Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division VII

STRUCTURAL ASSESSMENT OF A FRENCH PRE-STRESSED CONTAINMENT STRUCTURE: MECHANICAL STUDY IN SITUATION OF SEVERE ACCIDENT AND EXPERIMENTAL RESEARCH PERSPECTIVE

Julien Clément[1], Georges Nahas[2], Benjamin Richard[3], François Tarallo[4]

[1] Nuclear engineer, Structural Performance Modeling and Analysis Laboratory, IRSN, 31 avenue de la Division Leclerc, 92260, Fontenay- aux-Roses, France (julien.clement@irsn.fr)
[2] Research engineer, Structural Performance Modeling and Analysis Laboratory, IRSN, 31 avenue de la Division Leclerc, 92260, Fontenay- aux-Roses, France (georges.nahas@irsn.fr)
[3] Head of the Structural Performance Modeling and Analysis Laboratory, IRSN, 31 avenue de la Division Leclerc, 92260, Fontenay- aux-Roses, France (benjamin.richard@irsn.fr)
[4] Civil Engineer - Senior Expert, Equipment and Structure Assessment Department, IRSN, 31 avenue de la Division Leclerc, 92260, Fontenay- aux-Roses, France (francois.tarallo@irsn.fr)

ABSTRACT

Some French pressurized water reactors (PWRs) include a double containment structure, the inner one being made of a pre-stressed concrete wall. Leak tightness of the latter is a fundamental safety requirement for the reactor building. Within the framework of the level 2 probabilistic safety assessments (PSA), studies of the inner containment vessel behavior subjected to severe accident conditions have been performed by IRSN. The loading scenario lies in the total loss of the electrical sources, which led to the core meltdown and then, to the breakthrough of the reactor vessel by the corium. In this context, mechanical simulations with a three-dimensional model have been carried by IRSN with the objective of assessing the behavior of the containment under inner pressure and thermal loads. The results show that, for extreme temperatures, damage by concrete cracking develops firstly in the dome. Under most severe loadings, for instance, the computation results show that damage may develop up to 50% of the wall thickness from the outer face to the inner face. The thermal field computed is such that temperature in the beams placed under the dome quickly rises over 100°C whereas the temperature evolves more slowly in the major part of the thickness of the dome wall. The difference in temperature between the beams and the dome's and the thermal strains induced tends to explain most of the damage computed with the model.

INTRODUCTION

French nuclear power plant (NPP) fleet under operation consists in fifty height pressurized water reactors (PWRs). In order to ensure leak tightness of the third barrier, two designs are used: either single-wall pre-stressed concrete containment with a metal liner, or a double-wall with an outer reinforced concrete containment in combination with internal pre-stressed containment without liner and a depressurized annulus between them. Among those fifty height reactors, twenty four see their leak tightness ensured by a double-wall containment. For this type of containment, the operating criterion is the overall rate of leak through the internal wall during the periodic pressure test occurring every ten years.

Within the framework of the level 2 probabilistic safety assessments (PSA), IRSN studies the behavior of the double-wall containment subjected to severe accident conditions. The loading scenario lies in the total loss of the electrical sources, which leads to the core meltdown and then, to the breakthrough of the reactor vessel by the corium. This scenario results in an increase of the inner pressure and an overheating of the gas in the containment, as described by the curves in Figure 1. The time evolution of the different thermohydraulic parameters (pressure, temperature, flux, etc.) are calculated with the ASTEC software developed by IRSN.

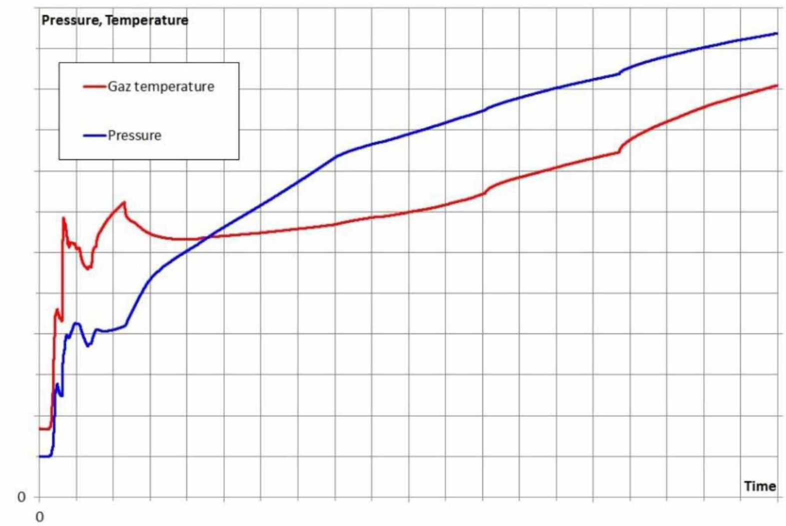

Figure 1. Evolution of the inner pressure and gas temperature with respect to the time. The approximately maximal pressure and temperature are respectively 10 bars and 200 °C after one week.

To assess the behavior of the containment under these particular thermohydraulic conditions, mechanical simulations using the CAST3M finite element software, developed by CEA, have been carried out by IRSN. This paper describes the mechanical study performed, focusing on a specific behavior of the containment's upper part, the dome. In the following, we'll firstly focus on the results in the dome part obtained with a calculation performed on a complete three-dimensional model of the containment, then in a second step, we'll present the calculation performed on a refined local model of the dome itself.

STUDY ON THE COMPLETE MODEL

A first calculation has been made with a three-dimensional model of the containment structure. As shown in Figure 2, concrete has been meshed by solid finite elements, rebars and pre-stressing tendons have been meshed by truss finite elements. The main openings (down to 1 m diameter) are represented with a refined mesh for the equipment hatch area. In addition, a coarser mesh of the outer wall, the internal structures and the soil is used to save computational time. Finally, a surface mesh of the system that ensures the enclosure of the hatch (tampon, brides and ferrule) is also introduced. The mechanical calculations are carried out using nonlinear constitutive laws for both concrete (OTTOSEN constitutive law, Charras and al (1995) and Ottosen and al (1979)) and steel[1].

Before applying pressure and thermal load on the structure, the initial stress and strain states have to be determined. In particular, the compressive stress in concrete due to pre-stressing must be taken into account. The nonlinear solver is based upon the well-known incremental/iterative method. More specifically, seventeen steps are considered to apply the full pre-stressing. At each step, thirty to forty tendons are considered. At each step, mechanicals loads taken into account are the incremental forces of tensioning, the variation of delayed strain from the previous state (NF EN 1992-2 (2005), Raphael (2002)

[1] The behaviour of the outer wall, the internal structures and the soil are considered as linear elastic as they are not of primary interest in this study.

and RCC-CW (2016)) and the dead loads. Figure 3 shows the stress state in the containment at the end of the seventeen tensioning steps. A noticeable variation of the stress distribution over the containment can be observed. The severe accident occurs after forty years of operation. Therefore, the initial state of the containment is calculated by taken into account forty years delayed strain.

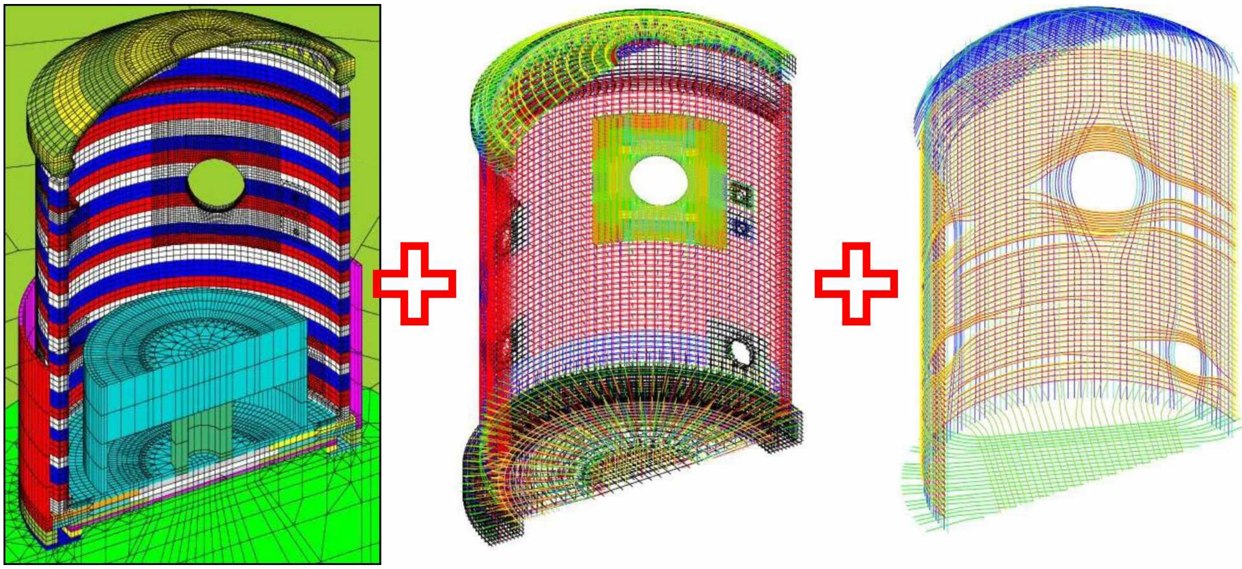

Figure 2. Mesh of the containment vessel. From left to right: the concrete (with simplified mesh of the outer wall, inner structures and soil), rebars and pre-stressing tendons.

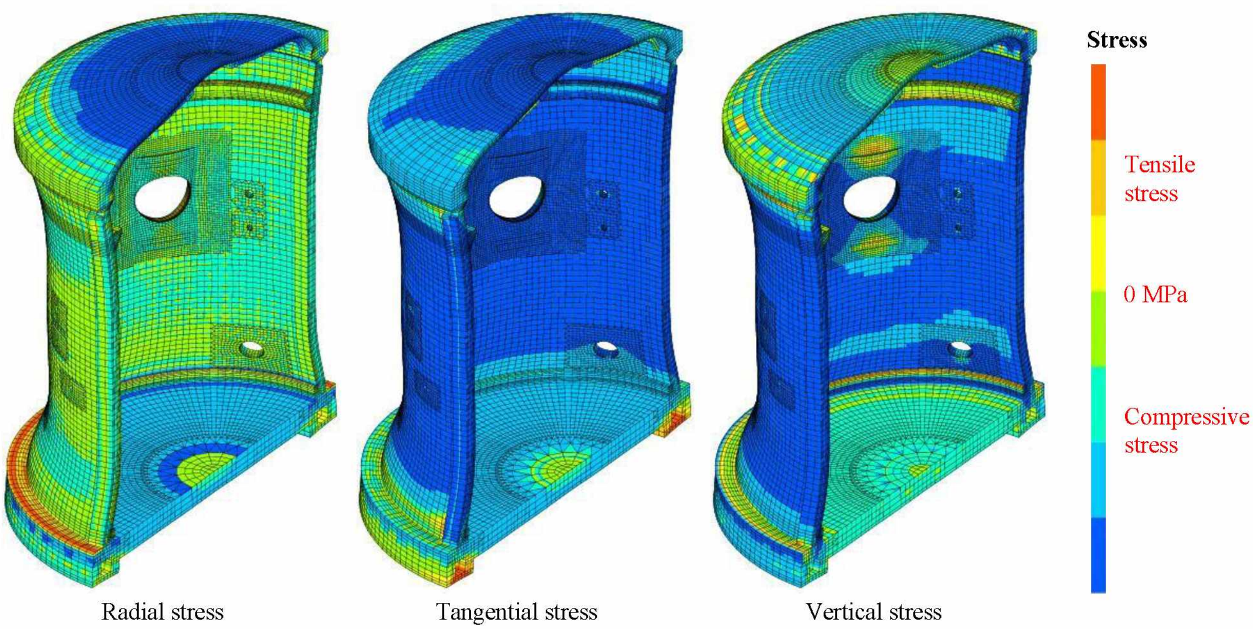

Figure 3. Stress state distribution in the inner wall at the end of the tensioning. Mechanical loads are dead loads, tensioning forces, and forces induced by the delayed strains.

Once the initial state is obtained, the simulation of the severe accident is carried out. It is performed with a step by step strategy adding an incremental mechanical load of pressure and temperature at each step. This approach enables to know the behavior of the containment at different times of the severe accident.

Therefore, one of the main results is that soon after the beginning of the scenario (about 12 hours) and for a low pressure level (between 3 and 5 bar), a large damage area appears in the dome model, as shown in Figure 4. Although this damage does not represent continuous cracks from one side of the dome to the other, the model shows damage developing in more than half of the whole dome thickness.

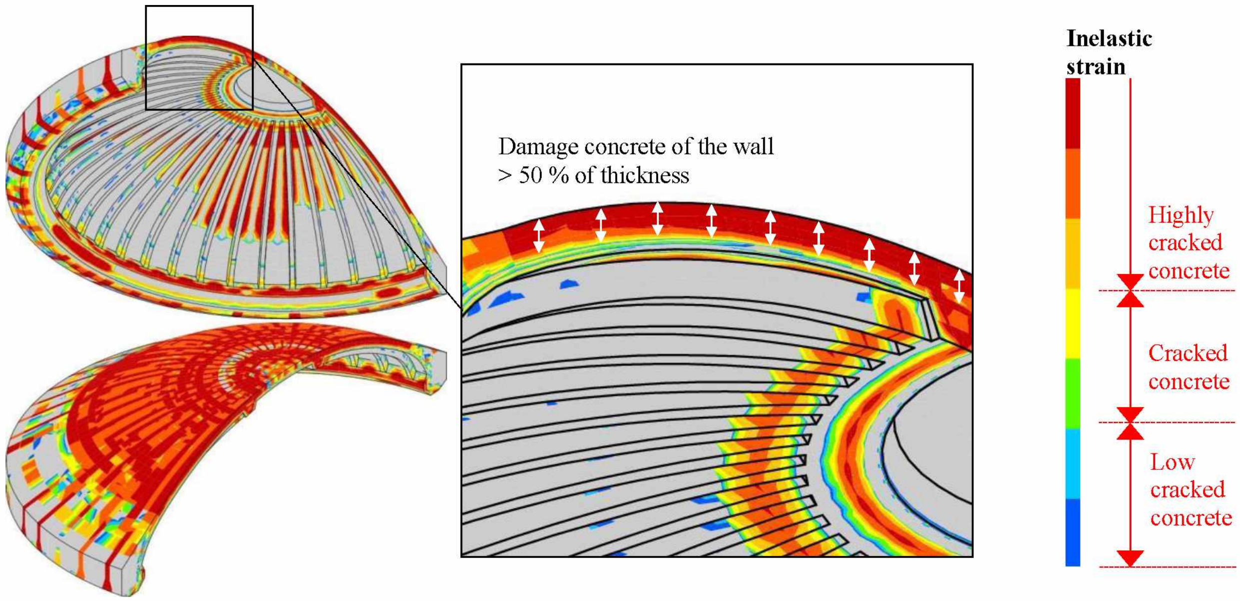

Figure 4. Result of the crack opening (sum of the inelastic strains for the three directions) about half a day after the start of the accident.

Such a behavior is specific to certain geometries of French containments (N4 and P'4) and is likely caused by the thermal dilatation of precast beams in the dome model during the severe accident, as shown in **Figure 5**. Indeed, the thermal flux penetrates the beams by three sides whereas it penetrates the wall by one side. Therefore, the temperature of the beams rises quite quickly (over 100°C) compared to the one of the wall. This induces a bending moment, putting in tension the outer face of the wall. It must be mentioned that this specific behavior was not expected. To save computational time, one single finite element in the precast beams width has been considered. However, this is not sufficient to describe correctly the thermal gradient and that is why a second calculation with a more refined mesh was carried out. This latter model is named the local model. It is presented in next section.

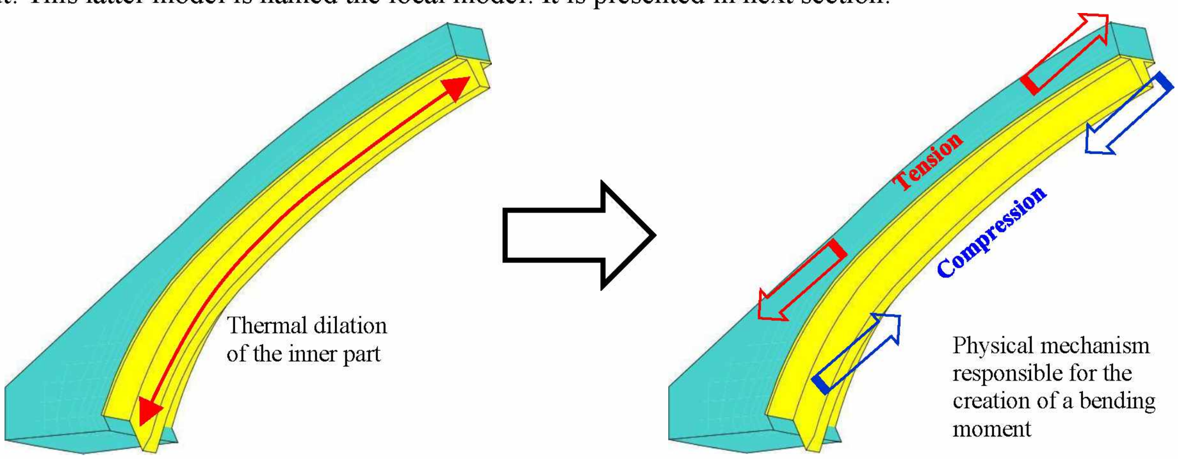

Figure 5. Differential expansion between the beams of the dome and the wall.

STUDY ON THE DOME LOCAL MODEL

A local model of the dome has been developed, as shown in **Figure 6**. The global modal is reduced to keep only the part above the lower face of the edge of the beam which supports the polar crane bridge. The mesh is very similar to the previous one, excepted for the precast beams and for the top of the dome which have been refined. The initial stress and strain states for the local model at the time of the assumed severe accident (40 years) are obtained from the results of the calculation of the initial state on the global model. In addition, the boundary conditions under the edge beam related to the polar bridge (displacement during severe accident) lie in applying the displacement over time calculated on the global model at each time step of the simulation of the severe accident.

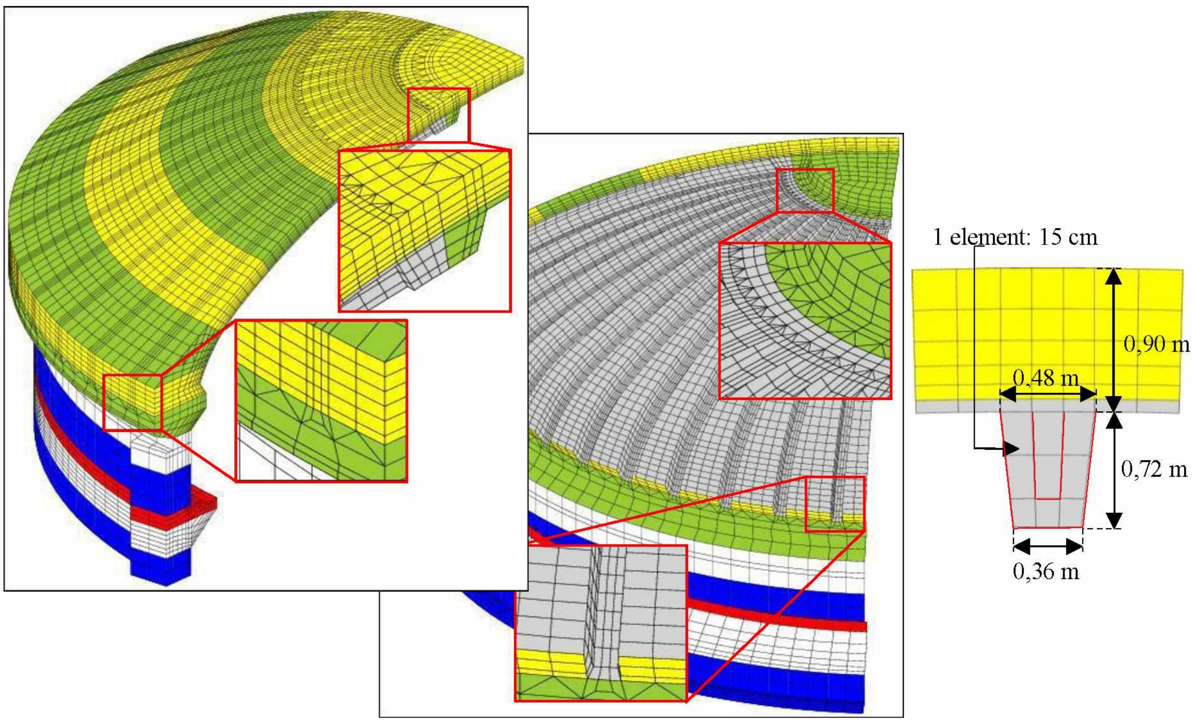

Figure 6. Concrete mesh of the local dome model.

The local model globally follows the same behavior as the global model. In addition, results also show that there is still about 20 cm of compressed concrete on the inner face of the dome and that rebars on the outer face still behave in elastic range. Therefore, there is no risk of structural collapse nor of potential loss of leak-tightness as long sufficient thickness of concrete remains under compression. In any case, such predictions include uncertainties that need to be investigated in order to consolidate the conclusion.

Besides the abovementioned response, the mesh refinement enables to observe an even more specific behavior. As shown in **Figure 7**, early after the start of the scenario, circular cracks open in the center of the dome (the central "clavage") and under the toroidal belt. Again, these are not continuous cracks from one side to the other, but computed damage appears to develop through about 80% of the wall thickness from the outer face of the wall. **Figure 8** shows views on a radial/vertical plan of the deformed shape of the containment. As it can be seen, the comparison between strains at time of the start of the scenario (t=0) and at time of the early cracking indicates there are rotations of the two massive parts of the dome that are the circular beam of the central clavage and the toroidal belt. Because of tensile forces associated to rotations, early cracks appear in the vicinity of those two massive parts. This rotation might be due to the heating of the precast beams for which elongation generates thrust on the lower part of those massive structural members.

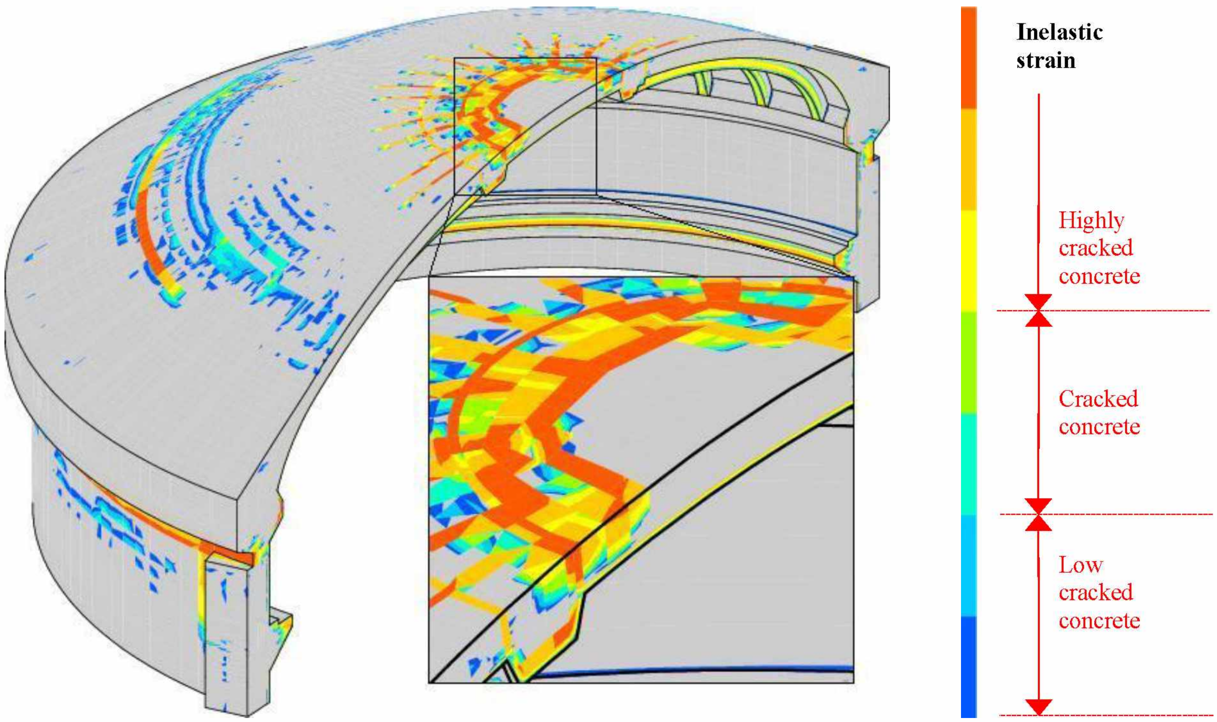

Figure 7. Concrete crack opening estimation right after the start of the scenario.

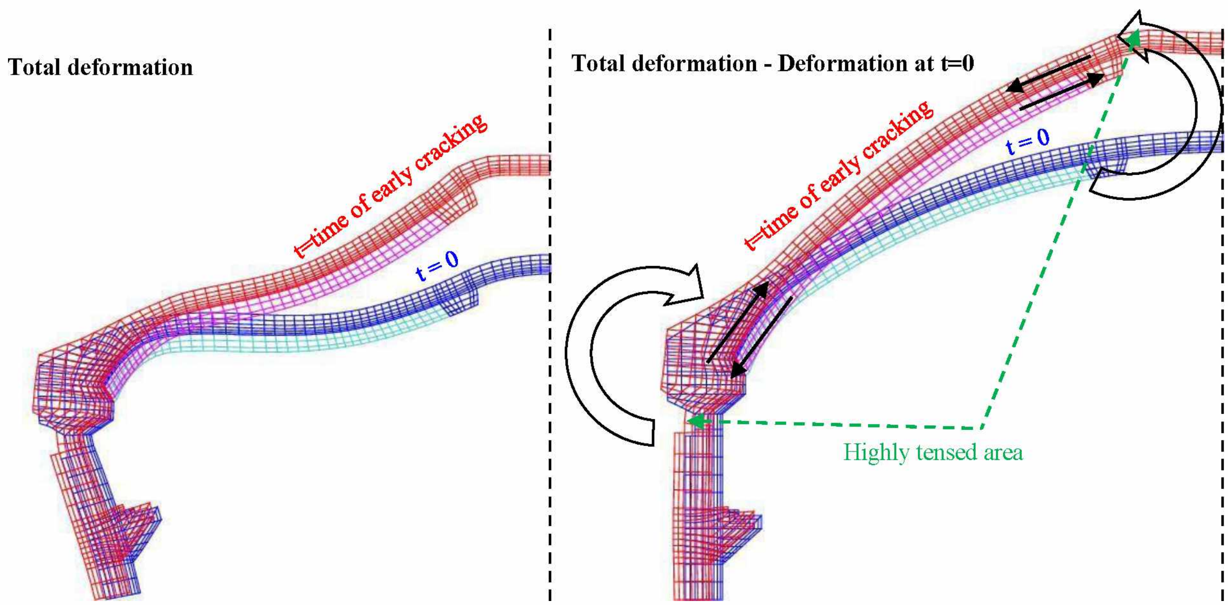

Figure 8. Comparison of deformed shapes (amplification factor equal to 200) between the time at the start of the scenario (t=0) (in blue) and the time of the early cracking (in red). On the left, the total deformed shape; on the right the total deformed shape minus the deformed shape at the start of the scenario (in blue).

CONCLUSION

In the framework of PSA studies, IRSN developed a model of the mechanical behavior of the inner wall of French double-wall containments under inner pressure and thermal loads. For some of them (N4 and P'4 containment geometry), calculation shows a particular behavior in the dome area:

- under thermal load, precast beams located on the inner face of the modeled dome heat up quickly as they are subjected to a three-faces thermal flux. The resulting elongation of the precast beams generates thrust on the lower part of the two massive areas upon which the beams are supported: the central clavage and the toroidal belt. This leads to a rotation of these members which locally increases the damage parameter in the outer face at the center of the dome and under the toroidal belt;

- soon after, the increasing temperature in the precast beams leads to a significant difference of elongation between the wall and the precast beams. This leads to the development of a bending moment which puts in tension the outer face of the dome, leading to an increase of the damage computed, reaching about 50 % of the wall thickness.

It can be noticed that these results are obtained for a moderate value of the inner pressure. Therefore, the main reason which explains why the abovementioned behavior appears is due to the thermal gradient between the wall and the precast beams. Furthermore, the results also show that there is still about 20 cm of compressed concrete on the inner face of the dome and that rebars on the outer face still behave in elastic range. Therefore, there is no risk of structural collapse nor of loss of leak-tightness as long sufficient thickness of concrete remains under compression. Finally, it must be mentioned that the interpretation of the results obtained in this study needs further discussions. Indeed, advanced methods were used to obtain such results and therefore, it is recognized they are subjected to uncertainties. However, orders of magnitude and the trends observed in that study might not be changed.

REFERENCES

Barré F., (2011) *Containment technology - Containment design*, course material, ESTP Nuclear Civil Engineering option.

Charras Th., Combescure A., De Mersseman B., and Millard A. (1995). *Introduction du modèle OTTOSEN dans CAST3M2000 - Formulation, implantation*, CEA repport DMT/94-705.

NF EN 1992-2 (2005) *Eurocode 2: Design for reinforced concrete structure – Part 2: Concrete bridges*.

Ottosen N. S. (1979) *Constitutive Model for Short-Time Loading of Concrete*, Journal of the Engineering Mechanics Division ASCE 105, p.127-141.

Raphael W., Kaddah F., Geara F., FavreJ.-L., and Calgaro J.-A. (2002). *Nouveau modèle de calcul pour la prédiction du fluage du béton*, CEA report DMT/94-705.