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STUDY OF THE CONTAINMENT HISTORY OF THE VERCORS MOCK-UP AND PREDICTION OF THE LEAKAGE RATE UNDER PRESSURIZATION TESTS

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Abstract: As part of EDF's study program for the safety and life extension of its Nuclear Power Plants fleet, an experimental mock-up of a reactor containment building at 1/3 scale has been built at "EDF Lab Les Renardières". The construction has been completed at the end of 2015. Because of the scaling effects, the drying effects on the mock-up are about 9 times faster than in a full scale containment vessel. The mock up's behaviour is monitored from the beginning of the construction: since the concrete pouring and for the duration of the research program, extensive data are collected.

EDF proposes three successive benchmarks to challenge the international research community. Each benchmark deals with updated experimental measures. This paper focuses on themes 2 and 3 of the second benchmark (EDF, 2018): mechanical behaviour and air leakage.

The behaviour of the containment building is modelled throughout its concreting followed by the prestressing cables tensioning and the 5 pressurization tests (PreOp, VC1, VD1, VD1bis and VD2). Some notable improvements are taken into account compared to previous works by M. Mozayan-Kharazi [1] and Thénint et al. [2]:

- drying shrinkage, basic creep and drying creep are modelled by sate of the art numerical models, following results of Benboudjema [6];

- concrete cracking is modelled in the constitutive law: cracks open and close;

- cracks can be introduced in the initial state, to deal with cracks observed in situ and not reproduced in our numerical simulations (no early age behaviour);

- leakage rate is now deduced from an orthotropic non-linear gas flow, computed from all the information given by the non-linear constitutive law, including crack opening width.

These improvements have been integrated, checked and validated in our in-house version of Code_Aster® and give very promising results. After updating the material parameters based on tests on specimens, the global model leads to an accurate prediction of the mechanical state. More, leakage rate is in very good agreement with the available at that time experimental measures. Finally, ad hoc post-processing gives insightful information on the local and global behaviour of the mock-up, leading to a better understanding of the involved physical phenomena and their interactions.

1 INTRODUCTION

Our experience of the leakage tightness behaviour of pressure containment vessels without steel liner is that prediction of its future capacity to withstand an internal pressure event requires a certain level of knowledge of its construction and aging process. Considering the complexity of the construction and the numerous physical phenomena involved in the early age of concrete casting and its evolution over several decades of operation with periodic tests, the numerical modelling shall be based on simplifications, assumptions and calibrations.

As part of EDF's study program for the safety and life extension of its fleet of Nuclear Power Plants, an experimental mock-up of a reactor containment building at 1/3 scale has been built at "EDF Lab Les Renardières". The construction was completed at the end of 2015. Because of the scaling effects, the drying effects on the mock-up are about 9 times faster than in a full scale containment vessel. The mock up's behaviour has been monitored from the beginning of its construction. More than 700 captors and 2 km of optical fibre cables have been positioned in the concrete, both on the steel reinforcement and prestressing cables. Since the concrete pouring and for the duration of the research program extensive data has been collected.

Hundreds of samples have been prepared and tested in order to determine their material behaviours and parameters, and especially: hydration, elastic properties, drying, creep (basic and drying) and permeability. The experimental campaign consists of a daily measurement of the whole sensors and in a periodic air pressure test of the mock-up every year. During this test, the containment is pressurized at 5,2 bar absolute.

This paper presents the approach developed at NECS to study the VeRCoRS mock-up for themes 2 (containment history) and 3 (leakage prediction) of the VeRCoRS 2018 benchmark. Some notable improvements in the methodology have been implemented compared to previous works ([1], [2] and [3]).The behaviour of the containment building is modelled from its concreting followed by the prestressing cables tensioning and the 5 pressurization tests (PreOp, VC1, VD1, VD1bis and VD2). All numerical analyses are carried out with an in-house version of Code_Aster software edited by EDF [4].

2 METHODOLOGY OF THE LEAKAGE PREDICTION

Leakage rate prediction is made by solving five chained problems: thermal state, hydric state, mechanical state, crack state and hydraulic state. An effort has been made to model each phenomenon with state of the art models; some notable improvements are taken into account compared to previous works ([1], [2] and [3]):

- drying shrinkage is proportional to the relative humidity and not to the water saturation,
- creep model is inspired by Burger Ageing behaviour, as described in (EDF [5] and Benboudjema [6]): temperature, water saturation and age of the concrete modify creep rate,
- concrete cracking is modelled with the mechanical constitutive law (and no longer computed a posteriori from linear elastic computations): cracks open and close following the pressure conditions, creep and prestressing losses, damaged concrete leads to force redistribution, constitutive law is orthotropic,
- some cracks can be introduced in the initial state, to deal with cracks observed in situ and not reproduced in our numerical simulations (no early age behaviour),
- leakage rate is now deduced from an orthotropic gas flow, computed from all the information given by the non-linear constitutive law.

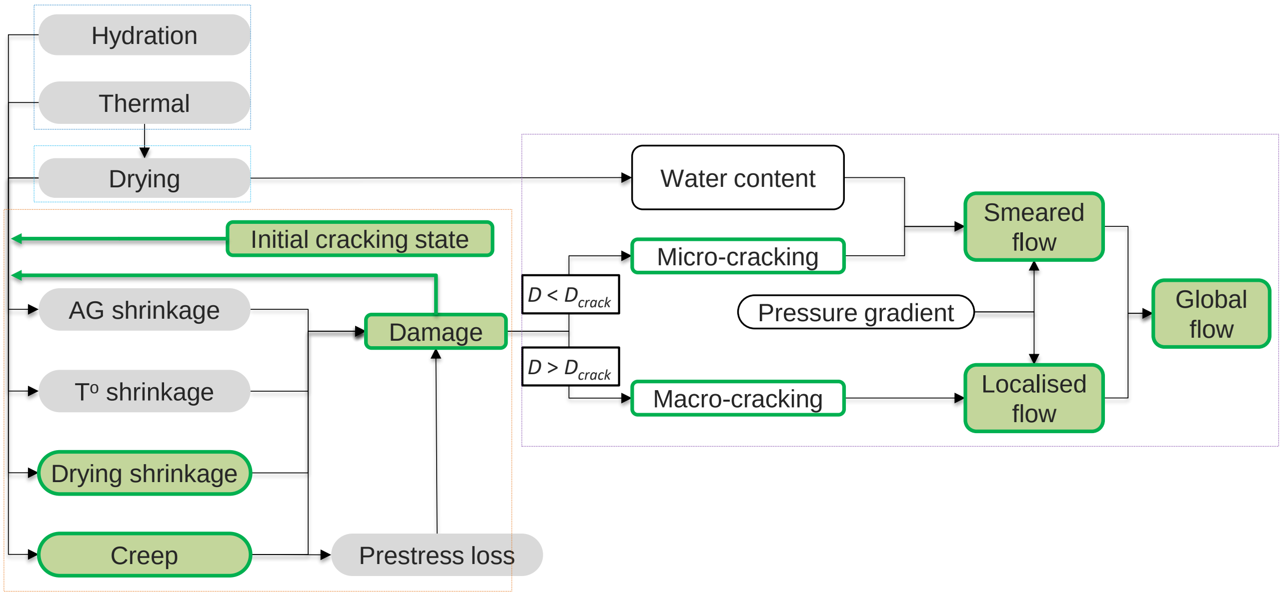

Figure 1: Steps of leakage rate prediction (green steps have been improved)

In detail, the methodology is based on a decomposition of the total strain of the concrete following:

$$\begin{cases} \varepsilon = \varepsilon^{el} + \varepsilon^{te} + \varepsilon^{ds} + \varepsilon^{bc} + \varepsilon^{dc} + \varepsilon^{cra} + \varepsilon^{cmp} \\ \sigma = \mathrm{E} : \varepsilon^{el} \end{cases}$$

where ε is the total strain, ε^{el} the elastic strain, σ the stress and E the tensor of elasticity; ε^{te} and ε^{ds} are the thermal expansion and drying shrinkage strains; ε^{bc} and ε^{dc} are the basic creep and the drying creep strains; ε^{cra} and ε^{cmp} are the strains related to concrete cracking in tension and concrete damage in compression.

The drying shrinkage strain is computed with the following isotropic relation: $\dot{\varepsilon}^{ds} = k_{ds}\dot{h}$ where h is the relative humidity, computed from the water concentration C with the desorption curve.

The basic creep strain ε^{bc}, separated in reversible $\varepsilon^{bc,r}$ and irreversible $\varepsilon^{bc,i}$ components, is deduced from the stress σ and the water concentration C following:

$$\begin{cases} k_r \boldsymbol{\varepsilon}^{\mathbf{bc,r}} + \eta_r \dot{\boldsymbol{\varepsilon}}^{\mathbf{bc,r}} = \dfrac{C}{C_0}\left(\dfrac{1+\nu^c}{1-2\nu^c}\sigma_H \mathbf{Id} + \boldsymbol{\sigma}_{\mathbf{H}}\right) \\ \zeta(t)\eta_i \dot{\boldsymbol{\varepsilon}}^{\mathbf{bc},i} = \dfrac{C}{C_0}\left(\dfrac{1+\nu^c}{1-2\nu^c}\sigma_H \mathbf{Id} + \boldsymbol{\sigma}_{\mathbf{H}}\right) \end{cases}$$

where the stress is decomposed in hydrostatic and deviatoric components $\sigma_H \mathbf{Id}$ and $\boldsymbol{\sigma}_{\mathbf{H}}$. The function $\zeta(t)$ introduces the effect of concrete age on basic creep; stiffness and viscosity coefficients depend on temperature via an Arrhenius activation term.

The nonlinear constitutive law (see illustrations in Figure 2) is based on a rotating-crack type damaging model in traction, with a negative linear strain hardening, and irreversible strains in compression ruled by a Drucker-Prager criteria on stress and a strain hardening.

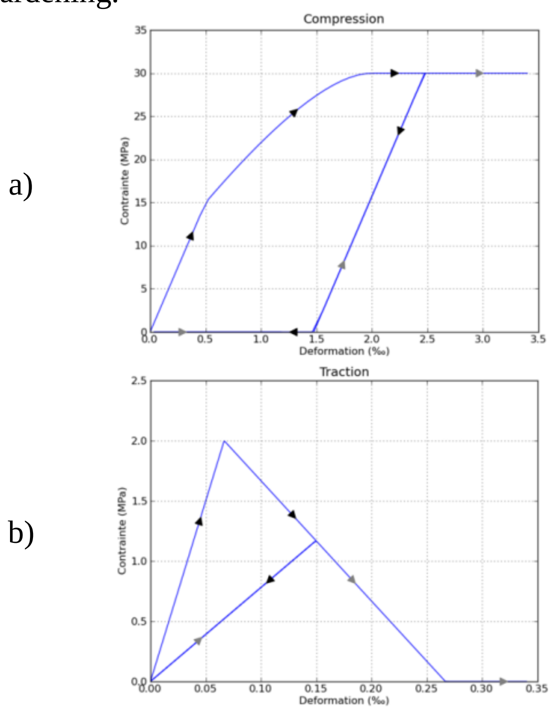

Figure 2: Concrete's behaviour in simple compression (a) and in simple traction (b)

The principles of the leakage prediction are similar to those described in (Mozayan [1]) but extended to an orthotropic implementation. Each crack contributes to the gas flow in the two directions of its plane; the contribution of sound or damaged concrete and cracks to the gas flow are added in an equivalent conductivity term. Hence, there is no more hypothesis of a global mean behaviour in a fixed flow direction for each element but every integration points contributes to the gas flow in directions depending on the instantaneous crack directions. This new implementation uses all the local information given by the concrete constitutive law.

4 FE MODEL

The hydro-thermal model is calculated based on linear volume elements with a mass lumped model. This model allows us to calculate the temperature, the hydration and the water saturation. The hydration is taken into consideration only by the heat provided. Indeed, the mechanical properties are independent of this magnitude because the concrete is supposed to be perfectly hydrated when it is demolded.

The mechanical model is calculated with a representation of concrete, concrete linear volume elements. For the purposes of this study, the mesh is discretized with a variable size element in the thickness of the cylindrical wall. The mechanical model depends on the temperature and drying fields via thermal expansion and long-term strains (shrinkage, creep). Creep and cracking are taken into account.

The prestressing tendons are composed of class 1860 MPa strands. Each tendon was tensioned at 1488 MPa at active extremities before anchorage slip, as in full scale structures. They are modelled as truss elements and are perfectly bounded with the surrounding concrete.

Reinforcement is introduced in the numerical model by unidirectional shell elements, perfectly bounded with the surrounding concrete.

The concrete parameters are supposed to be homogeneous in all the structure and equal to the mean property of all lifts following properties given by EDF.

11 initial through cracks are introduced in the model: internal variables of the constitutive law are initialized to represent cracks with a crack opening of 0.1 mm. These cracks are vertical and localized in the gusset, following data given by EDF.

The retained boundary conditions for the thermal and hydric states are deduced from data given by EDF: mean values over one month are used in the numeric model. Thermal state is driven by inner and outer air temperature and exchange coefficients. Hydric state is driven by imposed relative humidity. On the following figures, inner skin of the containment correspond to red curve and outer skin to blue curve; pressure tests are denoted by dashed black vertical lines, for information. Once atmosphere regulation is stabilized, inner air is at 35°C and 30% RH, outer air at 20°C and 55% Rh.

The inner pressure loading for the pressure tests is as follows: increase from 0 to 4.2 bar (relative pressure) in 21 h, with an intermediate plateau, 12 h plateau at 4.2 bar, decrease to 0 in 16 h. The duration of this cycle is 45 h.

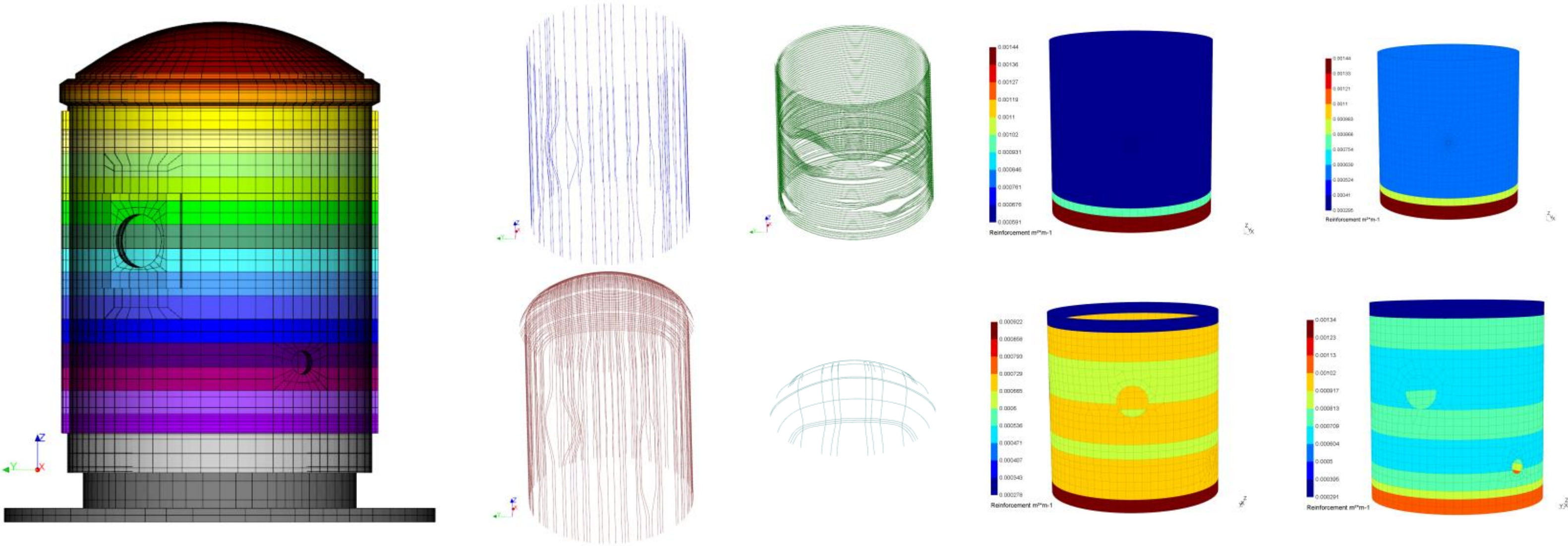

Figure 3: Views of the numerical model: concrete, prestressing cables and reinforcements

a)

b)

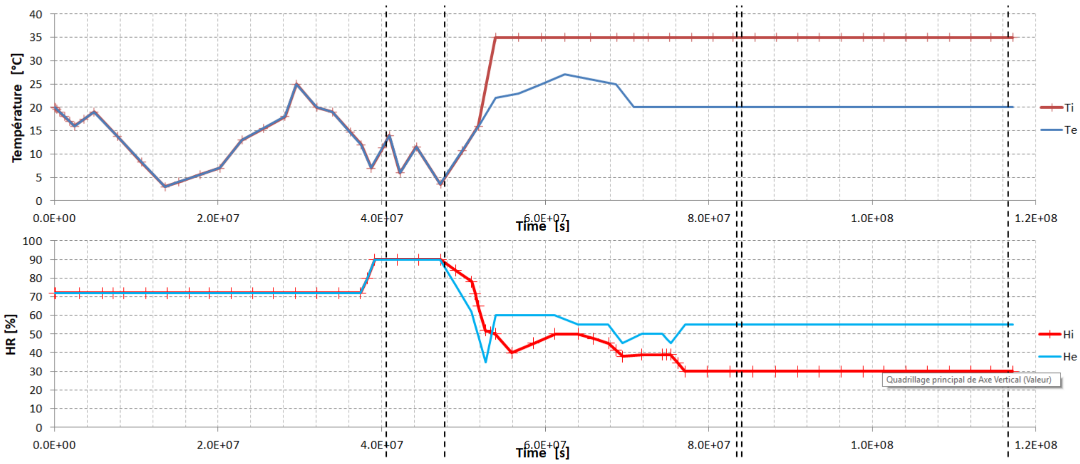

Figure 4: Air temperature (a) and relative humidity (b). Inner skin is plotted in red and outer in blue.

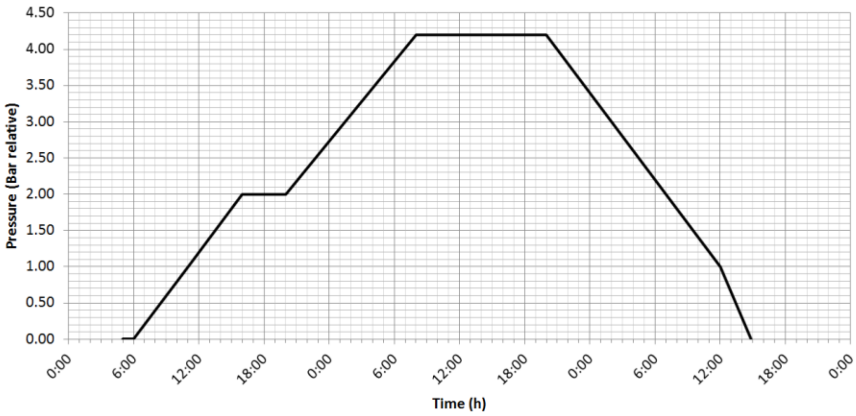

Figure 5: Relative pressure during pressure tests

5 UPDATING OF THE PARAMETERS

Material properties are updated following experimental results on concrete specimens given by EDF (5478-F1, 5478-F3, 5478-F4 and 5478-F7). The implemented models (water loss, drying shrinkage, creep, drying creep), with updated parameters, lead to numerical results in very good agreement with experimental measures (Figure 6). Long term behaviour of concrete is thus simulated with a very satisfactory precision.

a)

b)

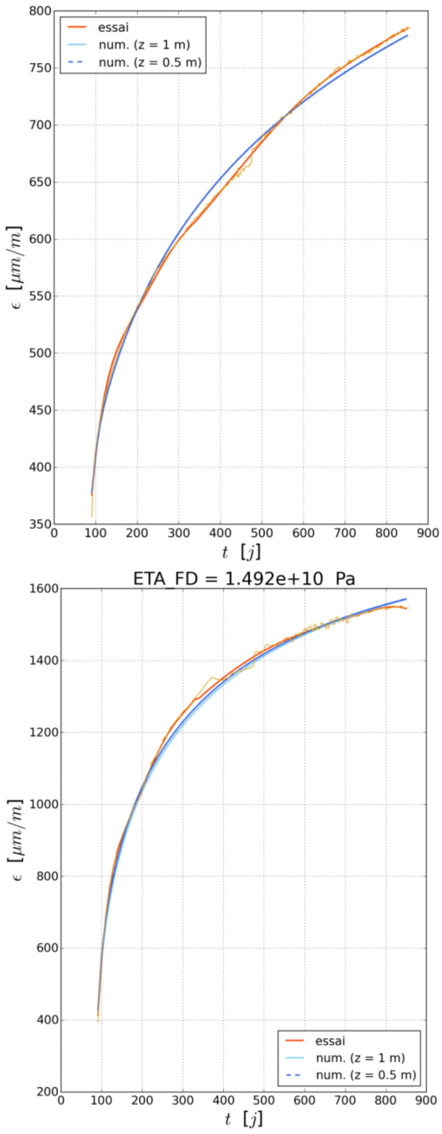

Figure 6: Comparison of experimental (orange) and numerical (blue) results
a) creep strain, b) total creep strain

6 NUMERICAL RESULTS

The first quantities computed are temperature and water concentration (Figure 7 and 8). As long as the external shell is open, there is no variation of these quantities in the thickness of the inner wall, the retained hypothesis for water concentration implying no activation of the drying process. After 400 days, water concentration imposed on the inner and outer skins of the containment wall leads to water saturation of the wall. After 620 days, atmosphere control is activated: temperature and water saturation are imposed at constant values on inner and outer skins, which leads to spatial gradients. Temperature water concentration evolutions have different characteristic speeds: the temperature was constant since 800 days whereas the drying process is not finished after 1 400 days (the water concentration has not reached a stationary state).

Mechanical state is then computed, using temperature and water concentration results. Creep is activated as soon as prestressing is applied to the model, which leads to a smaller global stiffness of the mock-up as time goes by (see Figure 9). The magnitude of the displacement is coherent with previous analyses (NECS [3], for example). It is important to remark that concrete cracking is taken into account in this computation but that it does not seem to modify the global behaviour of the containment.

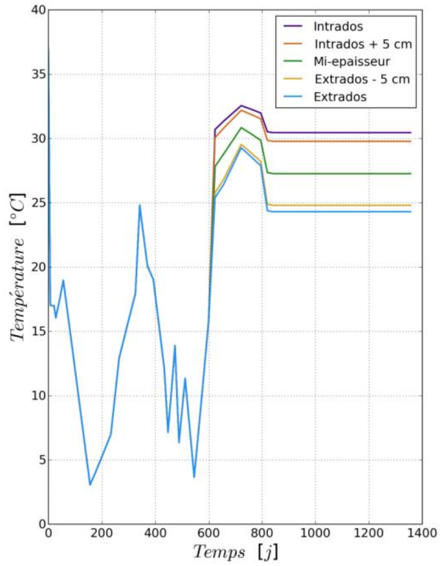

Figure 7: Time history of temperature for different points in the thickness of the cylindrical wall

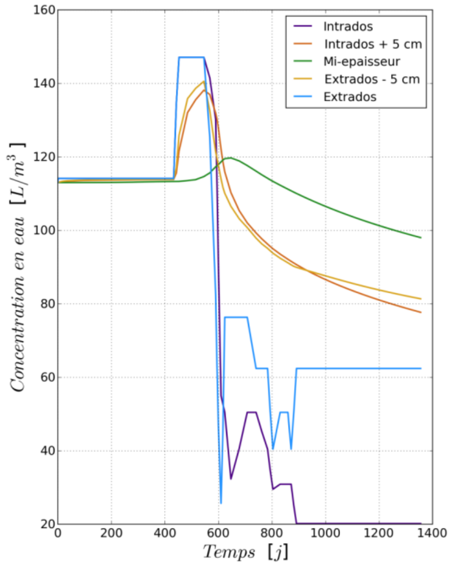

Figure 8: Time history water concentration for different points in the thickness of the cylindrical wall

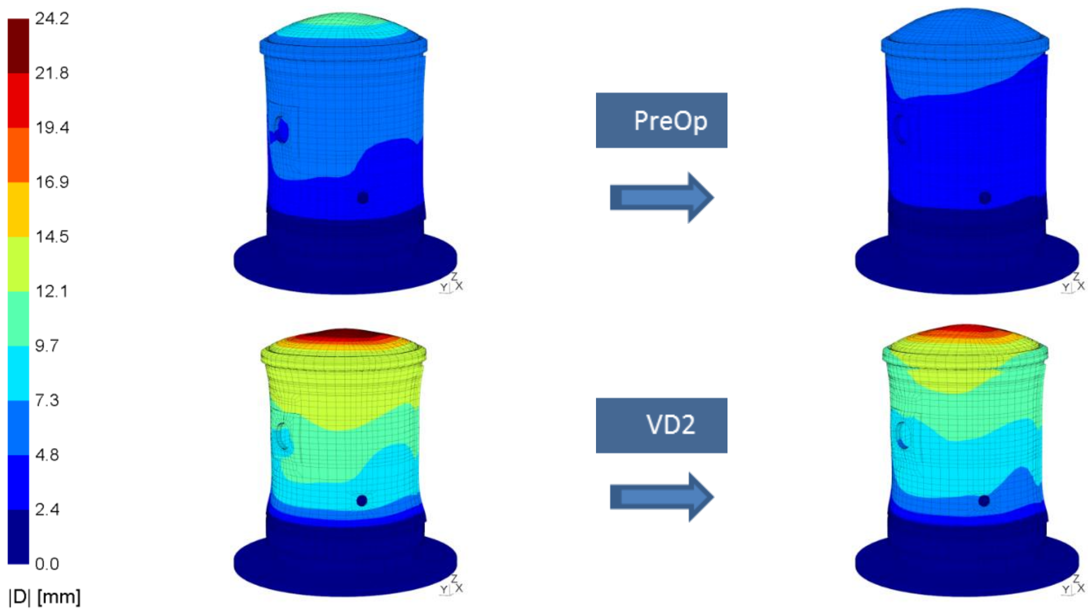

Figure 9: Time history water concentration for different points in the thickness of the cylindrical

VeRCoRs mock-up experimental strains have been given by EDF. Comparison of these measures with numerical results has been done on all the available points (see example in Figure 10). We can draw the following conclusions: global behaviour is similar between experimental mock-up and numerical model but spatial discrepancy is observed between numerical strain at exact sensor location and among surrounding points. This discrepancy is under investigation (mesh element size effect? proximity to a cable element?). On Figure 10, measure of the temperature at the location of the sensor is also shown (thin red curve). The comparison of total strain and temperature explains the decrease in total strain after 600 days: creep strain is cancelled by thermal expansion.

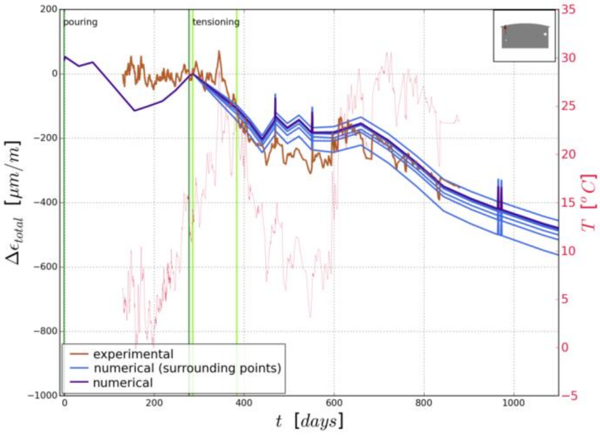

Figure 10: Comparison of experimental (brown) and numerical (blue) total strains for one sensor

The cracking state obtained from the mechanical resolution (crack width, open/closed state) is post-processed to build a nonlinear orthotropic hydraulic model: pressure and gas flow are then computed. Total flow is shown in the following Figure for inner and outer skin during PreOp and VD2. Maximal flow is respectively 1.9 Nm3/h and 12.7 Nm3/h. The kinetics and localisation of air flow give precious information. In VD2, contrary to PreOp, inner flow is equal to outer flow which is a consequence of crack opening (gas kinetics is instantaneous through cracks, not through sound or micro-damaged concrete). Moreover, the proportion of gas flow through the gusset is more important during VD2: open cracks seem to be localised in the gusset.

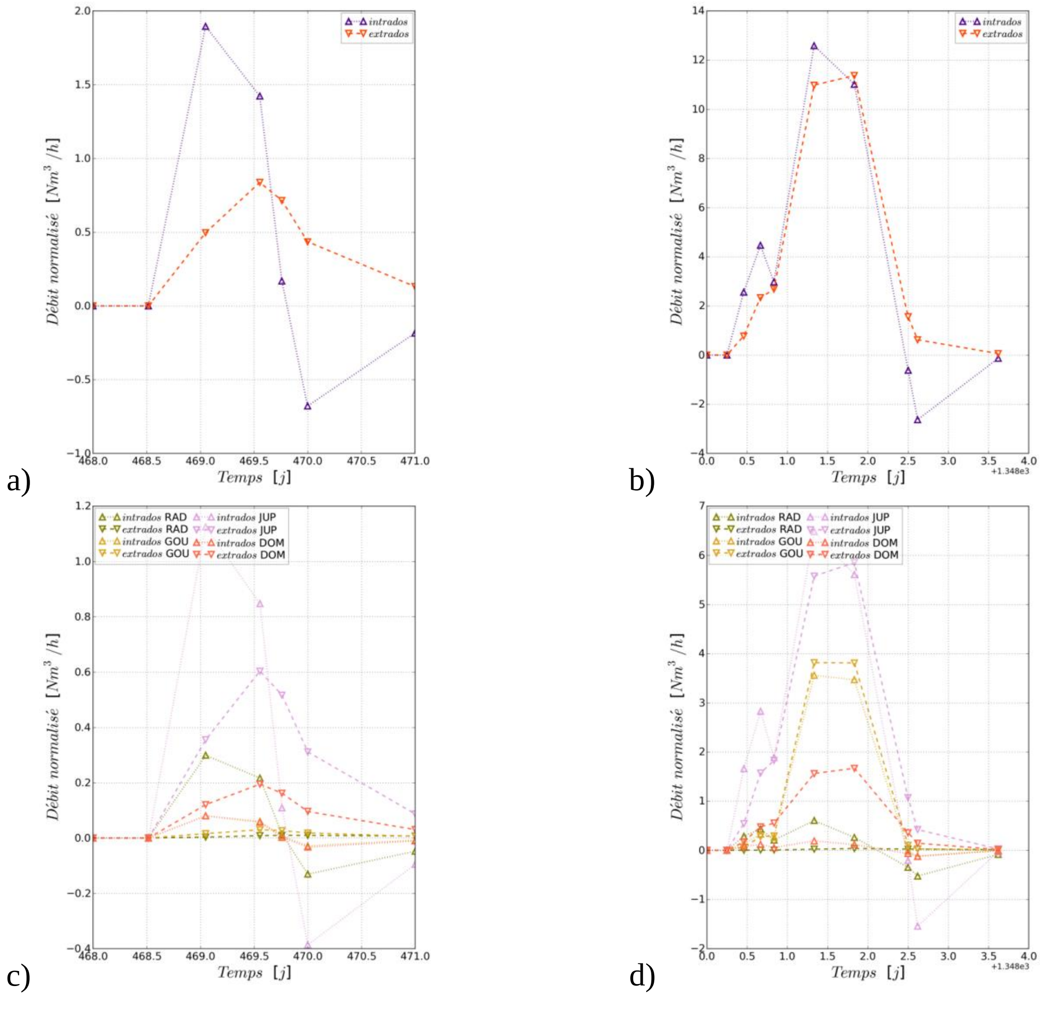

Figure 11: Leakage rate during PreOp (a and c) and during VD2 (b and d)
Comparison of total flow (a and b)
Contribution of raft (RAD), gusset (GOU), wall (JUP) and dome (DOME) (c and d)

Local quantities of interest give additional information. Gas flow is shown in Figure 12 for VD2 and presents some very localised maximums: the elements of the gusset where an initial crack has been introduced. If we look at the cracking state (blue: sound concrete, red: closed crack, green: open crack), we can identify through-wall cracks at the junction between raft and gusset (open crack from inner to outer skin).

Figure 12: Gaz flow (left) and cracking state (right) during VD2

8 CONCLUSIONS AND FUTURE OUTLOOK

The implementation and updating of state of the art models in the five chained computations give very satisfactory results in the prediction of leakage rate. Global flow is in agreement with VeRCoRs measures. Adequate post-processing gives meaningful information to better understand mechanical state and its consequence on gas flow. Initial crack state is identified as a key parameter. Correlation between measures and numerical results (strains) is to be improved and better understood.

This work is being continued to finish validating the model and extract increasing knowledge from numerical simulations. As parameters are numerous (>50) and boundary conditions sometimes unknown, some sensitivity analyses are to be made (see example below): for example, initial cracking state and material parameters (tensile stress or desorption curve) may significantly modify global gas flow. However, with few updating, the results in terms of global flow are accurate.

Table 1: Updating with first experimental measures

Global flow [Nm3/h]	Measure	No initial crack	Initial crack	Initial crack & sorption curve
PreOp	7.7	1.9	1.9	4.5
VC1	9.5	1.0	1.0	6.0
VD1	-	7.0	7.8	22
VD1bis	-	7.1	7.9	23
VD2	-	10.3	12.7	57

Table 2: Updating with more experimental measures

Global flow [Nm3/h]	Additional measure	Initial crack & sorption curve	Updated parameters
PreOp	7.7	4.5	7.7
VC1	9.5	6.0	8.9
VD1	29.6	22	30.8
VD1bis	31.3	23	32.0
VD2	-	57	78.0

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