Standard problem exercise SPE - 3

Performance of pre-stressed concrete containment vessel under severe accidents

Part – I: Structural Analysis

AERB, India
• Introduction
  – Objective
  – Scope

• Phase-1 analysis
  – Model-1
  – Model-2
  – Model-3

• Phase-2 analysis: Case - 1

• Summary
Objective

- Improve knowledge in the areas of:
  - Local containment behaviour under beyond design basis pressures
  - Characterization of leakage behaviour as a function of pressure and temperature
  - Probabilistic aspects of containment response.
• Assessment of the ultimate load capacity of a Prestressed Concrete Containment Vessel (PCCV) structure.

• Principally based on the data of 1:4 scale model containment tests carried out at Sandia National Laboratories (SNL) in 2000-2001

• The SPE consists of two phases
Phase – 1:

- Examination of local effects which were observed to require more study in the previous round robin analyses

  - Effects of containment dilation on prestressing force
  - Slippage of prestressing cables
  - Steel-concrete interface
  - Failure mechanisms
  - Use of nominal versus in-situ conditions
Phase – 2

- Examination of methods to estimate leakage rate as a function of pressure
- Evaluation of the methods relative to the PCCV test results
- Enumeration of methods for predicting leakage of PCCV as function of pressure and temperature
- Application of these methods to characterize performance, in terms of leakage rate, under pressure and temperature
- Transition of performance to probabilistic space
• Model – 1: Tendon behavior model
  – Study tendon forces as a function of containment dilation
    • Change of tendon stress distribution from the classical angular friction design assumption to an approximately uniform distribution
  – Slippage of pre-stressing cables
    • Allow change in position of the tendon relative to the concrete after initial pre-stress to simulate tendon behaviour during over-pressurization
• Model – 2: Local model of equipment hatch
  – Ovalizations of concrete versus steel
    • Study the displacement and leakage that can be caused by this
  – Slippage between the liner and the concrete
    • Influence on tearing and leakage
  – Failure mechanisms
    • Predict tears in the liner from the FE model strains
• Model – 3: Global analysis model
  – Incorporate lessons from model 1 & 2
  – Provide PCCV response at all locations
  – Provide liner strain mapping
  – Response data versus pressure for the “55 standard output locations”
- Finite element model developed in ABAQUS
- Analysis of model – 1 had to be discontinued due to
  - Issues related to convergence
  - Memory & hardware limitations
- Planned to be taken up further in future
• Modeling
  – Rebars as sub-elements of concrete wall
    • Smeared layer
  – Individual stirrups as 2-node truss elements
  – Horizontal and vertical cables using truss elements
    • Average initial stresses of 800 MPa in horizontal
    • Average initial stresses of 1200 MPa in vertical
• Boundary conditions
  
  – Symmetric boundary conditions applied to two vertical surfaces.
  
  – Bottom surface kept vertically restrained.
  
  – Two horizontal rotations at the top surface are restrained
  
  – Top surface allowed to slide vertically as plane surface by applying constraint equation
• Loading & analysis
  – Pre-stress applied and model allowed to reach equilibrium
  – Internal pressure and meridional pull at top surface
  • Pull is a function of internal pressure
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model – 2a (Integral connection)</th>
<th>Model – 2b (Friction contact)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate capacity</td>
<td>3.44 Pd</td>
<td>3.05 Pd (Convergence issues)</td>
</tr>
<tr>
<td>Concrete hoop cracking</td>
<td>1.64 Pd at 0° Azimuth</td>
<td>1.626 Pd at 0° Azimuth</td>
</tr>
<tr>
<td>Tendon strain</td>
<td>0.312% at ultimate pressure near 0° Azimuth</td>
<td>0.302% at ultimate pressure near 18° Azimuth</td>
</tr>
</tbody>
</table>
Model - 2

Liner deformation contour - ultimate capacity

Model 2a

Liner strain contour - ultimate capacity

Model 2b
Modeling

- layered shell element with two layers
  - Layer – 1: Liner; Layer – 2: Concrete
  - Reinforcement and pre-stressing cables as embedded oriented surfaces within concrete layer
    - Uniformly distributed smeared surface
    - Thickness is the ratio of rebar area to spacing
  - Only equipment hatch and airlock openings are included in the model
• Material non-linear behavior
  
  – Concrete: Damage plasticity model
    • Bond slip and dowel action modelled by tension stiffening in concrete model
  
  – Rebars & cables: Metal plasticity model
  
  – Liner: Metal plasticity model
• Analysis: Two steps
  
  – Step – 1: Pre-stress (Average uniform value)
    
    • Hoop cable 840 MPa
    
    • Hairpin: Cylinder & dome till buttress 1250 MPa
    
    • Hairpin: Dome above buttress 1000 MPa
  
  – Step – 2: Internal pressure
Deformed shape

1.0 x Pd

3.0 x Pd

3.65 x Pd
Stress in prestress tendon – 3.65 Pd
Phase - 2 Analysis
Model calibration

- Confirm adequacy of mesh refinement

- Check performance w.r.t test results

- Results compared with two other models
  - Model refined near openings
  - Local detailed (3D) model near E/H
Model – calibration: Refinement near openings
Model – calibration: Local model near E/H

- Wall using 8 node solid elements
  - Concrete damage plasticity model for inelastic behavior
- Liner and pipe sleeve using 4 node shell element
  - Metal plasticity model to simulate inelastic behavior
Model calibration: Stress in tendon: $3.65 P_d$

Comparison of refined & unrefined models

Hoop

Hair Pin
Model calibration

- No difference in response of the global models with and without refinement near openings
  - Confirms adequacy of mesh refinement near openings
    - global mesh itself very fine, 0.2m x 0.2m

- Estimated PCCV ultimate capacity and liner damage locations match closely with global and local models

- Hence global model of phase-1 (model-3) used for phase-2 studies also
Case - 1 analysis
Calibrated Model-3 from phase-1

Modification to include temperature loading
- Number of layers changed from 2 to 4
  - Layer 1: Liner (9 integration points)
  - Layer 2 to 4: Concrete (9 integrations points each)

Modified model designated as model-4
Temperature & pressure variation

- As per problem statement
  - Stress free temperature = 25°C

- Temperature loading regions

- Temperature variation across thickness
Failure prediction criteria

- PCCV model is considered to have reached its ultimate structural failure capacity when
  
  - Yielding of following occur in any location in the structure
    
    - Reinforcing steel in both directions
    
    - Pre-stressing steel in both directions
Case-1 results: Deformed shape
Case-1 results: Deformed shape

3.74 Pd

3.46 Pd
Output at 55 standard output locations

- Output provided for 52 out of 55 locations
  - Output at base liner (loc 47) not provided
    - as the base liner is not modelled.
  - Output at anchorage loc. 54, 55 not provided
    - Pre-stressing tendons are modelled as smeared layer.

- Rebar strains: Generally provided for the outer layer.

- Liner strain: Integration point at inner surface of PCCV.

- Radial displ. at the centre of E/H and A/L:
  Mean of displ. at 4 nodes on the edge of E/H & A/L.
Displacement in general area

Vertical displacement: Location - 11

Dome crown

Cylinder general area

Radial displacement: Location - 4
Displacement at openings

Radial displacement: Location – 14

Radial displacement: Location – 15

A/L opening

E/H opening
Reinforcement strains
Liner strains
Liner strain contours

Hoop strain
After prestress
Liner strain contours

Hoop strain
Initial temperature
Liner strain contours - Hoop
Liner strain contours - meridional
Liner strain contours

Hoop

Meridional

3.46 Pd
Liner strain contours

3.74 Pd
Tendon stress profile

- Tendons not modeled individually
- Stress at tendon layer at the level of specified tendon
- Path for each tendon
Tendon stress profile

Tendon stress profile for H-35 cable

Tendon stress profile for H-68 cable
Tendon stress profile

Tendon stress profile for V-37 cable

- Tendon stress profile (N/sq.m)
- Azimuth (degrees)

Legend:
- 0–Pd
- 0–Pd(temp)
- 1.0–Pd
- 1.5–Pd
- 2.0–Pd
- 2.5–Pd
- 3.0–Pd
- 3.3–Pd
- 3.4–Pd
- 3.46–Pd
Ultimate capacity: $3.46 \, P_d$

Stress in reinforcement layers

- **Hoop - In**
- **Hoop - Out**
- **Mer - In**
- **Mer - Out**
Ultimate capacity: 3.46 P_d

Stress in prestress tendon layers

3.46 Pd
Stress in prestress tendon layers

Stress in prestress tendon layers

3.74 Pd
• Comparison of results with phase – 1
  – Ultimate capacity
    • Phase – 1: 3.65 x P_d
    • Case - 1: 3.46 x P_d
  – Displacement at center of E/H & A/L
  – Strain in rebar location – 31
Displacement at center of E/H & A/L
Comparison of Phase-1 & Phase2-case1
• Temperature has a significant effect on strains and displacement

• The compression provided by the pre-stress is compensated by temperature at early loading stage.