Toughness/crack resistance

i. Basic notations (transition fracture behaviour of steels, temperature dependence of strength properties, fractography and failure analysis – basic approach)

ii. (Empirical) tests of toughness/crack resistance (Charpy, Pellini diagram, NDTT)

iii. Linear – elastic fracture mechanics – LEFM (Irwin, fracture toughness tests), Elastic – plastic fracture mechanics EPFM (tests, interpretation)

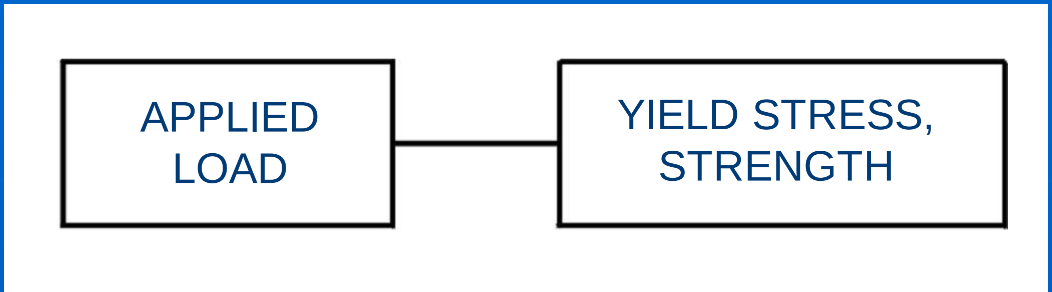
How to avoid brittle fracture of welded steel structure/component

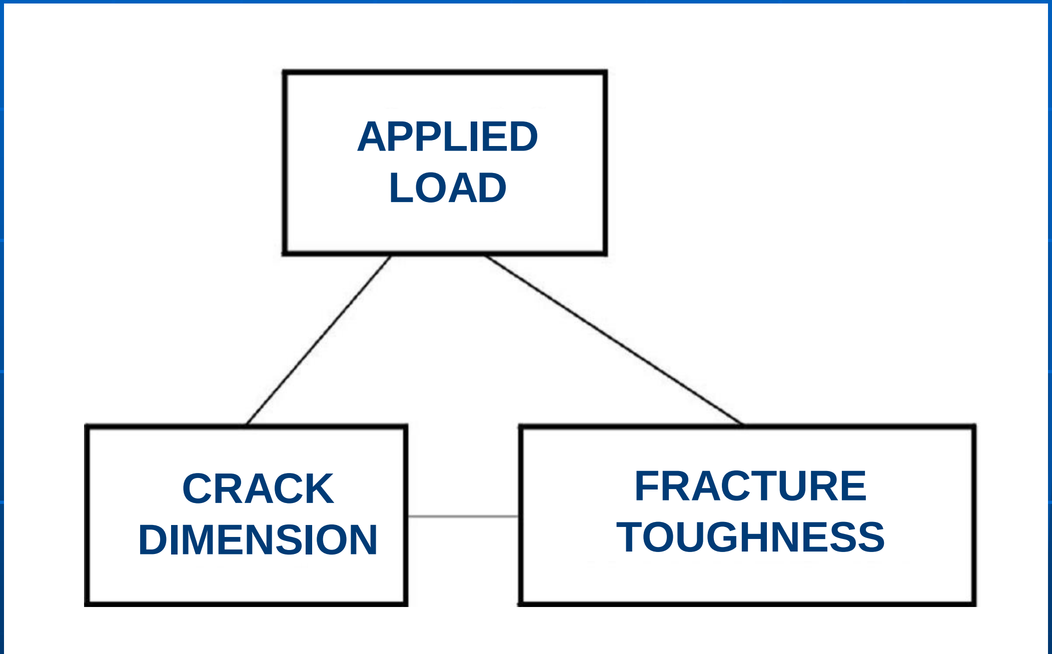
- crack arrest concept

– transition temperature

- concept of

– fracture mechanics





$$\sigma_{max} \leq R_f/k$$

k - safety factor

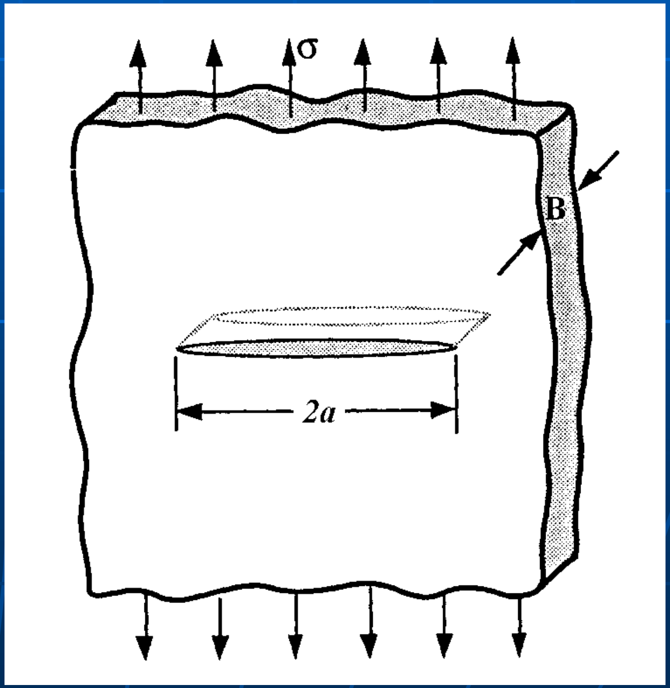
R_f - strength parameter

$$t_{min} \geq tt + \Delta t$$

tt - transition temperature

Δt – safety factor to trans. temperature

Fracture mechanics is a scientific field dealing with limit states of bodies with cracks/defects



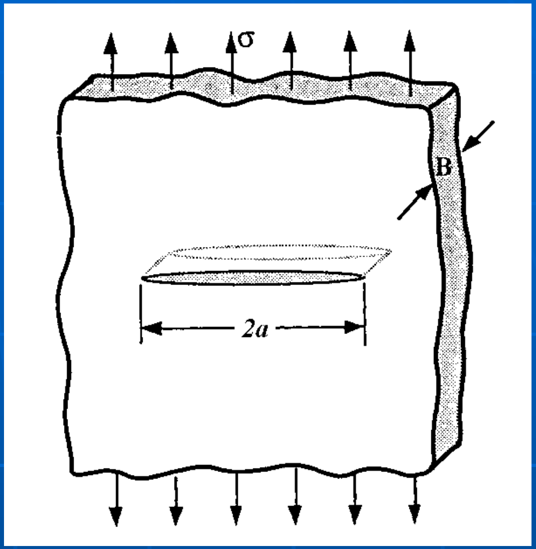
Fracture mechanics

Stressed (loaded) body with a crack – **energetic analysis** – **Griffith** – parameter ***G***

Stressed (loaded) body with a crack – **stress analysis** – **Irwin** (**Kinz**)– parameter ***K***

Energetic criterion - Griffith

- Infinitely large plate loaded by constant stress, internal crack, thickness B



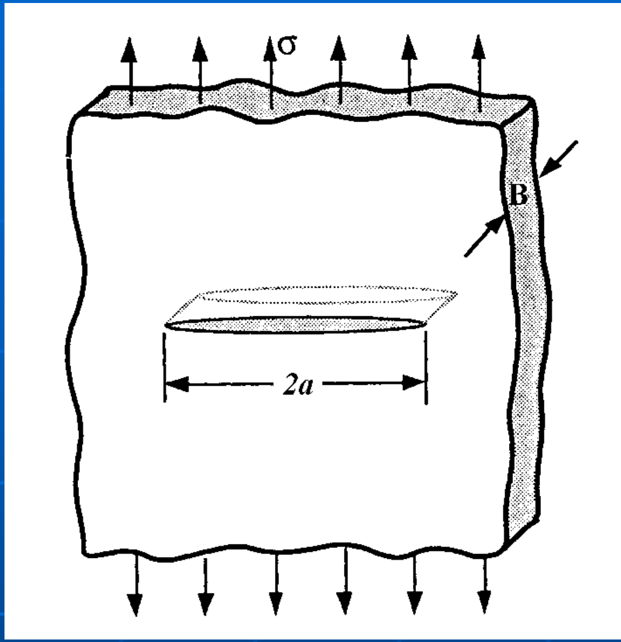
- Energy balance (energy conservation law)
- Work associated with new fracture surface increment (crack propagation) “covered” by elastic energy released in surrounding of the growing crack

$$\frac{dW}{dA} = \frac{dW_{el}}{dA} + \frac{dW_s}{dA} \leq 0$$

$$-\frac{dW_{el}}{dA} = \frac{dW_s}{dA}$$

Energetic criterion - Griffith

Crack may propagate only if the process leads to total energy decrease and/or is the same



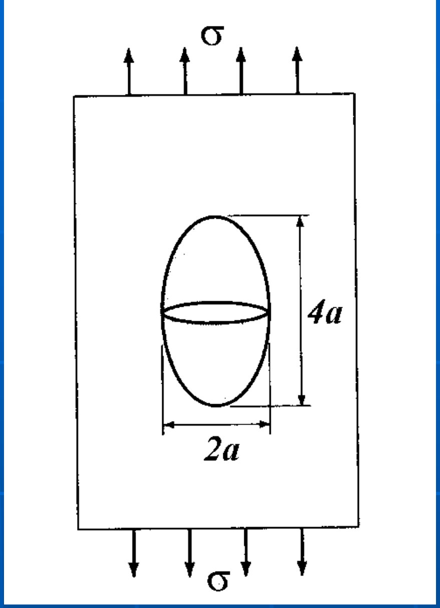
At accident, at sudden failures caused by brittle fracture, the work connected with fracture formation is covered by elastic energy accumulated in the structure

the fracture is possible only when released elastic energy at the crack tip is capable to create new surfaces

Energetic criterion - Griffith

$$\frac{dW}{dA} = \frac{dW_{el}}{dA} + \frac{dW_s}{dA} \leq 0$$

$$-\frac{dW_{el}}{dA} = \frac{dW_s}{dA}$$

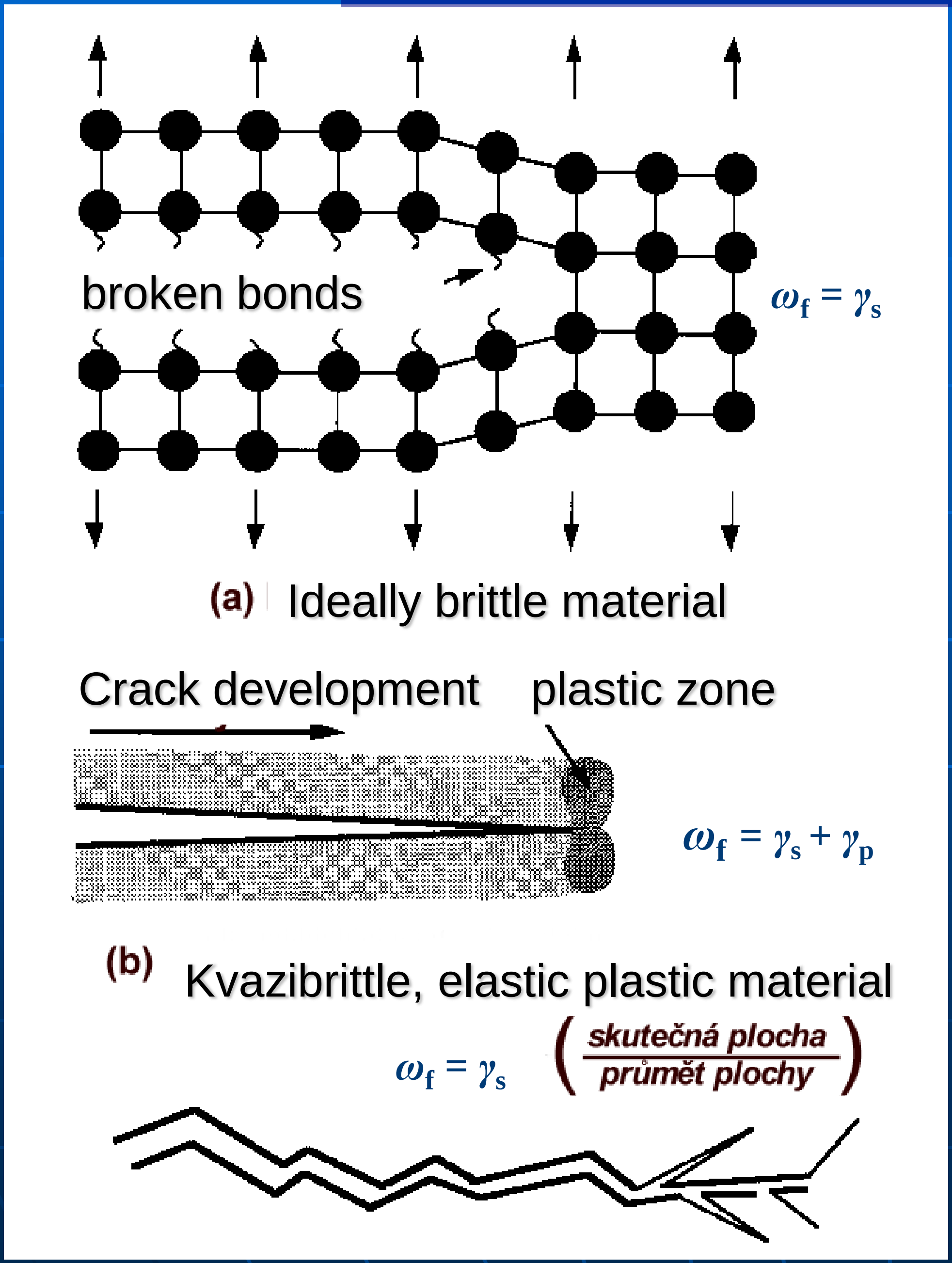


$$W_{el} = -\frac{\pi . a^2 . \sigma^2 . B}{E}$$

$$W_s = 2 * 2.a.B.\gamma_s$$

$$\sigma_f = \left(\frac{2.E.\gamma_s}{\pi . a} \right)^{1/2}$$

Energetic criterion – Griffith-Orowan



$$\sigma_f = \left(\frac{2.E.\gamma_s}{\pi.a} \right)^{1/2}$$

$$\sigma_f = \left(\frac{2E\omega_f}{\pi a} \right)^{1/2}$$

$$\sigma_f = \left(\frac{2E(\gamma_s + \gamma_p)}{\pi.a} \right)^{1/2}$$

Energetic criterion – Griffith-Orowan

(Irwin modification of Griffiths theory)

$$G = -\frac{dW_{el}}{da}$$

$$G = \frac{\pi\sigma^2 a}{E}\left[\frac{(MPa)^2}{MPa}m = \frac{MNm}{m^2}\right]$$

$\frac{MJ}{m^2}$ → **energy release rate**

$\frac{MN}{m}$ → **crack driving force**

Energetic criterion – Griffith-Orowan

$$\frac{dW_s}{da} = 2\omega_f = 2(\gamma_s + \gamma_p)$$

$2\omega_f$

- ***G_c*** **– fracture toughness of the material**
- ***R (R- curve)*** **- materials crack resistance**

Energetic criterion – Griffith-Orowan

CRACK DRIVING FORCE **G**

Energy release rate (rate of potencial energy change in dependence on fracture surface increement)

$$G = -\frac{dW_{el}}{dA} \qquad G = \frac{\pi\sigma^2 a}{E} \qquad \left[\frac{(MPa)^2}{MPa} m = \frac{MJ}{m^2} = \frac{MN}{m} \right]$$

MATERIALS CRACK RESISTANCE **R**

Rate of surface energy increase with increase of fracture surfaces, the critical value – condition for crack initiation

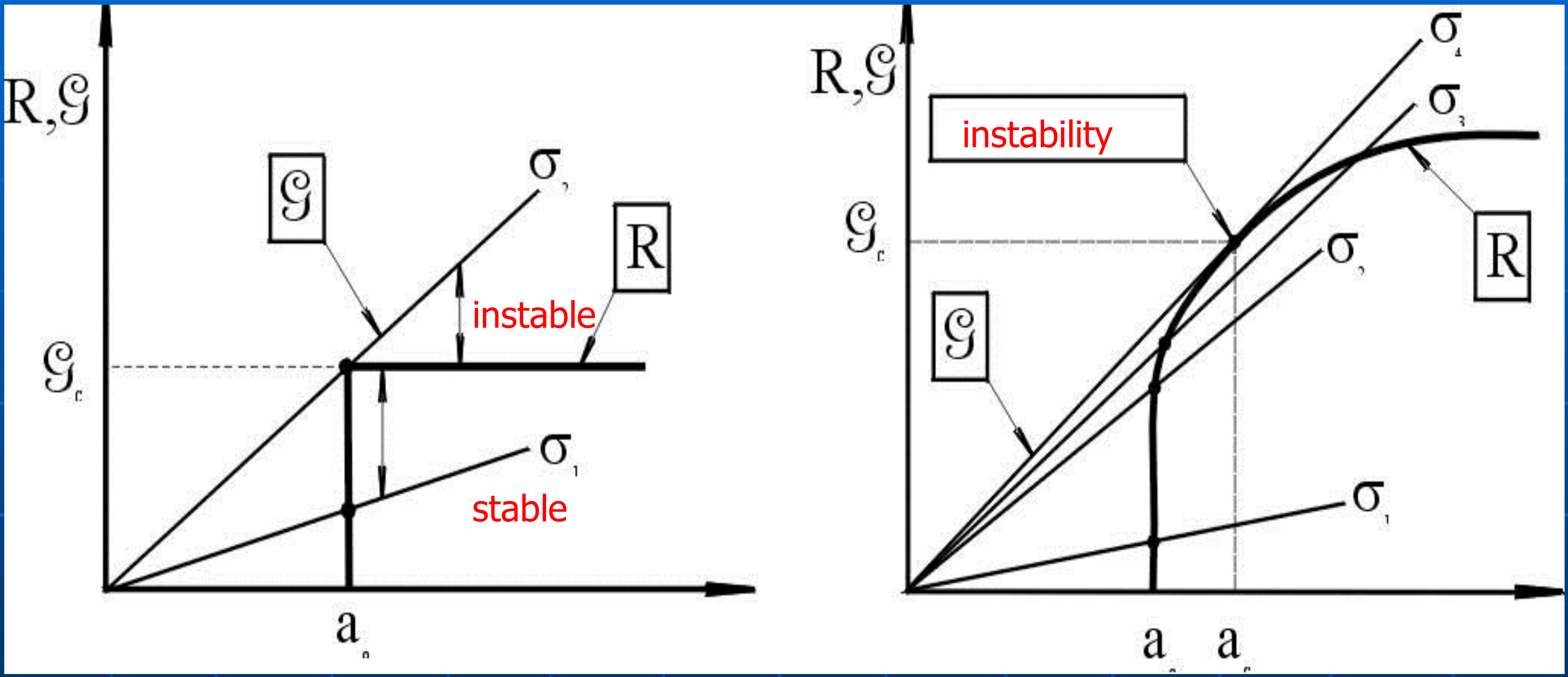
$$R = \frac{dW_s}{dA} \qquad R = 2(\gamma_s + \gamma_p) = G_C$$

toughness G_C

Energetic criterion – Griffith-Orowan

Crack resistance curve – inherent property of the material

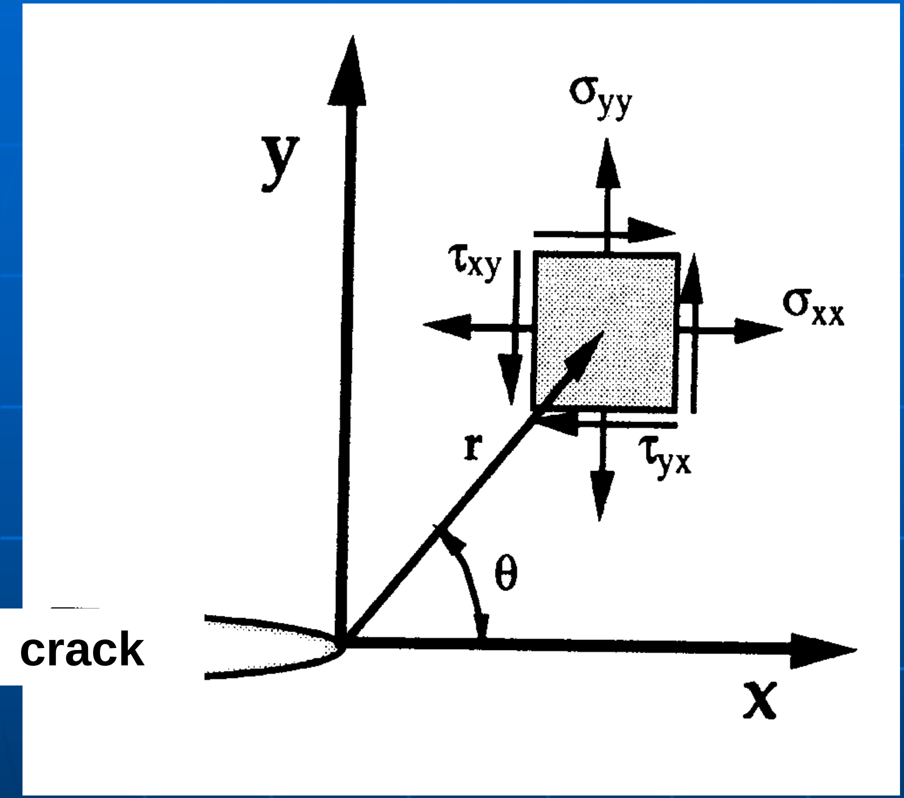
G_C – material property (fracture toughness)



stable crack propagation – crack does not propagate, as far as applied load increases

unstable crack propagation – crack propagates spontaneously, without necessity of further load increasing

Stress criteria - Irwin



r a θ - polar coordinates

σ_{ij} - components of stress tensor

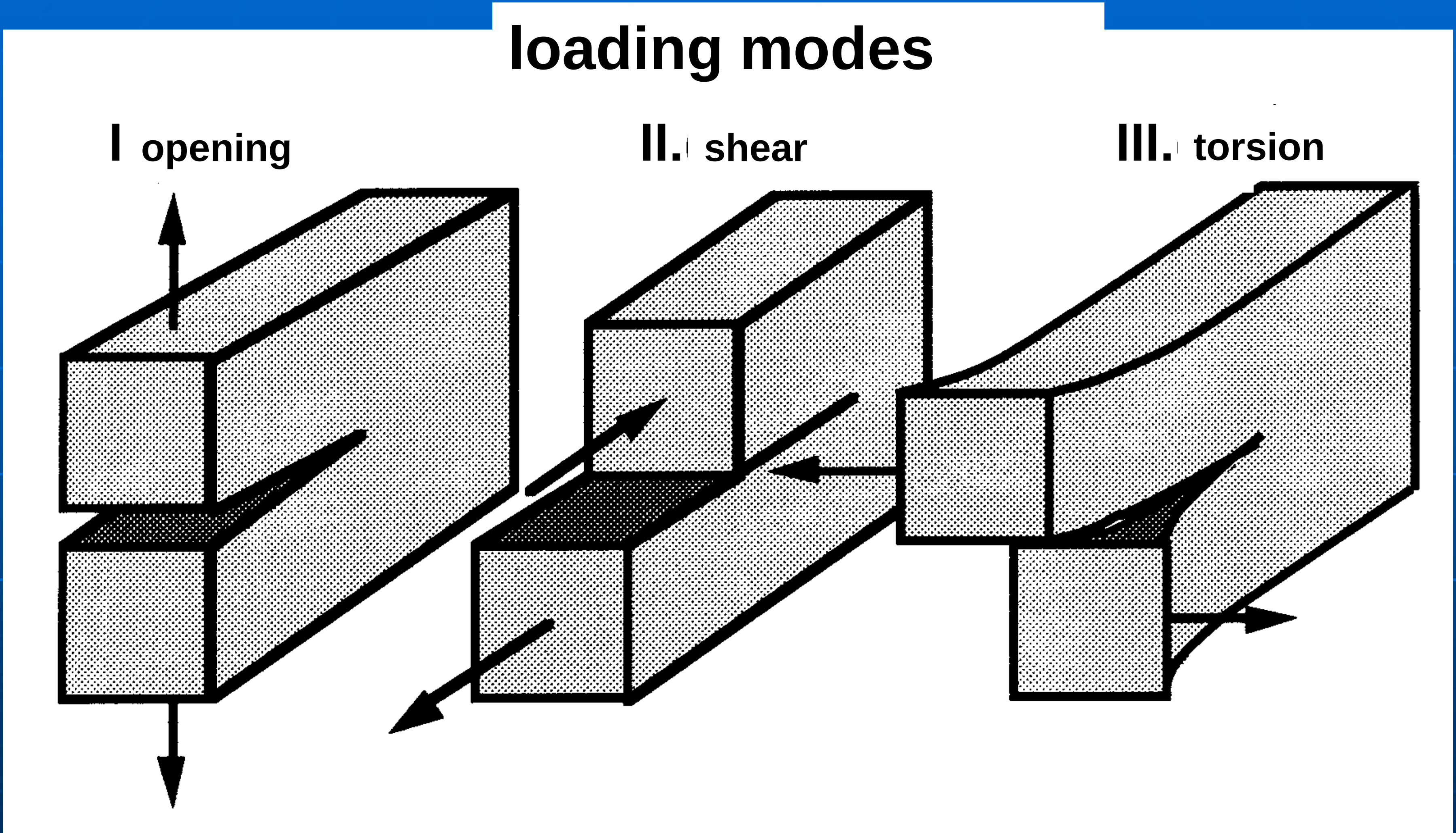
k - constant

$f_{ij}(\theta), g_{ij}(\theta)$

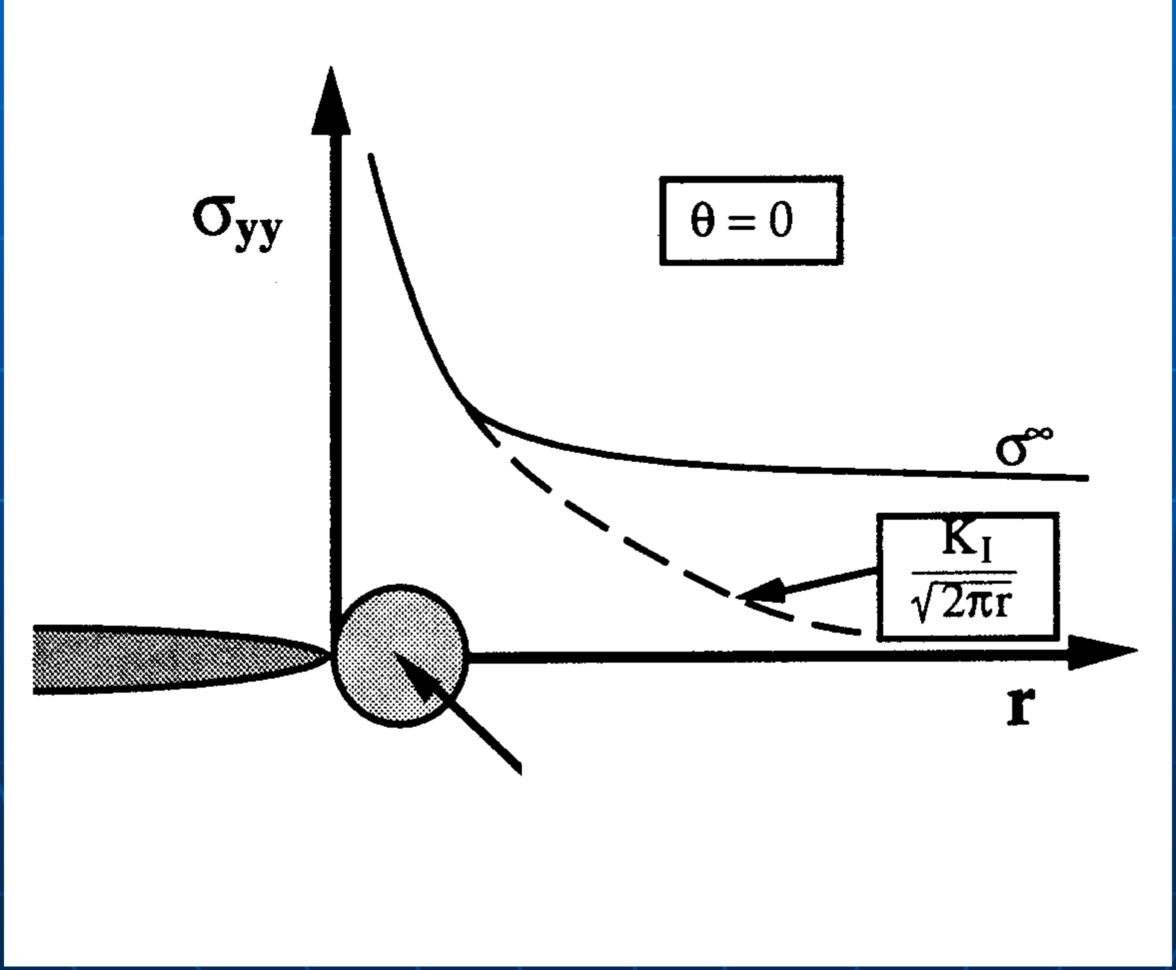
- dimensionless quantities (function of angle θ)

$$\sigma_{ij} = \left(\frac{k}{\sqrt{r}}\right).f_{ij}(\theta) + \sum_{m=0}^{\infty} A_m . r^{\frac{m}{2}} g_{ij}^{(m)}(\theta)$$

Stress criteria - Irwin



Stress criteria - Irwin



stress intensity factor

$$\sigma_{ij} = \left(\frac{k}{\sqrt{r}}\right).f_{ij}(\theta) + \sum_{m=0}^{\infty} A_m.r^{\frac{m}{2}} g_{ij}^{(m)}(\theta)$$

$$\sigma_{ij} = \left(\frac{k}{\sqrt{r}}\right).f_{ij}(\theta)$$

$$K_I = k.\sqrt{2\pi}$$

Stress criteria - Irwin

Napěťová pole před čelem trhliny pro Mód I a Mód II v lineárním elastickém a isotropním materiálu

	Mód I	Mód II
σ_{xx}	$\frac{K_I}{\sqrt{2\pi r}} cos\left(\frac{\theta}{2}\right)\left[1 - sin\left(\frac{\theta}{2}\right) sin\left(\frac{3\theta}{2}\right)\right]$	$-\frac{K_{II}}{\sqrt{2\pi r}} sin\left(\frac{\theta}{2}\right)\left[2 + cos\left(\frac{\theta}{2}\right) cos\left(\frac{3\theta}{2}\right)\right]$
σ_{yy}	$\frac{K_I}{\sqrt{2\pi r}} cos\left(\frac{\theta}{2}\right)\left[1 + sin\left(\frac{\theta}{2}\right) sin\left(\frac{3\theta}{2}\right)\right]$	$\frac{K_{II}}{\sqrt{2\pi r}} sin\left(\frac{\theta}{2}\right) cos\left(\frac{\theta}{2}\right) cos\left(\frac{3\theta}{2}\right)$
τ_{xy}	$\frac{K_I}{\sqrt{2\pi r}} cos\left(\frac{\theta}{2}\right) sin\left(\frac{\theta}{2}\right) cos\left(\frac{3\theta}{2}\right)$	$\frac{K_{II}}{\sqrt{2\pi r}} cos\left(\frac{\theta}{2}\right)\left[1 - sin\left(\frac{\theta}{2}\right) sin\left(\frac{3\theta}{2}\right)\right]$
σ_{zz}	0(rovinná napjatost) $\mu(\sigma_{xx} + \sigma_{yy})$ (rovinná deformace)	0(rovinná napjatost) $\mu(\sigma_{xx} + \sigma_{yy})$ (rovinná deformace)
τ_{xz} τ_{yz}	0	0

Stress criteria - Irwin

Posunutí před čelem trhliny pro Mód I a Mód II v lineárním elastickém a isotropním materiálu

	Mód I	Mód II
u_x	$\frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}\cos\left(\frac{\theta}{2}\right)\left[\kappa-1+2\sin^2\left(\frac{\theta}{2}\right)\right]$	$\frac{K_{II}}{2G}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)\left[\kappa+1+2\cos^2\left(\frac{\theta}{2}\right)\right]$
u_y	$\frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)\left[\kappa+1-2\cos^2\left(\frac{\theta}{2}\right)\right]$	$-\frac{K_{II}}{2G}\sqrt{\frac{r}{2\pi}}\cos\left(\frac{\theta}{2}\right)\left[\kappa-1-2\sin^2\left(\frac{\theta}{2}\right)\right]$

G je modul ve smyku, $\kappa = 3\text{-}4\mu$ (rovinná deformace), $\kappa=(3-\mu)/(1+\mu)$

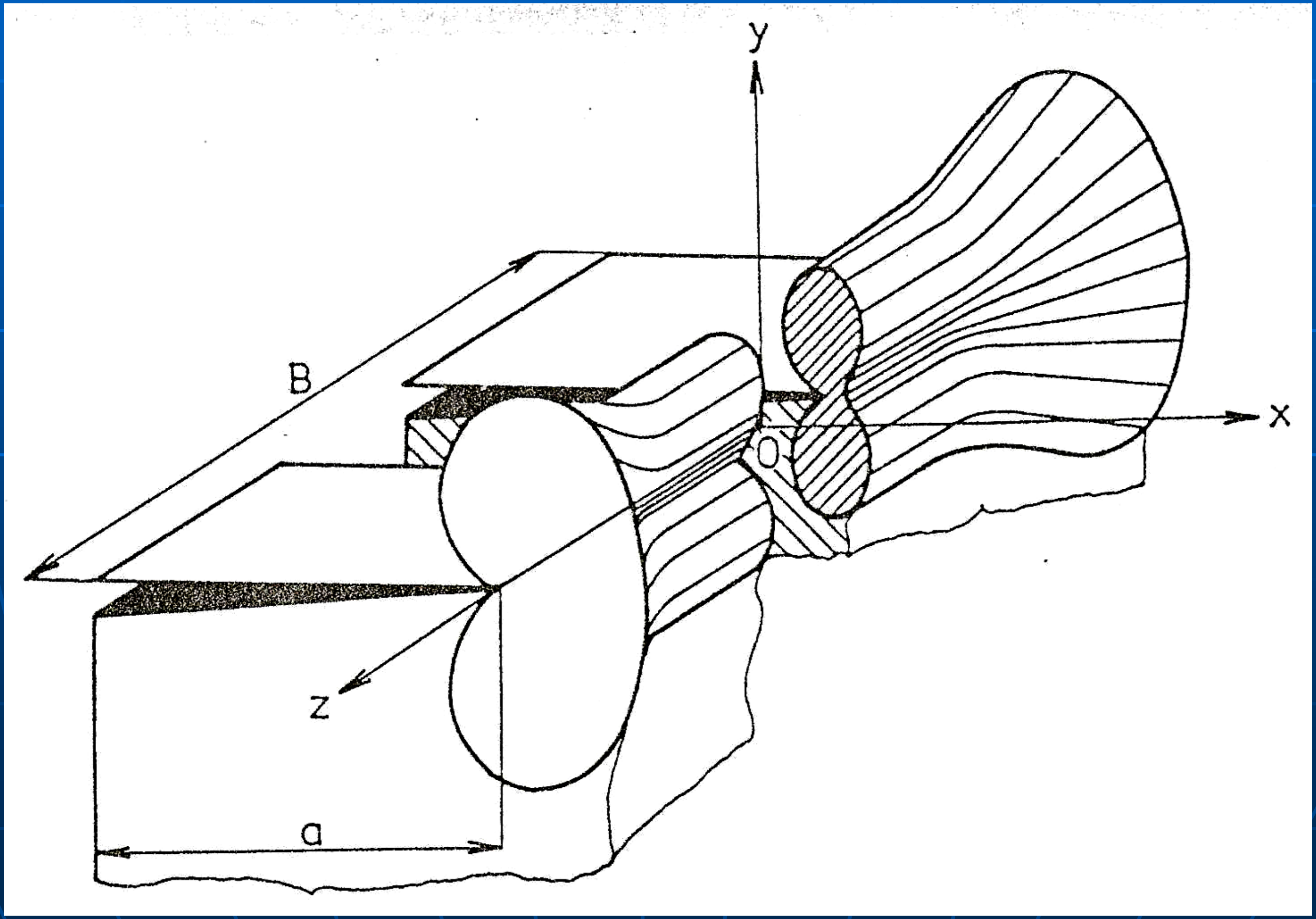
Tab. 3 Složky nenulových napětí a posunutí v Módu III v lineárním elastickém a isotropním materiálu

$\tau_{xz} = -\frac{K_{III}}{\sqrt{2\pi r}}\sin\left(\frac{\theta}{2}\right)$	$\tau_{yz} = \frac{K_{III}}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)$	$u_z = -\frac{K_{III}}{G}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)$

Stress criteria - Irwin

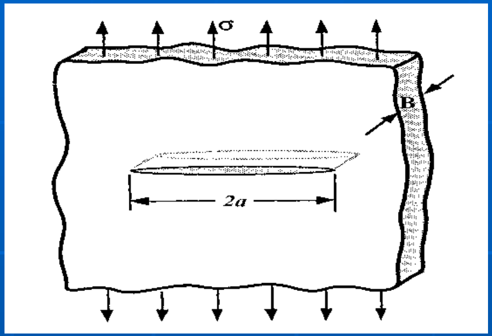
Stress distribution - biaxial vs. triaxial

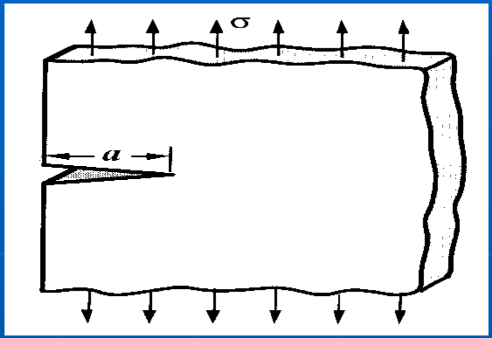
Strain distribution – triaxial vs. biaxial

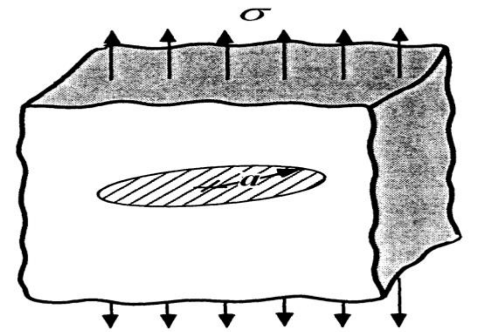


Stress criteria - Irwin

- Basic solutions







$$K_I \approx \sigma$$

$$K_I = \sigma\sqrt{\pi . a}$$

$$K_I = \frac{2}{\pi}\sigma\sqrt{\pi . a}$$

- General solutions (tabeled)

$$K_I = \frac{F}{B.\sqrt{W}}.f\left(\frac{a}{W}\right)$$

B – thickness
W – width / dimension in crack propagation direction
a – crack length
F – fracture force

Stress criteria - Irwin

units K_I

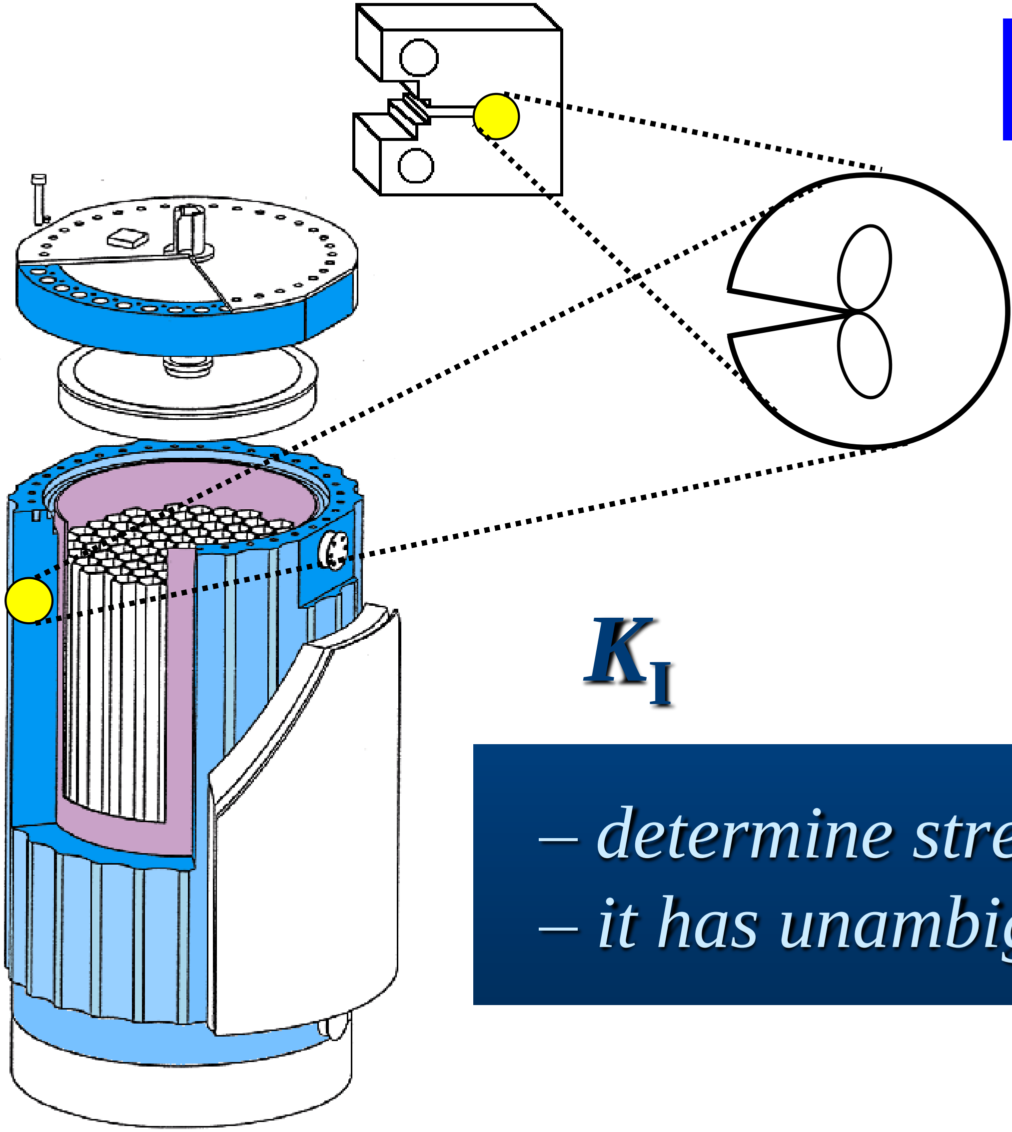
$$K_I = \sigma\sqrt{\pi.a} \qquad MPa\sqrt{m} = MPam^{1/2} = MPam^{0,5}$$

relationship between G_C a K_{IC}

$$G = \frac{\pi\sigma^2 a}{E} \longrightarrow G = \frac{K_I^2}{E} \longleftarrow K_I = \sigma\sqrt{\pi.a}$$

$$G = \frac{K_I^2}{E}(1-\nu^2)$$

Stress criteria - Irwin

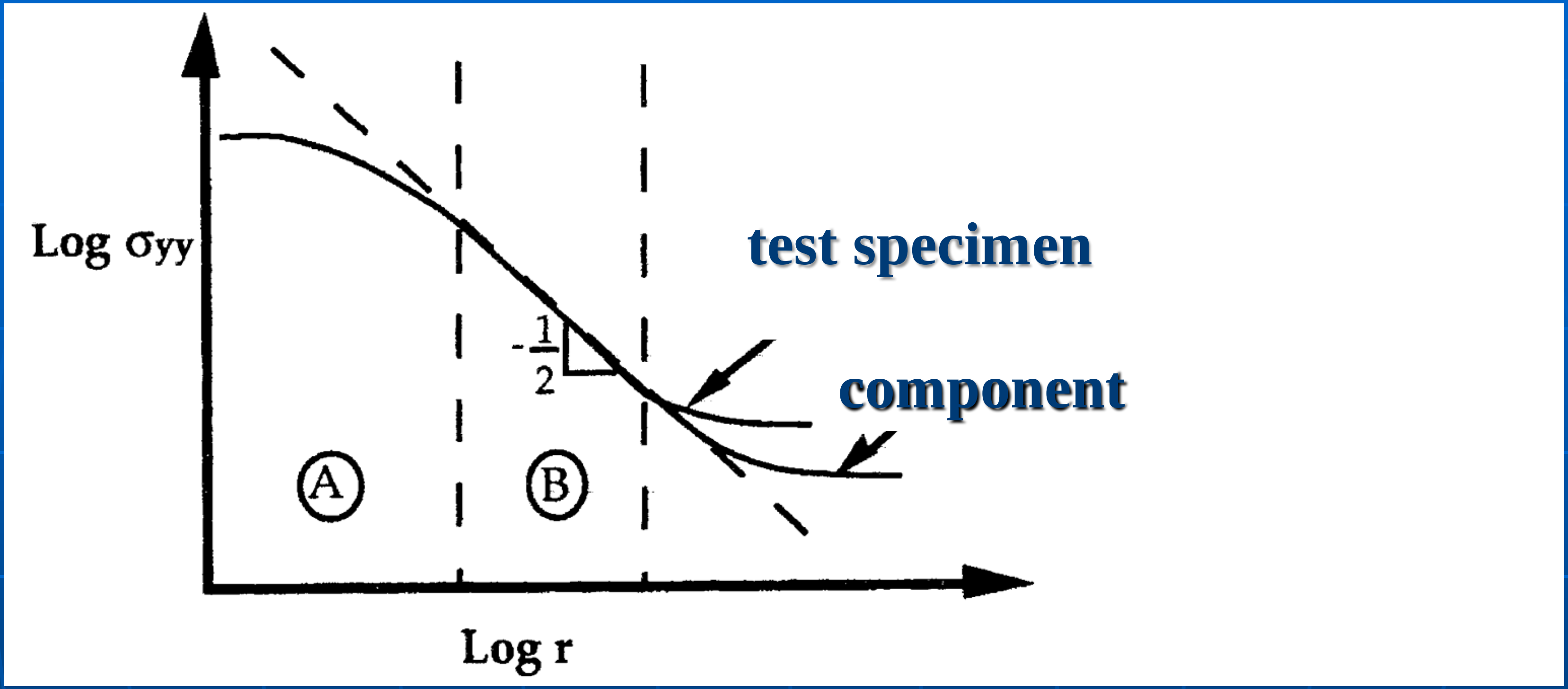


validity conditions

K_I

- *determine stress state at the crack tip*
- *it has unambiguous relation to G_C*

Stress criteria - Irwin



Fracture occurs when the stress intensity factor at the crack tip reaches the critical value $K_I \equiv K_C$
providing the region (process zone) where singularity dominates is the same

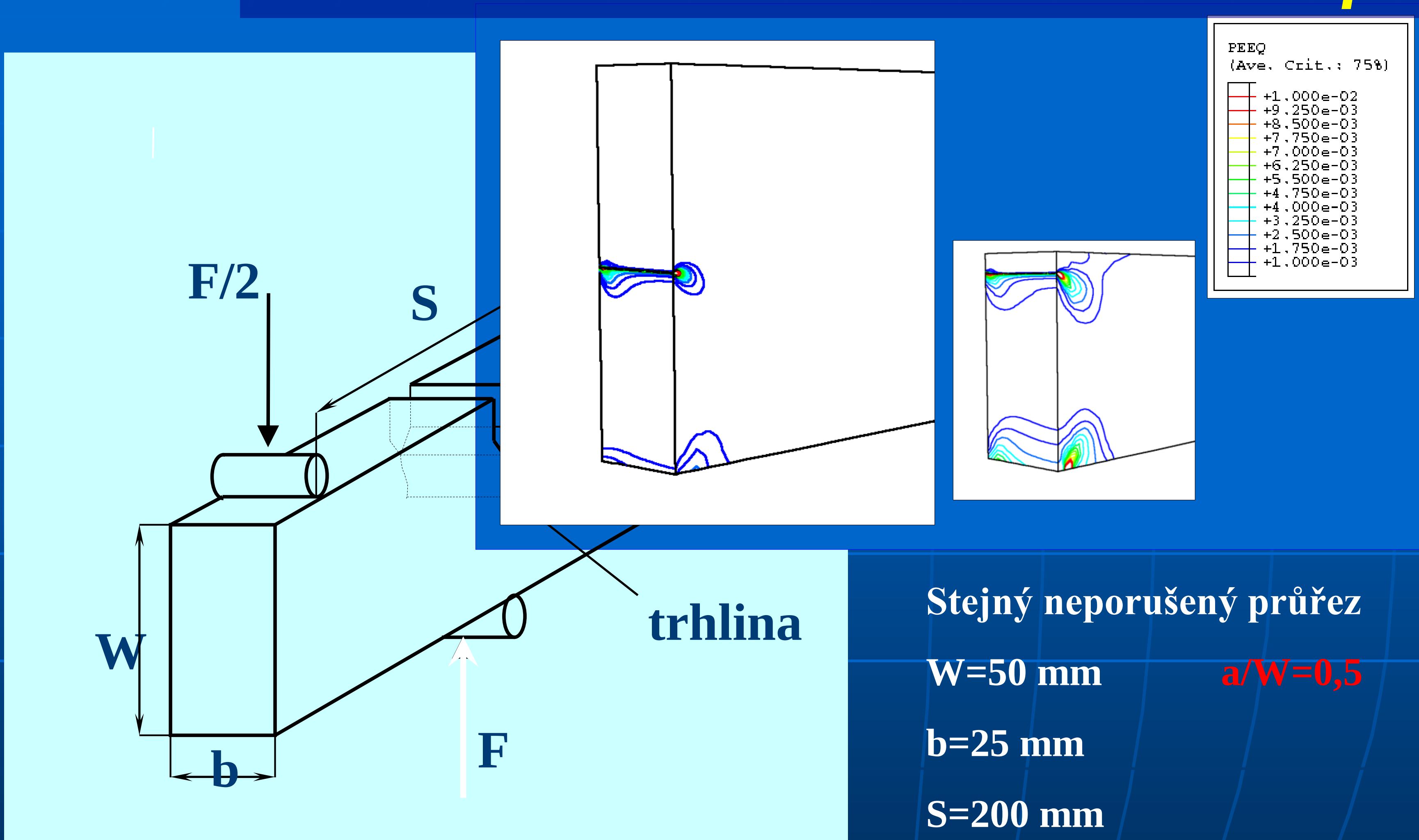
Linear elastic fracture mechanics – if the fracture occurs at small plastic zone (small scale yielding conditions, 2% velikosti tloušťky).

$$F_{fr} \leq (0{,}6 \div 0{,}8)\ F_{GY}$$

(ceramics, some plastics, aluminium alloys, high strength steels, for common steels only for very large thickness and/or dynamic loading).

determination of K_{Ic}

determination of K_{Ic}



Stejný neporušený průřez

W=50 mm **a/W=0,5**

b=25 mm

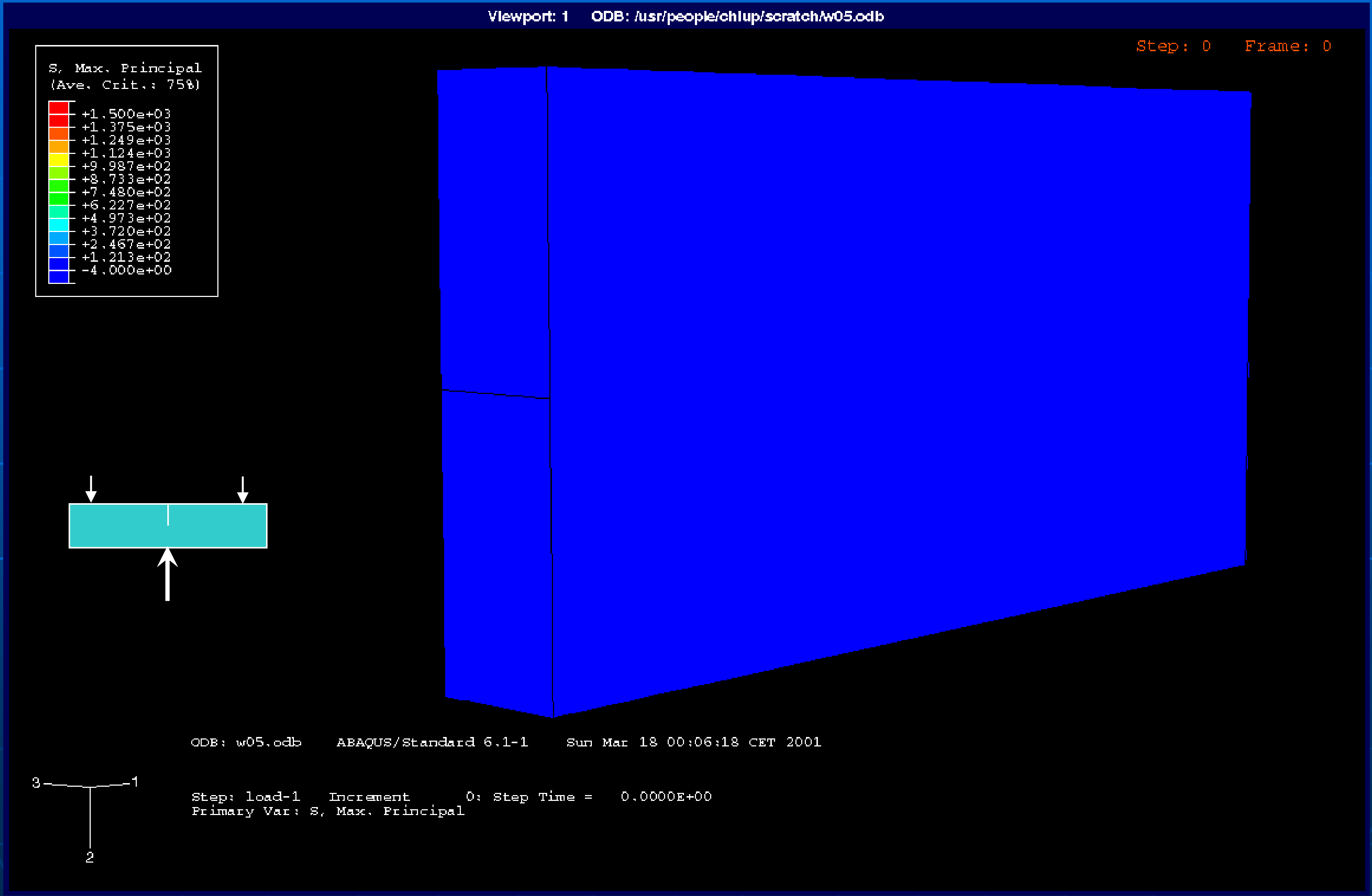
S=200 mm

W=26 mm **a/W=0,1**

b=25 mm

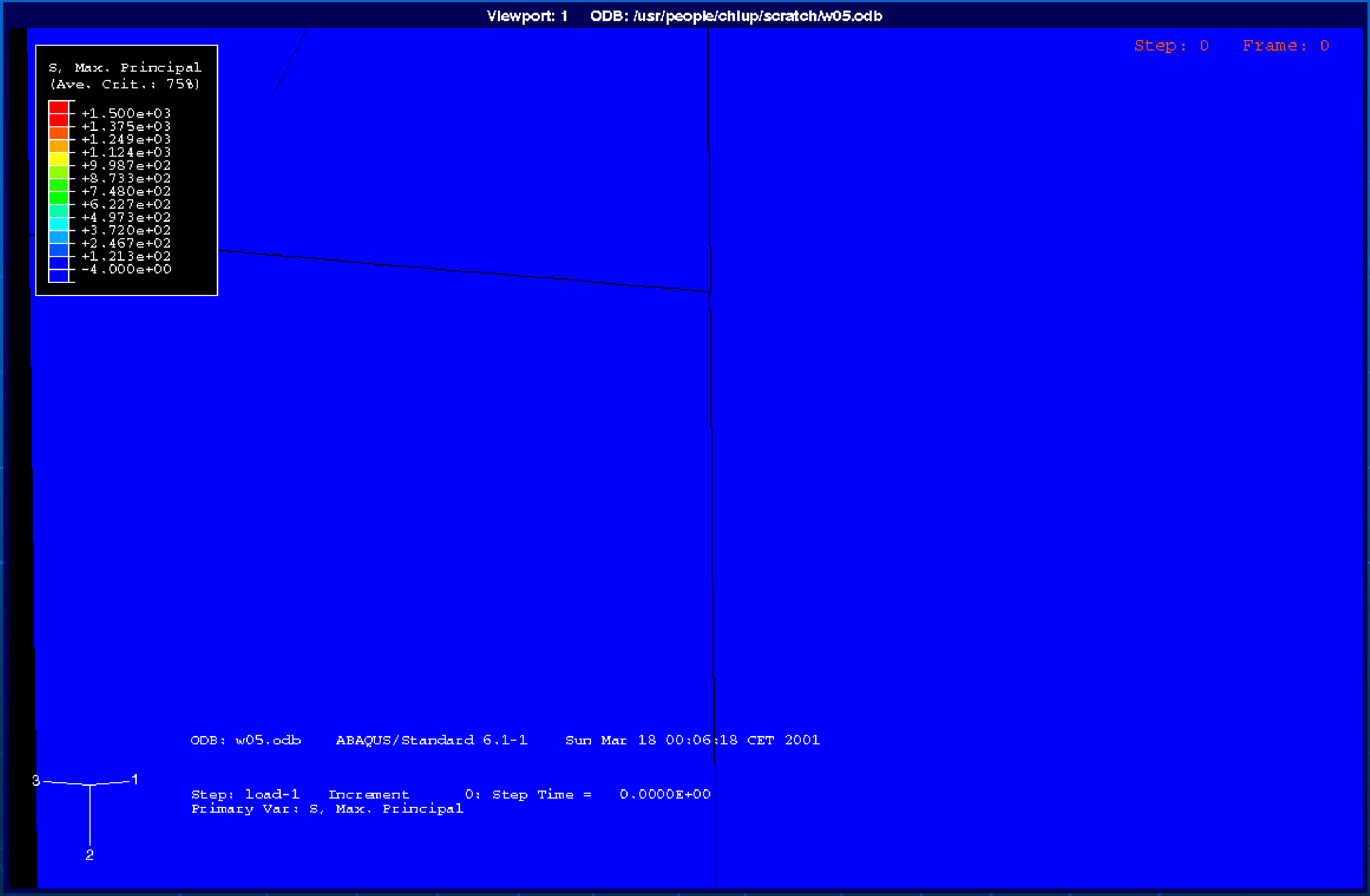
S=104 mm

a/W ≈ 0,5 maximum principal stress

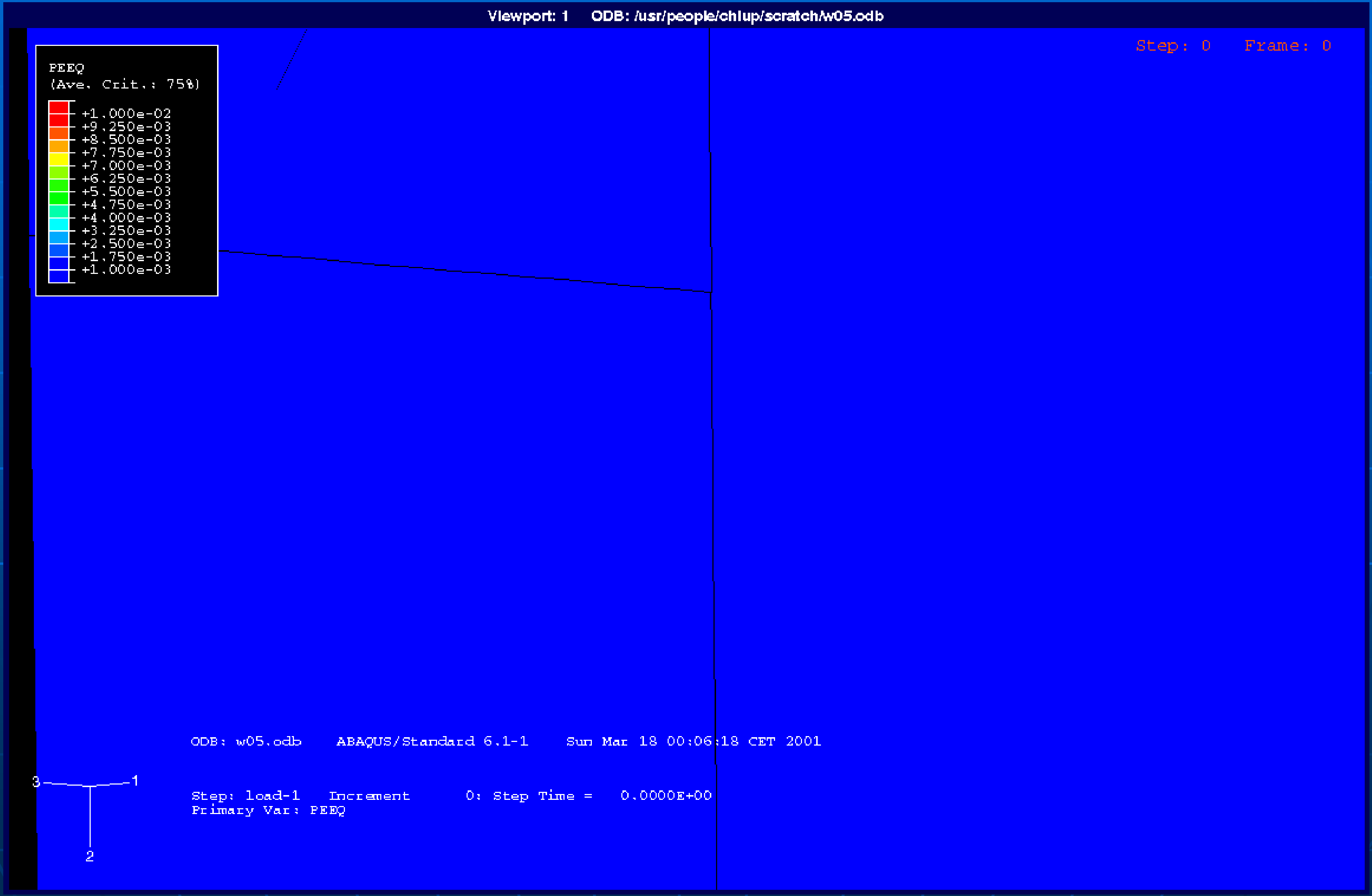


a/W ≈ 0,5

maximum principal stress / detail



a/W ≈ 0,5 plastic deformation - detail



a/W ≈ 0,1

maximum principal stress - detail

a/W ≈ 0,1 plastic deformation - detail