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Studies on Influence of Steel Liner and Pre-Stressing Tendons on Ultimate Load Capacity of Pre-stressed Concrete Containment Test Model

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ABSTRACT

BARC in-house finite element code **ULCA** (Ultimate Load Capacity Assessment) predictions for the ultimate load capacity assessment of a 1:4 size steel lined pre-stressed concrete containment vessel (PCCV) model of a PWR nuclear containment located at Ohi station in Japan are reported in this paper. This test was cosponsored jointly by Sandia National Laboratory, Nuclear Regulatory Commission, USA and Nuclear Power Engineering Corporation, Japan. ULCA code predictions are shown to have very good comparison with the experimental ultimate pressure test and subsequently the collapse test concluded in 2000 and 2001 respectively by Sandia laboratory. The influence of steel liner and pre-stressing tendons on the ultimate load capacity and the collapse behavior of the test model is highlighted in this paper which was used as a criterion to arrive at the limiting test pressures during the pre-test as per the requirements of the round robin analysis activity.

Key words: Steel Liner, pre-stressing, ultimate load capacity, concrete, containment, test, model

INTRODUCTION

Ultimate load capacity assessment of nuclear containments has been a thrust research area for Indian Pressurized Heavy Water Reactor (PHWR) power programme. For containment safety assessment of Indian PHWRs a finite element code ULCA was developed at BARC, Trombay. This code has been extensively benchmarked with experimental results of reinforced and pre-stressed concrete structures. The present paper highlights the analysis results for Prestressed Concrete Containment Vessel (PCCV) model tested at Sandia National Labs, USA in a Round Robin analysis activity co-sponsored by Nuclear Power Engineering Corporation (NUPEC), Japan and the U.S Nuclear Regulatory Commission (NRC). The test model (Fig1) is a scaled representation of 1:4 size containment of a Pressurized Water Reactor (PWR) station located at Ohi station in Japan. Three levels of failure pressure predictions namely the upper bound, the most probable and the lower bound (all with 90% confidence) were made as per the requirements of the round robin analysis activity. The most likely failure pressure is predicted to be in the range of 2.95 Pd to 3.15 Pd (Pd= design pressure of 0.39 MPa for the PCCV model) depending on the type of steel liners used in the construction of the PCCV model. The lower bound conservative value of the ultimate pressure of 2.80 Pd and the upper bound collapse pressure of 3.45 Pd are also predicted from the analysis. These limiting values depend on the assumptions of the analysis for simulating the concrete-tendon interaction and the strain hardening characteristics of the steel members. The ultimate capacity and the structural collapse tests have been concluded at Sandia Laboratory and the peak pressure reached during the ultimate capacity test is 3.3 Pd that is enveloped by our upper bound prediction of 3.45 Pd and is close to the predicted most likely pressure of 3.15 Pd. Our upper bound pressure prediction accounts for the tendon and concrete interaction and predicts the collapse pressure of 3.45 Pd which is close to the collapse test pressure of 3.65 Pd. The details of the experimental results would be published shortly from Sandia Laboratory and would serve as a benchmark for the code validation. Meanwhile based on the available preliminary test results it has been noted that BARC code ULCA predictions are in very good agreement with the ultimate capacity experimental results. The present paper highlights the features of non-linear finite element code ULCA and the numerical simulation of the PCCV test model up to the burst pressure. In addition it aims to address a few relevant modeling issues such as the steel concrete interaction, bond slip and pre-stressing load simulation for prediction of the ultimate load capacity behaviour of a large size real life problem. More details of the failure analysis for PCCV test model are reported by the present authors in Basha et. al. [2003].

The failure criterion for the PCCV model is liner tearing. Hence the sensitivity analysis with respect to various types of liners used in the construction of the PCCV test model is carried to evaluate its influence on the liner tearing characteristics. In addition, other failure modes such as first concrete cracking, rebar yielding, initiation of liner yielding, loss of bond between concrete and steel members and through thickness cracking of containment wall are also predicted in the present analysis. It is predicted that local failure could result in a large deformation (~93 mm) around the equipment hatch (E/H) opening. It has been shown that the dome crown region has residual compression left up to the ultimate pressure and small axial compression is retained in the cylindrical wall (except near E/H opening) up to the ultimate state. The paper finally brings out some important constitutive parameters, which would serve as guidelines for future test programmes. These parameters would be helpful in improving the numerical prediction in the post-test computations.

ULCA - BARC IN HOUSE FINITE ELEMENT CODE FOR NUCLEAR CONTAINMENTS

The analysis has been carried out with an in-house finite element code ULCA developed by Singh et al. (1993), Gupta et al. (1995, 1996). This is based on degenerate nine noded isoparametric shell elements with five degrees of freedom at each node. This code has been extensively used to predict the ultimate load capacity of Indian Pressurized Heavy Water Reactor (PHWR) reinforced and pre-stressed concrete containments for postulated severe, beyond the design basis accidents. The code is capable of modeling a number of concrete layers across the shell thickness along with different reinforcement patterns to accommodate the rebars with smeared approach. The material model includes orthotropic behaviour of concrete with stress and strain based failure criteria. The compressive yielding and crushing is predicted with the help of concrete compressive strength by Drucker Prager theory. In addition, the strain based failure criterion is also used which depends on the ultimate strain of concrete. The smeared crack model predicts the concrete cracking. The softening behaviour of concrete is predicted with the help of tension stiffening parameters that account for the bond effect between the steel members and concrete. The non-linear behaviour of the rebars and steel liners is simulated by Von Mises yield criterion. The finite element code ULCA includes a geometrical non-linear analysis module also to account for large displacements and large strains with moderate rotation assumptions, which is important for realistic response prediction near the ultimate state. The constitutive property data provided in the Sandia –Design package SO –97 – 047 (1997) were used in the present analysis.

PCCV TEST MODEL

The PCCV test model is a 1:4 scale test model of an existing pressurized water reactor (PWR) pre-stressed concrete containment vessel at Ohi power station in Japan. The model includes a steel liner and scaled representation of the equipment hatch, personnel airlock, and main steam and feed water line penetrations. The overall geometry of the test model is shown in Fig. 1. The PCCV test model with a hemispherical head has an inner radius of 537.5 cm and 27.5 cm thickness. The cylindrical portion of the model is 1075 cm long with an inner radius of 537.5 cm and thickness of 32.5 cm. The thickness of the liner is 1.6 mm. Concrete with compressive strength of 48.84 MPa has been used in the construction of the PCCV test model. The test model has been reinforced with three grades of steel rebars namely SD345, SD390, SD490 with six different diameter bars of specifications D6, D10, D13, D16, D19 and D22. The reinforcement consists of two layers of inner and outer vertical rebars and two layers of inner and outer hoop rebars. The design pressure (Pd) for the prototype containment vessel is 0.39 MPa. The containment has been pre-stressed with 90 vertical dome tendons and 90 hoop cylindrical tendons, in addition to the 18 numbers of hoop dome tendons. The level of pre-stressing force in each of the vertical dome tendons is 105.8 kN. Each of the hoop tendons is pre-stressed to a level of 78.7 kN. The horizontal tendons are anchored at the buttress located at an angular orientation of 90 and 270 degrees. The vertical tendons are anchored to the tendon gallery at the basement.

FINITE ELEMENT MODELS FOR PCCV ANALYSIS

In the present study two finite elements models have been used for the analysis of PCCV test model. Model-1 simulates the quadrant from 90 degrees near buttress to 180 degrees near the steam and feed water line penetrations (Fig. 1). This quadrant was selected due to the fact that most of the standard output locations are located in this portion of the test model. Model-1 is capable of predicting the free field response of the test model. Model-2 simulates the quadrant from 270 degrees near buttress to 360 degrees (Fig. 1). This quadrant has the largest opening due to equipment hatch (E/H). In this sector, the standard output locations are located around E/H. This model predicts the local behavior of the test model and the effect of the penetrations are suitably modeled. A typical view of Model-2 is presented in Fig. 2. The two finite element models intuitively evolved with engineering judgment adequately represent most of the details of the PCCV test model with buttresses, large opening and discontinuity regions and successfully predicted the expected behavior of the structure in the linear and non-linear regimes up the ultimate and the collapse pressures as shown subsequently in our paper Basha et. al. [2003].

The following assumptions are made in the numerical simulation of the PCCV test model with code ULCA.

- Smeared layers represent the entire hoop and meridional tendons and rebars with unidirectional stiffness.
- The liner is modelled with actual uniform thickness on the inside concrete surface.
- No slip is assumed between the steel members, liner and concrete in the elastic range.
- The bond between steel members and concrete is lost at the yield strains in the range of 0.18%-0.2%. This results in different tension stiffening parameters for the different steel member groups.
- The effect of pre-stressing load is accounted for hoop and meridional tendons in terms of effective pressure and concentrated loads.
- The stress-strain data for rebars and different types of liners in the PCCV Round Robin Analysis Design Package, SO-97-O47 provided by Sandia Labs are approximated with a 10th order polynomial fit to generate the strain hardening parameters for the analysis.

The finite element mesh for Model-1 consists of 405 numbers of degenerate shell elements, with each element having eight concrete layers and nine steel layers including inner liner across the thickness. The different reinforcement patterns were modeled with smeared steel layers. The total area of different steel bars in quarter plan for a particular elevation was converted into equivalent smeared steel layer thickness. The different steel layers consist of innermost layer of liner, to account for its stiffening effect in the hoop and meridional directions, two layers of inner and outer vertical bars, two layers of inner and outer hoop bars and two layers of tendons. In addition, the trim bars near the buttress were modeled as the ninth layer. This has resulted in 48 number of reinforcement layer patterns with 148 material properties depending on the orientation, size and position of the rebars in the containment model. Fixed boundary conditions were applied at the base of the structure and symmetry conditions are applied at the buttress end and the other end located 90 degrees away from the buttress.

The finite element mesh for Model-2 covers the quadrant from 270 degrees to 360 degrees. The largest opening E/H has a diameter of 0.773m and is located at an azimuth of 324 degrees. This mathematical model consists of 508 layered shell elements with each element having 8 concrete layers and seven steel layers including the liner across the PCCV model wall section. This discretization leads to 120 reinforcement layer patterns with 238 material properties depending on the orientation, position and size of rebars in the PCCV test model.

NUMERICAL CASE-STUDIES

As per the requirement of the round robin analysis activity the following three sets of predictions were required to be made before the model test at Sandia Laboratory.

- Best estimate of the ultimate pressure for the model with 90% confidence. This was obtained by considering actual strain hardening characteristics for the steel members.

- Lower bound conservative estimate of the minimum pressure, which the test model would at least reach during the test with 90% confidence. This case was analysed with the assumption of ideal elastic–plastic behaviour of the rebars and liner. It was noticed that the concrete cracking takes place before the yielding of rebars and liner. This assumption is conservative and simulates de-bonding of steel members present in the cracked concrete which has reached to its ultimate tensile strain ~0.2%. In an overall sense it accounts for the uncertainties in the construction, material properties and simulates the interface behaviour of concrete and steel members in a conservative manner.

- Upper bound estimate of the maximum collapse pressure beyond which the test model is unlikely to remain in pressurized condition with 90% confidence. In this case the influence of additional pre-stress on the concrete member is accounted during the dilation of the tendons. Simplified calculation showed that even in the cracked condition of the concrete initially the tendon response is in the elastic regime so this additional pre-stress would be available unless the slip between the tendon and the duct is initiated. Slip is initiated in the inelastic regime of the tendons when most of the weaker steel members such as the liner and rebars have undergone plastic deformation. The collapse failure is at the equipment hatch location due to large inelastic strains in the tendon.

In case of tendons, a slip condition (based on friction coefficient 0.21) was simulated when the net radial pressure near the cable ducts exceeded the residual slip pressure. In all the above cases a limiting nominal strain of 5% (as given in the stress-strain curves of the design package) was considered for the liner tearing. PCCV test model was constructed with seven different liner specifications. The standard deviation for the most likely ultimate pressure computed with different liner properties was found to be 0.084. Considering the uncertainties in the material properties and approximations in the numerical modelling, 90% confidence was thus ensured for the present results.

RESULTS AND DISCUSSIONS

For all the three predictions, first cracking in concrete, first through thickness cracking of concrete section, sequential yielding of steel members, de-bonding of rebars and finally liner tearing are predicted. These failures that could be observed on PCCV model during the test are summarized in table-1, which is self-explanatory. The inelastic behaviours are indicated in the membrane and discontinuity locations such as equipment hatch opening, cylinder head junction, buttress location and the base wall junction. In all the cases the peak liner strain is obtained from the triaxiality factor based strain multiplier which is ~2. This strain multiplier is derived from the principal stresses obtained in the different regions and is consistent with similar liner property reported by Tang et al. (1995). The failure mode is by liner tearing and the peak strain is observed near the equipment hatch. For the conservative lower bound estimate it is postulated that the tendon slip due to de-bonding could occur before the liner tearing at locations of high strain concentrations. Figs. 3-4 show the average strain and radial displacement at a typical standard output location 45 and another location 'E' additionally selected for illustration purpose. In these curves, results with all the seven liner types namely LPX-1, LPX-2, LPX-21, LPX-3, LPY-1, LPY-2 and LPY-3 are presented to study the sensitivity of the ultimate load on the constitutive properties of these different liner categories for Model-2. The best estimate of static failure pressure is 1.2285 MPa (3.15 Pd). The standard deviation among the different values of ultimate pressure with variation in liner properties is 0.084. Figs. 5-8 show the displacement and strain responses obtained with the two finite element models. It is noted that the peak radial dilation~93 mm and liner strain~2.34% are higher locally near the equipment hatch obtained in Model-2 compared to the predictions of peak radial dilation of 88.9 mm and liner strain of 0.5% for Model-1. Considering the effect of tri-axiality the peak liner strain of ~ 6.4% is thus predicted near the equipment hatch location. The displacement and strain gradients with respect to pressure were observed to be very sharp in the transition from the ultimate state to the structural collapse and the radial displacement of ~ 20 mm observed at the ultimate state rose to a value of ~ 90 mm in both the models at the ultimate collapse state (Table 1 and Figs 5&7). It is noteworthy that the free field membrane behavior prediction is identical in both the finite element models (Model-1 and Model-2). This justifies our modeling assumptions and the two finite element models adequately represent the behavior of the PCCV in the elastic, inelastic ultimate and collapse regimes and thus illustrate the capabilities of our finite element code ULCA.

CONCLUSIONS

The BARC in-house developed finite element code ULCA predictions for the most likely ultimate pressure of 3.15 Pd and the collapse pressure of 3.45 Pd with 90% confidence have been found to be consistent with the experimental ultimate test and collapse pressures of 3.3 Pd and 3.65 Pd respectively for the PCCV model. Moreover the maximum pressure prediction of 3.45 Pd and the minimum pressure prediction of 2.80 Pd, which are the upper and lower bound values satisfy the requirement of the round robin analysis activity. The important issue for the ultimate pressure and the collapse pressure predictions is the in-situ steel concrete interaction and the resultant maximum strain developed in concrete before de-bonding or slip of steel members is initiated. In addition, the strain multipliers could be derived from the liner strain data near the equipment hatch, the buttress region and the other discontinuity regions upon availability of the experimental data, which would improve the post-test predictions. Sandia Laboratory would release the detail output predictions of strains and displacements at the standard output locations shortly. The detail comparison of our predictions of strains and displacements at all the standard output locations with the Sandia Laboratory test data would assist in understanding the behaviour of nuclear containment under severe accidents. BARC, Trombay has also planned to carry out a round robin exercise for 500 MWe PHWR 1:4 size pre-stressed concrete containment model test in the Xth plan project, where all the national and international academic and research institutes would be invited to predict the behaviour of our test model. This would further help in improved understanding of the containment behaviour near the ultimate and the structural collapse states.

REFERENCES

- Basha S M, Singh R K, Patnaik R, Ramanujam S, Kushwaha H S, Venkat Raj V, " Predictions of Ultimate Load Capacity for Pre-Stressed Concrete Containment Vessel Model with BARC Finite Element Code ULCA", "Annals of Nuclear Energy" , pp 437-471, 30 (2003).
- Gupta, A., Singh, R. K., Kushwaha, H. S., Mahajan, S. C., Kakodkar, A., "Assessment of Ultimate Load capacity of Inner Containment For Indian PHWR", Invited Paper, Div. H, SMiRT XIII, Porto Alegre, 1995.
- Gupta, A., Singh, R. K., Kushwaha, H. S., Mahajan, S. C., Kakodkar, A., "Nonlinear Finite Element Analysis of Nuclear Reinforced and Prestressed Concrete Containments up to Ultimate Load capacity ", ICONE 4, March 10-14, New Orleans, USA, 1996.
- PCCV Round Robin Analysis Design Package, SO-97-O47 dated November 17th, 997, Sandia National Laboratories, USA.
- Singh, R. K., Gupta, A., Kushwaha, H. S., Mahajan, S. C., Kakodkar, A., " Ultimate Load Capacity Assessment of Indian PHWRs - Some Pre Test Results", U02/5, SMiRT-12, 1993.
- Tang, H. T., Dameron, R. A., Rashid, Y. R., "Probabilistic Evaluation of Concrete Containment Capacity for Beyond Design Basis internal pressures", Nuc. Engg. Des., pp. 455-467, vol. 157, 1995.

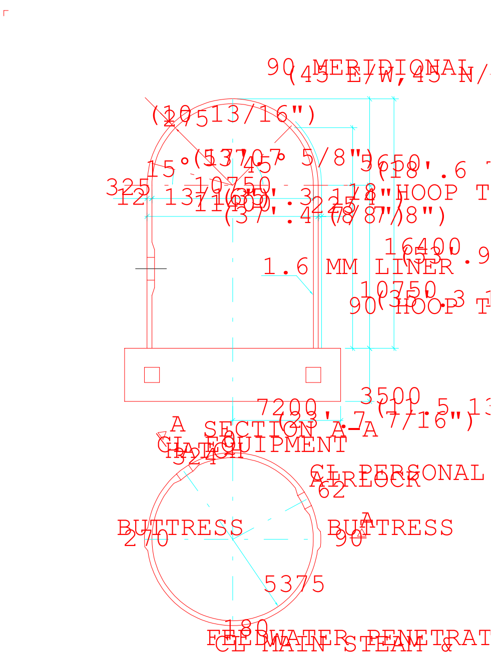

Fig 1 Outline Sketch of PCCV

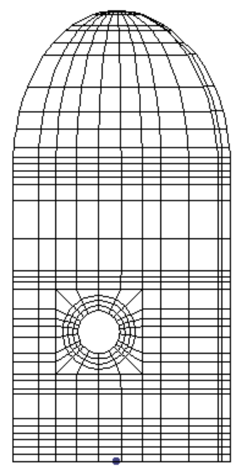

Fig 2 FEM Shell Model of PCCV

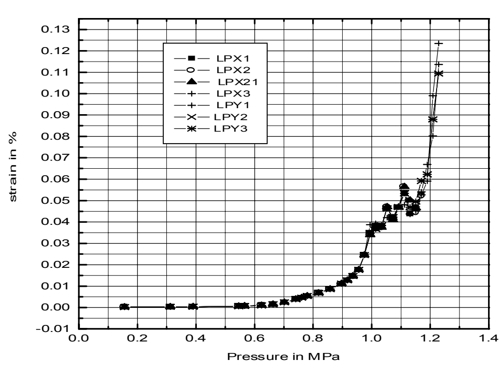

Fig. 3 Pressure Vs Strain at Output Location

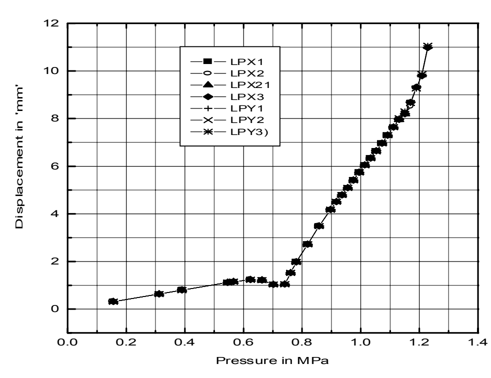

Fig. 4 Pressure Vs Displacement at Output Location

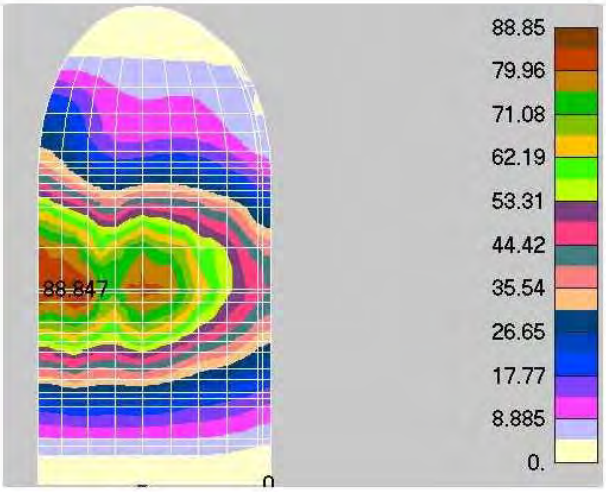

Fig5 Radial Dilation (mm) at 3.30 Pd FEM Model 1

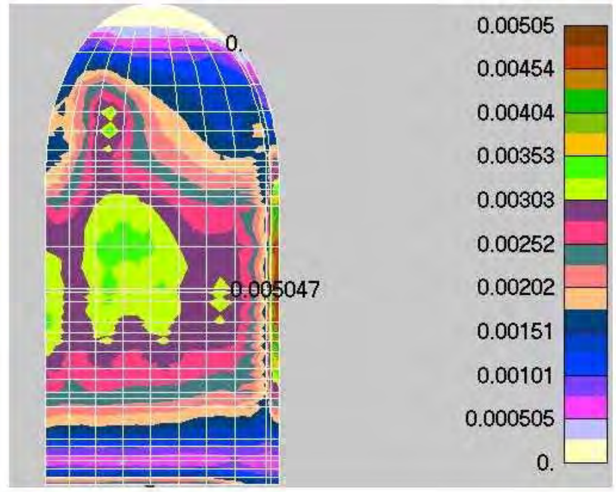

Fig. 6 Nominal Hoop strain in Liner at 3.30 Pd FEM Model

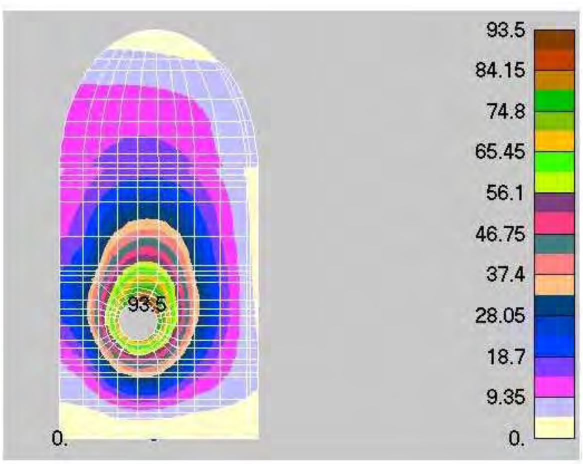

Fig.7 Radial Dilation (mm) at 3.15 Pd FEM Model 2

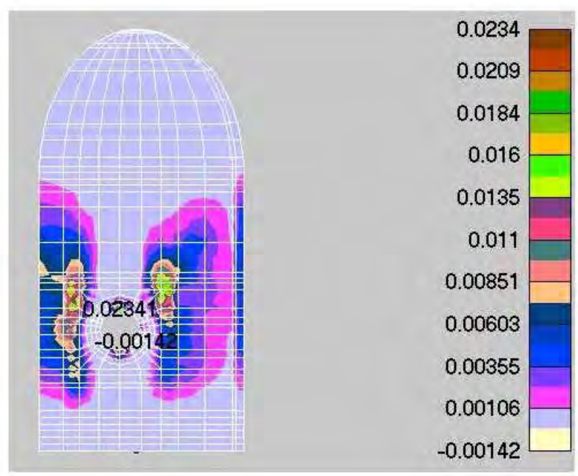

Fig. 8 Nominal Hoop Strain in Liner at 3.15 Pd FEM model 2

Remarks: Both models show identical free filed response and justify the modeling assumptions.

Status of PCCV near the Ultimate Collapse State

TABLE 9 Comparisons of Numerical Results for Three Pre-Test Estimates with Model 2

MILESTONES	Best estimate of pressure for different nonlinear features	Lower bound conservative estimate of minimum pressure	Upper bound estimate of maximum pressure
First appearance of axial crack with crack depth above 50%	1.40Pd	1.40Pd	1.60Pd
First appearance of local through thickness crack in concrete	1.60 Pd	1.60 Pd	2.20 Pd
First appearance of cylinder membrane crack in concrete (37.5% of thickness)	1.60 Pd	1.60 Pd	2.20Pd
First appearance of through the thickness cracks in membrane region of cylinder.	1.90 Pd	1.80Pd	2.20Pd
First appearance of doubly cracked region (Hoop cracks) in concrete.	1.80 Pd	1.80 Pd	2.20Pd
Local de-bonding of outer hoop rebars near E/H .	1.80 Pd	1.80 Pd	2.20Pd
Local de-bonding of outer vertical rebars near 3& 9 o' clock E/H .	1.90 Pd	1.90 Pd	2.30Pd
First appearance of local yielding in outer vertical rebars	1.95Pd	1.95 Pd	2.60 Pd
First appearance of local liner yielding in meridional direction	2.10 Pd	2.10 Pd	2.60 Pd
First appearance of local yielding in outer hoop rebars	2.20 Pd	2.20Pd	2.60Pd
First appearance of local liner yielding in hoop direction	2.30Pd	2.30 Pd	2.60 Pd

Table-1 (Contd.)

First appearance of liner yielding in free field membrane region.	2.30 Pd	2.30 Pd	2.60 Pd
First appearance of yielding of inner axial rebars.	2.50 Pd	2.50 Pd	2.80 Pd
First appearance of yielding in inner hoop rebars.	2.50 Pd	2.30 Pd	3.00 Pd
First appearance of axial tendon yielding or axial tendon slip.	2.50Pd	2.50Pd	2.80Pd
First appearance of hoop tendon yielding or hoop tendon slip.	2.80Pd	2.75Pd	3.20Pd
Minor Dome sagging due to bulging in the cylinder near E/H	2.90 Pd	2.75 Pd	3.45Pd
Liner tearing and failure of test model to sustain further increase in pressure.	2.95 Pd-3.15Pd	2.75 Pd	3.45Pd
Maximum radial displacement near 12 O' clock position of E/H.	~20 mm* 93.5 mm	74.2 mm	91.5 mm
Peak strain in liner at the collapse load around E/H.	6.4 % with peak strain multiplier of 2.0	5.4% with peak strain multiplier of 2.0	8.0 % with peak strain multiplier of 2.0
Postulated failure mode	Liner tearing near E/H.	Tendon slip	Liner tearing near E/H and large strains in the tendons.

Note: * 20 mm is the dilation value at mid height in the free field of cylinder at the ultimate state.
93.5 mm is the dilation value at the equipment hatch.