Standard problem exercise SPE - 3

Performance of pre-stressed concrete containment vessel under severe accidents

Part – I: Structural Analysis

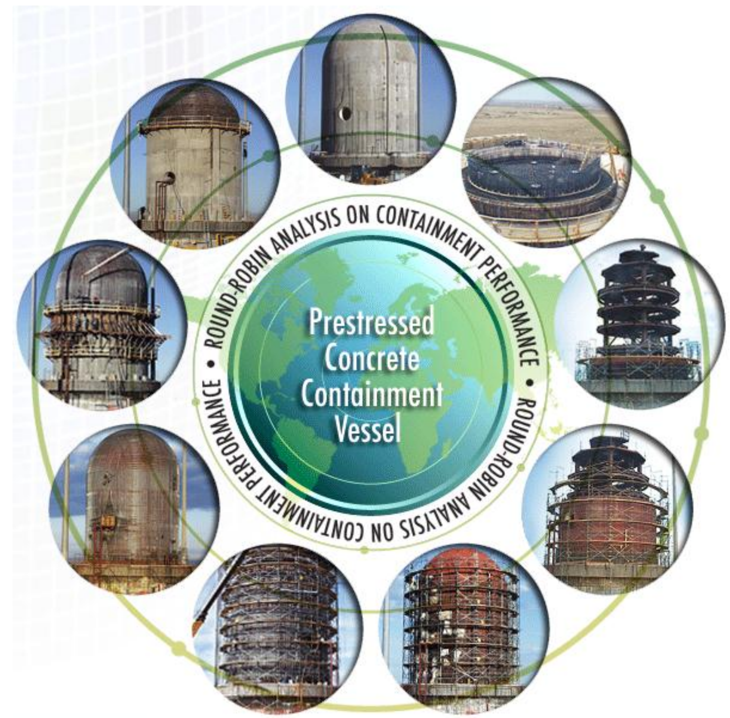
AERB, India

Outline

- Introduction
  - Objective
  - Scope
- Phase-1 analysis
  - Model-1
  - Model-2
  - Model-3
- Phase-2 analysis: Case - 1
- Summary

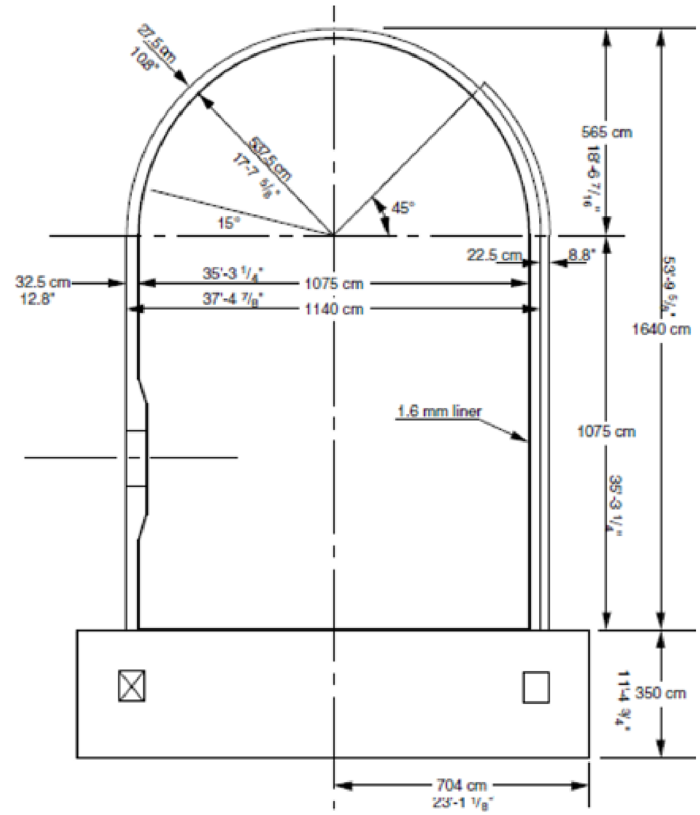
Objective

- 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.



Scope

- 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



Scope

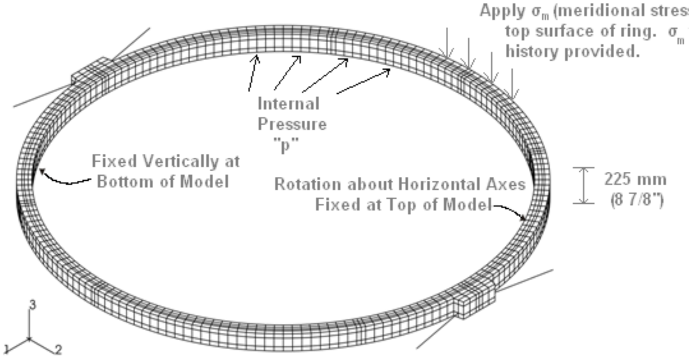
- Phase – 1:
  - Examination of local effects which were observed to require more study in the previous round robin analyses
    - Effects of containment dilation on prestressing force
    - Slippage of prestressing cables
    - Steel-concrete interface
    - Failure mechanisms
    - Use of nominal versus in-situ conditions

Scope

- 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

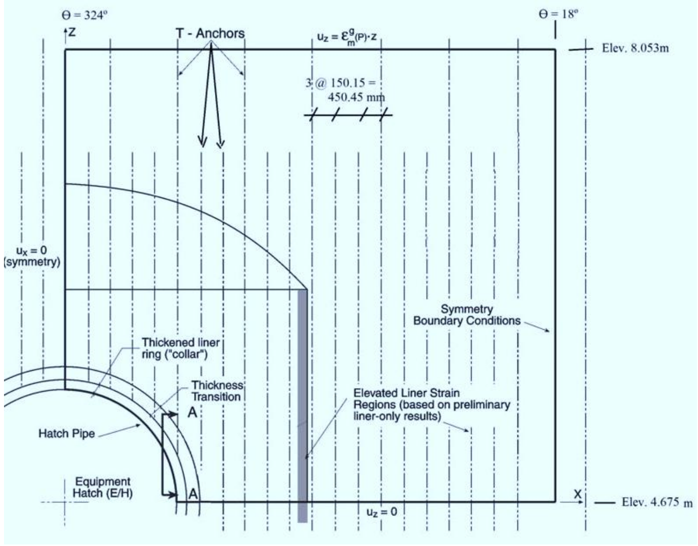
Phase - 1

- 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



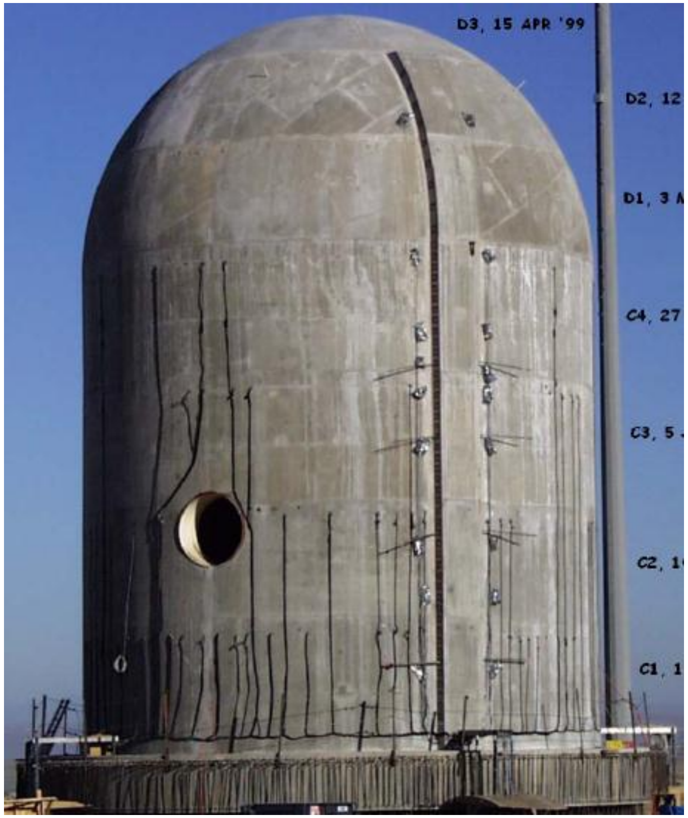
Phase - 1

- 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



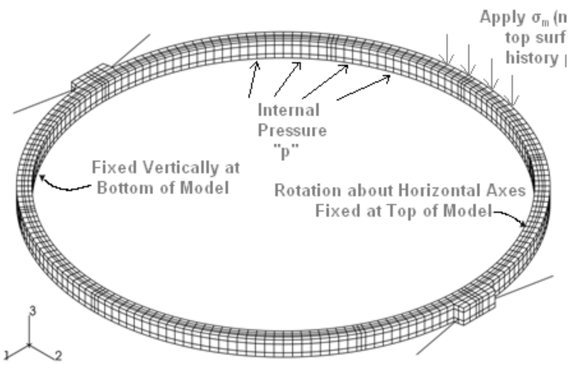
Phase - 1

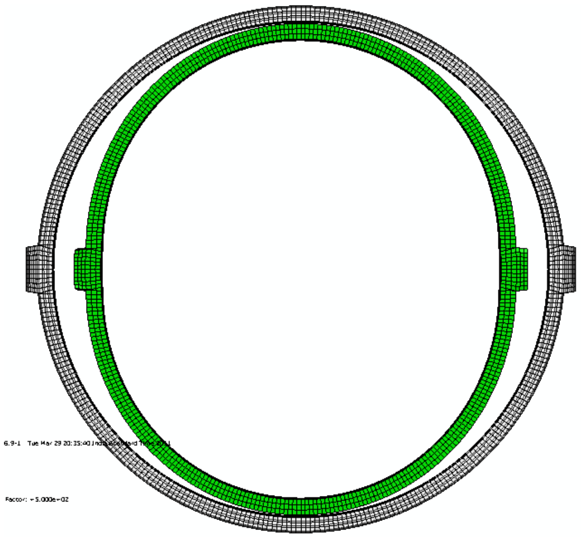
- Model – 3: Global analysis model
  - Incorporate lessons from model 1 & 2
  - Provide PCCV response at all locations
  - Provide liner strain mapping
  - Response data versus pressure for the "55 standard output locations"



Model - 1

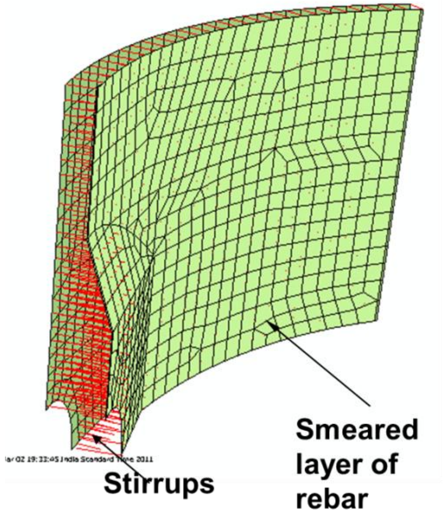
- Finite element model developed in ABAQUS
- Analysis of model – 1 had to be discontinued due to
  - Issues related to convergence
  - Memory & hardware limitations
- Planned to be taken up further in future

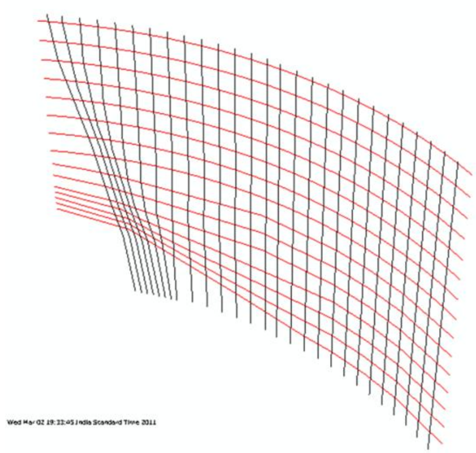




Model - 2

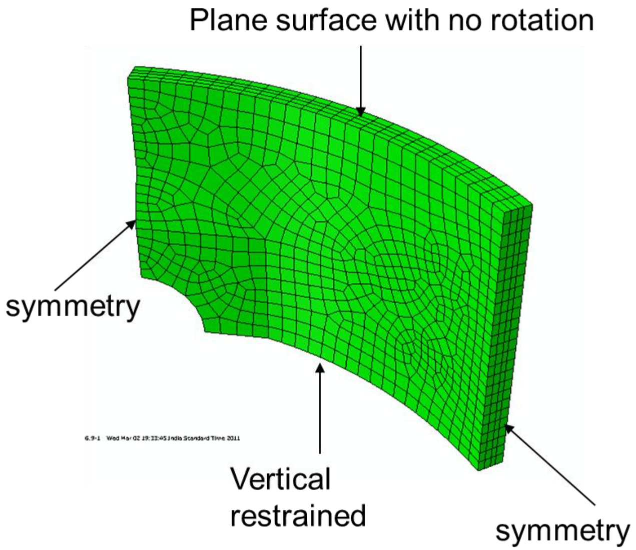
- Modeling
  - Rebars as sub-elements of concrete wall
    - Smeared layer
  - Individual stirrups as 2-node truss elements
  - Horizontal and vertical cables using truss elements
    - Average initial stresses of 800 MPa in horizontal
    - Average initial stresses of 1200 MPa in vertical





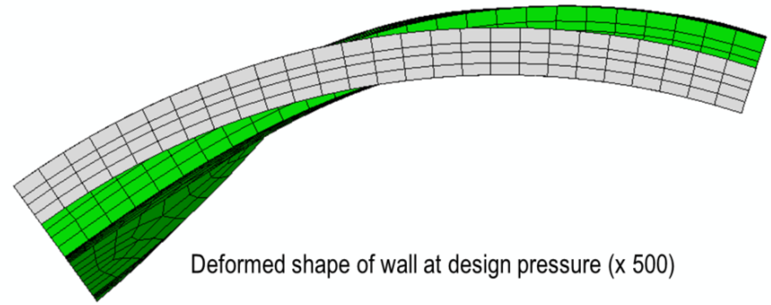
Model - 2

- 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

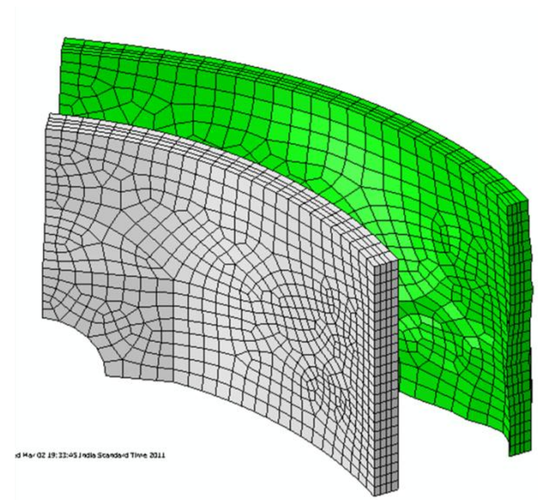


Model - 2

- 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



Deformed shape of wall at design pressure (x 500)

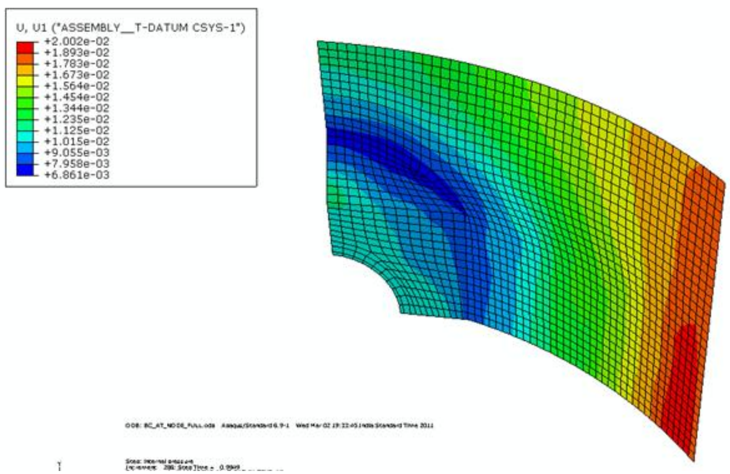


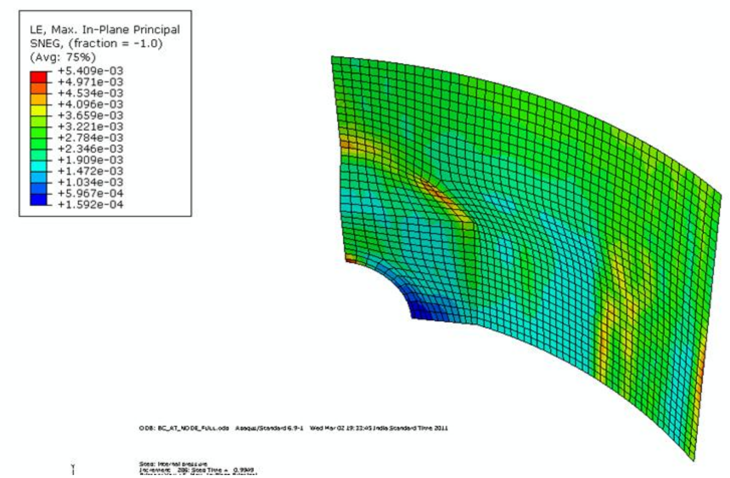
Deformed shape of wall at ultimate pressure 3.44Pd (x 100)

Model – 2

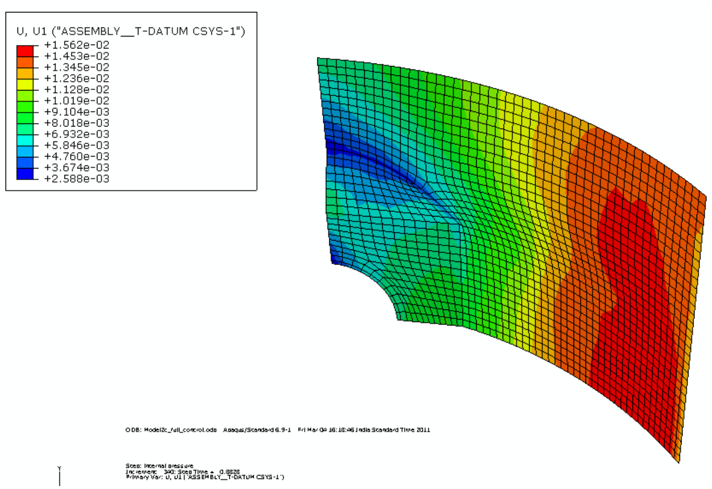
Parameter	Model – 2a (Integral connection)	Model – 2b (Friction contact)
Ultimate capacity	3.44 Pd	3.05 Pd (Convergence issues)
Concrete hoop cracking	1.64 Pd at 0^{o} Azimuth	1.626 Pd at 0^{o} Azimuth
Tendon strain	0.312% at ultimate pressure near 0^{o} Azimuth	0.302% at ultimate pressure near 18^{o} Azimuth

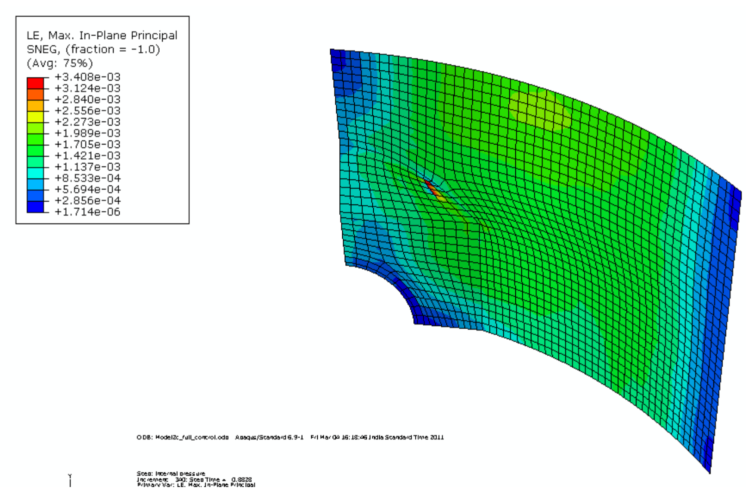
Model - 2





Model 2a





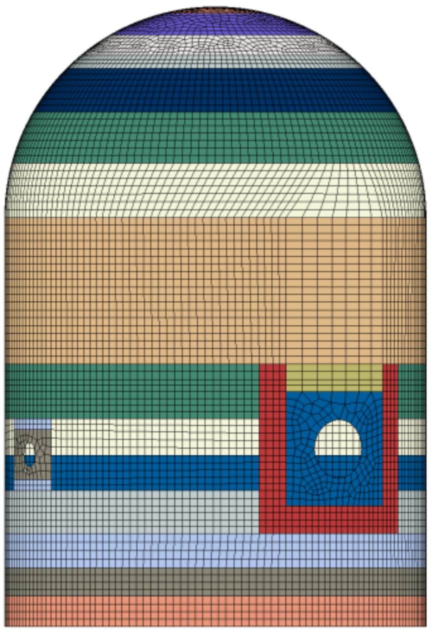
Model 2b

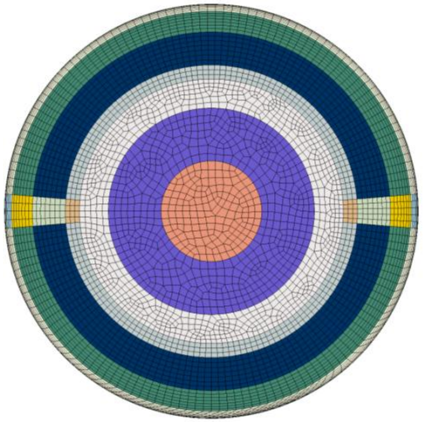
Liner deformation contour - ultimate capacity

Liner strain contour - ultimate capacity

Model - 3

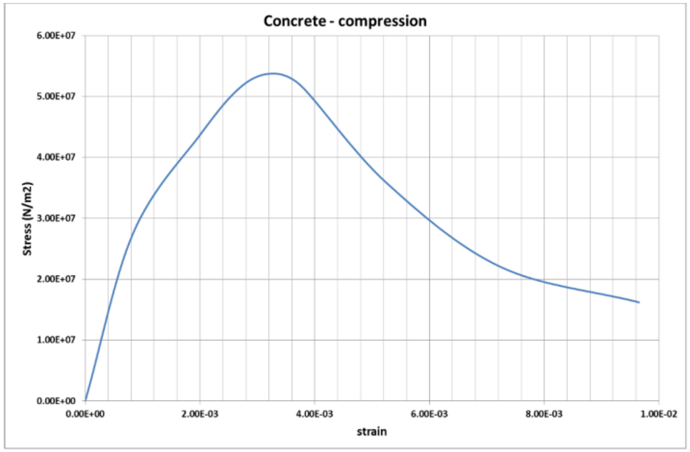
- Modeling
  - layered shell element with two layers
    - Layer – 1: Liner; Layer – 2: Concrete
  - Reinforcement and pre-stressing cables as embedded oriented surfaces within concrete layer
    - Uniformly distributed smeared surface
    - Thickness is the ratio of rebar area to spacing
  - Only equipment hatch and airlock openings are included in the model

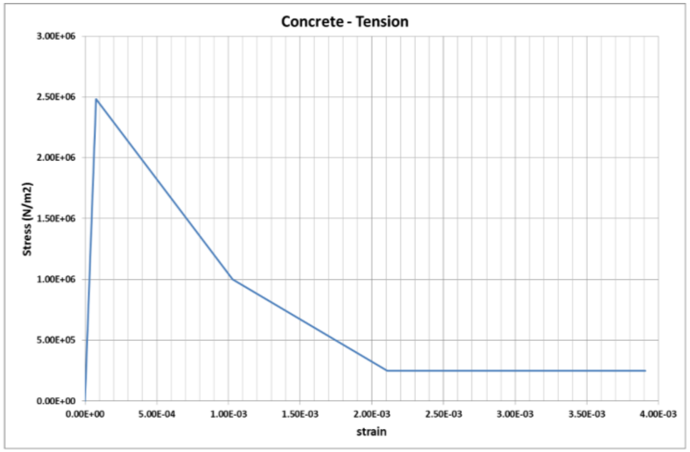




Model - 3

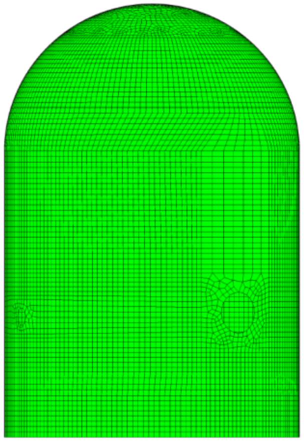
- Material non-linear behavior
  - Concrete: Damage plasticity model
    - Bond slip and dowel action modelled by tension stiffening in concrete model
  - Rebars & cables: Metal plasticity model
  - Liner: Metal plasticity model



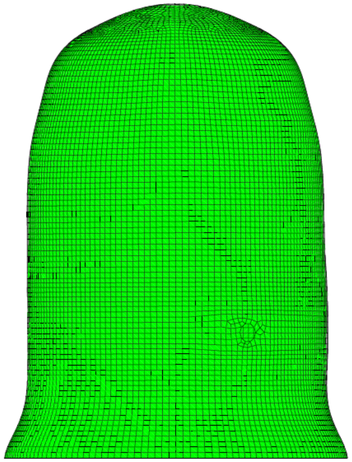


Model - 3

- 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

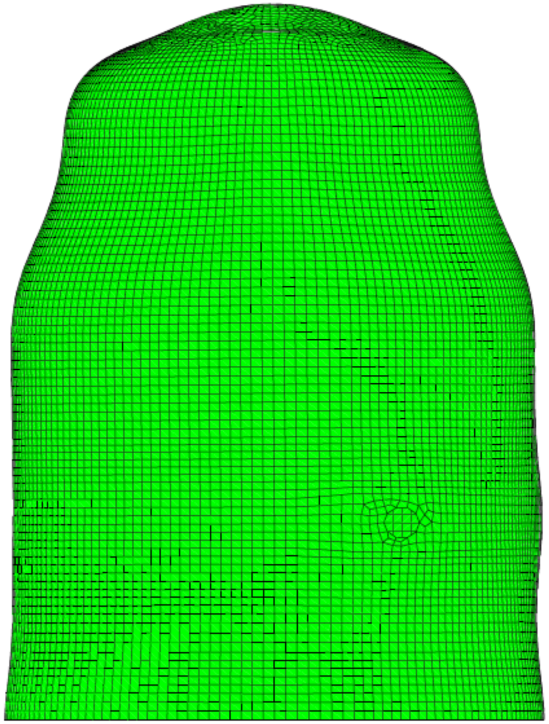


Un-deformed shape

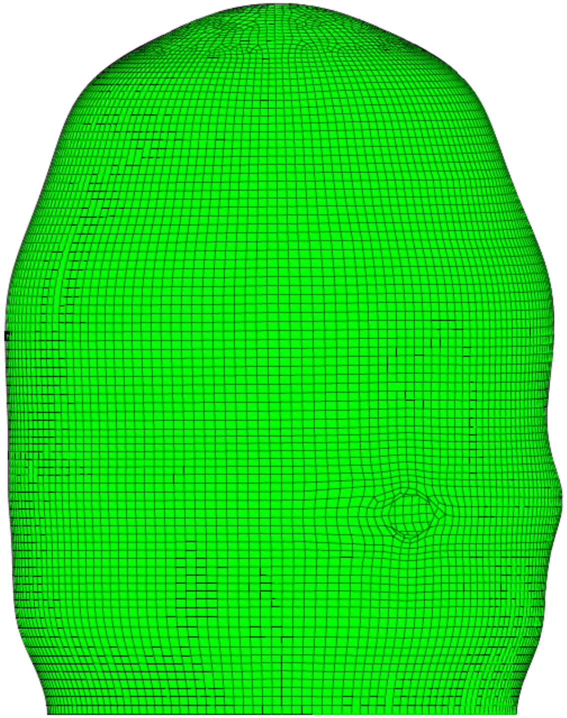


Deformed shape after pre-stress

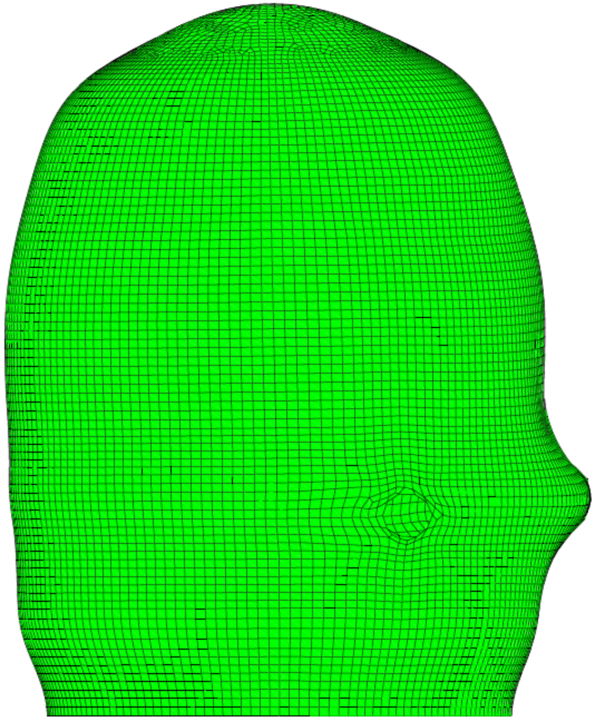
Deformed shape



1.0 x Pd

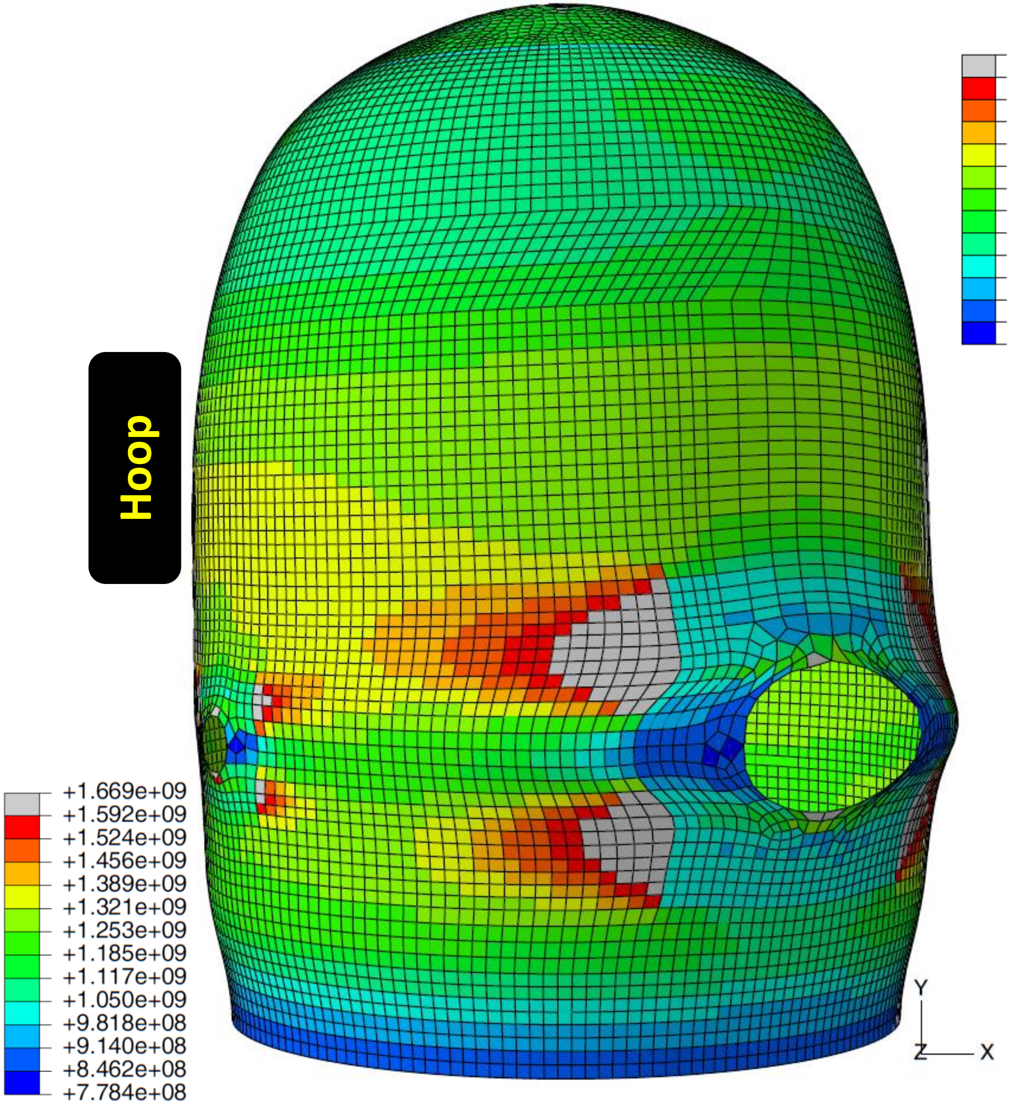


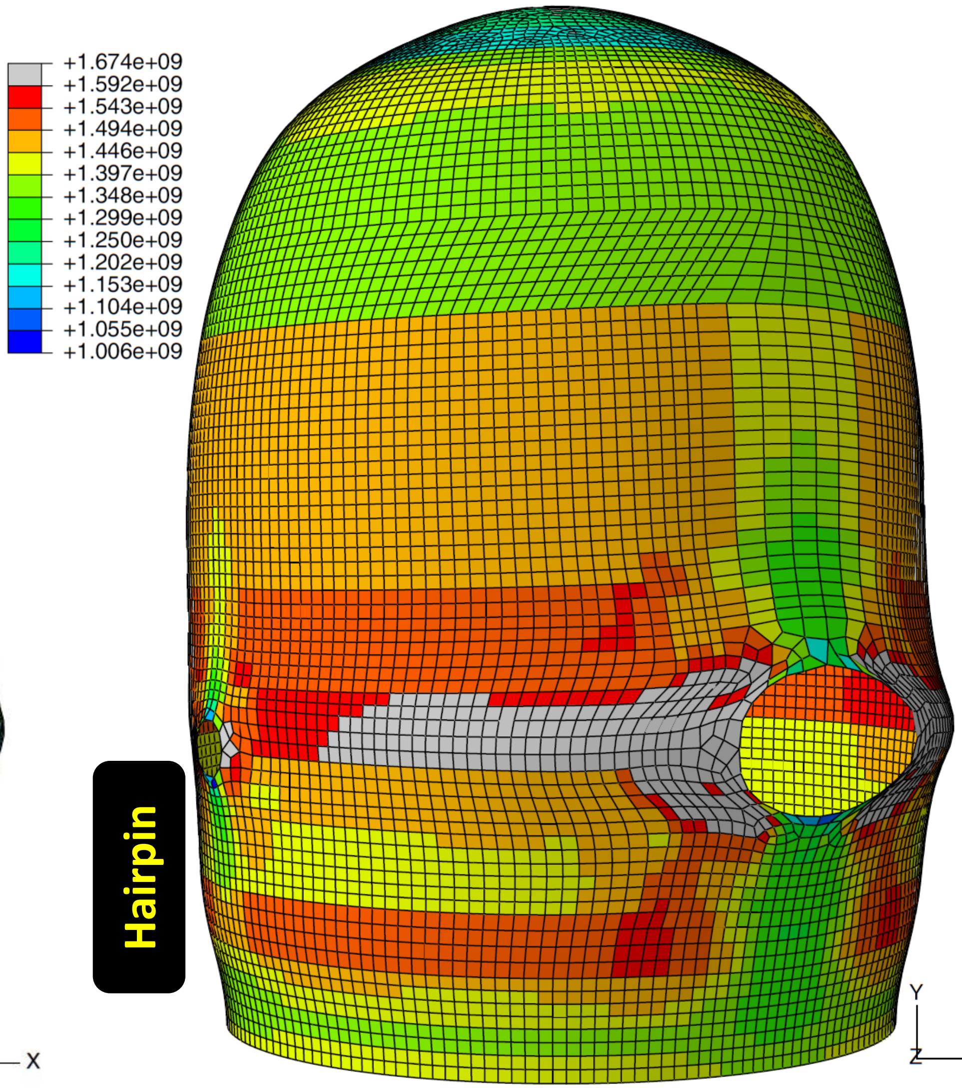
3.0 x Pd



3.65 x Pd

Stress in prestress tendon – 3.65 Pd

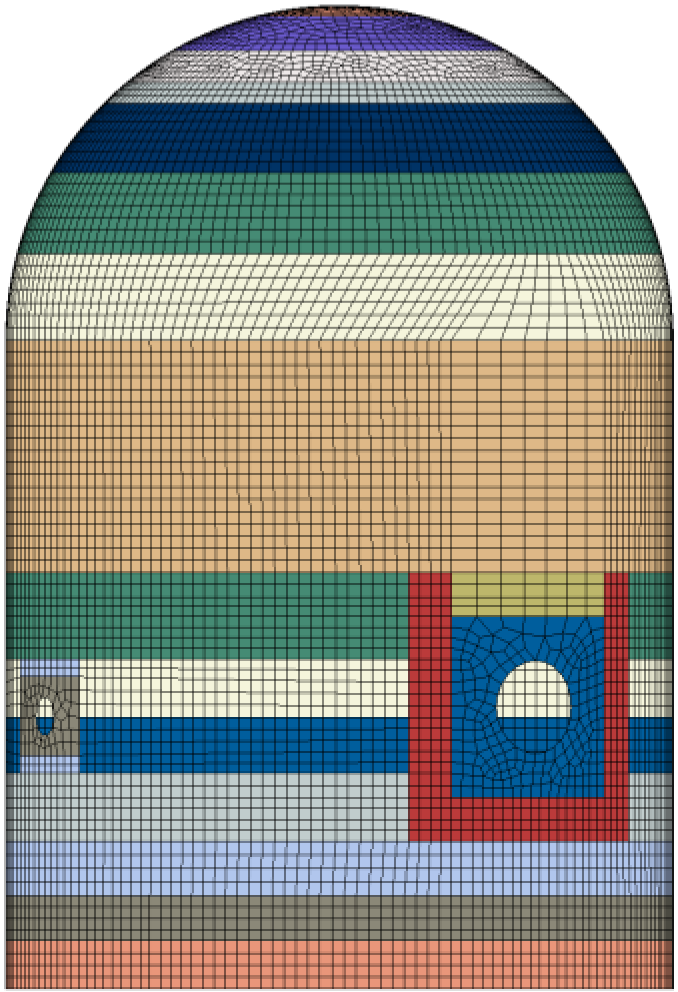




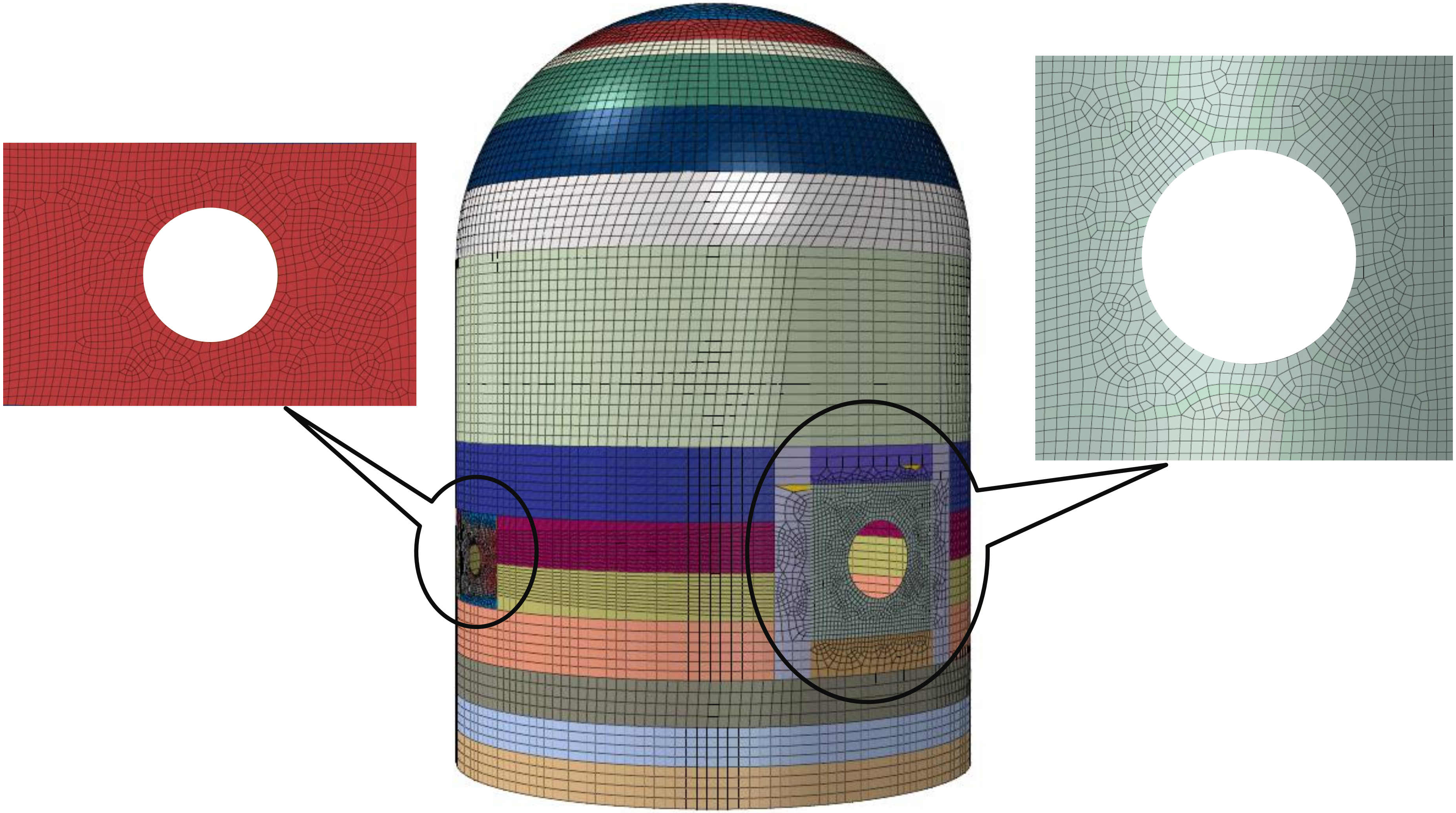
Phase - 2 Analysis

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

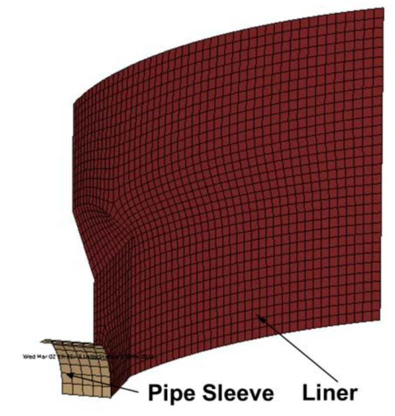


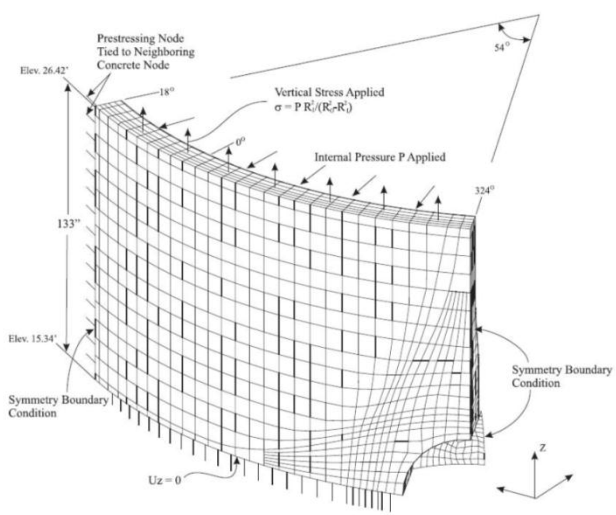
Model – calibration: Refinement near openings

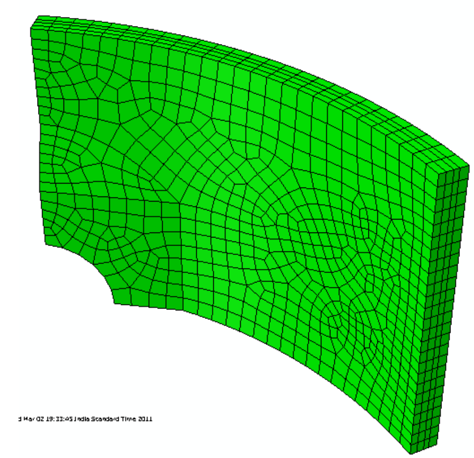


Model – calibration: Local model near E/H

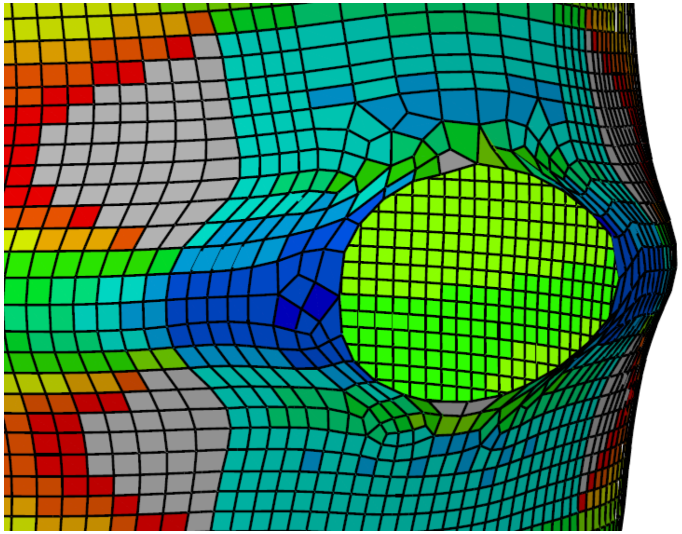
- Wall using 8 node solid elements
  - Concrete damage plasticity model for inelastic behavior
- Liner and pipe sleeve using 4 node shell element
  - Metal plasticity model to simulate inelastic behavior

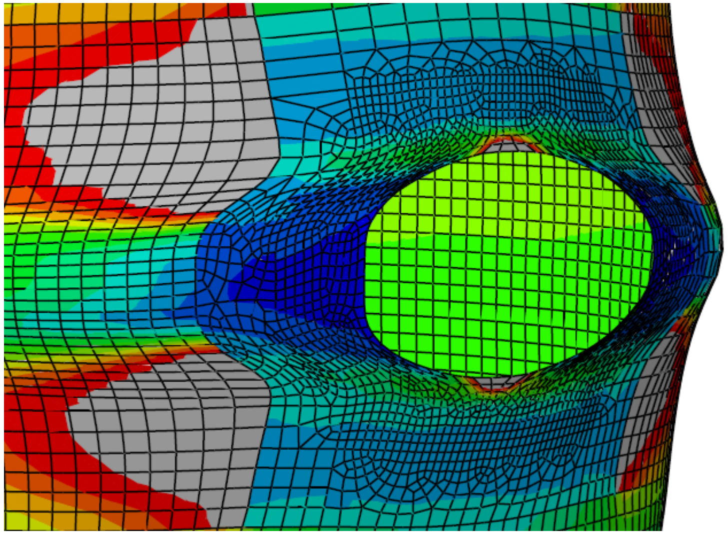






Model calibration: Stress in tendon: 3.65 P_d

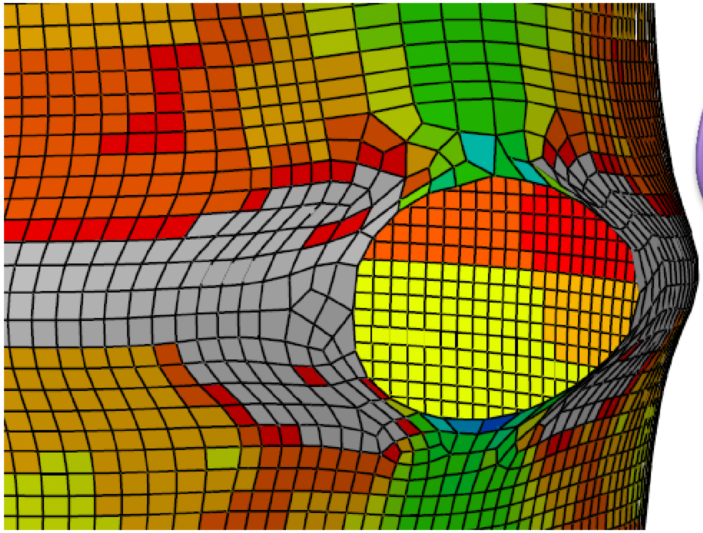


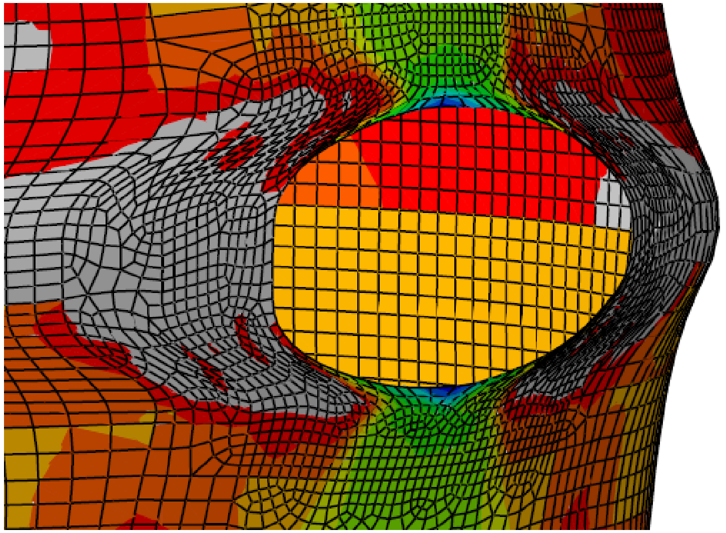


Hoop

Comparison of refined & unrefined models

Hair Pin





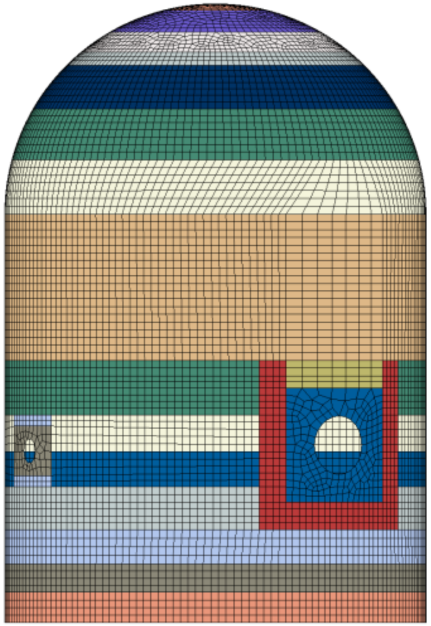
Model calibration

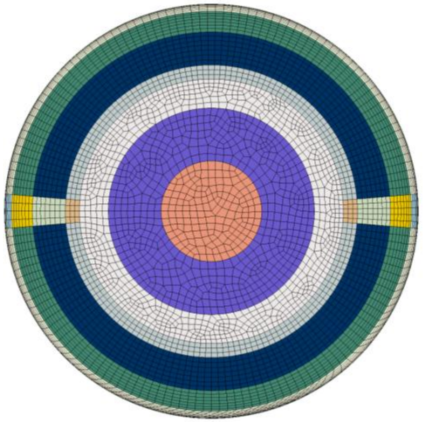
- No difference in response of the global models with and without refinement near openings
  - Confirms adequacy of mesh refinement near openings
    - global mesh itself very fine, 0.2m x 0.2m
- Estimated PCCV ultimate capacity and liner damage locations match closely with global and local models
- Hence global model of phase-1 (model-3) used for phase-2 studies also

Case - 1 analysis

Model

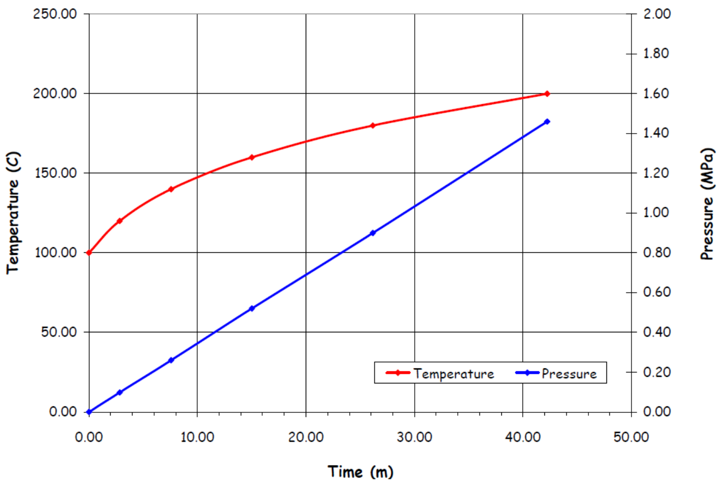
- Calibrated Model-3 from phase-1
- Modification to include temperature loading
  - Number of layers changed from 2 to 4
    - Layer 1: Liner (9 integration points)
    - Layer 2 to 4: Concrete (9 integrations points each)
- Modified model designated as model-4





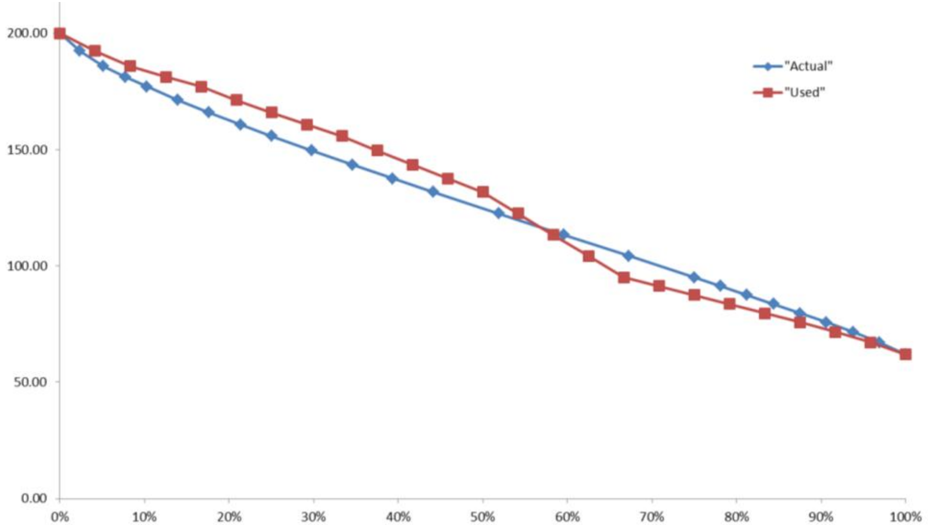
Temperature & pressure variation

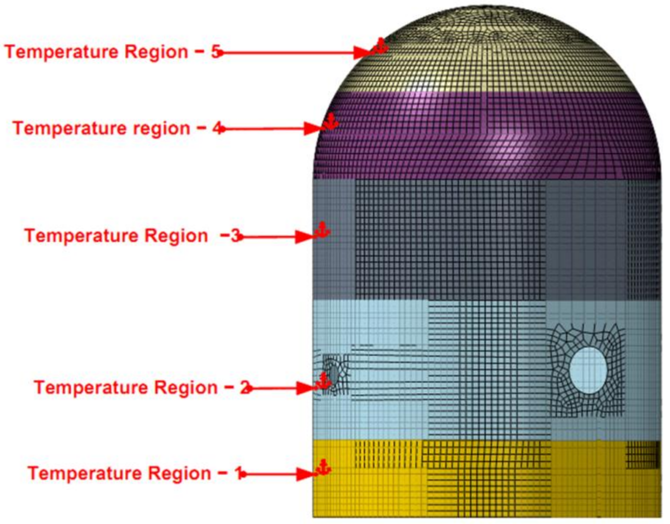
- As per problem statement
  - Stress free temperature = 25^{o}C



- Temperature loading regions

- Temperature variation across thickness

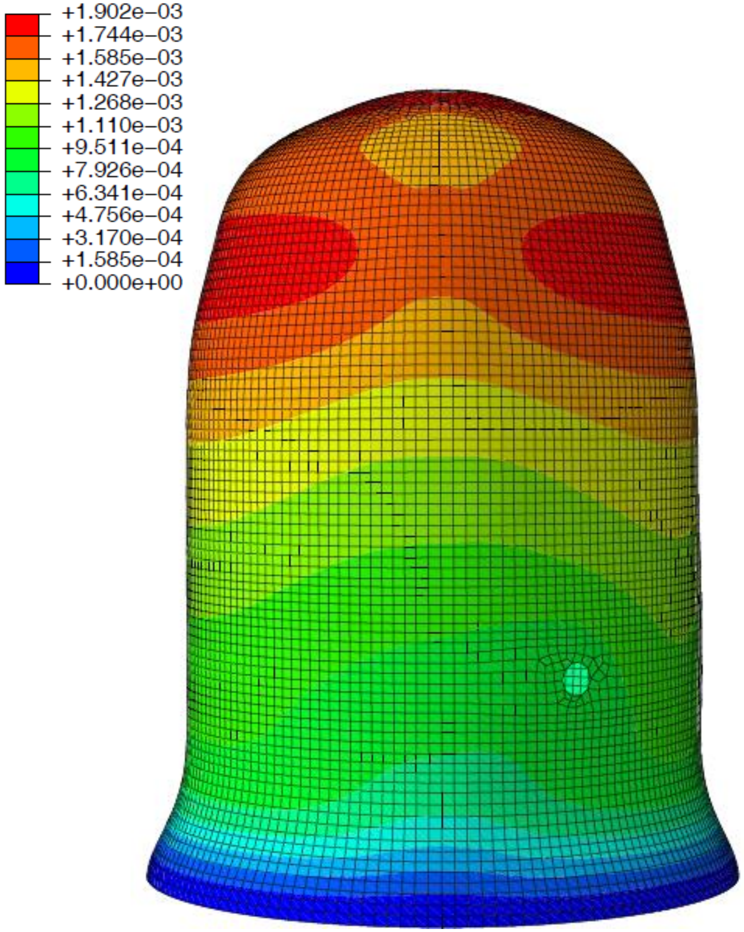




Failure prediction criteria

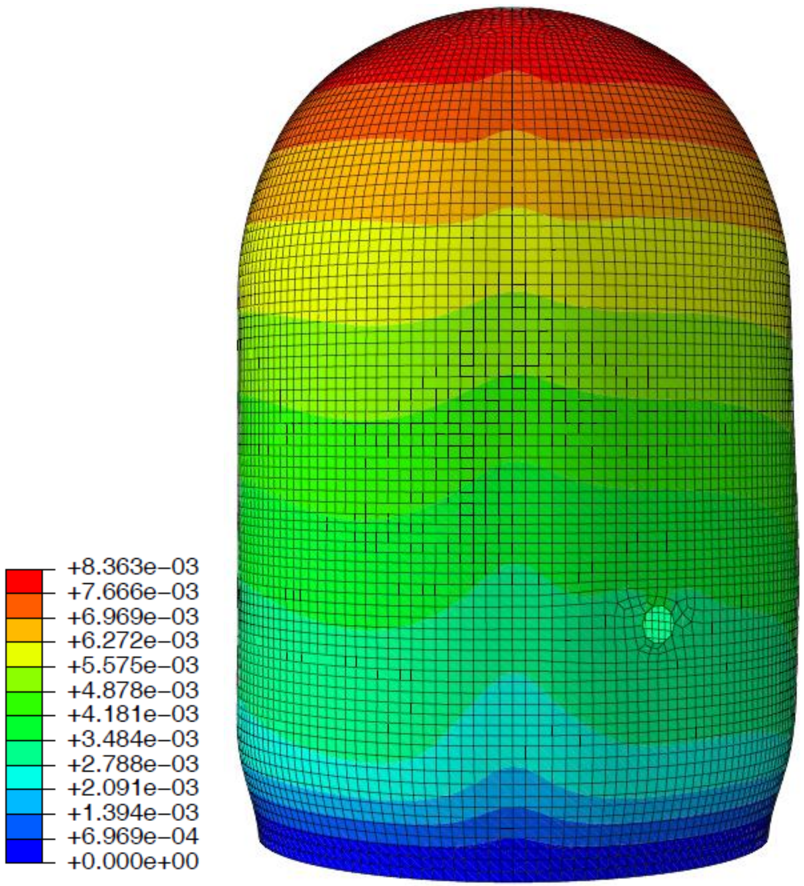
- PCCV model is considered to have reached its ultimate structural failure capacity when
  - Yielding of following occur in any location in the structure
    - Reinforcing steel in both directions
    - Pre-stressing steel in both directions

Case-1 results: Deformed shape



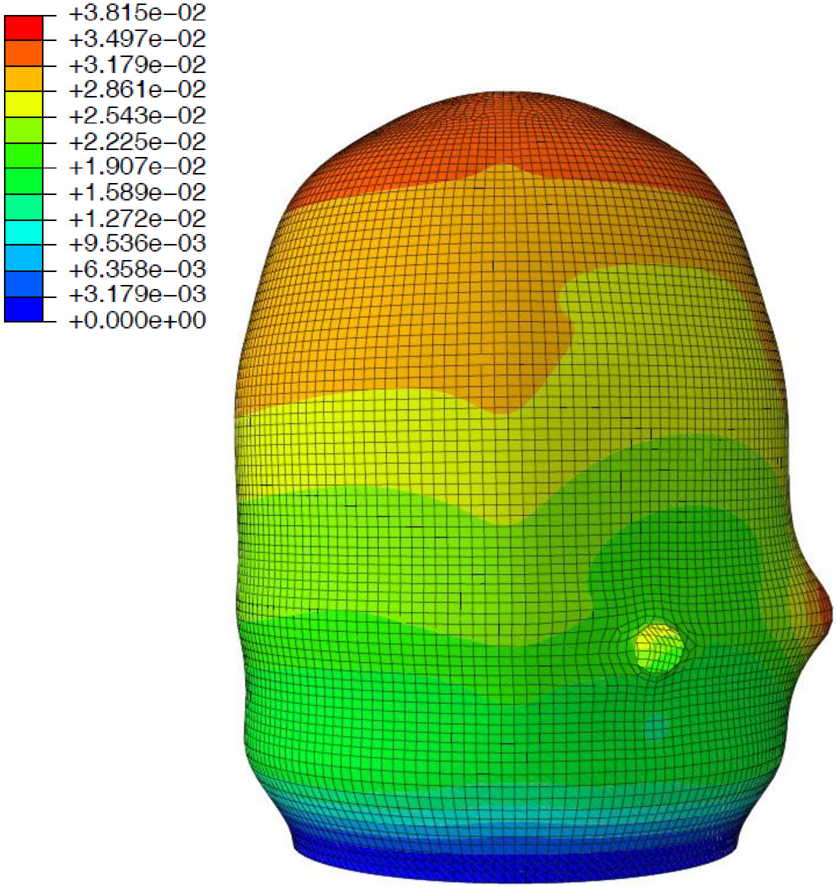
Prestress

Initial temperature

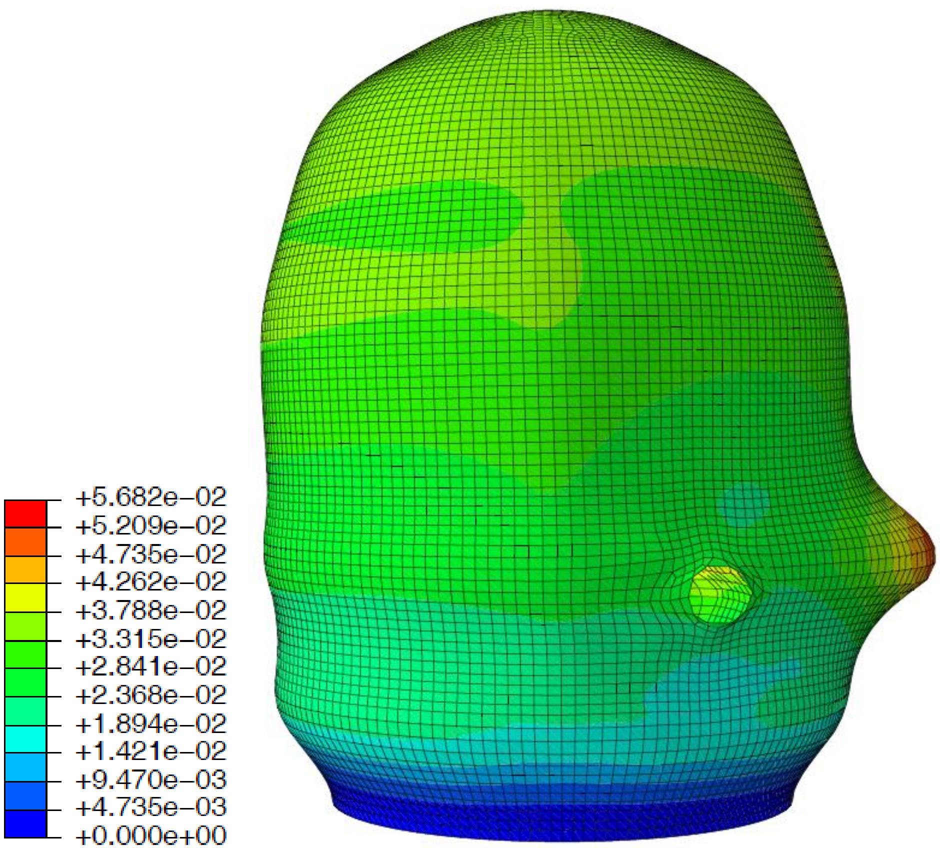


Case-1 results: Deformed shape

3.74 Pd

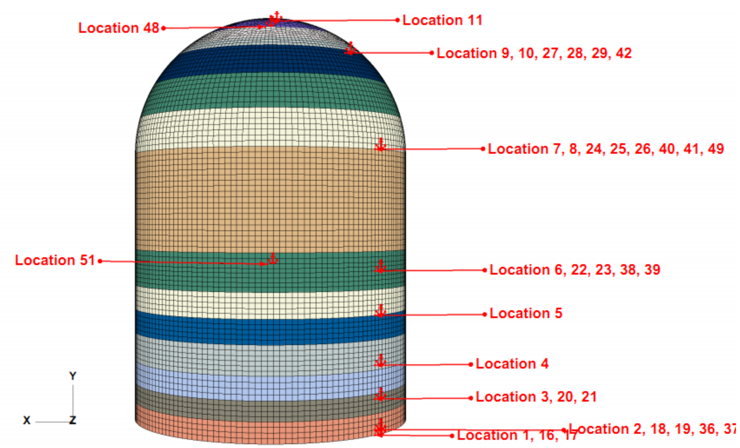


3.46 Pd

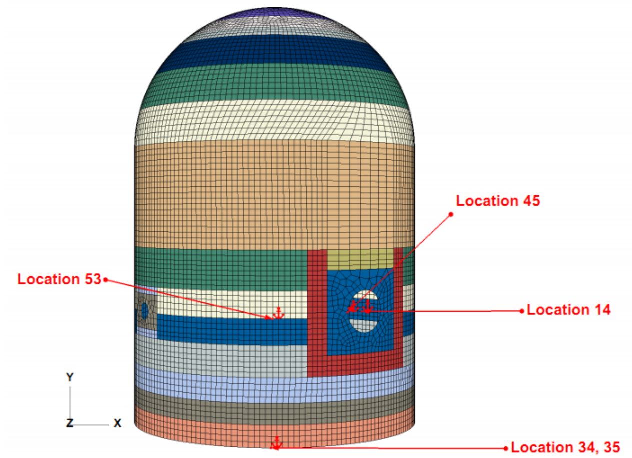


Output at 55 standard output locations

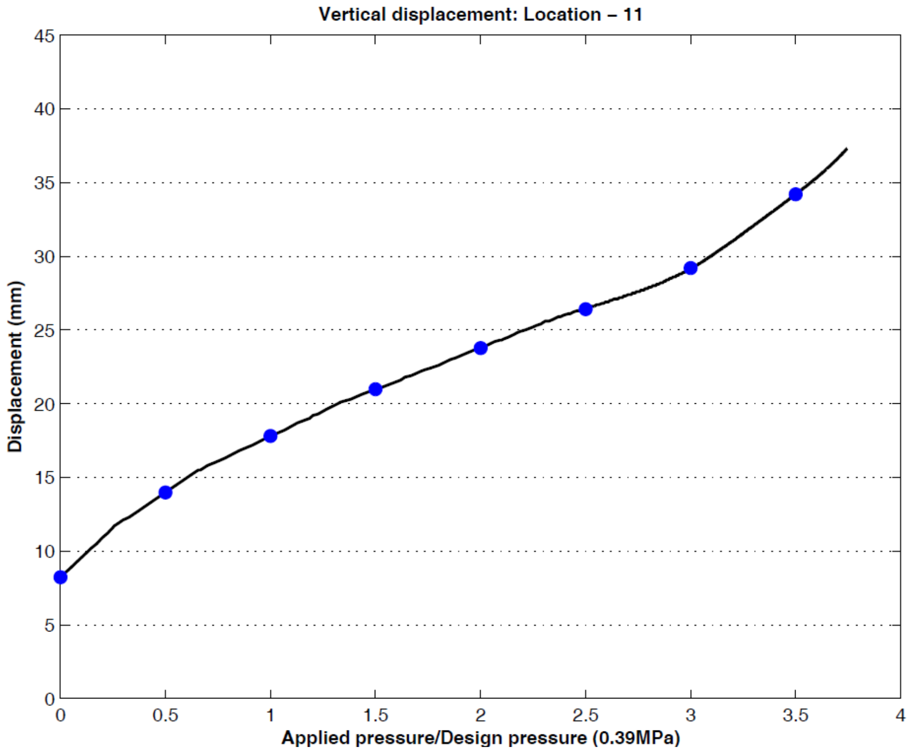
- Output provided for 52 out of 55 locations
  - Output at base liner (loc 47) not provided
    - as the base liner is not modelled.
  - Output at anchorage loc. 54, 55 not provided
    - Pre-stressing tendons are modelled as smeared layer.



- 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.

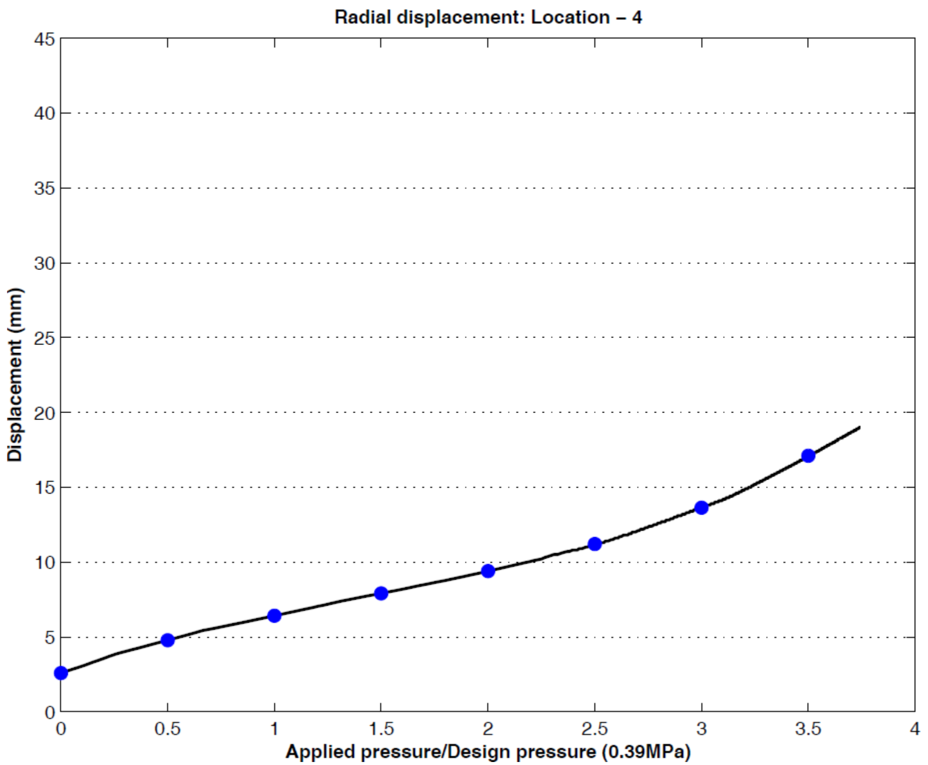


Displacement in general area

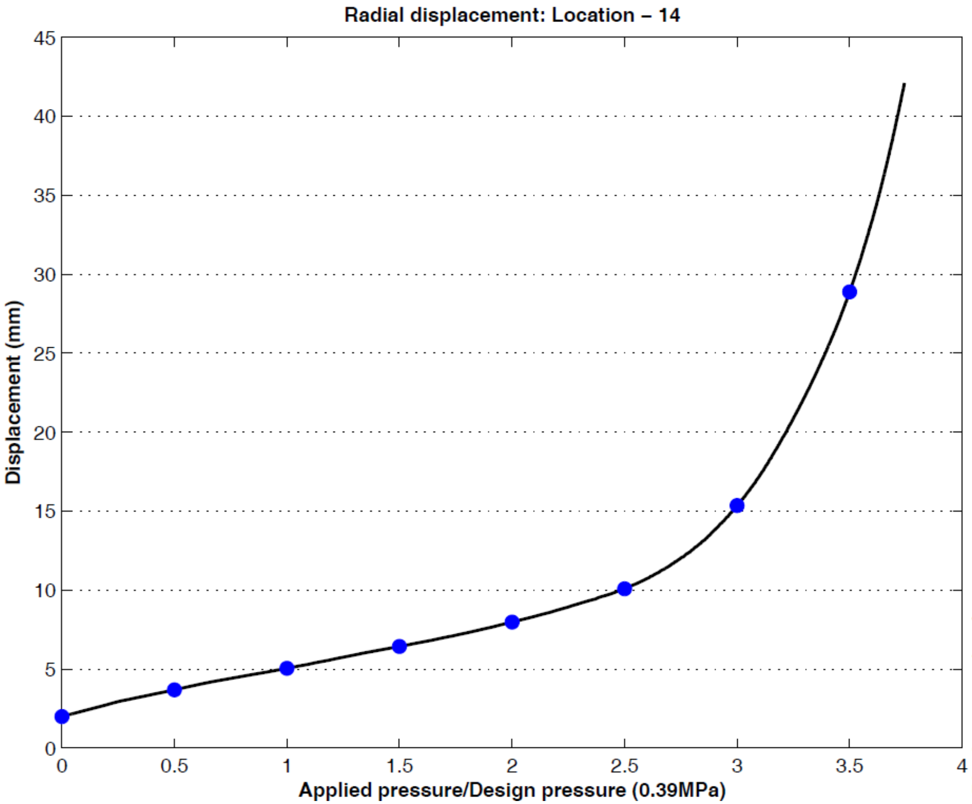


Dome crown

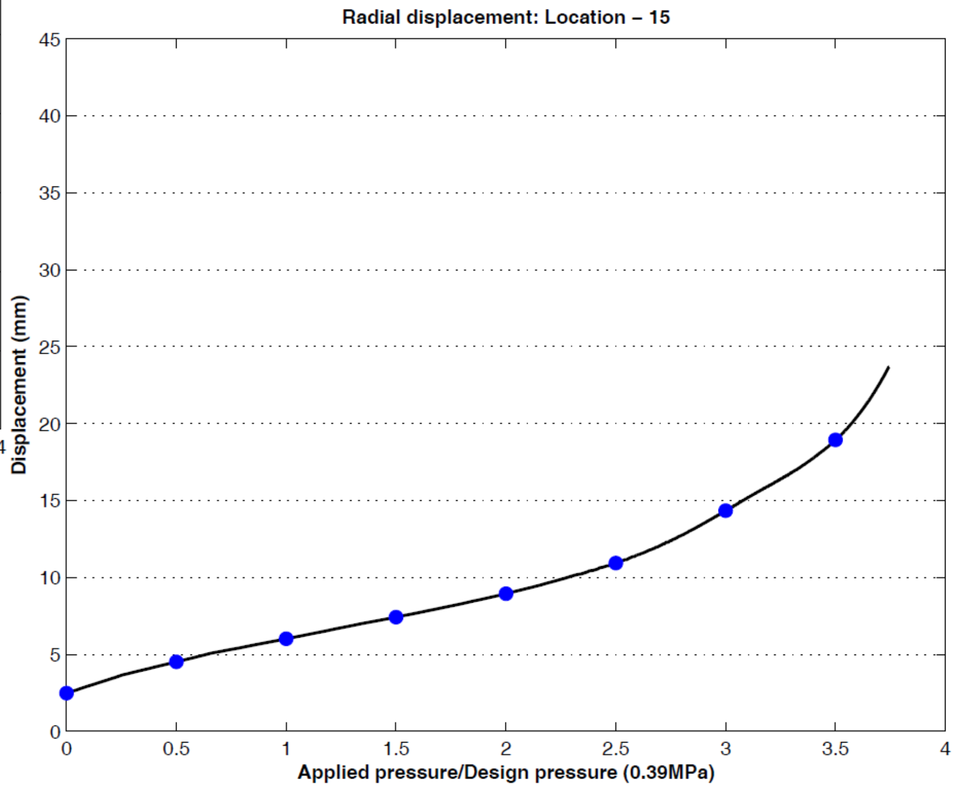
Cylinder general area



Displacement at openings

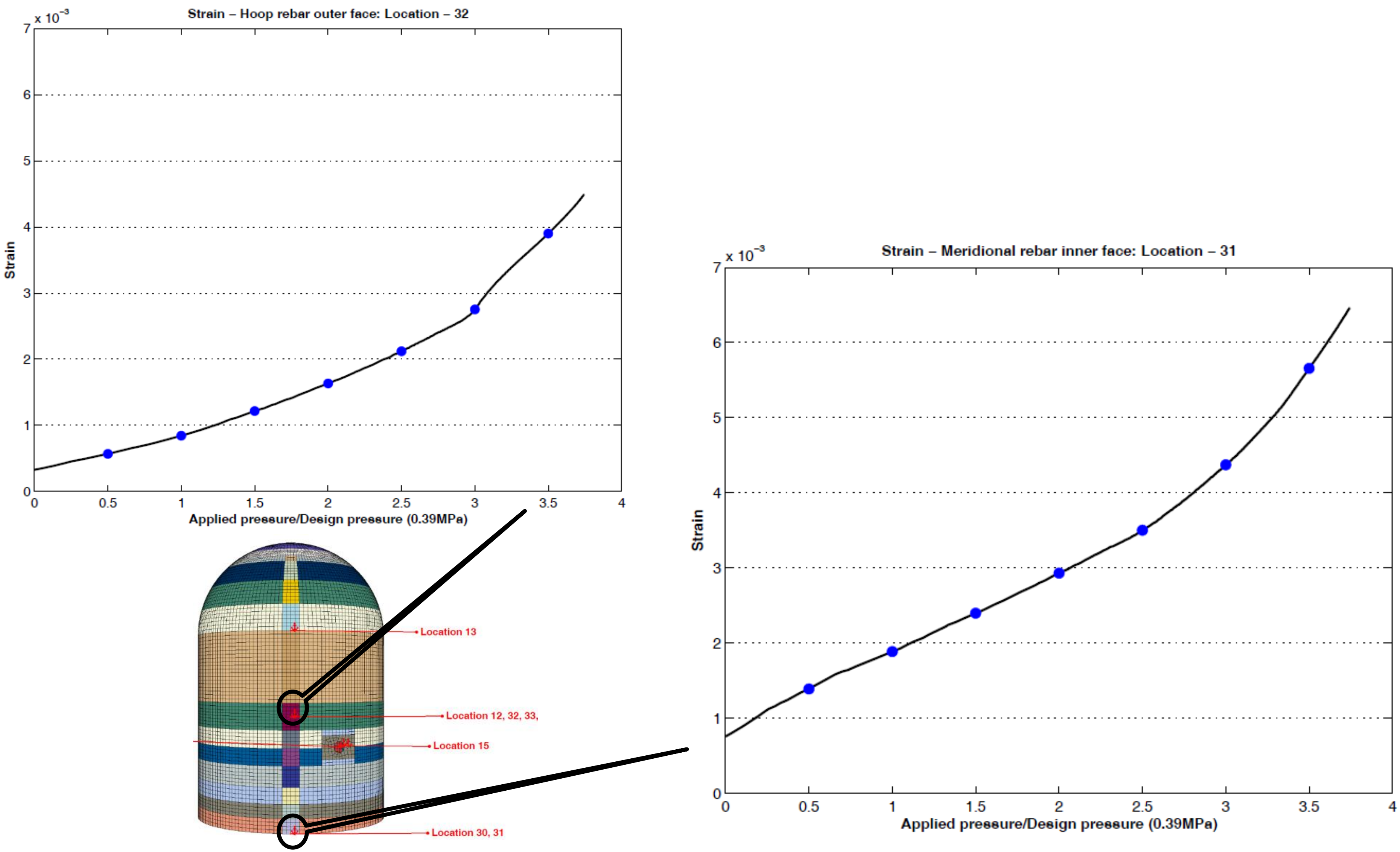


A/L opening

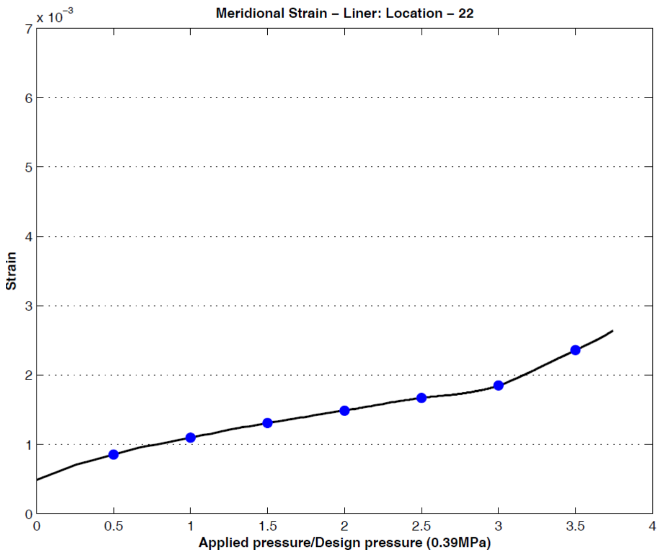


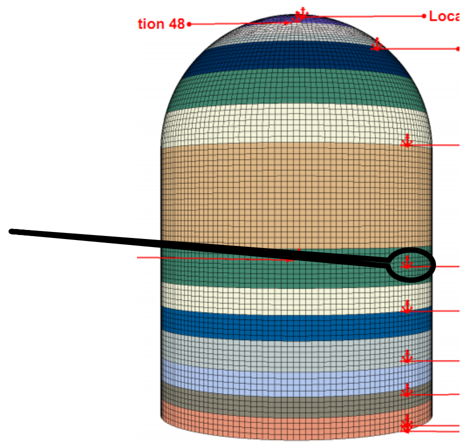
E/H opening

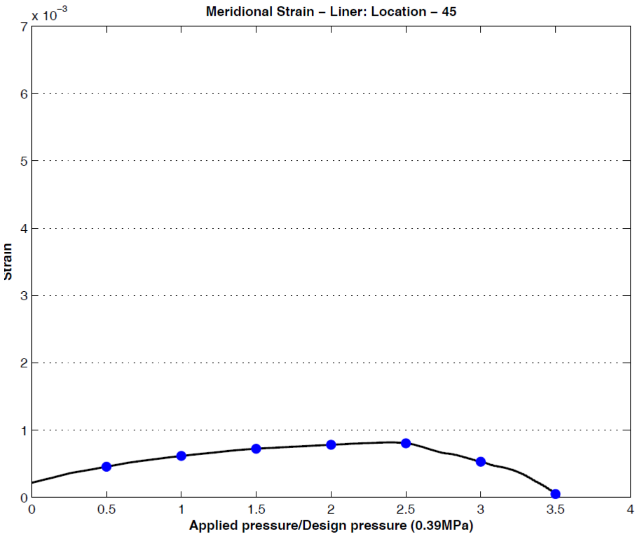
Reinforcement strains

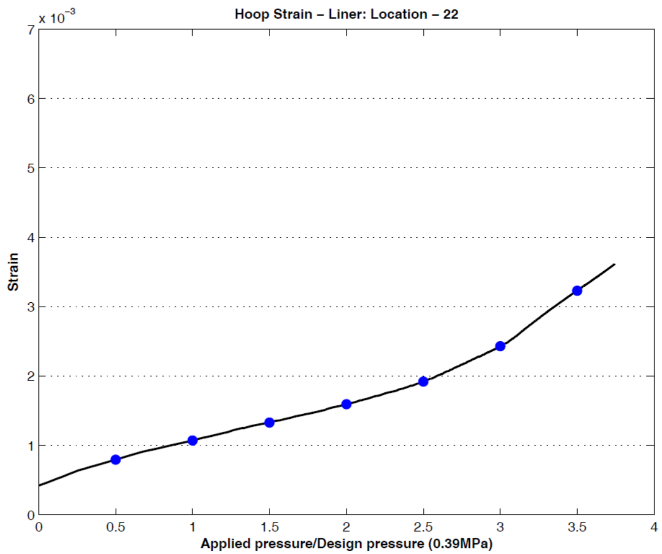


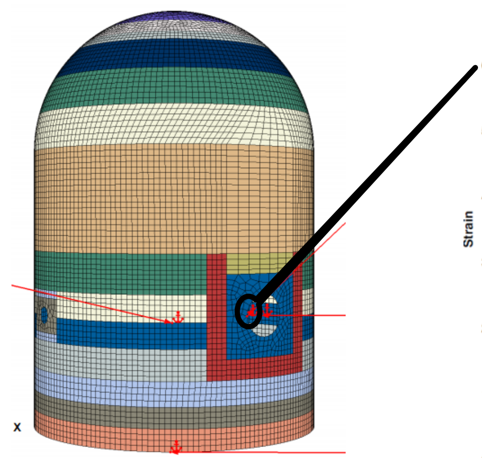
Liner strains

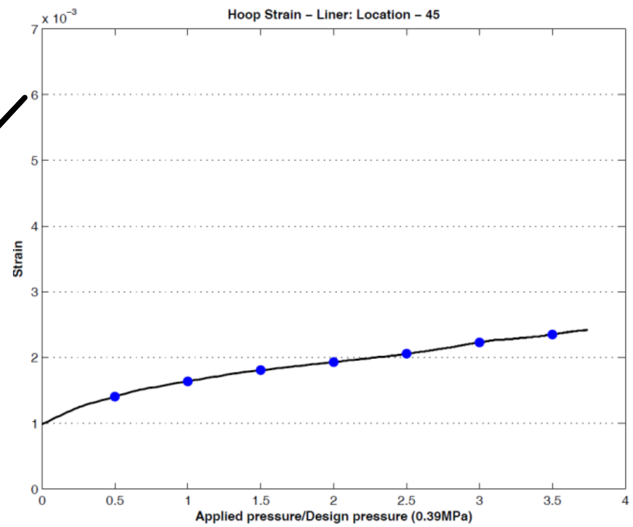




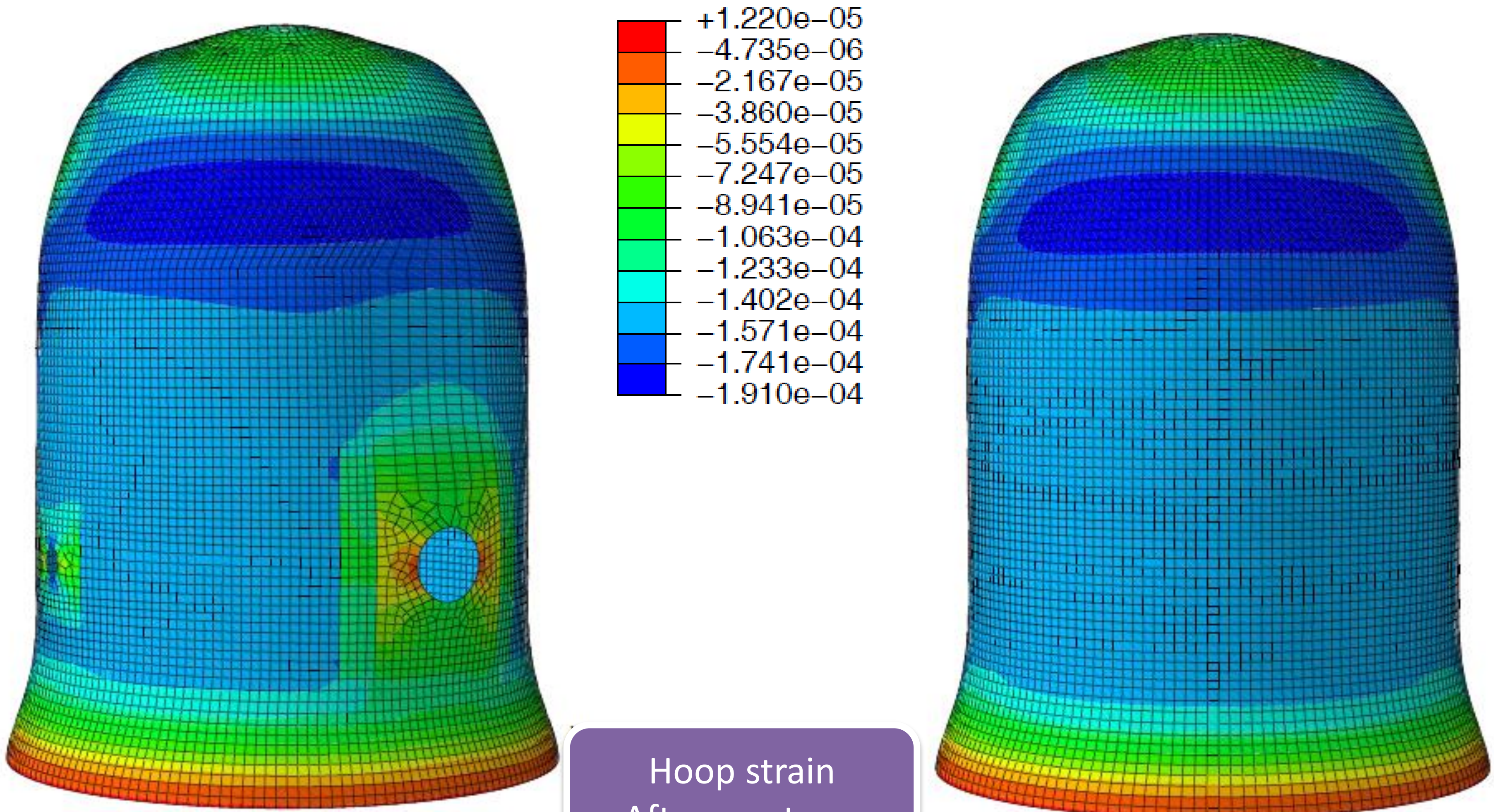






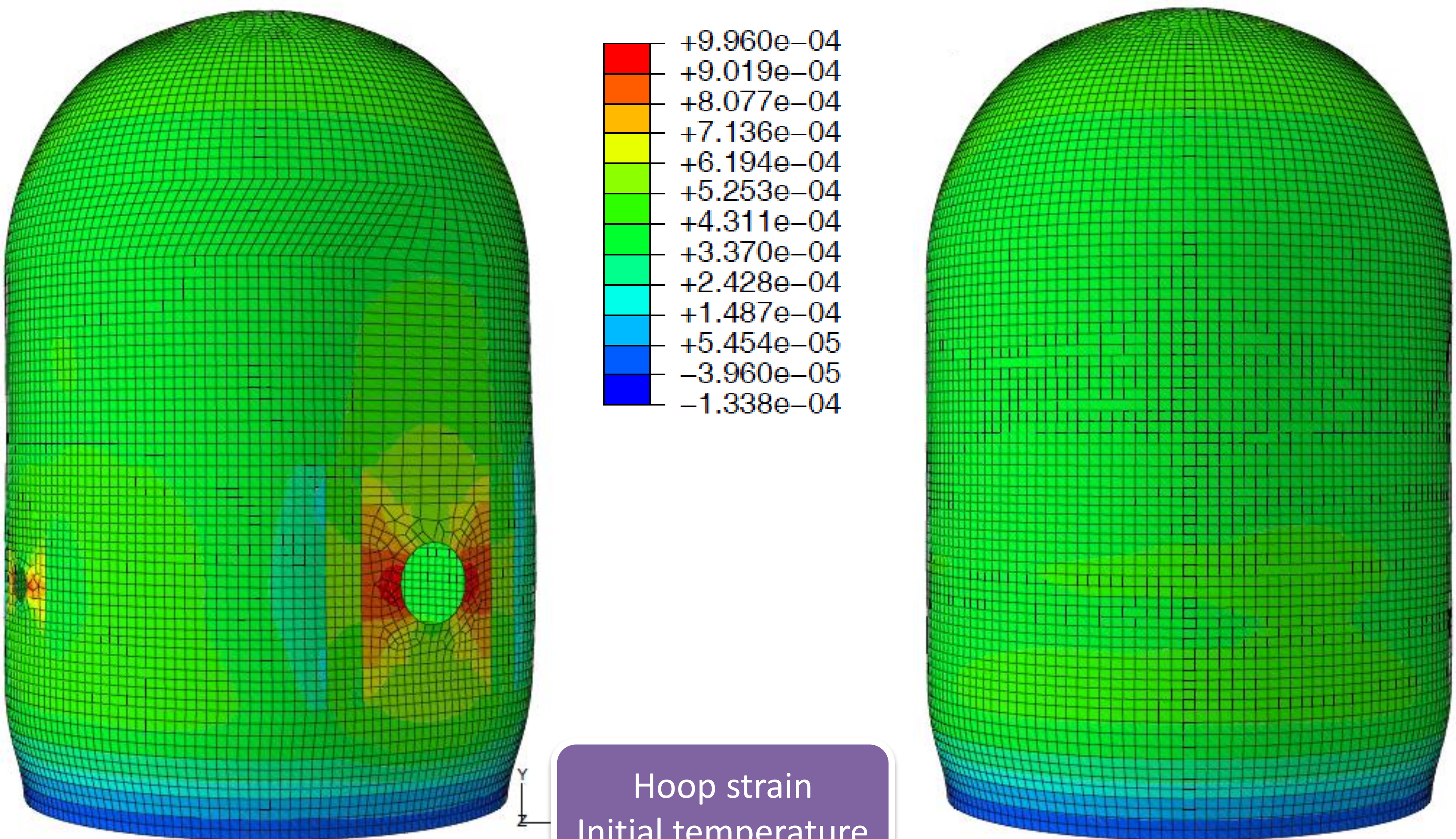


Liner strain contours



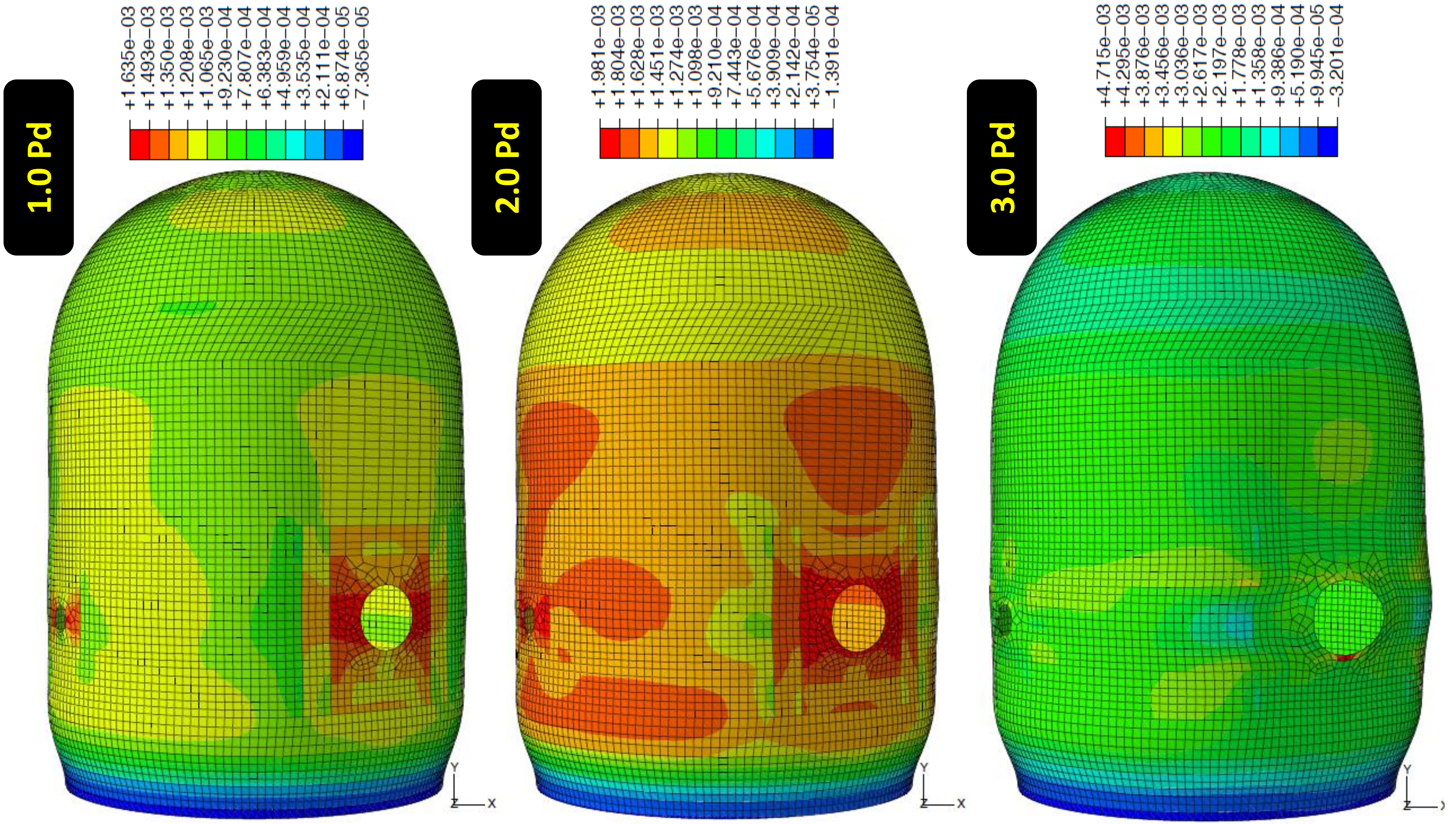
Hoop strain
After prestress

Liner strain contours

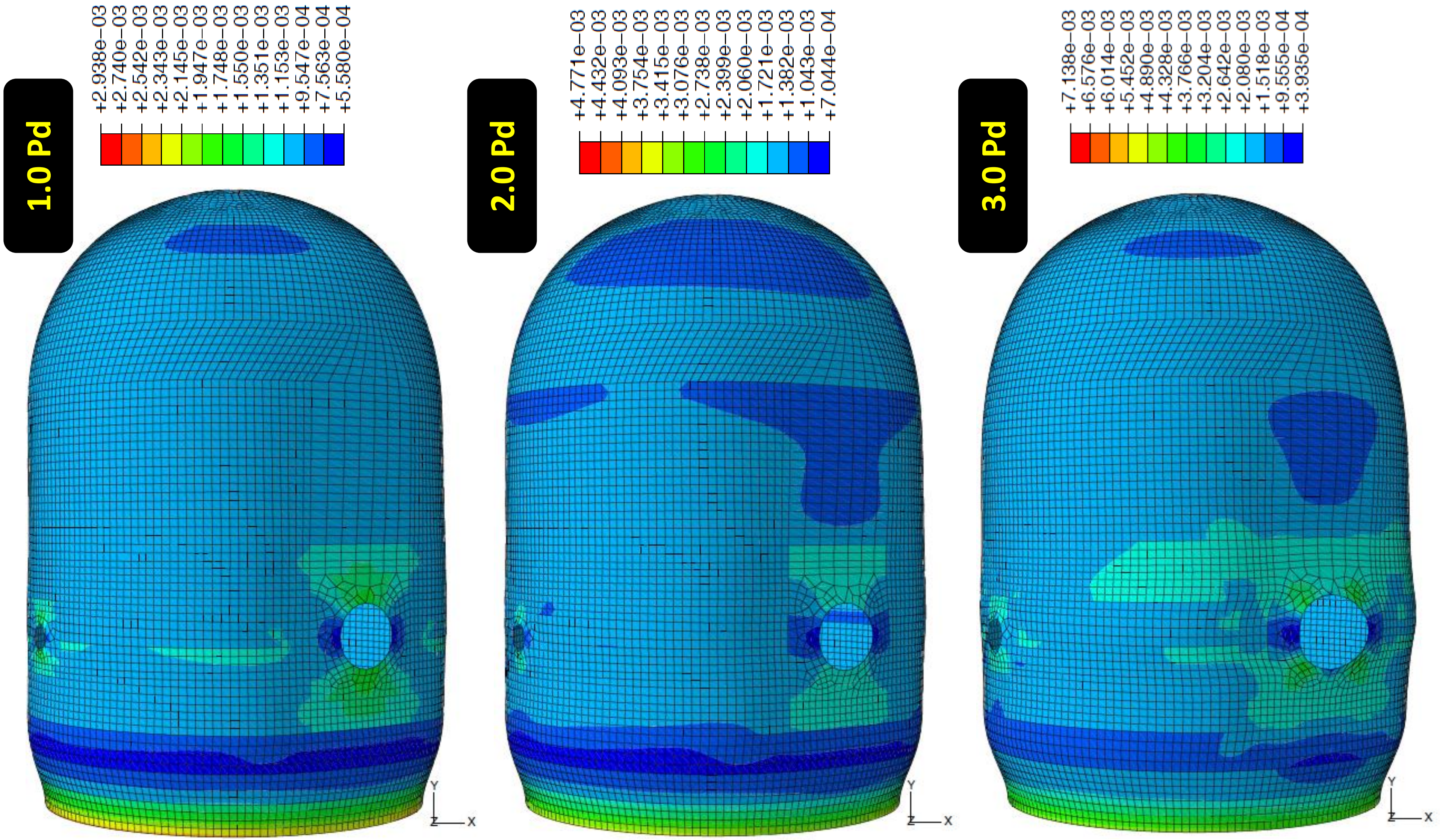


Hoop strain
Initial temperature

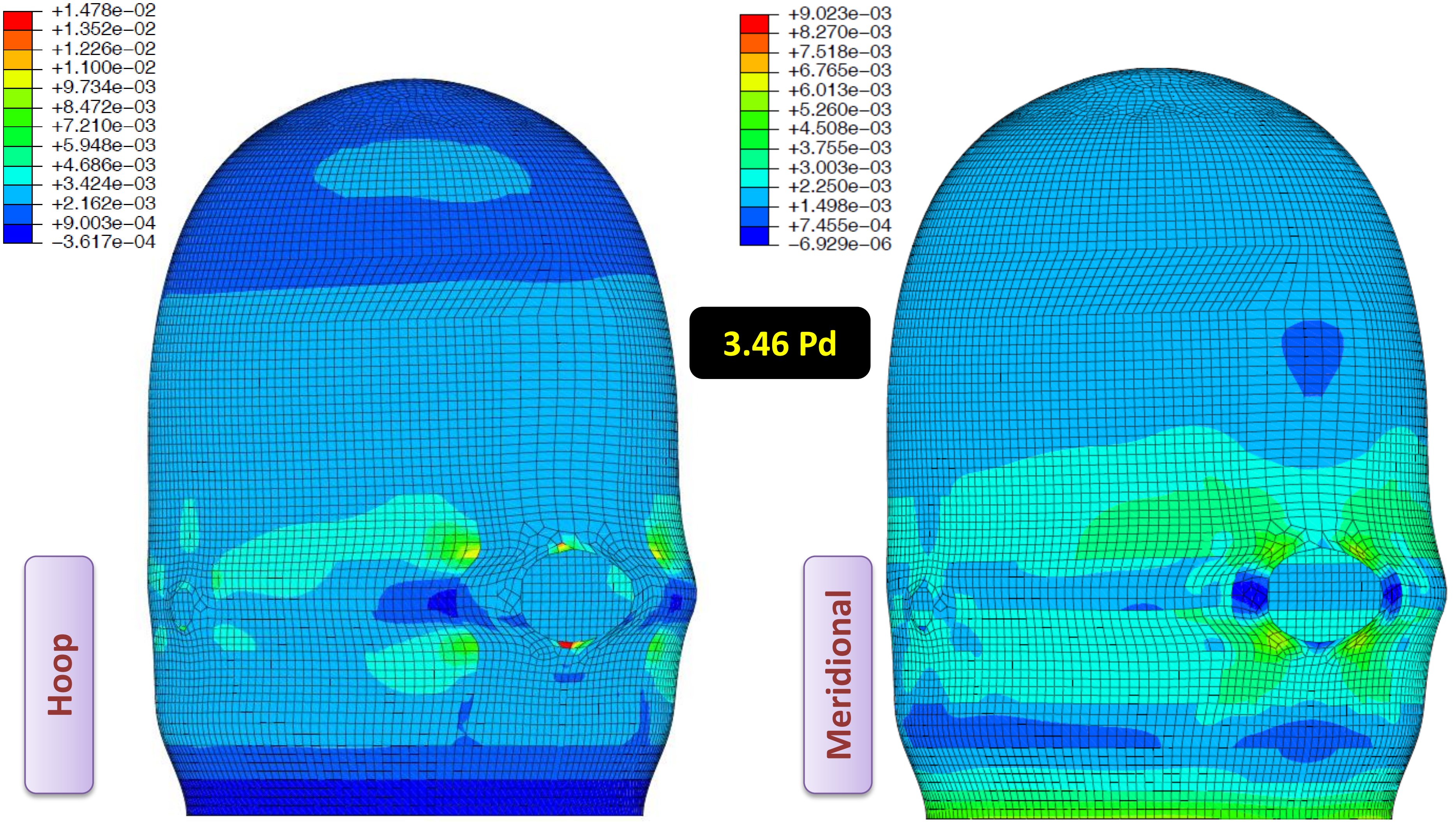
Liner strain contours - Hoop



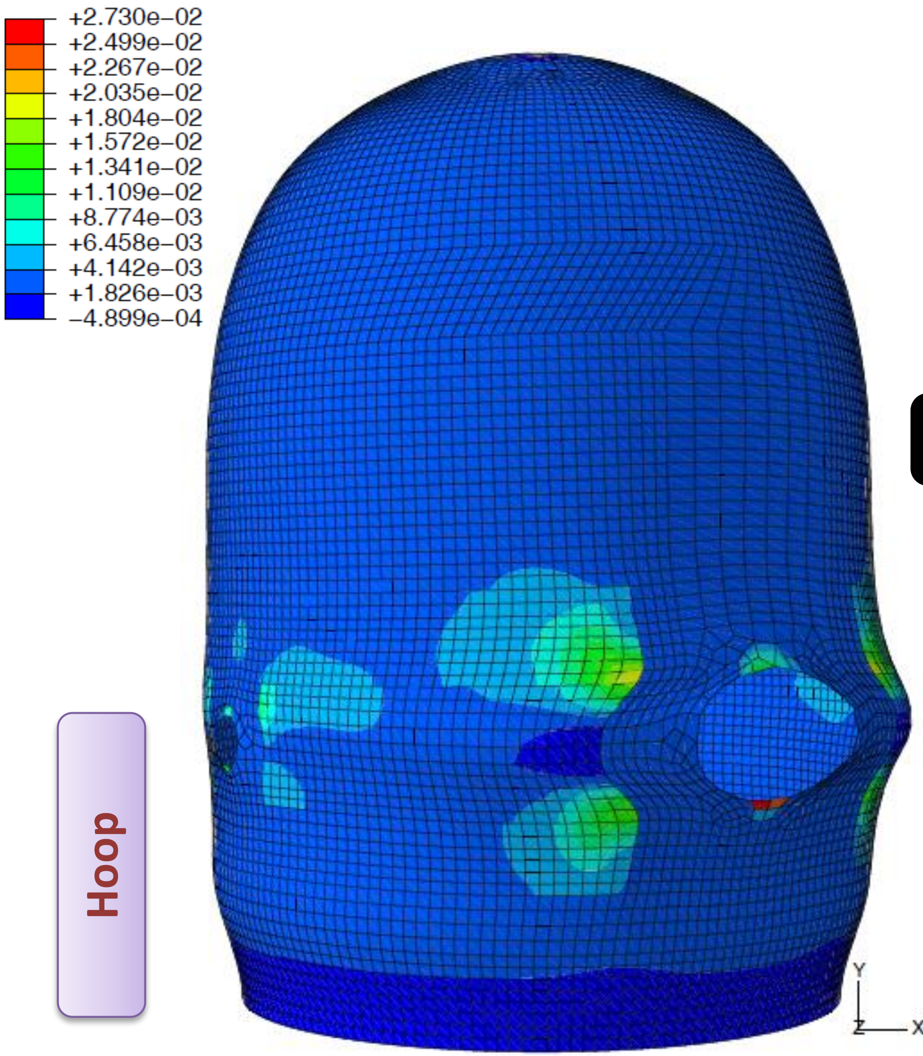
Liner strain contours - meridional



Liner strain contours

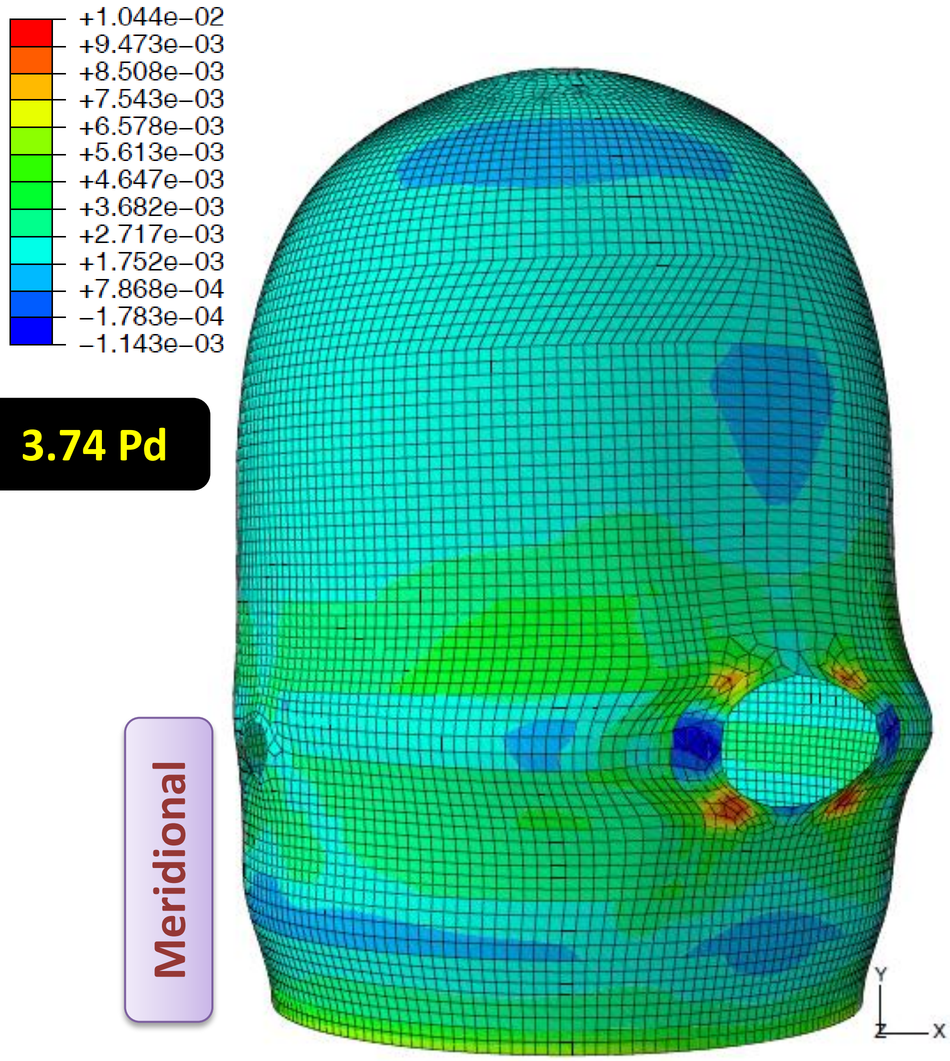


Liner strain contours



Hoop

3.74 Pd

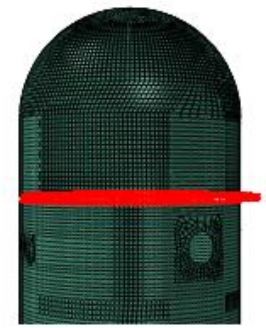


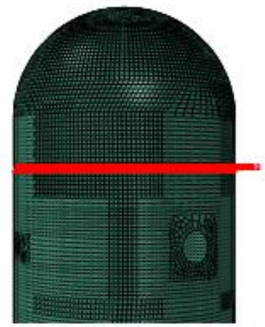
Meridional

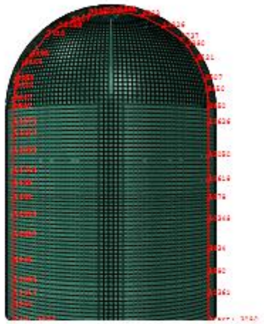
Tendon stress profile

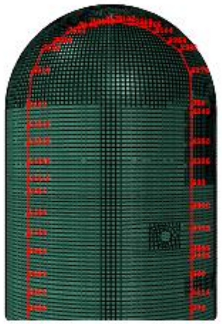
- Tendons not modeled individually
- Stress at tendon layer at the level of specified tendon
- Path for each tendon


H-35

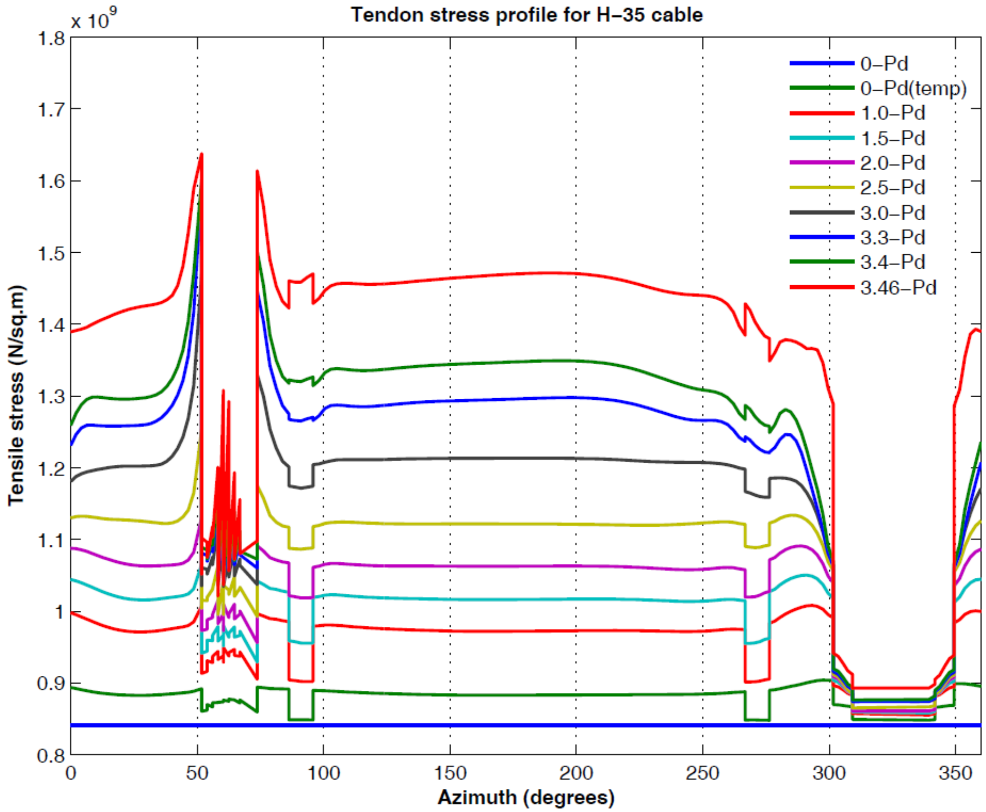

H-53

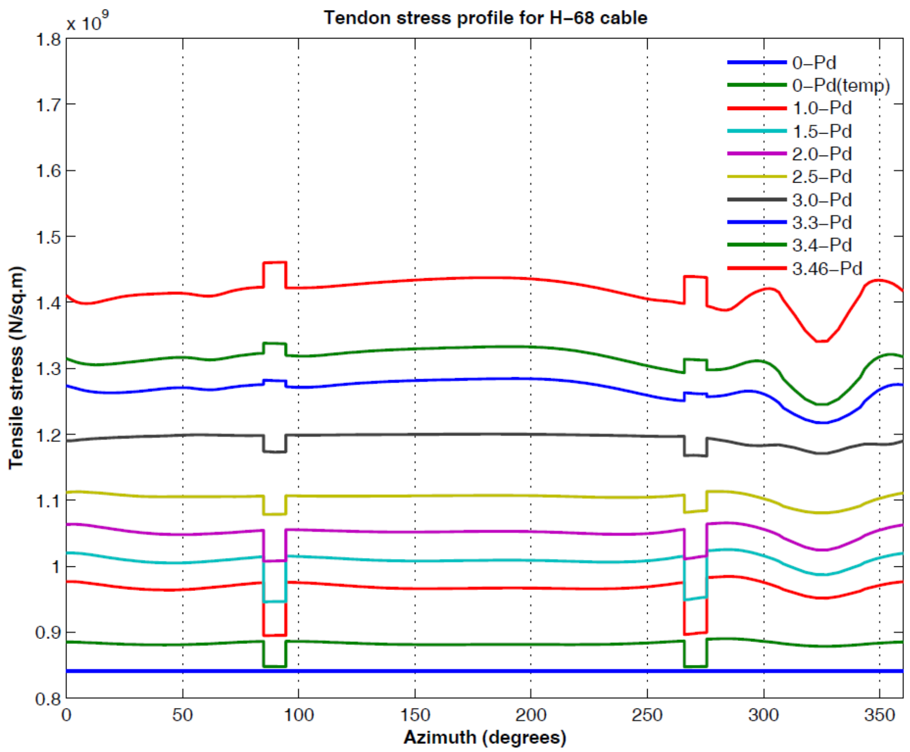

H-68


V-37

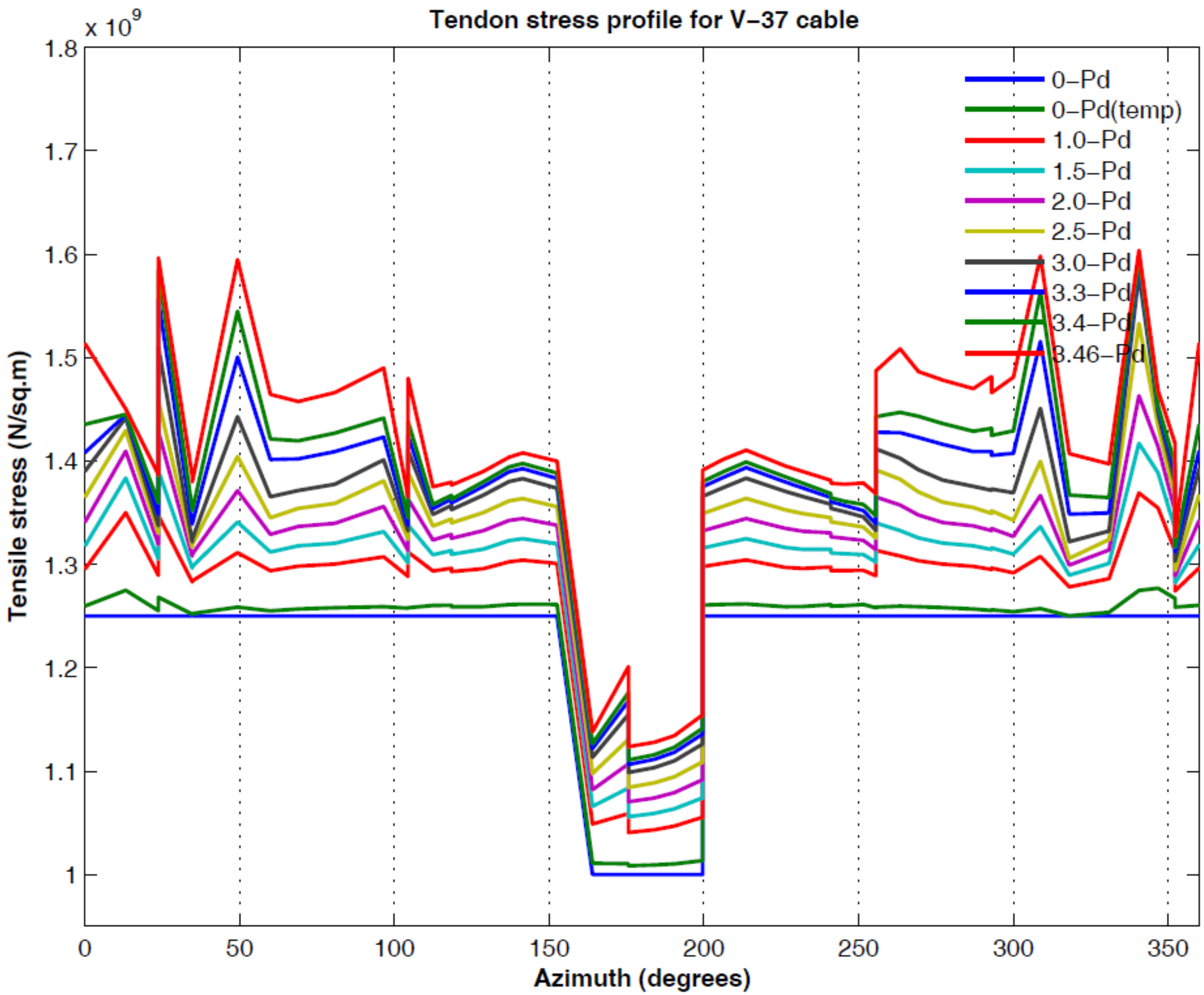

V-46

Tendon stress profile



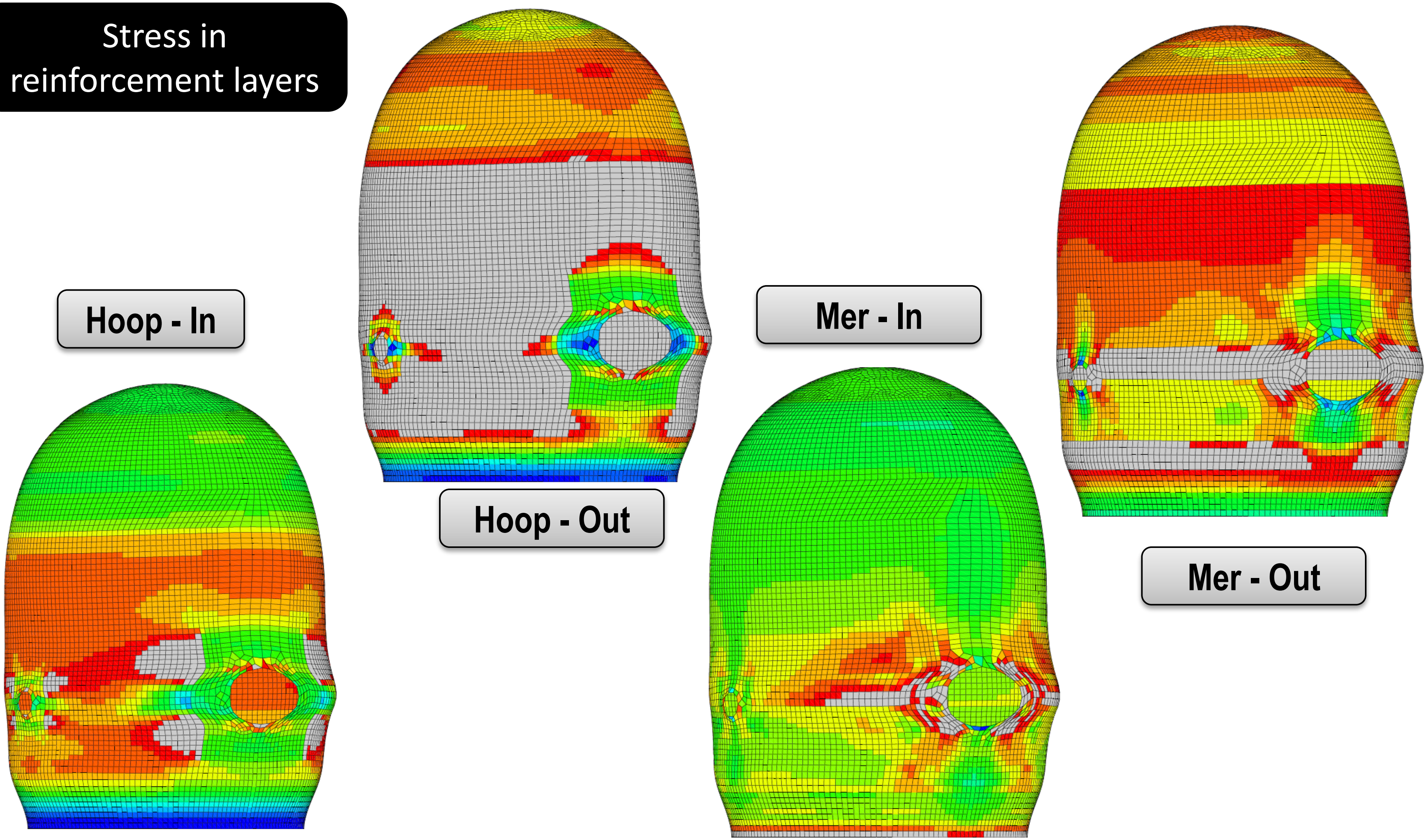


Tendon stress profile



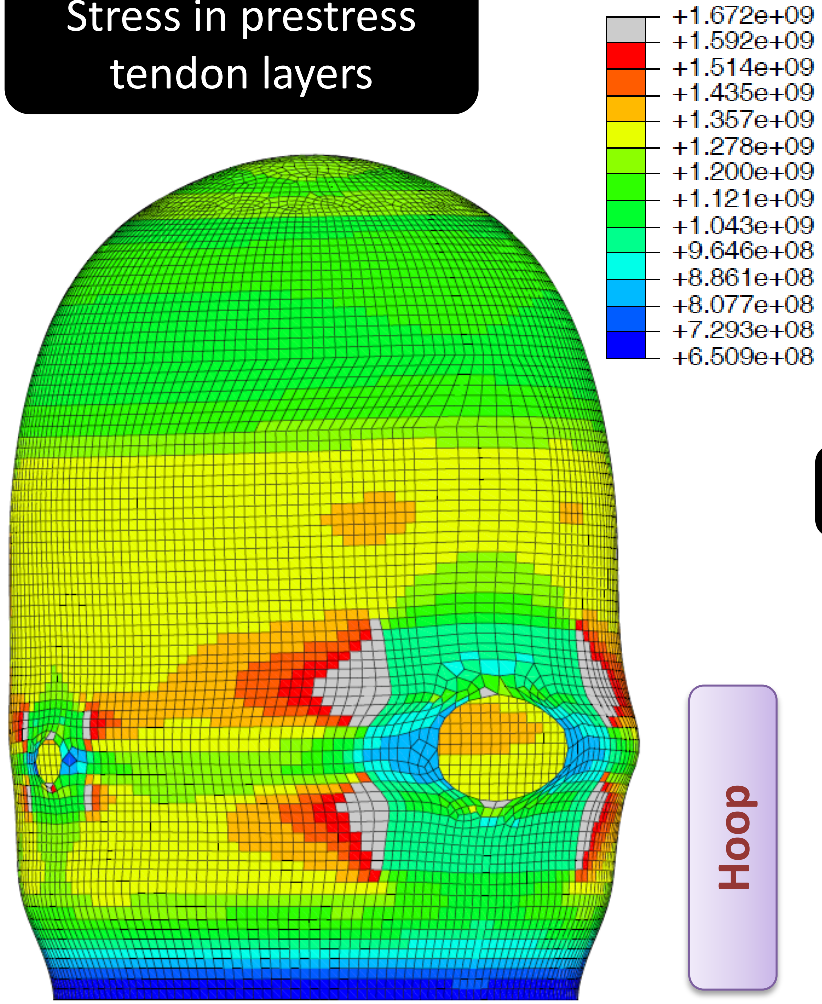
Ultimate capacity: 3.46 P_d

Stress in reinforcement layers



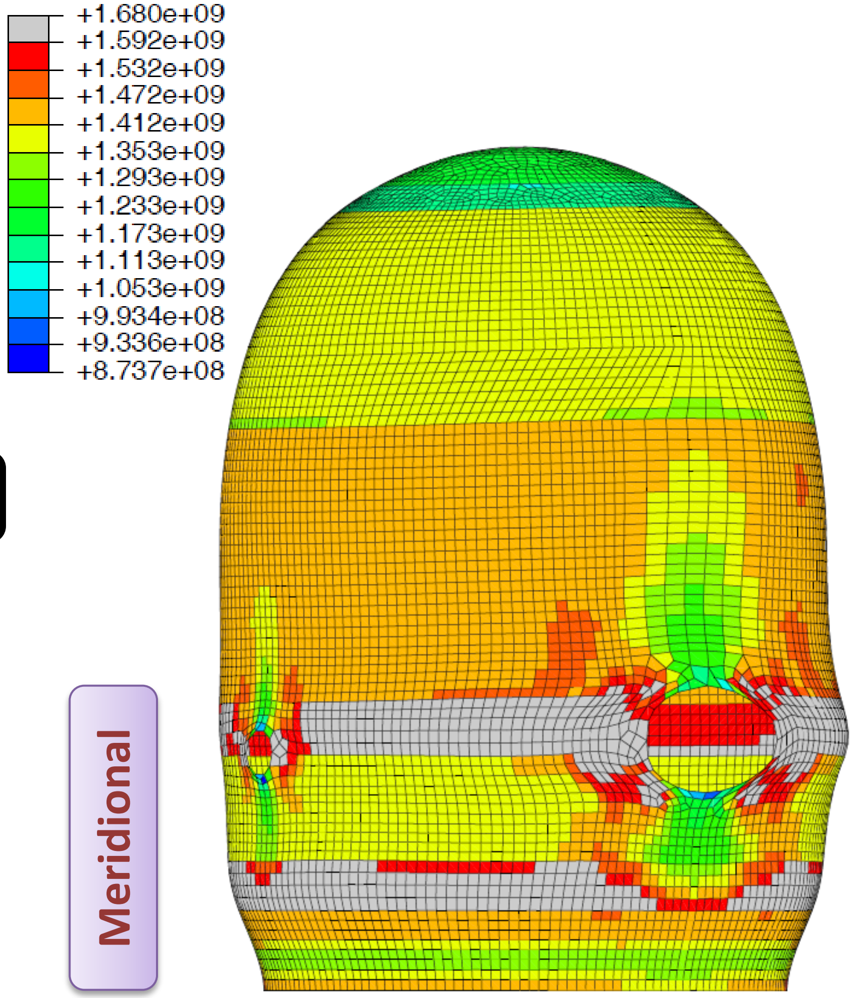
Ultimate capacity: 3.46 P_d

Stress in prestress tendon layers



Hoop

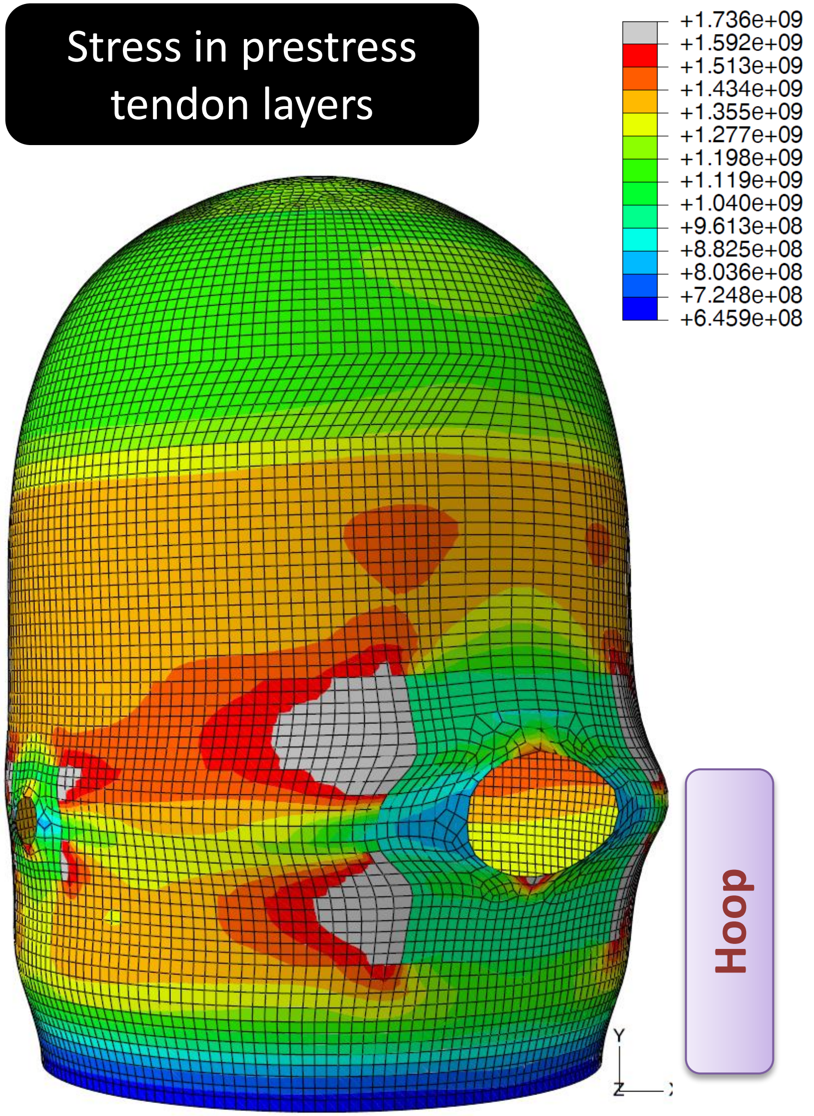
3.46 Pd



Meridional

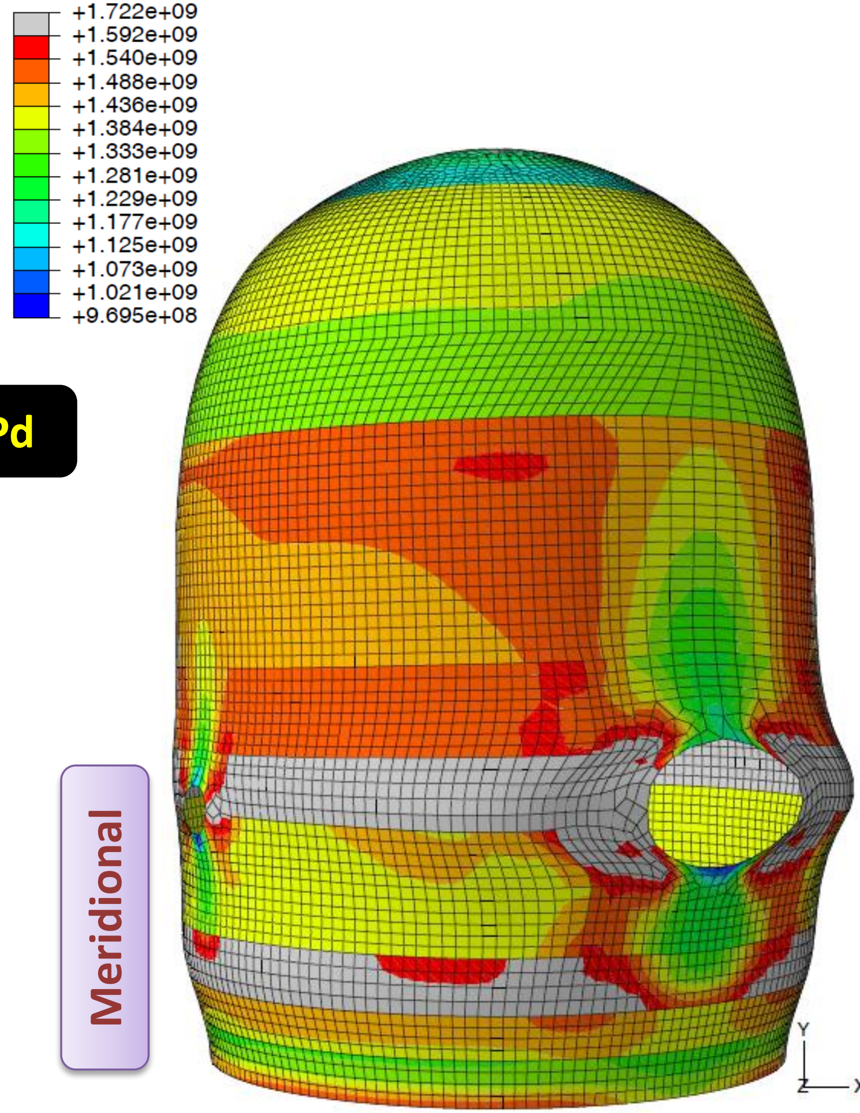
Stress in prestress tendon layers

Stress in prestress tendon layers



Hoop

3.74 Pd

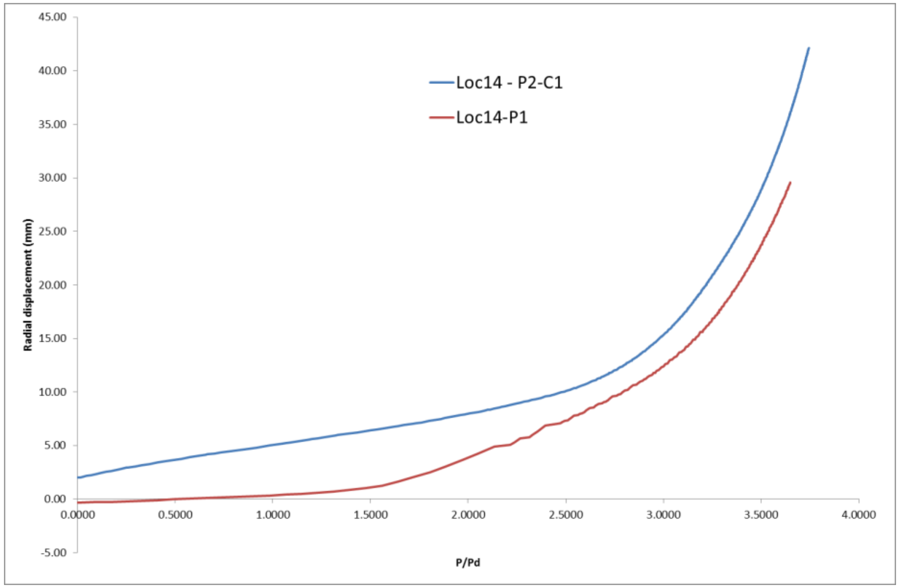


Meridional

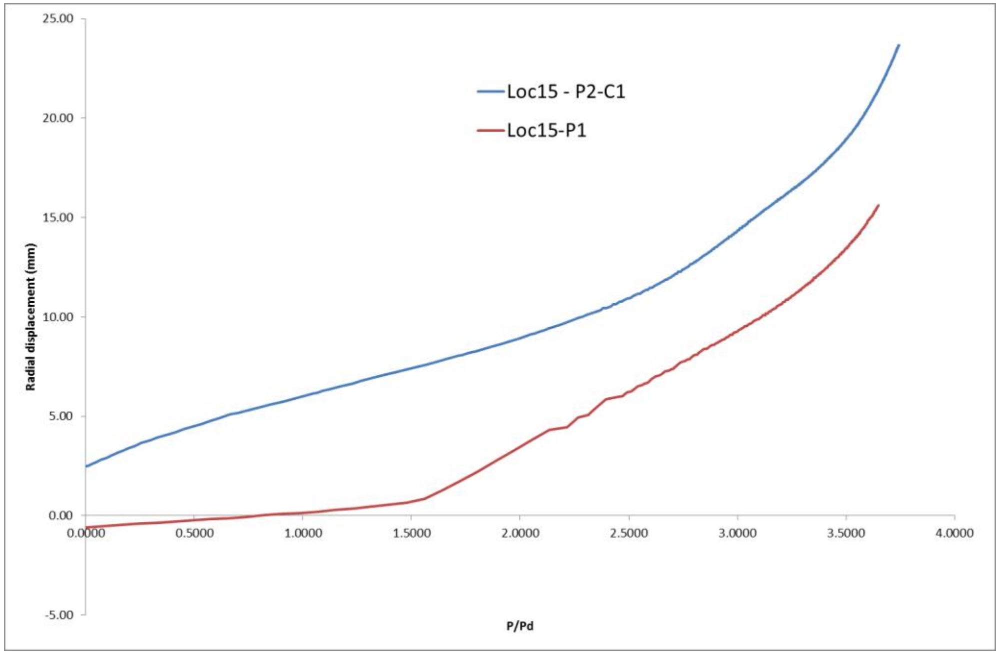
Summary

- 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

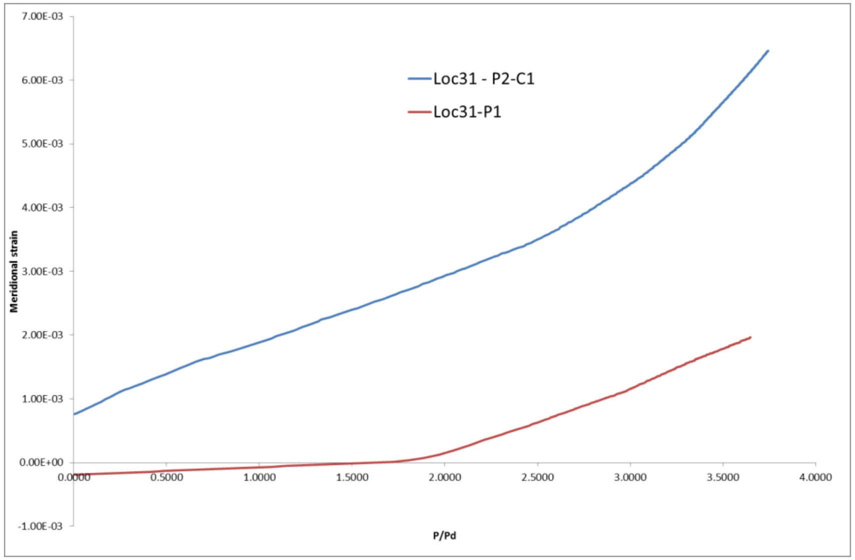
Summary



Displacement at center of E/H & A/L
Comparison of
Phase-1 & Phase2-case1



Summary



Strain in rebar location – 31

- Temperature has a significant effect on strains and displacement
- The compression provided by the pre-stress is compensated by temperature at early loading stage.

Thank You