Pretest Analysis of a 1:4 Scale Prestressed Concrete Containment Vessel

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Abstract: PRINCIPIA is one of the seventeen organizations who performed numerical simulations of a Prestressed Concrete Containment Vessel (PCCV), in the context of a Pretest "Round Robin" analyses. The goal of the calculations was to predict the response of a 1:4 scale PCCV, before it was subjected to internal pressurization up to failure.

All the participants were given the same documentation package with the description of the PCCV, and were asked to submit prediction of the evolution of a number of variables at specific points, to be monitored later during the test. This allowed direct comparisons with the actual outcome in the test and also between the various participants.

This paper summarizes the modelization and results obtained by PRINCIPIA, as well as some comparisons with other participants. Since it was an ultimate capacity test, the analyses must account for all the non-linearities in the problem: geometric non-linearity, cracking and plastic flow in the concrete and sliding of the prestressed tendons. PRINCIPIA carried out the analyses with ABAQUS/Standard.

1.- Introduction

1.1.- Preamble

The US Nuclear Regulatory Commission (NRC) and Nuclear Power Engineering Corporation of Japan (NUPEC) organised and sponsored a program to investigate the actual performance of nuclear containments beyond the design pressure. The program included several stages, one of them being the construction and internal pressurization up to failure of a 1:4 scale Prestressed Concrete Containment Vessel (PCCV). In this scope, organizations world-wide were invited by NRC and NUPEC to conduct numerical predictions prior to the development of the test. PRINCIPIA accepted this challenge and received the standard documentation package, which included a detailed description of the containment and the test planned.

1.2.- Goal

The containment was instrumented with strain gages and load cells in order to monitor the response during the test. The participants were asked to predict the evolution of variables at 55 Standard Output Locations. The variables included displacements, strains and forces; the locations had been selected to be representative of the containment response. Direct comparisons with the test and with the outcome and the other participants could therefore be done at 55 points.

1.3.- Participants

A total of seventeen participants registered and carried out predictive analyses. Nuclear regulators, utilities, laboratories, universities and consulting companies were involved. Eight of seventeen participants, including PRINCIPIA, used ABAQUS in their calculations. Table 1 lists all the participants and the numerical tools that they used in the analyses (Hessheimer, 2001).

2.- Modelization

2.1.- Description and general assumptions

The concrete containment is a cylinder capped with a half sphere. The overall height is 16.4 m and the radius is 5.3 m. The wall thickness of the cylinder is 0.32 m, reduced to 0.27 m in the dome after the transition of the springline. The lower part of the cylinder is fixed to a basemat with 3.5 m thickness, which completes the structure of the containment. Apart from the passive reinforcement, the concrete has prestressing tendons in both meridional and hoop directions. Finally, a liner of 1.6 mm of thickness is anchored as an internal skin. Figures 1 and 2 show a photograph and a schematic drawing of the containment.

Some details of the PCCV break its cylindrical symmetry. These are the equipment hatch, the personnel airlock, the main steam and feedwater penetrations. However, most of the monitored locations were sufficiently removed from the singularities to allow treating the structure as axisymmetric.

2.2.- Materials

The properties of the materials were derived from a statistical treatment of the data produced in destructive tests. Median values of strength were assigned to concrete, reinforcement steel, prestressing tendons and liner steel.

Classical metal plasticity was used to model the steel properties. Mises yield criterion and isotropic hardening plasticity were assumed for all the steel members. The properties of the liner and the tendon steel are presented in Table 2. The reinforcement rebars were made in various types of steels, showing the table their range of variation.

On the other hand, concrete required a sophisticated model capturing also cracking and softening of the material. The *CONCRETE model in ABAQUS includes an isotropically hardening yield surface in compression and a crack detection surface in tension. Beyond the failure in tension, the material softens as provided in the *TENSION STIFFENING option. The model is a smeared crack model, not tracking individual cracks, but the cracking directions. In addition, it is able to capture orthogonal cracking, like the expected behavior in the failure of the containment.

The cylinder and dome of the containment were built in concrete type C45, whereas the basemat was built in concrete type C29. Their properties are presented in Table 3.

2.3.- Mesh

Second order axisymmetric bricks were used to model the structure; the steel reinforcement was included as embedded rebars into these continuum elements. The liner was meshed with axisymmetric second-order shells. Hoop tendons were simulated as rebars, whereas the vertical tendons were modeled as prestressed trusses.

The sliding of vertical trusses was allowed, thus the analysis incorporated the contact between tendons and sheaths. The mesh is presented in Figure 3.

2.4.- Boundary conditions and loads

The ground under the basemat was assumed to be an elastic foundation. The design pressure of the containment (0.39 MPa) was applied first; pressure was then ramped up to failure. Once the analysis entered in a highly non-linear range close to failure, convergence became progressive more difficult.

The *STATIC, STABILIZE capability in ABAQUS was used in subsequent steps to add viscous forces that helped to reach equilibrium. Non-stabilized steps were also added to remove these artificial forces, check the actual equilibrium, and control the amount of viscous energy added to the model.

3.- Pre-test results

The complete predictions produced for the standard output locations can be found in (Luk, 2000). Figures 6 to 9 present four of them. PRINCIPIA's results can be summarized as follows: The containment is expected to behave linearly up to 2.0 times the design pressure. Between 2.0 and 3.6 times the design pressure, successive cracking of concrete, and liner and rebar yielding change the stiffness of the structure. Finally, the yielding of the hoop tendons leads to the failure.

The predictions of the main milestones of the process are presented in Table 4.

4.- Comparison of results

All the organisations provided results at the same 55 standard location points, which allowed direct comparison between all of them. The compared results can be found in (Luk, 2000).

Figures 5 and 6 present the calculated displacement at mid height of the cylinder and top of the dome. The compared strains of the vertical and hoop rebar at mid height are depicted in Figures 7 and 8.

It can be seen that the linear behavior could be predicted well by all the participants. However, beyond the linear range the results, when provided, begin to diverge.

5.- Conclusions

Ultimate capacity tests are always a very good benchmark to test the non-linear capabilities of both the numerical tool and the modeling team. The test mentioned provided an excellent opportunity. Seventeen organisations accepted to test their codes and know-how against a strongly non-linear event, like the ultimate capacity of a nuclear containment. PRINCIPIA built in ABAQUS an axisymmetric model with library elements and materials, combined with its stabilization capabilities.

The final predictions issued by PRINCIPIA were:

- Linear behavior of the PCCV is expected up to 2.0 times the design pressure. At this point, vertical cracks become significant and change the stiffness of the containment.
- Hoop rebars start yielding at 2.9 times the design pressure, while vertical rebars yield in the range of 2.9 and 3.3 times the design pressure.
- The Limit State is approximately given by the yielding of the horizontal tendons, which occurs between 3.3 and 3.6 times the design pressure.

6.- References

1 - Hessheimer, M.F., (2001) "Pretest Round Robin Analysis of 1:4-Scale Prestressed Concrete Containment Vessel Model", Workshop in the SMiRT 16, Washington DC.

2 - Luk, V. K., (2000) "Pretest Round Robin Analysis of a Prestressed Concrete Containment Vessel Model", NUREG/CR-6678. Albuquerque, NM: Sandia National Laboratories.

7.- Tables

Table 1 - Participants in the PCCV Round Robin

Organization	Country	Code
Atomic Energy of Canada Limited (AECL)	Canada	ABAQUS
Argonne National Laboratory (ANL)	United States	Neptune
Comissiariat à l'Énergie Atomique (CEA)	France	Castem 2000
Électricité de France (EDF)	France	Aster
University of Glasgow	United Kingdom	In-house code
Health and Safety Executive (HSE)	United Kingdom	ABAQUS
Nuclear Safety Institute (IBRAE)	Russia	CONT-2D &3D
Institute of Nuclear Energy Research (INER)	Rep. of China	ABAQUS
Institut de Protecction et Sûreté Nucléaire (IPSN)	France	Castem 2000
Japan Atomic Energy Research Institute (JAERI)	Japan	ABAQUS
The Japan Atomic Power Company (JAPC)	Japan	FINAL
Korea Institute of Nuclear Safety (KINS)	Korea	DIANA
Korea Power Engineering Corporation (KOPEC)	Korea	ABAQUS
Nuclear Power Engineering Corporation (NUPEC)	Japan	ABAQUS
PRINCIPIA	Spain	ABAQUS
Russia Int. Nuclear Safety Center (RINSC)	Russia	DANCO
Sandia National Laboratories/ANATECH	United States	ABAQUS

Table 2 - Steel properties

Element	Property	Value
Liner	Yielding stress (MPa)	370
Liner	Ultimate stress (MPa)	600
Liner	Ultimate strain	0.2
Tendon	Yielding stress (MPa)	1750
Tendon	Ultimate stress (MPa)	2050
Tendon	Ultimate strain	0.08
Rebar	Yielding stress range (MPa)	375 - 530
Rebar	Ultimate stress range (MPa)	600 - 780
Rebar	Ultimate strain	0.2

Table 3 - Concrete properties

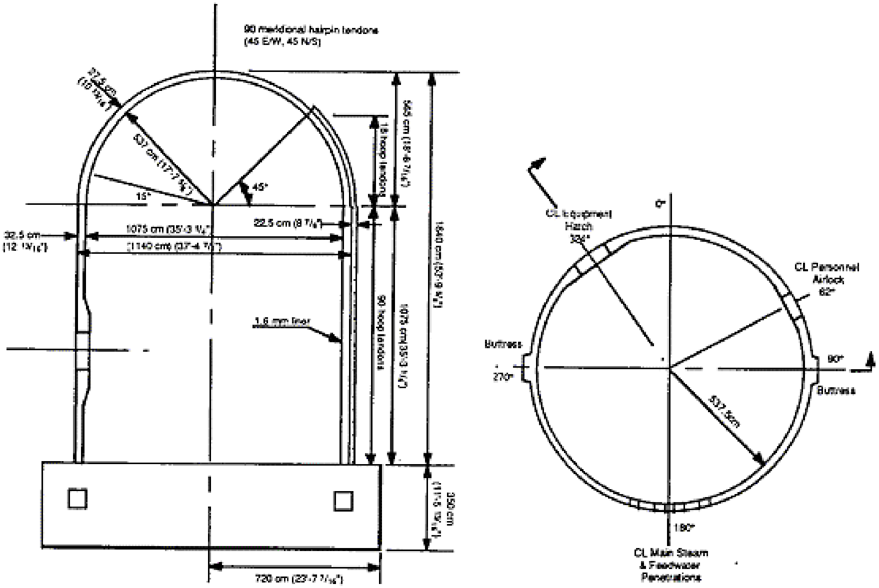
Type of concrete	Property	Value
C29	Compressive strength (MPa)	44
C29	Tensile strength (MPa)	3.6
C45	Compressive strength (MPa)	55
C45	Tensile strength (MPa)	3.6

Table 4 - Predicted sequence of events

P/P_{design}	Event
1.7	First cracking in cylinder in hoop direction
2.0	First significant change in stiffness
2.6	Liner starts yielding
3.0	First cracking in cylinder in meridonal direction
2.9	Hoop rebars start yielding
3.0	Vertical rebars start yielding
3.3	Hoop tendons start yielding
3.6	Failure of the containment

8.- Figures

Figure 1.- Photograph of the PCCV



Figure

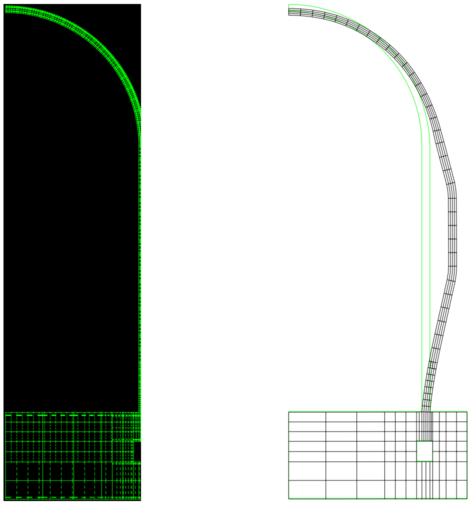


Figure 3.- Original mesh and deformed shape at 3.6 P/Pd

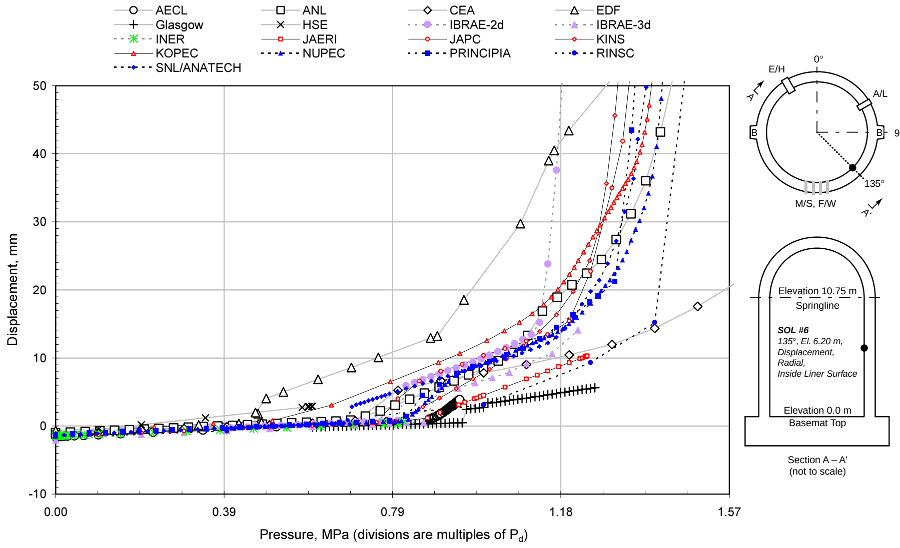


Figure 6.- Compared radial displacement at mid height vs. pressure

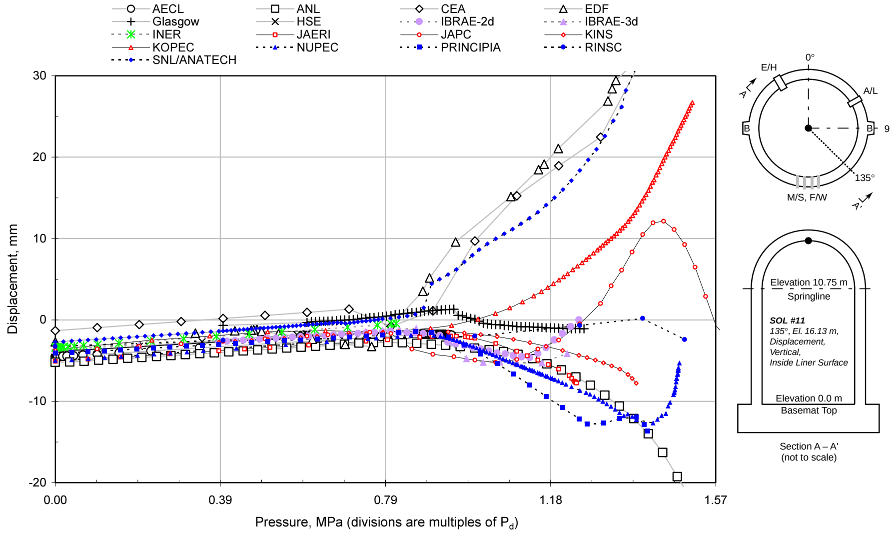


Figure 7.- Compared vertical displacement at dome vs. pressure

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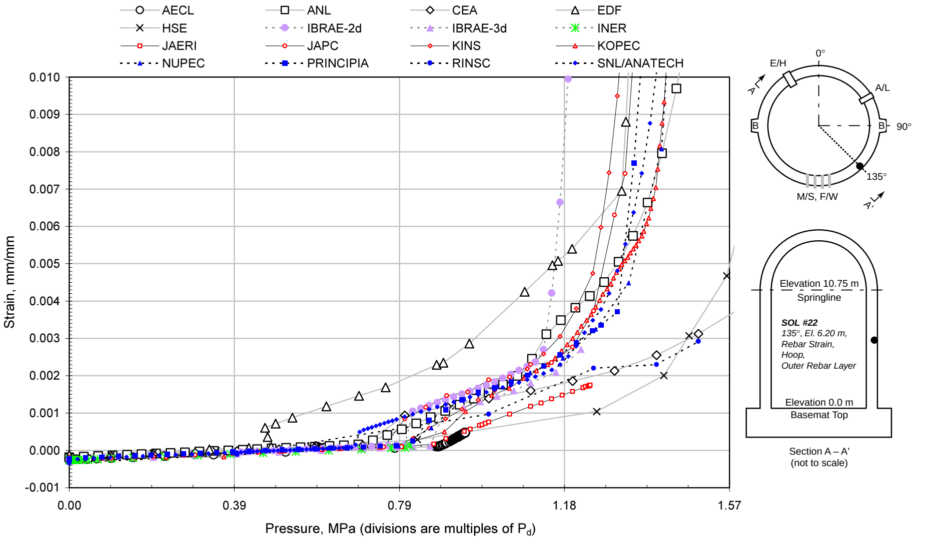

Figure 8.- Compared vertical rebar strain vs. pressure

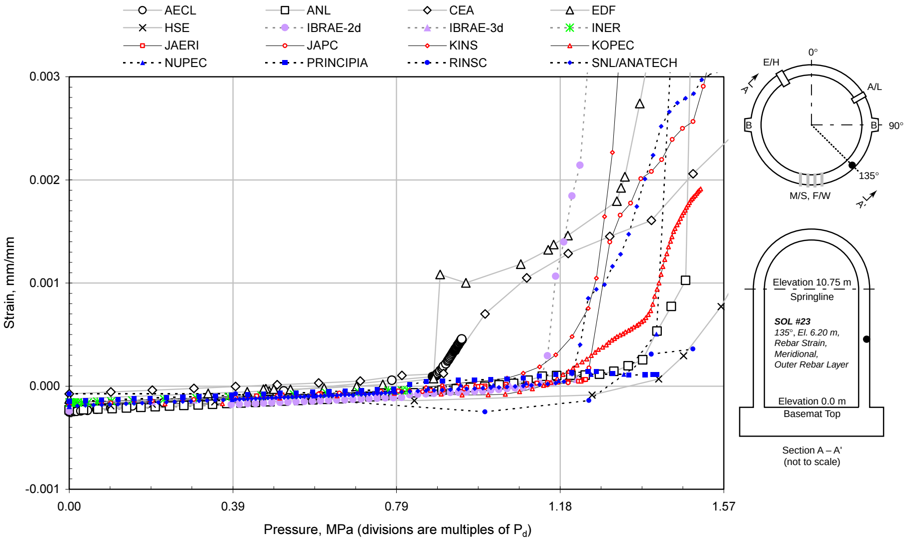

Figure 9.- Compared hoop rebar strain vs. pressure