

PRETEST INELASTIC ANALYSIS OF BARC PRESTRESSED CONCRETE CONTAINMENT TEST MODEL USING 3D FE BRICK MODEL

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ABSTRACT

In order to evaluate the ultimate load capacity of Indian PHWR containments an experimental program has been initiated by Reactor Safety Division (RSD) of Bhabha Atomic Research Centre (BARC). For this study, BARC Containment (BARCOM) Test Model, which is 1:4 scale representation of Tarapur Atomic Power Station (TAPS) unit-3&4 540 MWe PHWR Inner Containment of Pre-stressed Concrete has been constructed at BARC Tarapur Containment Test Facility.

The objectives of the present paper are to predict the behavior of containment model under internal over-pressurization, calculate the response of BARCOM at specified sensor locations and obtain the various failure modes. In the present work, the pretest analysis of BARCOM has been performed with three-dimensional finite element model and comparison of response is presented at few Specified Sensor Locations (SSLs).

INTRODUCTION

Reactor Safety Division (RSD) of Bhabha Atomic Research Centre (BARC) has initiated an experimental program to evaluate the ultimate load capacity of Indian PHWR containments. For this study, BARC Containment Model (BARCOM), which is 1:4 scale representation of Tarapur Atomic Power Station (TAPS) unit-3&4 540 MWe PHWR Inner Containment of Pre-stressed Concrete has been constructed at BARC Tarapur Containment Test Facility. The model includes all the important major design features of the prototype containment and simulates Main Air Lock (MAL), Steam Generator (SG), Emergency Air Lock (EAL) and Fueling Machine Air Lock (FMAL) openings. The design pressure (P_d) of BARCOM is $1.44\text{kg/cm}^2(\text{g})$, which is same as the prototype. The details of the model geometry are shown in Fig. 1.

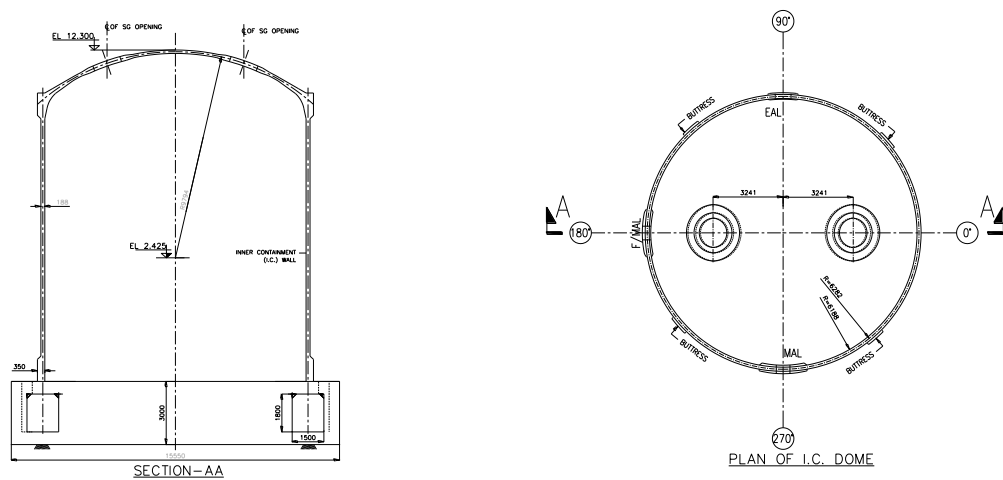


Fig. 1: Outline sketch of BARC Containment Model (BARCOM) [1]

The objective of the present numerical simulation is to understand the responses of containment model under overpressure loadings due to beyond design basis accidents at Specified Sensor Locations (SSLs) and obtain the various failure modes in terms of wall and dome displacement, cracking of concrete, longitudinal and hoop strains, reinforcement yielding and tendon inelastic behavior and finally the maximum static pressure sustained by the model for the structural failure assessment.

The pretest analysis of BARCOM has been performed with a detail three-dimensional finite element model, which simulates all the five major openings namely MAL, FMAL, EAL and the two SG openings. This model has

been evolved from the information provided in the design document and the associated drawings [1] and with inputs of Pre-Test Report on International Round Robin Analysis of BARC Containment (BARCOM) Test Model [2]. The present three-dimensional finite element model predicts maximum pressure sustained by the model before massive leakage signifying the functional failure, based on tendon strain level of 1%, at 1.87 Pd near MAL. The failure modes and the response at few Specified Sensor Locations (SSLs) are compared with experimental data.

DESCRIPTION OF NUMERICAL MODEL

Three-dimensional finite element models have been developed for the present pre-test analysis using the formulation available in the in-house code ULCA [3]. 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 material model includes orthotropic behaviour of concrete with stress and strain based failure criteria. The compressive yielding and crushing is predicted by Drucker Prager theory using the concrete compressive strength. In addition, the strain based failure criterion is also used which depends on the ultimate strain of concrete. For tensile load, the smeared crack model predicts the concrete cracking. Tensile strength based criterion is used to detect the crack initiation in concrete. In the numerical simulation the crack initiation is assumed when the principle stress in concrete reaches the tensile strength of concrete in uniaxial tension at any integration point. The stress biaxiality is considered with the help of Kupfer's experimental curve [4]. 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 detail theoretical formulation is available in [5].

BARCOM geometry was modeled with the help of eight noded brick elements while two nodes truss elements are used to model reinforcements and tendons. All the geometric features such as buttresses and SG,MAL,EAL,FMAL openings which may influence the local and global behavior of the scaled model while testing are represented in the FE model. A constant pre-stress has been applied as initial stress in the tendon elements. In present study, it is assumed that there is no slip between the concrete and reinforcements / tendons. Fig. 2 shows the FEM model details that have been used for the present numerical analysis. Total 142926 elements are used to model the concrete structure. For the reinforcement bars and tendons a total 121831 and 47681 truss elements are used respectively. At the wall base fix boundary conditions are applied.

The nonlinear analysis is carried out with both the models using Newton Raphson Method of incremental load stepping technique [6]. In the initial first step the dead weight and pre-stressing forces are considered for analysis. Subsequently the design pressure of 0.1413 MPa (1.44 Kg/sq cm) is applied, which is incremented in steps to arrive at the ultimate load capacity of the model. Displacements, stresses, strains and the inelastic response in terms of concrete cracking, reinforcement and tendon yielding are studied at different load steps.

MATERIAL TEST DATA FOR ANALYSIS

Concrete :-

For analysis parabolic Eq-1 is used for curve fitting of given uniaxial Stress- Stain curve data (Table 1) of concrete.

$$\sigma = E_0 \varepsilon - (0.5 E_0 \varepsilon^2) / \varepsilon_0 \quad (1)$$

Where

σ = Stress in MPa

ε = Stain

E_0 = Modulus of Elasticity

ε_0 = Stain with respect to Ultimate stress (0.002 form IS- 456)

Table 1: Concrete Material Data

| | |
|---|-------------------------|
| Cubic Characteristic Compressive Strength | 45 N/mm ² |
| Modulus of Elasticity | 33540 N/mm ² |
| Ultimate tensile Strength | 2.78 N/mm ² |

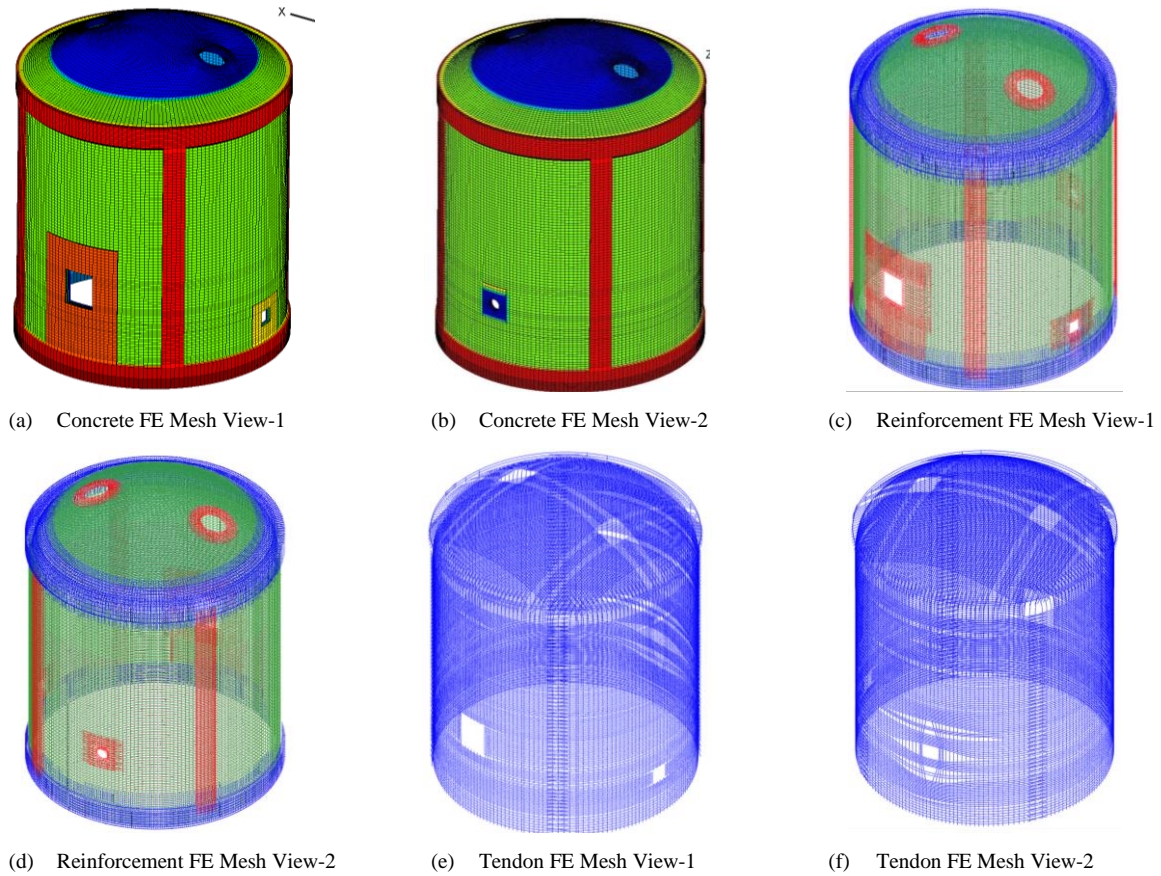


Fig. 2: Three-Dimensional Finite Element Model of BARCOM

Steel Rebar:-

For steel bar bilinear elastic-plastic stress strain curves are used. That is generated from given data in Table 2.

Table 2: Steel Material Data

| | |
|-----------------------|--------------------------|
| Yield Stress | 415 N/mm ² |
| Modulus of Elasticity | 200000 N/mm ² |

Tendon

For steel bar bilinear elastic-plastic stress strain curves are used. This is generated from given data in Table 3.

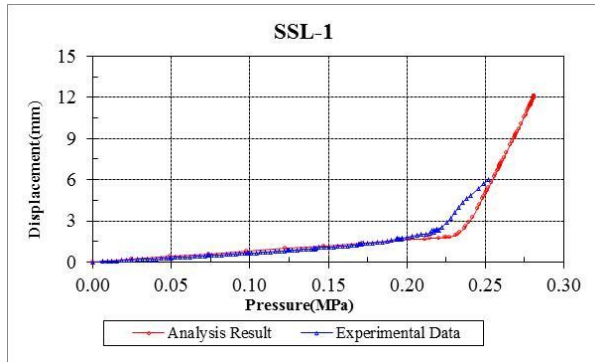
Table 3: Steel Material Data

| | |
|---------------------------|--------------------------|
| 0.2 % Proof Stress | 1683 N/mm ² |
| 1% Extension Stress | 1649N/mm ² |
| Ultimate tensile strength | 1848 N/mm ² |
| Modulus of Elasticity | 189600 N/mm ² |

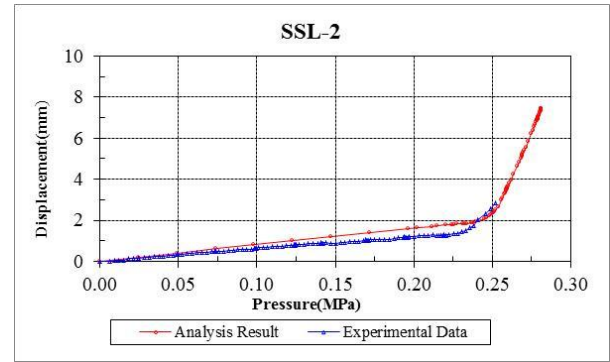
PLOTS OF STRAIN AND DISPLACEMENT HISTORIES AS FUNCTION OF PRESSURE AT SPECIFIED SENSOR LOCATIONS (SSLs)

During the analysis 69 Standard Sensor Locations (SSL) have been monitored, out of which response at few locations were as shown in Fig. 3 and compared with experimental results. The plots present the linear and nonlinear responses of containment due to pre-stress with dead load, design pressure and further due to over-pressurization respectively. The present numerical results are in good match with experimental results for the displacement

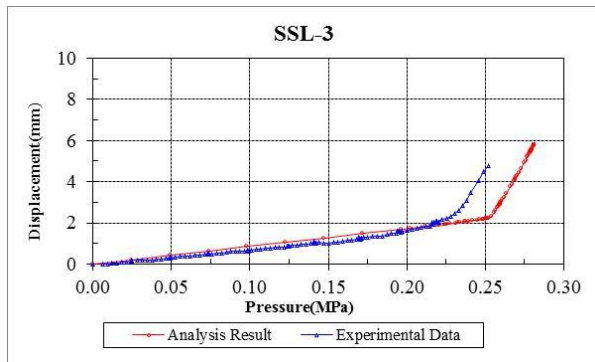
response of containment structure as shown in Fig. 3 (a)-Fig. 3 (e). Further, our numerical results have good compression with experiment response in terms of stains at selected locations near openings Fig. 3 (f)-Fig. 3 (p)



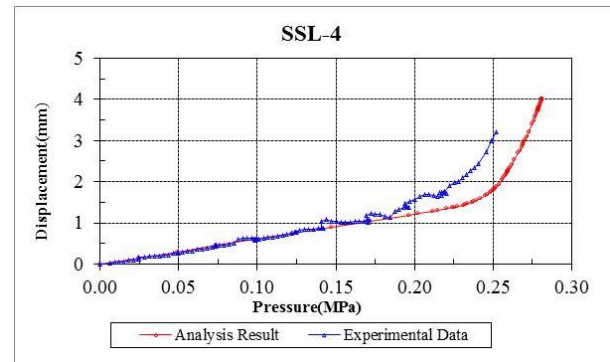
(a) Displacement at 0° Azimuth and EL -0.45 m



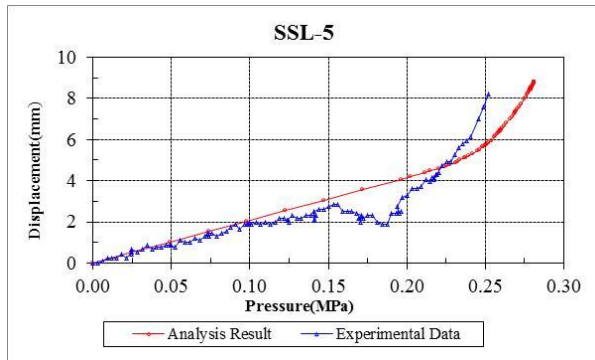
(b) Displacement at 0° Azimuth and EL 3.35 m



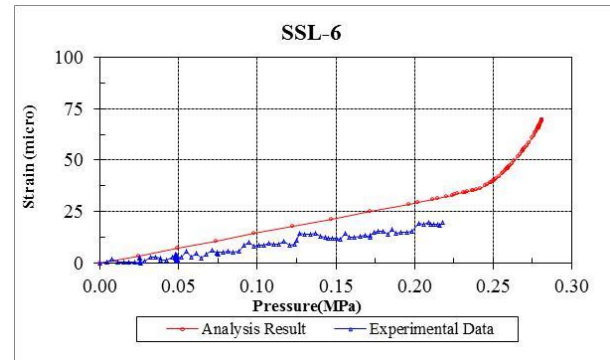
(c) Displacement at 0° Azimuth and EL 6.90 m



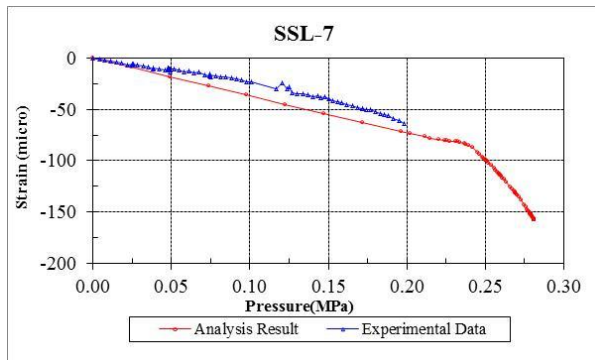
(d) Displacement at 0° Azimuth and EL 10.256 m (Ring Beam Top)



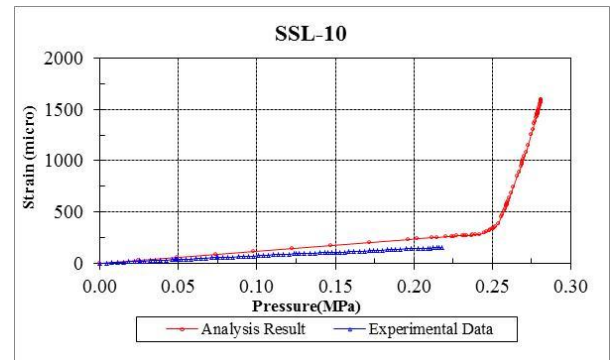
(e) Displacement at 0° Azimuth and EL 12.30 m (Dome Crown)



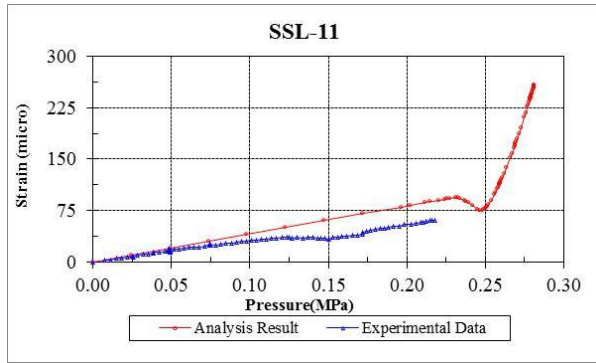
(f) Hoop Strain in Outer Surface of Concrete at Base of Wall



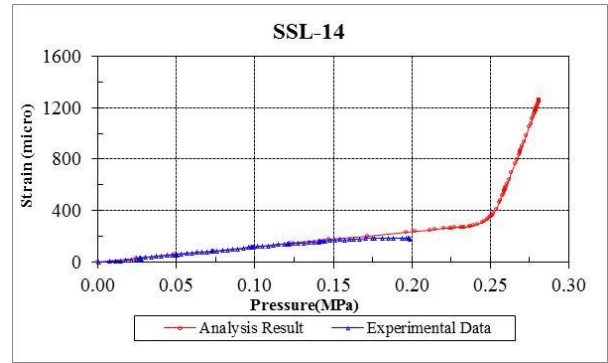
(g) Longitudinal Strain in Outer Surface of Concrete at Base of Wall



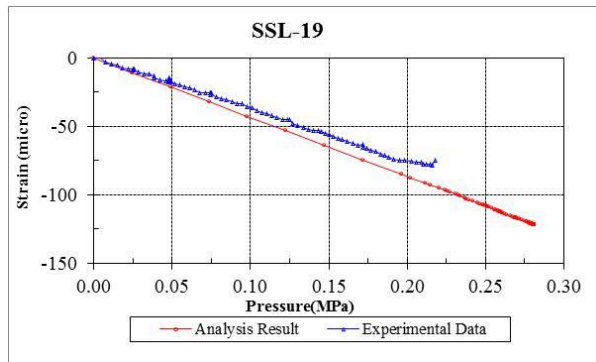
(h) Hoop Strain in Outer Surface of Concrete at mid height of Wall



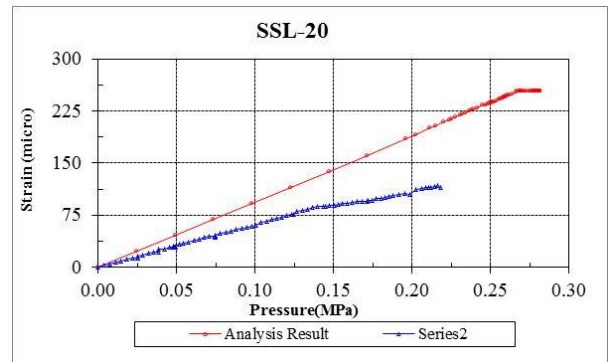
(i) Longitudinal Strain in Outer Surface of Concrete at mid height of Wall



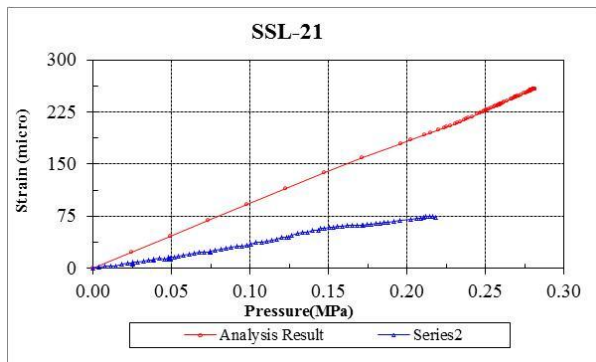
(j) Strain in Outer Layer of Hoop Reinforcement at mid height of Wall



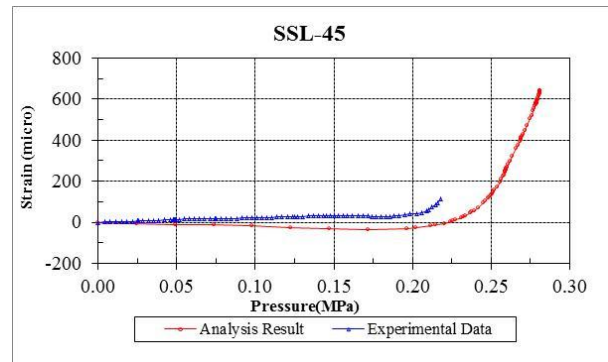
(k) Radial Strain in Middle Surface of Concrete at Dome Crown



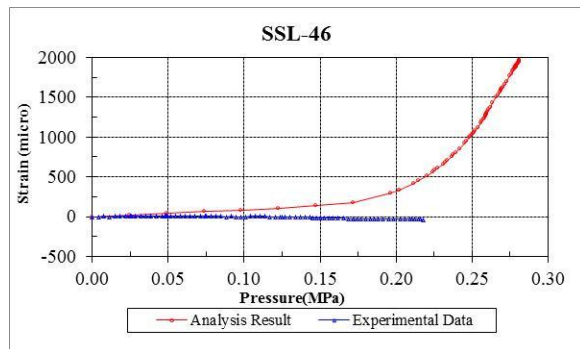
(l) Hoop Strain in Middle Surface of Concrete at Dome Crown



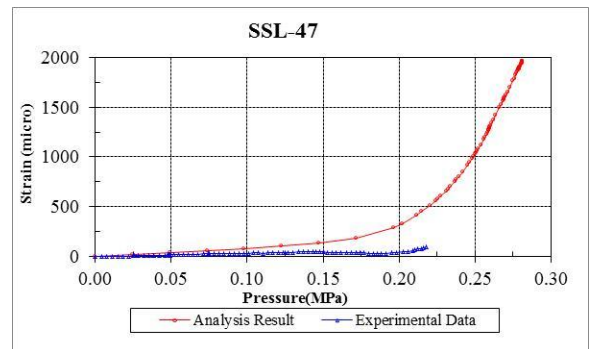
(m) Meridional Strain in Middle Surface of Concrete at Dome Crown



(n) Hoop Strain in Outer Surface of Concrete at above MAL



(o) Longitudinal Strain in Outer Surface of Concrete at above MAL



(p) Strain in Outer Layer of Hoop Reinforcement at above MAL

Fig. 3: Plots at different Standard Sensor Locations

MILESTONES

The response of the containment has been obtain in terms of various milestone such first appearance of concrete cracking , first through wall thickness cracking, as described and discussed in Table-4.

Table 4: Milestones of Predicted from Analysis

| Milestones | Location | Pressure |
|---|---|----------|
| First appearance of concrete cracking in free field (based on a tensile strain of 100 micro-strains[2]) | IC Wall (Inner Face) Fig. 4(a) | 1.58Pd |
| | Dome Crown(Inner Face) Fig. 4(b) | 1.78Pd |
| First appearance of crack at discontinuity field (based on a tensile strain of 100 micro-strains[2]) | FMAL(Outer Face) Fig. 4(c) | 1.27Pd |
| | MAL(Inner Face) Fig. 4(d) | 1.27Pd |
| | EAL(Outer Face) Fig. 4(e) | 1.40Pd |
| | SG (Outer Face) Fig. 4(f) | 1.27Pd |
| | Ring Beam(Inner Face) | 1.45Pd |
| First through wall thickness cracking in free field | IC Wall | 1.60Pd |
| | Dome Crown(No though thickness cracking) Fig. 5 | ** |
| First through wall thickness cracking at discontinuity | MAL | 1.50Pd |
| First yielding of the reinforcement | MAL Thicken Part Inner Reinforcement | 1.65Pd |
| Tendon rupture | | ** |
| Maximum pressure sustained by the model before massive leakage signifying the functional failure based on tendon strain level of 1% | observed at MAL | 1.87Pd |

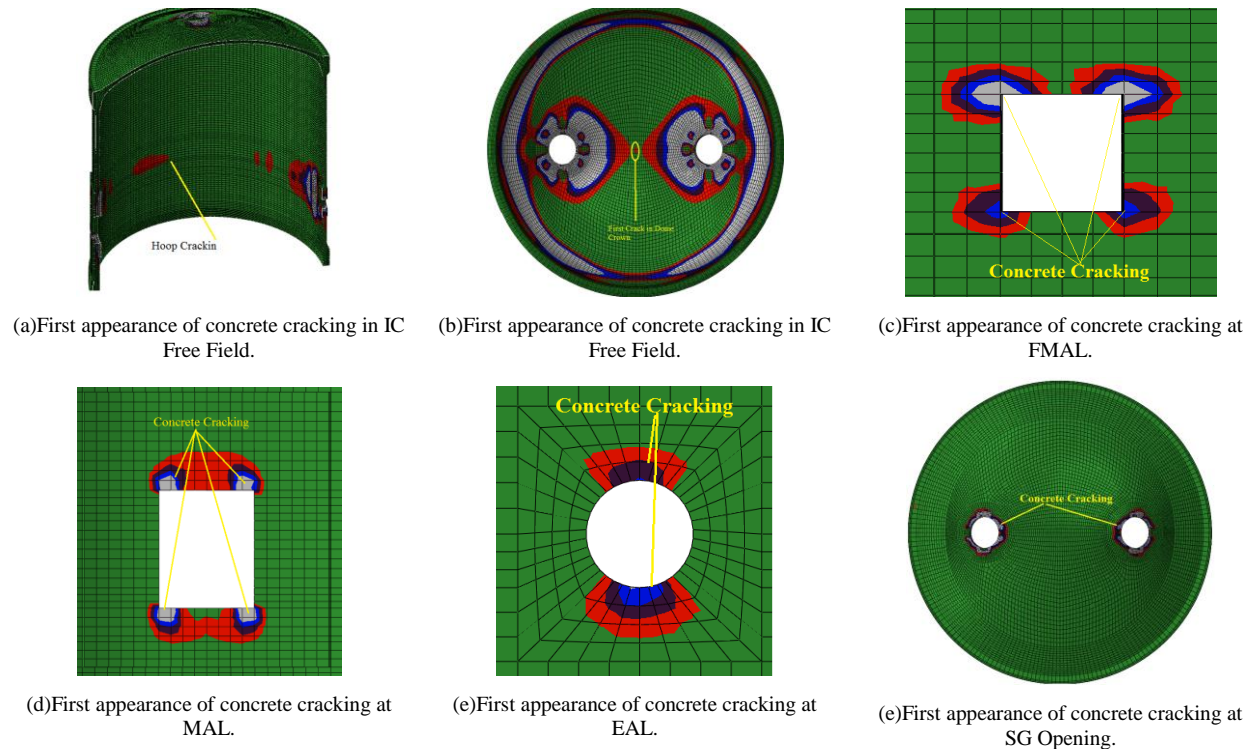


Fig. 4: First Cracking in Concrete

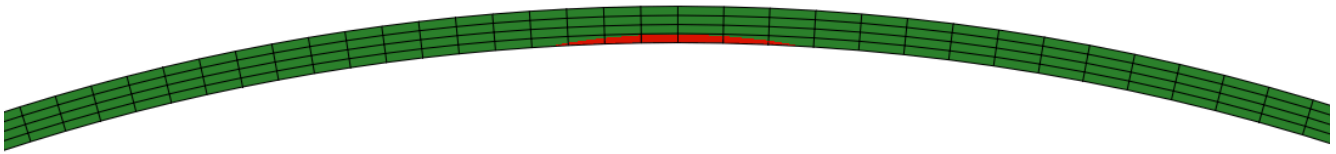
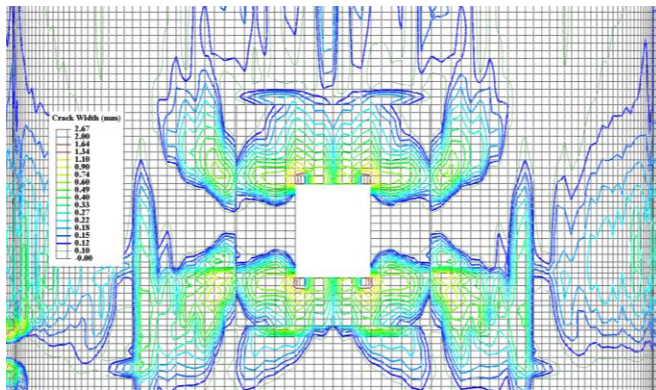


Fig. 5: No Through Wall Thickness Crack at Dome Crown

At 1.87 Pd through thickness crack of width more than 2mm has been develop as in Fig. 6(a), which will result in to large leakage and further pressurization will be possible only through augmentation of third compressor. The crack profile around MAL form FE analysis has good match with the crack profile observed after experiment Fig. 6(b). Ultimate deformed shapes of containment is shown in Fig. 7



(a) Crack Contour around the MAL at 1.87Pd



(b) Cracking observe after experiment at upper corner of MAL

Fig. 6: Crack Profile Around MAL

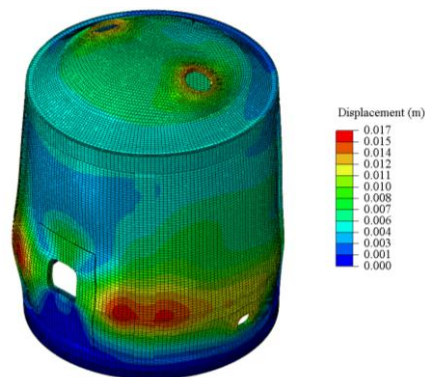


Fig. 7: Deformed shape of Containment Model.

CONCLUSIONS

In the present study 3D finite element model has been used to predict the ultimate load capacity of BARCOM test model. FE model predicts the crack initiation and maximum pressure sustained by the model before massive leakage signifying the functional failure, based on tendon strain level of 1%, with the pressure of 1.87Pd due to local failure around MAL. The displacement and strain plots obtained in 3D FE Model show good comparison with experimental results in the free filed and reasonable comparison in the discontinuity regions of base wall junction and ring beam. However, near opening due to large discrete crack formation the strains are not predicted correctly due to limitation in smeared crack modeling of concrete. The presented model in this paper is able to predict the

behavior of containment model under internal over-pressurization and it is also seen from the experimental results that the various failure modes of the containment are captured. Further improvement needs in terms of local refine modeling of MAL and improvement in concrete model with fracture energy criteria.

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