Contraintes mécaniques induites lors du gel d'une solution acqueuse dans un réservoir

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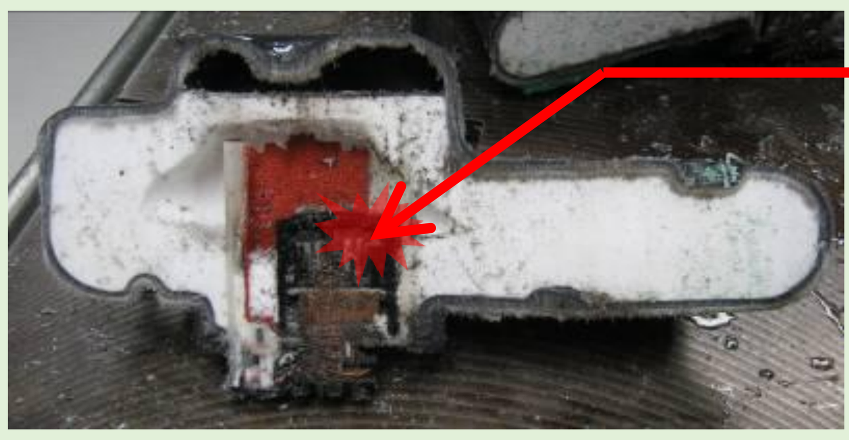
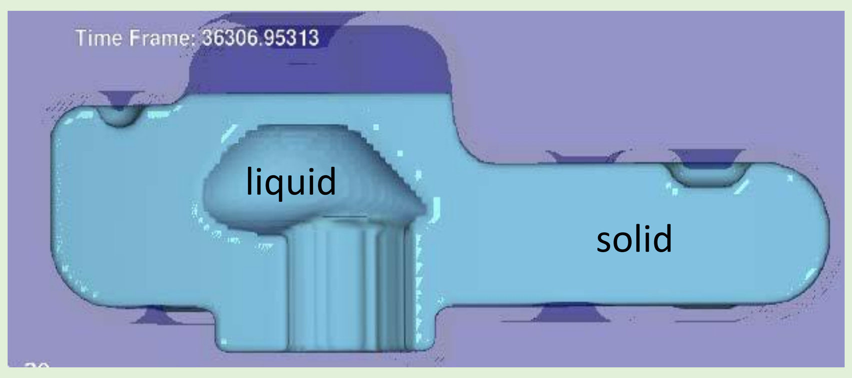
Contexte : rupture de réservoir provoquée par l'expansion induite par le gel d'un liquide

A tank filled with aqueous urea solution

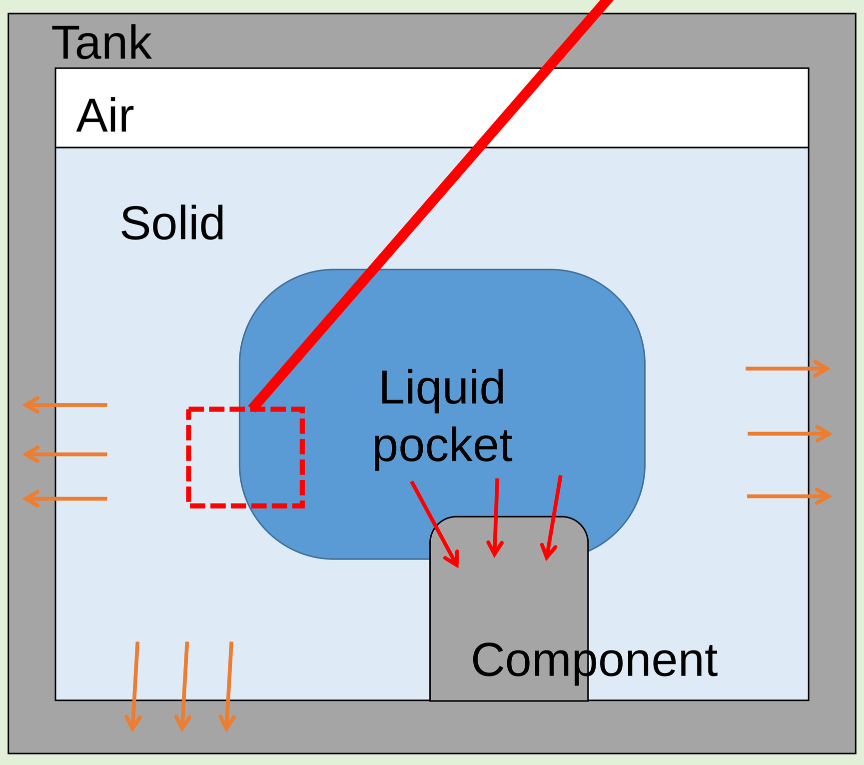


Component failure due to high pressure in the liquid pocket.

Half cut of the tank during freezing

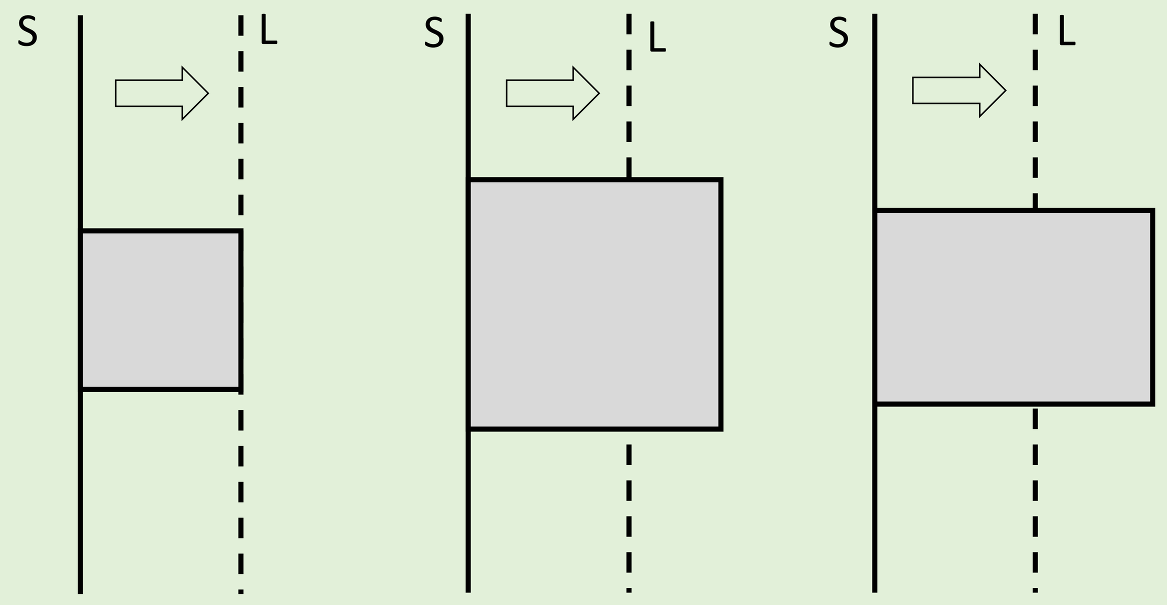


Simulation by thermal conduction: geometric prediction of solidification interface



Possible mechanical interferences

Non-isotropic phase-change expansion (PCE) at the solidification interface:



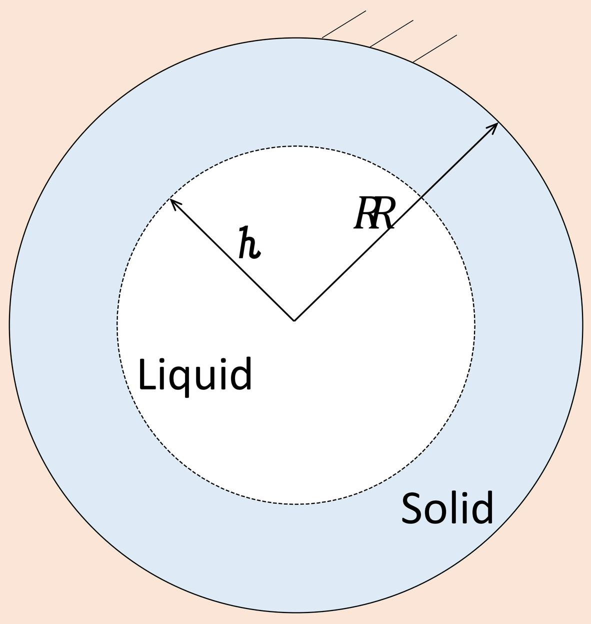
Unexpanded: determined by thermal analysis

Isotropic PCE: Expands uniformly in all directions

Non-isotropic PCE: expands more in normal direction of interface

Weeks & Wettlaufer (1996): "As polycrystalline ice grows, favorably oriented crystals expand at the expense of less favorably oriented ones."

Approche analytique : contraintes et pression dans un réservoir sphérique



$$\sigma = \lambda \mathrm{tr}(\varepsilon - \varepsilon_{pp})\mathbf{I} + 2\mu(\varepsilon - \varepsilon_{pp})$$

$$\sigma = \begin{bmatrix} \sigma_{rr} & & \\ & \sigma_{\theta\theta} & \\ & & \sigma_{\theta\theta} \end{bmatrix} \quad \varepsilon = \begin{bmatrix} \varepsilon_{rr} & & \\ & \varepsilon_{\theta\theta} & \\ & & \varepsilon_{\theta\theta} \end{bmatrix}$$

Rigid spherical vessel

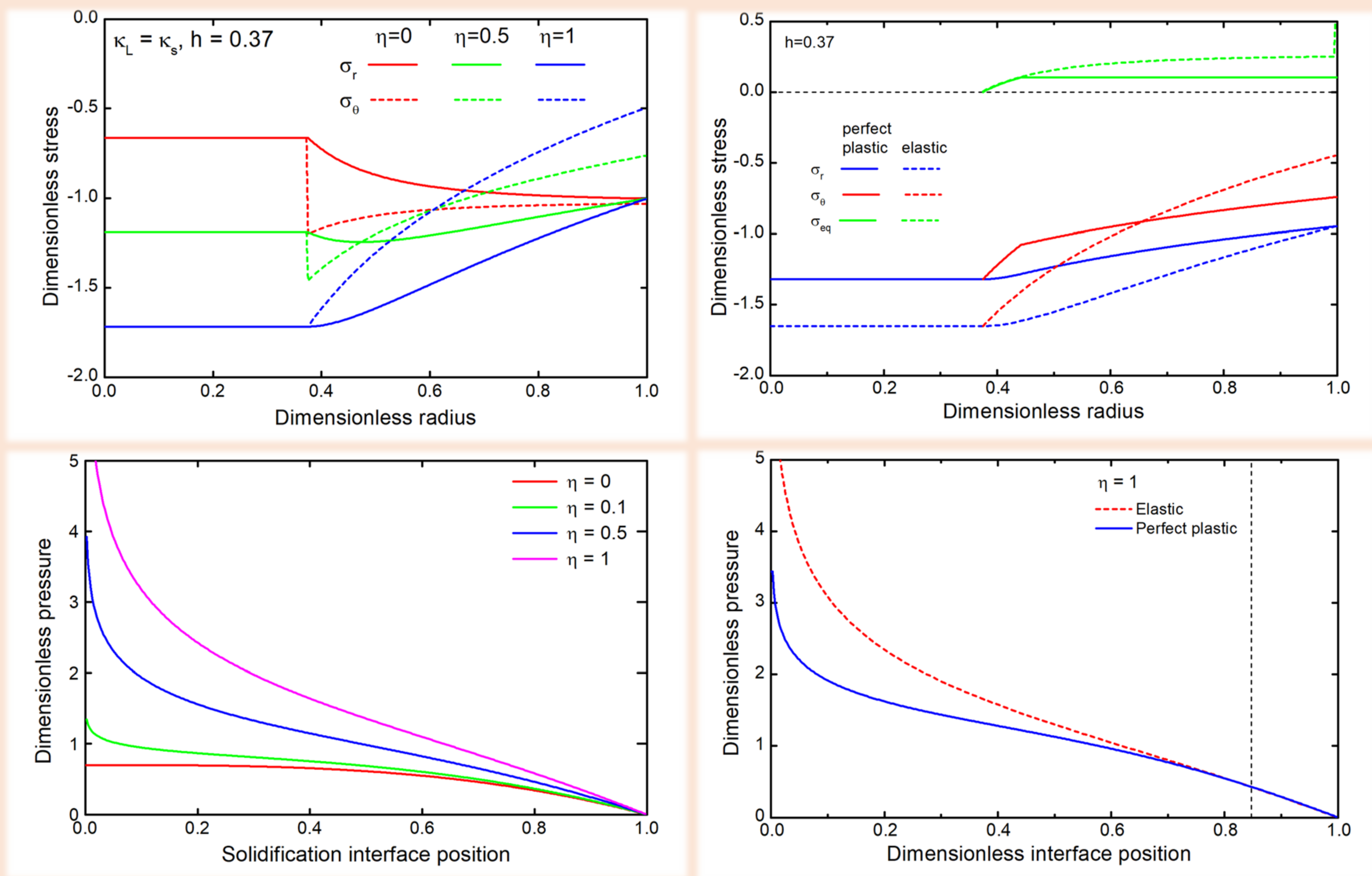
h is current interface position. Thermal expansion in solid/liquid phase is neglected, only PCE is considered.
Solid and liquid are treated elastically.
A PCE orientation factor η is introduced.

PCE orientation factor η

$$\varepsilon_{pp} = \begin{bmatrix} 1+2\eta & & \\ & 1-\eta & \\ & & 1-\eta \end{bmatrix} \varepsilon_0$$

$$\varepsilon_0 = \frac{\Delta V}{3V} = \frac{\text{phase change vol.}}{3 \times \text{initial vol.}}$$

If $\eta = 0$, isotropic PCE
If $\eta = 1$, PCE only in normal expansion



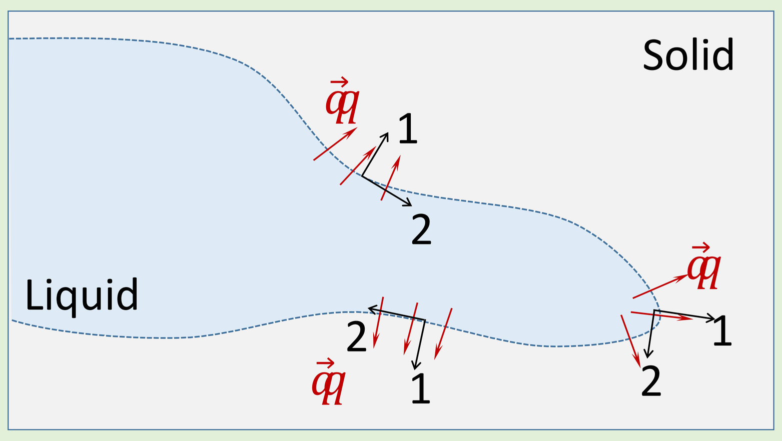
Elastic response

Elastic + perfect plasticity

Approche numérique : solidification par éléments finis en thermo-mécanique couplés

Numerical model

- Liquid phase is treated as in static state solid with small shear stress:
  - Small shear modulus
  - Small yield strength to plasticity
- The non-isotropic PCE is modeled using local heat flux, which is always in the normal direction to the phase-change interface during solidification.



- For the solid phase:

$$\dot{\sigma} = \mathbb{C} : (\dot{\varepsilon} - \dot{\varepsilon}_{th} - \dot{\varepsilon}_n)$$

with a viscoplastic function:

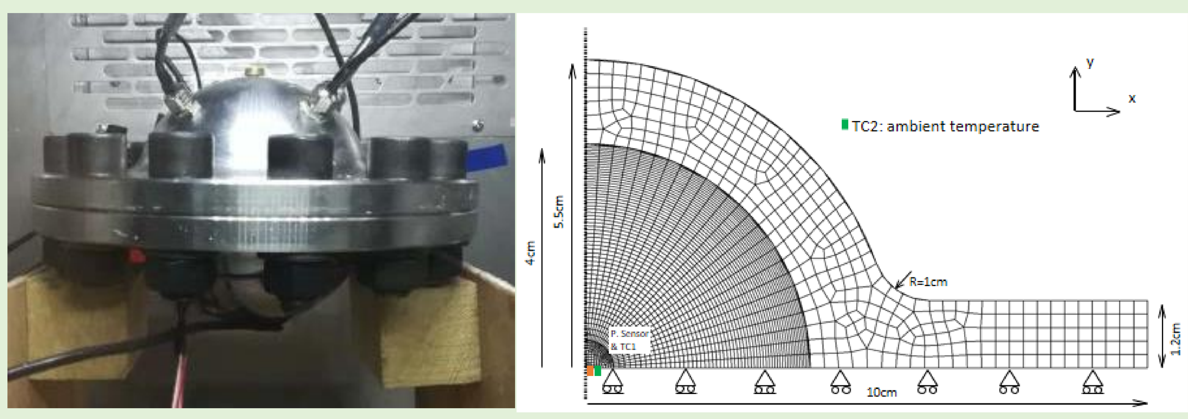
$$\dot{\bar{\varepsilon}}_n = f(\bar{\sigma} - \eta(\bar{\varepsilon}_n), T)$$

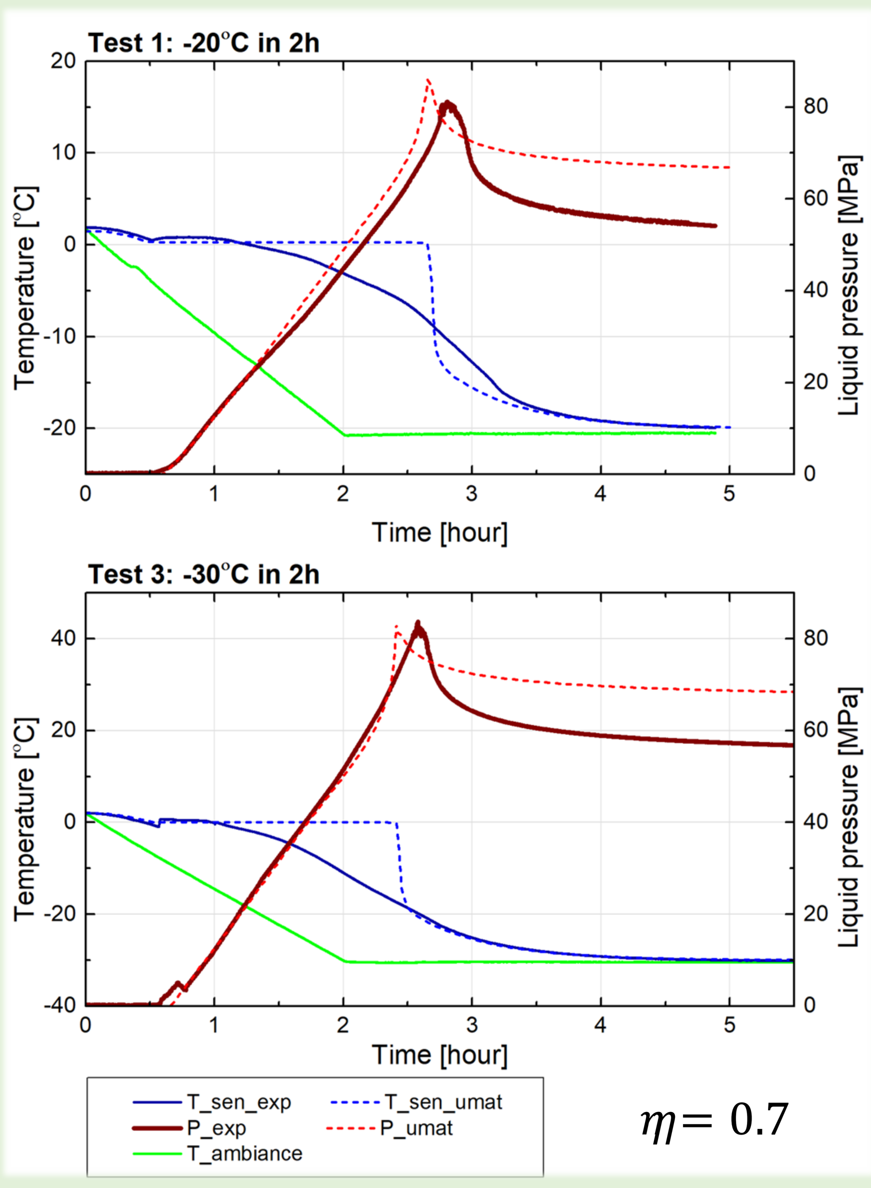
$\eta(\bar{\varepsilon}_n)$: isotropic hardening function

This material model is implemented into Abaqus via a user-defined subroutine UMAT. The method is validated by the analytical solution of the spherical model.

Benchmark test in a steel vessel, filled with water

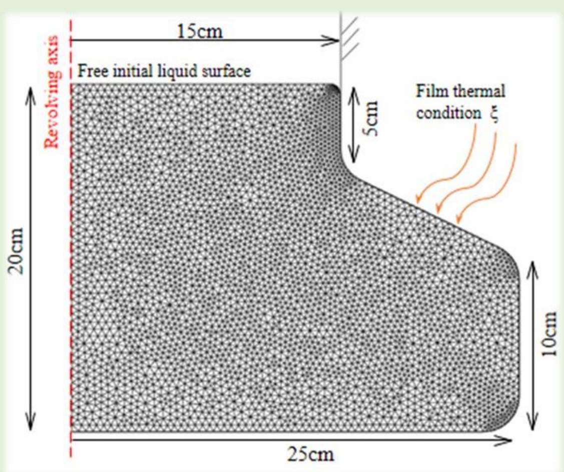
with a pressure censor and a thermocouple in the center.





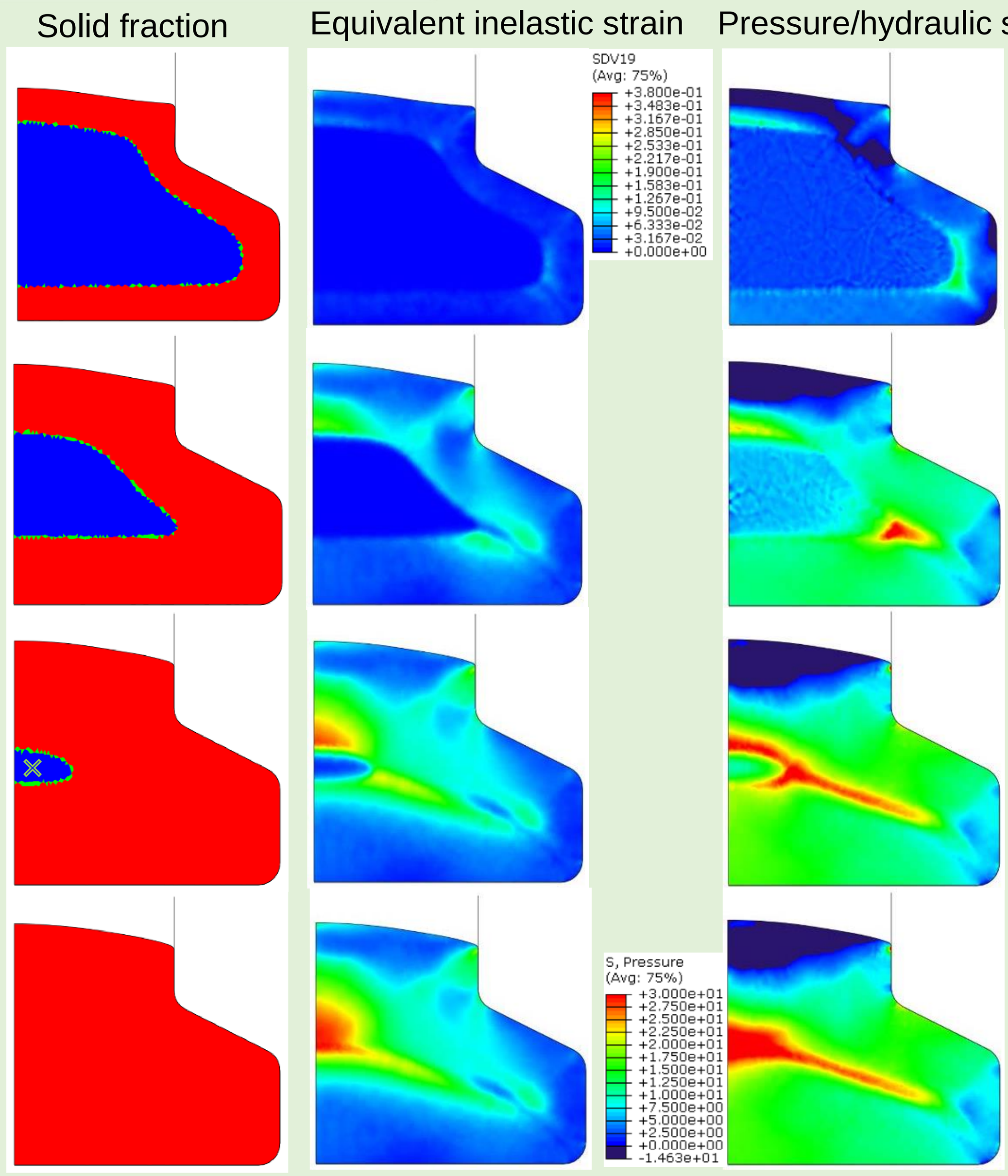
$\eta = 0.7$

Application exp: freezing in an open reservoir



- Rigid reservoir example
- Pressure near the last liquid pocket is high, component of the tank should avoid these positions.
- Inelastic deformation above liquid region is big, cracks of the solid may occur. >> Future work
- Simulation in 3D is also available, contacts between liquid and tank wall should be carefully defined.

Solid fraction | Equivalent inelastic strain | Pressure/hydraulic stress



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