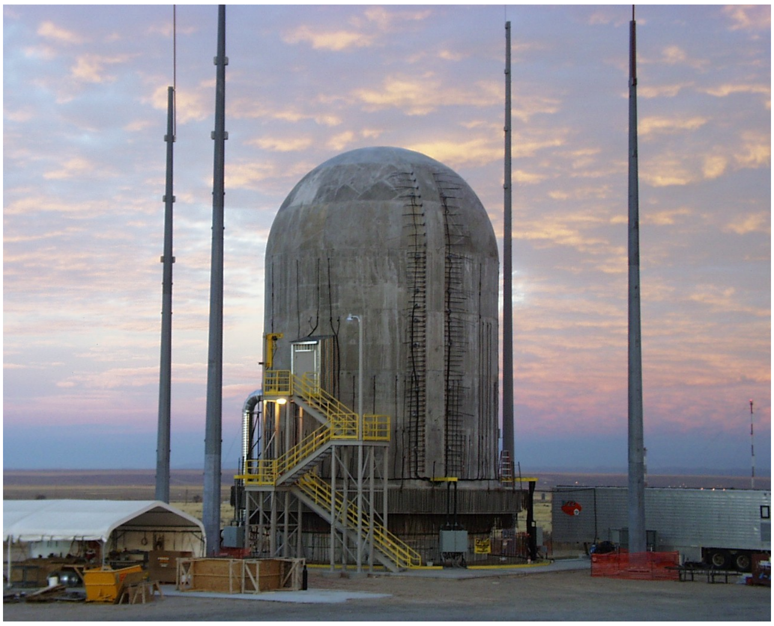
AC&E Case Study – FEA Visualisation

Modelling Structural Failure of Pre-stressed Concrete Structures

Accurately predicting failure modes and limit loads of pre-stressed concrete structures, using finite element analysis, is one of the most difficult challenges for engineers. Developing an accurate method of modelling the performance of a pre-stressed concrete containment vessel was the subject of a round robin analysis held by the Sandia National Laboratories (SNL) USA.

Under a UK Health and Safety Executive contract, National Nuclear Corporation (NNC) took part in the round robin, along with sixteen organisations from USA, Canada, France, Japan, Korea, UK, Spain, China, India and Russia, to perform predictive modelling of a uniform 1:4 scale model of a typical pre-stressed concrete containment vessel (PCCV). The design was based on Unit 3 of the Ohi Nuclear Power Station in Japan. Ohi Unit 3 is a 1180 MW pressurized water reactor (PWR) plant. The containment vessel is a steel-lined pre-stressed concrete cylinder with a hemispherical dome and two vertical buttresses. The design pressure is 0.39 MPa. The model was designed by Mitsubishi Heavy Industries (designer and constructor of the full size Ohi Unit 3).

The round robin was sponsored by the Nuclear Power Engineering Corporation (NUPEC) of Japan and the US Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research.



A pre-test Limit State Test (LST) on the PCCV was undertaken to gain an understanding of its mode of failure, behaviour up to the limit load, and to assess the accuracy of the design pressure, Pd, for the PCCV of 0.39 MPa.
NNC / HSE chose to use a completely three-dimensional global model, using ABAQUS finite element code, which included sufficient details of all the important local features such as the pre-stressing tendon layout, penetrations into the containment area, buttresses, stressing gallery, soil foundations and containment area liner.

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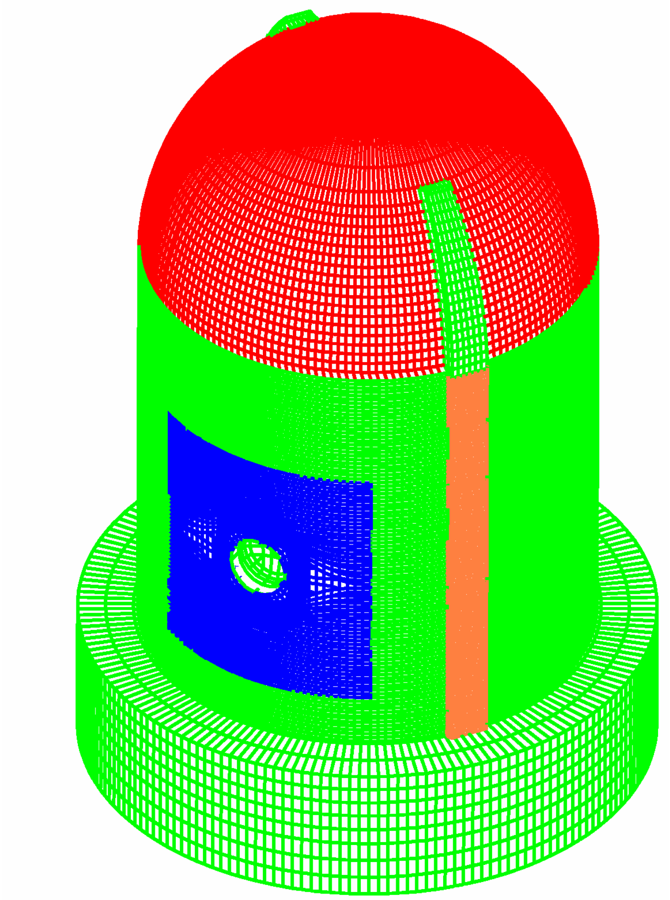
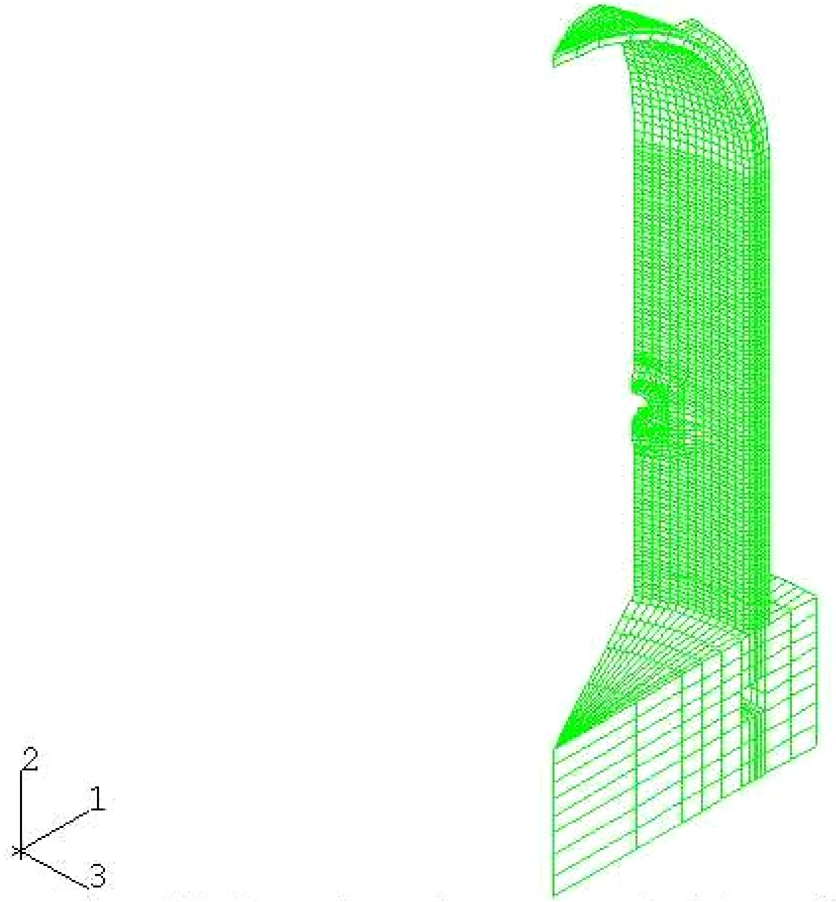


Full 3D global model of the PCCV

The NNC / HSE model was one out of four models to successfully predict that the tearing of the liner would determine the limit load. It also predicted accurately that the main structural components such as tendons and reinforcing bars would not fail up to this load. Even though some discrepancies remained between the response recorded during test and that predicted by finite element (FE) analysis, the failure mode was accurately predicted.

Unfortunately, the ABAQUS concrete material model gave numerical problems when concrete cracking became significant and the global 3D model could not be analysed beyond an internal pressure of 0.71 MPa. To take the analysis beyond 0.71 MPa at the pre-test stage, a small sector model was produced. “Getting over the limitation of the constitutive models in simulating extensive cracking in concrete was the biggest technical challenge to be overcome in this project”, commented Nawal Prinja, technical manager, Applied Engineering at NNC.

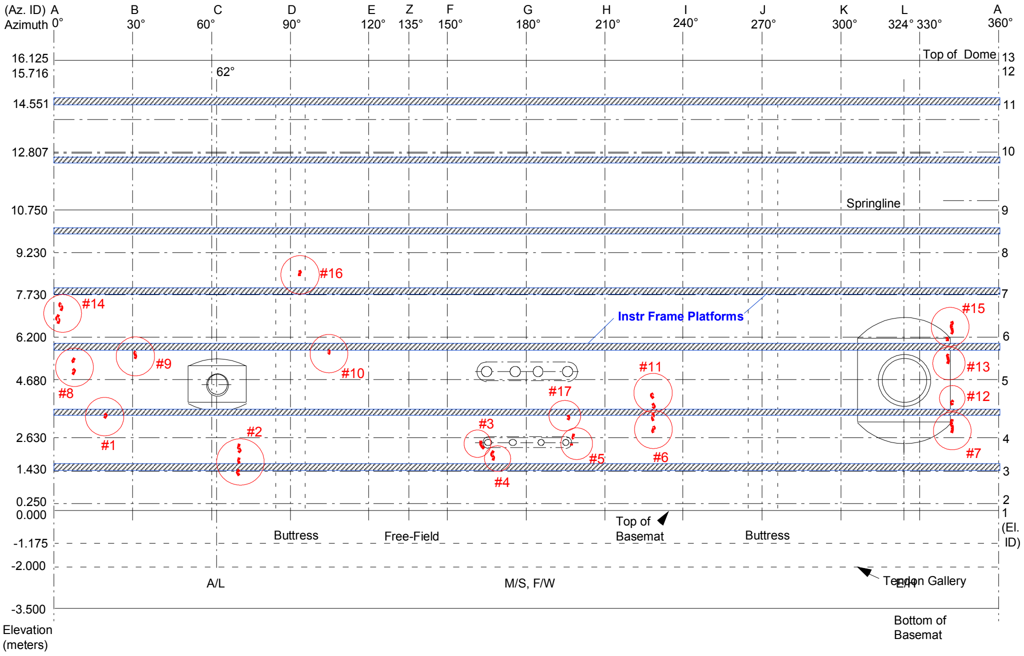


Sector model of the PCCV

LST data sets showed an early anomaly in establishing a baseline for measured displacement, strains and tendon loads. It showed a jump between the initial measurements and those taken just before pressurization. This lead to a discontinuity when the pressure reached 0.6 MPa. However, close inspection of acoustic measurement devices showed that extensive concrete cracking initiated at 0.6 MPa (about 1.5 Pd).

Comparison between the LST results and the pre-test analysis predictions shows that the FE analysis successfully predicted the stiffness behaviour up to 1.5 Pd and the mode of failure by liner rupture, well before any failure of the pre-stressing tendons.

The locations of the liner tears along the edge of the feedwater penetration insert plate, for example, were indicated by liner strains which were less than 0.2% until the pressure passed 1.1MPa (or 2.8Pd), after which they increased very rapidly.



Location of the tears in the liner after the LST

Inspection of the liner tears showed that they were all associated with vertical field welds and almost all exhibited evidence that the liner was locally thinned prior to pressure testing due to grinding of the welds either during initial fabrication or during repair welding.

The first tears occurred along the edge of the equipment hatch embossment - the one location where it does not appear the liner was significantly thinned during fabrication. The FE analysis predicted the largest strain at this location because of the step change in the liner thickness. Due to the lack of information about the rupture strain of the welded liner, the pre-test analysis could not predict the exact pressure at which the liner rupture would occur but it accurately identified the failure mode and the location.

Whilst the LST achieved a pressure of 1.295 MPa (3.3 Pd) well beyond the design basis, the test was limited because the vessel leak rate was greater than the pressurization system. SNL sealed the leaks and conducted the Structural Failure Mode Test (SFMT). The SFMT was carried out by sealing the liner with an elastomer, and then filling the PCCV to the 97% level with 'water'. The vessel could then be quickly pressurized with nitrogen gas as a hydrostatic test. The test was successful in reaching global collapse of the PCCV structure at 1.423 MPa (3.65 Pd). The tendons ruptured and the vessel wall burst under high pressure.

At this point the original scope of NNC's finite element analysis was extended to predict the behaviour up to the global collapse of the PCCV.

Nawal Prinja commented, "There was a general agreement in the predictions up to the design pressure of 0.39 MPa. However, there was significant difference in the behaviour predicted by the participants at higher pressures as material and structural non-linearity become more important." In part this was due to some of the participants making simplifying assumptions and predicting the limit load based on simple global models of the PCCV. Others had made detailed models of local features such as the penetrations and buttresses but did not have a full global model."

(GLview Model images here)

Post-test analysis of the PCCV was intended to address the discrepancies observed at higher pressures where the failure mode was predicted accurately, but significant differences remained between the response recorded during test and that predicted by finite element (FE) analysis. In addition, it was hoped that the post-test analysis would improve the FE modelling, identify features that affect the model and improve the level of accuracy for future FE analysis of PCCV structures.

In modelling the SFMT, NNC had to take into account the presence of the two buttresses creating a strong asymmetric pattern in the deformed shape. In addition, the limit load of the PCCV was dictated by liner rupture. Therefore, detailed modelling of the liner was required.

Moreover, there was a hold period of over 6 months between the pre-stressing and the LST pressurization during which other tests were carried out. The cumulative effect of these smaller tests and concrete ageing cannot be easily simulated in an analysis to obtain absolute values of deformation from the virgin state of the model.

Tension stiffening data to simulate behaviour of the cracked concrete was also required. There was some evidence of the liner thinning due to grinding of the welds, which could not be easily modelled. In a detailed study of welded liner, NUPEC reported that the elongation was as low as 6% compared to the design value of 12% minimum. Due to this variability, it was difficult to define the strain to failure accurately. "There was a step increase in some of the measured displacements and strains at 1.5Pd. This was attributed to onset of concrete cracking or increase in temperature during the hold period," says Prinja.

In its post-test analysis, NNC replaced the standard concrete material model in ABAQUS with ANACAP - a specialised concrete material model routine developed by ANATECH Research Corp. It offered a more numerically robust simulation of cracking in concrete. "We used the software to extend the range of pressure over which predictions could be made in the post-test analysis of the LST and SFMT," explained Prinja.

Visualisation of results

The SFMT results were visualized using a program supplied by one of NNC's long-term supplier-partners. The company, Applied Computing & Engineering Ltd. proposed and supplied GLview software for the PCCV project. “GLview allowed us to bring to life the PCCV analyses in a way that's simply impossible using tables and figures,” notes Prinja. “GLview offered us an opportunity to produce highly informative visualizations, fast. This meant that we could increase the understanding of our engineers contributing to the project much more quickly, leading to better understanding and more accurate conclusions. Applied Computing & Engineering have worked with us for over 15 years and understand the nature of our highly non-linear problems, partly because of their own work in the CFD area. The value of producing efficient visualizations in a quick and easy manner should not be under-estimated for complex problems. Our success with the PCCV project will enable us to extend our usage of GLview on other key projects within the company,” he continued.

Summary of post-test analysis

Type of test	LST with data at 55 locations		SFMT with data at 28 locations
FE model	Sector model	Full 3D global model	
Concrete material model	ABAQUS	ABAQUS	ANACAP
Analysis approach	Gravity, creep, shrinkage, pre-stress and pressurization	Gravity, creep, shrinkage, pre-stress and pressurization	Gravity, pre-stress and pressurization
Max. pressure analysed	2.155 Mpa	0.606 Mpa	1.64 Mpa
Failure Mode	Liner rupture	Liner rupture	Structural collapse

The LST and SFMT data in conjunction with the pre-test and the post-test analysis show that the structural response of the pressurized PCCV is indicated by progressive damage in three stages:

Linear elastic stage: The first stage of predominantly elastic response can be predicted with very good accuracy using standard finite element technology Almost all the participants predicted this stage accurately. The behaviour becomes non-linear at the onset of extensive cracking in the concrete.

Local failures: The second stage involving inelastic response with extensive concrete cracking requires specialist concrete material models and detailed geometric representation of the main structural features. It is important to model the interaction between various structural elements to simulate load redistribution as some components yield or fail. Such local yielding or rupture may lead to loss of functionality or breach of pressure boundary. Careful geometric modelling with specialist concrete material models can predict the second stage behaviour with acceptable accuracy.

Structural collapse: The third stage involving gross deformation leading to structural collapse requires solution of a highly non-linear problem. Extensive concrete cracking, well beyond the tension stiffening range, occurs and requires robust constitutive models capable of simulating extensively cracked concrete. Provided such a specialist FE package is available, an experienced analyst can predict the collapse limit and failure mode with acceptable accuracy.

Nawal Prinja believes that an analyst with knowledge and experience of performing non-linear analysis needs specialist FE codes to predict the failure limits of a pressurized PCCV with reasonable accuracy. “To simulate the complex interaction between the various structural elements, we found a full 3D model, together with post-processing visualization, was a particularly useful approach where the limit load is dictated by a local failure of a structural element” he said.

And the lessons for predicting limit loads for concrete vessels? Nawal Prinja makes the following suggestions: in order to predict limit loads for a PCCV, a failure criteria should be defined. Can a functional failure, e.g. unacceptable leakage, be used to define the failure criteria in terms of engineering parameters such as displacement or strain? And finally, Displacements are easier to measure. It is preferable to use a displacement based failure criteria.

NNC would like to acknowledge the help and support of Dave Shepherd, Principal Inspector (Nuclear), NII, HSE, in his role as Technical Officer representing the NII in this project.