Ultimate Behaviour of Belgian Prestressed Containments

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1. INTRODUCTION

In Belgium, the electrical power from nuclear origin is generated essentially by seven PWR units ranging from 450 MW to 1000 MW; four of these are located at DOEL, north-west of Antwerp along the left bank of the river Scheldt and three in Tihange along the river Meuse.

The containment of the five most recent and powerful ones consists in a prestressed concrete cylinder and a torispherical dome, lined by anchored carbon steel plates.

The containments were designed for the internal pressure generated by a conventional loss of coolant accident and the associated temperature rise.

Recently, severe accident studies were undertaken by TRACTEBEL, who designed the Belgian nuclear power stations, with the objective to determine the containment behaviour under such highly hypothetical scenarios and to elaborate mitigation procedures in order to avoid catastrophic consequences.

The present paper outlines the studies and the calculations performed to determine in each Belgian prestressed containment the maximum pressure, from which the probability of a significant leak or a structural rupture is no longer negligible.

2. DESCRIPTION

The five Belgian prestressed concrete containments, although designed separately and according to successive code revisions, have a lot of similarities in their concept and their details :

- shape : cylindrical wall;
  torispherical dome;
  flat mat (nevertheless two of them include a reactor cavity);
- prestressing : horizontal, vertical and dome prestressing for all of them; moreover, three have a prestressed mat;

- liner : 6 mm plates, stiffened and anchored into the concrete generally by horizontal and vertical angles and by studs; self supporting and used as formwork;

- material : high class concrete; rebar with fy = 400 MPa, prestressing by strands with fpu $\geq$ 1700 MPa; cement grout injection; carbon steel liner fy = 275 MPa;

- size : inside wall diameter : 21.0 m (Tihange) and 21.25 (Doel);
  inside wall thickness : 0.7 m to 0.9 m;
  wall height : 50 to 60 m;
  dome radius : 30.5 to 33.0 m;
  dome thickness : 0.6 m to 0.8 m;
  mat thickness : 1 to 3 m;

- secondary containment designed for a heavy civil airplane and a military jet impact;

- LOCA pressure : from 0.3 to 0.37 MPa;

- equipment hatch : circular (diameter ± 8.8 m) or rectangular (8.1 x 6.9 m);

- discontinuities : 2 to 5 buttresses for horizontal anchorages;

- foundation : mat resting on rock or on piles.

3. CRITERIA OF ULTIMATE STATE

The ultimate pressure is determined when one of the two following ultimate states is reached :

- ultimate resistance of a meridional or a circumferential section, occurring if any additionnal pressure increment leads to gradual rupture of all the structural elements of the section (concrete, rebars, prestressing steel and liner);

- loss of tightness or leak, occurring if a liner part is so stressed or strained that it tears over a sufficient length to depressurize the containment; the concrete structure is then assumed to be cracked, such that air and vapor escape outside the containment.

We consider the following limiting strain from which a rupture is highly probable :

rebar : 10 %
liner : ε_{eq} = 14 % (von Mises equivalent strain)
prestressing : ε = 4 %

4. CONCRETE MODEL

The Fortran CONC modulus was implemented to allow 3D representation of the behaviour of reinforced/prestressed concrete submitted to multiaxial tension or compression loads. This model complies with the OTTOSEN's modified theory.

5. METHODS

Several analyses were performed involving three steps.

1. Axisymmetric analyses : the containments were assumed to have an axisymmetric geometry with no influence of the local discontinuities on the results.

2. Three-dimensional analyses of the local discontinuities : material hatch, buttresses, any contact with an external structure....

3. Considerations concerning the liner behaviour and effects of strain concentration on tightness.

6. SUMMARY OF RESULTS

6.1. Axisymmetric models

The two most representative containments were modelised axisymmetrically (see figures 1 and 2).

Both simulations converged to similar results at the ultimate state :

- ultimate pressure equal to 2.4 times the design pressure;
- ultimate strength controlled by dome prestressing steel rupture;
- wall lateral displacement, at this pressure, of approximatively 0.05 m, which corresponds to ten times the elastic deformation under design pressure;
- reinforcement steel strain in the vicinity of the rupture area in the range of 3.5 ‰ (far below the criteria);
- liner average equivalent strain is less than 1 % everywhere, even in the rupture area (concentration factor excluded);
- concrete fully cracked in the dome and in the wall both meridionally and circumferentially; wall/dome junction is partially cracked, no cracking in the mat;
- rupture for the first simulation takes place at the spring of the dome with a displacement at the top of 0.08 m; for the second simulation the rupture appears at the top so that a larger displacement of 0.12 m results.

One of these two simulations was conducted with and without thermal effects, allowing to conclude that the thermal shock has no effect on the results at ultimate pressure, but influences the stress and strain history to get this final state.

6.2. 3 D Models

3D models are performed to determine the effects of local discontinuities. The early results of these studies are summarized as follows.

- The buttresses do not affect the ultimate behaviour of the containment; for low pressure, a buttress acts as an external stiffener of the cylinder and induces a non axisymmetrical response of the structure; for higher pressure and after cracking of concrete, this stiffener effect vanishes and the structure tends to behave as a perfect cylinder. No strain concentrations were found in the liner near the buttresses.

- With some containments, a contact with an external structure is possible at high pressure : this is the case with biological concrete around the fuel inlet penetration at mid-height of the cylinder. For the most unfavourable value of the gap between the cylinder and the external structure, a strain concentration factor c = 3.4 appears in the liner (the c factor is defined in paragraph 7).

- The behaviour of the structure around the equipment hatch (seals and doors are not included in these studies) is of major concern. For the structures reviewed to date, this part of the containment does not appear to be a weak point. A slight strain concentration factor appears near the opening.

  If the 3D models of local discontinuities reviewed so far do not appear to reveal as weak point in their own containment, it must be emphasized, however, that this conclusion may not be generalized for all containments. Only a case by case analysis can describe the behaviour of the discontinuities as a part of the structure.

7. LINER AND ANCHORAGE BEHAVIOUR

The liner is made of 6 mm thick steel plates. The anchorage system for the cylinders and domes is generally made of a rectangular frame of angles. The design of this frame was intended to provide as much as possible continuous angles. Nevertheless the angles frame had to be interrupted around penetrations without connection with the flange.

Several elastoplastic analyses of the area around a penetration were performed in order to determine the strain concentration factor c, i.e. the ratio between the average strain and the strain close to the discontinuity.

It can be shown that a strain concentration factor $c > 15$ corresponds to a leak in the liner ($\varepsilon eq = 14$ %) even though the strain in the prestressing steel remains below the yield point ($\varepsilon < 0.2$ %).
On the contrary, a factor $c < 2$ corresponds to a break of the prestressing steel ($\varepsilon > 4$ %) with the liner remaining gastight ($\varepsilon eq < 14$ %).

We can conclude the following.

- The transition area between the liner and the flange, complying with ASME III division 2 requirements, does not induce large strain concentration (no pinching effect).

- There is a large strain concentration factor where the liner anchorage system is interrupted : the angles welded perpendicularly to the frame surrounding a penetration do not spread smoothly the plastic strain over the plate.

  In this analysis, the adjacent concrete was modelled by equivalent springs. Boundary values of those springs were estimated from available data. The resulting strain concentration factor is in the range of c = 8 to c = 12. A coefficient has to be taken over this value, as a margin to cover uncertainties on the geometry, material, welding, etc.

  This coefficient appears then to be the governing parameter for the ultimate behaviour of prestressed containments where the liner is anchored by continuous angles. Indeed all those containments have penetrations in the cylinder and several have penetrations in the dome. All have discontinuities in the dome anchorage system.

  By comparaison with the criteria of § 3 we can say that, if a prestressing component yields in the cylinder or in the dome, it is most likely (but not 100 % certain) that a leak of the liner will preclude any break in the same area.

For the containments under review, the weld between cylinder and mat does not seem to govern the tightness.
Indeed, in spite of a large strain concentration factor, due to the prestressing and the gusset, any plastic strain only appears after the yield has already been reached elsewhere.

8. CONCLUSIONS

By the studies undertaken for the five Belgian prestressed concrete containments, we can presently conclude that the structural part of these containments (excluding penetration and equipment) behaves in a very homogeneous way : when rupture occurs in a certain area, the strain everywhere else is also close to the ultimate limit.

The probability is high of having a rupture at an internal pressure close to 2.5 times the design pressure. Rupture is initiated by prestressing steel breaking, more or less at the same pressure as anticipated by the preliminary estimation considering that the wall and dome act as a membrane. The discontinuities, involved here, whether circumferential or local do not appear to be weak parts of the structure.

Despite the relatively small order of magnitude of the average liner strain, which should bring the ultimate leak pressure to very high values, strain concentration factors calculated by case by case studies (c up to 12) are sufficient to lower the leak pressure to the same level as the structural rupture pressure : at the best only 0.01 MPa separates both pressures.

For that reason, it is not allowed to state precisely which failure mode prevails between leak or break.

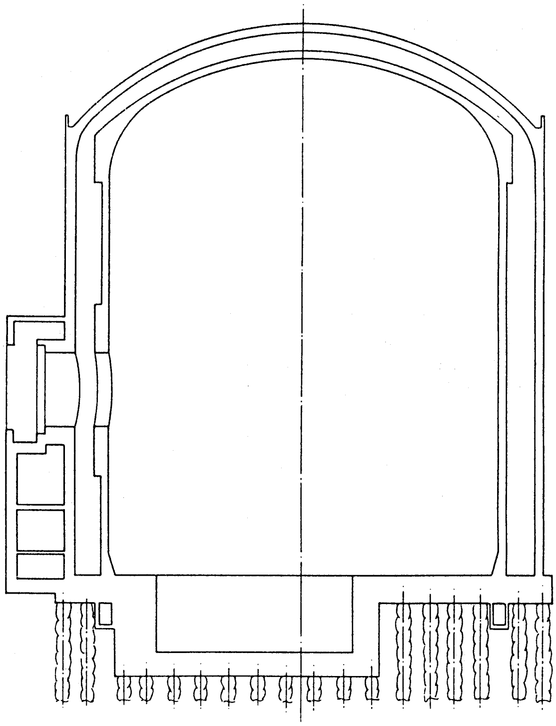

Figure 1 : Vertical section of DOEL unit 4 primary and secondary containment.

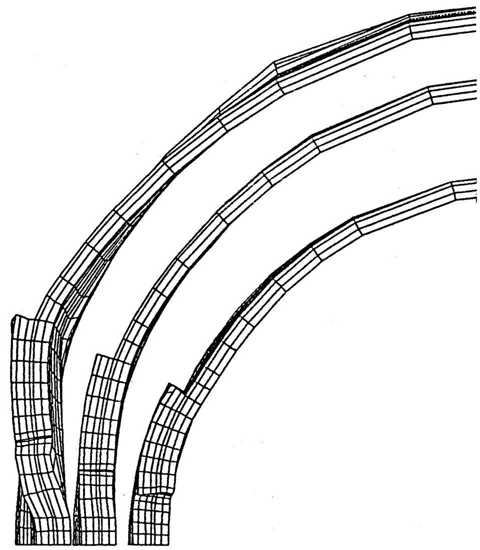

Figure 4 : 3D model of the equipment hatch opening horizontal section of one fourth of the cylinder. Deformed structure at ultimate pressure = 0,825 MPa, at 0,6 MPa (fig. 4.b) and at 0 MPa (fig. 4.c).

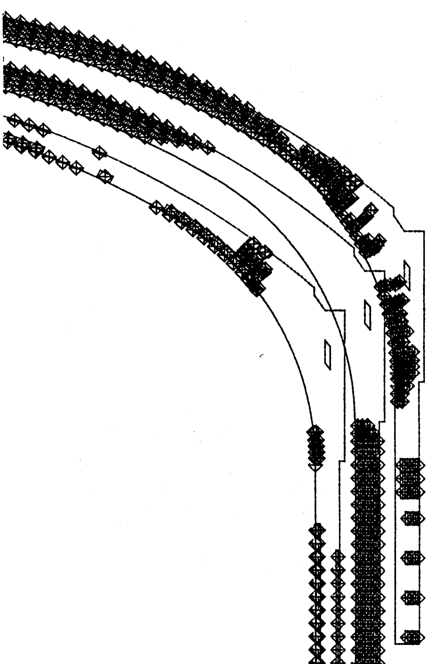

Figure 3 : 2D model of wall and dome, results at ultimate pressure : plastified rebar (fig. 3.a), concrete cracking due to circumferential stresses (fig. 3.b), concrete cracking due to meridional stresses (fig. 3.c).

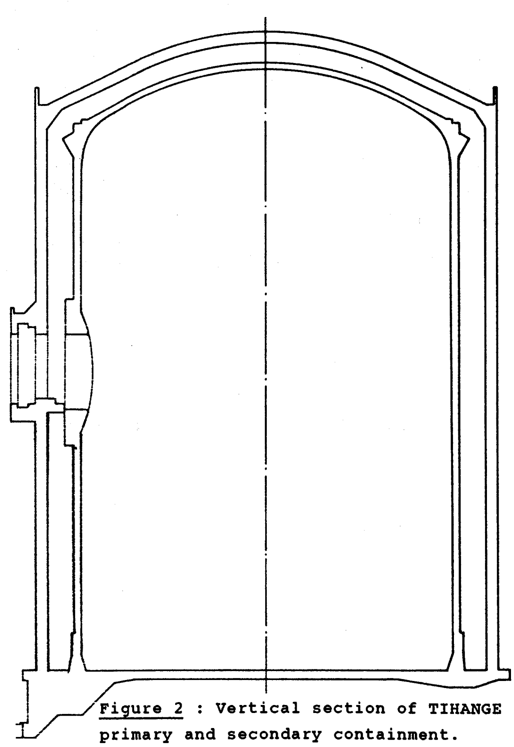

Figure 2 : Vertical section of TIHANGE 3 primary and secondary containment.