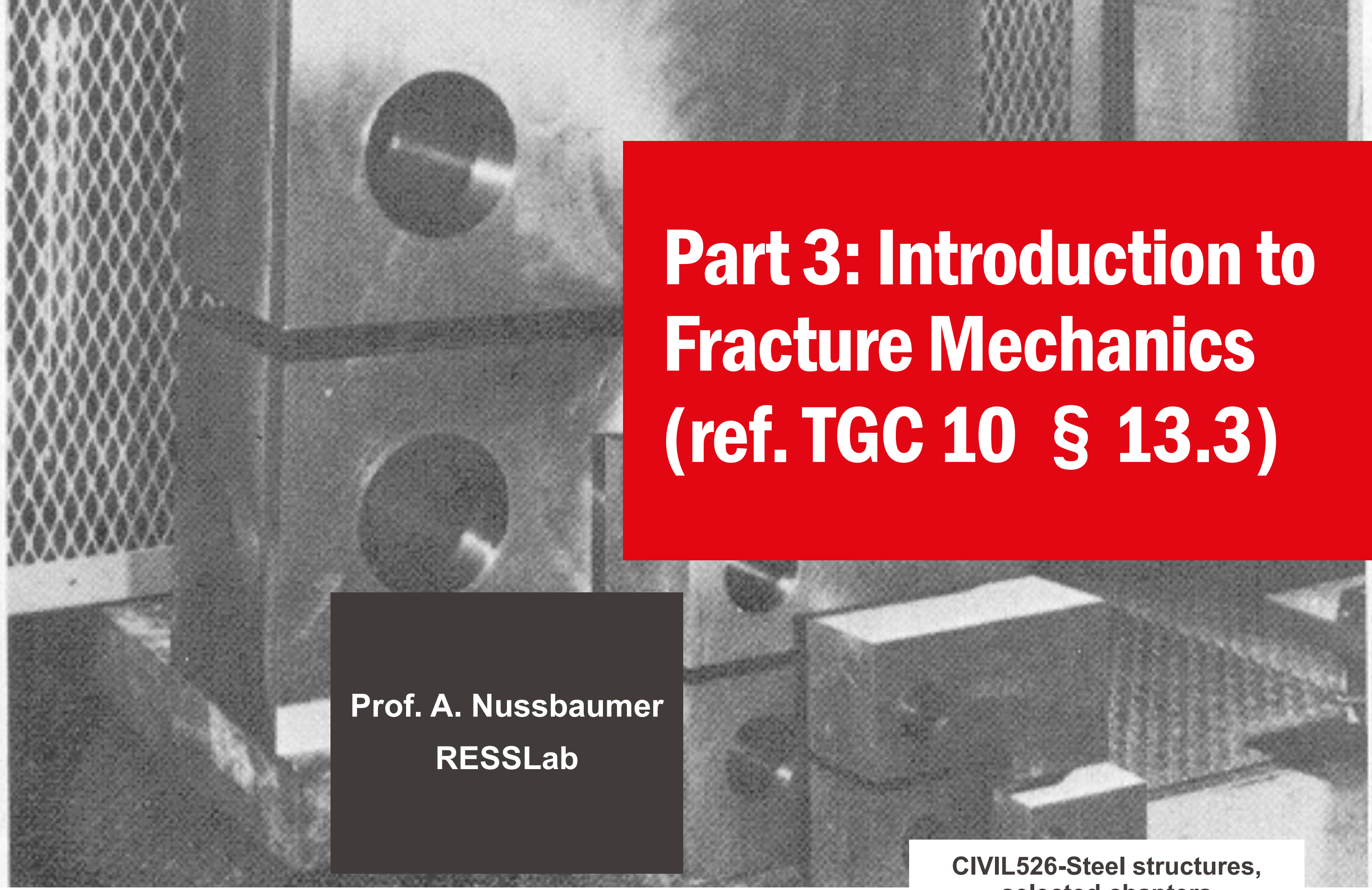


Part 3: Introduction to Fracture Mechanics (ref. TGC 10 § 13.3)

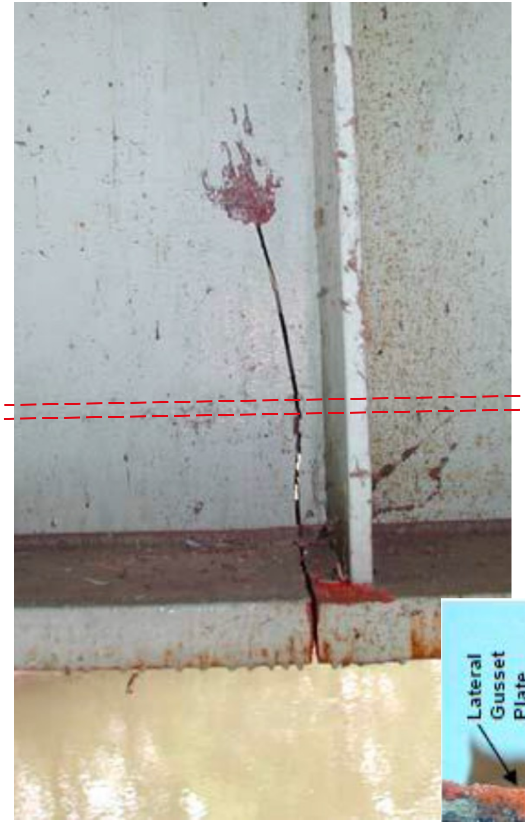
Prof. A. Nussbaumer
RESSLab

CIVIL526-Steel structures, selected chapters

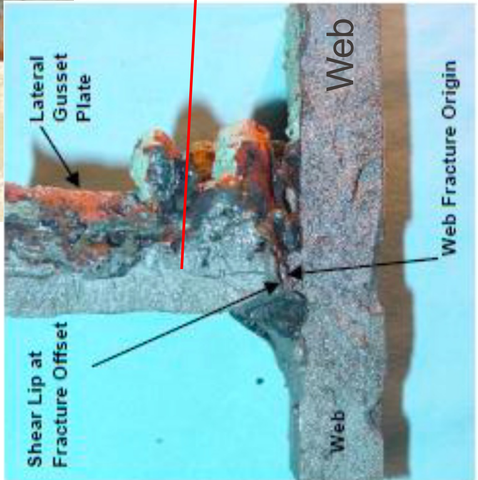
Content

- **Introduction**
- Stress Intensity Factor
- Influence of shape, correction factors
- Other influences:
  - Environment
  - Similarity conditions (deformation state, 2D vs 3D)
- Toughness ⇔ Charpy V

  (Ténacité ⇔ Résilience)



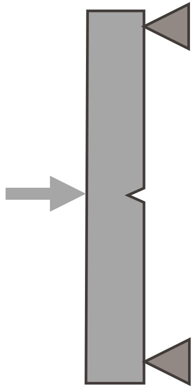
Longitudinal Stiffener

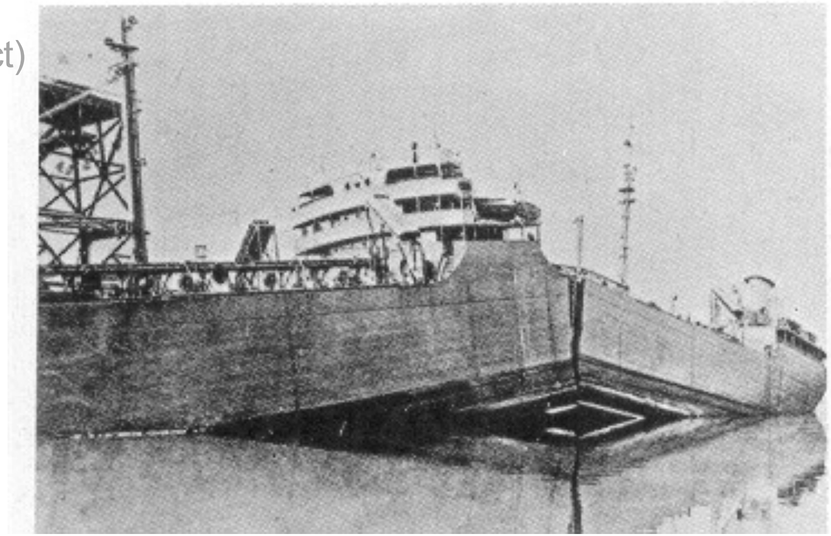


Kaufmann, and al. (October 2004). Failure Analysis of the US 422 Girder Fracture. *National ATLSS center, Lehigh Univ.*

Intro: brittle failures, 1940-45

Charpy test (impact)





Fracture of the USS Schenectady "liberty ship" in San Diego Harbor

⇔ poor welds, high clamping/triaxiality, and low temperature

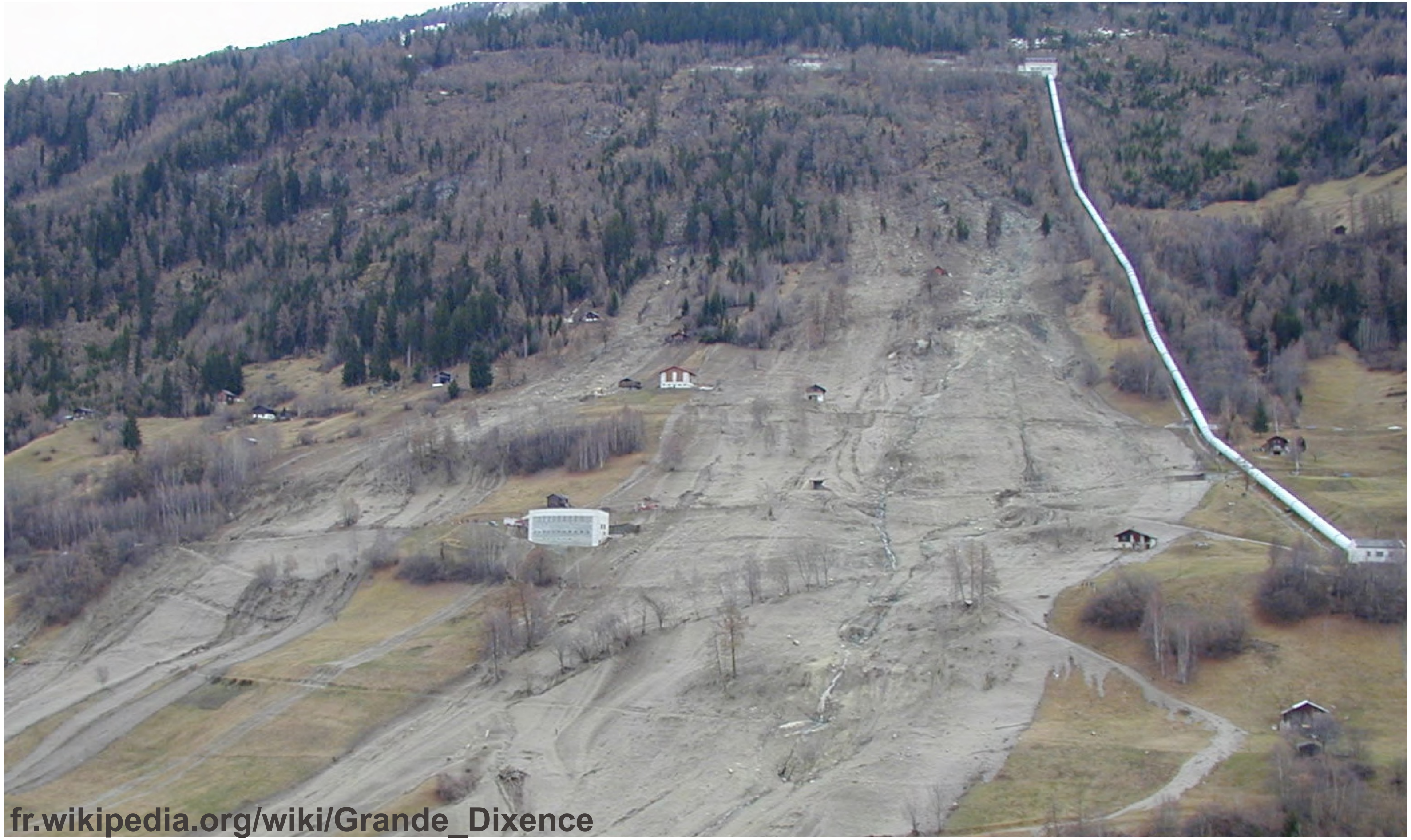
⇔ again in 1979, same type of failure: MSV Kurdistan oil tanker

G.R. Irwin (left) and J.A. Kies

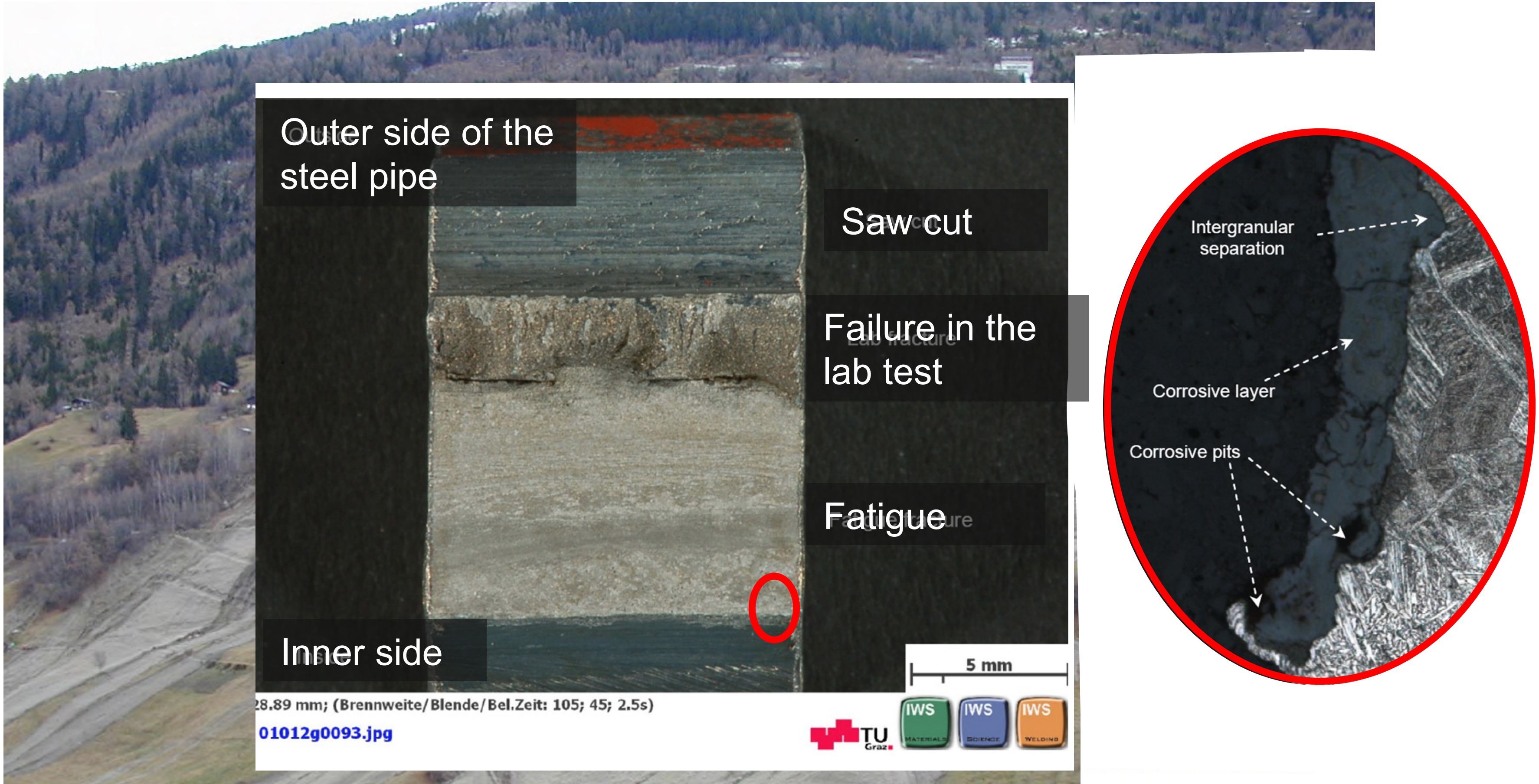
Failure problems solved in the 1950s:

- Failure of Liberty ships
- High-altitude explosions of DeHaviland Comet aircraft
- Explosions of electrical generators
- Explosions of combustion chambers in HSS for rockets.

INTRO: Cleuson-Dixence penstock failure (2000)

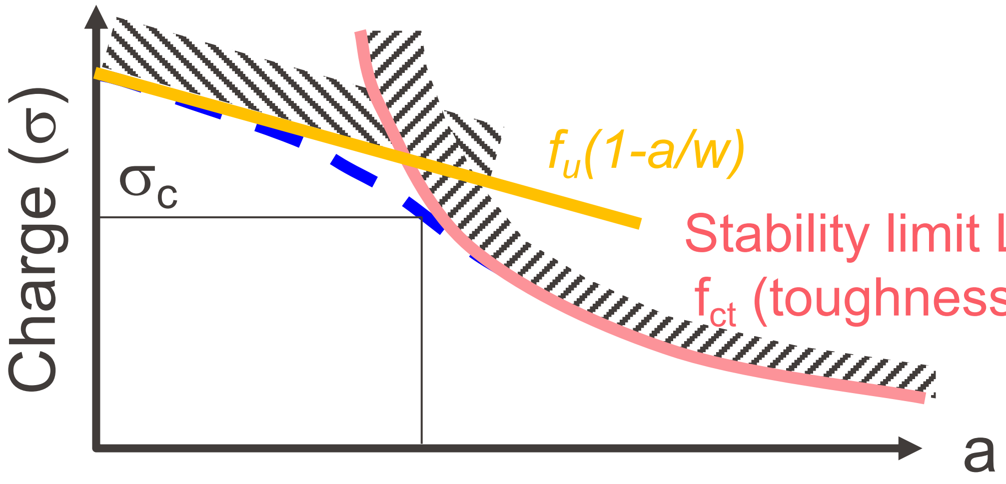


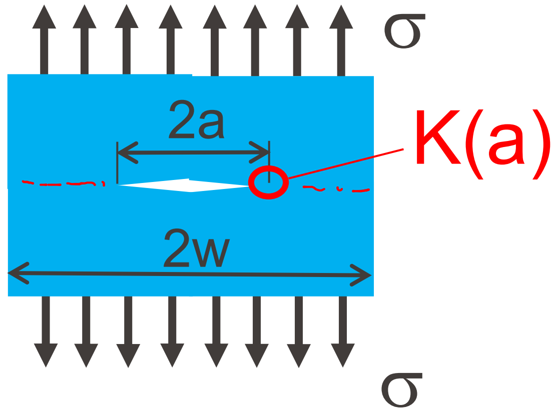
INTRO: Cleuson-Dixence penstock failure (2000)



fr.wikipedia.org/wiki/Grande_Dixence

INTRO reminder: solution to the problem of crack instability



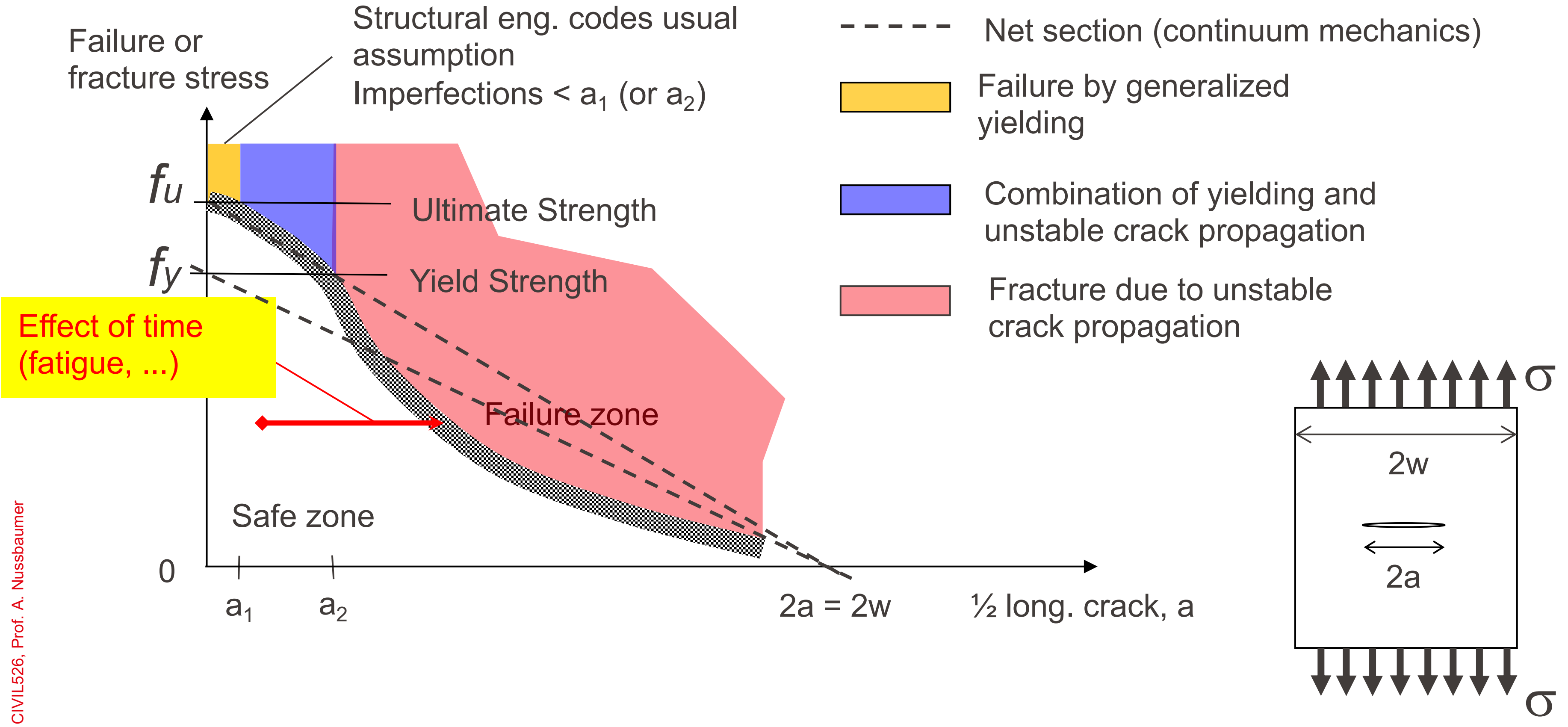


Parameters:

- Imperfections, concentration σ
- Effects of scale, triaxiality
- Residual stresses

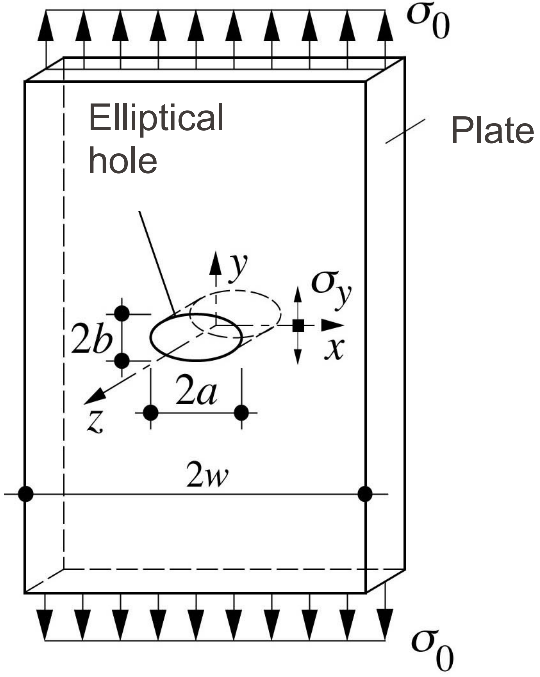
INTRO Tolerance or residual strength in the presence of a crack

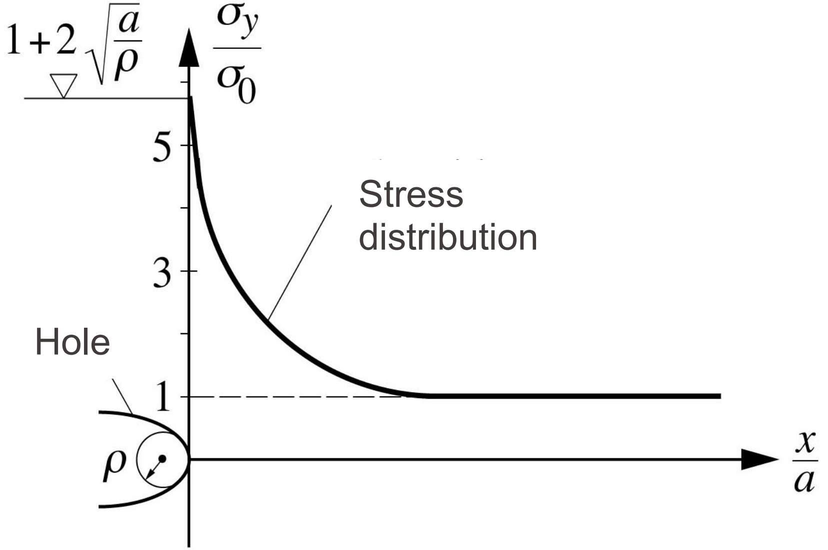
At a given temperature



INTRO reminder: basic problem of non-continuum mechanics (at fracture)

Resolved by Timoshenko: $$\sigma_{y,\max} = \sigma_0 \cdot k_t = \sigma_0\left(1+2\frac{a}{b}\right) = \sigma_0\left(1+2\sqrt{\frac{a}{\rho}}\right)$$

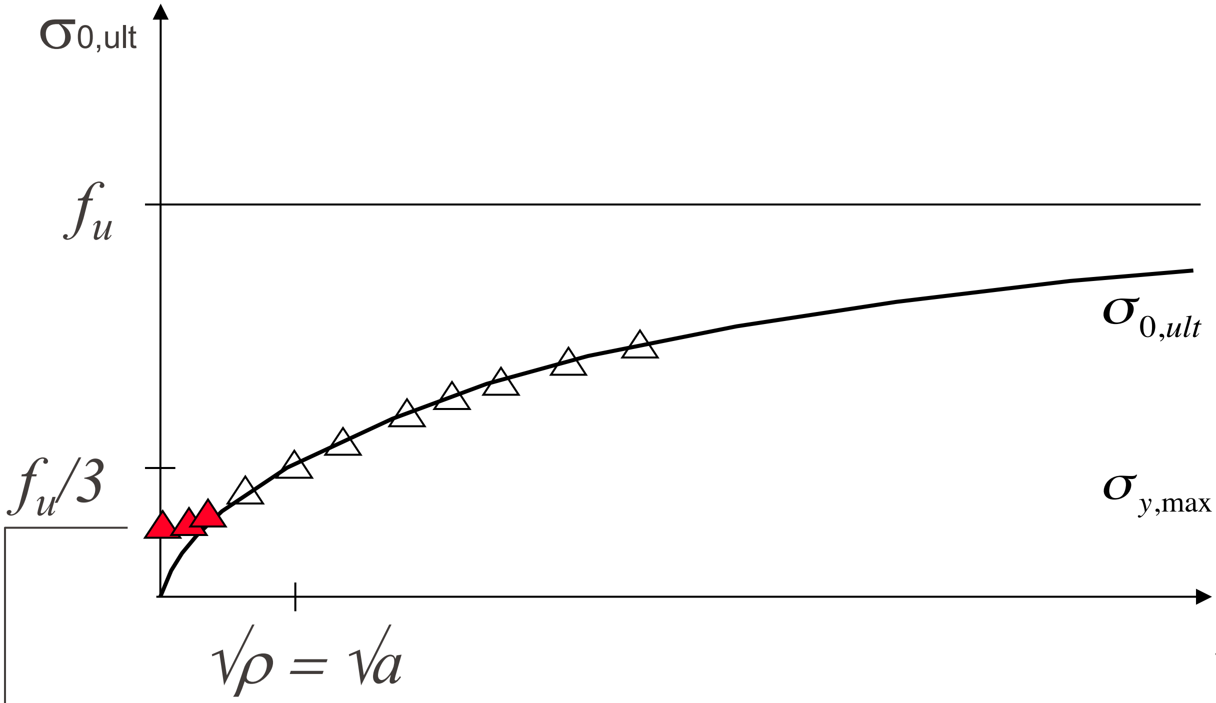




(TGC 10, 2015, fig. 13.4)

Important note: even if drawn in 3D, the problem and its solution are 2D

INTRO: basic problem of non-continuum mechanics (at fracture)



$$\sigma_{0,ult} = \sigma_{y,\max}\left(1 + 2\sqrt{\frac{a}{\rho}}\right)^{-1}$$

$$\sigma_{y,\max} \approx \sigma_0 2\sqrt{\frac{a}{\rho}} \quad si\ \rho \to 0$$

$$\boxed{\sigma_{0,ult}\sqrt{a}} = \lim_{\rho \to 0}\frac{1}{2}\sigma_{y,\max}\sqrt{\rho}$$

→ Toughness of material

Content

- Introduction
- **Stress Intensity Factor**
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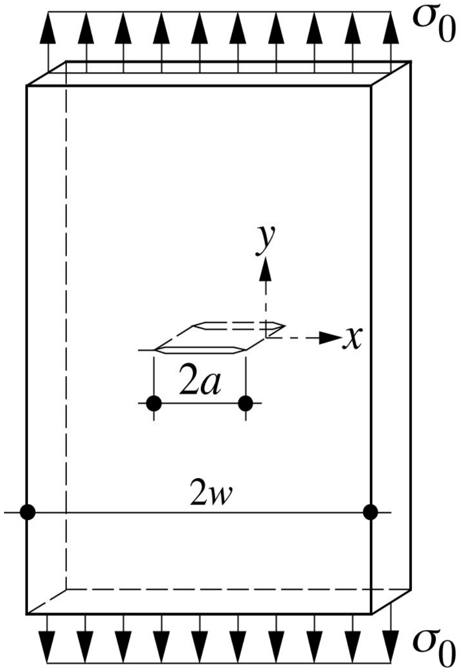
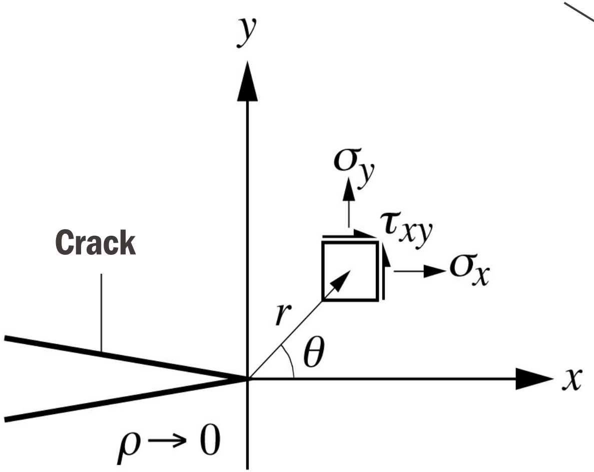
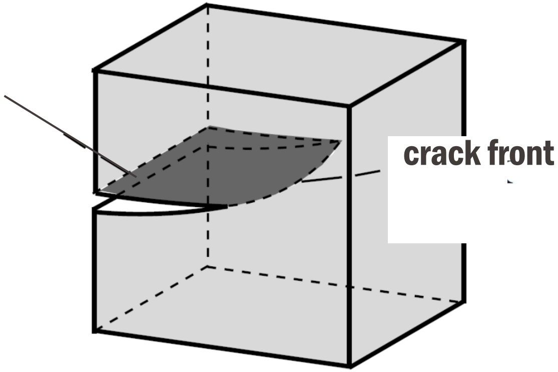
- Toughness ⇔ Charpy V

Fig. 13.5: Stress field near a crack







$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta)$$

K = ? With the only variables of the problem:

$$\boxed{K_I \approx \sigma_0 \sqrt{a}}$$

Verification: $K_{Ed} \leq K_{Rd}$ (toughness)

Description of the stress field in Mode I (opening)

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

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

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

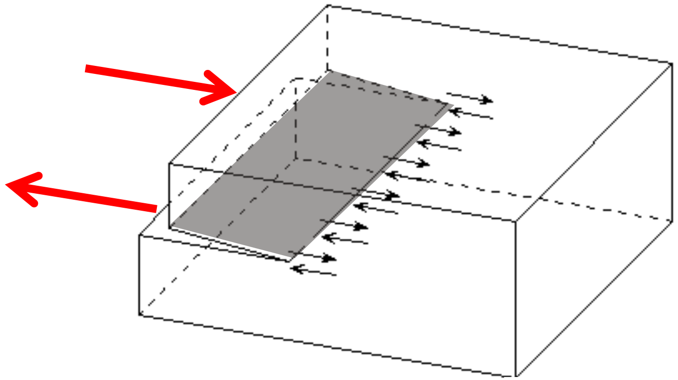
$$K_I = \underbrace{Y}_{Y = Y_e \cdot Y_f \cdot Y_s} \cdot \sigma_0 \cdot \sqrt{\pi a}$$

$$Y = Y_e \cdot Y_f \cdot Y_s$$

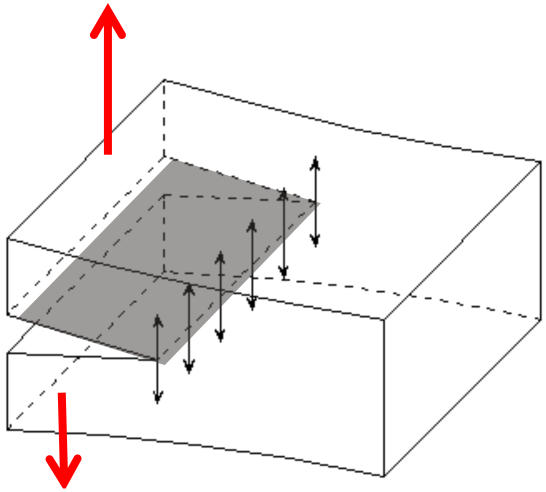
shape finite dim. surface

K_I [MPa·mm$^{1/2}$]: Stress Intensity Factor
Y [-]: Geometrical correction factor
σ_0 [MPa]: Normal stress perp. to the crack
a [mm]: Crack dimension (depth or half-length)

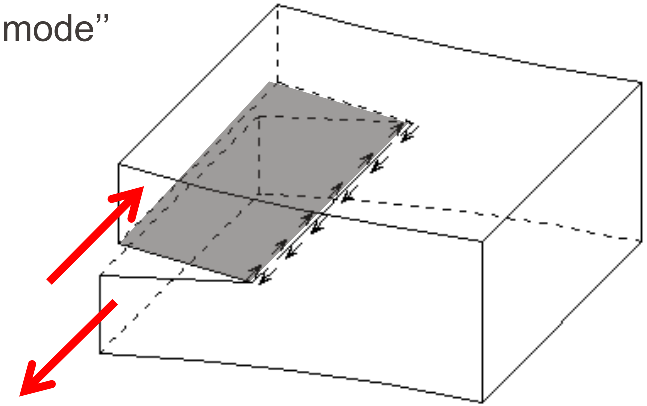
The 3 crack faces displacement modes



(b) Mode II ”shearing mode”



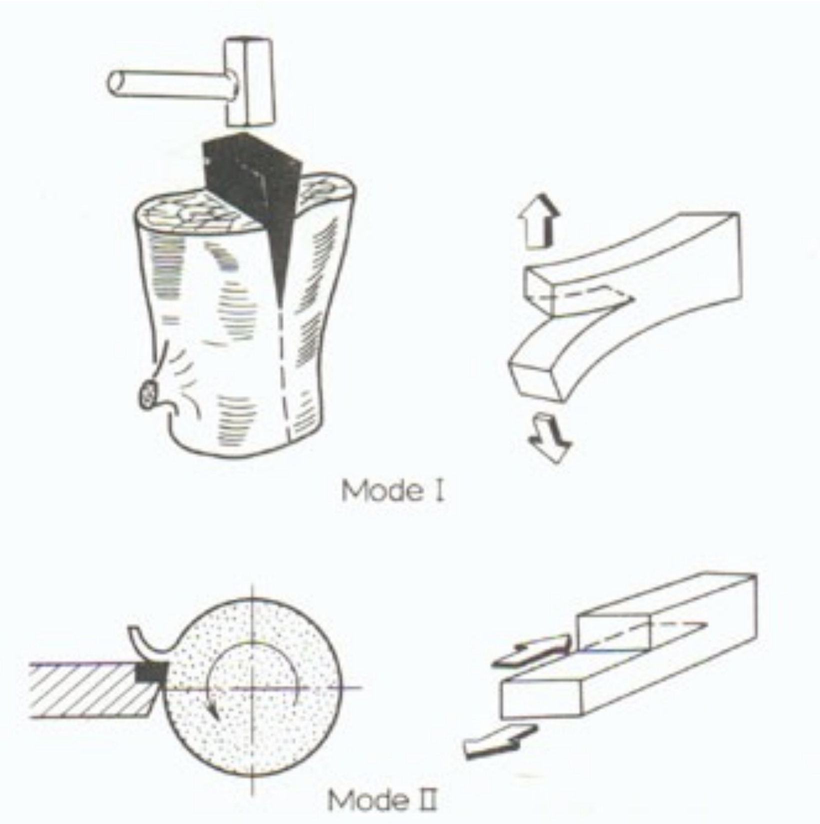
(a) Mode I ”opening mode”

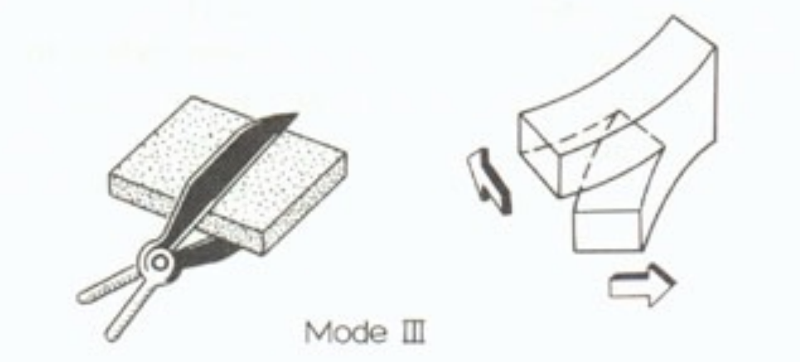


(c) Mode III ”tearing mode”

Important note: even if drawn in 3D, the problem and its solution are 2D

Practical examples of the 3 Modes

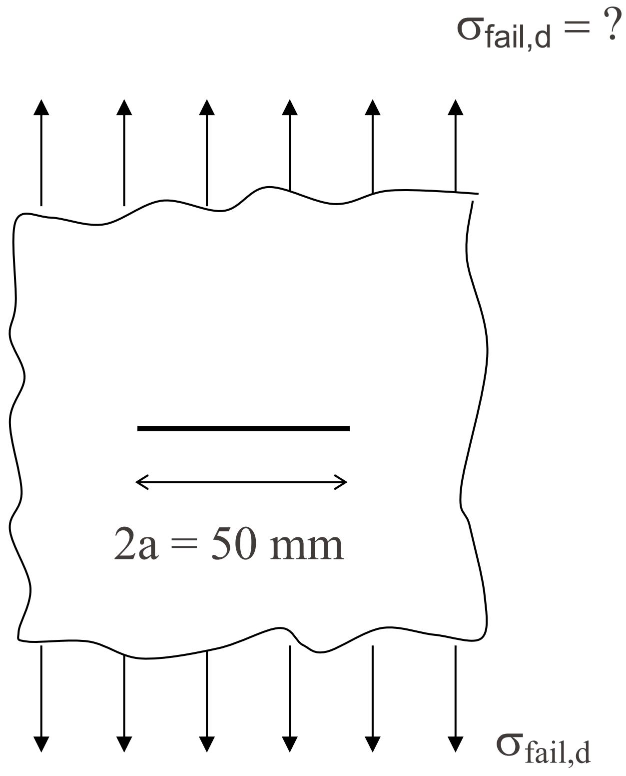




(From Parton V.Z. *Fracture Mechanics from Theory to Practice Pg. 66 Figure 47, Gordon and* Breach Science Publishers.)

Simple application example

- Aluminium alloy plate (7075, T651):
- $f_u = 560\ \text{N/mm}^2$
- $E = 70\ \text{kN/mm}^2$
- Toughness $K_{Ic} = 920\ \text{N/mm}^{3/2}$
- $\gamma_{safety} = 1.5$



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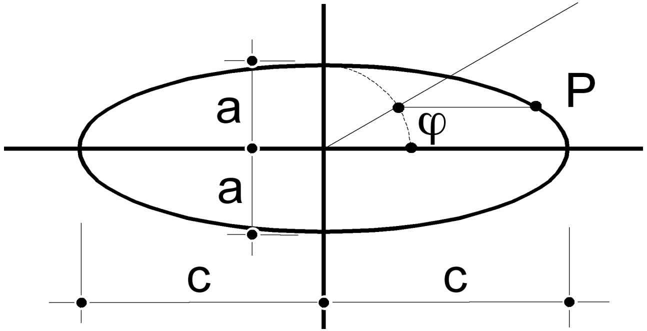
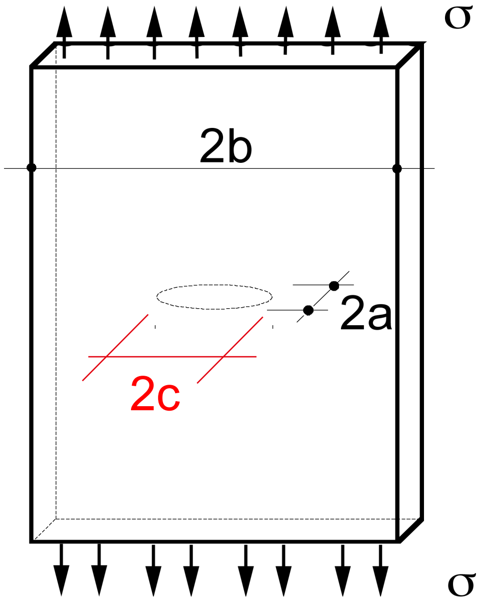
Solutions for K: an elliptical crack in a horizontal plane loaded perpendicularly (approx. by Irwin)





$$K_{I,P} = \frac{\sigma\sqrt{\pi a}}{\phi}\left(\sin^2\varphi + \frac{a^2}{c^2}\cos^2\varphi\right)^{1/4}$$

$$\phi = \sqrt{1 + 1{,}464\left(\frac{a}{c}\right)^{1{,}65}} \quad pour \quad \frac{a}{c} \leq 1$$

Generic equations for elliptical cracks

- Newman & Raju solution (NASA, 1970's):

$$Y = F \cdot f_w \cdot (F_{km} F_m + F_{kb} F_b)$$

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19840015857.pdf

F_i , f_w influence : 1, 1/2 ou 1/4 ellipse, finite dimensions, loading mode (tension or bending)

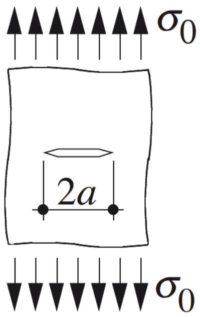
- TGC 10, only solutions in tension, but different cracks (edge, semi-elliptical, ...):

$$Y = Y_e \cdot Y_f \cdot Y_s$$

Fig. 13.6: K for different geometries

Bidimensionnal case

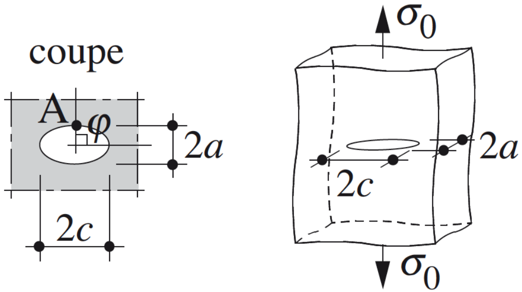
Infinite plate



$$K = \sigma_0 \sqrt{\pi a}$$

Tridimensionnal case

Correction for the crack's shape



For point A $(\varphi = \pi/2)$:

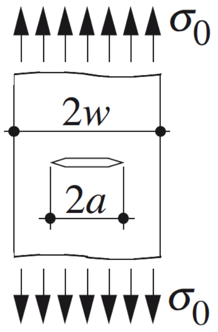
$$Y_e = \frac{1}{\int_0^{\pi/2} \left[1 - \frac{c^2 - a^2}{c^2} \sin^2\theta\right]^{1/2} d\theta}$$

Approx.:

$$Y_e = \left[1 + 1.464\left(\frac{a}{c}\right)^{1.65}\right]^{-1/2} \qquad \frac{a}{c} \le 1$$

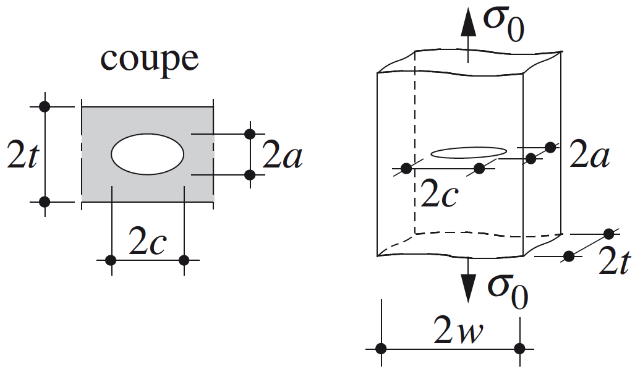
Fig. 13.6: K for different geometries

Correction for the plate dimension



$$Y_f = \frac{1}{\sqrt{\cos \dfrac{\pi a}{2w}}}$$

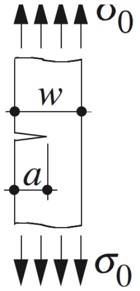
Correction for the plate dimensions



$$Y_{fa} = \sqrt{\frac{2t}{\pi a} \tan \frac{\pi a}{2t}} \quad \text{et} \quad Y_{fc} = \sqrt{\frac{2w}{\pi c} \tan \frac{\pi c}{2w}}$$

Fig. 13.6: K for different geometries

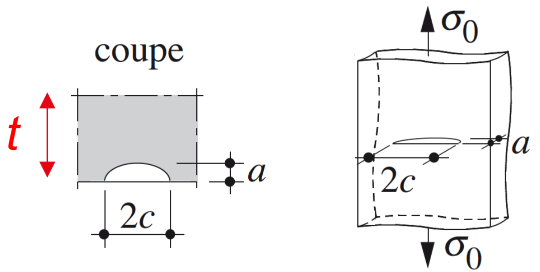
Correction for a surface crack



$$Y_s = 1.12 \text{ pour } \frac{a}{w} \leq 0.05$$

$$Y_s = 1.12 - 0.23\frac{a}{w} + 10.6\left(\frac{a}{w}\right)^2 - 21.7\left(\frac{a}{w}\right)^3 + 30.4\left(\frac{a}{w}\right)^4 \text{ pour } \frac{a}{w} < 0.45$$

Correction for a surface crack



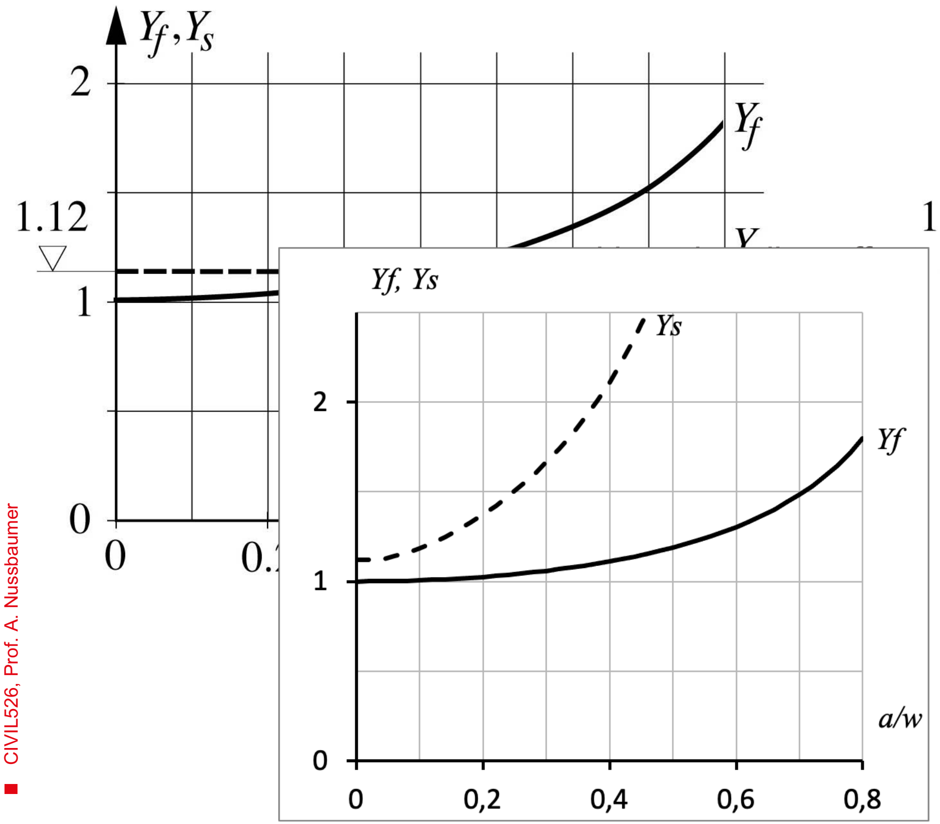
$$Y_s = 1 + 0.12\left(1 - 0.75\frac{a}{c}\right)$$

$a < 0.1 \cdot t$

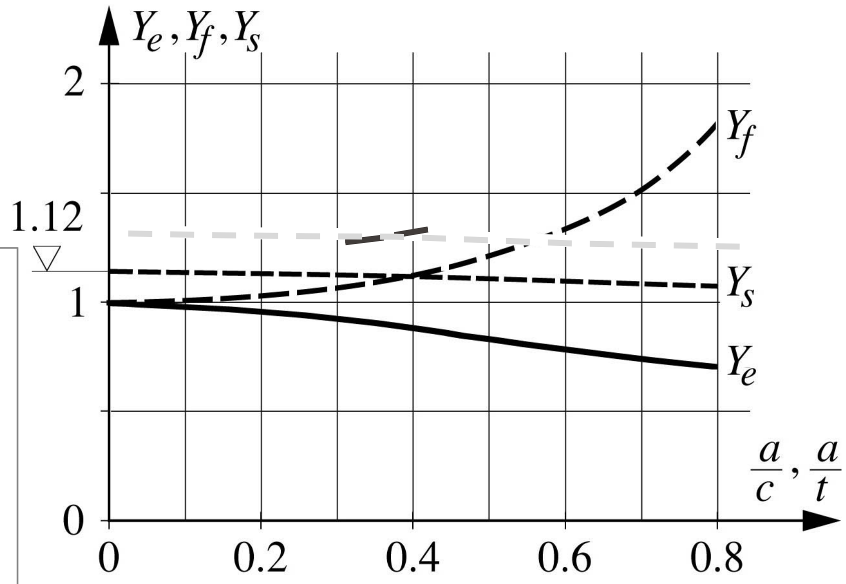
Y_s: Solutions for small cracks are only valid when secondary bending effects caused by cracking can be neglected

Fig. 13.7: Correction factors evolution for simple geometries

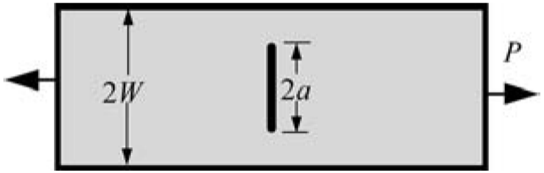
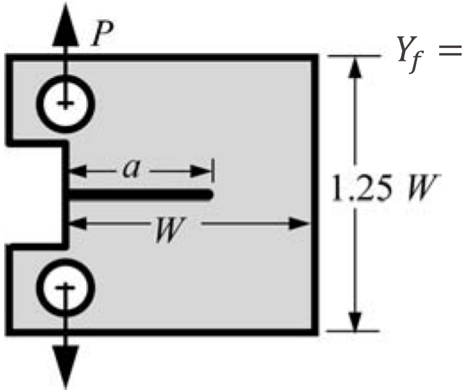
Two-dimensional case



Three-dimensional case



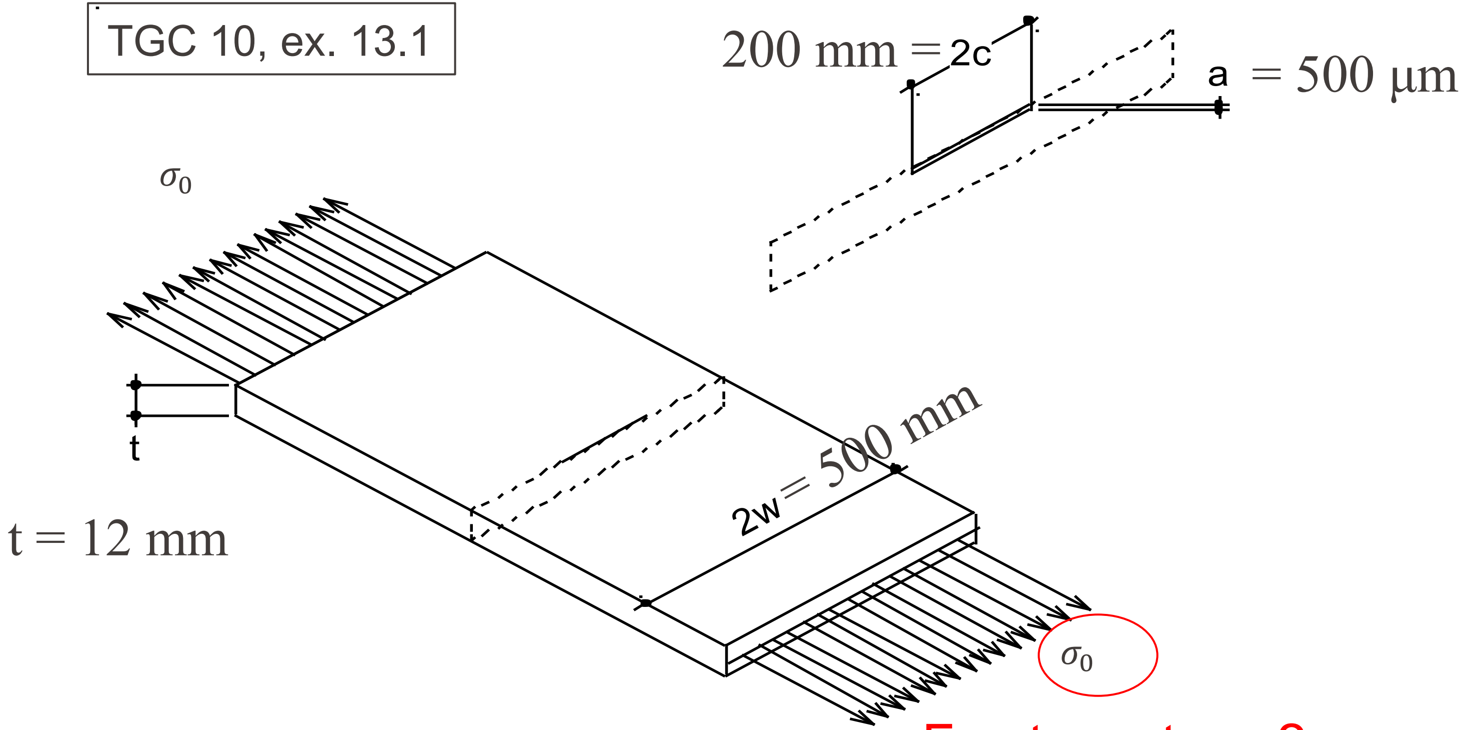
K for standard specimens (Anderson's book)

GEOMETRY	Y F(a/w) =
Double Edge Notched Tension (DENT) 	$$\frac{\sqrt{\frac{\pi a}{2W}}}{\sqrt{1-\frac{a}{W}}}\left[1.122-0.561\left(\frac{a}{W}\right)-0.205\left(\frac{a}{W}\right)^2+0.471\left(\frac{a}{W}\right)^3+0.190\left(\frac{a}{W}\right)^4\right]$$
Compact Specimen 	$$Y_f = f\left(\frac{a}{W}\right)=\frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}}\left[0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.60\left(\frac{a}{W}\right)^4\right]$$

$$^*K_I = \frac{P}{B\sqrt{W}}f\left(\frac{a}{W}\right)$$ where B is the specimen thickness.

Example: Calculation of fracture stress of plate with defect

TGC 10, ex. 13.1

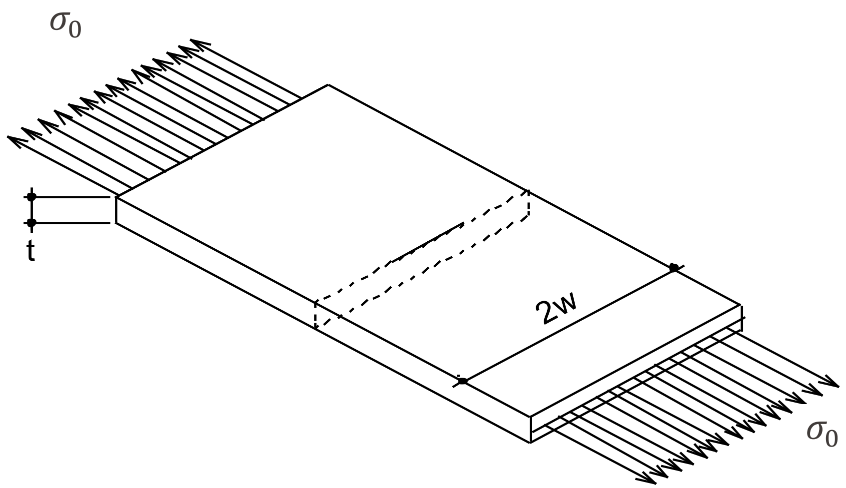


Toughness highly depends on material microstructure

Fracture stress?

- Glass plate, K_{Ic} = 24 N/mm$^{3/2}$
- Steel plate, K_{Ic} = 75 MPa·m$^{1/2}$

Example: Calculation of fracture stress of plate with defect



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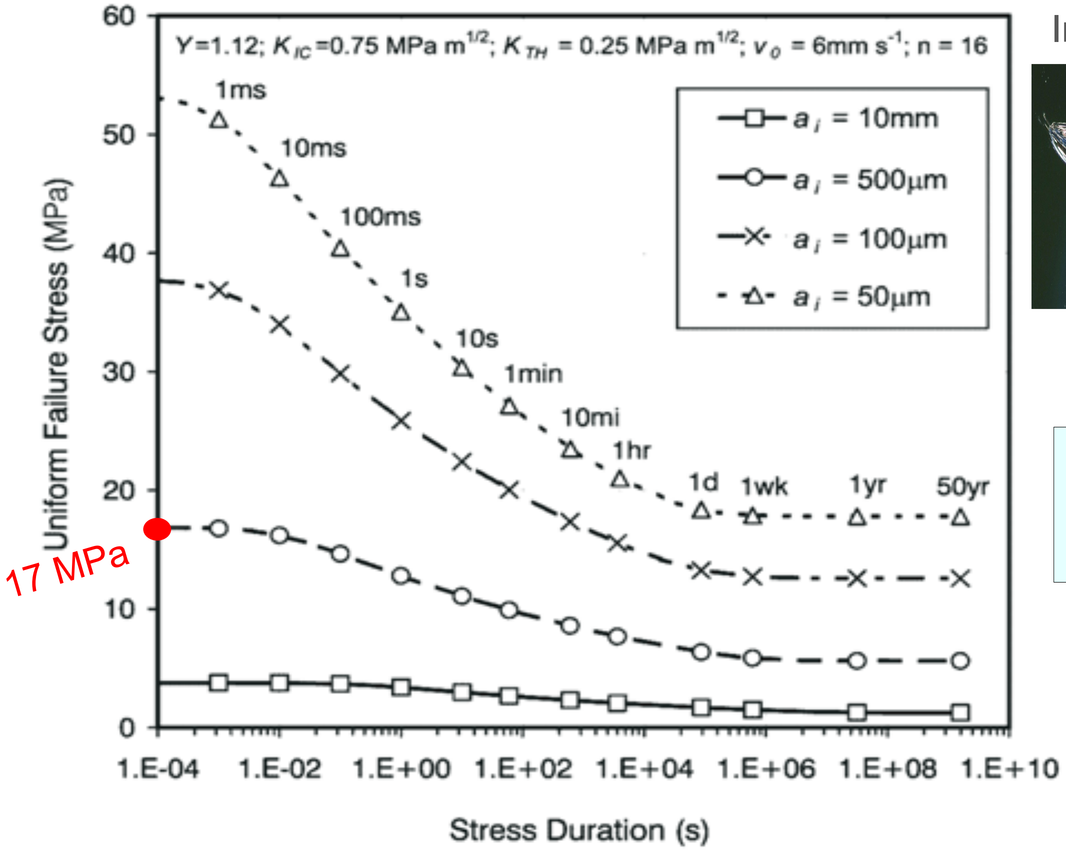
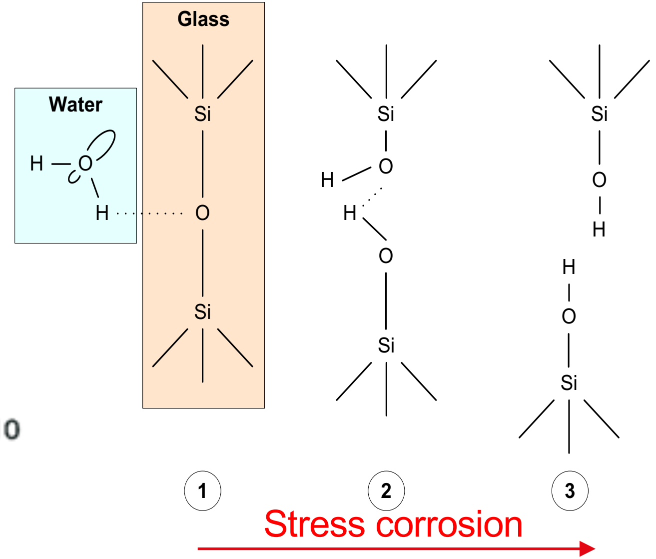
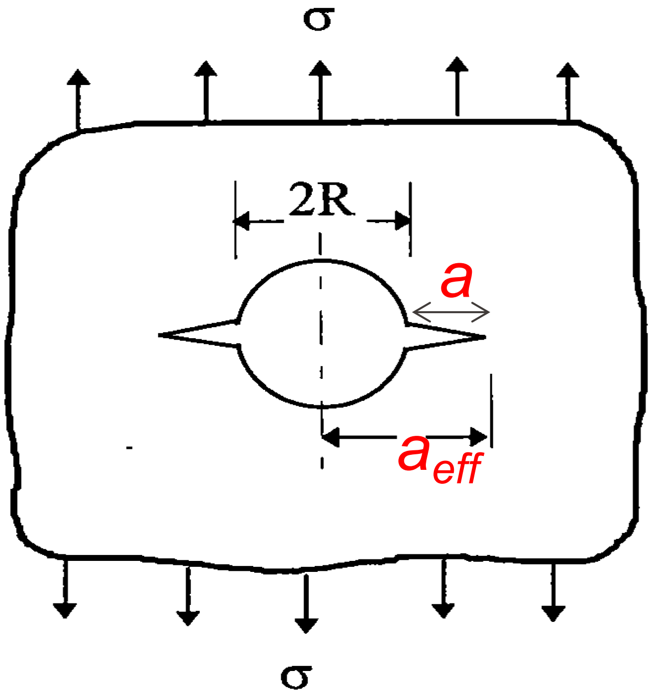
Glass resistance, influence of crack and environment

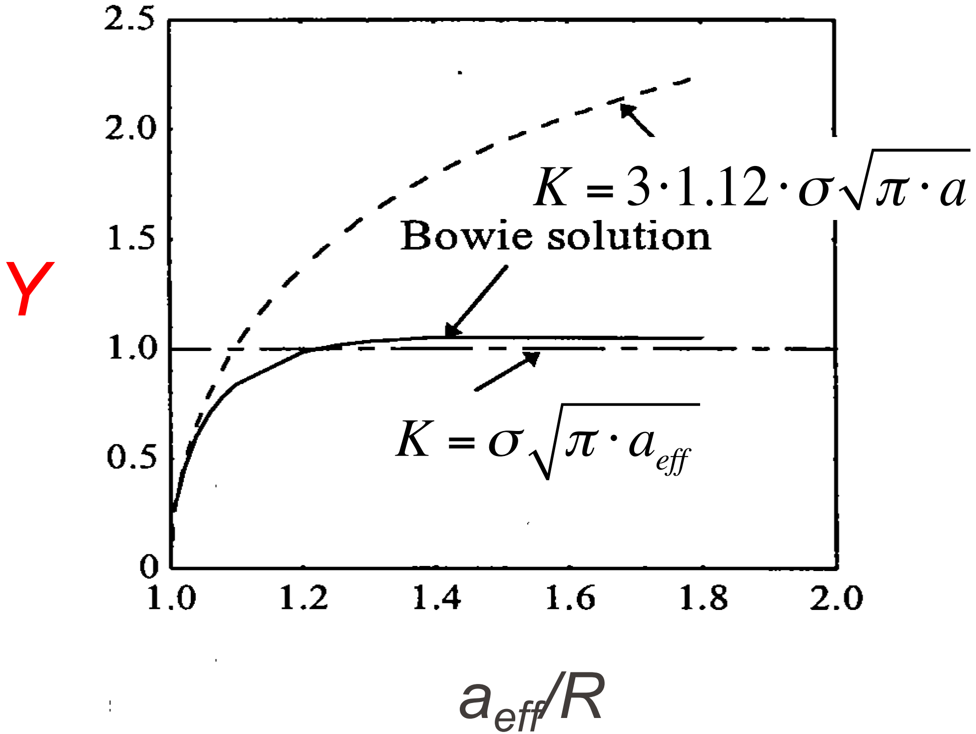


Imperfection at SURFACE



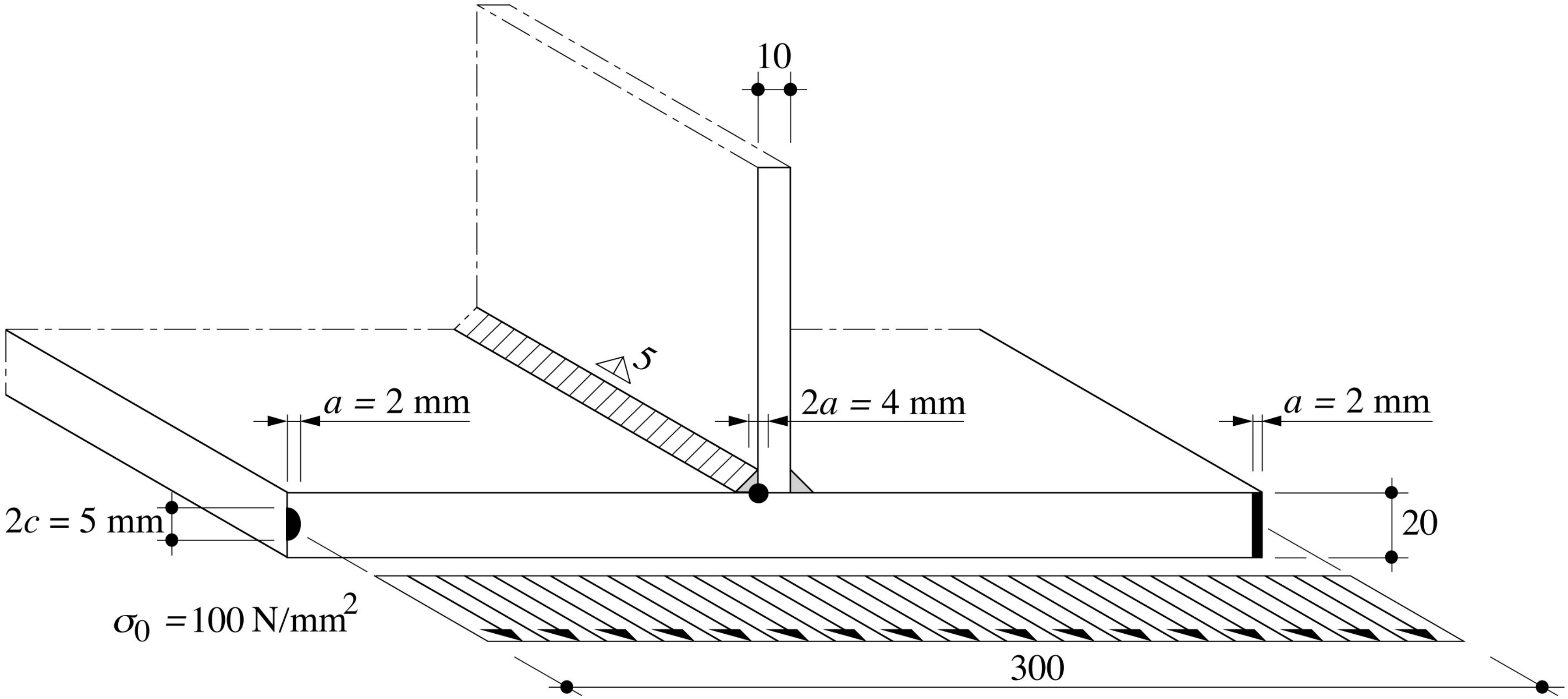
Comparison of K for a plate with a crack from a hole



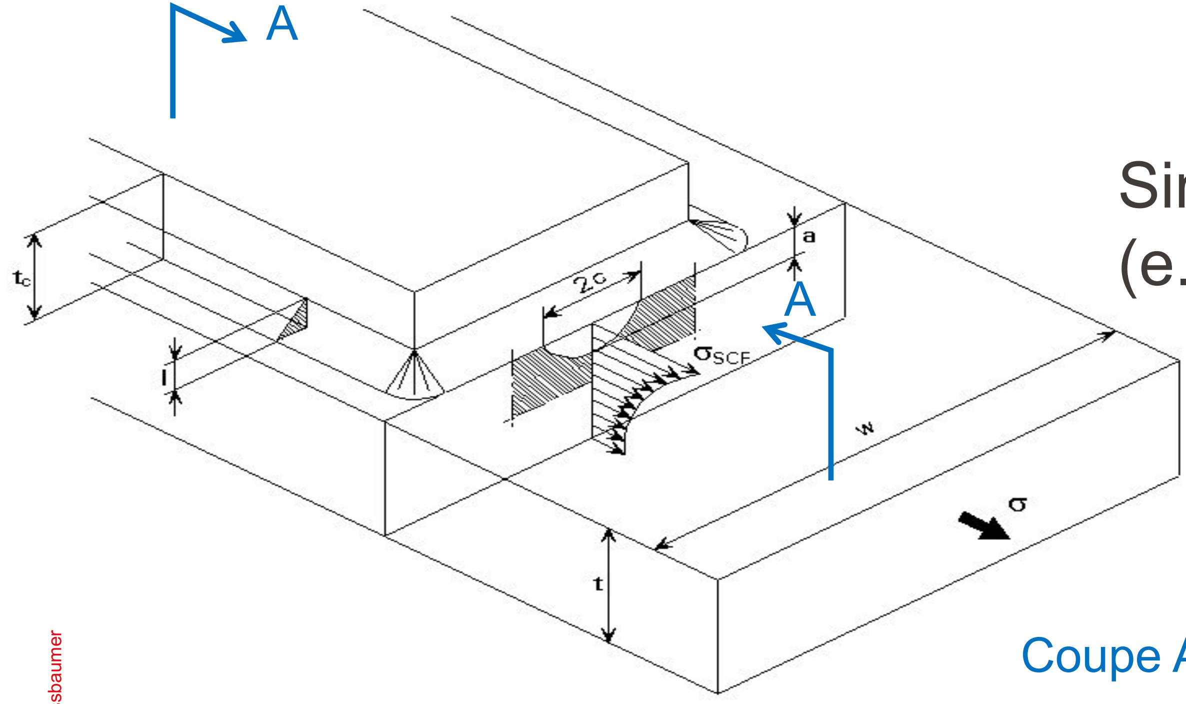


Bowie solution:
https://engineeringlibrary.org/reference/fracture-mechanics-stress-intensity-factor

TGC 10, numerical examples of K calculation (Fig. 13.8)



Solutions for K in the case of welded joints

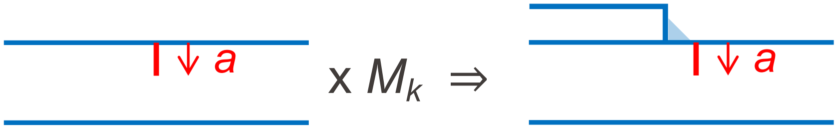


$$K_I = M_k \cdot Y \cdot \sigma\sqrt{\pi a}$$

Simple generic solution:
(e.g. Hobbacher)

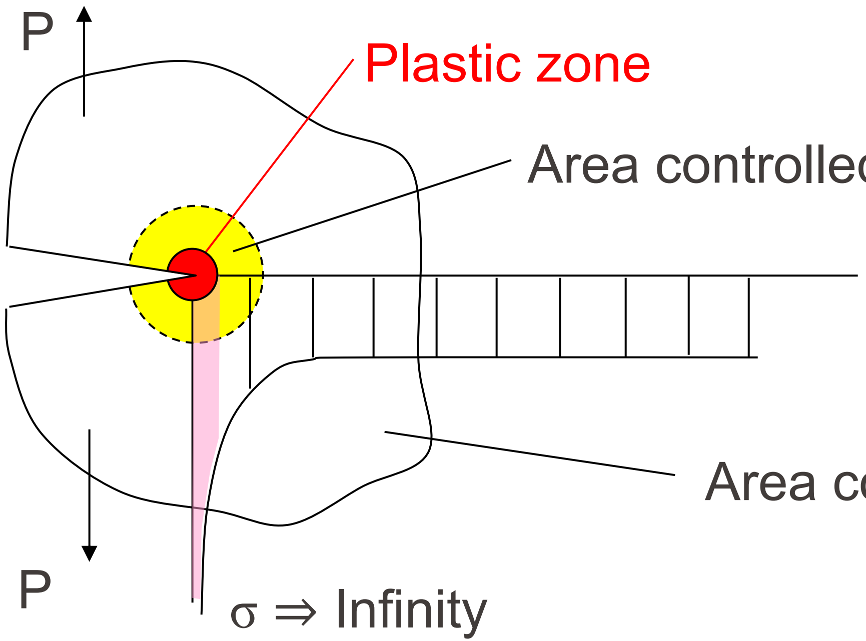
$$M_k = v\left(\frac{a}{t}\right)^w$$

Coupe A-A



Réf. : Hobbacher, A., Recommendations for Fatigue Design of Welded Joints and Components, Springer, 2016
http://link.springer.com/10.1007/978-3-319-19198-0

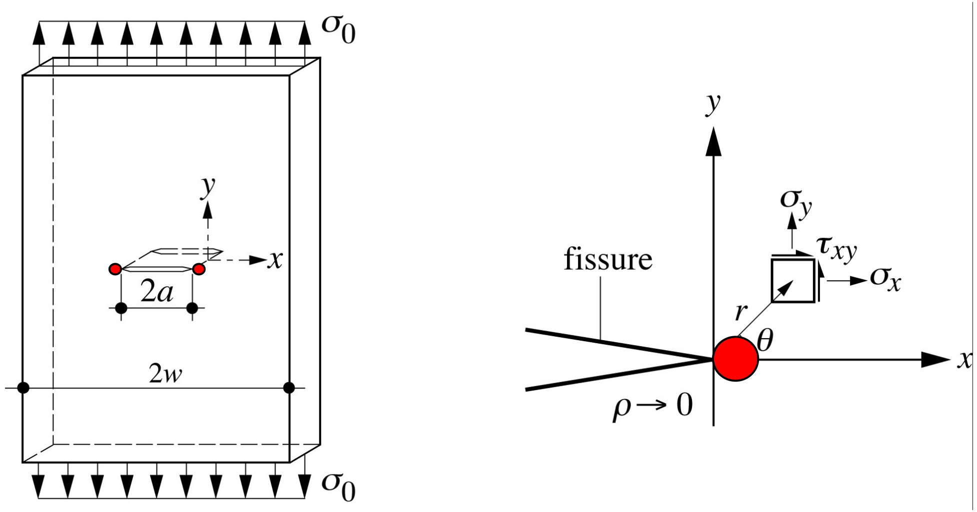
Linear-Elastic Fracture Mechanics: Similarity condition on K



Only a 2D representation !!

Conditions for K to be a similarity parameter

1) The size of the plastic zone (or FPZ=Fracture Process Zone) is small compared to crack size and the cracked body

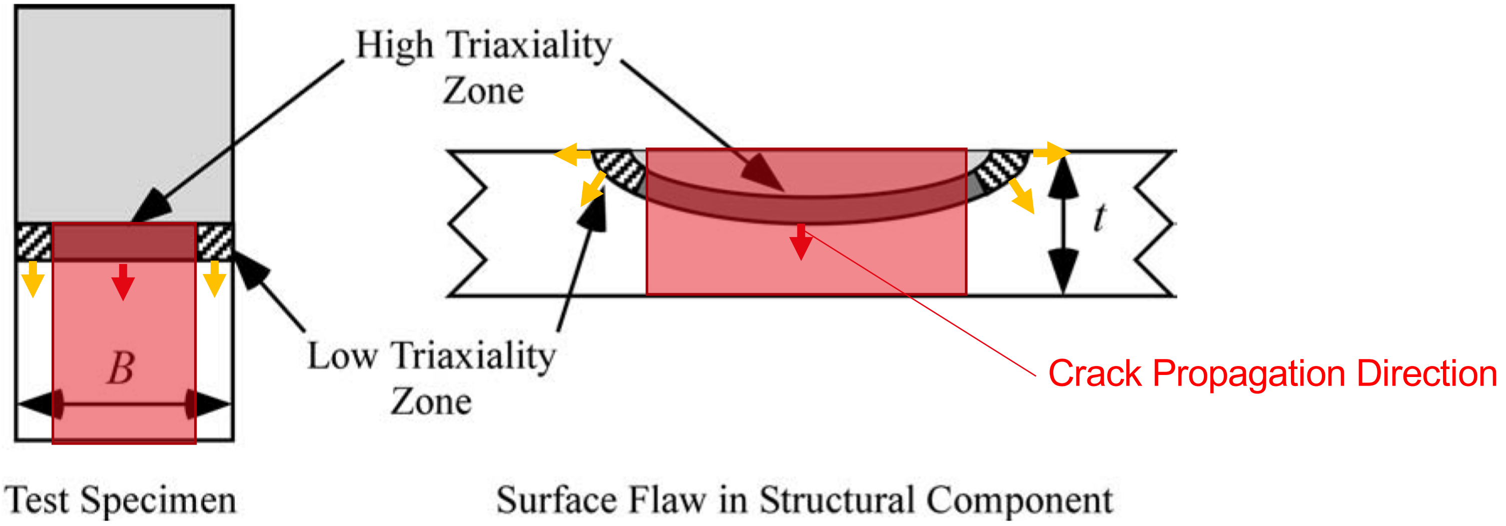


2) The out-of-plane stress states (triaxiality) at crack tip are identical

⇒ Conditions needed: plane strain state

⇒ Approximative model of reality, generally conservative

Containment – different states of triaxiality



- The length-to-diameter ratio of the roll is important in defining the stress state along the crack front
- (Empirical) condition for having the most critical case = plane strain state:

$$\frac{B}{r_p} \propto \frac{B}{\left(K_I / f_y\right)^2} \geq 2.5$$

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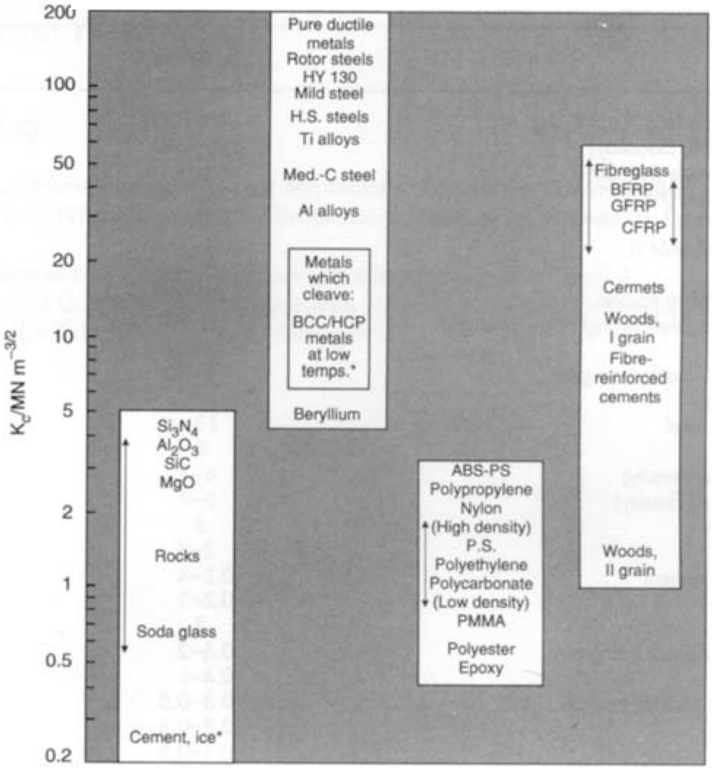
In summary: toughness of materials at fracture

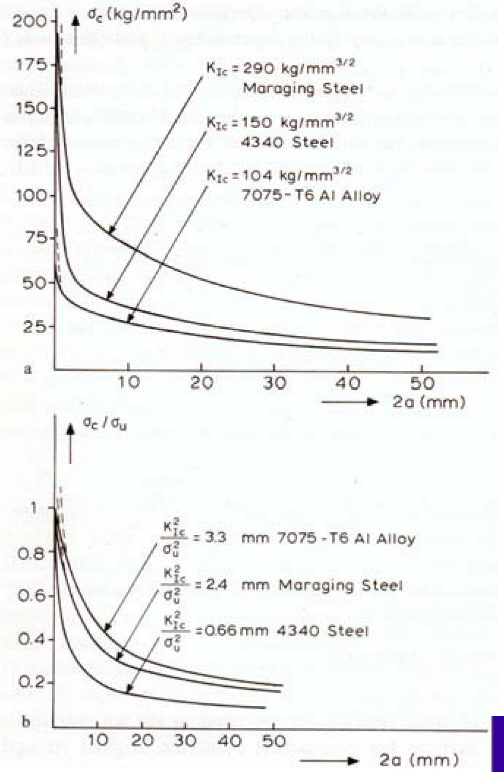
It depends on the microstructure, the triaxiality, and external variables

Temperature (and environment) (degradation)

Loading rate

Ceramics Metals Polymers Composites





FITNET European Fitness-for-service Network

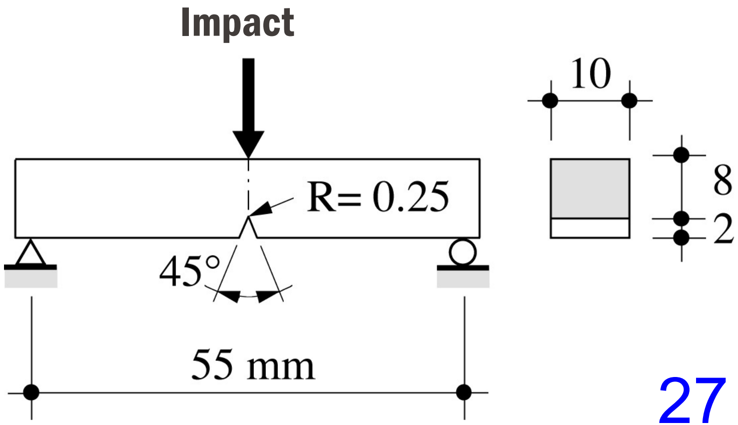
welded structures • design • fabrication • structural integrity

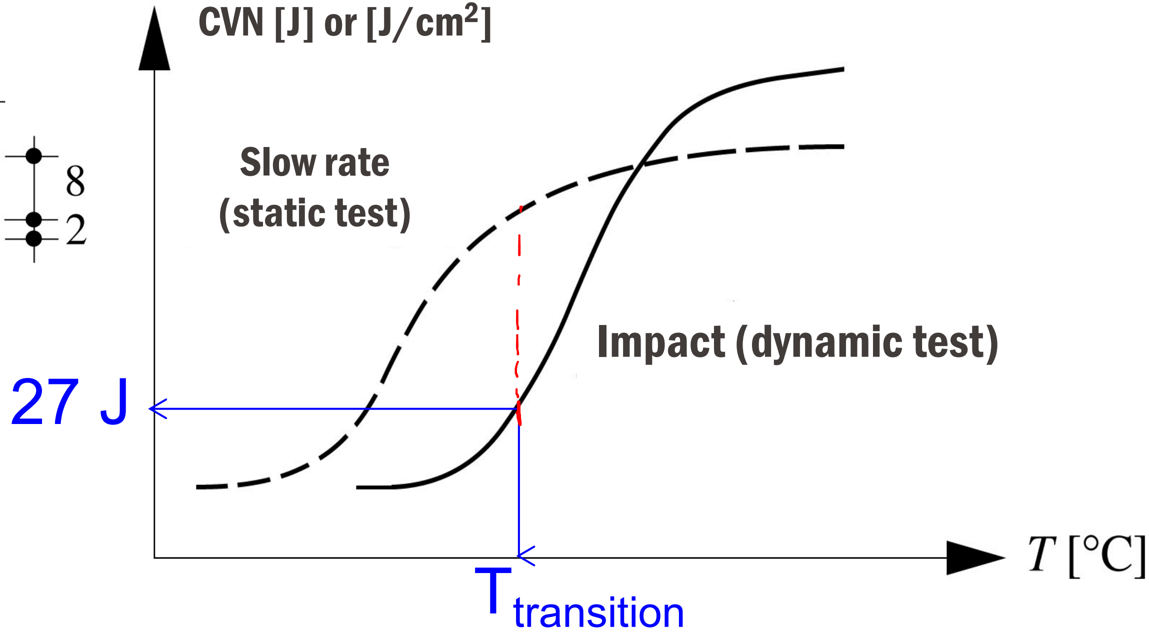
Typical toughness values K_{Ic} (plane strain state, at ambiant temperature, quasi-static loading)

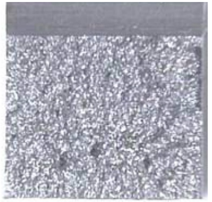
Matériau	Particularités	Limite élastique ,f_y , f_t	Ténacité, K_{Ic}		Epaisseur minimale requise B
		[N/mm^2]	[N/mm$^{3/2}$]	[ksi√in]	[mm]
Acier					
S 235	acier carbone	235	> 5000	> 140	1100
S 355	acier carbone	355	> 5000	> 140	500
4340	acier durci	1810	1470	43	1.7
Titane					
6A1-4V	$(\alpha+\beta)$STA	1100	1200	35	3
13V-11Cr-3A1	STA	1130	870	25	1.5
Aluminium					
7075	T651	540	920	27	7.3
2014	T4	450	880	26	9.6
2014	T3	390	1080	31	19
Non-métalliques					
PVC	chlorure de vinyle	45	60-250	2-8	77
Résine époxyde		30-100	16	0.5	-
Polymethyl methacrylate	Plexiglas		22 to 50	0.6 to 1.5	-
Verre ordinaire	Soda-lime glass	3600	22	0.7	-
Bétons	C12/15 to C50/60	1.6 to 4	7 to 44	0.2 to 1.3	-
Béton (selon doc. Brühwiler)		3.6	58.8	1.7	-

Note : ksi√in ≅ MPa√m

TGC 10, figs. 3.19 and 3.20: for steels, Charpy impact test (or Charpy V notch test)







Note: test invented by G.R. Irwin

Relationship CVN - Toughness

For a first estimation, deduction from Charpy V tests (for C-Mn steels):

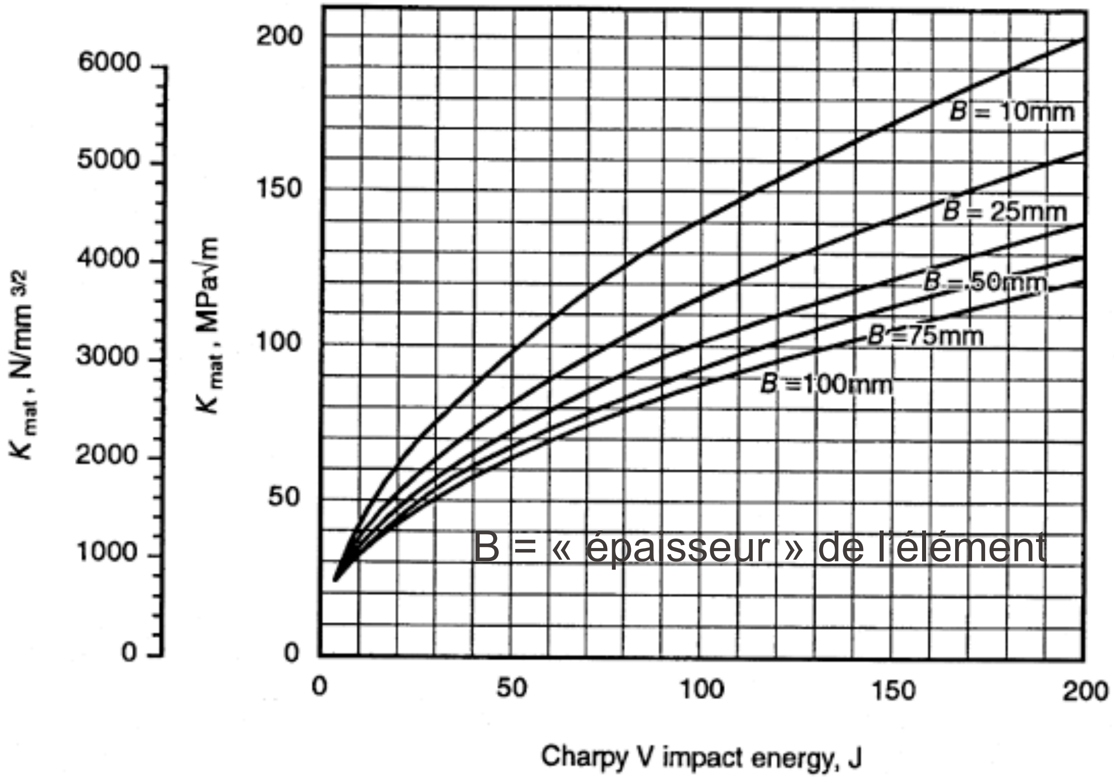


Figure J.2 — K_{mat} plotted against Charpy V impact energy for lower shelf and transitional behaviour

(tiré de BS PD7910, 2005)

Reminder: Example of a material certificate

MARCEG.GLIA SAN GIORGIO DI NOGARO RL

via Enrico Fermi, 33 - 33058 S.GIORGIO DI NOGARO -Udine - Italy - Tel. 0431/624111 - Fax 0431/624222

Sede legale e amministrativa :via Bresciani, 16 - Gazoldo degli Ippoliti - Mantova - Italy -

CERTIFICATO DI COLLAUDO / INSPECTION CERTIFICATE (EN 10204/92 3.1B)

CLIENTE / CUSTOMER : LUDWIG STAHL AG

INDIRIZZO / ADDRESS : TWS GEWERBEZENTRAM POSTFACH

CAP. CITTA' / TOWN : 8370 SIRNACH CH

N° ORDINE / ORDER No : 105582

PRODOTTO : LAMIERE IN ACCIAIO LAMINATE A CALDO - HOT ROLLED STEEL PLATES

STANDARD : EN 10025, EN 10029

Ns. ORDINE / MILL ORDER: 464633

N° CERTIFICATO / CERTIFICATE No : 013270

Data: 27/02/02

QUALITA' QUALITY	ID.LAMIERA ID.PLATE	DIMENSIONI DIMENSIONS			Fogli Plates	N° COLATA HEAT No	ANALISI CHIMICA CHEMICAL COMPOSITION											CARATTERISTICHE MECCANICHE MECHANICAL TEST			
							C %	Mn %	Si %	S %	P %	Cr %	Ni %	Cu %	Al %	Mo %	CEQ %	Rm TS	ReH YP	A Elong.	Kv -20 °C J
S355J2G3	36972	15	2000	6000	7	1107372	0,16	1,49	0,32	0,009	0,020	0,05	0,02	0,03	0,040			529	364	26,0	51
S355J2G3	36408	25	2000	6000	4	215157	0,20	1,45	0,21	0,015	0,027	0,030	0,010	0,010	0,033			542	369	26,5	47
S355J2G3	36849	30	2000	6000	1	315275	0,20	1,36	0,21	0,016	0,025	0,050	0,020	0,200	0,023			537	356	27,0	40
S355J2G3	36980	30	2000	6000	1	215182	0,21	1,39	0,23	0,011	0,022	0,040	0,020	0,020	0,043			540	359	27,0	40

DEBRUNNER TAVELLI SA

SI CERTIFICA CHE IL PRODOTTO SOPRAELENCATO E' CONFORME ALLE PRESCRIZIONI DELL'ORDINE.
WE HEREBY CERTIFY THAT THE ABOVE MENTIONED MATERIAL IS CONFORM TO THE QUALITY SPECIFIED.

Pagina 1 di 1

GEMAESS UHP-ZEICHEN MM1901719a - LGA

MARCEGAGLIA SAN GIORGIO DI NOGARO S.R.L.
CONTROLLO QUALITA'

AVVISO DI SPEDIZIONE : SHIPPING NOTICE 730497 del 20/02/02

SIA 263, Appendix A: Maximum permissible thicknesses

Railway steel bridge S 355, t_{max} = 75 mm, T_{min} < -10 °C ⇔ **S355 K2**

Température de service déterminante de l'élément de construction		$T_{min} \geq 0\,°C$		$0\,°C > T_{min} \geq -10\,°C$		$T_{min} < -10\,°C$	
Catégories de service		SC1	SC2	SC1	SC2	SC1	SC2
Nuances d'aciers	S 235 JR	$t \leq 150$	$t \leq 40$	$t \leq 100$	$t \leq 30$	$t \leq 40$	–
	S 235 J0	250	100	250	85	180	60
	S 235 J2	250	140	250	120	250	85
	S 355 JR	40	–	30	–	20	–
	S 355 J0	120	80	80	65	60	45
	S 355 J2	250	110	180	90	150	65
	S 355 K2	250	120	250	100	250	80
	S 355 N	250	130	250	110	250	90
	S 355 NL	250	175	250	150	250	130
	S 460 N	180	50	150	40	100	30
	S 460 NL	250	150	250	100	250	70

- Table similar to those of EN 1993-1-10: choice of quality for toughness

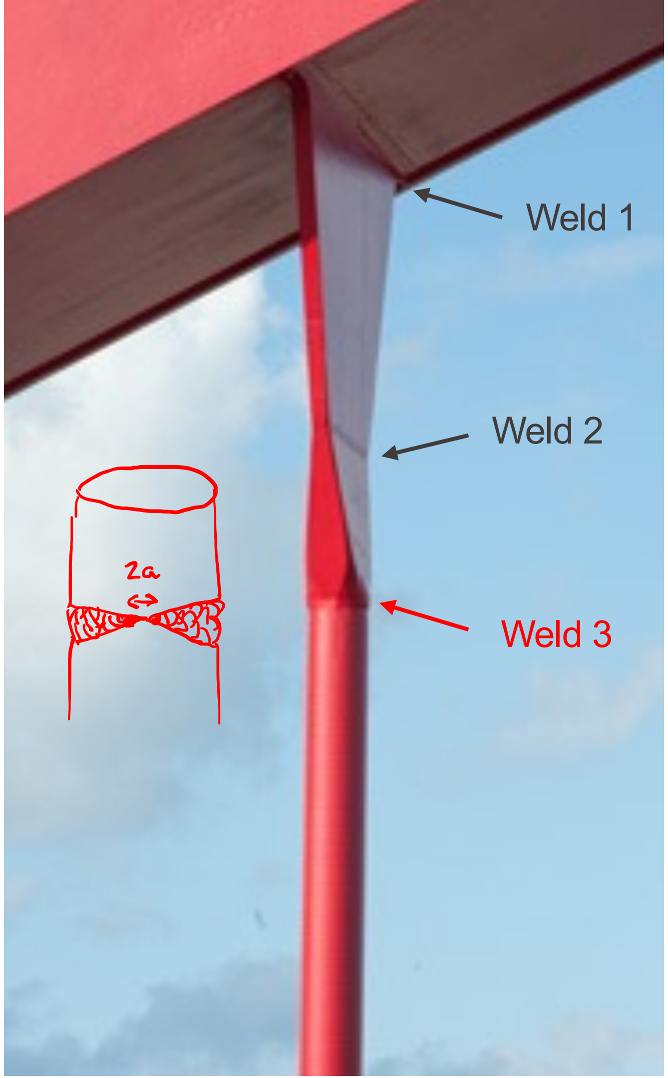
EXERCISE FAT3: Stress Intensity Factor Calculations

- Arch bridge hanger: 100mm S690 steel round bar
- Welded (full penetration) at its ends: connecting piece then plate
- Weld 3 to be checked
- Measured CVN (valid down to -60°C) 135 J = guaranteed min. value

Questions:

1. Max. circular internal imperfection size? Bar designed using σ_{Ed} = 80%·f_y
2. Semi-elliptic, imperfection a/c = 0.5, 2c = 30 mm critical σ_{Ed} = 1.1· 80%·f_y ?

Note: no additional partial factors.



EPFL

Eprouvettes CT de différentes tailles (acier A533B, f_y = 480 MPa), réf.: Barsom&Rolfe, 1987

Thank you

Prof. A. Nussbaumer
RESSLab

EXERCICE FAT3:
Sketch of solution

Cross-sectional view of hanger bar:

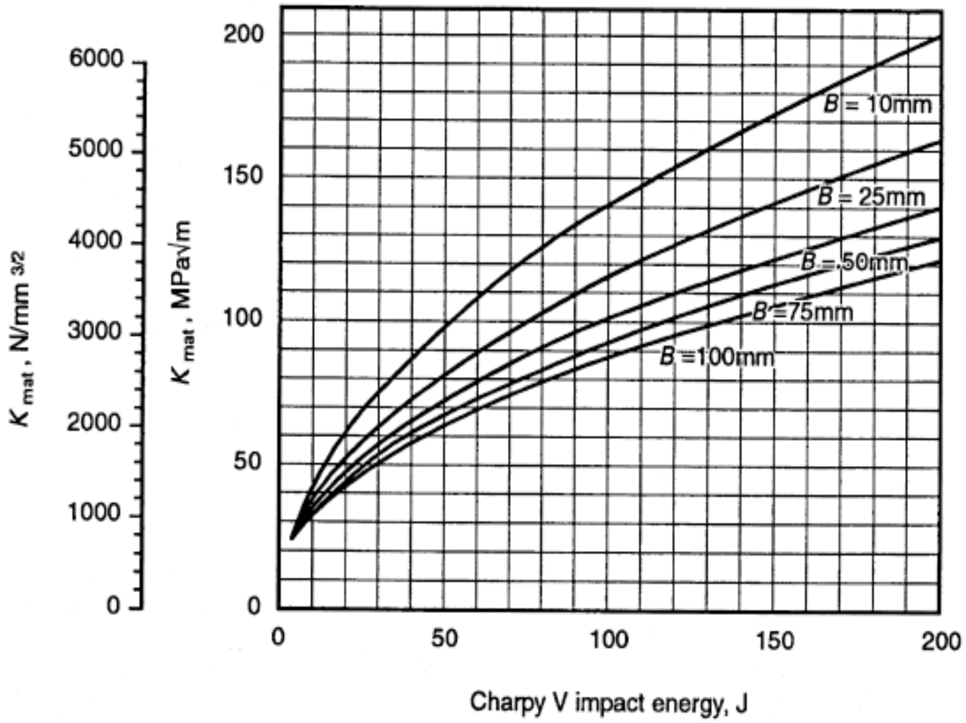
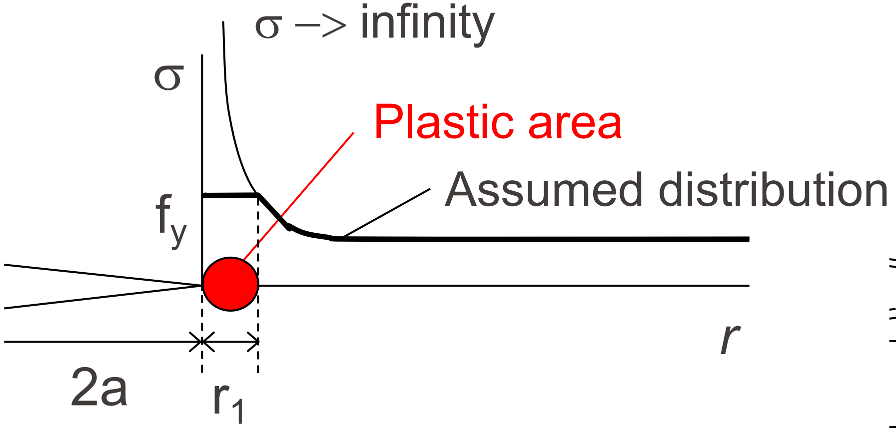
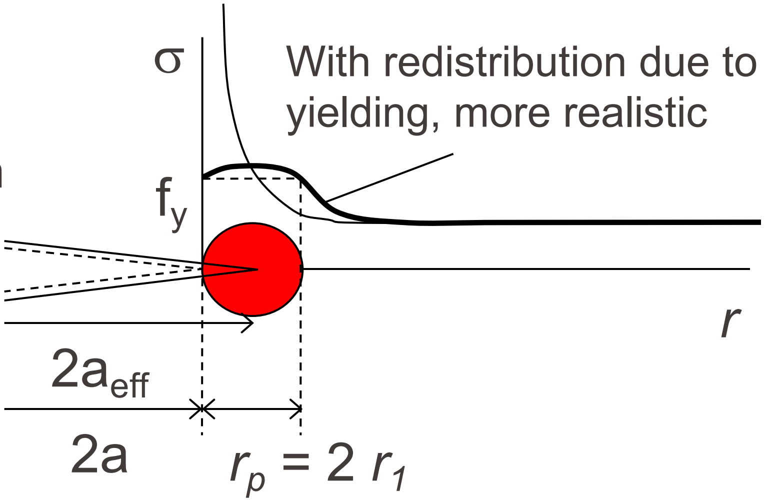


Figure J.2 — K_{mat} plotted against Charpy V impact energy for lower shelf and transitional behaviour

EXERCICE FAT3:

Appendix: Plastic crack tip zone – Triaxiality





$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r_1}} f_{ij}(\theta = 0) = f_y$$

$$r_1 = \frac{K_I^2}{2\pi f_y^2}$$

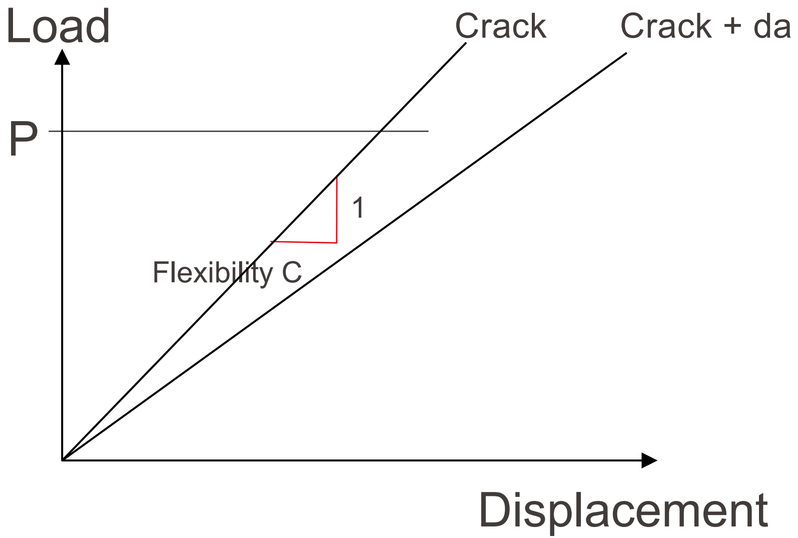
$$r_1 = \frac{K_I^2}{6\pi f_y^2}$$

$\sigma_z = 0$ Plane stress state

$\varepsilon_z = 0$ Plane strain state

APPENDIX: Irwin, crack driving force concept

- Parameter $\mathcal{G}$ is a direct measure of the material's ability to support the plastic area, to resist, in front of the crack peak until it propagates.



- Under disp. or cst load :

$$\mathcal{G} = \frac{1}{2} P^2 \frac{dC}{dA}$$

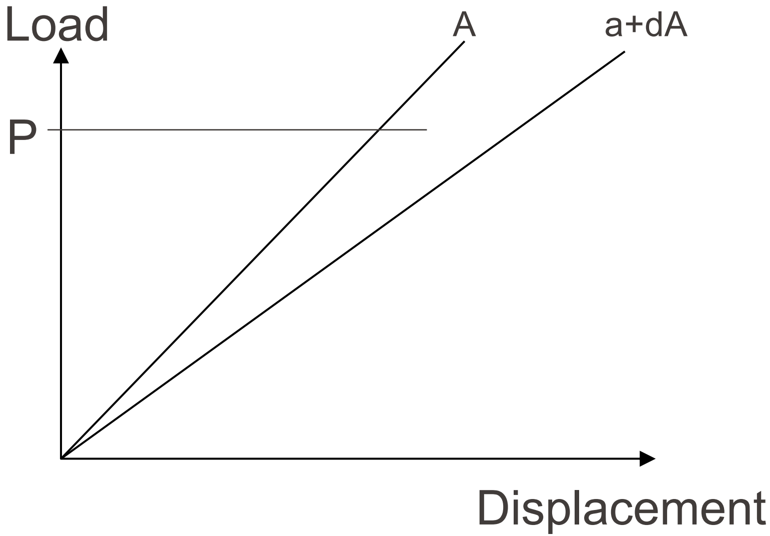
- Link to K:

$$\mathcal{G} = \alpha \frac{K_I^2}{E}$$

$\alpha = 1$ Plane Stress State

$\alpha = 1 - \nu^2$ Plane Strain State

Irwin theory, crack driving force concept



- Under constant load:

$$\mathcal{G}_C = \frac{1}{2} P^2 \frac{dC}{dA} = \mathcal{G}_\Delta$$

Under constant displacement

- The proof that this parameter is a direct measure of material capacity to withstand a plastic zone, to resist, in front of crack tip

- Modified Griffith energy criterion, add to it plastic dissipation:

$$\sigma \sqrt{a} \geq \sqrt{\frac{E \cdot \mathcal{G}}{\pi}} \qquad \mathcal{G} = 2\gamma + \mathcal{G}_{Plast}$$