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PREDICTION OF A CONTAINMENT VESSEL MOCK-UP CRACKING DURING OVER DESIGN PRESSURE TEST

Sandrine KEVORKIAN*
Phone: SOCOTEC Industries
+33 1 30 12 85 18, E-mail: sandrine.kevorkian@socotec-industries.fr

Grégory HEINFLING, Alexis COURTOIS
EDF – SEPTEN, Civil Engineering Division, Villeurbanne, France

ABSTRACT

Numerical modelling for a complex reinforced and pre-stressed concrete structure containment vessel mock up has been carried out. These calculations allow a comprehensive prediction for the behaviour of the structure and for the initiation and localisation of new cracks (generated by simulated loading), as shown by comparisons with NDE and monitoring data.

Keywords: Containment vessel, concrete, cracking, non-linear modelling, acoustic emission

1 INTRODUCTION

French 1300 – 1450 MWe PWR containments, constructed from prestressed concrete, have been designed to deal with any likely accident scenarios. The structures are subjected to periodical pressure tests which aim to verify their ability to fulfil their function of confinement. The tests however only subject the structure to the effects of pressure, whilst the conditions that would be expected during an accident would submit the structure to a combination of both pressure and temperature effects.

EDF, with the contributions of its French partners, had built a mock-up from prestressed concrete which represents the normal section of a PWR containment [1] : MAEVA (MAquette Enceinte en Vapeur et en Air, Steam and Air tests confinement mock-up), with the aim of :

- understanding better the behaviour of a reactor containment subjected to the combined loading of pressure and temperature, by means of knowing the behaviour during pressure tests ;
- studying the evolution of the permeability by leak rate measurements and also the state of cracking of the concrete containment wall, in air tests then in steam tests ;
- studying the behaviour of a composite liner contributing to the leaktightness of the concrete containment wall.

2 MAEVA MOCK-UP

The objectives of the MAEVA mock up is to study experimentally the behaviour of a prestressed concrete structure under mechanical and thermal loads, similar to the conditions expected in an accident situation inside a reactor building [1].The situations considered are similar to the following conditions : Acceptance tests (at design pressure) and LOCA (Loss of Coolant Accident) design accident test.

The main goals of these tests are :

- To study the behaviour of heat propagation in a concrete wall in the presence of an air + steam mixture;
- To study the development of wall permeability and its cracking status under air and air+steam mixture loads;
- To study the behaviour of the composite liner ensuring the leaktightness of the concrete wall.

2.1 General description

As shown Figure 1, MAEVA has several components :

- a cylinder of 16 m interior diameter, 5 m high and with a wall thickness of 1.2 m. Like real containment, the mock up is biaxially prestressed : 13 16T15 tendons horizontally, in two layers, ensuring an average prestress of 5 MPa, 70 MAC-ALLOY bars of 75 mm diameter as vertical prestressing in the cylinder, providing an average prestress of 3 MPa ;
- a 1.4 m diameter access passes into the mock-up at mid-height;
- two prestressed concrete “bases” (mat and cover) of 20.40 m diameter and 1.00 m thickness ;
- neoprene pads, placed at the interface between the cylinder and the bases (mat and cover), leaving the cylinder free to radial displacement, in order to obtain an accurate simulation of the standard section of a real containment ;
- four prestressed reinforced concrete columns linking the bases ;
- an external metal cladding creates four separate zones, denoted quadrants 1, 2, 3 and 4 (Figure 2), where the leak-rates can be measured. The concrete wall of two of the quadrants is covered with a leaktightness complementing composite liner which should contribute to its leaktightness.

A High Performance Concrete (HPC) has been used for MAEVA, providing a 28th day characteristic compressive strength of 50 MPa. The design pressure of the mock-up is 0.65 MPa absolute. Its ultimate pressure is estimated at 1.8 MPa. The initial design foresaw that at 0.75 MPa absolute, concrete cylinder goes into tension and micro-cracks and the macro-cracks would start to develop. As friction parameters were underestimated, the pressure value for cracks initiation is updated at 0.93 MPa absolute.

The mock-up was built at CIVAUX, in France, near operating PWR units (N4 series). The facilities are now decommissioned. 5 campaigns of tests have been carried out from December 1996 to December 2002. For each campaign, an average of 2 sequences (one test with air, another with steam) have been performed.

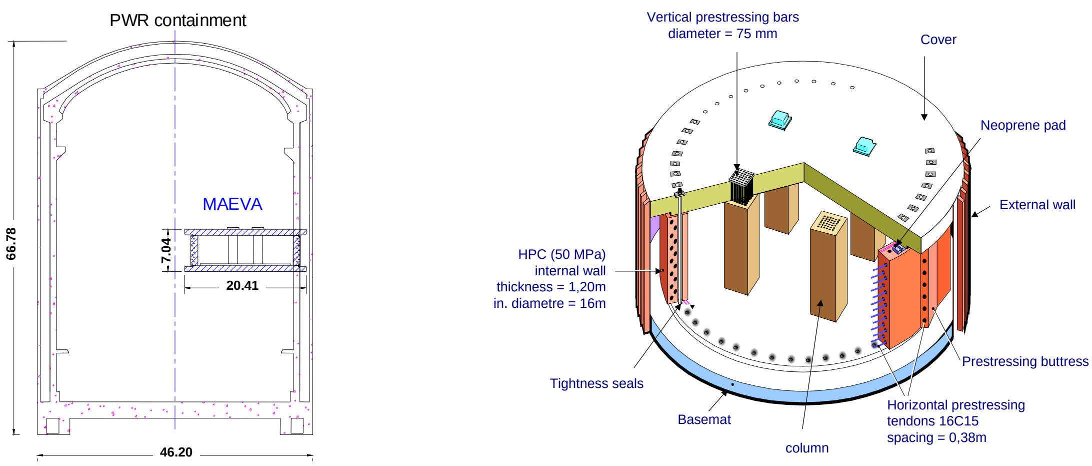


Figure 1 : general view of MAEVA Mock up

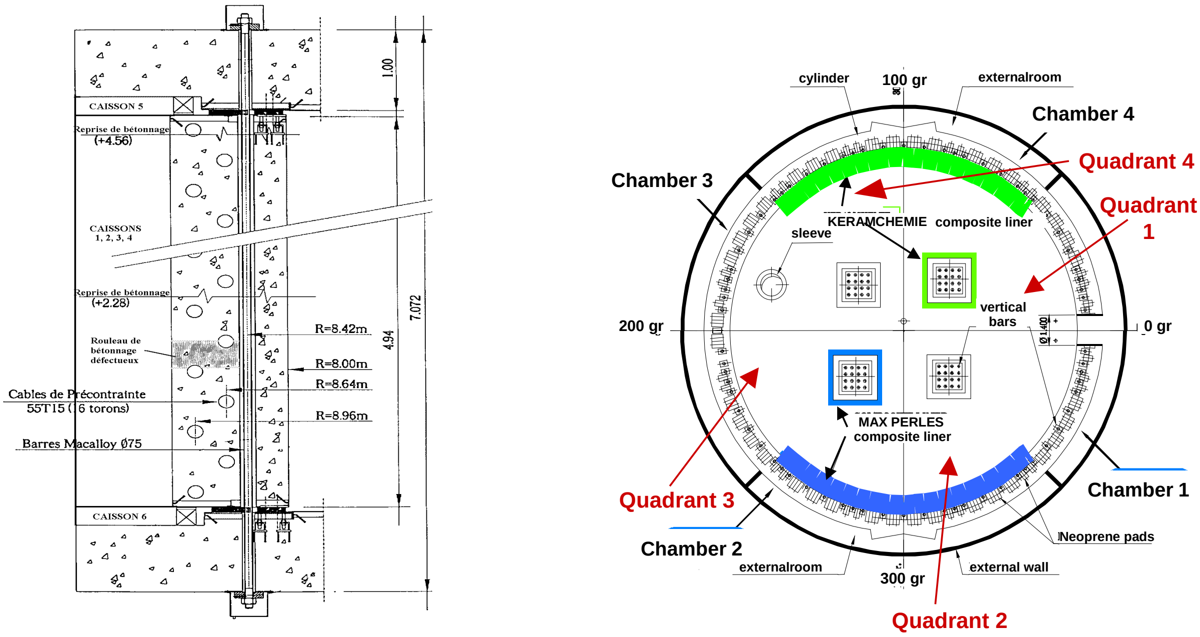


Figure 2 : MAEVA sectional views - The four quadrants

2.2 Instrumentation

The instrumentation of the mock-up is set to allow the study of the behaviour of the structure from the moment of the concreting, throughout the prestressing process then during the air tests (pressure only) and steam tests (pressure and temperature). Almost all of the instrumentation for the structure aims to follow the evolution of the temperature, the deformations and the displacements of the chosen measuring points situated in or on the concrete wall surfaces (Figure 3). The monitoring of the deformations is assured by :

- GLÖTZL extensometers,
- C110 TELEMAC extensometers.

These are grouped in three, spread through the thickness of the cylinder in order to measure the tangential and vertical gradients of deformation.

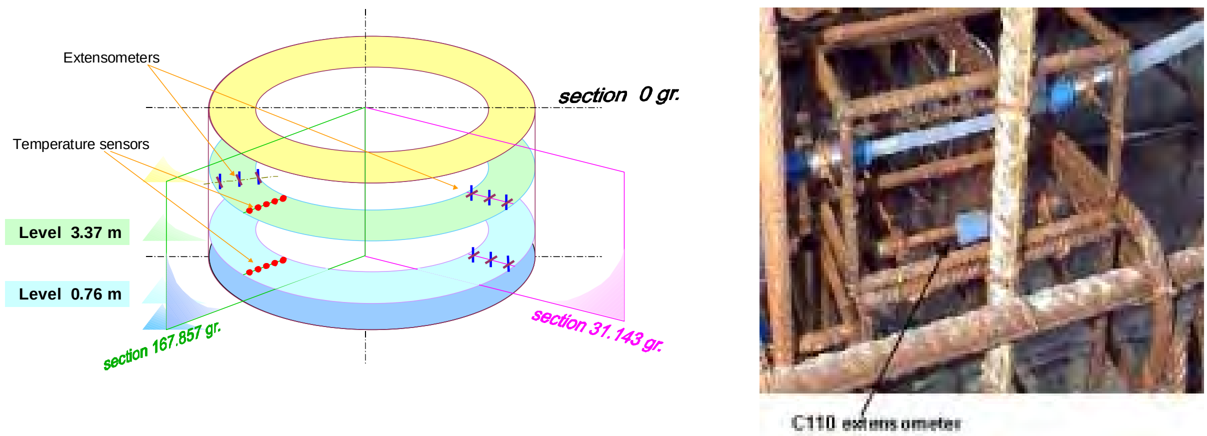


Figure 3 : Extensometers in the wall thickness

The monitoring of the global displacements of the structure is assured by 12 pendulums (Figure 4). These measures of radial and tangential displacements on the external surface of the cylinder allow the verification of the coherence of the extensometer measures in the wall thickness. The pendulums were installed in pairs on the external surface along the centerlines of 0, 32, 100, 200, 232, 300 grades on the external surface of the cylinder. Eight of these pendulums (0, 32, 200, 232 gr) are complete with telemeasured device (telependulum SAFTEL TOP) for automatic monitoring.

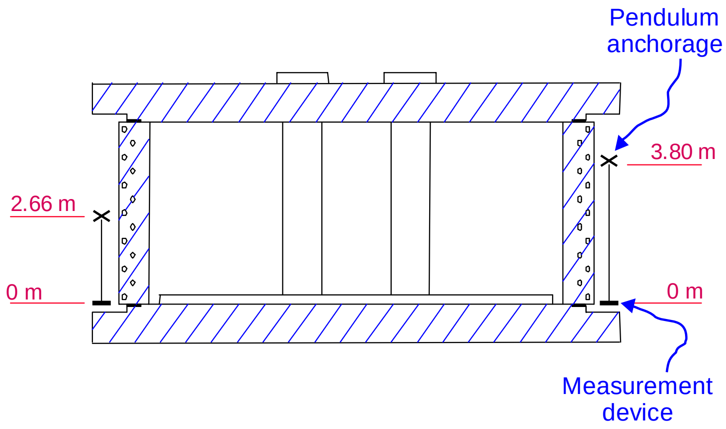


Figure 4 : Pendulums on the external wall

3 THE OVER DESIGN PRESSURE TEST (ODPT)

The 7th and last sequence of pressure test on MAEVA Mock Up has been performed out in December 2002. Pressure within the cylinder has been led up twice up to 1.5 times the design pressure (i.e. up to 0.975 MPa) to allow monitoring of the new cracks after the first pressure rise (Figure 5). This test is called “Over Pressure Design Test” (ODPT). The loading was applied with dry air, and at ambient temperature.

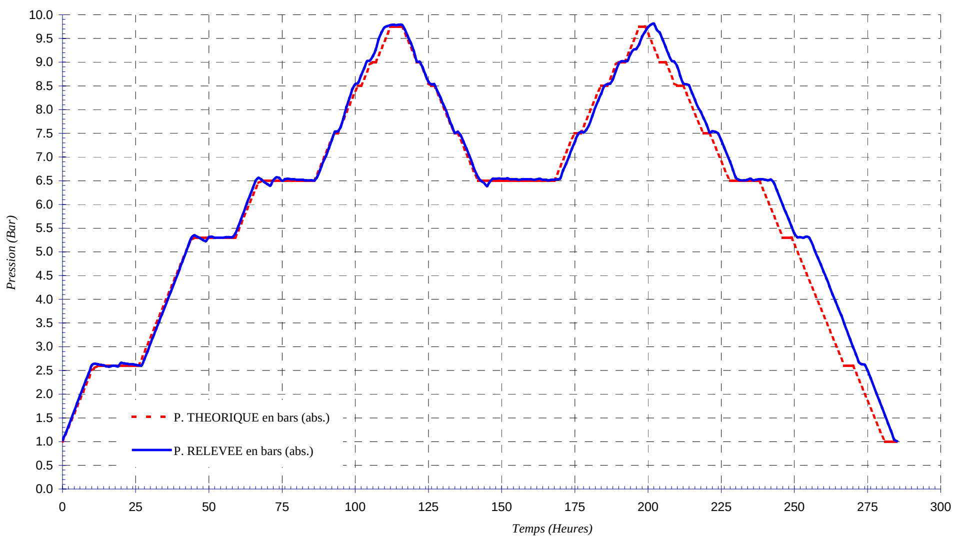
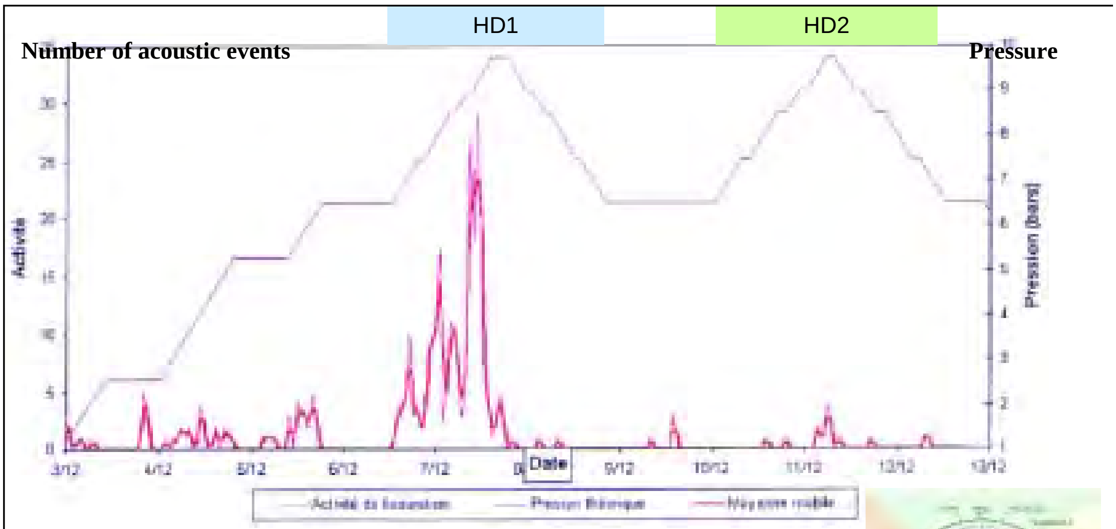


Figure 5 : pressure applied during the ODPT

For this specific test, a continuous concrete crack detection system was set. It consists in acoustic emission devices using Sound Print Systems used to detect new cracks generation and former cracks growing. 20 sensors were set on the inner wall and 20 others on the outer one, covering 3 quadrants (Figure 6).



	Total	Before HD1	During HD1	During HD2
Quadrant 1	150	30	118	2
Quadrant 2	111	24	76	11
Quadrant 3	57	8	43	6
Total	**318**	**62**	**237**	**19**

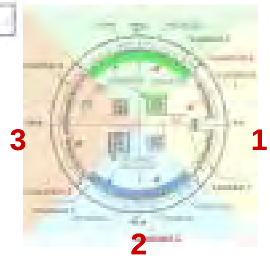


Figure 6 : Detection of cracks events during over-design pressure test

This technology of NDE allows the detection of degraded areas during a rise of pressure, *or a new loading*, beyond the historically undergone loading of the structure, as shown by the high number of acoustic events (interpreted as cracks formation or growth) during the 1st rise of pressure and the very low number during the second one, see Figure 6.

Several displacement or deformation sensors have given useful information on the local or global behaviour of the structure during ODPT, including crack opening. Unfortunately, after more than 6 years of experimentation in severe conditions (pressure, heat, moisture), a lot of sensors didn't withstand the rise of pressure of the ODPT. It entails a lack of useful information in monitoring to compare calculations to real response of the structure.

4 FEA MODELLING OF MAEVA BEHAVIOUR DURING OPDT

The technical options for the FEA calculations of MAEVA mock up have been defined on the basis of the modelling feed back provided previously by CESA Project [2]. The calclations have been performed using Edf's finite element code *Code-ASTER*$^{(R)}$ [4].

4.1 General description of the model

A 3D model has been built, simulating one half of the structure, taken into account the symmetry of the structure, of the boundary conditions and of the loading.The FE model accounts for the different structural elements : concrete, prestressing tendons, reinforcement rebars...Calculation methodologies have been applied in order to allow for linear as well as non linear calculations in different situations : initial state, service life, testing over the design pressure. Loss of prestress due to creep and shrinkage in each situation is assessed.

A lot of local deterioration and cracks on the external face of the cylinder have been observed during visual inspections driven before the ODPT. The origin of this cracks is probably linked with damage induced by the previous tests. Nevertheless, our FEA didn't attempt to simulate the effects of these observed damage. It should be on one of the possible improvement for our further modeling works.

4.2 Material properties

<u>*Concrete*</u>

Standard parameters have been chosen as follows :

- Young Modulus E = 34567 MPa
- Poisson Ratio ν = 0,2
- Tension Strength σ_t = 4,430 MPa

6 parameters are needed for Mazars law [3]:

- ε_{d0}, threshold of damage growth, $(1,5.10^{-4} \leq \varepsilon_{d0} \leq 0,5)$
- β, ranging between 1 and 1.1, should be fitted from the response of plain concrete to shear. Code_Aster user guide suggests a value of 1.06.
- Coefficients A_t and B_t are related to softening in tension, A_c et B_c to softening in compression :
  - $1 \leq A_c \leq 1,15$
  - $0,7 \leq A_t \leq 1$
  - $1000 \leq B_c \leq 2000$
  - $10000 \leq B_t \leq 100000$

Finally, due to the fact that any appropriate test have not been carried out on MAEVA HPC, we considered the following parameters as input data, suggested by scientific references as standard values [3]:

- A_t = 0,8
- A_c = 1,15
- B_t = 10000
- B_c = 1391,3
- ε_{d0} = $9,375.10^{-5}$
- β = 1,06

Neoprene pad

Neoprene's response is supposed to remain elastic

- Young modulus E = 120 MPa
- Poisson ratio ν = 0,2

Reinforcement rebar

- Reinforcement are supposed to be elastoplastic with a small hardening effect in plastic regime.
- Density ρ = 7850 kg/m^3
- Young modulus E = 200000 MPa
- Yielding strength σ_e = 500 MPa

Horizontal tendons

Horizontal tendons are supposed to be elastoplastic with a small hardening effect in plastic regime.

- Area = 2400 mm²
- Density ρ = 7850 kg/m^3
- Young modulus E = 190000 MPa
- Yielding strength σ_e = 1650 MPa

Vertical Prestress (Mac Alloy bar)

Mc Alloy bars are supposed to be elastoplastic with a small hardening effect in plastic regime.

- Area = 4418 mm²
- Density ρ = 7850 kg/m^3
- Young modulus E = 205000 MPa
- Yielding strength σ_e = 835 MPa

4.3 3D Mesh

Considering symmetries in geometry, loading and boundary conditions, only one half of the mock up has been meshed in the model, made up of :

- 3D volumic elements for concrete (Figure 7) ;
- Rod elements for tendon (Figure 8 and Figure 9) ;
- Shell elements (grid) for reinforcement (Figure 10) ;
- Penalty contact surface for neoprene pad (Figure 11).

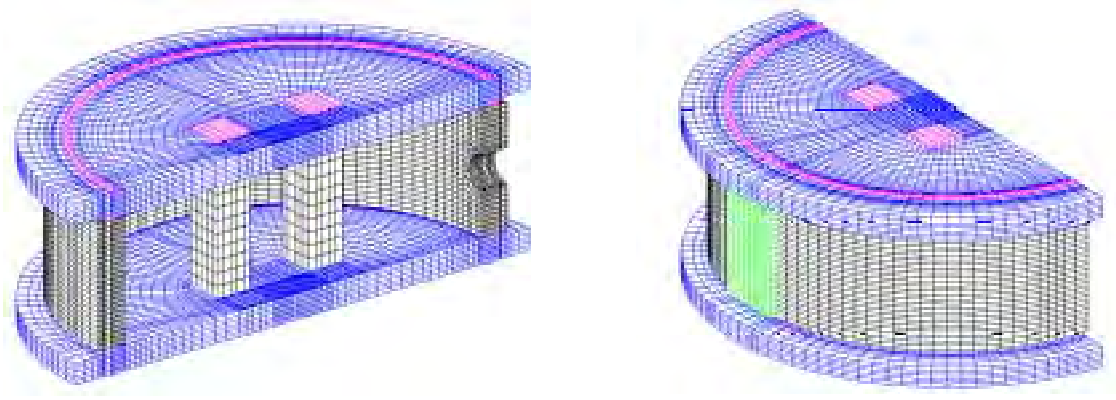


Figure 7 : 3D mesh (general external view)

Figure 8 : horizontal tendons

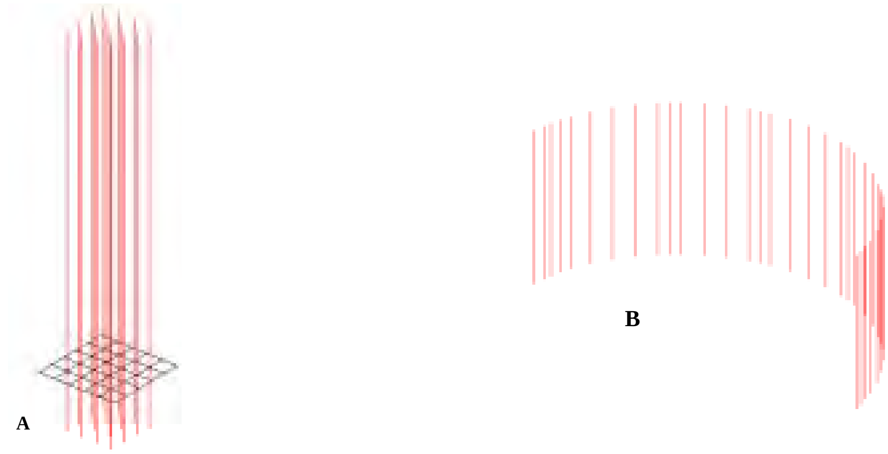


Figure 9 : vertical prestressing bars in the column (A) and in the cylinder (B)

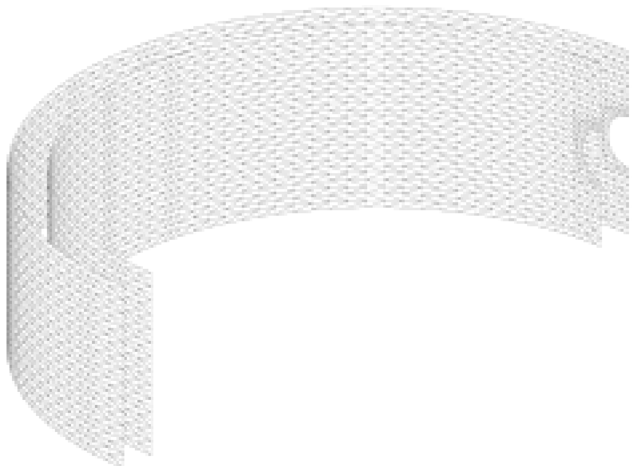


Figure 10 : reinforcement modeled by orthotropic grid element (stirrup not modeled)

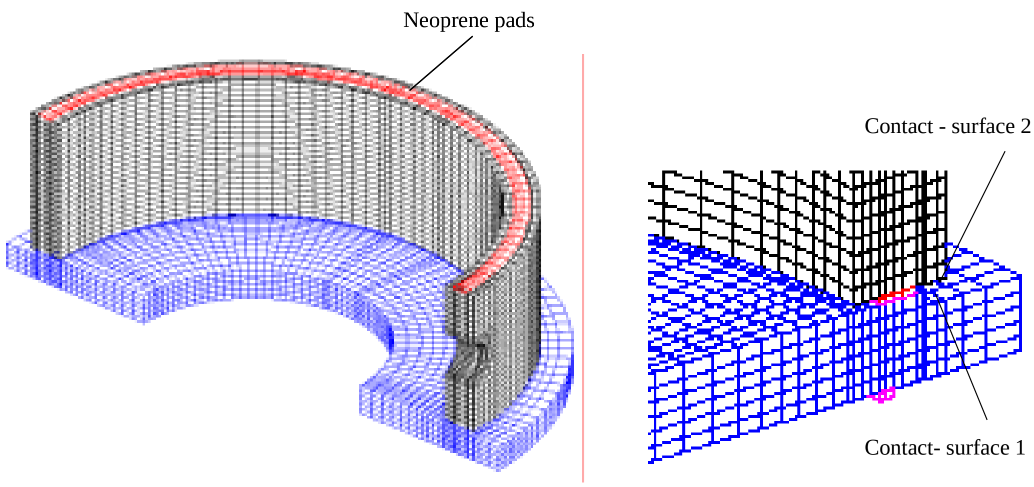


Figure 11 : neoprene pads simulated with contact surface

4.4 Boundary conditions

The structure is assumed to be support by a rigid soil. Unilateral contact is introduced under the footing slab to allow deflection of the basemat.

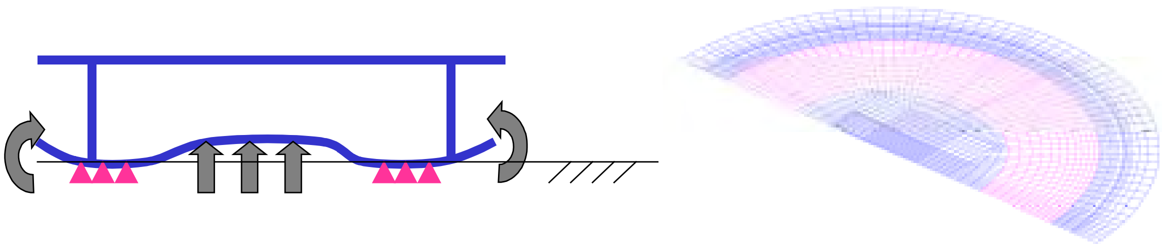


Figure 12 : support boundary conditions under the basemat

4.5 Loads

The main load of the ODPT is applied as a uniform internal pressure according to the curve represented on Figure 5. It has been decided to limit the calculations to the first rise and decrease of pressure (first cycle, denoted HD1 on Figure 6). Symmetry conditions are applied to take into account the unmeshed half of the structure (normal displacement retrained to 0).

Prestress loss was assessed according to French design code, taken into consideration :

- Elastic losses corresponding at the level of a tendon to the combined effects of others tendons;
- Friction losses, due to friction between tendon and its duct, depending on curvature;
- Slip that necessary occurred when prestressing force is transferred to the anchorage Anchor set;
- Steel relaxation of cables;
- Shrinkage/creep of concrete.

The distribution of tension along the tendons (see Figure 14) has been calibrated with available monitoring data. As only one half of the real structure has been considered, it entailed several calculations to estimate the tension to apply at the "fictitious" extremities of the cable cut by the plane of symmetry.

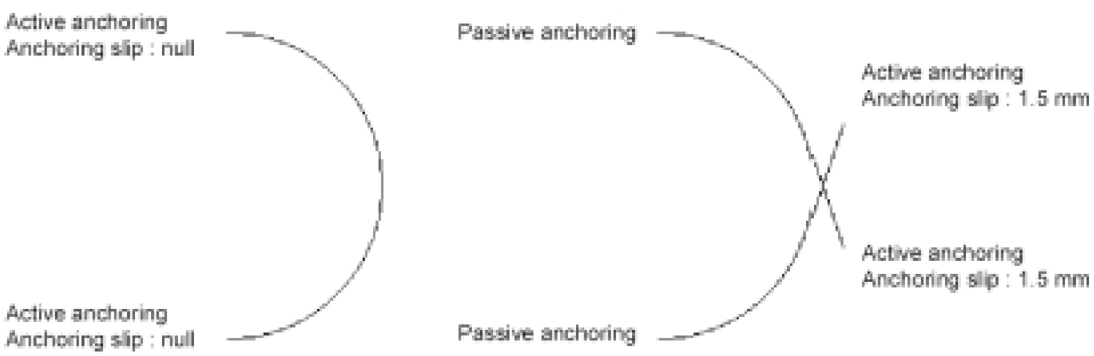


Figure 13 : different kinds of tendon in the model

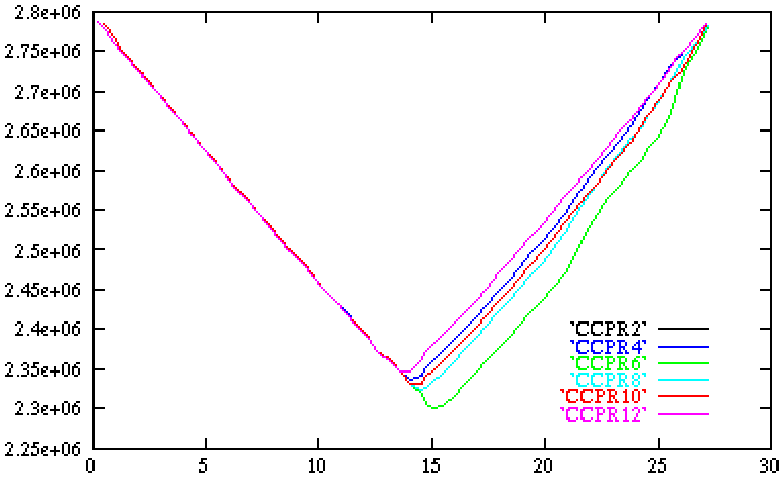


Figure 14 : tendon tension profile (in [N]) in case of the achorage of the tendon is not included in the mesh (left configuration on Figure 13)

5 RESULTS AND COMPARISON WITH AVAILABLE MEASUREMENTS

Comparison monitoring/FEA for displacements

When looking at the global deformation of the structure (Figure 15, it can be said that it is qualitatively consistent with the measurement (Figure 16 and Figure 17). This qualitative agreement is true at a local level too.

From a quantitative point of view, it appears that the FEA gives lower displacements than monitoring. One can infer that the global rigidity of the mock up is overestimated by the model. It must be kept in mind that the structure has been considered "healthy", i.e. without any crack, at the beginning of the calculations. Actually, it is not the case : former cracks affected the structure before the ODPT. Thus, the structure has been assumed to be stiffer than it was actually.

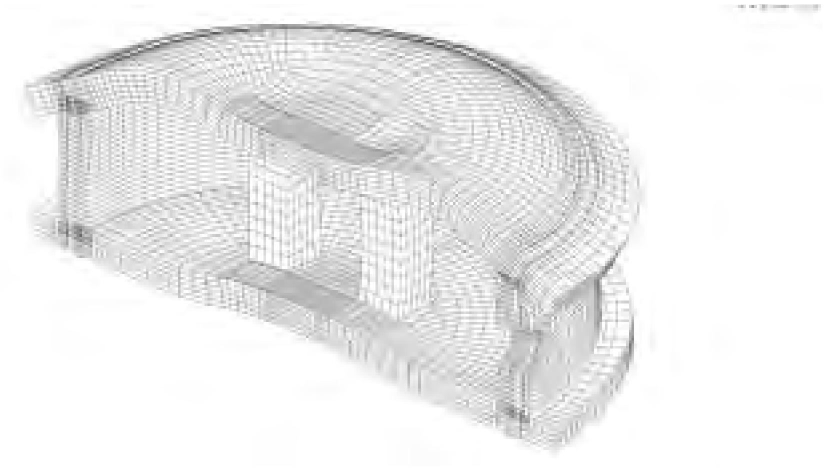


Figure 15 : global 3D deformed shape of MAEVA (EDF study)

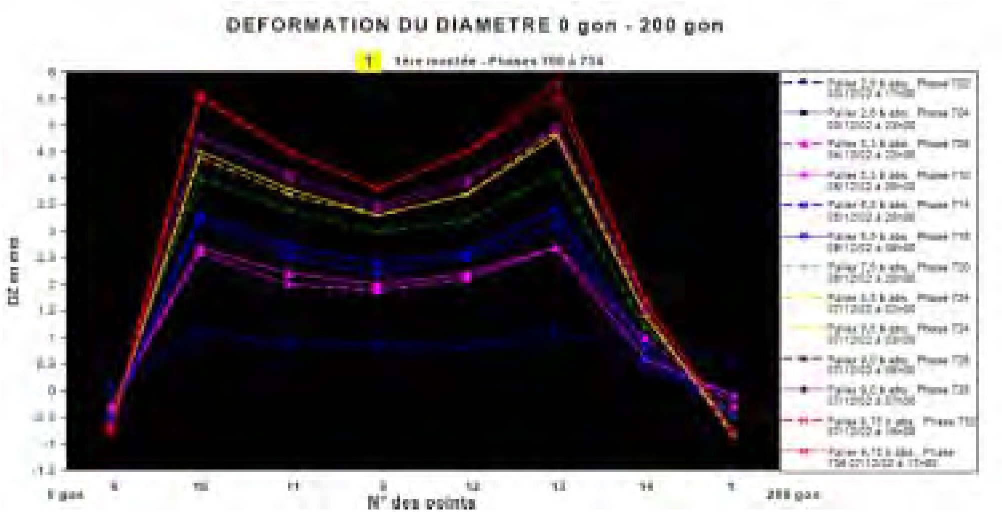


Figure 16 : vertical displacement [mm] profile of the top of the cover slab along the symetry diameter (monitoring measures, for each step of pressure evolution)

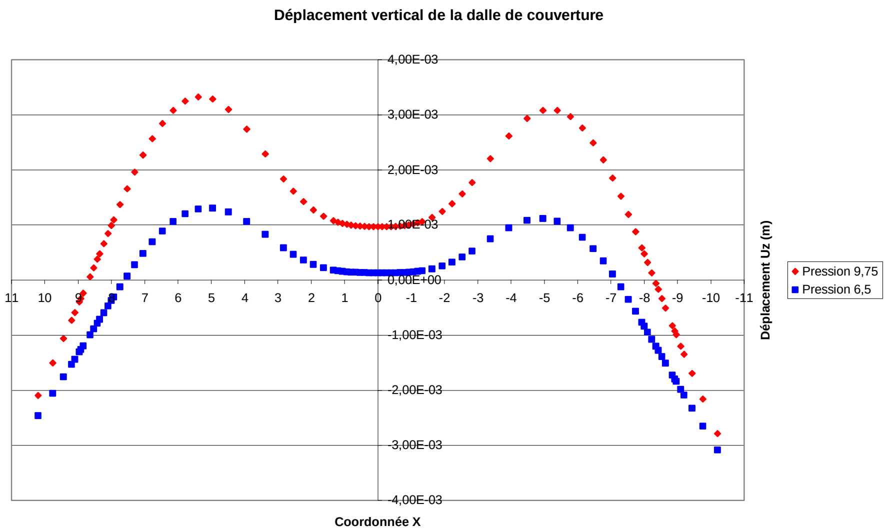


Figure 17 : vertical displacement [mm] profile of the top of the cover slab along the symetry diameter (FEA results, at 9.75 bar and 6.5 bar)

5.1 Comparison NDE/FEA for cracking initiation

The comparison between the damage variable of the model D (which stands for cracking) and the locations of acoustic events allows to assess the reliability of the FEA tools. This comparison has been done near the penetration, near the buttress and in the area at the opposite of the penetration.

Around the penetration (quadrant 1), both FEA and NDE exhibit crack initiation and development. Crack patterns are quite similar (Figure 18). Near the buttress (quadrant 2), FEA prediction and NDE measurements are in good agreement too (Figure 19).

To go further in the comparison, it should have been of high interest to compare acoustic intensity (or energy dissipated by the opening cracks) with amplitude of evaluated damage by FEA.

Nevertheless, FEA didn't manage to detect any crack initiation far from buttress or pipe entry, at 180° azimuth angle of the penetration (Figure 20). It is consistent with the conclusions stated previously for the axisymetrical modelling. We suppose that in fact, acoustic events could be linked with former cracks already generated by previous tests on the mock up that have grown with ODPT loading. We can make a link with the previous observation on displacement and the actual stiffness in relation with cracking.

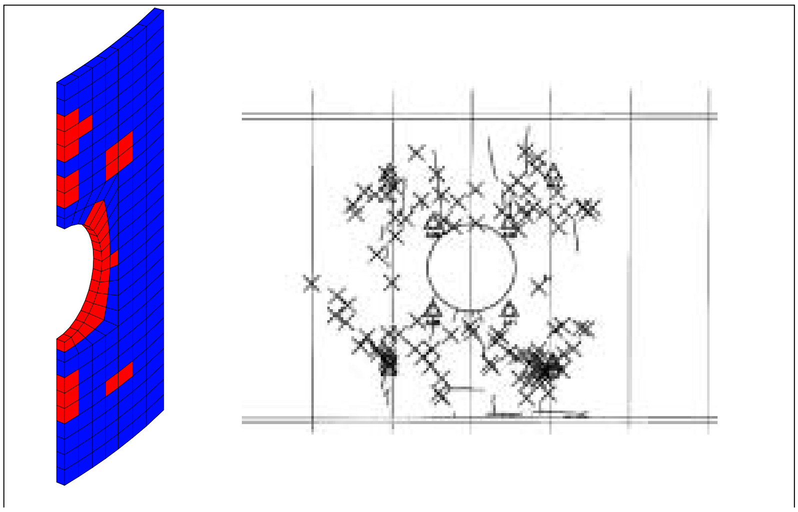


Figure 18 : Quadrant 1 - comparison between damage zone deduced from FEA and acoustic event from NDE around the penetration

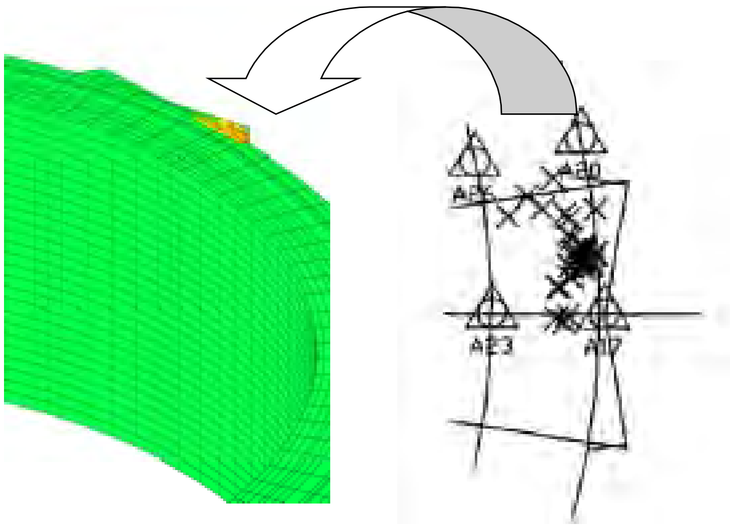


Figure 19 : Quadrant 2 - comparison between damage zone deduced from FEA and acoustic event from NDE nera the butress

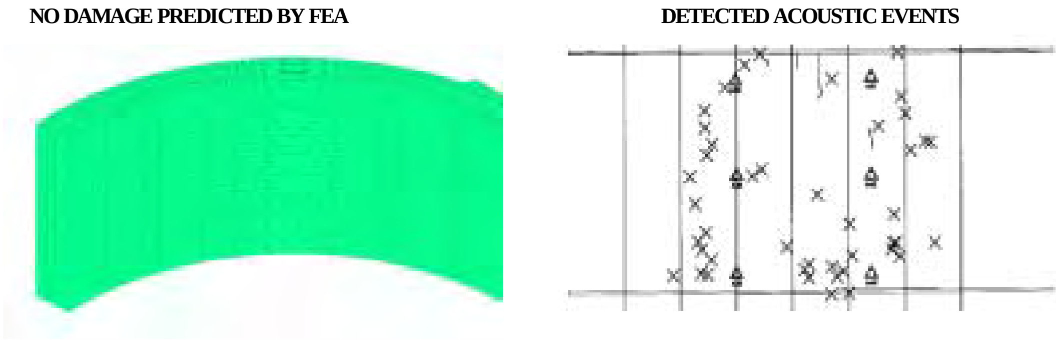


Figure 20 : Quadrant 3 - comparison between result from FEA (no forcast damage) and acoustic event from NDE in a standard area of the cylinder

6 CONCLUSION

Numerical modelling for a complex reinforced and pre-stressed concrete structure containment vessel mock up has been carried out. These calculations allow a comprehensive prediction for the behaviour of the structure and for the initiation and localisation of new cracks (generated by simulated loading), as shown by comparisons with NDE and monitoring data.

Analysis methods and tools should however be improved to go further and to get quantitative reliable predictions of the behaviour of nuclear buildings. For example, the initial state seems to have more influence on local behaviour (opening/closure of former cracks under applied loading). If the purpose is to estimate leak rate through a prestressed reinforced concrete wall, knowledge on crack configuration, and then more sophisticated analysis, are required (see CESA report [1] to get an overview of such analysis). EDF ongoing work are dedicated to initial state assessment in structure that have undergone complex loads for several years. Bayesian approaches can help in this way.

Another point to stress is the use of smeared crack concepts. It is well known that engineers using them should be very careful with mesh dependency or localisation, once convergence difficulties overcome (see chapter 5.2). A simple isotropic damage model such as Mazars one is only a first step to better understand and predict building behaviour, but more realistic models are also less easy to handle with and then quickly unsuitable for engineer uses.

7 REFERENCES

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