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DETAILED ANALYSIS OF THE BEAMS' EFFECT ON THE AGEING BEHAVIOR OF THE DOME OF PWR 1300 MWE NUCLEAR CONTAINMENT BUILDINGS AND ON THEIR PERFORMANCE UNDER SEVER ACCIDENT CONDITIONS – VERCORS MOCK-UP CASE STUDY

Mouhammad Chahine[1], David Bouhjiti[2], Benjamin Richard[2]

[1] 2nd year Master student from ENS Paris-Saclay (internship at IRSN/PSN-EXP/SES/LMAPS)
[2] IRSN/PSN-EXP/SES/LMAPS, B.P. 17 - 92262 Fontenay-aux-Roses Cedex, France (david.bouhjiti@irsn.fr)

ABSTRACT

The VeRCoRS program (VeRCoRs, 2021) aims at studying and understanding the ageing of double-walled nuclear containment buildings under service conditions and the associated effects on the evolution of dry air tightness over time. Up to now, the program encompasses three international benchmarks (2015, 2018 and 2023) within the OECD/NEA framework where several modeling strategies and constitutive models have been compared and assessed. Though the VeRCoRs program offers a good opportunity to test and validate numerical models, the extrapolation of the observed behaviour or the retained modelling assumptions to a real full scale French PWR 1300 MWe double-walled concrete containment buildings (CCB) remains a challenging task. In this work, we focus on the effects of geometrical differences at the dome area (upper part of the CCB): some full scale CCBs have beams whereas the VeRCoRs dome has none. So, this paper offers a comparative analysis of the VeRCoRs dome's behaviour with and without beams to enlighten the effects of such structural elements on the ageing of concrete in this area prior to any extrapolation of VeRCoRs results to the full-scale case.

INTRODUCTION

The VeRCoRS mock-up (Figure 1 left) is a 1:3 scale double-walled concrete containment building (CCB) representative of a French PWR 1300 MWe. Given its reduced scale, the VeRCoRs mock-up dries 9 times faster than a full scale CCB of the same type. This leads to an acceleration of water loss, delayed strains and prestressing losses. So, one-year time at the scale of the VeRCoRs mock-up would be around nine-year time at the full scale. In addition, the VeRCoRs concrete material has been extensively characterized and the mock-up is heavily instrumented offering the possibility of thoroughly analyzing in real time the evolution of quantities of interest such as the temperature, the relative humidity, the displacements, the strains and the air tightness within the reinforced concrete and the prestressing losses in cables. This has been done during three international benchmarks (2015, 2018 and 2023) within the OECD/NEA framework where several modeling strategies and physical models have been compared.

One topic that these benchmarks have not covered concerns the possibility of extrapolation of the observed behaviour or the retained modelling assumptions at the scale of VeRCoRs mock-up to a real full scale French PWR 1300 MWe CCB. Indeed, several aspects need to be considered amongst which one finds size effects, thermal and drying gradients in the thickness, structural restraining effects, accurate knowledge of other concrete materials (such knowledge is not as extensive as in the case of old concrete containment buildings CCBs), geometrical singularities at full scale, etc.

In this paper, we focus only on the effects of geometrical differences between the reduced and full scale CCBs. Indeed, at the dome area (upper part of the CCB), the VeRCoRs mock-up was designed with no beams whereas some French PWR 1300 MWe full scale CCBs have beams in their domes (Figure 1 right). So, one can legitimately question the representativeness of the VeRCoRs dome of real domes (given the same concrete material). To answer this question, this paper offers a comparative analysis of the VeRCoRs dome's behaviour with and without beams to enlighten the effects of such structural elements on the ageing of concrete in this area prior to any extrapolation of VeRCoRs results to the full-scale case. This paper covers in extension the behaviour of the dome (with and without beams) under severe accident conditions as well (inner pressure and temperature increase). Eventually, results are presented in terms of the structural performance (cracking and damage state) vs. the functional performance (air leak tightness) due to the presence of such beams.

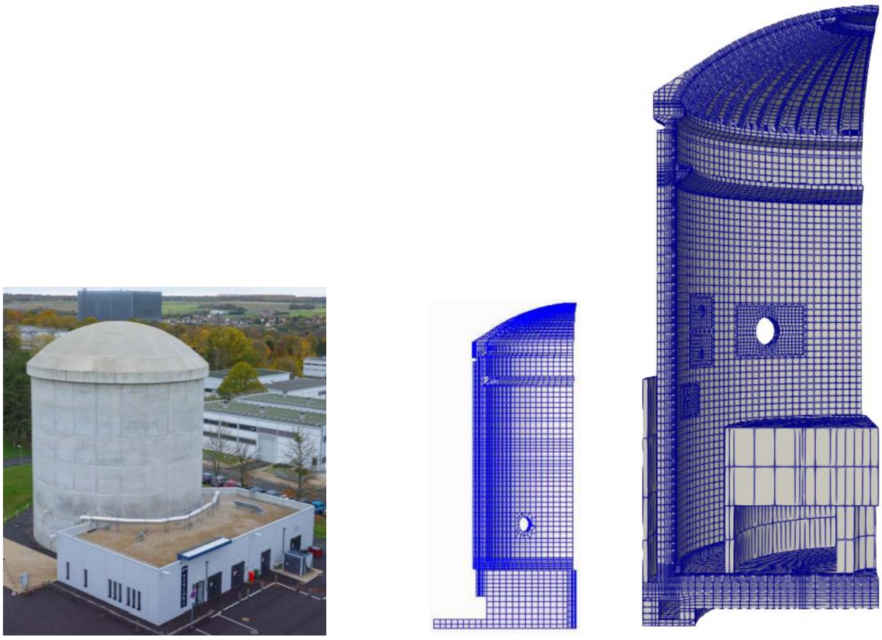

Figure 1: (left) Aerial view of VeRCoRs mock-up - EDF Lab Les Renardières. ©EDF (middle) FE model of 1:3 scale VeRCoRs mock with no beams in the dome (right) FE model of a full-scale containment buildings with beams in the dome

FINITE ELEMENTS MODEL

All here after calculations are achieved using Cast3m software (Cast3m, 2022).

Geometry and mesh of the mock-up

For this study, two finite elements of the VeRCoRs mock-up are developed (Figure 2). The first mesh is representative of the real VeRCoRs mock with no beams in the dome. The second mesh represents a virtual VeRCoRs mock-up with 24 beams in the dome used for sensitive analyses. Both meshes are edited with respect to a characteristic finite elements' length of 35 cm. However, given the presence of beams in the second mesh, the finite elements' size in the dome is slightly smaller to cope with this geometric constraint.

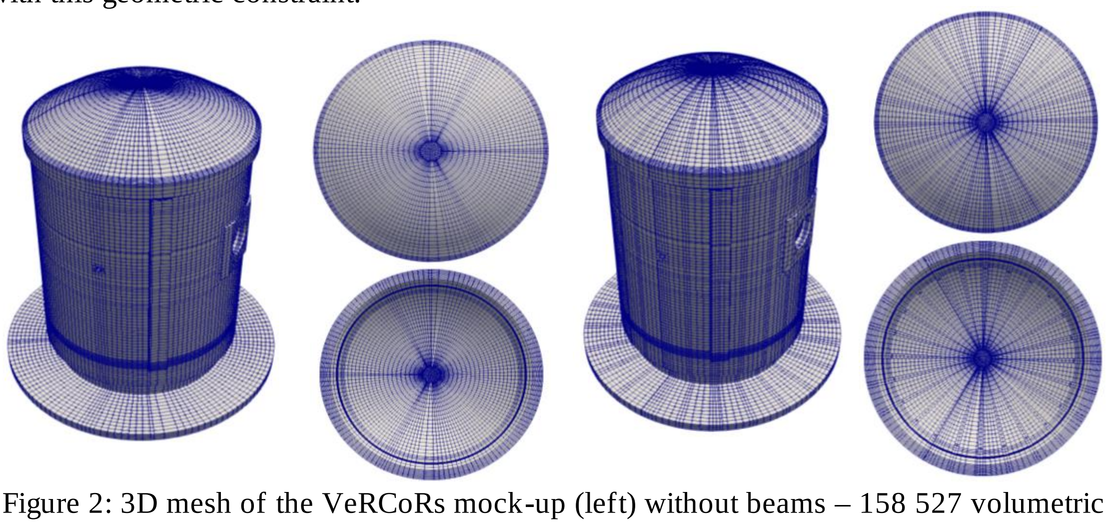

Figure 2: 3D mesh of the VeRCoRs mock-up (left) without beams – 158 527 volumetric finite elements (right) with beams – 181 587 volumetric finite elements

Thermo-Hydro-Mechanical (THM) modelling

The general modelling scheme of the THM behavior of reinforced and prestressed concrete is detailed in the work of Meng et al. (2023). For the thermal part, calculations are achieved by solving the classical heat equation using a source term for the hydration phase (descriptive of the exothermal reaction of cement and water). This part of simulation allows for the modeling of temperature evolution over time as concrete hardens. As for the long-term behavior of concrete, it is based on the principle of strain superposition including thermal strain, autogenous strain, drying shrinkage, basic and drying creeps. All are described using a simplified phenomenological approach according to regulatory formulae in Table 1. The accuracy of these simplified models at the specimen scale is illustrated in Figure 4.

Table 1: Delayed strain formulae in BPEL (1999)

Strain component	Formula	
Thermal strain ε_{TH} (m/m)	$\varepsilon_{TH} = \alpha_{th}[T(x,t) - T(x,t_0)]$	
	α_{th}	Coefficient of thermal expansion (m/m/°C)
	T	Temperature value (°C)
	x	Spatial position (m)
	t	Time (days)
	t_0	Reference time (days)
Autogenous strain ε_{ad} (m/m)	$\varepsilon_{ad}\ (t \geq 28\ days) = (f_{c28} - 20)\left[2.8 - 1.1\ exp\left(-\frac{t}{96}\right)\right].10^{-6}$	
	f_{c28}	Characteristic compressive strength (MPa) at 28 days
Drying shrinkage ε_d (m/m)	$\varepsilon_d = \frac{K.\ [72exp(-0.046f_{c28}) + 75 - \rho_h]}{1 + 8.4\frac{r_m^2}{(t-t_0)}}\ .10^{-6}$	
	ρ_h	Relative humidity at the boundary condition (%)
	K	A multiplying factor depending on the compressive strength $K(f_{c28})=\begin{cases} 18, & 40 < f_{c28} < 57\ MPa \\ 30 - 0.21f_{c28}, & 57\ MPa < f_{c28} \end{cases}$
	r_m	Drying radius (ratio between the drying area and its perimeter (cm)
	t_0	Drying starting time (days)
Basic creep ε_{fp} (m/m)	$\varepsilon_{fp} = 1.4\frac{\sigma}{E_{i28}}.\frac{\sqrt{t-t_1}}{\left[\sqrt{t-t_1} + 0.4.\ exp\left(3.4\frac{f_c(t_1)}{f_{c28}}\right)\right]}$	
	σ	Applied stress in a given direction (Pa)
	E_{i28}	Young's modulus at 28 days (Pa)
	$f_c(t_1)$	Characteristic compressive strength at the time t_1
	t_1	Loading starting time (days)
Drying creep ε_{fd} (m/m)	$\varepsilon_{fd} = 3.2\frac{\sigma}{E_{i28}}[\varepsilon_{ds}(t) - \varepsilon_{ds}(t_1)].10^3$	
	ε_{ds}	Drying shrinkage calculated using ε_d equation.

These strain components are computed for each gaussian point in the model and their values depend on the computed drying radius per structural element and on the calculated stress level at each iteration. One should also note that the presence of steel is accounted for using a multiplying factor $\frac{1}{1+15.\rho_s}$ applied to ε_{fp}, ε_{fd}, ε_d and ε_{ad}. As for prestressing losses, they are computed according to the same code BPEL, 1999.

During the simulations, the nonlinear behaviour of concrete is described using a damage-based approach (Mazars, 2015) where two damage variables are used. The first one accounts for damage under tensile loads and the second accounts for the contribution of damage under compressive loads. In both cases, the damage variable is isotropic and depends on an equivalent strain value (Figure 3 right). One should note that this damage model accounts for the unilateral effect allowing for the restitution of stiffness due to cracks' closure under cyclic loads. Also, as we are using the local formulation of behaviour law, an energy-based regularization scheme (Hillerborg, 1976) is applied to limit the effects of mesh size discrepancy. Steel elements in the model (reinforcement bars and prestressing cables) are supposed elastoplastic with kinematic hardening (Figure 3 left).

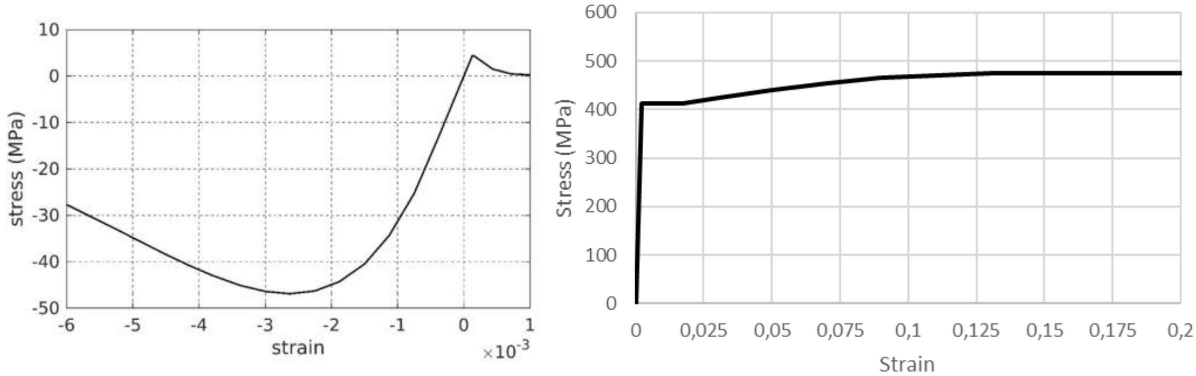

Figure 3: 1D behaviour laws under compressive and tensile loads (left) concrete (right) steel

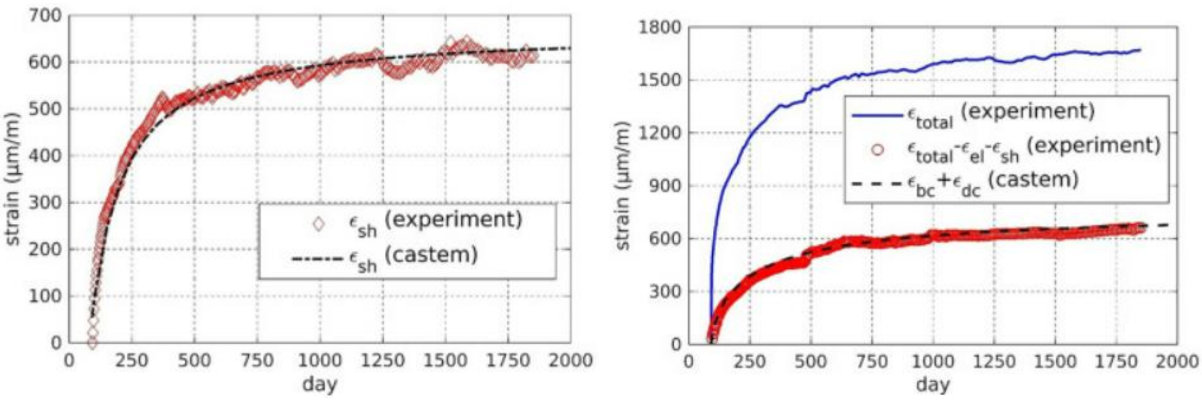

Figure 4: Comparison between measured and simulated (left) shrinkage strains (right) total creep strains (under 12 MPa compressive load)

Boundary conditions

The boundary conditions consist of considering an inner temperature as measured on site with values around 35°C during the heating phase (figure 5). Heating stops during the pressurization tests. Outer temperature is also monitored and is applied accordingly. The outer relative humidity is considered around 50% and the inner one (due to the applied heating) around 20%. From a mechanical point of view, a perfect bond between steel and concrete elements is applied. And tensile forces are applied to the tendons (prestressing cables) at the anchorage zones. Instantaneous and delayed prestressing losses are computed according to BPEL, 1999.

In addition to dead load and prestressing forces, the mock-up undergoes each year what is called a pressurization test consisting of an inner applied relative pressure of 4.2 bars. During these pressurization tests, the dry air leakage values are monitored which allows for the assessment of the evolution of air tightness due to ageing. During these tests, we are mainly interested in the evolution of existing crack opening values (due to prestressing losses), the appearance of new cracks (due to restraining effects amplification), the water loss in concrete's porosity (due to drying). All these phenomena do increase the air leakage over time.

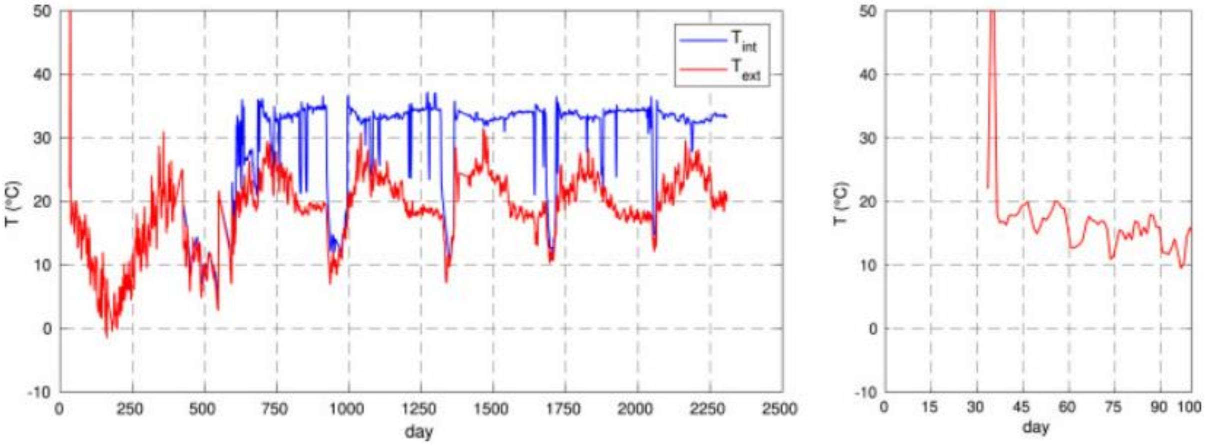

Figure 5: Temperature profiles on the inner and outside of the VeRCoRs CCB

Table 2: Previsional calendar of pressurization tests (VeRCoRs program)

Phase	ID	Pressurization date in years	
		VeRCoRs mock-up time	Real CCB equivalent time
1	VO1	1.3	11.7
2	VC1	1.5	13.5
3	VD1	2.6	23.4
4	VD2	2.7	24.3
5	VD3	3.7	33.3
6	VD4	4.7	42.3
7	VD5	6.6	59.4
8	VD6	7.7	69.3

Hereafter, the applied relative pressure starts at 4.2 bars as achieved during the pressurization tests and is then increased until the convergence of calculations is no longer possible due to advanced damage in the structure. This pressure increase describes virtual severe accidents conditions applied to the VeRCoRs mock-up.

NUMERICAL DESIGN PLAN and RESULTS

Numerical design plan

As we aim at studying the effect of the presence of beams on the structural behavior of the dome, the numerical design plan of 16 calculations is retained in Table 3. In addition to the sensitivity analysis regarding beams, this also allows for the evaluation of the effect of time (ageing phenomena) on the structural behavior of the dome at normal pressure conditions (relative pressure of 4.2 bars) and beyond design conditions.

Numerical results and analysis

The shown results here cover mainly the cracked state of the dome using a global demand parameter defined as the percentage of damaged volume in the dome (damage due to the elastic strain exceedance of the cracking strain threshold in the used damage law Mazars, 2015).

Table 3: Numerical design plan for sensitivity analysis

ID	Beams in the dome		Age at pressurization (years)		
	With	Without	ID	Real time	Equivalent time
1		x	VO1	1.3	11.7
2		x	VC1	1.5	13.5
3		x	VD1	2.6	23.4
4		x	VD2	2.7	24.3
5		x	VD3	3.7	33.3
6		x	VD4	4.7	42.3
7		x	VD5	6.6	59.4
8		x	VD6	7.7	69.3
9	x		VO1	1.3	11.7
10	x		VC1	1.5	13.5
11	x		VD1	2.6	23.4
12	x		VD2	2.7	24.3
13	x		VD3	3.7	33.3
14	x		VD4	4.7	42.3
15	x		VD5	6.6	59.4
16	x		VD6	7.7	69.3

- At nominal pressurization level (relative pressure of 4.2 bars): In Figure 6, one can observe the constant increase of damaged areas of the dome with time due to the application of constant pressure whilst prestressing diminishes over time. The % of cracked volume in the dome is multiplied by a factor 7. However, this does not jeopardize the air tightness of the dome as cracks do not propagate through the whole thickness of dome. A second interesting observation is that the presence of beams has indeed non negligeable effect as some of the applied loads go through them limiting hence the tensile stresses in the rest of the dome. This is rather a beneficial effect under pressure-based severe accidents.

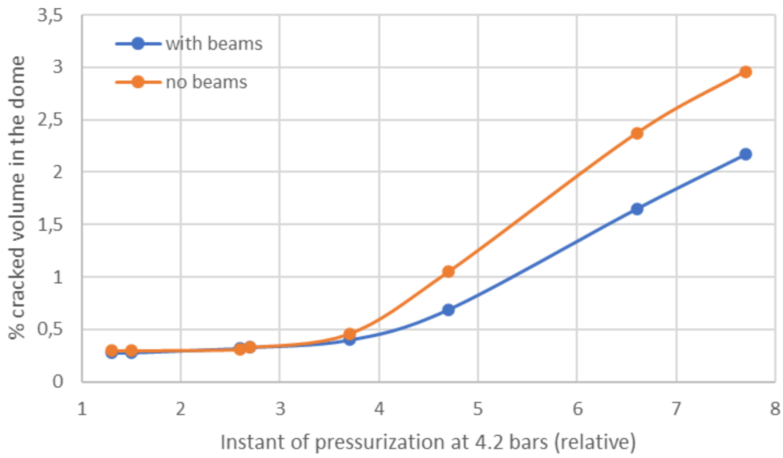

Figure 6: Percentage of cracked volume in the dome under pressurization at 4.2 bars (relative)

- At beyond design pressurization level (relative pressure up to 7 bars) results differ considerably between the cases with and without beams.
  - In the presence of beams (Figure 7): numerical results show that ageing phenomena reduce the level of prestressing in concrete and thus limit its structural resistance to extreme inner pressure loads. For example, the percentage of damaged volume at VC1 is 6% at a relative pressure of 6.9 bars. At VD6, the same percentage of damaged volume is obtained for a relative pressure of only 5.8 bars. This corresponds to a 16% reduction in the mechanical capacity of the dome after 6 years of ageing.

- In the absence of beams (Figure 8): the general trends mentioned above are also confirmed in the presence of beams. In addition, we observe overall more significant damage compared to cases with beams at an equal level of pressure and ageing (at VD6, the amplification damage factor ranges from 1.5 at 4.2 bars to 4.3 at 6 bars). This result confirms the significant contribution of the beams to the mechanical resistance of the dome in severe accidents situation (pressure only) as part of the forces induced by the inner pressure passes through the beams (Figure 9).

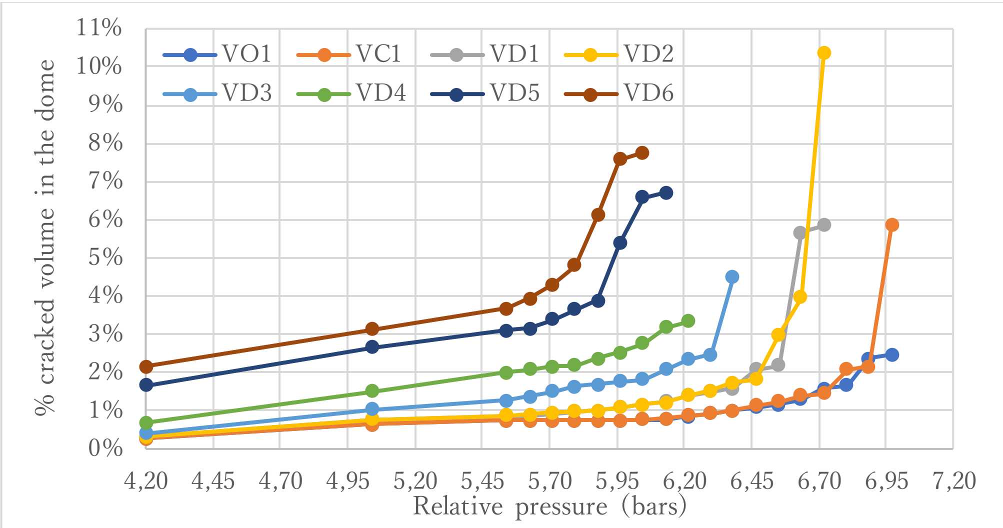

Figure 7: Percentage of cracked volume in the dome under beyond design pressure (with beams)

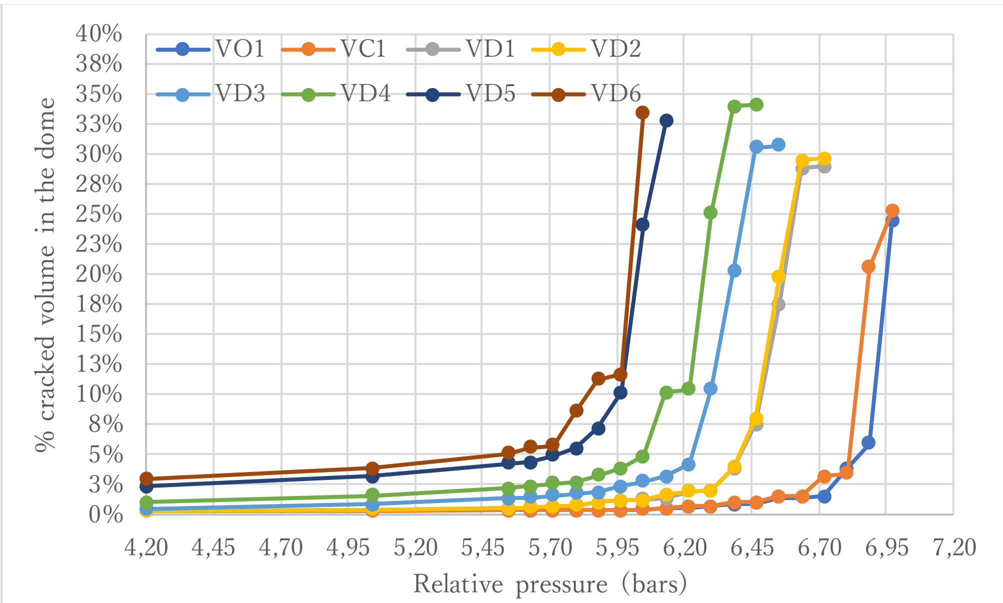

Figure 8: Percentage of cracked volume in the dome under beyond design pressure (without beams)

CONCLUSIONS AND PERSPECTIVES

This paper deals with the issue of beams' effect on the structural behavior of domes in French PWR 1300 MWe double walled CCBs. It summarizes the main thermo-hydro-mechanical calculation hypotheses to (a) simulate the delayed behavior of concrete in the model; and to (b) predict the evolution of its cracking as a function of the applied internal pressure (nominal relative pressure of 4.2 bars and beyond for accidental scenarios). The explored numerical design plan covers calculations with and without beams in the dome in addition to pressurization tests applied at several ageing time and ageing conditions.

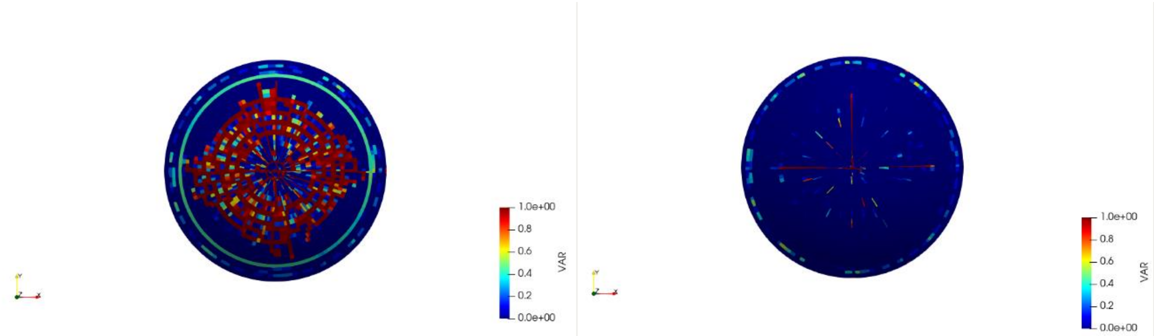

Figure 9: Damage profile of the dome at a relative pressure of 6 bars (VD6) (left) without beams (right) with beams

The conclusions obtained from this numerical study and the achieved sensitivity analyses clearly state the non-negligible effect of beams and the one of ageing duration on the behavior of domes whether this concerns normal or accidental conditions:

- The percentage of damaged volume in the dome, at the relative nominal pressure of 4.2 bars, increases by a factor of 7.7 between the first pressurization test VO1 and the last VD6 (after 6 years of ageing). This does not call into question the tightness of the dome which remains ensured in the absence of through cracks at this pressure level.
- Aging reduces the level of prestress in the concrete and thus limits the strength to extreme inner pressure loads. The level of reduction in the mechanical capacity of the dome is approximately 16% between the VC1 test and the VD6 test.
- The presence of beams contributes to the recovery of the forces induced by the inner pressure and makes it possible to improve the mechanical capacity of the dome by a minimum factor of 1.5.

Based on the results obtained from this numerical study, one can conclude that the extrapolation of the observed structural behavior, at least for the dome, of the VeRCoRs mock-up (dome with no beams) is not so straightforward at the full scale (dome with beams), especially under severe loadings.

The perspectives of the work carried out here shall focus on two main aspects. First, next step would lead to an accurate quantification of the dry air leakage rates associated with the mechanical damaged states obtained here before. The second main perspective shall cover the sensitivity of the dome's behavior to the presence of beams and the state of ageing under severe thermomechanical conditions with a simultaneous increase in pressure and temperature.

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