

A new creep model for NPP containment behaviour prediction

A.Foucault^{1,2}, E.Galenne¹, S.Michel-Ponnelle^{1,2}

¹ EDF R&D, Analysis in Mechanics and Acoustic

² LaMSID – UMR EDF/CNRS/CEA 8193

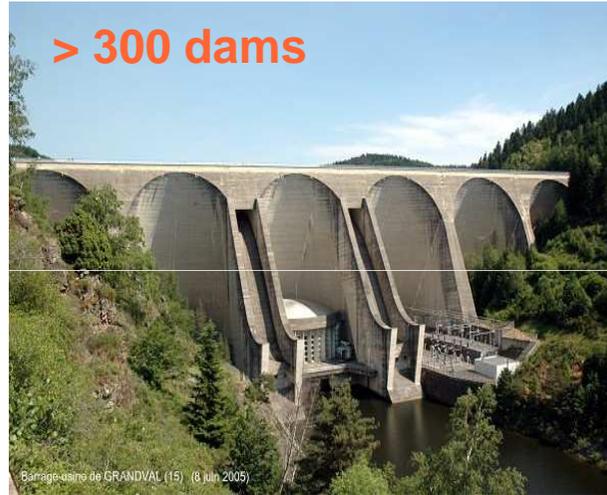


LaMSID

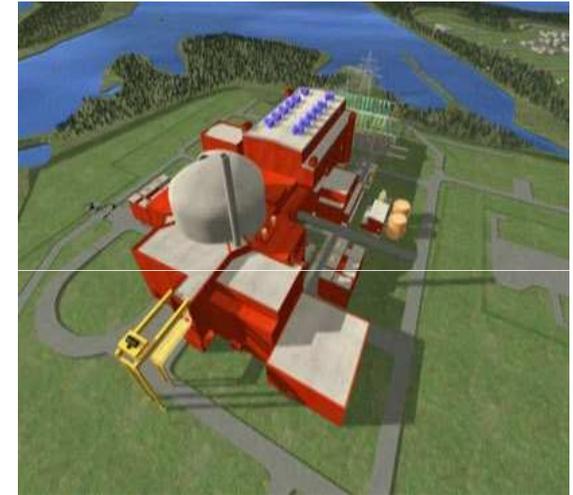


Several types of concrete structures considered

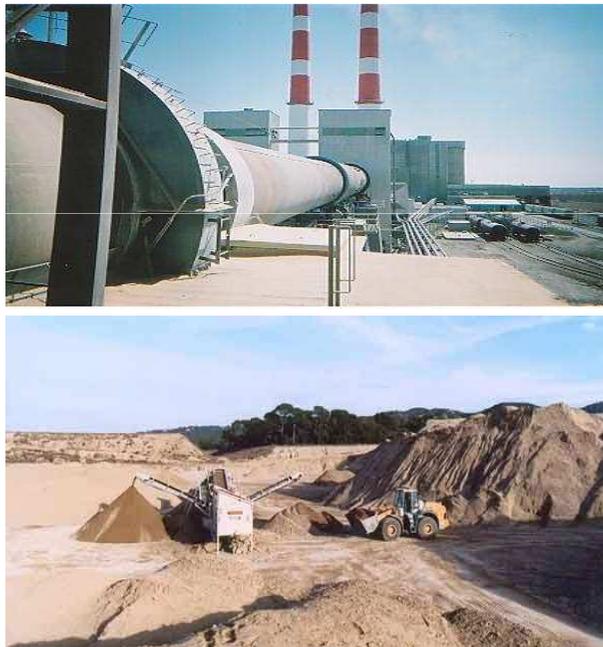
EDF facilities (France only)



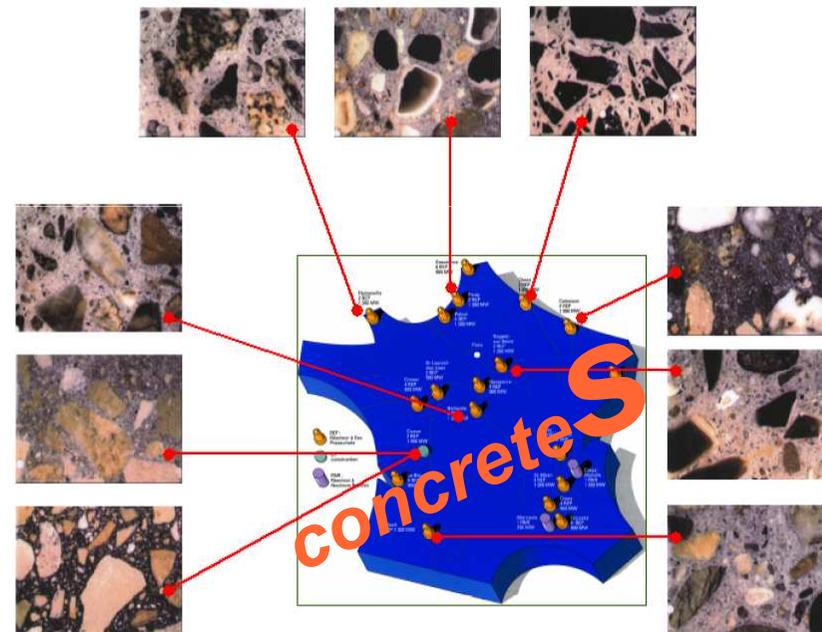
new facilities (EPR)



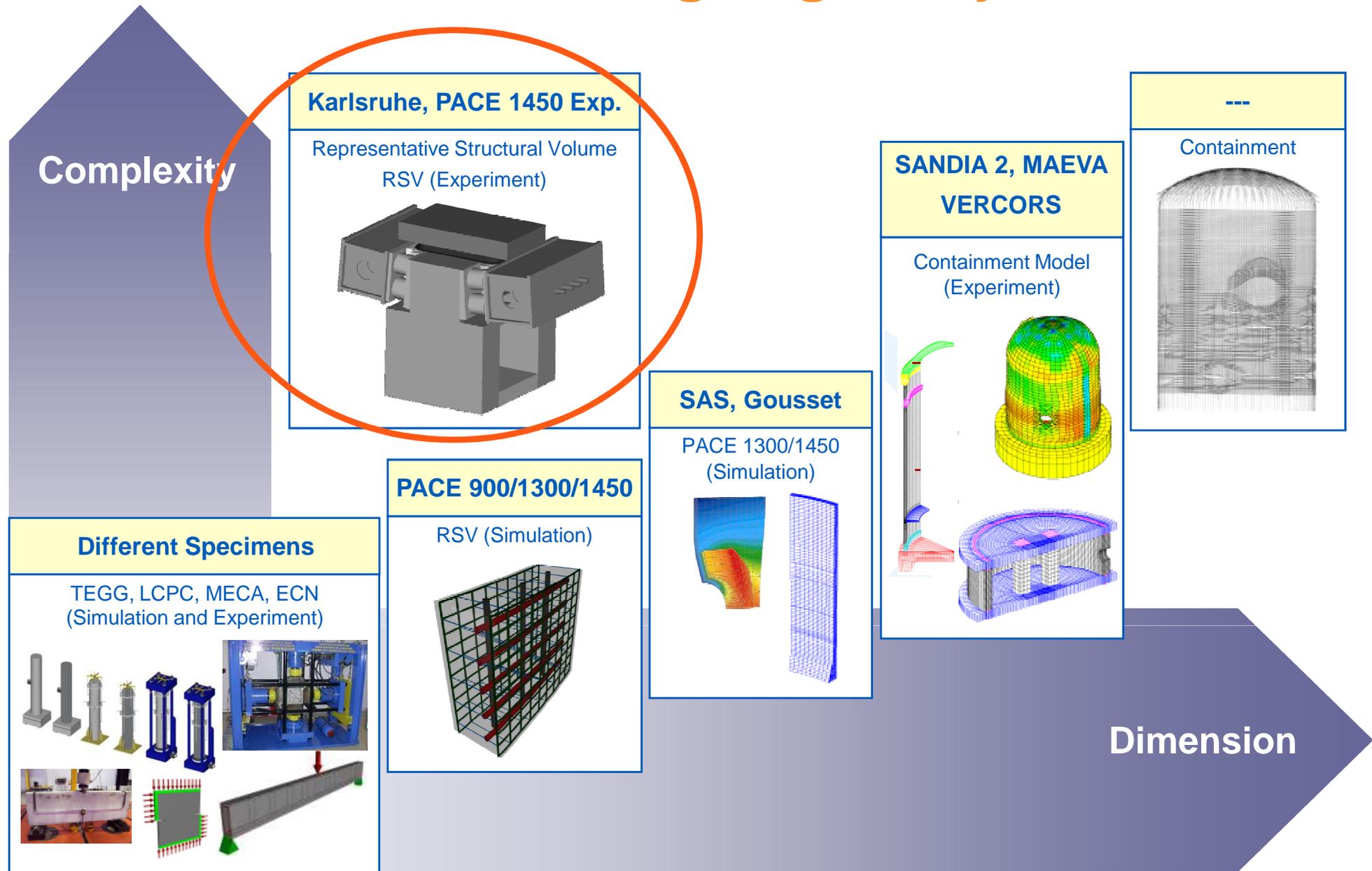
local cement and aggregates



large set of concrete mixes (>1000)



Nuclear Power Plant – ageing study



Contents

1. Numerical study presentation: PACE 1450

- Represented physics phenomena
- Loading schedule

2. Focus on basic creep simulation: 2 tested models

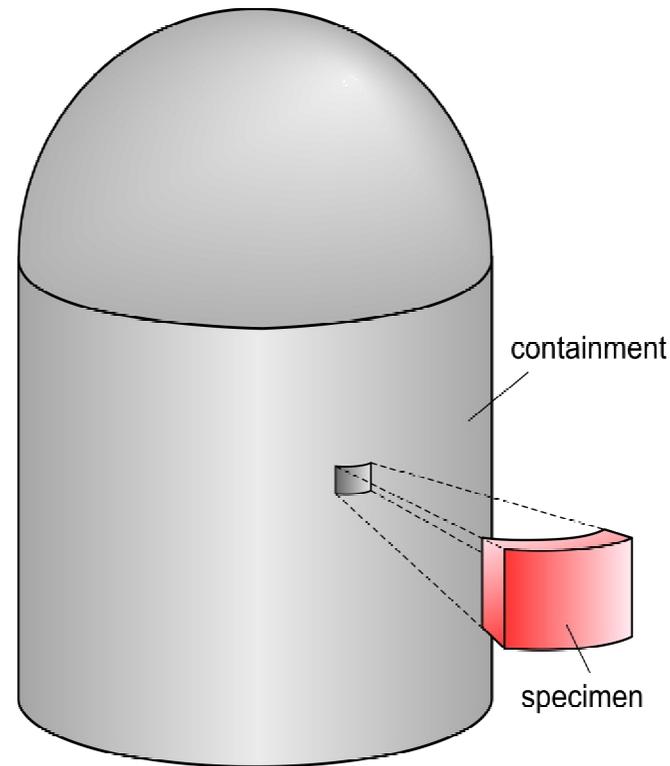
- Formulation
- Restrictions
- Model parameters identification

3. PACE 1450 simulation results

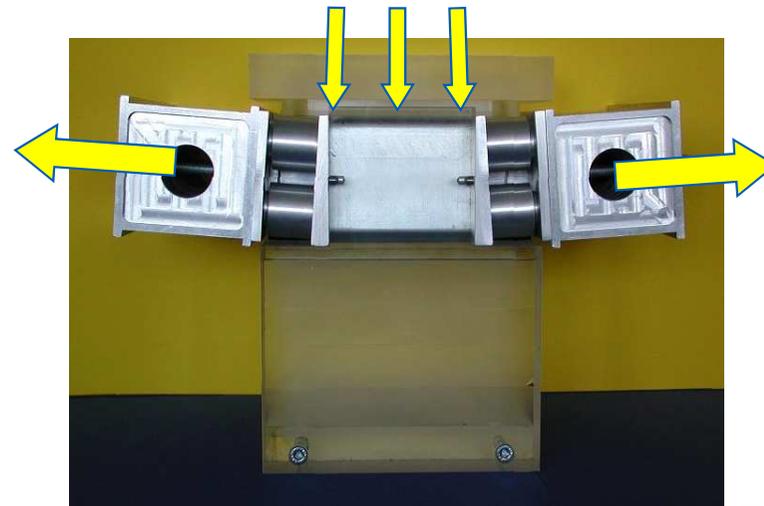
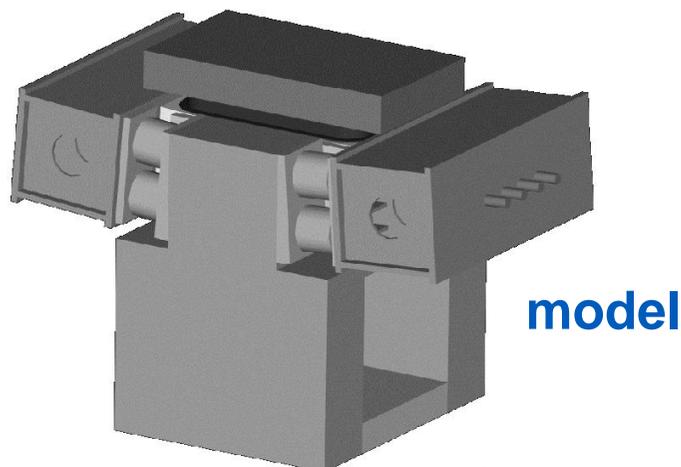
- Comparison of models results to experimental data

4. Conclusion and future works

1 - Specimen out of the cylindrical part of the containment



- ▶ Curved specimen
- ▶ Partially reinforced as in reality
- ▶ Horizontal and vertical external pre-stressing with the possibility of adjusting the pre-stressing force simulating the aging
- ▶ Fitting to the boundary conditions of the laboratory



1 - Numerical study – (only curved specimen)

▶ Computing path : 3 successive calculations

- Hydration: estimated through an empirical relation
- no Temperature effect

■ Drying simulation

- **Data** : T° field, SECH_GRANGER
- **Boundary conditions** : water flux
- **Results**: water concentration (SECH) field

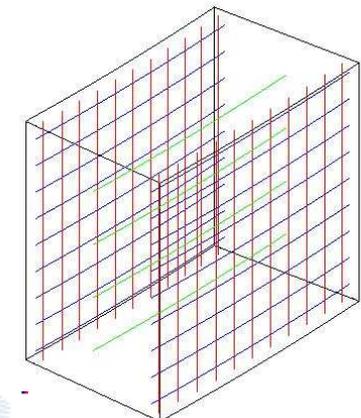
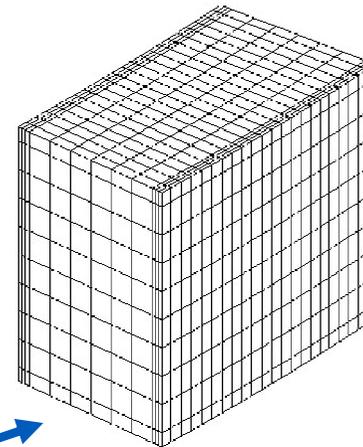
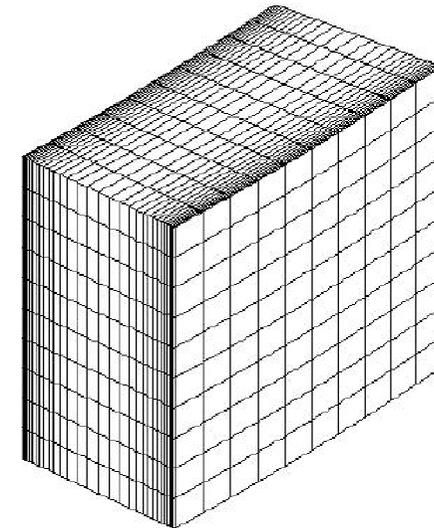
■ Mechanical simulation

- **Data**: T°, SECH and HYDR fields
- **Behaviour**:
 - Drying and autogenous shrinkage
 - 2 options for basic and drying creep
 - BETON_UMLV_FP (Benboudjema et al., 2002)
 - BETON_BURGER_FP (Sellier et al., 2009; Foucault, 2011)

- **Results**: Stress, Strain fields

- concrete with 3D quadratic elements (2640)
- vertical and horizontal reinforcements with 1D linear elements (1232)
- 4 horizontal tendons with 1D linear elements (80)

Mesh information
Concrete
3D linear elements
3000 HEXA8



Strain decomposition

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{bc} + \boldsymbol{\varepsilon}^{dc} + \boldsymbol{\varepsilon}^{as} + \boldsymbol{\varepsilon}^{ds}$$

► Elasticity :

$$\varepsilon_{ij}^e = \frac{1}{E} \left[(1 + \nu) \sigma_{ij} - \nu \delta_{ij} \sigma_{kk} \right]$$

► Basic creep : BETON_UMLV_FP or BETON_BURGER_FP

Water concentration [l/m ³]	0	51.5	57.5	69.1	105.7
Moisture h (%)	0	22.5	27	39	100

► Autogenous shrinkage : [Granger, 1996] $\dot{\varepsilon}^{as} = -B_ENDOGE \times \dot{\xi}$

► Drying shrinkage : [Torrenti et al., 1997] $\dot{\varepsilon}^{ds} = -K_DESSIC \times \dot{C}$

► Drying creep: [Bazant and Xi, 1994] $\dot{\varepsilon}^{dc} = \frac{1}{\eta^{dc}} |\dot{h}| \sigma$

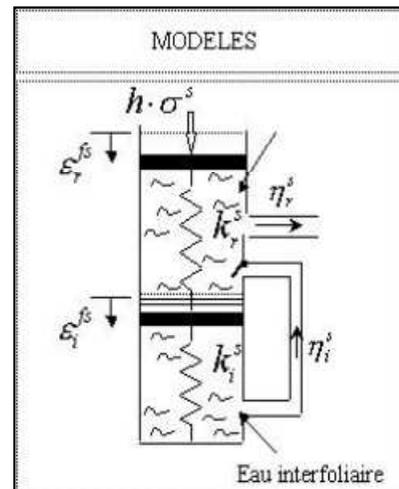
2 - Context – initial basic creep model

BETON_UMLV_FP [Benboudjema et al., 2002]

- ▶ Basic creep formulation (small strains)
 - Basic creep elementary phenomena
- ▶ Strain tensor decomposition in 2 uncoupled parts
 - Spherical
 - deviatoric

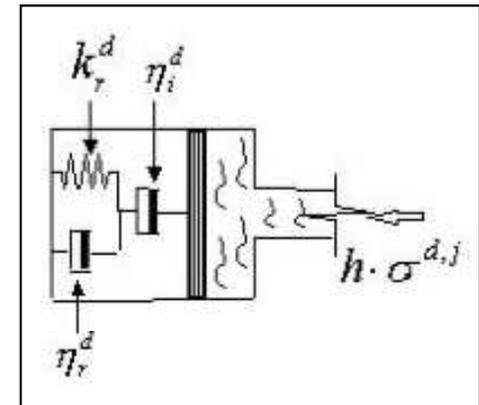
▶ Spherical part

- Recoverable strain
- Dissipated strain
- limited values
- 4 parameters



▶ Deviatoric part

- Recoverable strain
- Dissipated strain
- unlimited values
- 3 parameters



▶ Proportional strain to relative humidity

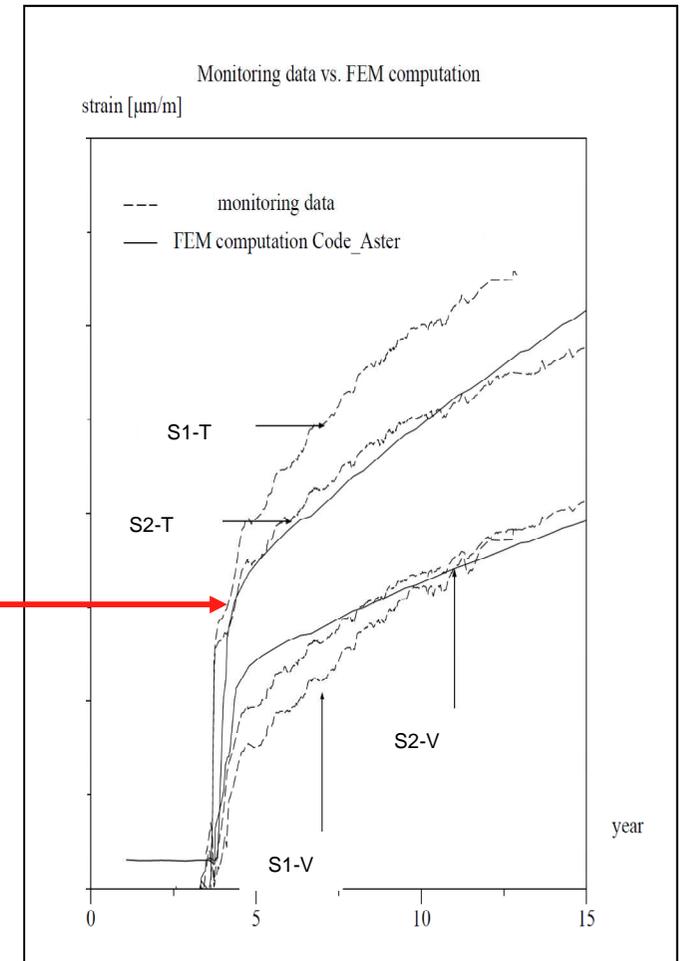
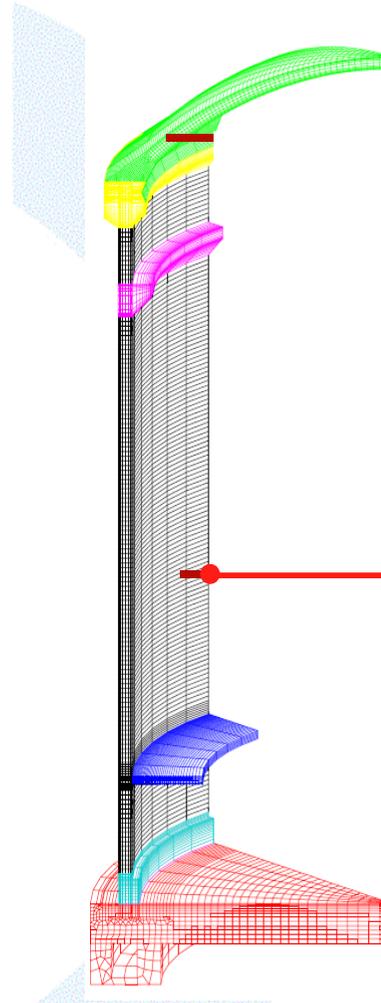
2 - Basic creep results at NPP level - Feedback

► Advantages

- Delayed strain decomposition
- Very high quality for 15 years
- OK for 3D prediction at mid-height

► Drawbacks

- Basic creep rate
 - Linear creep rate non-adapted
 - Logarithmic creep rate (Brooks, 2005)
- Limited spherical part
 - Ok but linked to deviatoric part
- Apparent Poisson ratio
 - Uncontrolled over time



Creep strain [Le Pape, 2005]

2 - Proposal of improvements for BETON_UMLV_FP: BETON_BURGER_FP

► Basic creep formulation (small strains)

- Phenomenological model based on works of [Sellier et al., 2009]

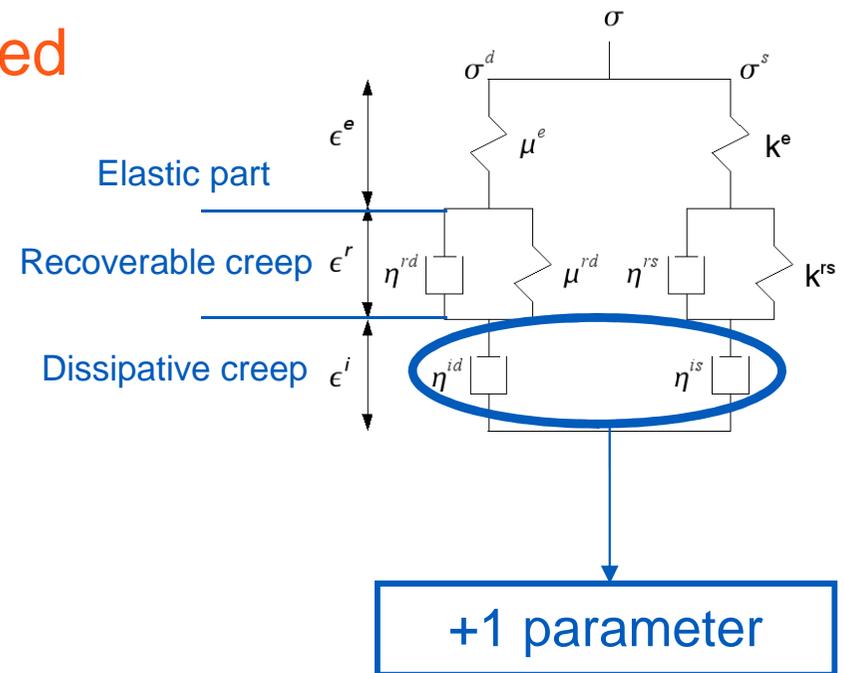
► Strain Decomposition in 2 parts **coupled**

► Spherical part

- Burger skeleton
- Recoverable part
- Dissipative part
- Unlimited strain
- 3 parameters

► Deviatoric part

- Burger skeleton
- Recoverable part
- Dissipative part
- Unlimited strain
- 3 parameters



► Proportional strain to relative humidity

$$\begin{cases} \eta^{id} = \eta_0^{id} C \\ \eta^{is} = \eta_0^{is} C \end{cases} \rightarrow C = \exp\left(\frac{\sqrt{\epsilon^i : \epsilon^i}}{\kappa}\right)$$

2 - Keypoints of proposal

▶ Homogeneity of rheological chains

- Apparent Poisson ratio control

$$\frac{\eta_0^{is}}{\eta_0^{id}} = \frac{\eta^{rs}}{\eta^{rd}} = \frac{k^{rs}}{\mu^{rd}} = \frac{k^e}{\mu^e} = \frac{2(1+\nu)}{3(1-2\nu)} = \beta$$

Few parameters for the model

▶ Burger model well adapted to

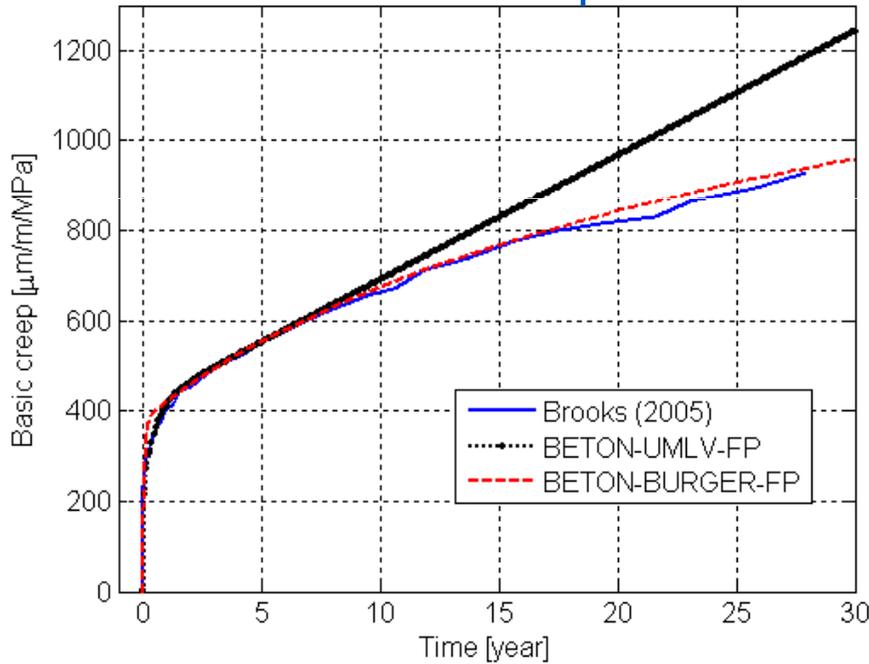
- Instantaneous behaviour – elastic body
- Short-term behaviour – Kelvin-Voigt stage – recoverable creep
- mid-term behaviour – nonlinear viscosity – dissipative creep

▶ Non-linear viscosity

- logarithmic evolution of basic creep rate
- **Link to dissipative creep**

2 - Predictions over 30 years (Brooks, 2005) uniaxial creep test

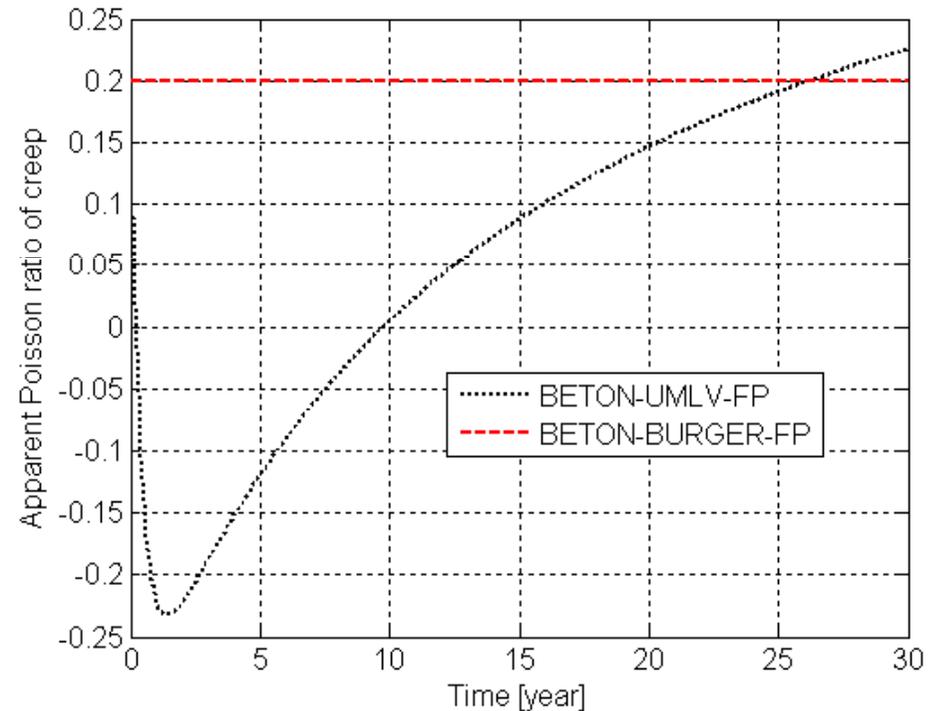
Basic creep



$$\tilde{k} = \frac{1}{3\varepsilon_v^{bc}} \quad \tilde{\mu} = \frac{1}{2\varepsilon_d^{bc}}$$

$$\tilde{\nu} = \frac{1}{2} \frac{3\tilde{k} - 2\tilde{\mu}}{3\tilde{k} + \tilde{\mu}}$$

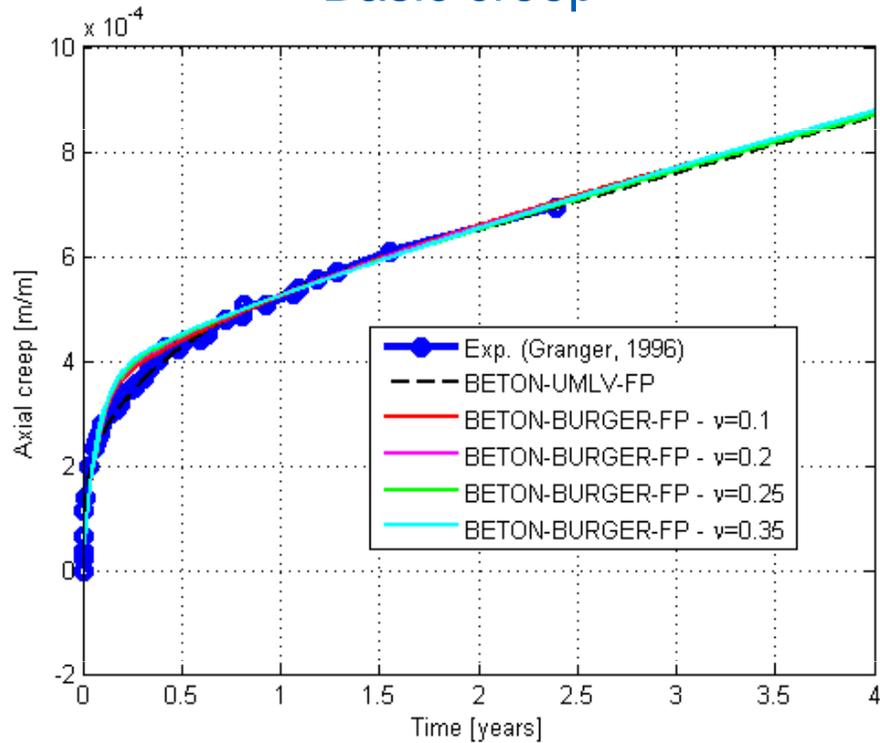
Apparent Poisson ratio evolution



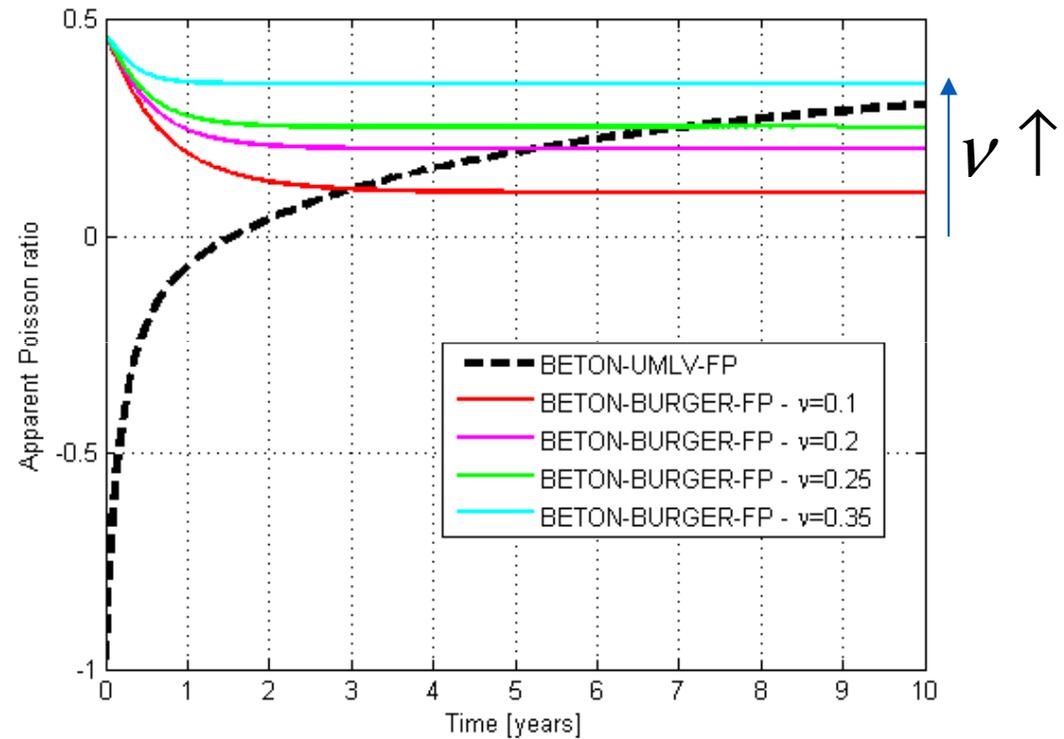
geosciences.mines-paristech.fr

2 - Fitting models on Granger results (PhD, 1996) uniaxial basic creep test

Basic creep



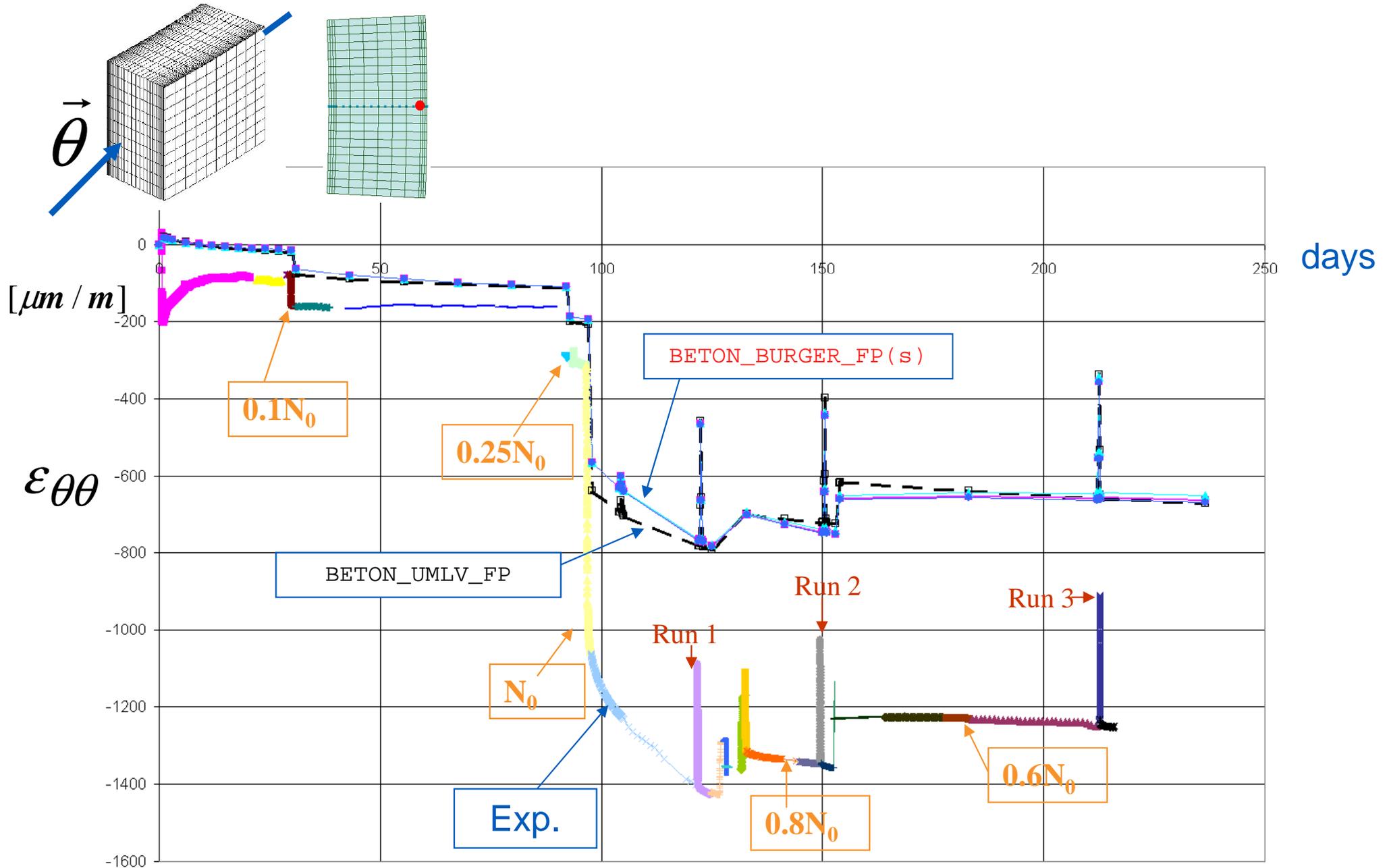
Apparent Poisson ratio evolution



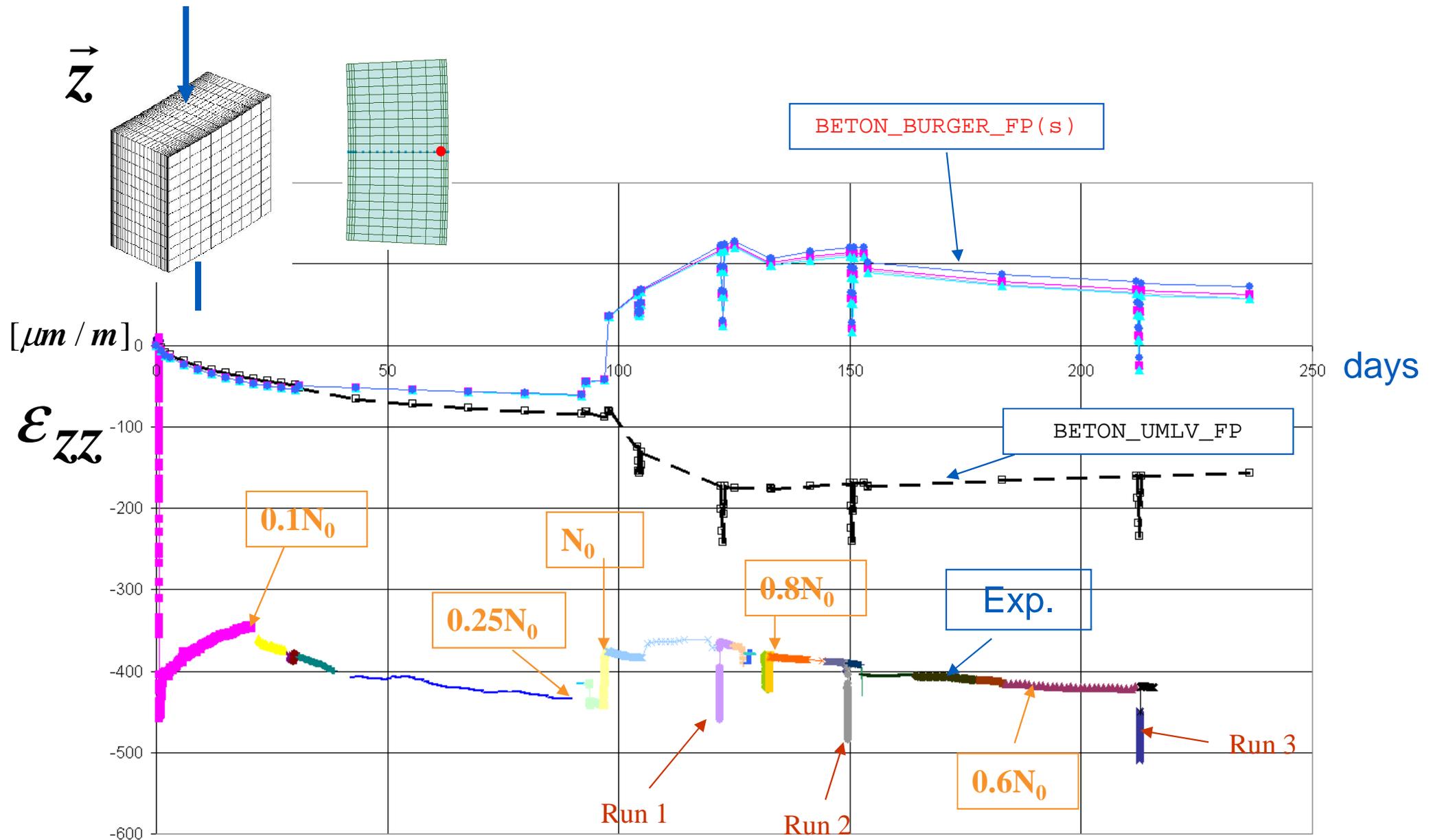
1 - Loading schedule

RUN	real age (years)	experimental age (days)	pressure (bar_{abs})	temp. (°C)	prestressing (%)
0	0	60	1.43	20	25%
1	0	90	5.30	20	100%
2	10	120	5.30	20	80%
3	35	150	5.30	20	60%

3 - PACE Results: Numerical versus experiment



3 - PACE Results: Numerical versus experiment



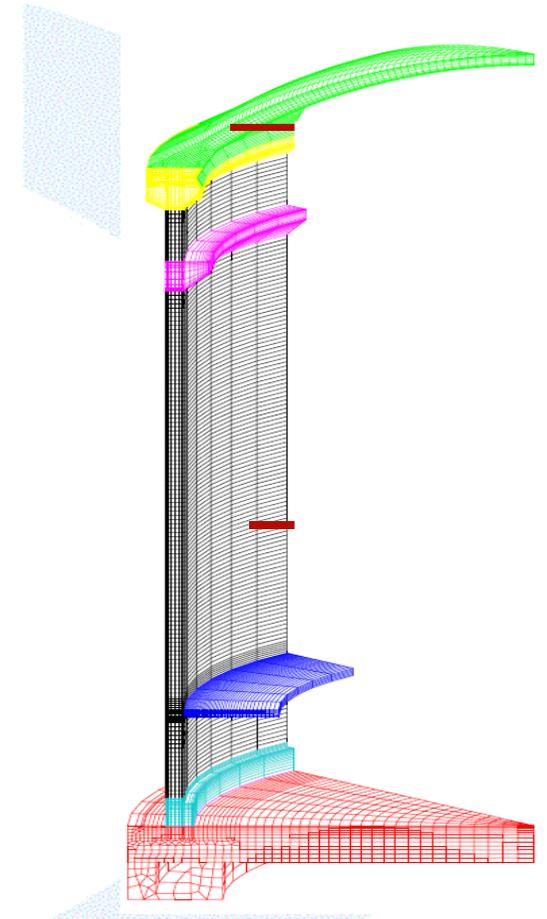
4 - Conclusion and future works

► Pace Simulations

- Good correlation between experimental and numerical evolution
 - Except for the 1st month (Temperature effect ?)
- Underestimate creep values for the pre-stress phase
- 3D effects
 - BETON_UMLV_FP
 - negative values for apparent Poisson ratio
 - Inverse evolution for “r” and “z” directions
 - BETON_BURGER_FP
 - positive values for the apparent Poisson ratio
 - Coherent evolution but creep rates too high

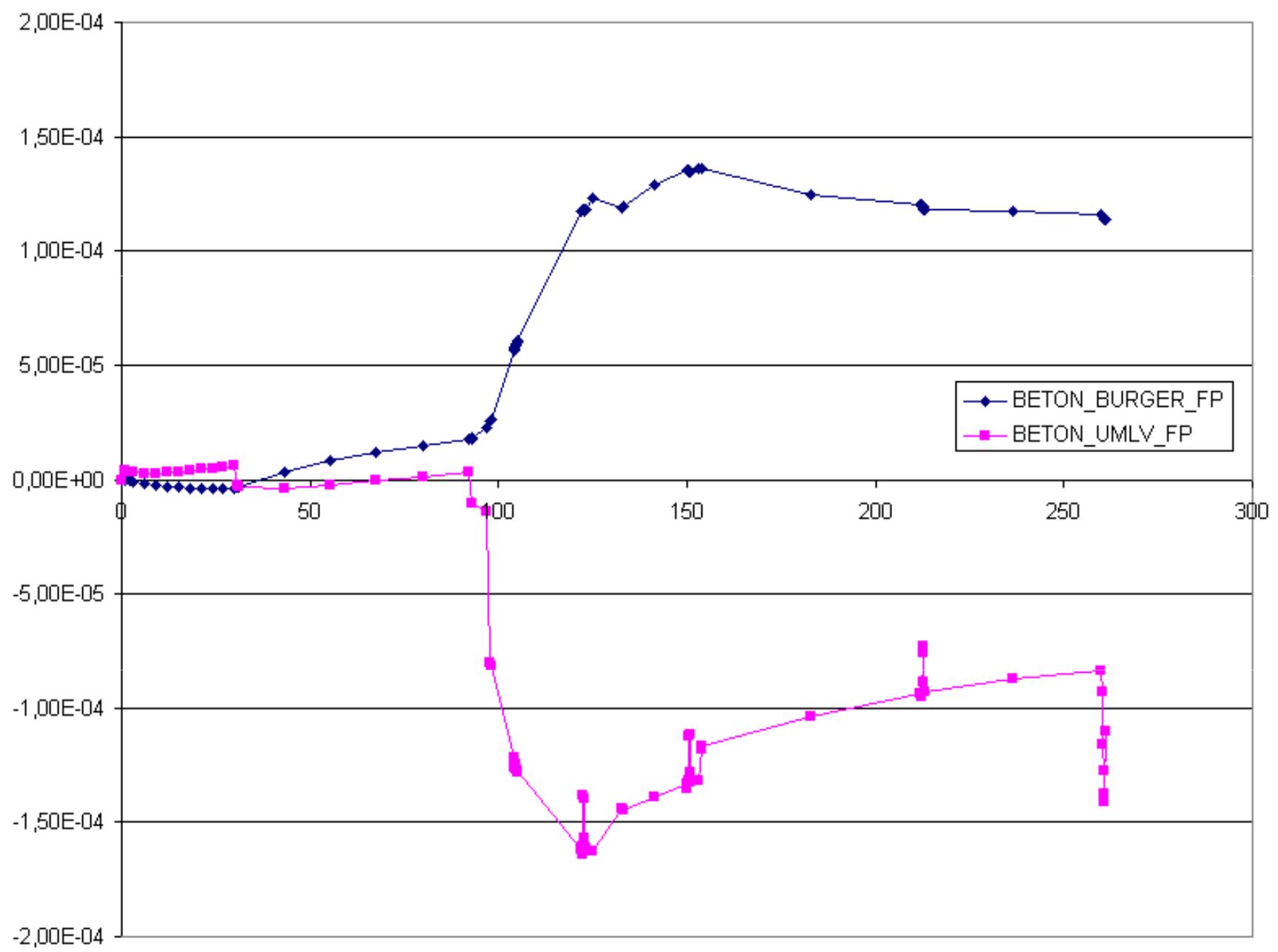
► Future works

- BETON_BURGER_FP
 - Hydration sensitivity of mechanical parameters
- Pace model
 - Improvement of the hydration and thermal simulations
- Other structures – models comparisons on long behavior terms
 - 3D 9° Sector of NPP
 - VERCORS mock-up (E.Galenne’s presentation)

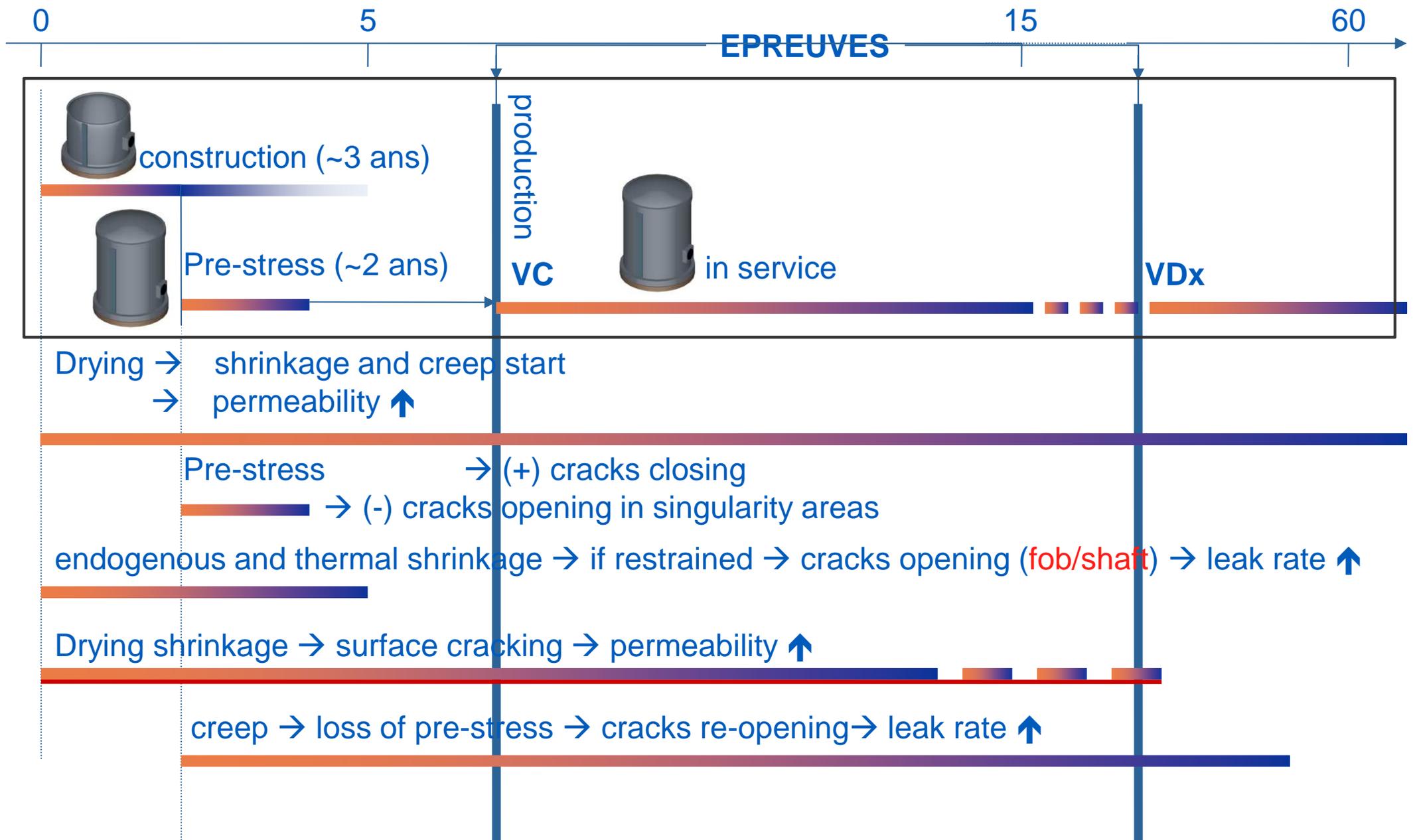


Thanks for your attention

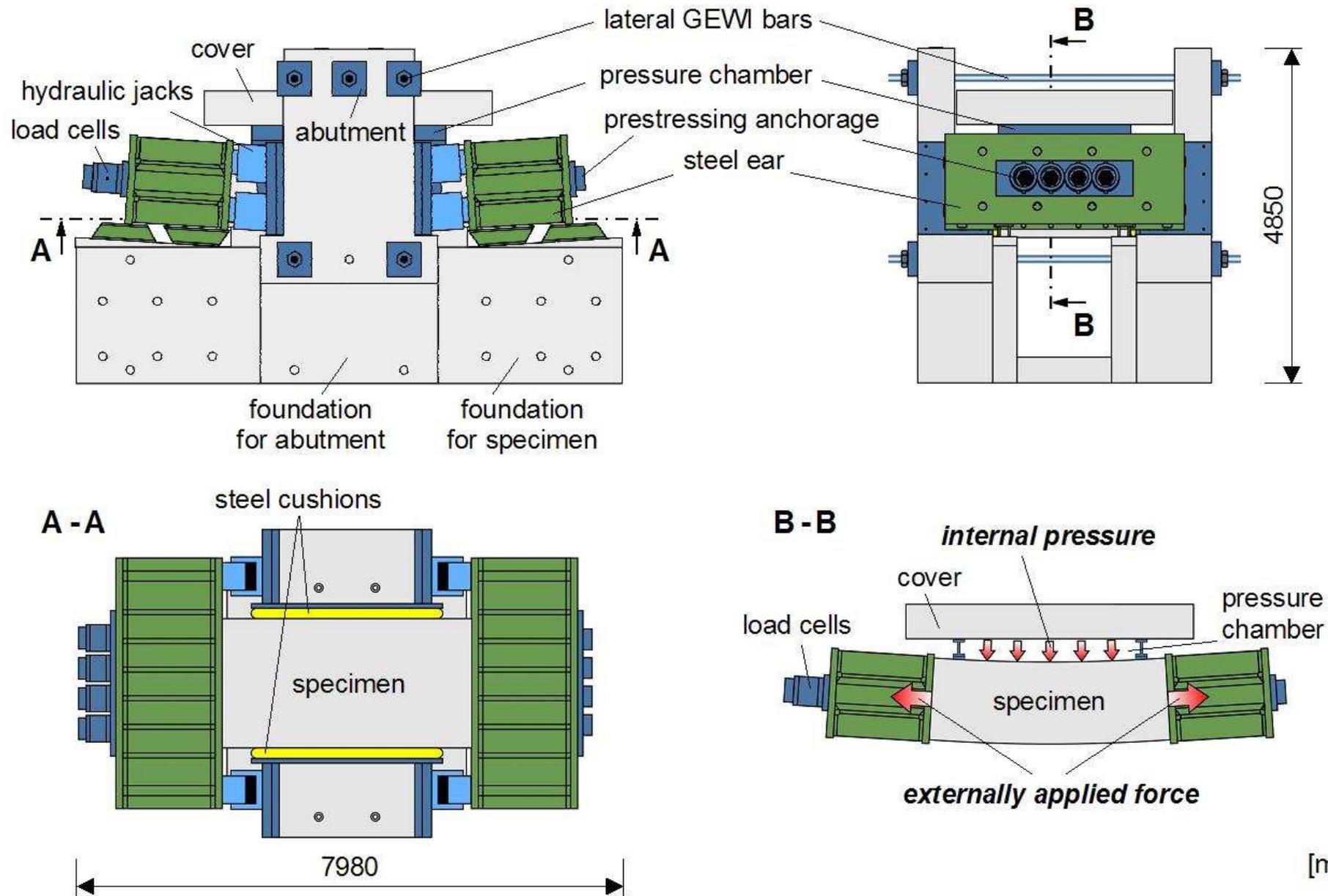
QUESTIONS ?



NPP containment - Ageing mechanisms



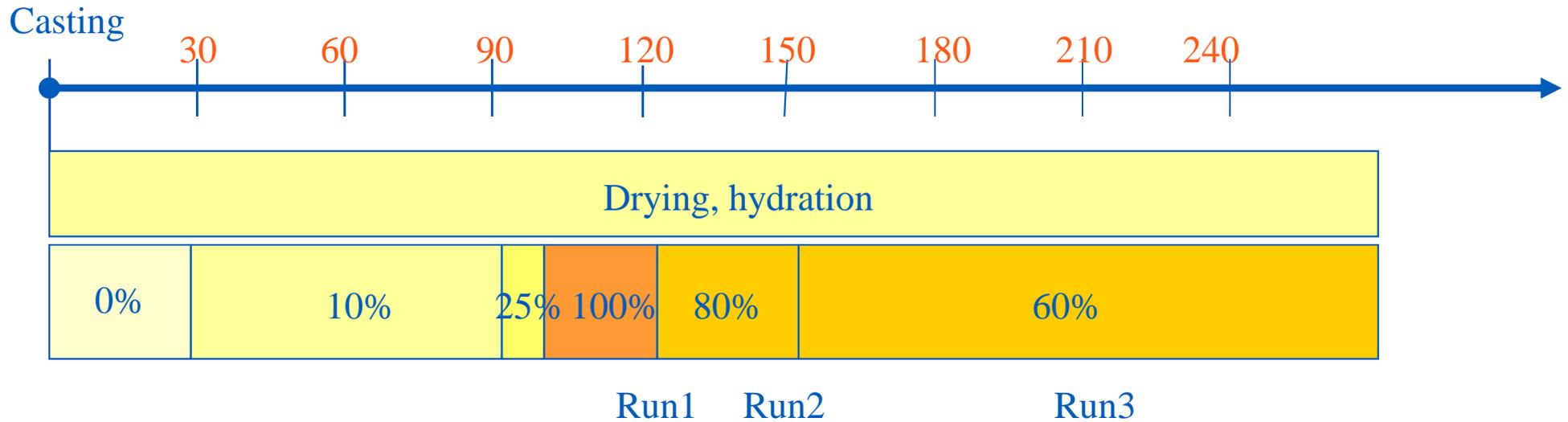
Mechanical setup



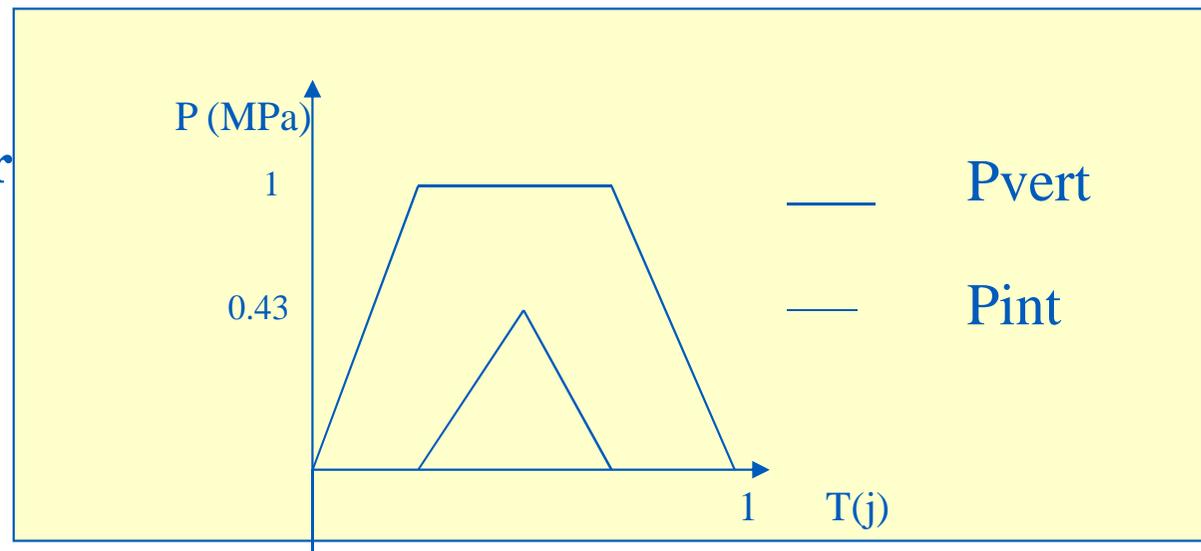
Test program

17/07/2007

14/03/2008



Pressure loads used for simulation



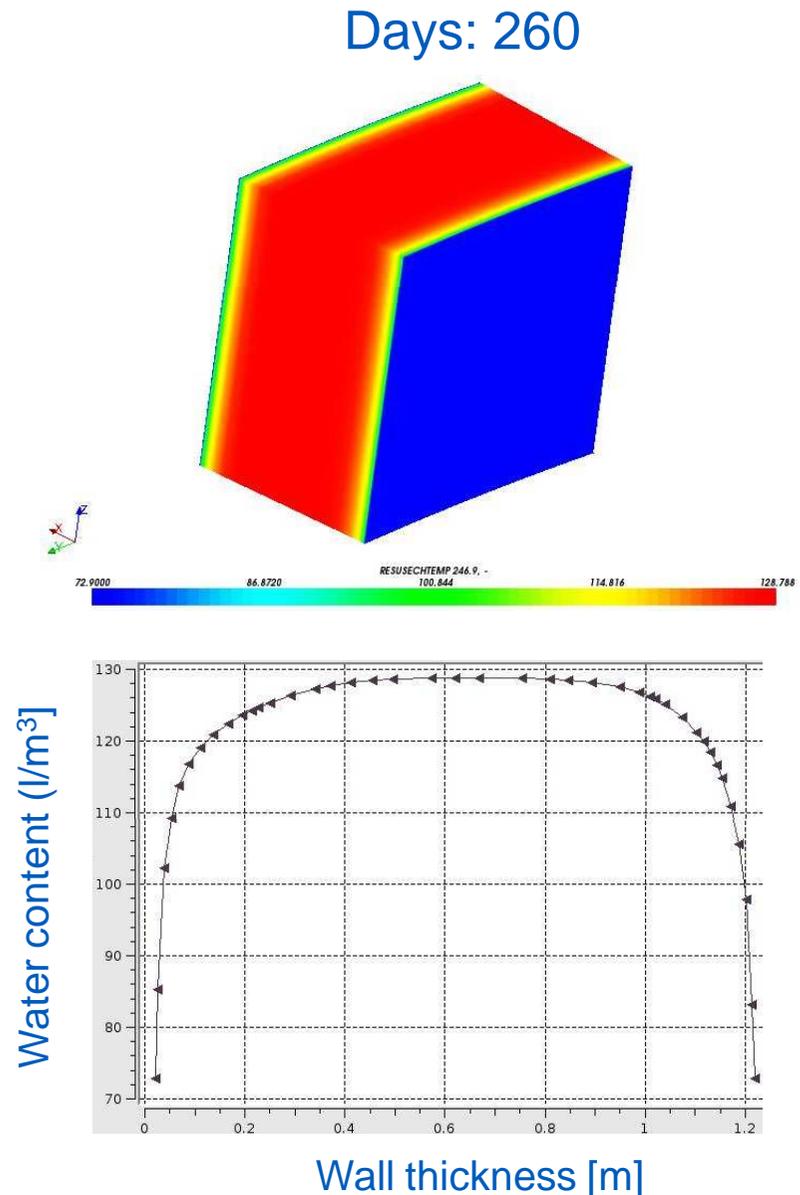
Drying calculation

Water content Variation between

- $C = 128.8 \text{ L/m}^3$ (in core)
- $C = 72.2 \text{ L/m}^3$ (surface)

Constant Temperature (23°C)

- No thermal dilation



Strain decomposition

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{bc} + \boldsymbol{\varepsilon}^{dc} + \boldsymbol{\varepsilon}^{as} + \boldsymbol{\varepsilon}^{ds}$$

► Elasticity :

$$\varepsilon_{ij}^e = \frac{1}{E} \left[(1 + \nu) \sigma_{ij} - \nu \delta_{ij} \sigma_{kk} \right]$$

► Basic creep : BETON_UMLV_FP or BETON_BURGER_FP

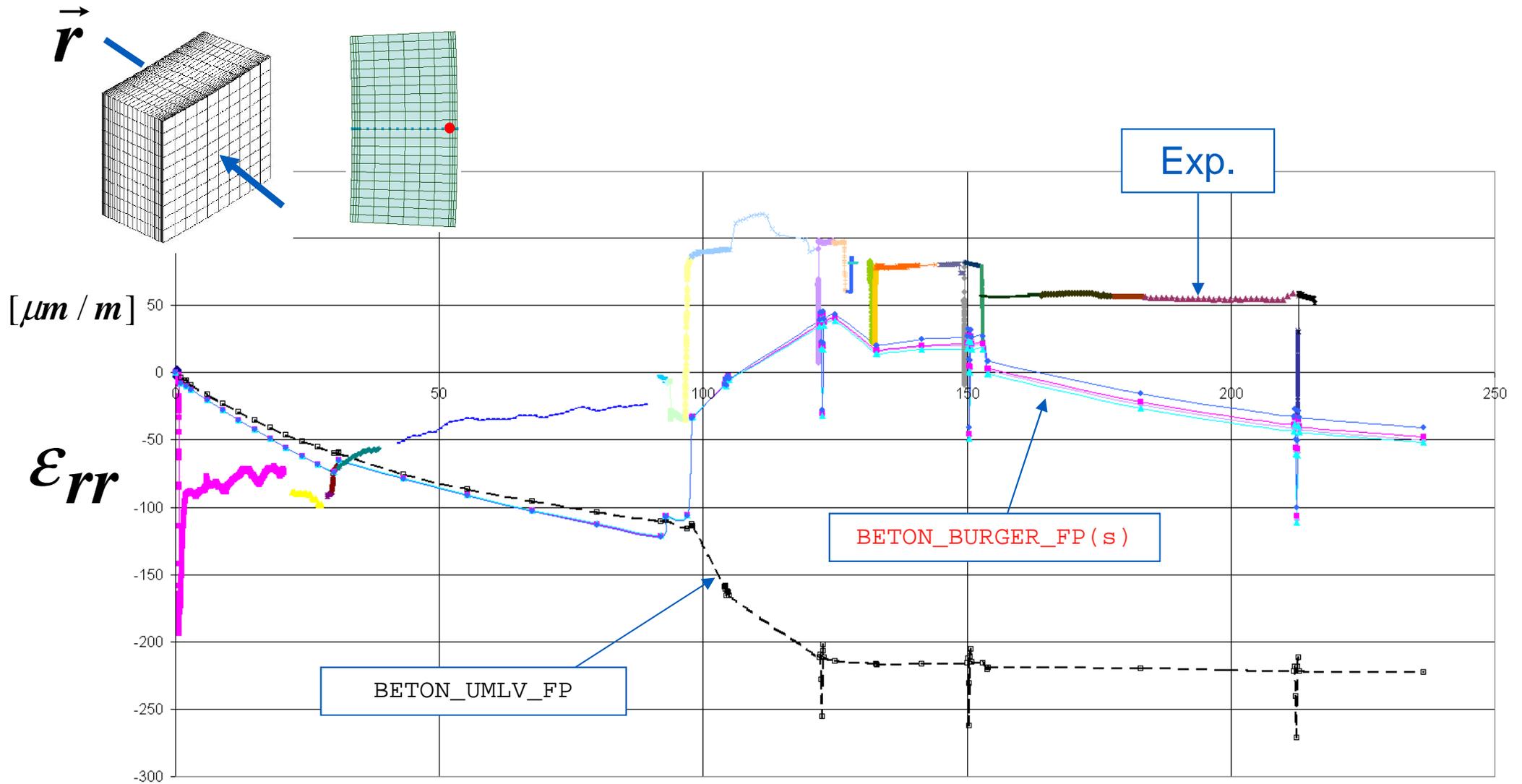
Water concentration [l/m ³]	0	51.5	57.5	69.1	105.7
Moisture h (%)	0	22.5	27	39	100

► Autogenous shrinkage : [Granger, 1996] $\dot{\varepsilon}^{as} = -B_ENDOGE \times \dot{\xi}$

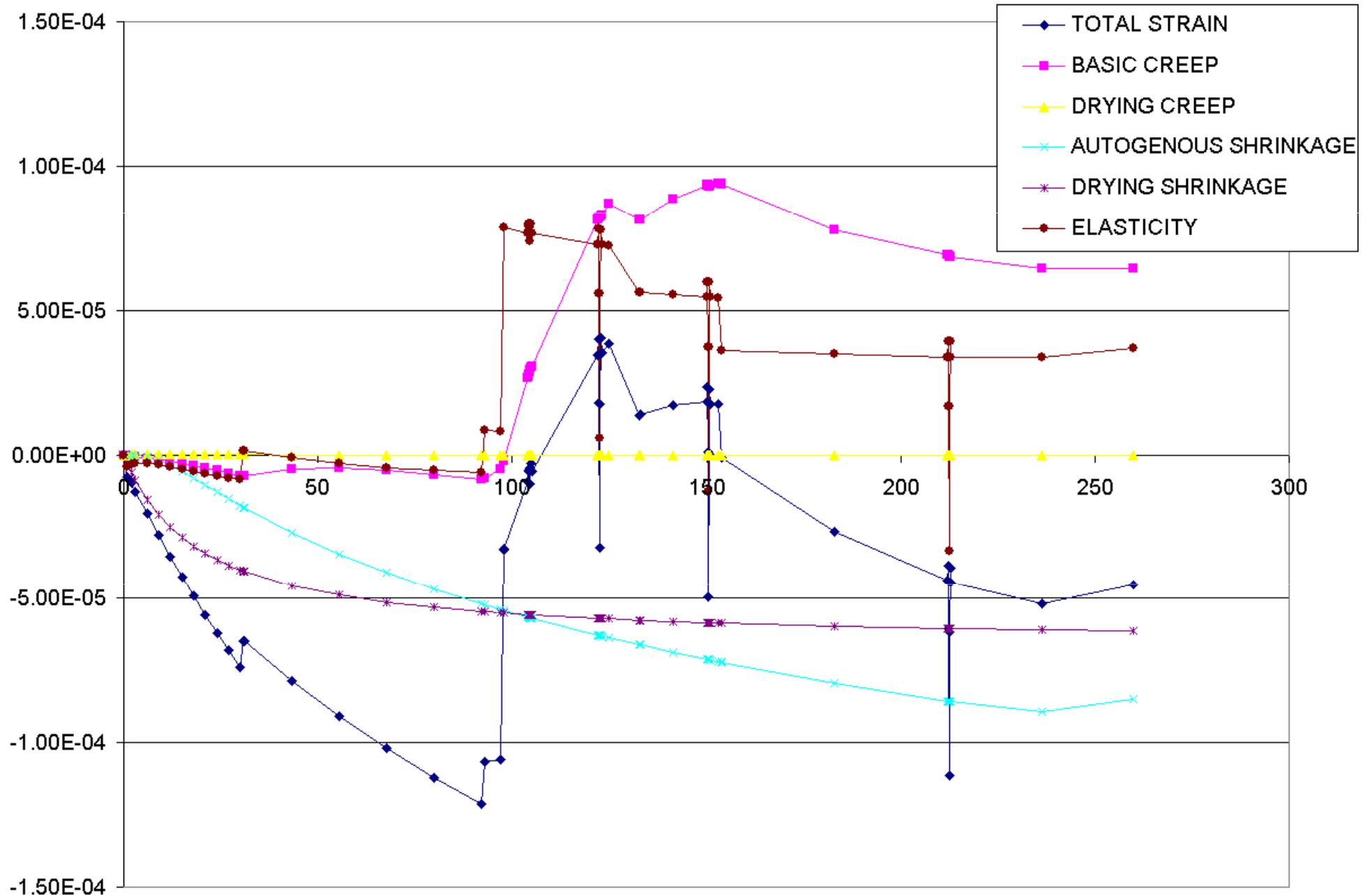
► Drying shrinkage : [Torrenti et al., 1997] $\dot{\varepsilon}^{ds} = -K_DESSIC \times \dot{C}$

► Drying creep: [Bazant and Xi, 1994] $\dot{\varepsilon}^{dc} = \frac{1}{\eta^{dc}} |\dot{h}| \sigma$

3 - PACE Results: Numerical versus experiment



PACE: Ageing mechanisms contribution



Radial basic creep

