About Discrete Element modeling in EPX

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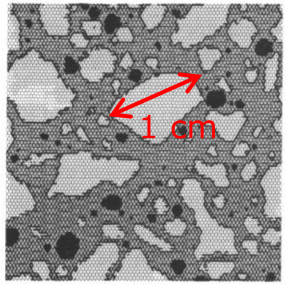
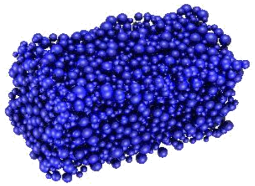
Spherical Discrete Element Method

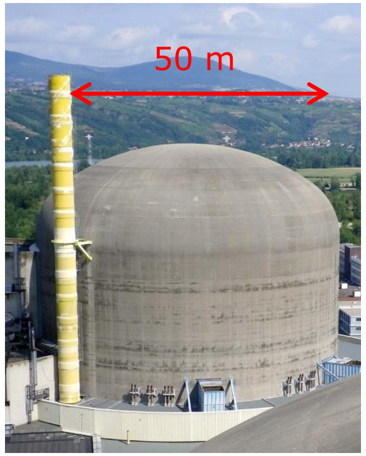
Material scale



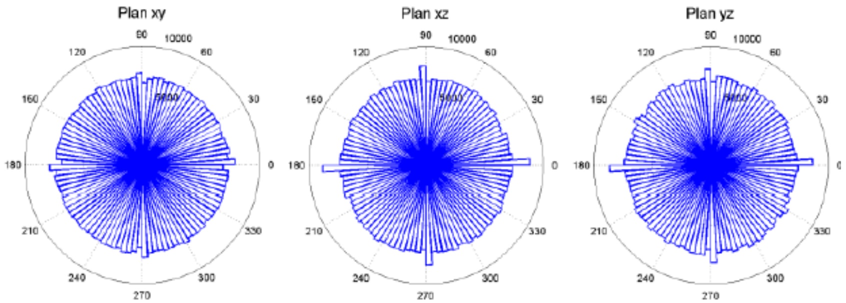


Intermediate modeling scale representative of the macroscopic behavior

Structure scale

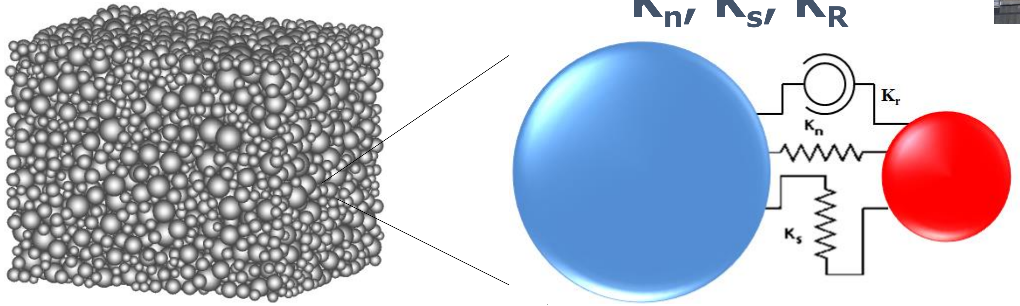


Initial isotropy

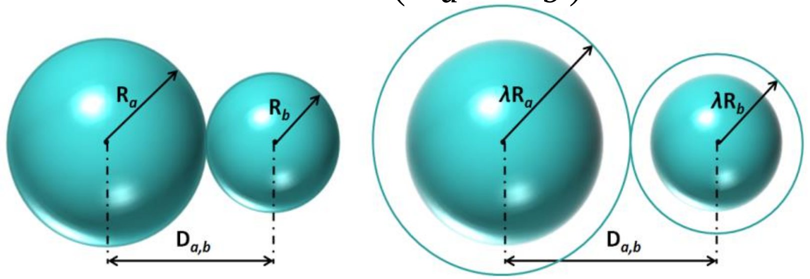


E, ν

K_n, K_s, K_R

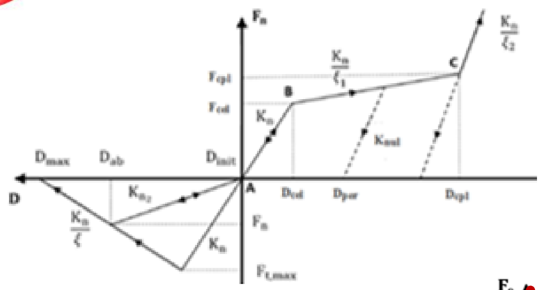


Interactions $\lambda(R_a + R_b) \geq D^{a,b}$



Contact Interaction, $\lambda = 1$ Cohesive Interaction, $\lambda > 1$

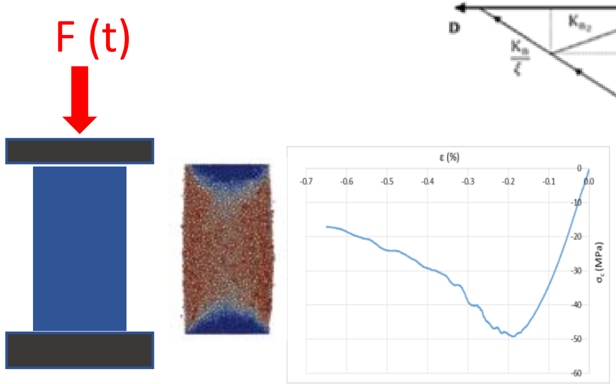
Normal Interaction



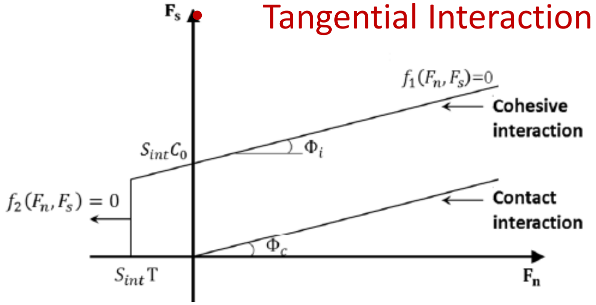
Micro-macro relations

$$
\begin{cases}
K_N = E \dfrac{S_{\text{int}}}{D_{\text{eq}}} \dfrac{1+\alpha}{\beta(1+\nu)+\gamma(1-\alpha\nu)} \\
K_S = K_N \dfrac{1-\alpha\nu}{1+\nu}
\end{cases}
$$

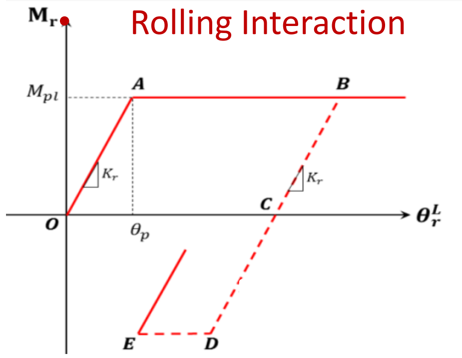
α, β, et γ must be identified only once



Tangential Interaction

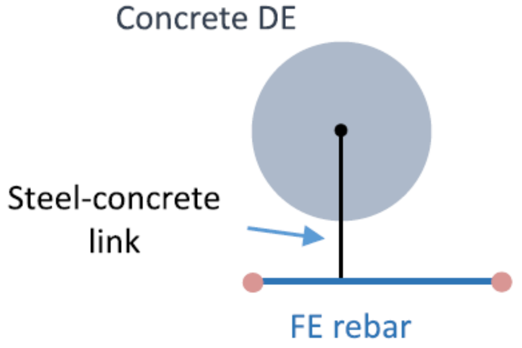


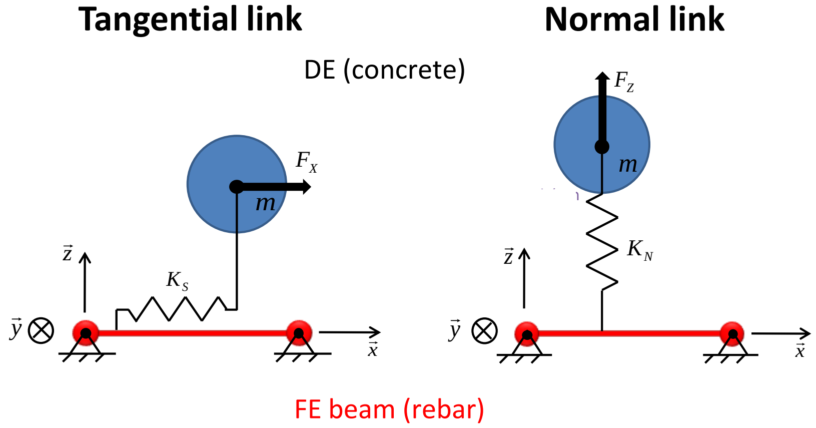
Rolling Interaction

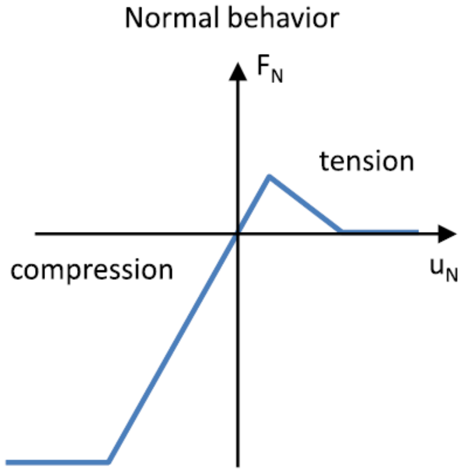


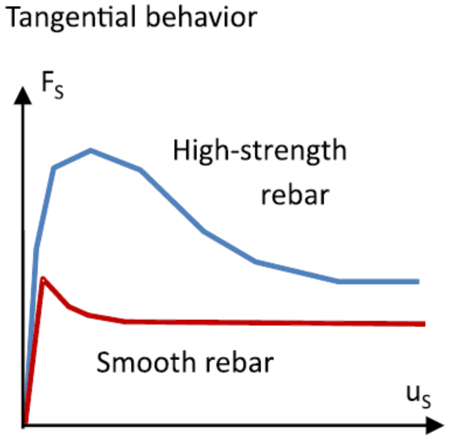
Steel reinforcement model

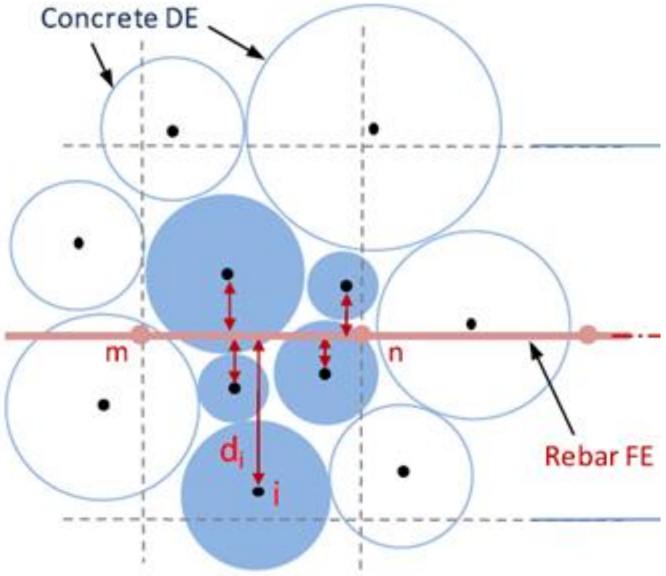
- **DE** modeling for **concrete**
- **FE beam** modeling for **rebars**



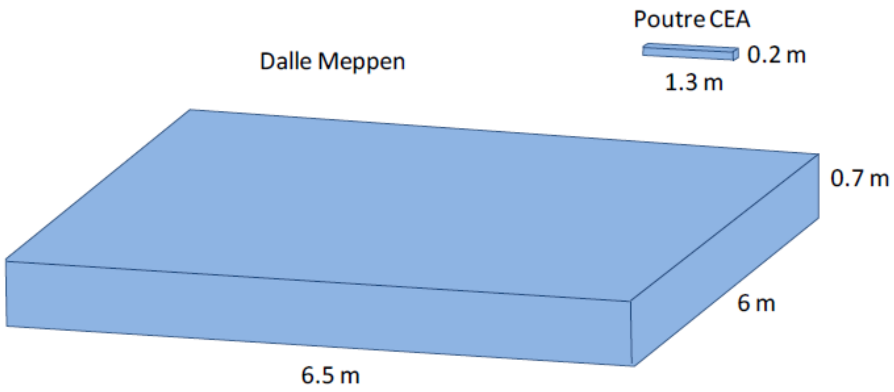


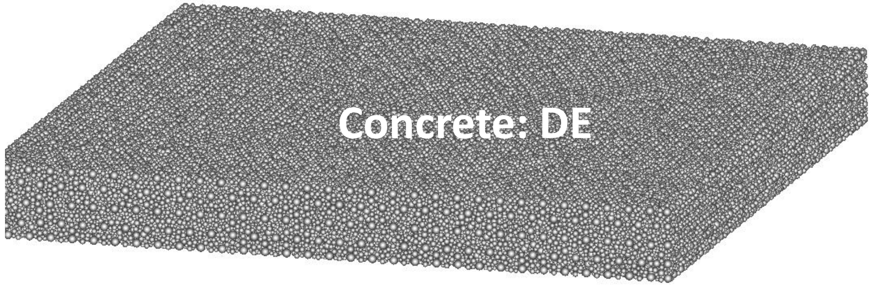




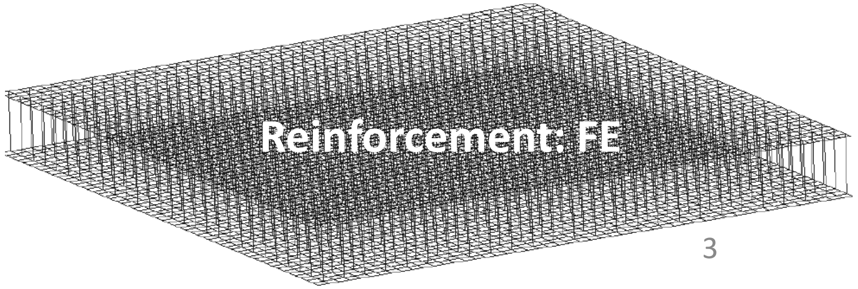


Industrial size structure





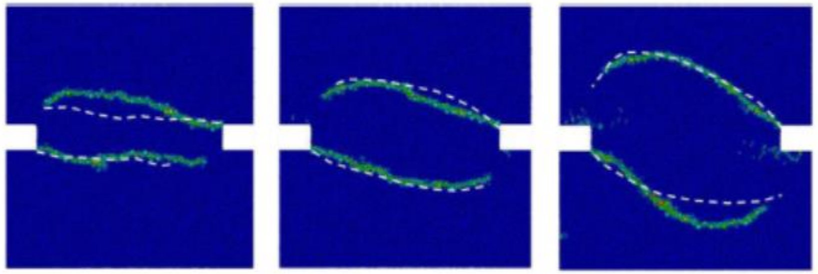
Bending and shear reinforcement



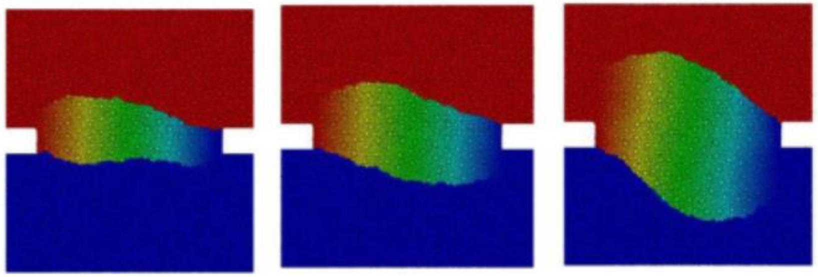
Simulations of plain and reinforced concrete structures

Tension-shear experiment

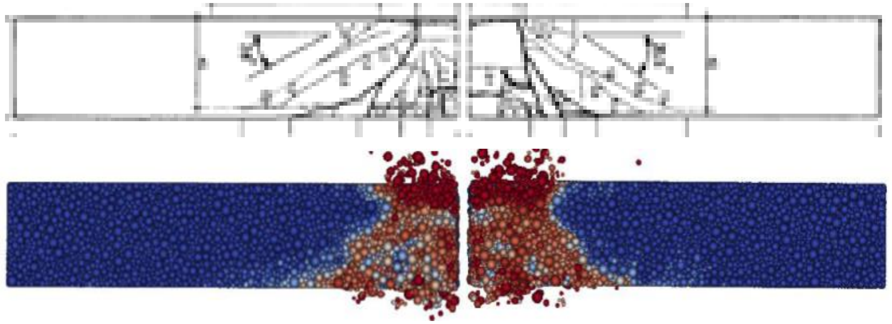
Damage path (broken links)



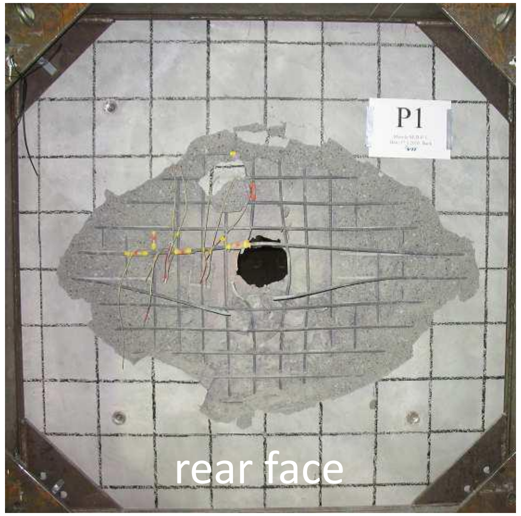
Vertical displacement

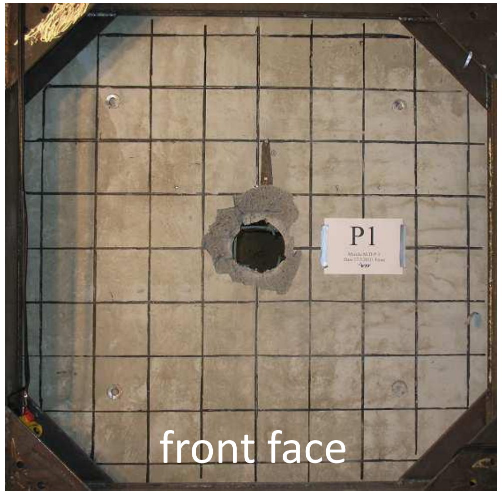


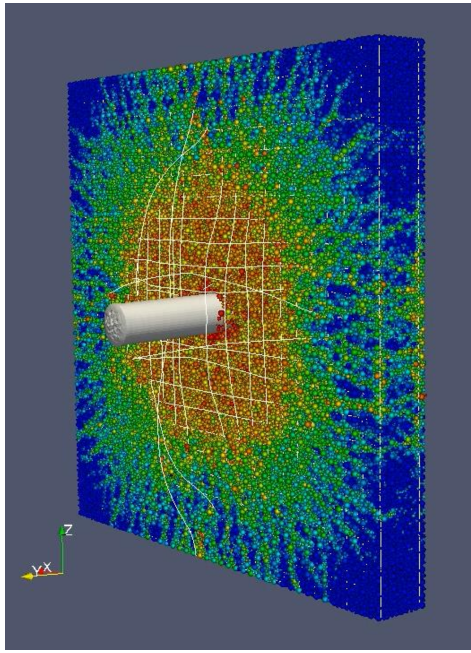
Meppen-IV (impact with damage)

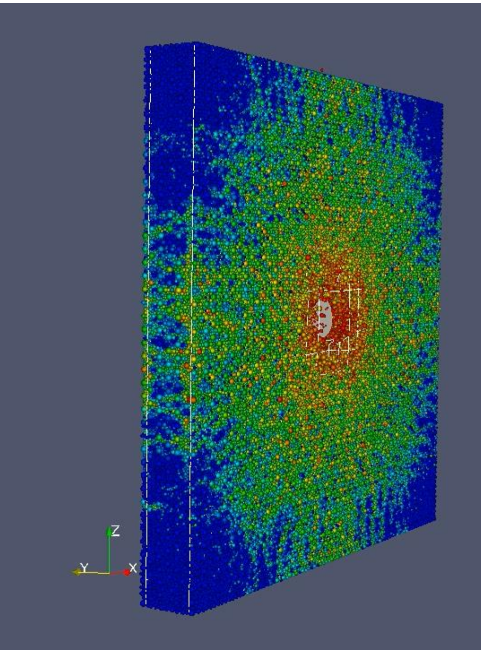


VTT P1 perforation test



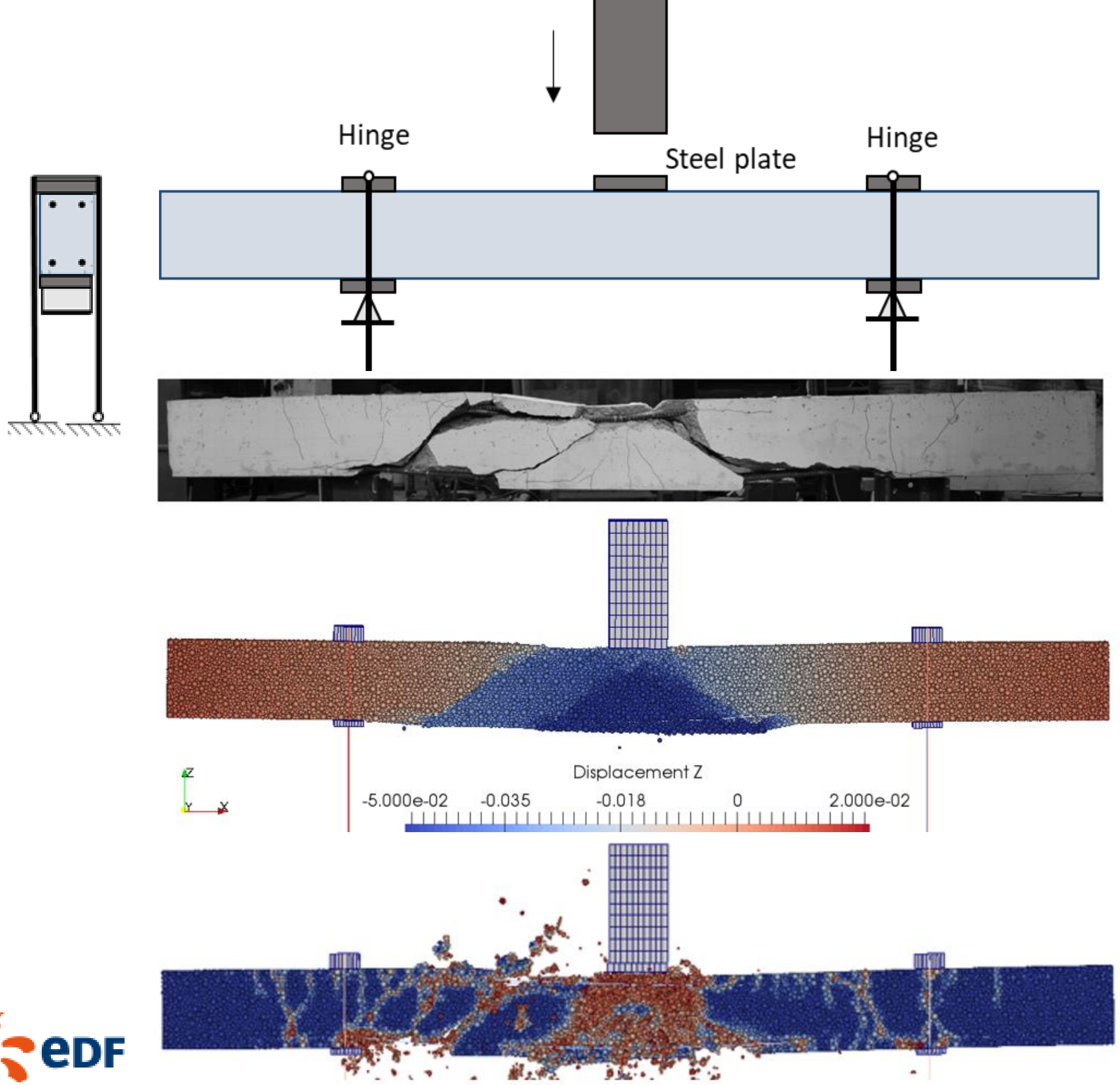




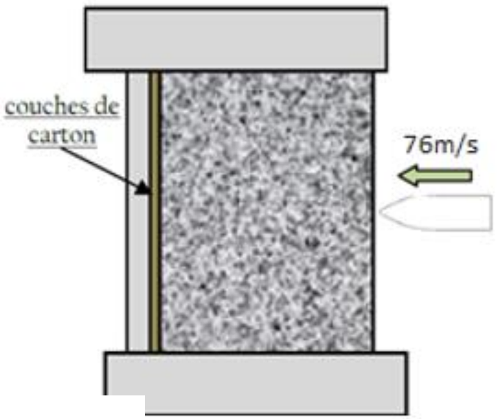


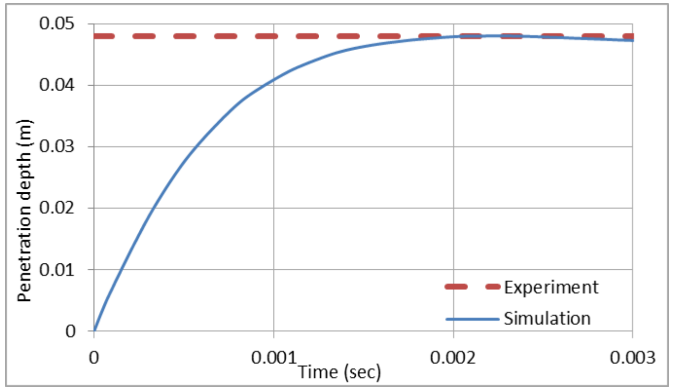
Simulations of plain and reinforced concrete structures

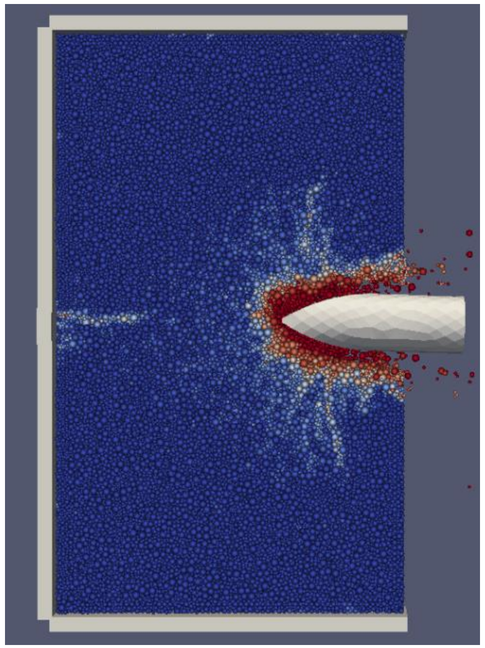
Fragmentation



Penetration of rigid projectile







Loss of Coolant Accident (LOCA)

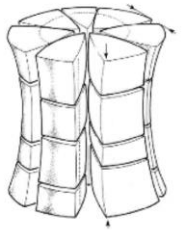
1) Fuel state evolution in normal operating conditions

→ New fuel: 20 bars helium pre-pressurised rod with 155 bars pressure in the primary fluid outside the cladding tube

→ First rise in power:

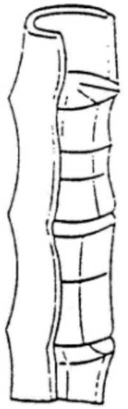
- Fuel pellets dilation
- Diabolo-shape deformation
- First fracturing *(cracking)* of pellets and radial fragments relocation

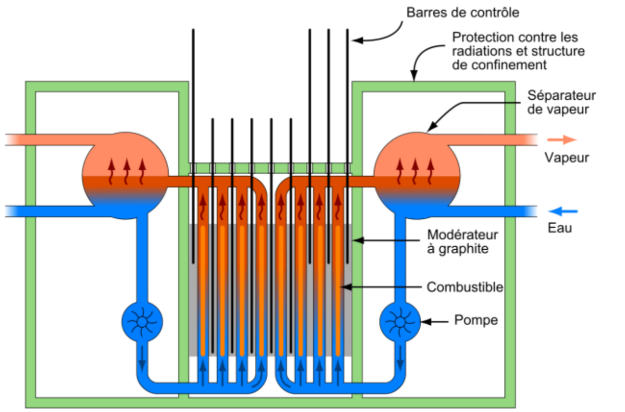
=> fuel-cladding gap decreasing

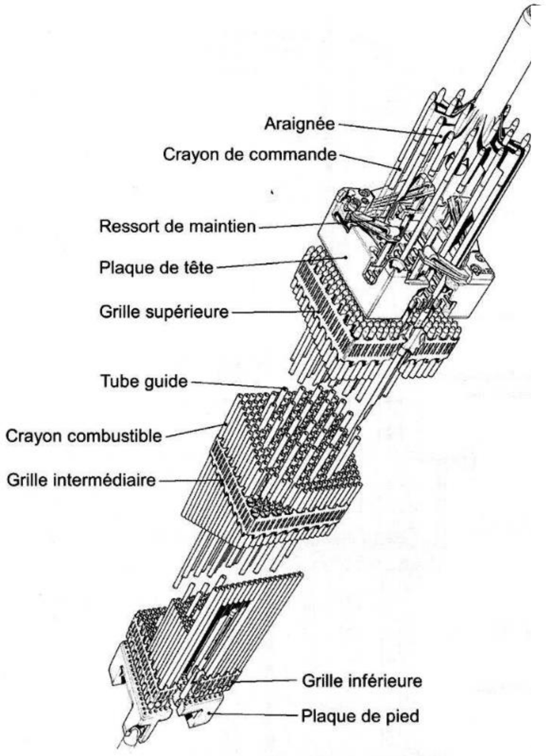


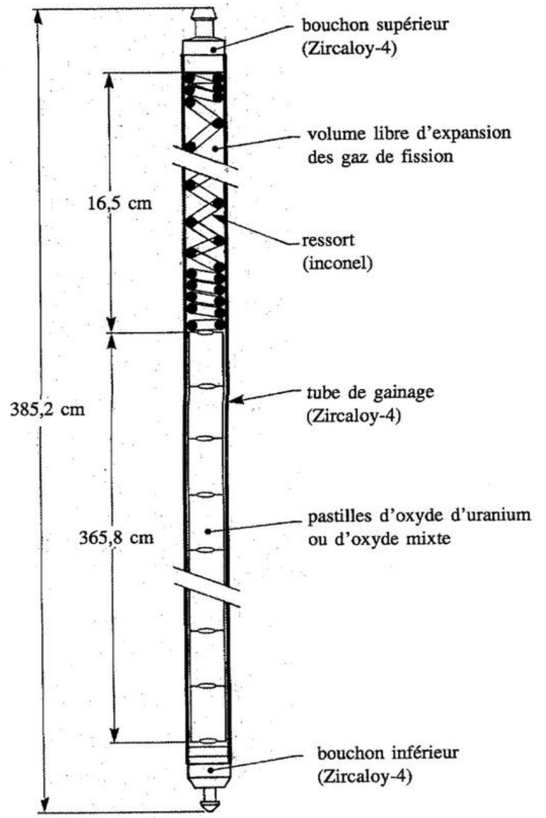
→ 1st and 2nd cycles: gap closing, folds creation, fuel – cladding interaction

→ 3rd and 4th cycles: swelling and creep of the fuel that deforms the cladding









Cladding: first confinement barrier between radioactive fuel and the outside environment

Loss of Coolant Accident (LOCA)

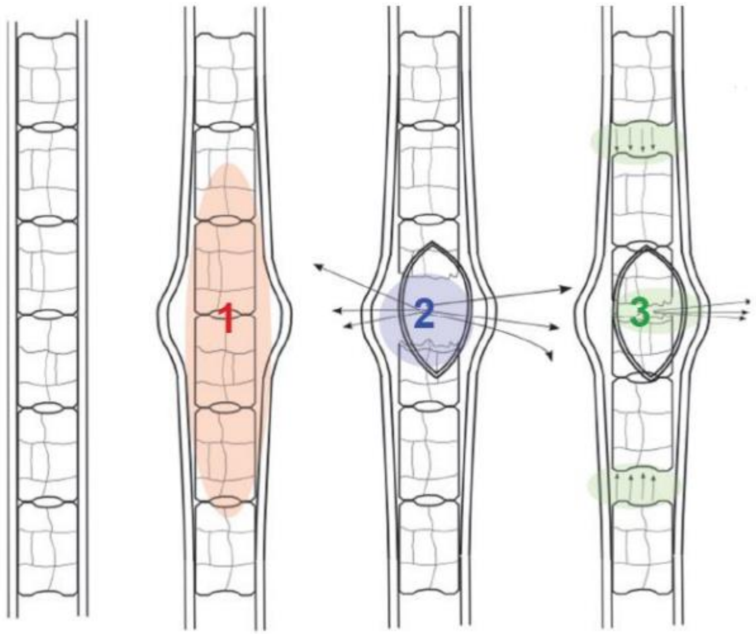
2) Fuel rod behavior during LOCA

1.
- Outside depressurization and fission gas pressure increases inside the cladding tube => large pressure difference ($\Delta P = P_{int} - P_{ext}$) => **Deformation/ swelling of the cladding tube**
- **Temperature increase in the cladding**

Plastic instability, local **ballooning** => **relocation** of fragments in the ballooned zone

2. **Eventual break-up of the cladding** => loss of fission gas, inside depressurization and additional fragmentation of the primary fragments

3. **Ejection of fragments** outside the cladding



Evolution de l'état du crayon combustible (gaine + combustible) lors du transitoire thermique APRP.

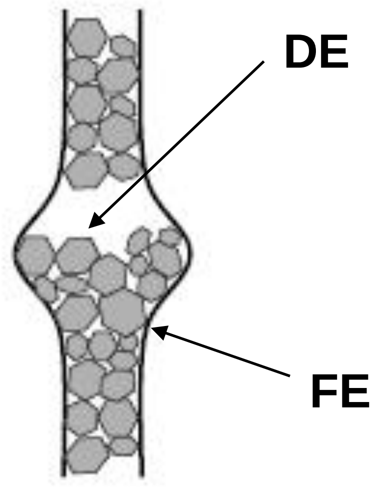
Need of numerical modeling to complete experimental studies

Objective: to build a 3D model accounting for fragments interactions, their over-fragmentation, fragments – cladding and fragments – fluid interactions, etc.

Which modeling to choose?

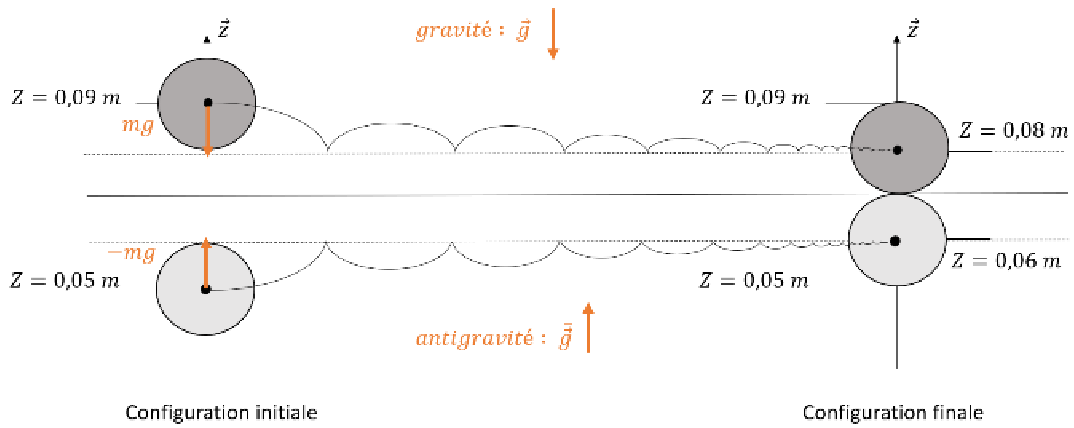
Discrete element method: widely used to granular media:

- Accounting for contacts, friction, rolling, different couplings
- Robust, performant and easy to implement



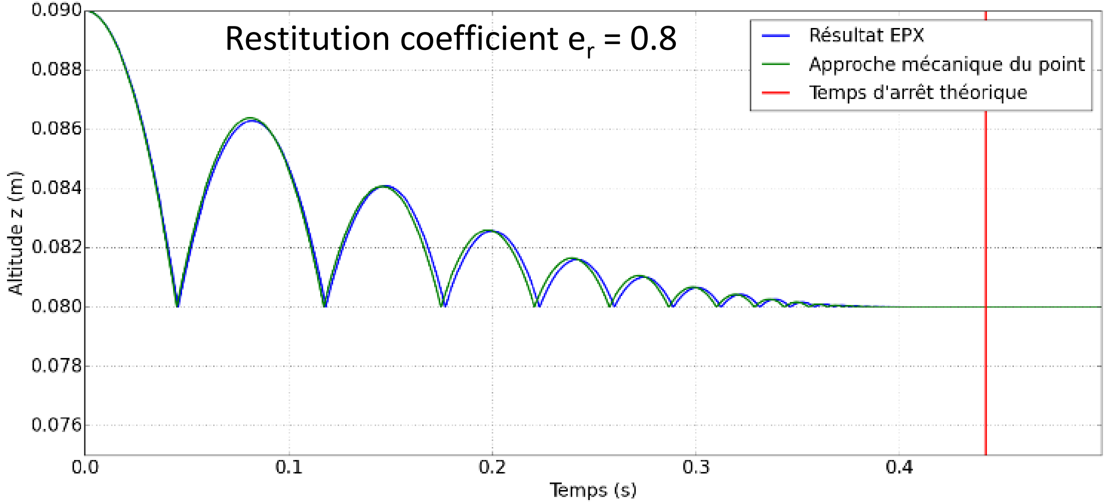
Normal and tangential interactions modified

Inelastic normal collision

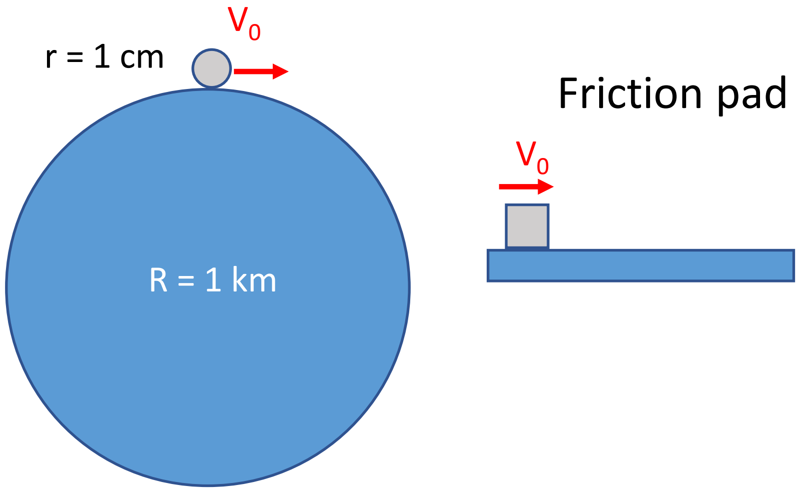


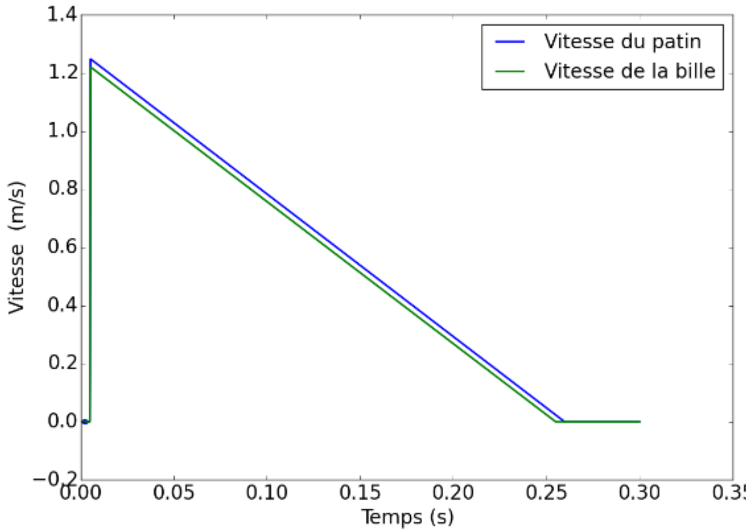
Inelastic multi-rebound

Restitution coefficient $e_r = 0.8$



Tangential interaction with friction

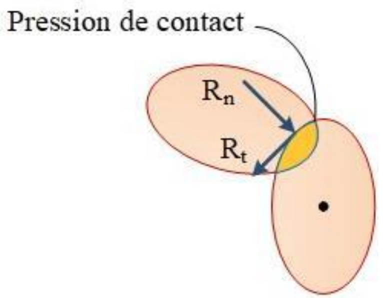




Rolling resistance

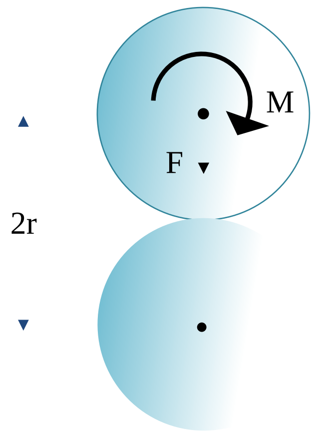
- Maximum rolling torque

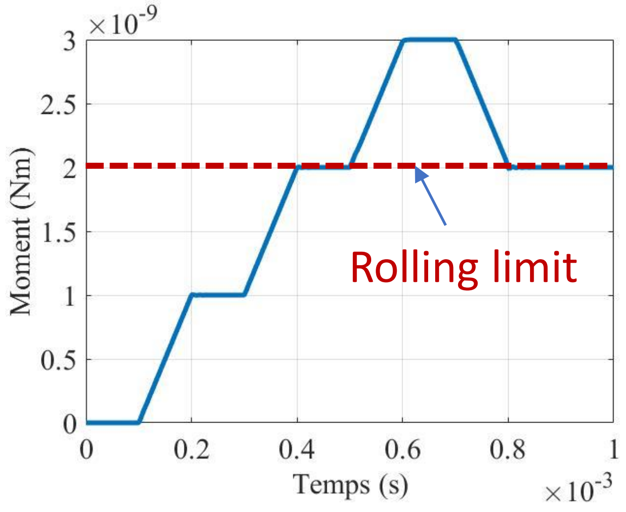
$$M_r = sign(-K_r\theta_r)\mu_r r_{min} R_n$$



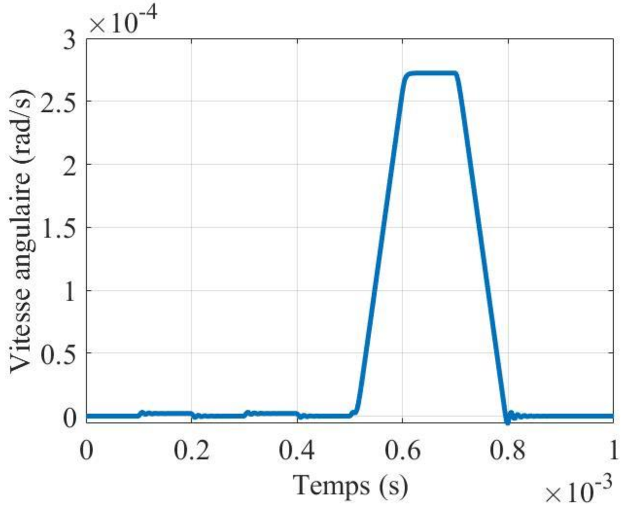
- Modification of rolling coefficient μ_r to account for a non spherical shape of grains
- Calibration of rolling resistance for a spherical shape

Rotational particles interaction





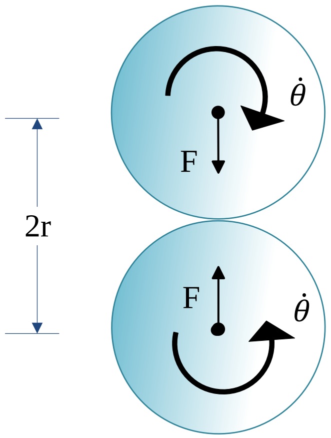
loading



result

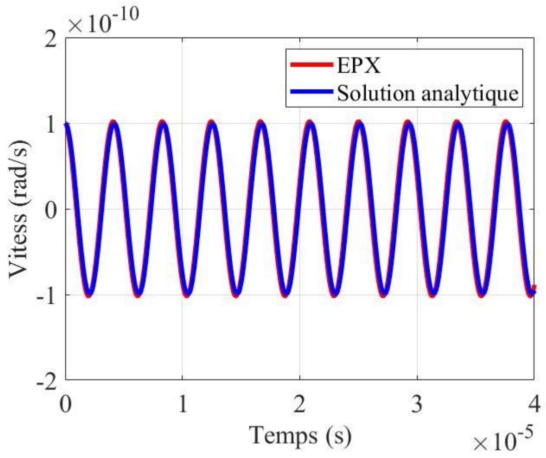
Rolling damping

$$\eta_r = \frac{C_r}{C_r{}^{crit}} = \frac{C_r}{2\sqrt{I_r K_r}}$$

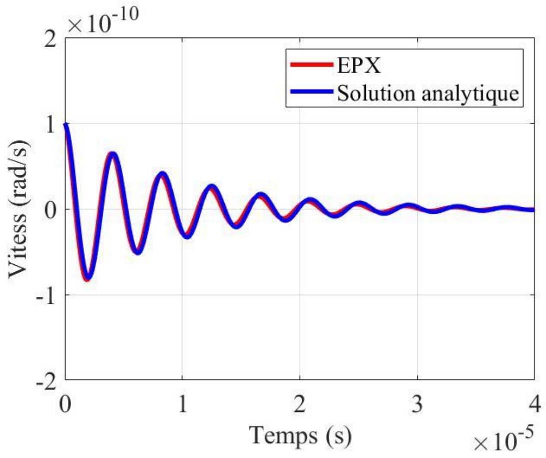


variables	valeur
diamètre	0,002 m
masse volumique	2500 kg/m^3
module de Young	20× 10^9 N/m^2
coefficient de Poisson	0,2
coefficient de restitution	0,87
coefficient de friction	0,5
coefficient de roulement	0.2

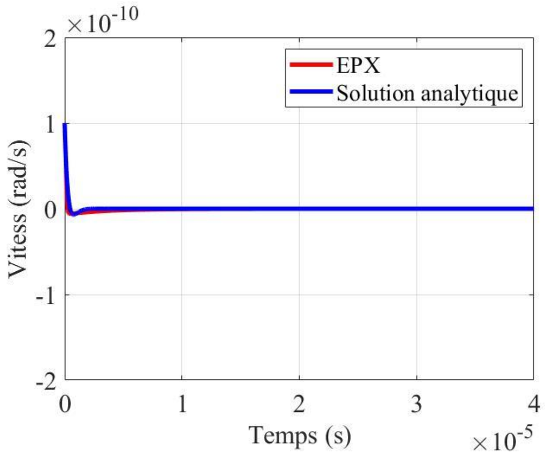
undamped: $\eta_r = 0$



subcritical damping: η_r =0,07



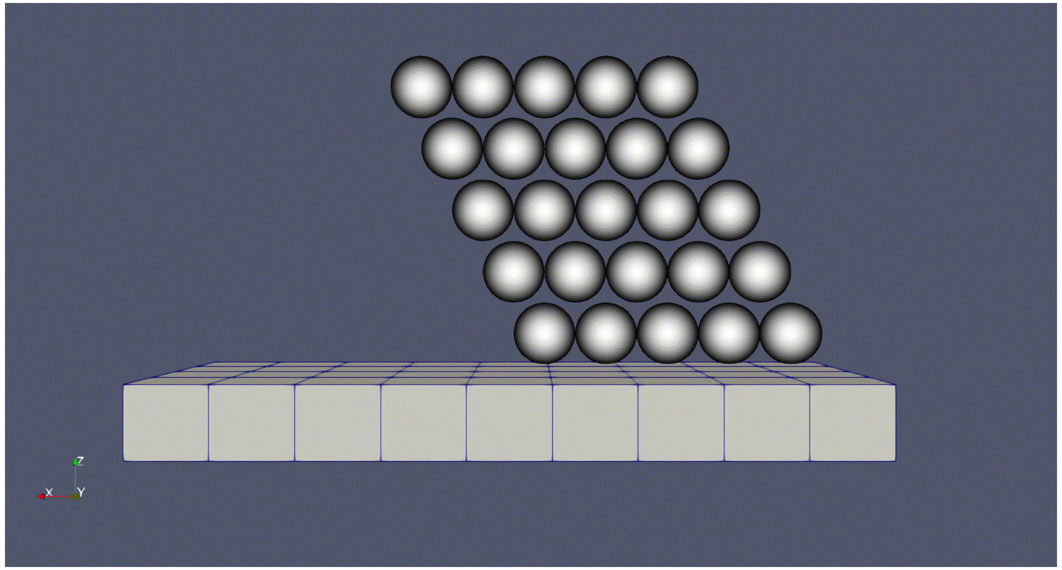
critical damping: $\eta_r = 1$



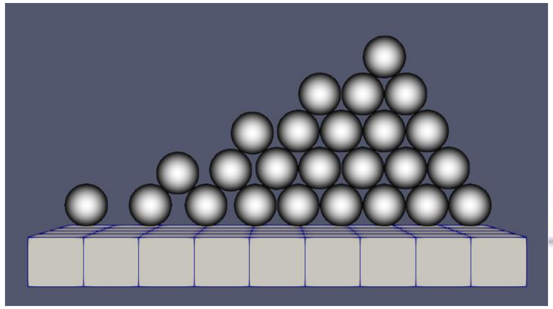
Spheres assembly collapse

- 25 discrete elements
- Time step 1×10^{-5}s
- Référence: AI, J., CHEN, J., ROTTER, J. & OOI, J. Y., 2011. Assessment of rolling resistance models in discrete element simulations. Powder Technology, 3 206, pp. 269-282.

Variables	Particules	Boîte	Unité
masse volumique	1056	1056	kg/m3
module de Young	40×10^6	40×10^6	N/m2
coefficient de Poisson	0,49	0,49	-
coefficient de restitution	0,82	-	-
coefficient de friction	0,8	0,8	-
résistance de roulement	0.2	-	-
coefficient d'amortissement	0.6	-	-



EPX result



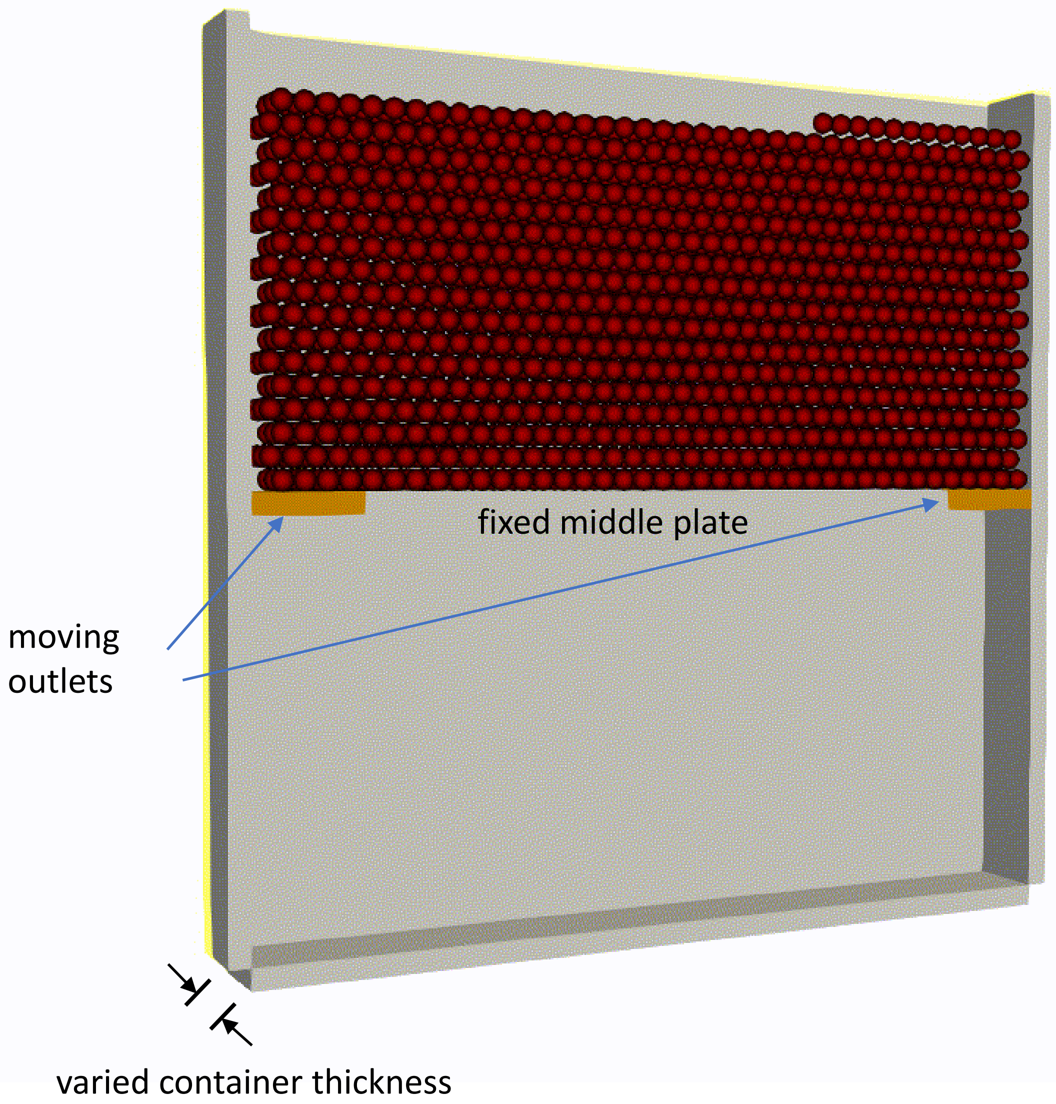
Reference

Sandpile formation with glass beads

- 2000 particles (2mm)
- Glass particles, wooden container
- Time step 1×10^{-5}s
- Reference : AI, J., CHEN, J., ROTTER, J. & OOI, J. Y., 2011. Assessment of rolling resistance models in discrete element simulations. Powder Technology, 3 206, pp. 269-282.

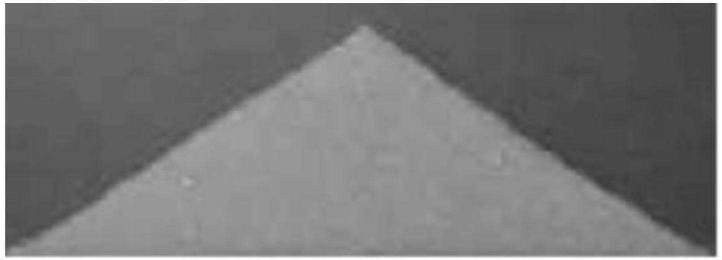
Paramètres Matériaux

variables	particules	boîte	unité
masse volumique	2500	2500	kg/m3
module de Young	$2{,}16 \times 10^6$	$2{,}16 \times 10^6$	N/m2
coefficient de Poisson	0,3	0,3	-
coefficient de restitution	0,82	-	-
coefficient de frottement	0,3	0,3	-
résistance de roulement	0,05	-	-
coefficient d'amortissement	0.001	-	-
ratio de ks et kn	0,2	-	-

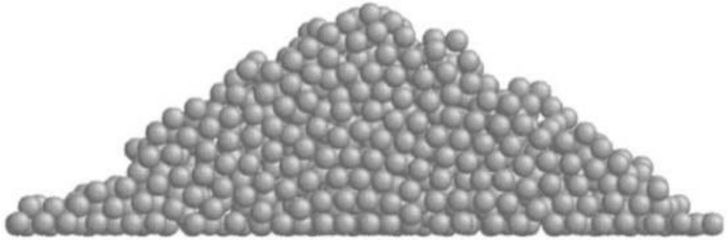


Sandpile formation with glass beads

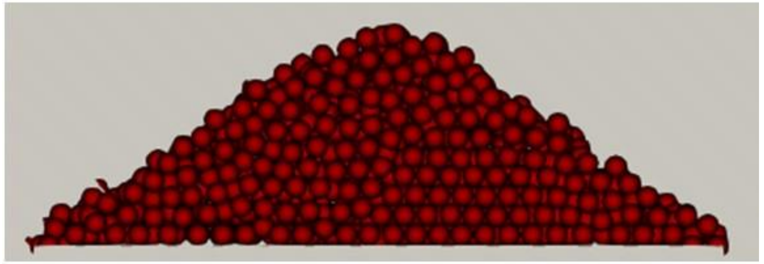
Box thickness = 4 × d



tas final de l'essai (33°)

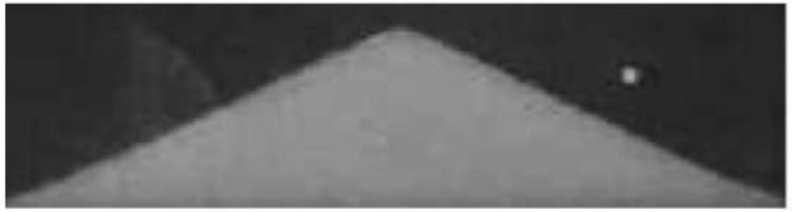


tas final de la simulation de Zhou (34°)

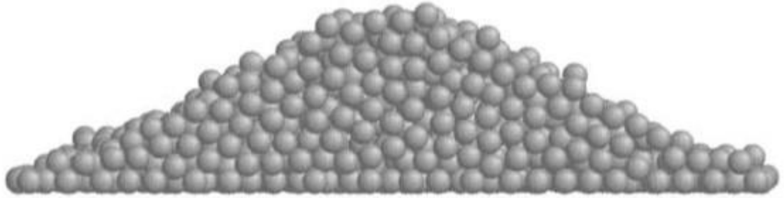


tas final de la simulation EPX (34°)

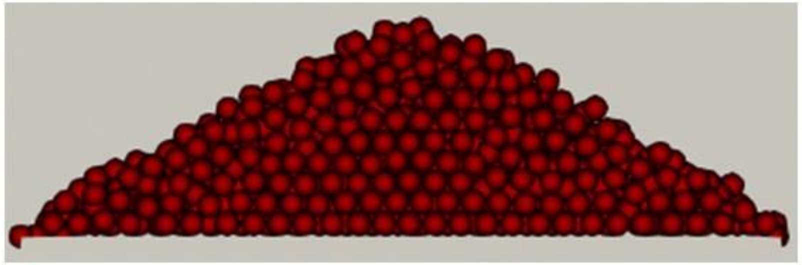
Box thickness = 20 × d



tas final de l'essai (26°)



tas final de la simulation de Zhou (27°)

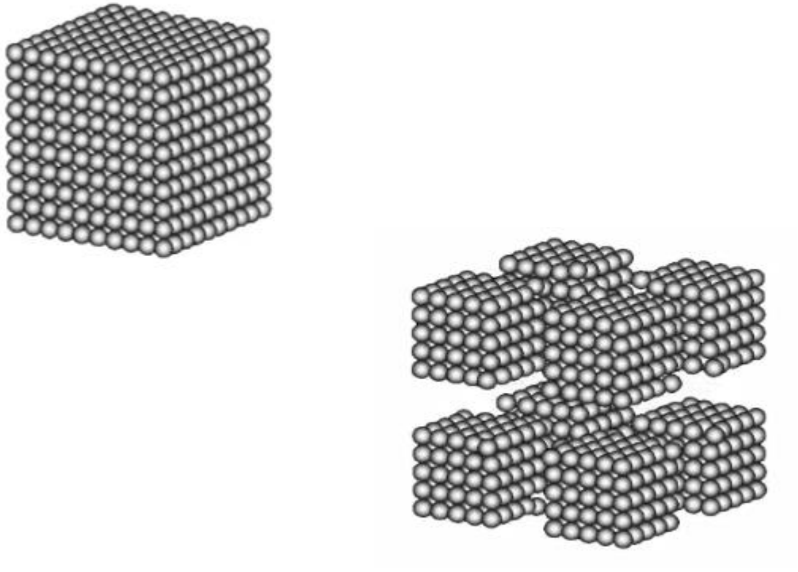


tas final de la simulation EPX (29°)

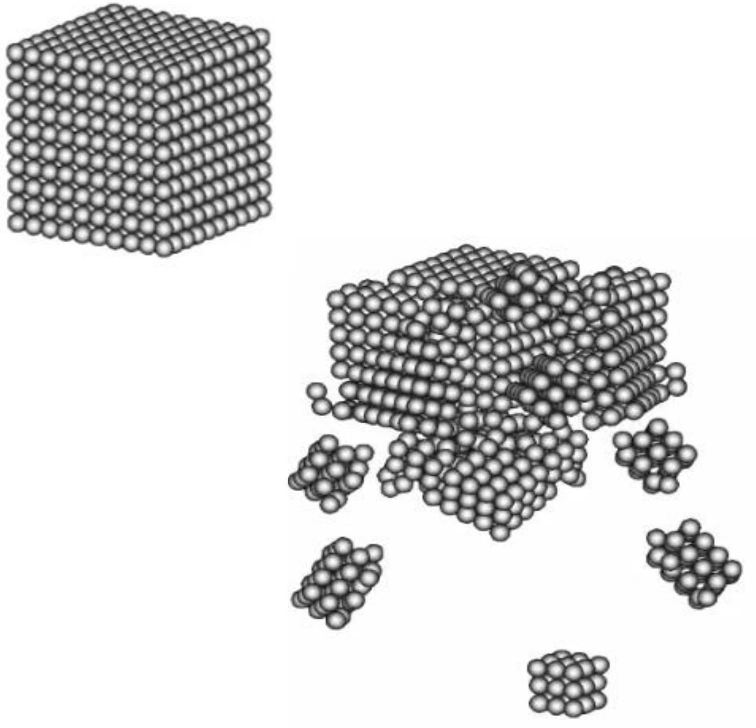
Fragment break-up

Cube-like fragment composed of 1000 discrete elements glued together by cohesive links

Pressure applied in the center



Off-center pressure



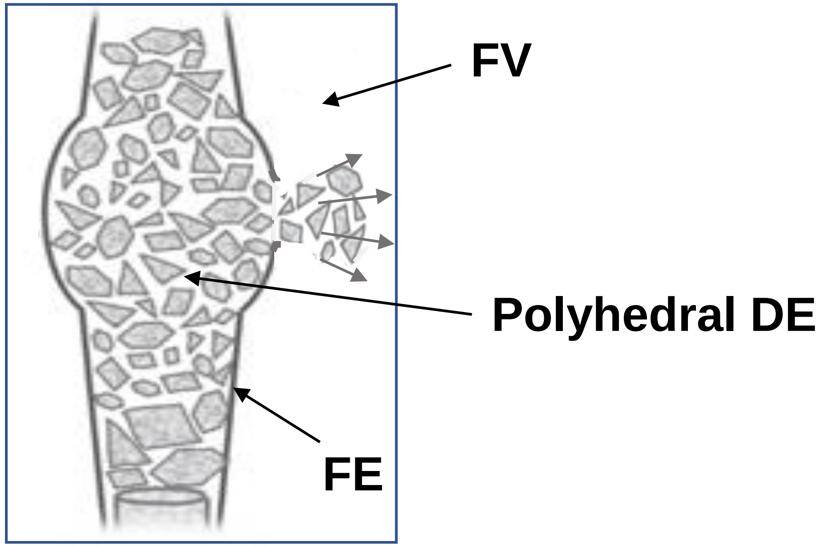
Modeling relocation and ejection of fuel fragments during LOCA

EDF-LMGC Montpelier thesis

Physics to model:
- El-pl. swelling of the cladding
- Account for porosity
- Relocation of fragments
- Cladding rupture
- Ejection of fragments in gas flow

Expert opinion:
- Size and shape of particles play a crucial role in dynamics of relocation and fragments ejection
- Spherical DE overestimate relocation/ejection
- Additional porosity of spherical DE prevent from obtaining realistic results for DE-fluid coupling

To be implemented in EPX:
- Polyhedral DE with contact interactions
- DE – FV coupling
- Mixed model: DE + FE + FV + FLSX FSI

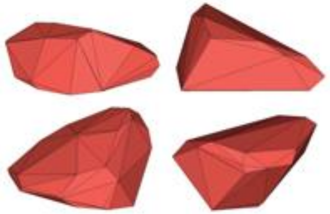


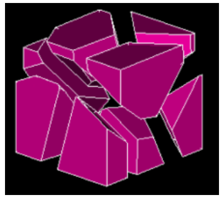
<u>1st year</u> : Polyhedral DE with contact interactions
<u>2nd year</u> : DE – fluid interaction: porosity modeling then DE – FV coupling
<u>3rd year</u>: Interaction of (DE) fragments with elastic-plastic ballooned cladding (FE) and (FV) fluid

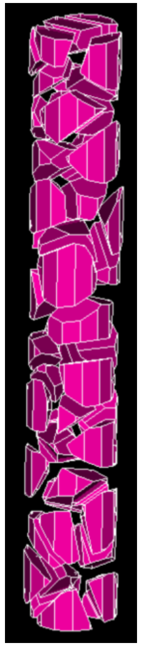
EDF

Ingredients to implement/use

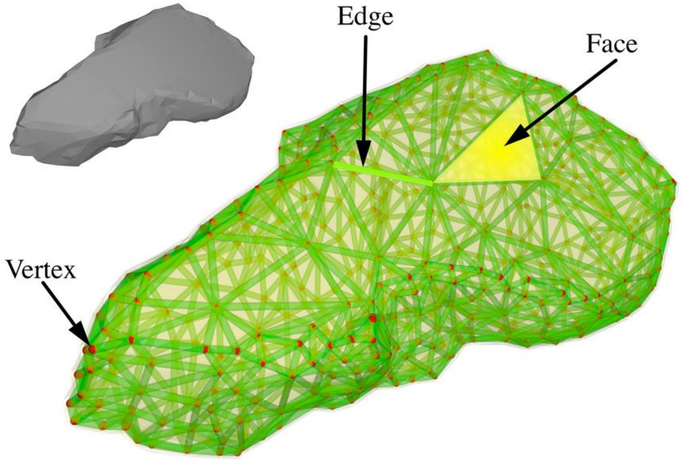
- MAP tool (EDF) to generate polyhedra
- Polyhedral mesh in MED format
- Paraview output in EPX for polyhedra







- New concept: rigid sphero-polyhedron
- New technique to manage contacts issued from LMGC Montpellier code Rockable
- Use of quaternions to define orientation



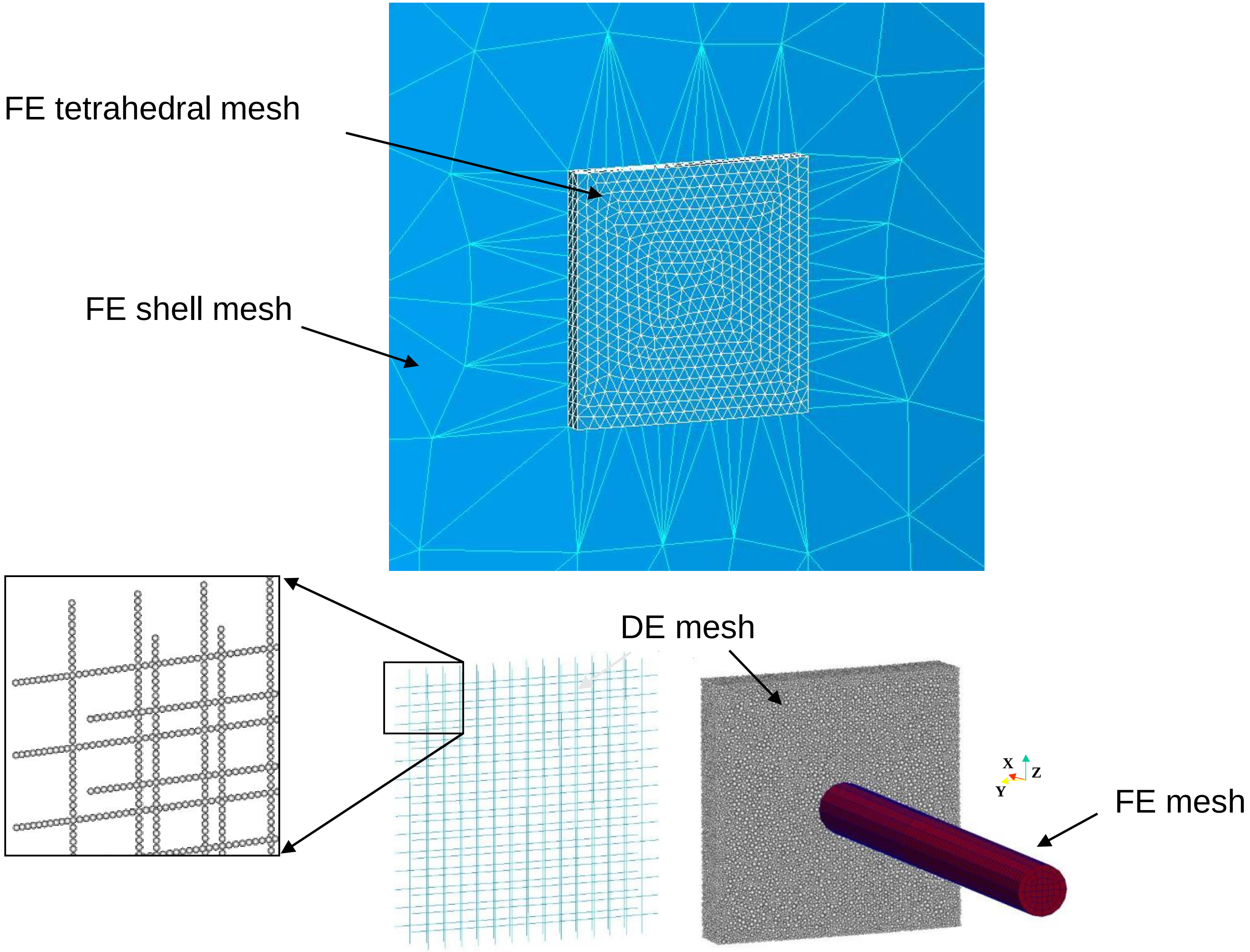
- **New modules in EPX :** m_eldi_poly.F90, m_eldi_poly_liaisons.F90, …

  - Motion of 6-dof barycentres
  - Positions of polyhedral's verticies to be deduced to define contact geometry

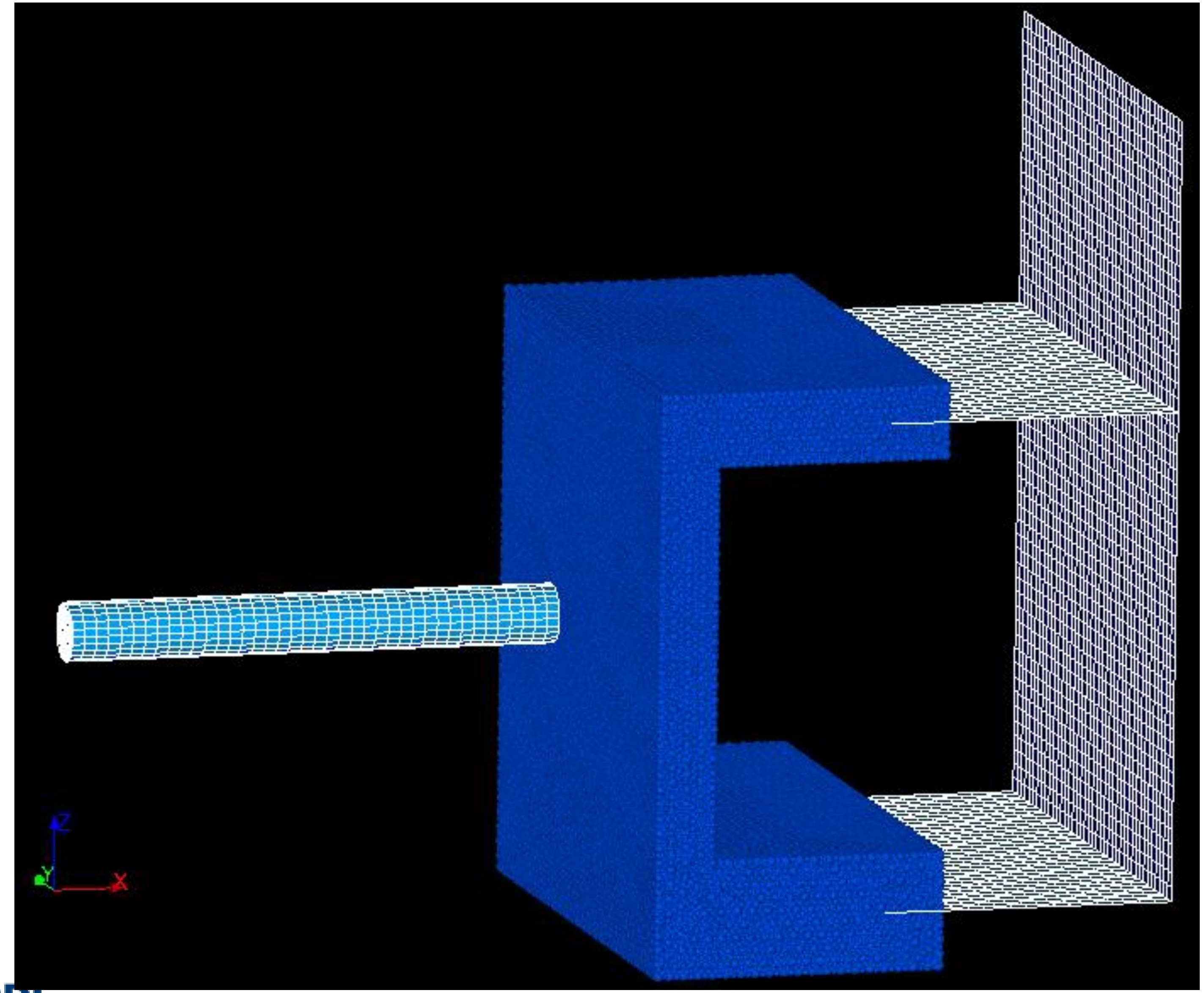
EDF

Annexes

Impact on large RC structures



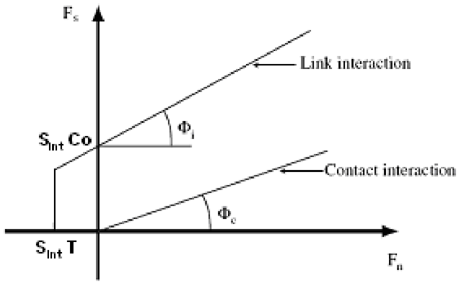
Modèles mixtes à géométrie complexe – essai IRIS3

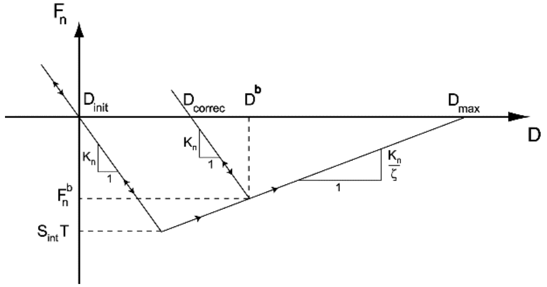


- Géométries non parallélépipédiques avec SpherePadder++
- Plusieurs zones de collage ED-EF coque

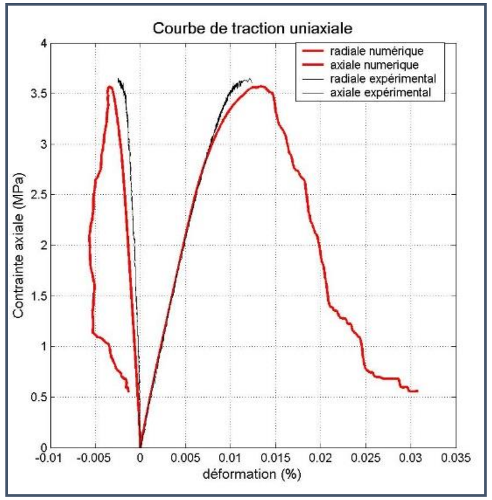
Brittle behaviour

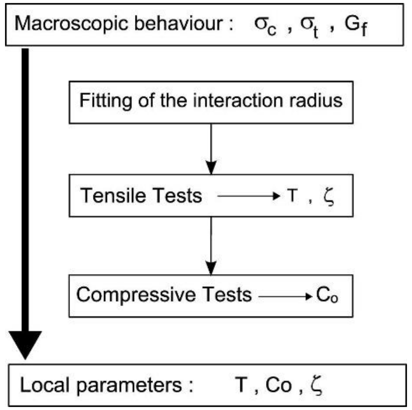
- cohesive links
- contact behaviour

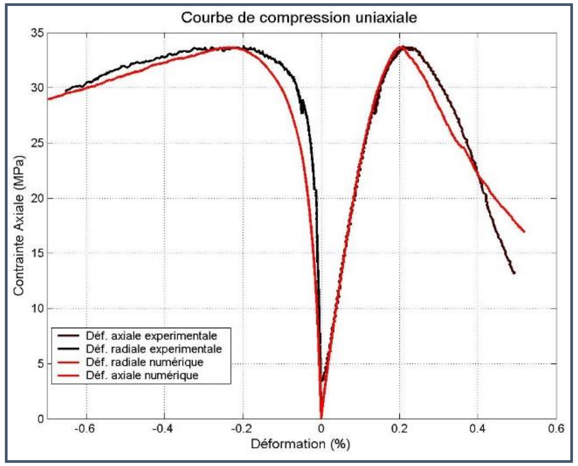


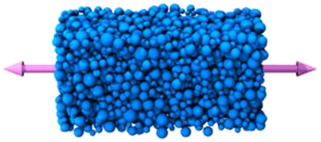


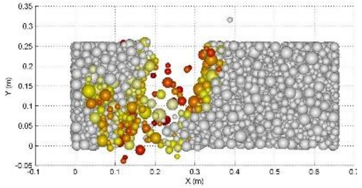
Identification of T, ⍰, C_0 on experimental data

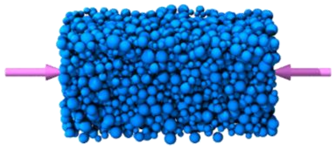


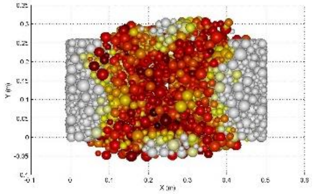












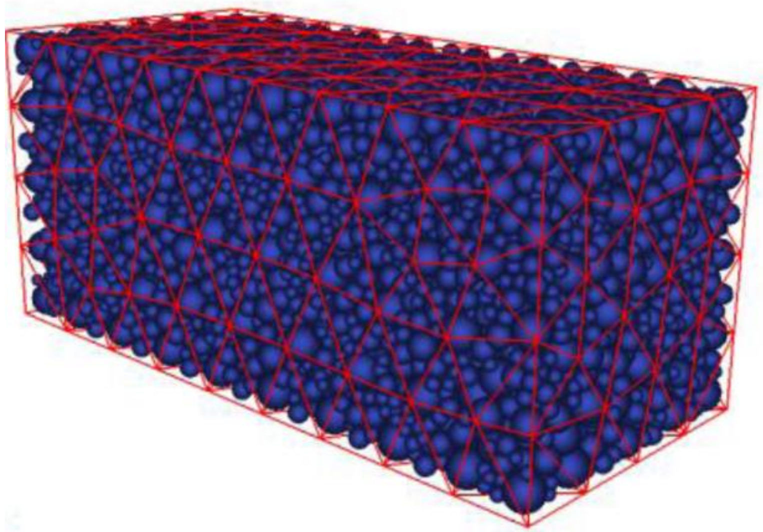
Discrete Element "mesh"

- Tetras-to-DE assembly packing algorithm: Geometric algorithm proposed by Jerier et al. (2009)

- Iterative generation of a mesh with DE of different sizes and masses

- Non-overlapping spheres connected by beam-like interactions

- Typical assumptions to create a homogeneous mesh:
  - R_{max}/R_{min} = 3.0
  - FE/DE = 4
  - Compactness around 0.58

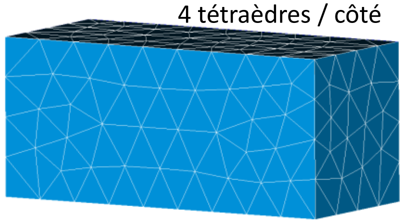


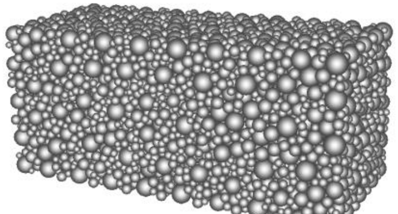
DE are not constituents of concrete

(macroscopic modeling)

Recalage automatique via Adao du modèle ED

SpherePadder++ (SMESH)

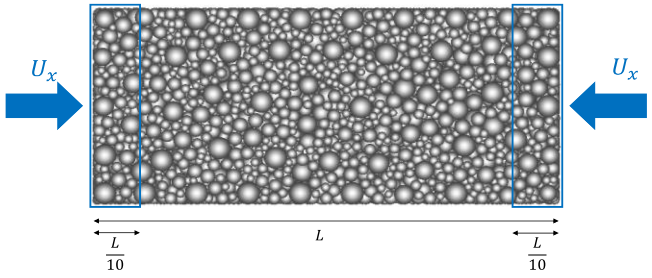


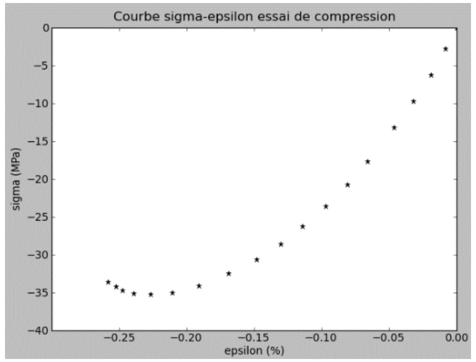


Identification manuelle des paramètres locaux non-linéaires en 2 étapes :

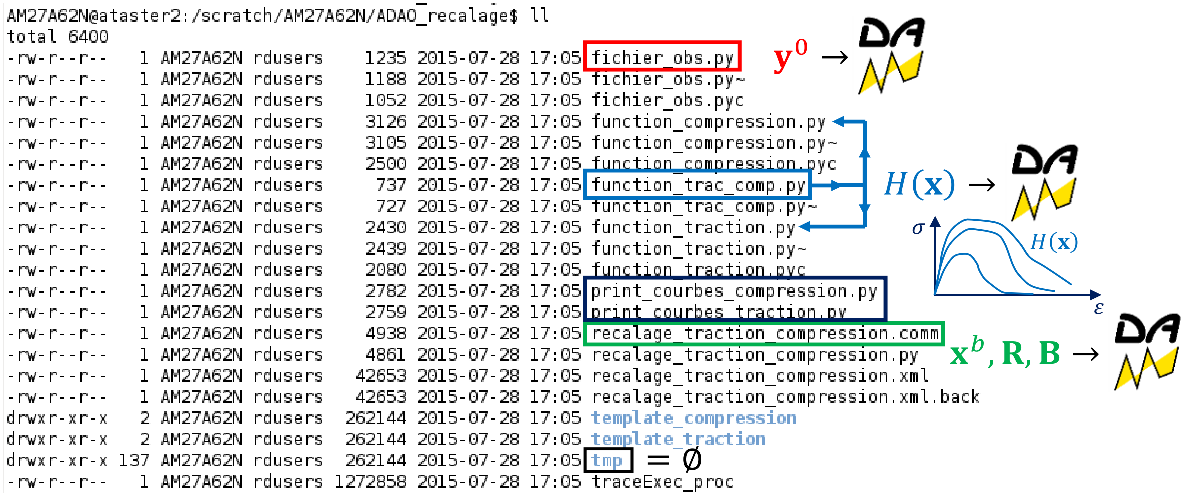
- on identifie **T** en simulant un essai de traction simple
- on identifie **C_0** en simulant un essai de compression simple

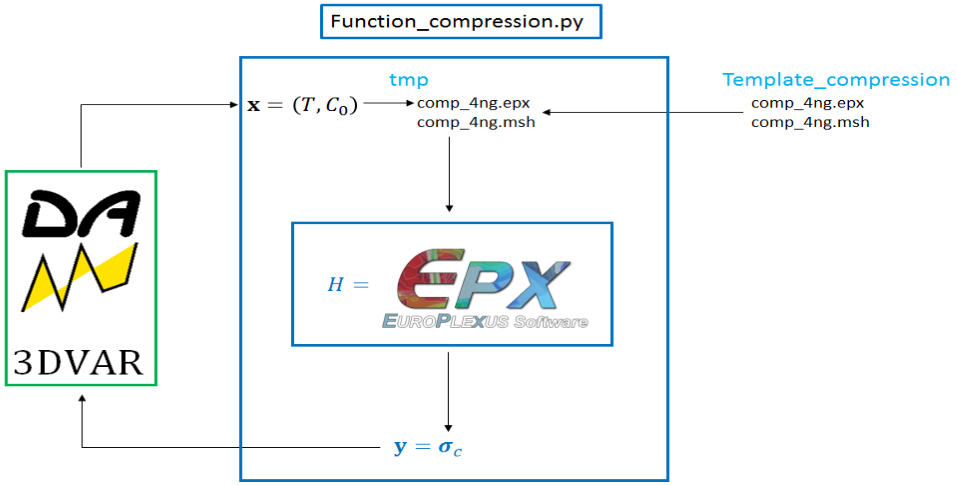
Europlexus





Identification automatique sous Salome





Bilan :

- recalage automatique global traction-compression
- algorithme 3DVAR non approprié (Salome 7.6)
- utiliser les algorithmes sans gradient disponibles dans Salome 7.7