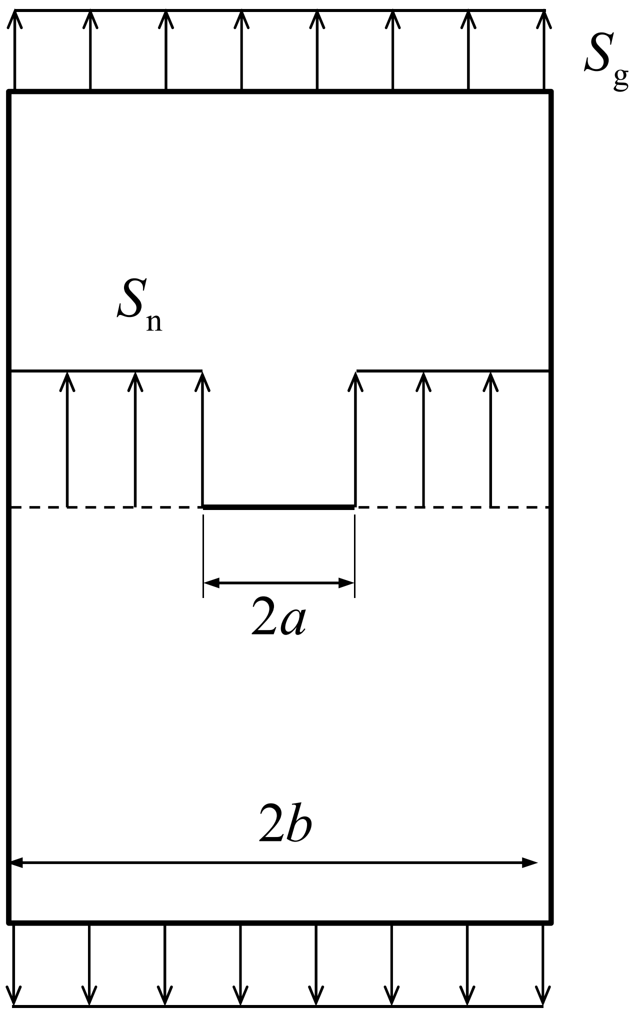
$$F(a_t) = 1.0$$

$$\frac{b}{b - a_t} = 1.0$$

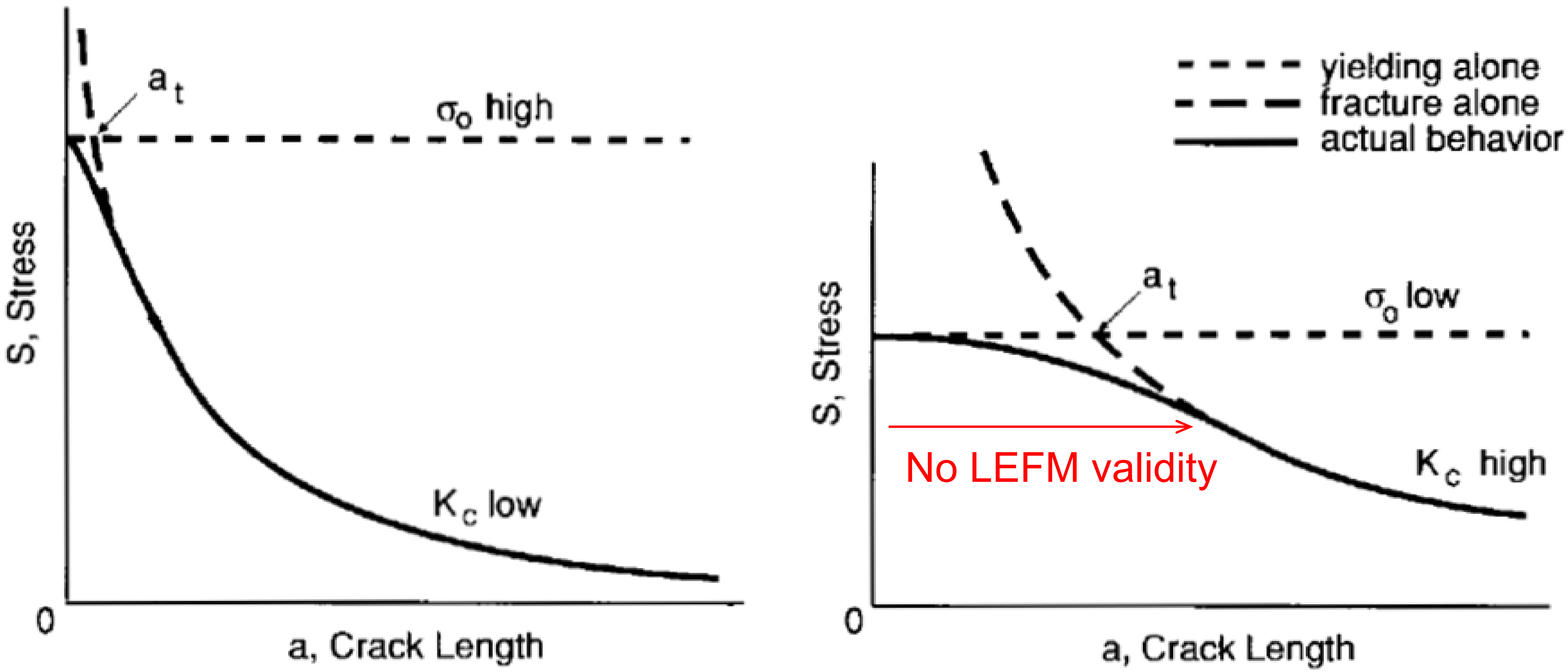
then the transition length a_t is:

$$a_t = \frac{1}{\pi}\left(\frac{K_{Ic}}{S_Y}\right)^2$$

which is again related to the plastic size



Largely different material properties



"Leak-before-Break"

Ductile material is preferred for pipes to have:

$$c_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma_t}\right)^2 > t \text{ (pipe thickness)}$$

high K_{Ic}, with a low S_Y

$$\sigma_t = p\frac{r}{t}$$

p: internal pressure

r: pipe radius

t: pipe thickness