Spontant brott vid expanderande fasomvandling

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Spontant brott vid expanderande fasomvandling

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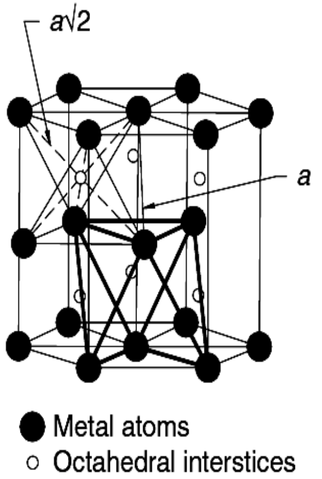
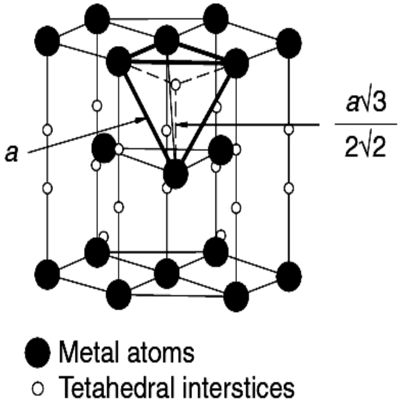
Zr-H solid solution and hydride

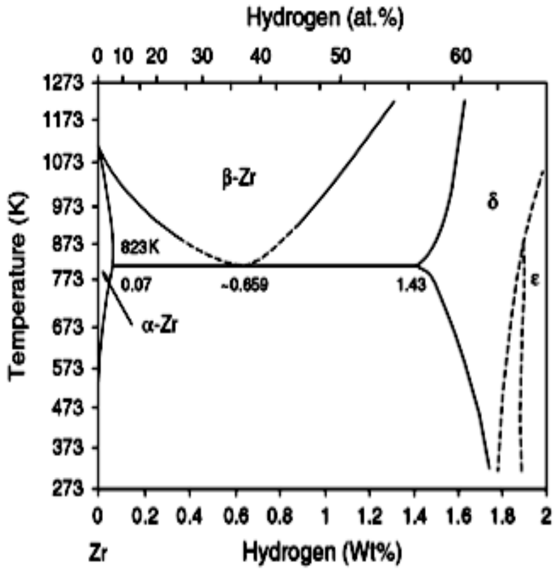
Hydrogen occupies tetrahedral sites in Zr-H solid solution

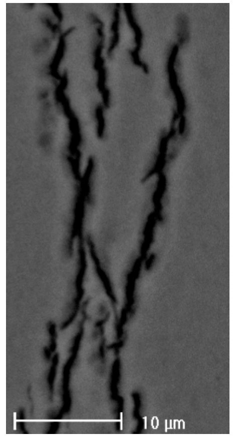
α-lattice distorts to match the γ and δ structures

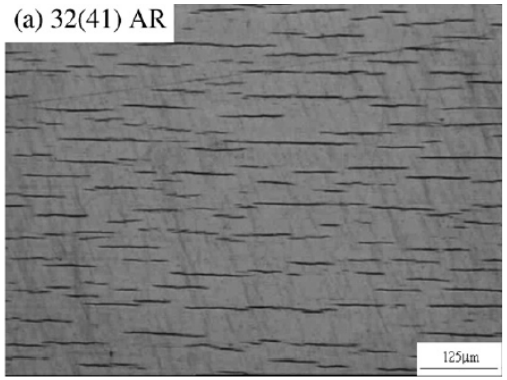
Interstitial ordering results in periodic occupation of tetrahedral sites











Zr exhibits two allotropic modification: low T hcp (α) and high T bcc (β) phases

Two stable hydrides (δ and ε) and one metastable (γ) hydride forms in this system

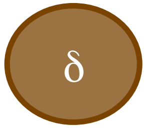
Under optical microscope the traces of hydrides appears as dark lines

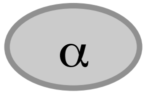
At higher magnification the hydride plates reveal several smaller entities

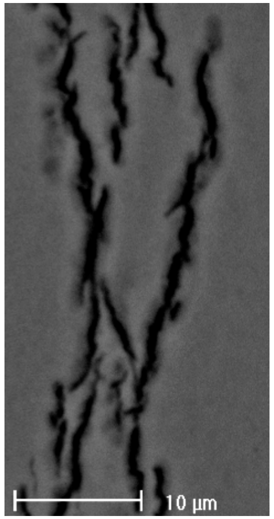
Hydride plate comprises of platelets stacked side by side

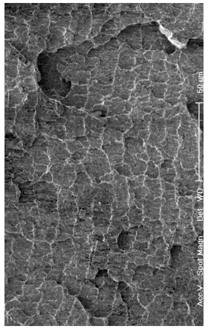
Each platelet comprises of sub-platelets stacked end to end

Multi-scale Structural Mechanics

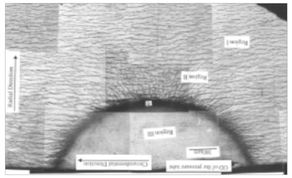




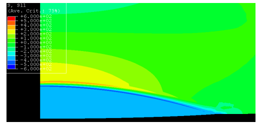




10-50 µm

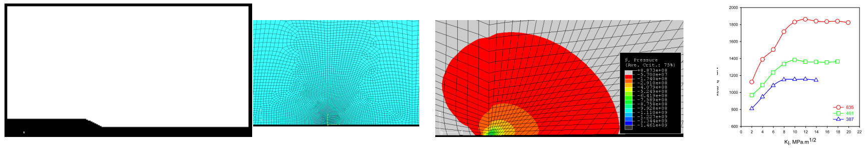


>mm



Hydride blisters
Fracture toughness

Delayed Hydride Cracking



Few Å

Few µm

Ten µm

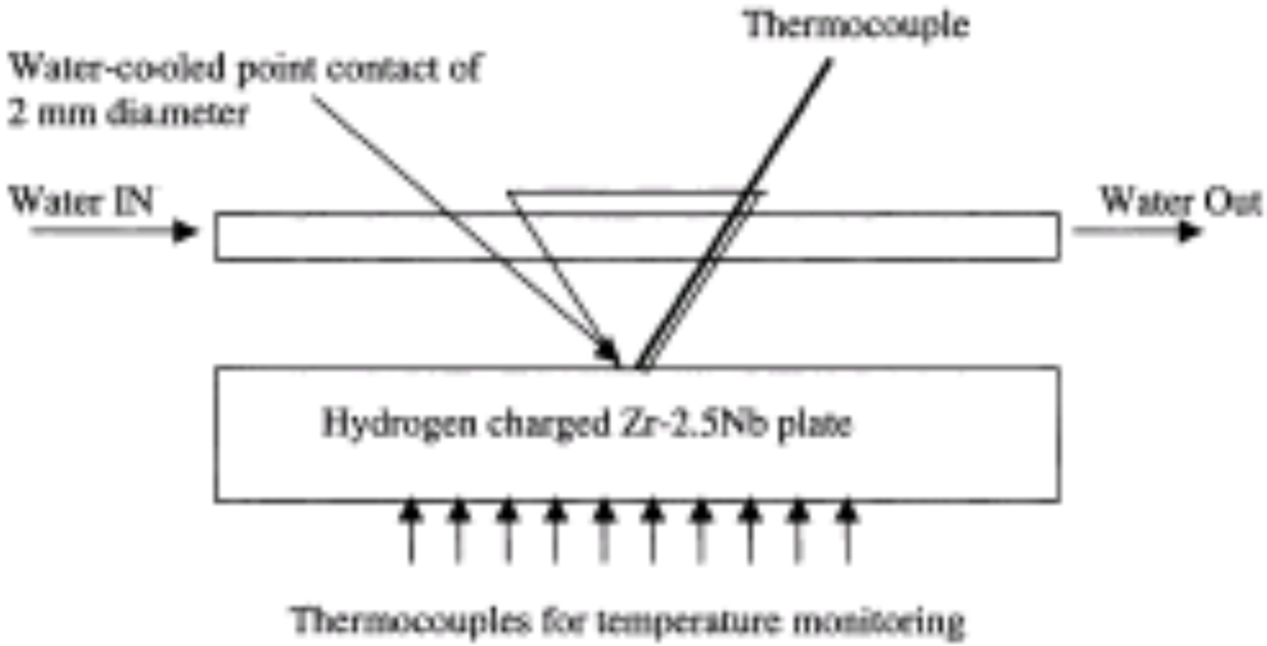
Hydrogen related problems in Zirconium alloys

Autocatalytic Nucleation
Mechanism of hydride transformation
Stress Reorientation of hydrides

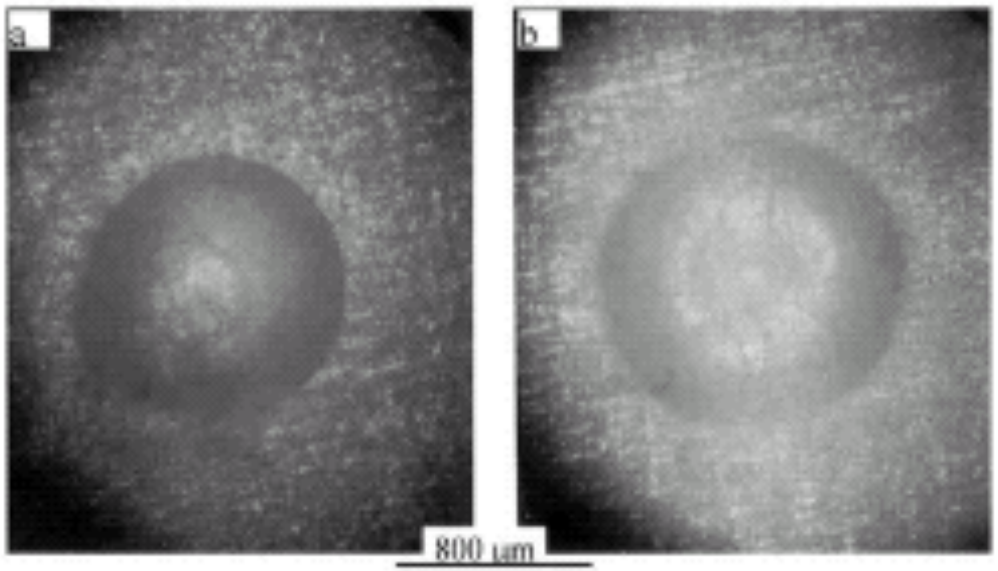
Shape and Habit plane of hydride plate
TSS Hysteresis

Transformation strain

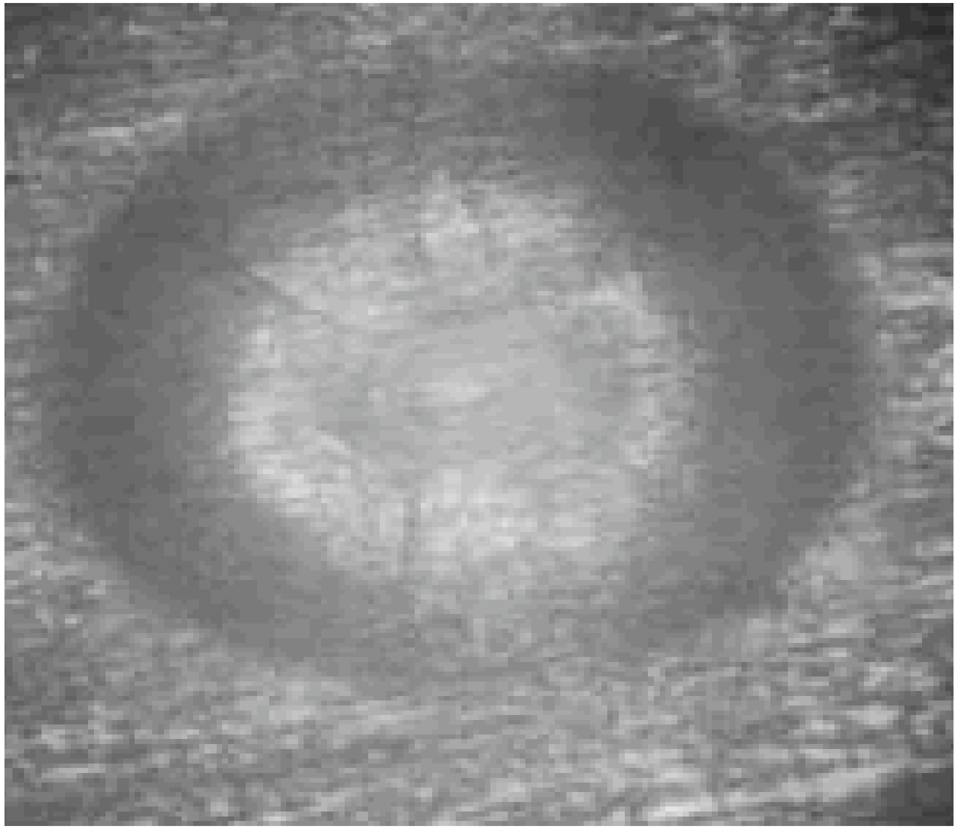
Experimental setup



Top view of
hydride blister



Top view of a hydride blister grown in Zr–2.5wt%Nb pressure tube alloy (Singh *et al*., 2001)



Examination of a section of blister (grown in Laboratory)

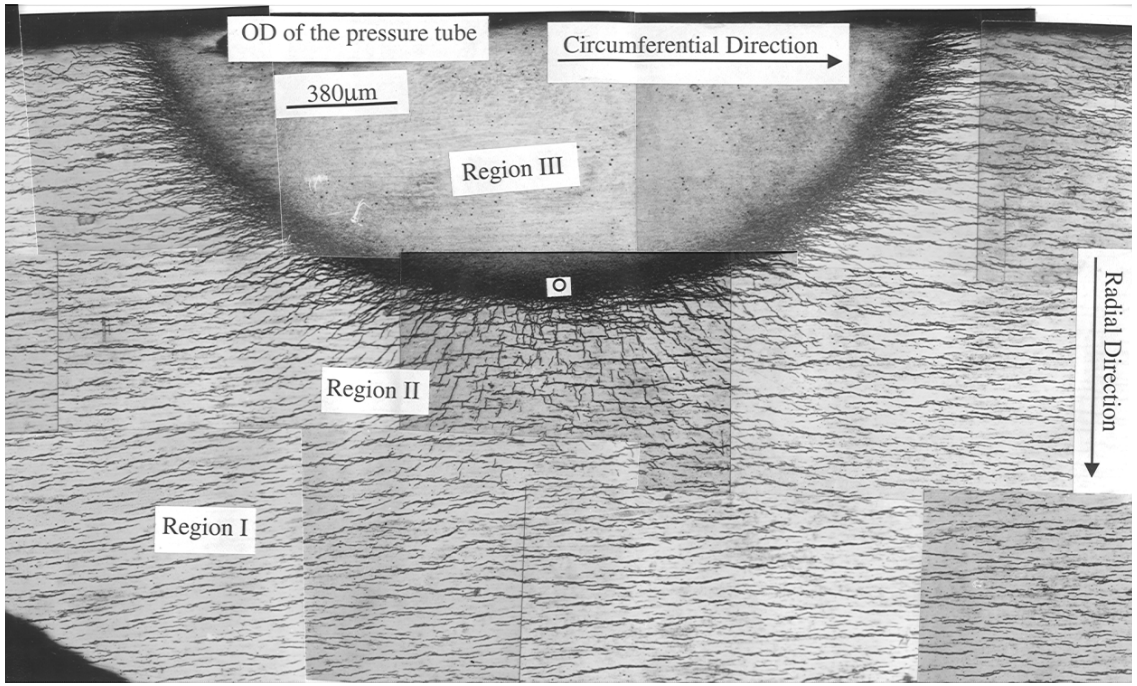
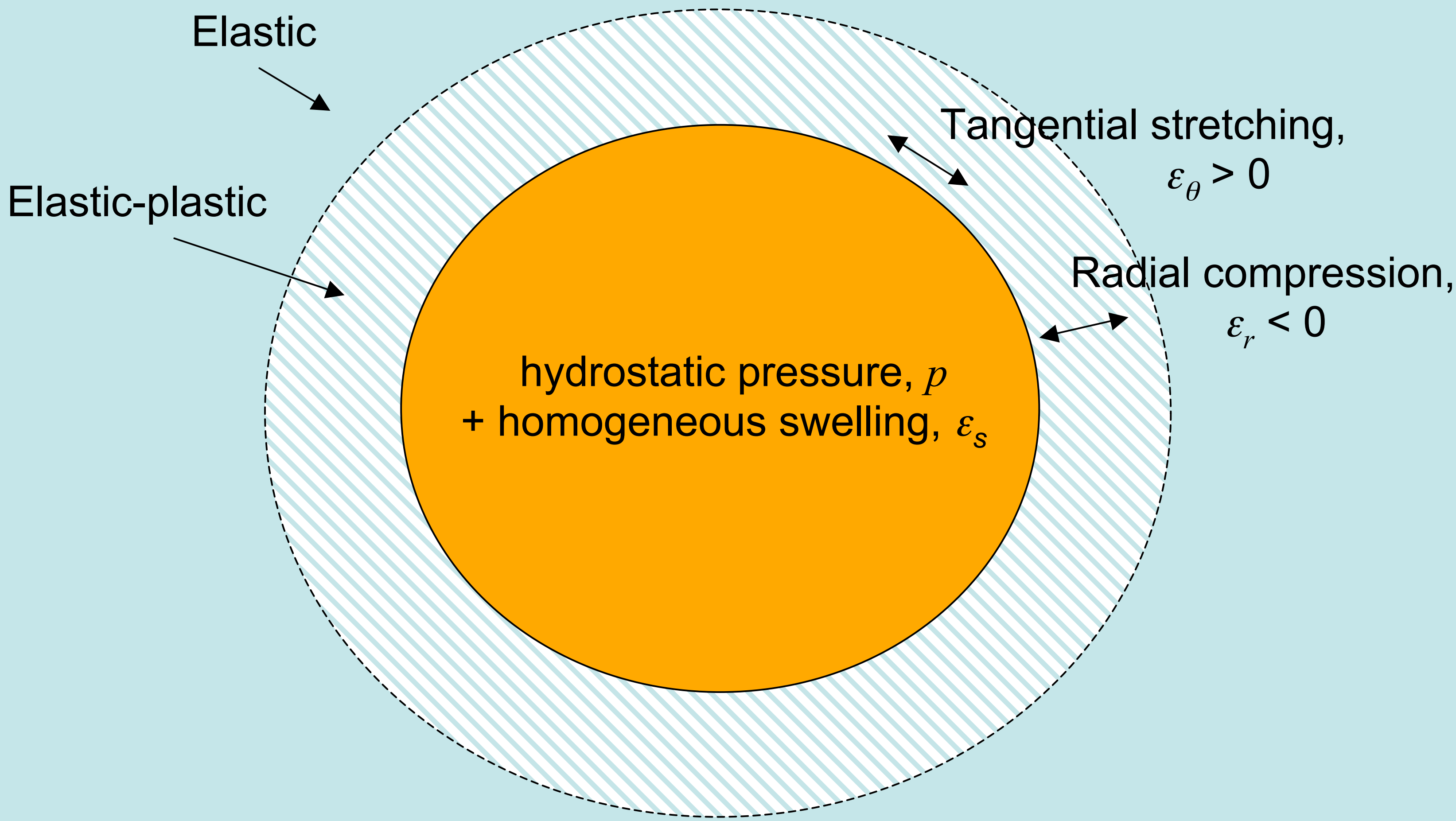
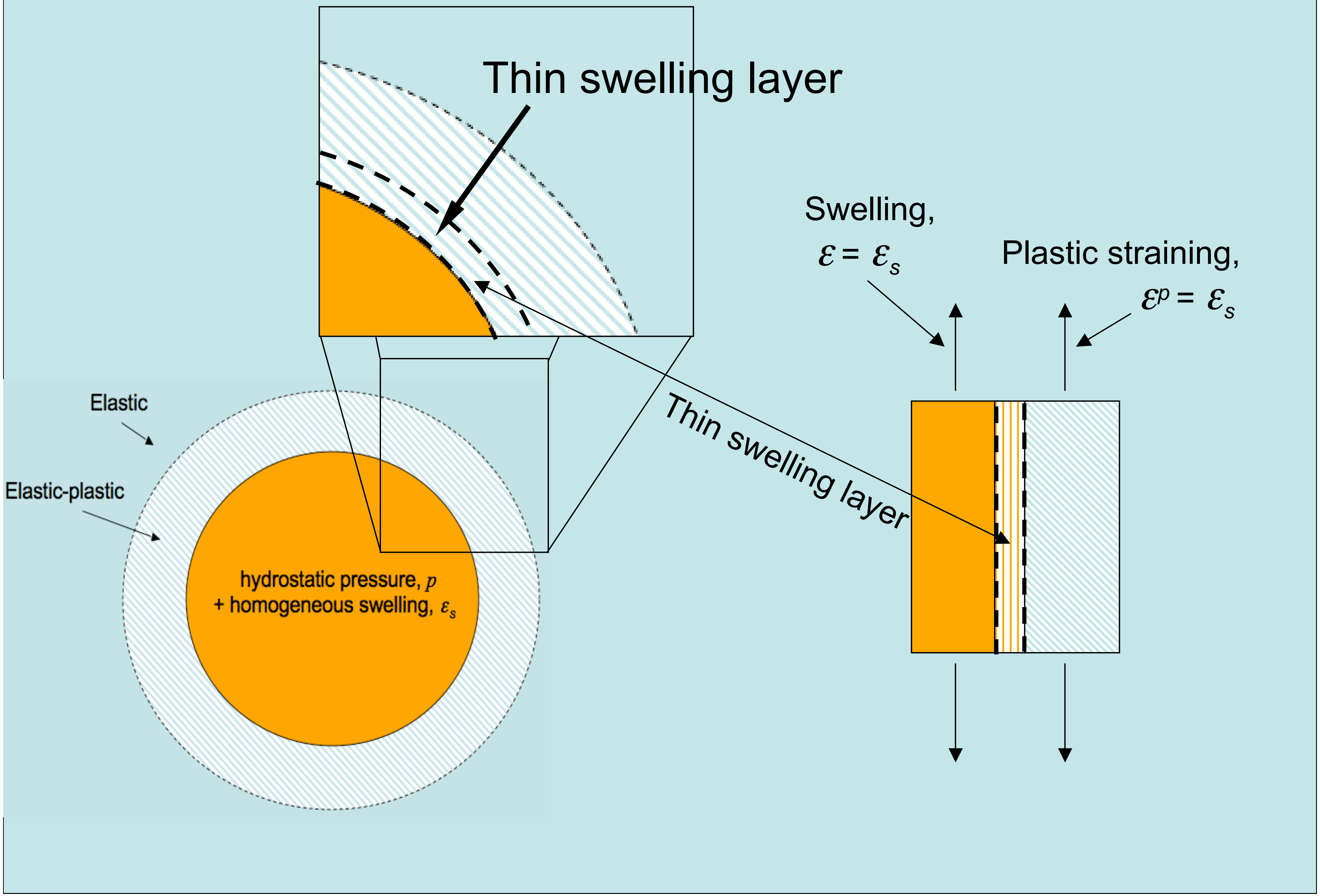


Figure : Optical micrograph of hydride blister section, grown in Zr-2.5wt.% Nb pressure tube material. Three regions - Region I - matrix & circumferential hydrides, region II - matrix containing both radial and circumferential hydrides and region III - mainly of δ-hydride.

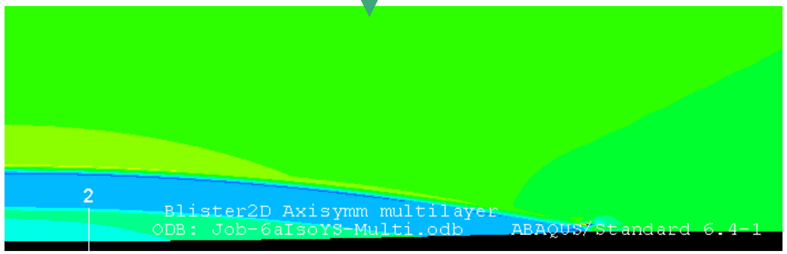
Expanding elastic-plastic inclusion (Hill, 1950)

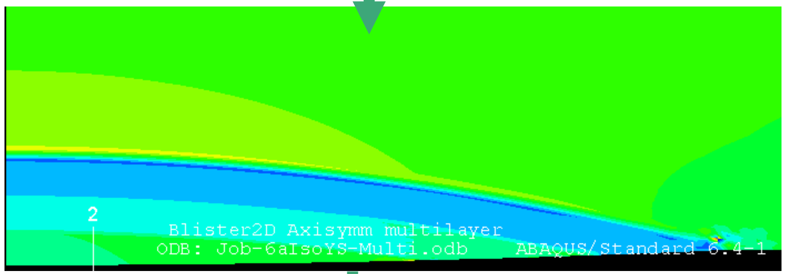


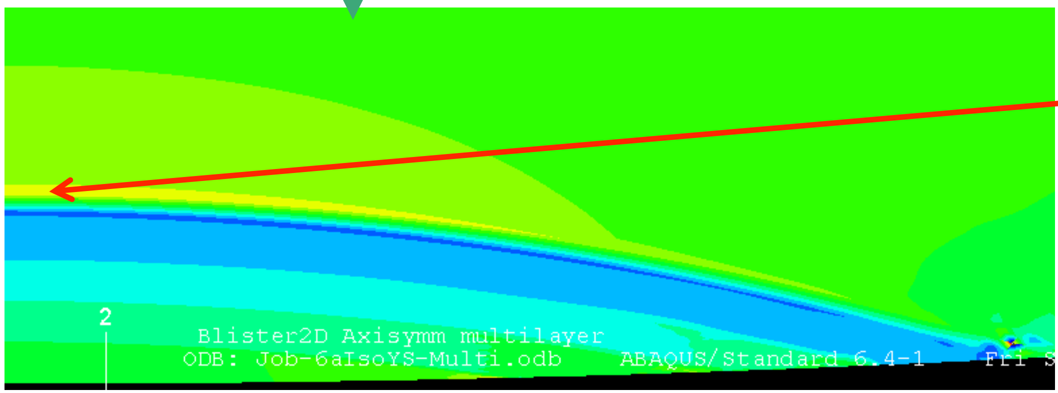
Thin layer increasing inclusion volume (and mass)

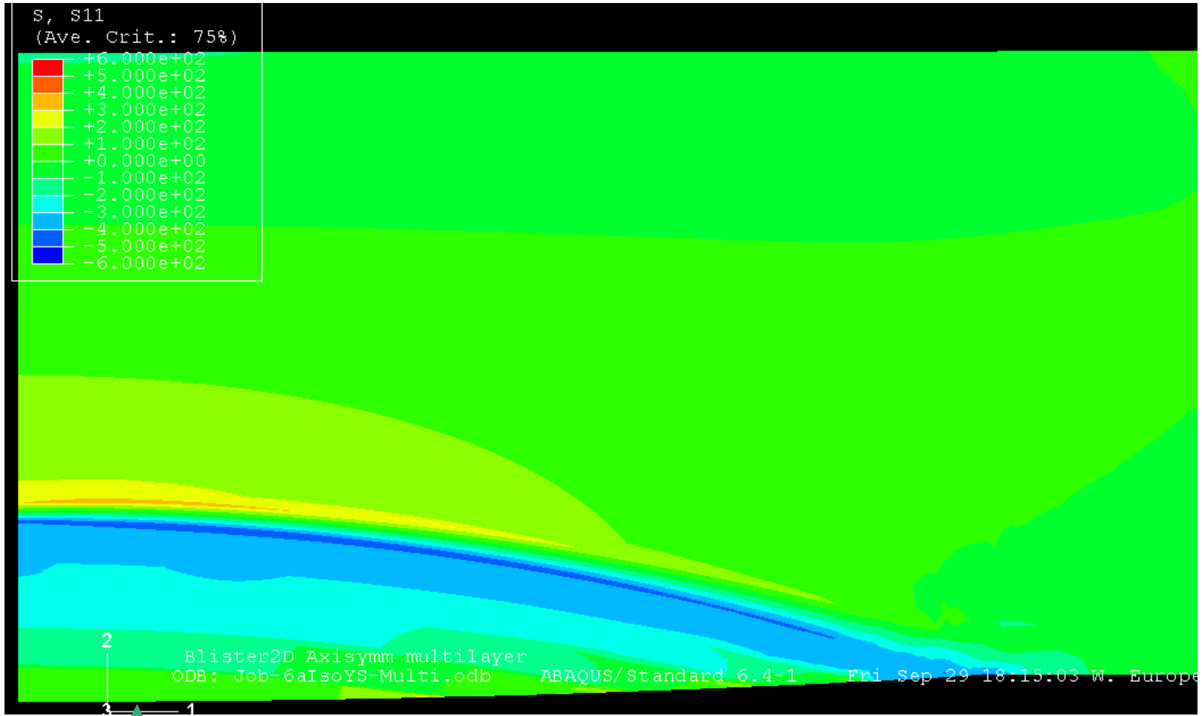


Blister formation - Stress field computation – Multi step

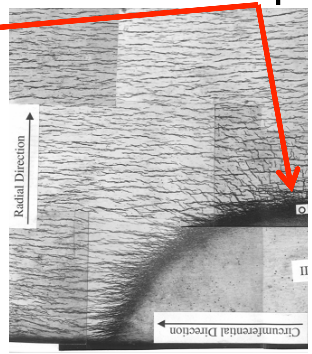




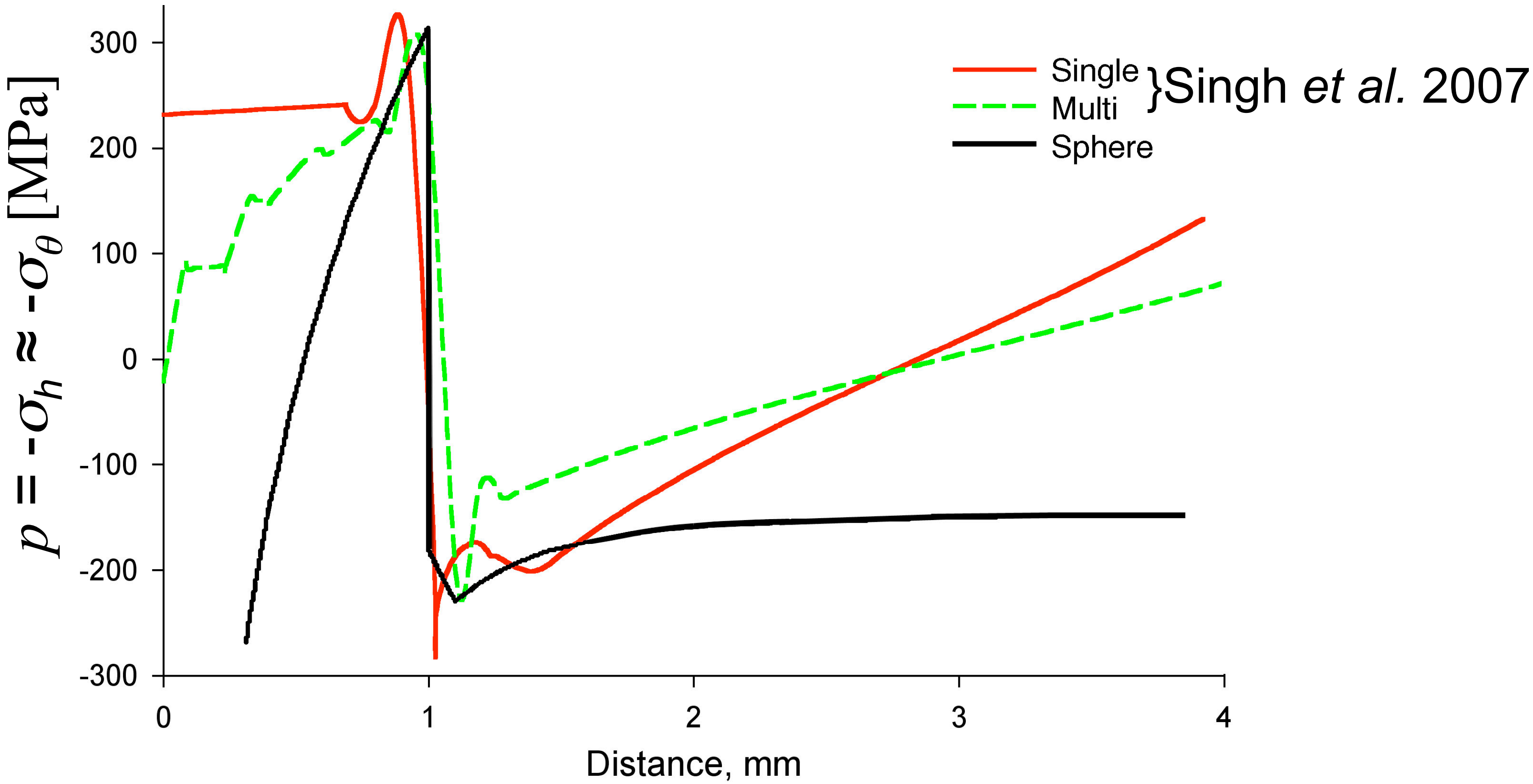




Multi-step transformation in 5 steps
Expansion achieved by raising temperature
Max tensile stress near the deepest point



Essential result of FEM and present solution



Strains

$$\epsilon_r = \frac{\partial u_r}{\partial r}, \quad \epsilon_\theta = \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r},$$
$$\epsilon_{r\theta} = \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r} + \frac{1}{r}\frac{\partial u_r}{\partial \theta}.$$

Equilibrium

$$\frac{\partial \sigma_r}{\partial r} + \frac{1}{r}\frac{\partial \sigma_{r\theta}}{\partial \theta} + \frac{1}{r}(2\sigma_r - \sigma_\theta - \sigma_\psi + \sigma_{r\theta}\cot\theta) = 0.$$

$$\frac{\partial \sigma_{r\theta}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_\theta}{\partial \theta} + \frac{1}{r}[(\sigma - \sigma_\psi)\cot\theta + 3\sigma_{r\theta}] = 0.$$

Decomposed strains

$$\epsilon_r = \epsilon_r^e + \epsilon_r^p + \epsilon^s,$$
$$\epsilon_\theta = \epsilon_\theta^e + \epsilon_\theta^p + \epsilon^s,$$
$$\epsilon_\psi = \epsilon_\psi^e + \epsilon_\psi^p + \epsilon^s \text{ and } \epsilon = \epsilon_{r\theta}^e + \epsilon_{r\theta}^p$$

Plast. strain prop. to deviatoric stress

$$\frac{\epsilon_r^p}{\sigma_r - \sigma_h} = \frac{\epsilon_\theta^p}{\sigma_\theta - \sigma_h} = \frac{\epsilon_\psi^p}{\sigma_\psi - \sigma_h} = \frac{\epsilon_{r\theta}^p}{\sigma_{r\theta}},$$

DE: $$\frac{\mathrm{d}^2 u_r}{\mathrm{d}r^2} + 2\frac{\mathrm{d}u_r}{r\mathrm{d}r} - 2\frac{u_r}{r^2} - \frac{1-2\nu}{1-\nu}\left(\frac{\mathrm{d}\epsilon^p}{\mathrm{d}r} + 3\frac{\epsilon^p}{r}\right) = 0$$

Displacements: $$u_r = \epsilon_s r - \frac{2(1-2\nu)}{3}\left(1 + 3\ln\frac{r_p r}{R^2}\right)\frac{\sigma_o r}{E} \quad \text{in } r \leq \text{R}.$$

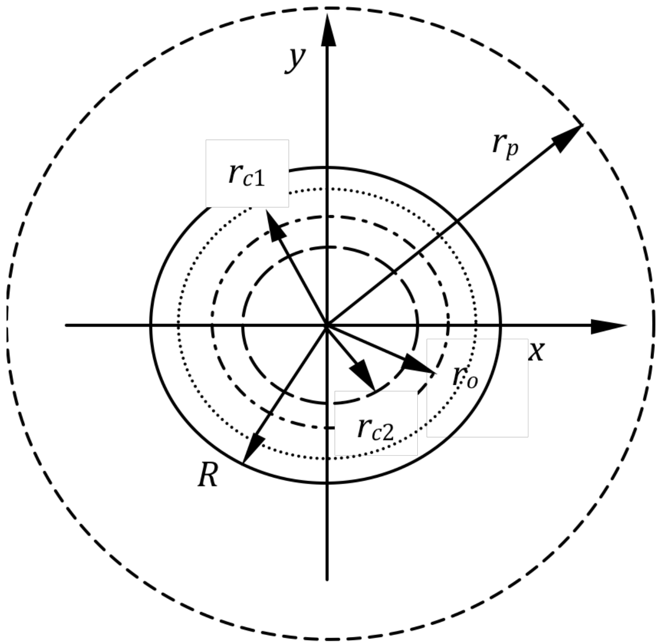
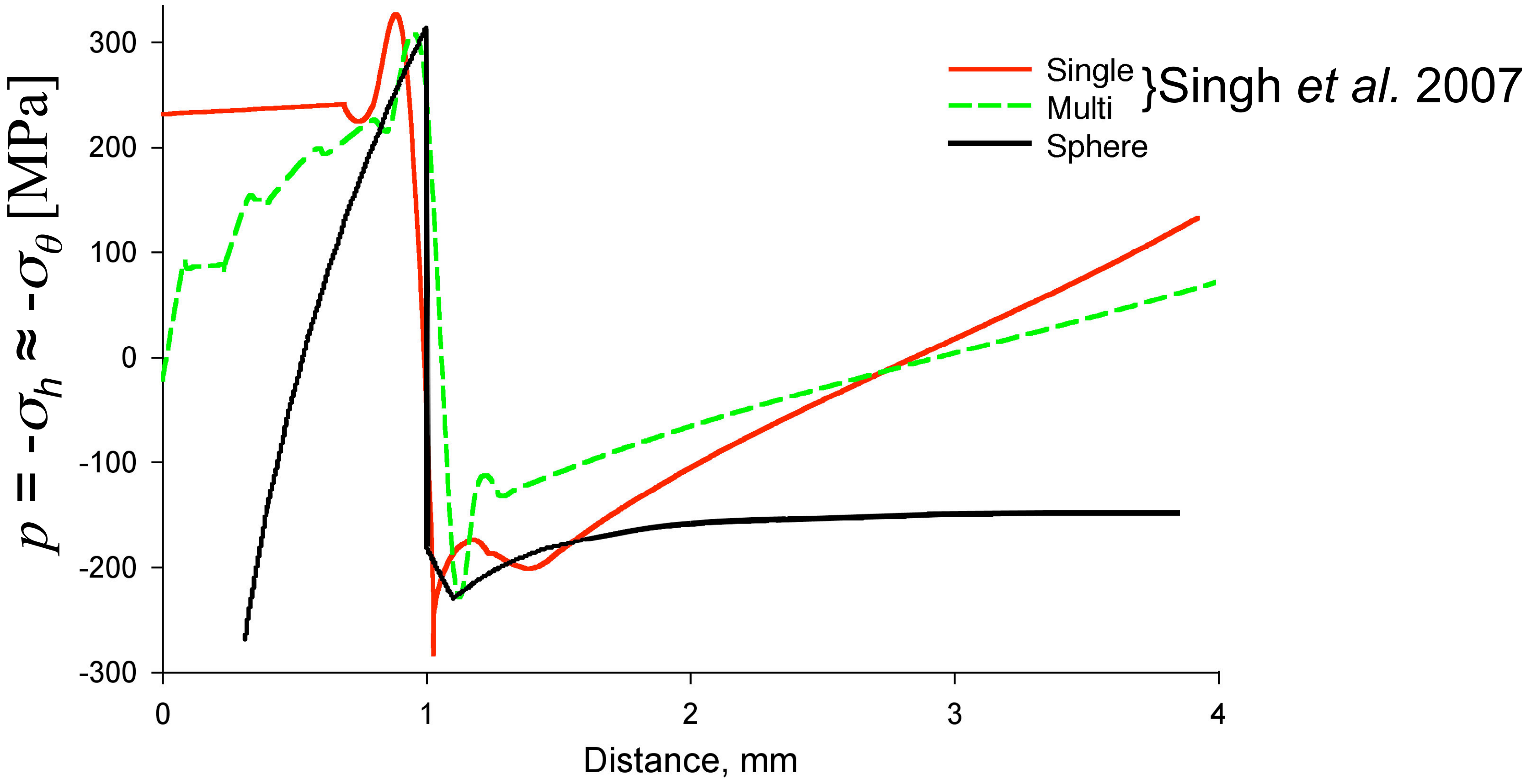


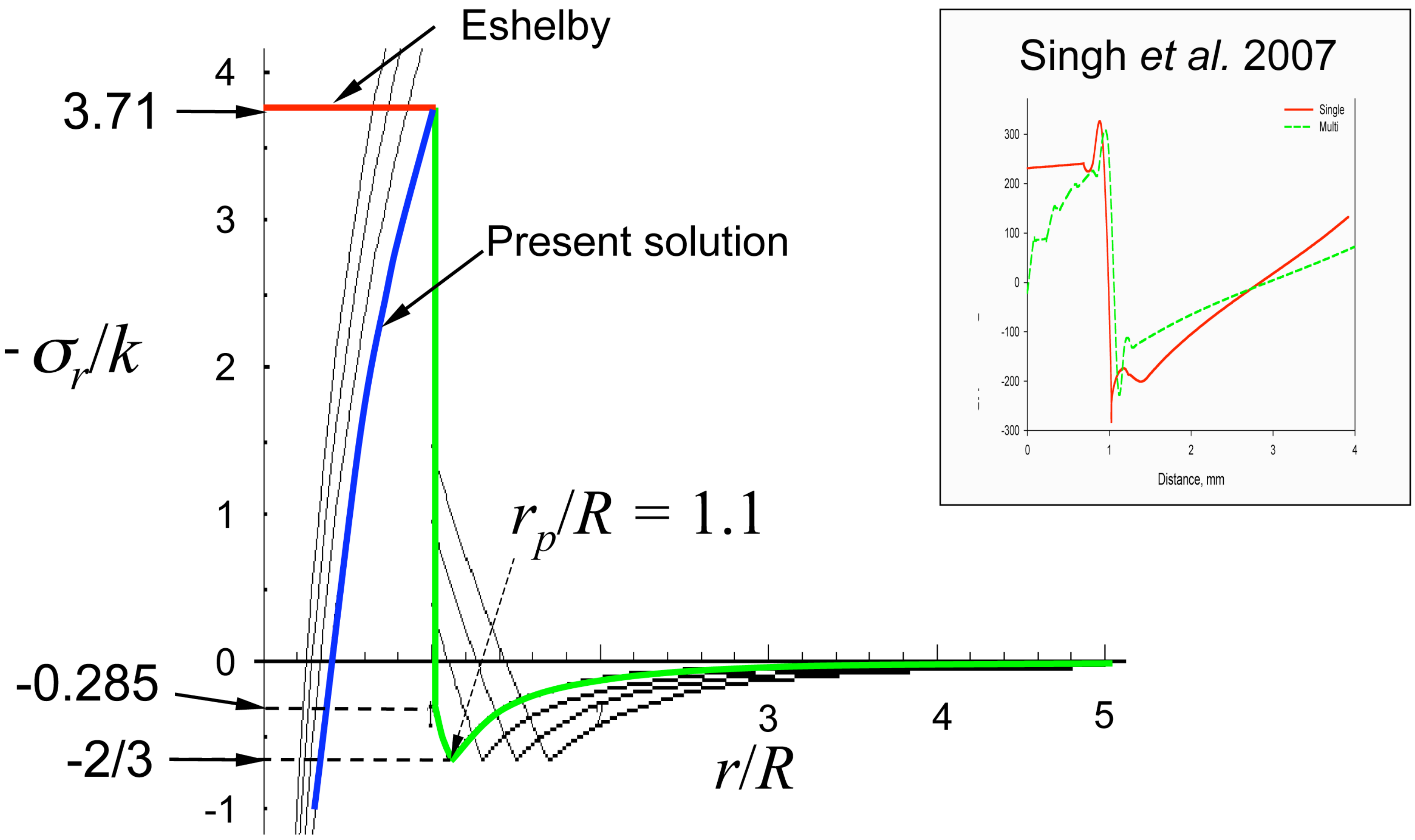
Fig. 2 Different characteristic regions of the solution. In $r > r_p$ the material is elastic; in $r \leq r_p$ the material is plastic; in $r_{c1} < r < R$ no tensile stress; in $r_o < r < r_{c1}$ tensile radial stress; in $r_{c2} < r < r_o$ tensile radial stress and hydrostatic stress; in $r < r_{c2}$ all stresses are tensile.

$$r < r_{c1} = \frac{R^2}{r_p e^{1/3}}, \quad r < r_o = \frac{R^2}{r_p e^{2/3}} \quad \text{and} \quad r < r_{c2} = \frac{R^2}{r_p e^{5/6}}$$

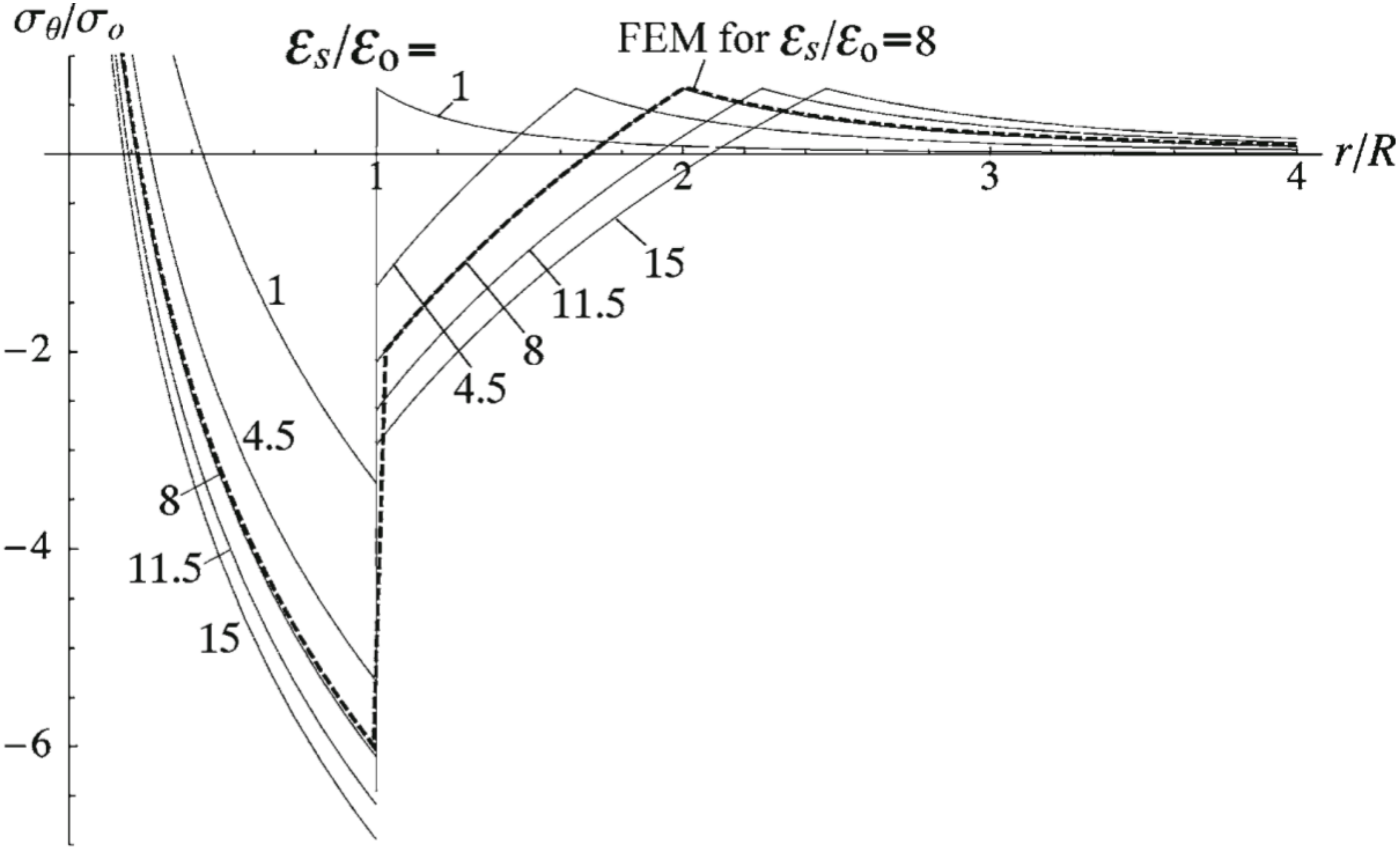
Essential result of FEM and present solution



Radial pressure, - σ_r/k, versus vs. distance r/R

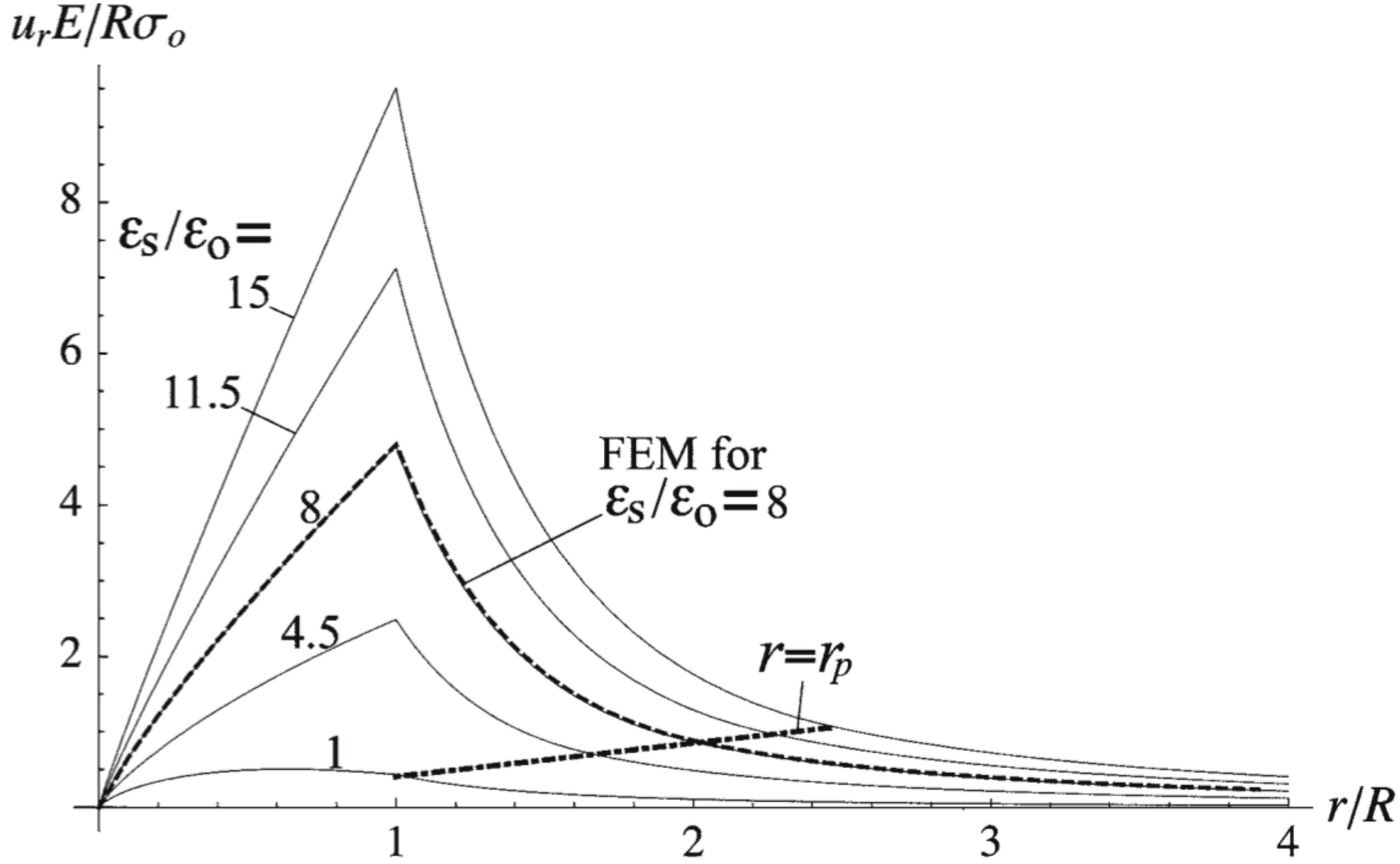


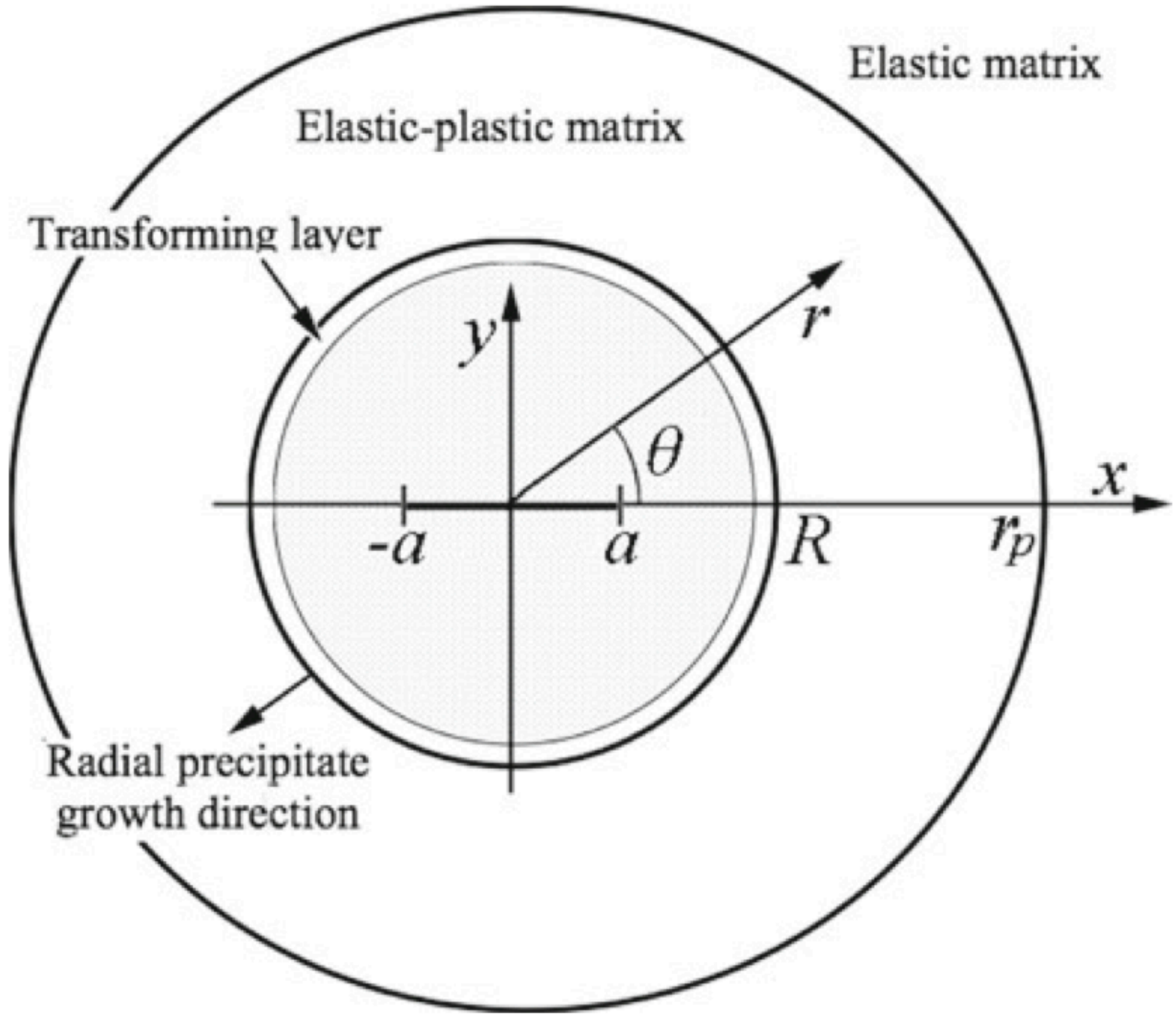
Hoop Stress



σ_θ/σ_o
$\varepsilon_s/\varepsilon_0 =$
FEM for $\varepsilon_s/\varepsilon_0 = 8$
1
1
4.5
8
11.5
15
4.5
8
11.5
15
r/R
1
2
3
4
−2
−4
−6

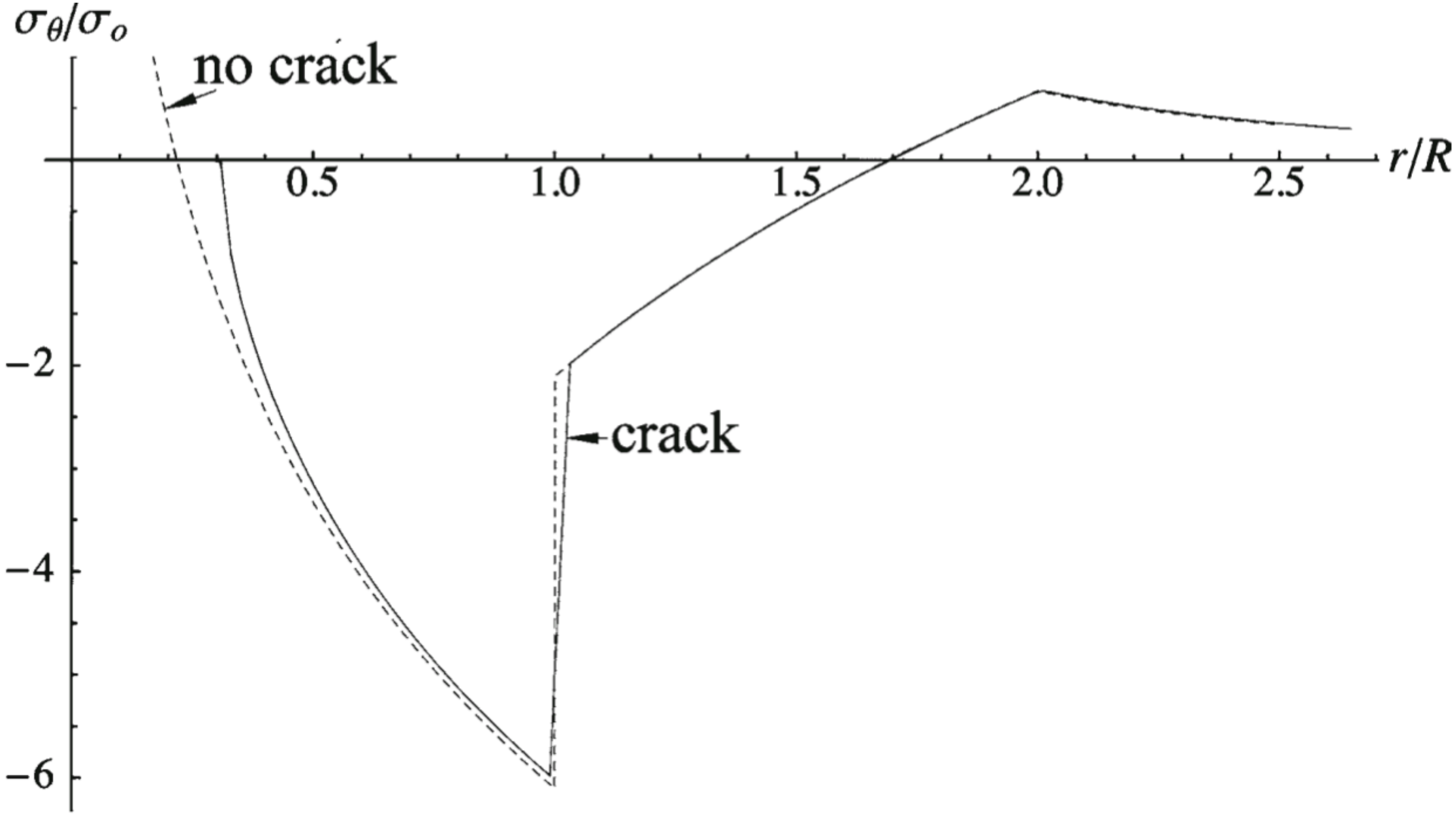
Radial Displacement



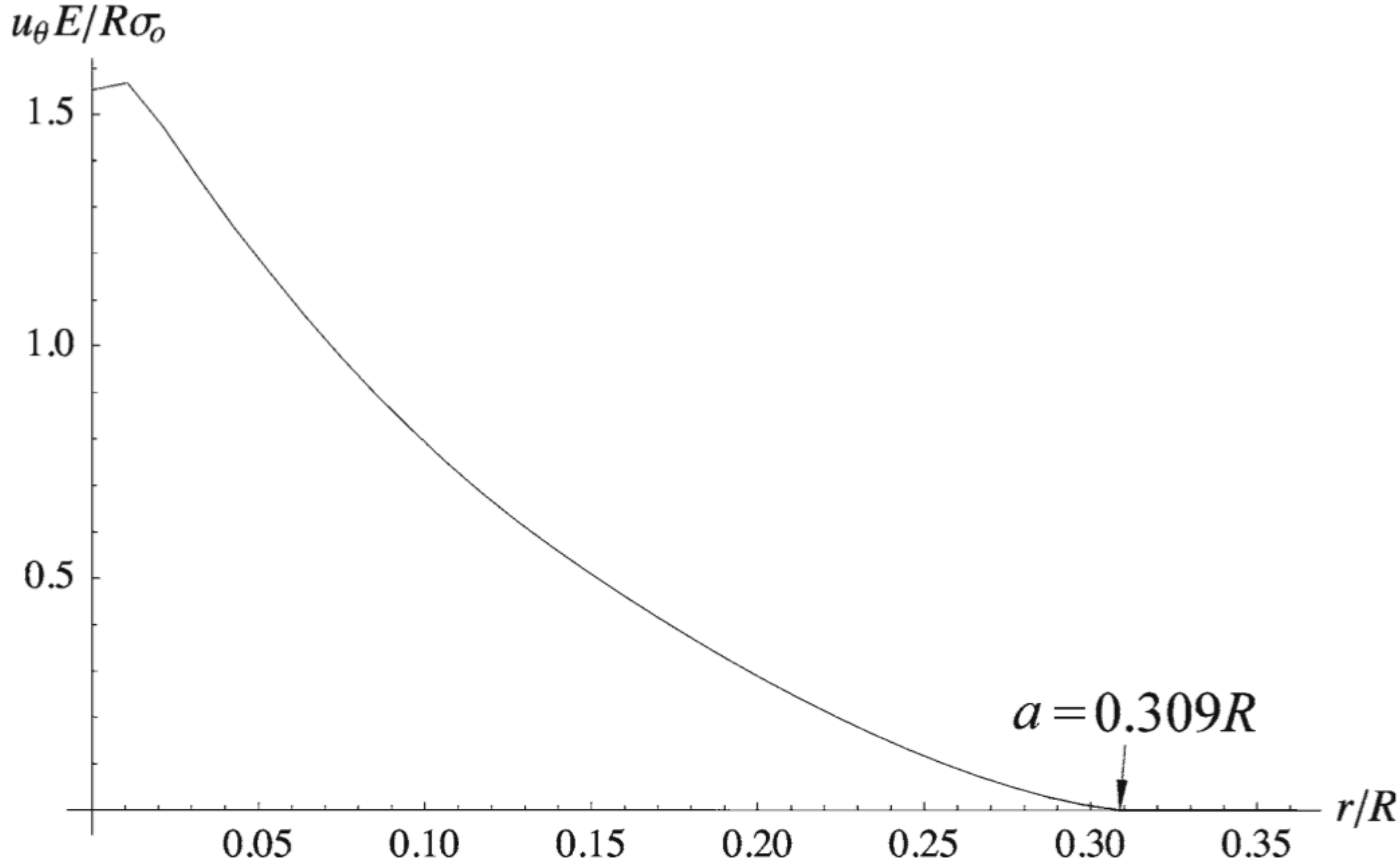


Elastic matrix
Elastic-plastic matrix
Transforming layer
y
r
θ
x
-a
a
R
r_p
Radial precipitate
growth direction

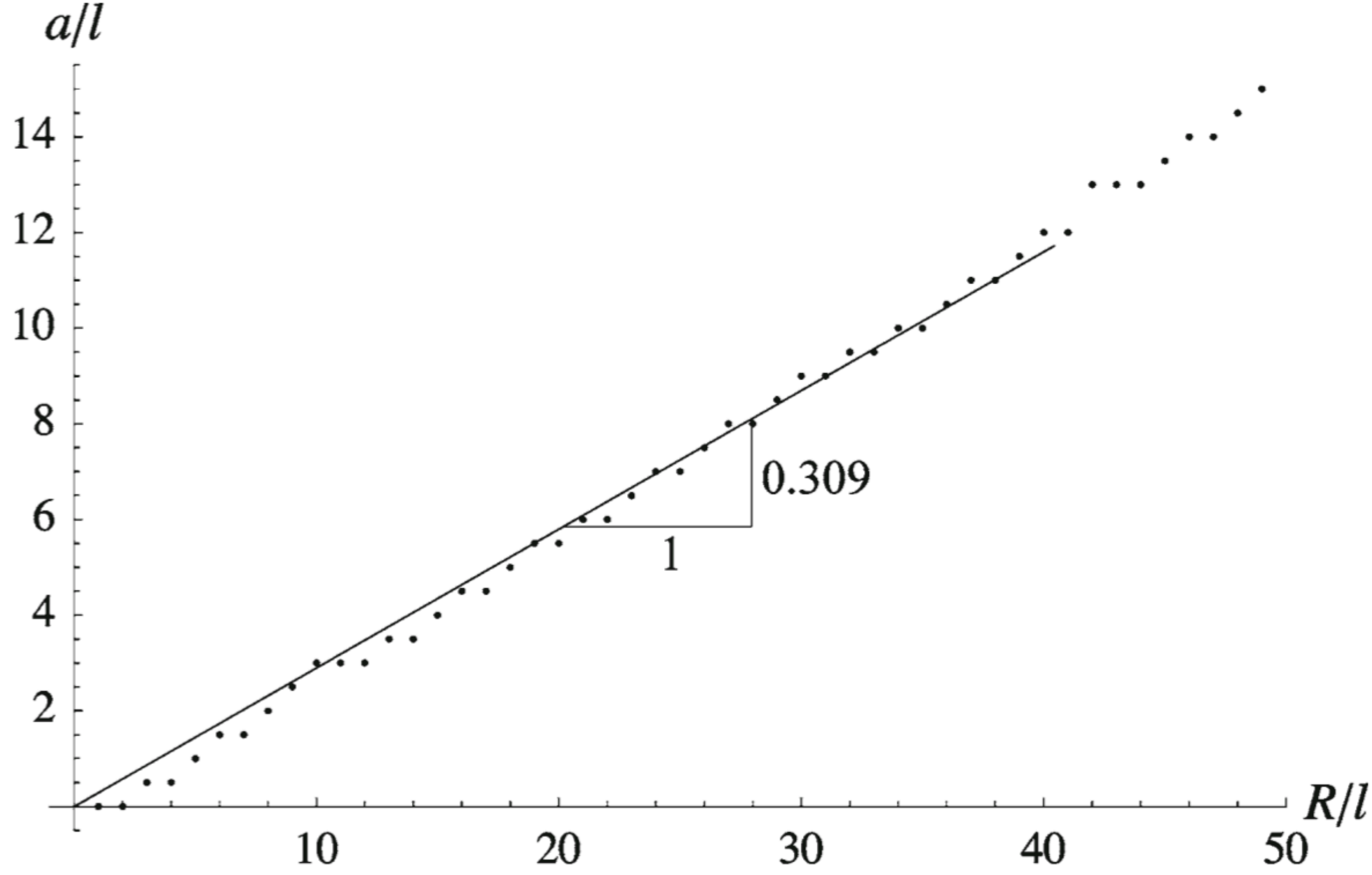
Hoop Stress



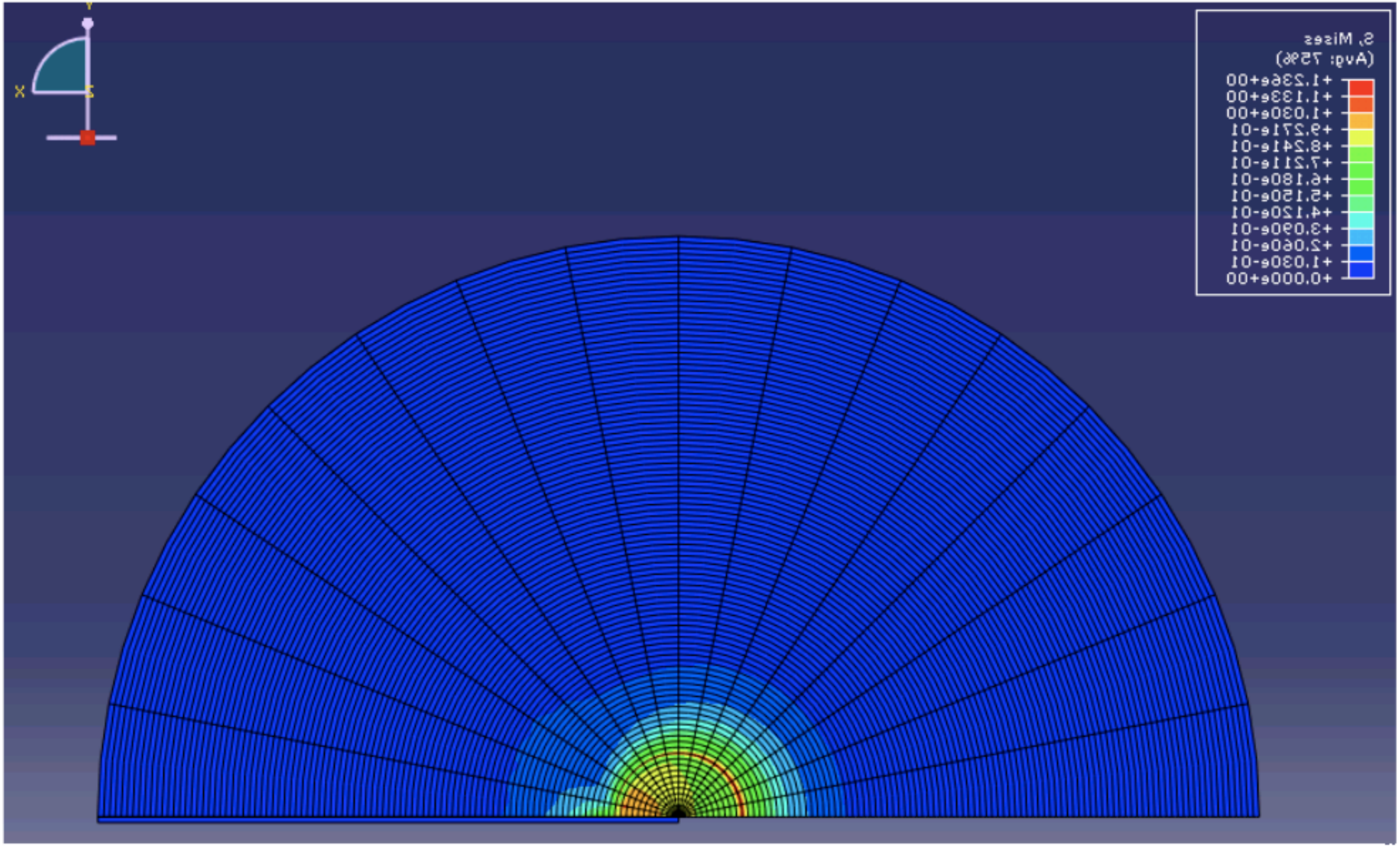
Crack Surface Displacement



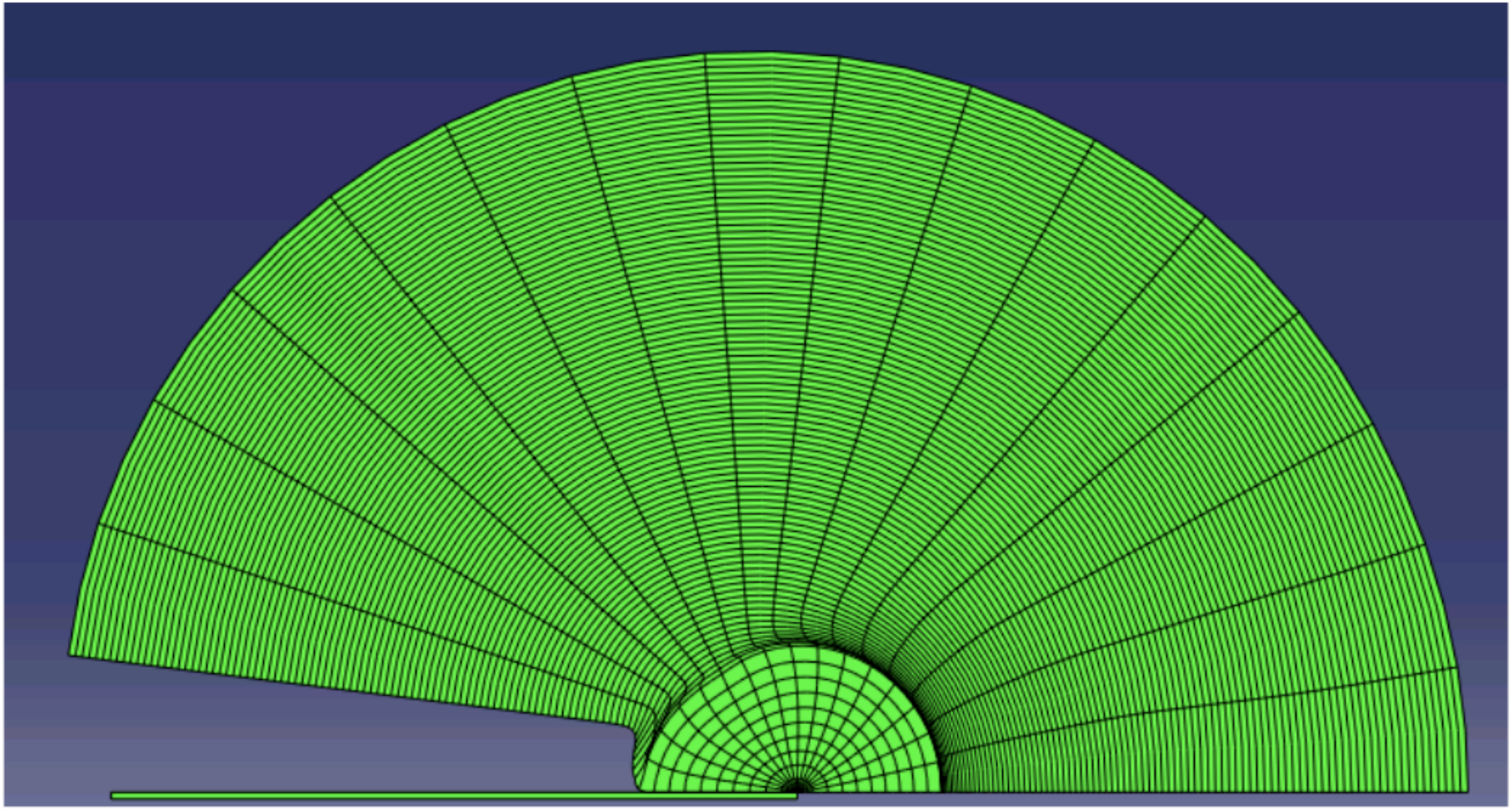
Crack Length vs. Inclusion Radii



v Mises Stress, Incremental Growth
Expanding Cylinder ahead of a Crack



Deformation, Simultaneous Growth
Expanding Cylinder ahead of a Crack



Deformation, Incremental Growth
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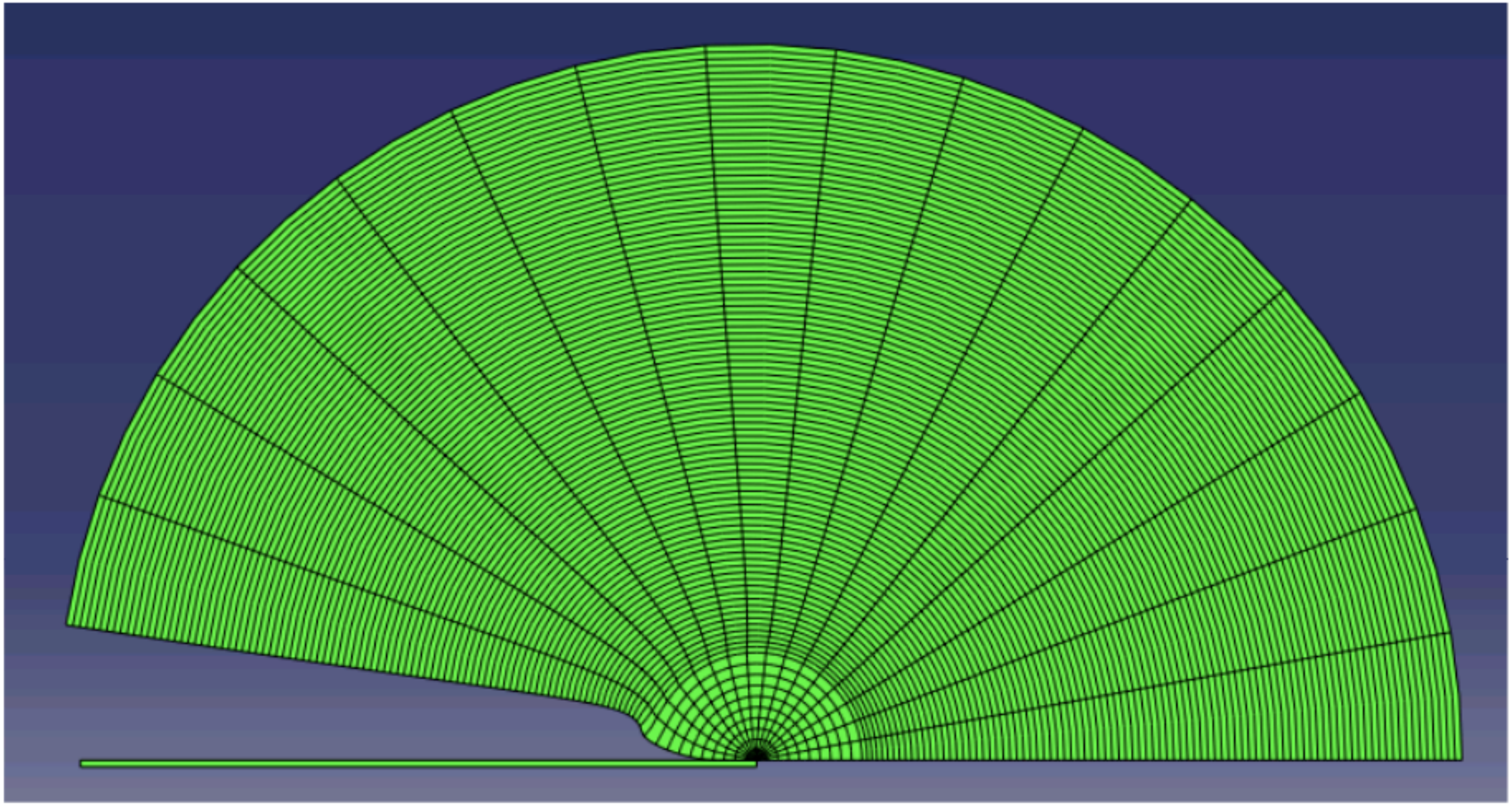

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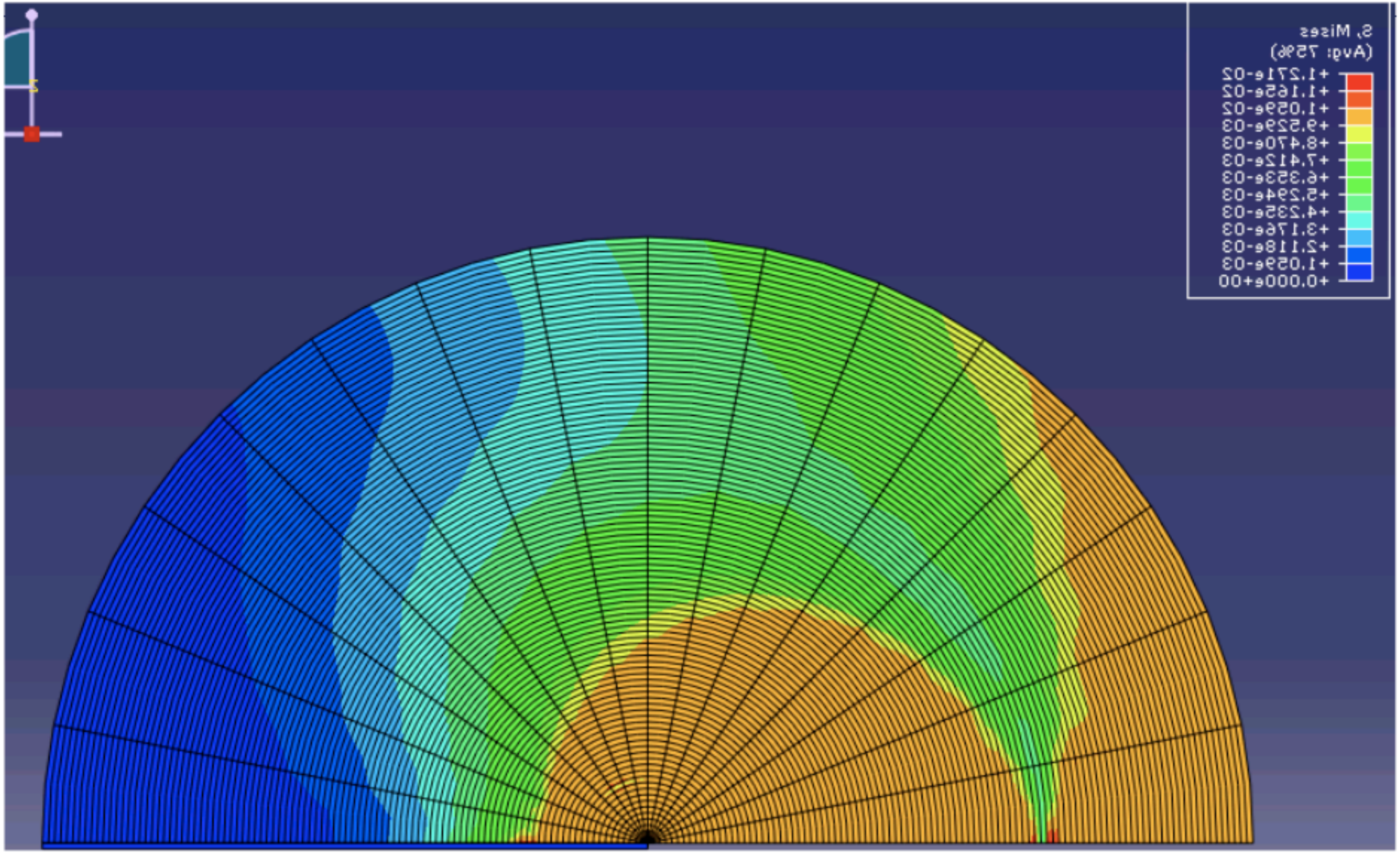

Conclusions

- Precipitates that grow at its edges obtain reduced pressure in its interior.

- At self-similar growth, stresses become logarithmically singular for all precipitates shapes.

- The mechanical state of the matrix of homogeneously growing precipitates matches the present solution exactly but for larger expansion.

- Spontaneous crack growth may occur