EVALUATION OF

ULTIMATE LOAD BEARING CAPACITY

OF

CONTAINMENT STRUCTURES OF NPPs

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Salient Features of Containment System of Indian NPPs

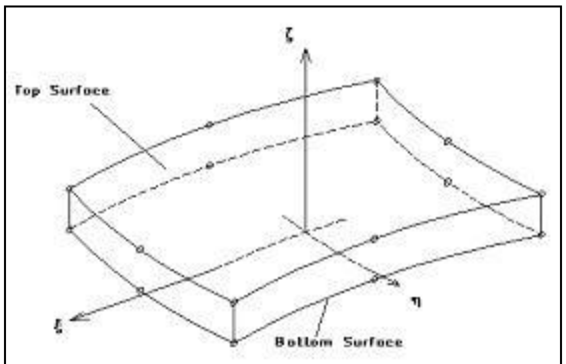
- Double Containment Concept
  - Pre-stressed Concrete Primary Containment
  - Reinforced Concrete Secondary Concrete
    - Cylindrical Wall with Spherical Segmented Dome
      - » Wall & Dome Connected through Thick Ring Beam
- No Metallic Liner
- Pre-stressing System
  - Bonded

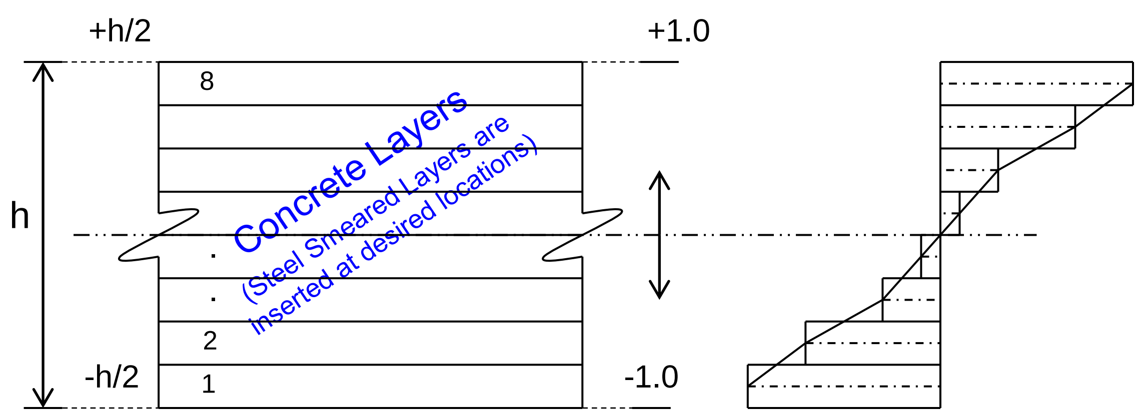
- **Experience so far**
  - Evaluation of ULBC Containment Structures of Indian Nuclear Power Plants
    - For all Series of Containment Structures

ANALYSIS METHODOLOGY ADOPTED

- 3D ANALYSIS USING LAYERED SHELL ELEMENT (DEGENERATE QUADRATIC SHELL ELEMENT)
  - Layering System helps in Tracing the progress of cracking through the Thickness of the section

- STEEL LAYERS (Both Reinforcement & Pre-stress) ARE INTRODUCED IN RELEVANT DIRECTIONS ACROSS THICKNESS OF THE SHELL





Layered Shell Element with Stress Distribution across Thickness of Shell

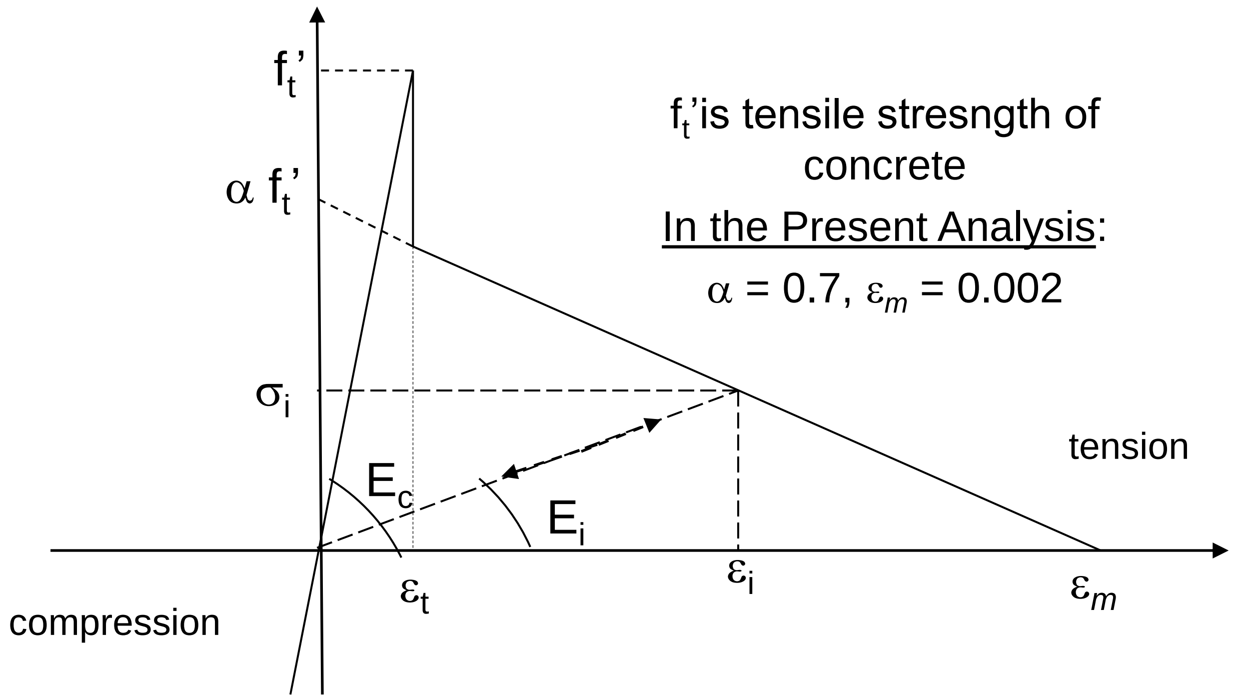
Material Modelling

- MATERIALS SIMULATED
  - Concrete under
    - Tension
    - Compression
  - Reinforcing & Prestressing Steel

Material Modelling

- BEHAVIOUR OF CONCRETE UNDER TENSION

Concrete behaves linearly up to tensile strength, then it cracks and the tensile strength gradually reduces to zero with increase in strain



Loading and Unloading behaviour of Cracked Concrete illustrating Tension Stiffening Behaviour

Material Modelling

- BEHAVIOUR OF CONCRETE UNDER TENSION
  - Concrete is assumed to Crack in the Perpendicular Direction of Maximum Principal Stress (‘1’ or ‘2’) , when it reaches corresponding Tensile Strength (f_t')
  - If the crack closes, the un-cracked shear modulus is restored in the corresponding direction
    - Maximum Tensile Strain & the Direction of the Crack is also Stored

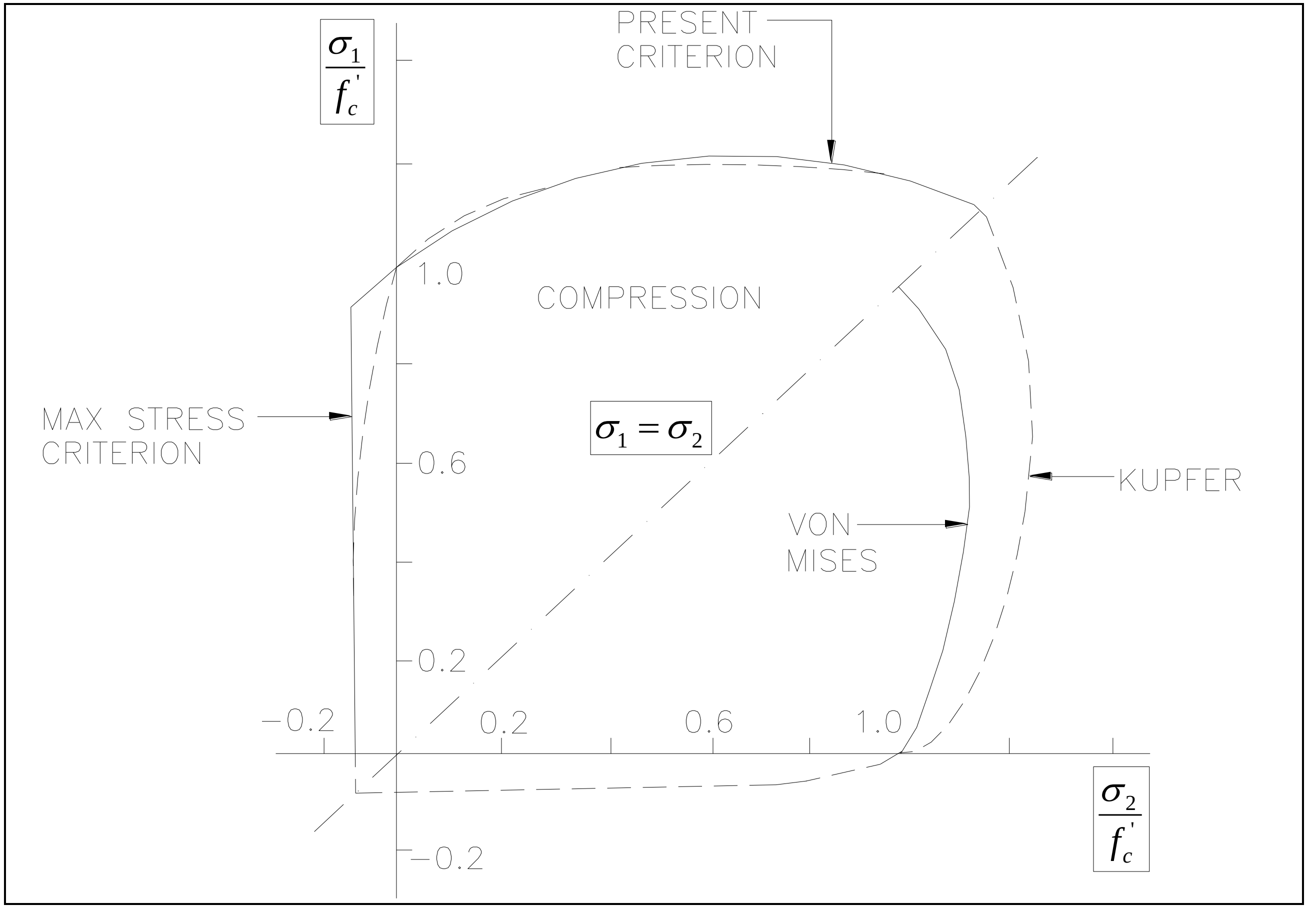
Material Modelling

BEHAVIOUR OF CONCRETE UNDER COMPRESSION

- Formulation Required to Capture Elasto-plastic Behaviour of Structure
  - Before Yielding
    - $\sigma - \varepsilon$ *Relationship in Elastic Range*
  - At Yielding
    - *A Yield Criterion*
  - Beyond Yielding
    - *A Relationship of* $\sigma - \varepsilon$ *for Post Yield Behaviour for accumulation of Plastic Strain*
      - Flow Rule

Material Modelling

BEHAVIOUR OF CONCRETE UNDER COMPRESSION



TWO DIMENSIONAL STRESS SPACE REPRESENTATION OF CONCRETE CONSTITUTIVE MODEL

Material Modelling

➢ BEHAVIOUR OF CONCRETE UNDER COMPRESSION

- Yield Criterion – Stress Based

$$f(I_1, J_2) = [\beta(3J_2) + \alpha I_1]^{0.5} = \sigma_o$$

$$\beta[(\sigma_1^2 + \sigma_2^2 + \sigma_3^2) - (\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)] + \alpha(\sigma_1 + \sigma_2 + \sigma_3) = \sigma_o^2$$

$$f(\sigma) = 1.355[(\sigma_x^2 + \sigma_y^2 + \sigma_x\sigma_y) + 3(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)] + 0.355\sigma_o(\sigma_x + \sigma_y) = \sigma_o^2$$

- Flow Rule
  - Accumulation of Strain in Plastic Range
    - Normality of the plasticity deformation rate vector to the yield surface is used

$$d\varepsilon_{ij}^p = d\lambda\left(\frac{\partial f(\sigma)}{\partial \sigma_{ij}}\right)$$

Where, Proportionality constant, $d\lambda$ determines the magnitude of plastic strain increment

Gradient, $[\partial f(\sigma) / \partial \sigma_{ij}]$ defines its direction to be perpendicular to yield surface

Material Modelling

➢BEHAVIOUR OF CONCRETE UNDER COMPRESSION

- Crushing Condition – Strain Based

$$\left[\beta\left(3J_2\right)+\alpha I_1\right]^{0.5}=\varepsilon_u$$

$$1.355\left[\left(\gamma_x^2+\gamma_y^2+\gamma_x\gamma_y\right)+0.75\left(\gamma_{xy}^2+\gamma_{xz}^2+\gamma_{yz}^2\right)\right]+0.355\varepsilon_o\left(\varepsilon_x+\varepsilon_y\right)=\varepsilon_u^2$$

➢REINFORCING AND PRESTRESSING STEEL

- Considered as smeared layer of equivalent thickness
  - Uni-axial Behaviour in Bar Direction
- Linear Elastic and Plastic Hardening behaviour is assumed

Salient Features of ULBC Study of Indian Containment Structures

- 3-D F. E. Mesh Generated
  - With All Geometric Features Modelled

- Modelling of Reinforcement & Pre-stressing Layout
  - As per As-built Drawing : For Already Constructed Containments
  - As per Design Drawings : For Containments under Construction

- Exact Simulation of Loading of Containment Structure during Construction, where necessary
  - To Represent the State of Stress of the Containment Structure after Construction
    - To Estimate Realistic ULBC Number for the Containment Structure under Consideration

- Mesh Sensitivity Study
  - Analysis with Finer Mesh
    - Time Consuming & Costly Computing
  - Methodology Adopted Based on Research Findings
    - Bazant and Cedolin have reported little mesh sensitivity is observed in F.E. discretisation when energy criterion based on fracture mechanics is employed
    - If Gauss Point Distances of elements < Characteristic Length computed based on fracture energy (G_f)
      - Finite Element Computations are Insensitive to Mesh Sensitivity
      - Characteristic Length may be defined as
      - $l_{ch} = E\, G_f / f_t^2$, G_f = *Fracture Energy of Concrete*

        f_t = *Tensile Strength of Concrete*

        E = *Young's Modulus of Concrete*

Both Methods are Applied in Different Projects

A Brief Review of Work Done & Experience Gained So Far

RESULT IN NUTSHELL : Margins Over Design Basis Condition

Stages	Latest **220** MWe Units (From Kaiga-1to4 & RAPP-3to6)			**540** MWe (TAPP-3&4)		
	LOCA Pr. [Kg/cm^2]	Failure Pr. [Kg/cm^2]	***Min. Factor***	LOCA Pr. [Kg/cm^2]	Failure Pr. [Kg/cm^2]	***Min. Factor***
Functional Failure	**1.06** (1.73*)	3.20	**3.02** (1.85**)	**0.8** (1.44*)	2.71	**3.39** (1.88**)
Structural Failure		3.41	**3.22** (1.97**)		3.00	**3.75** (2.08**)

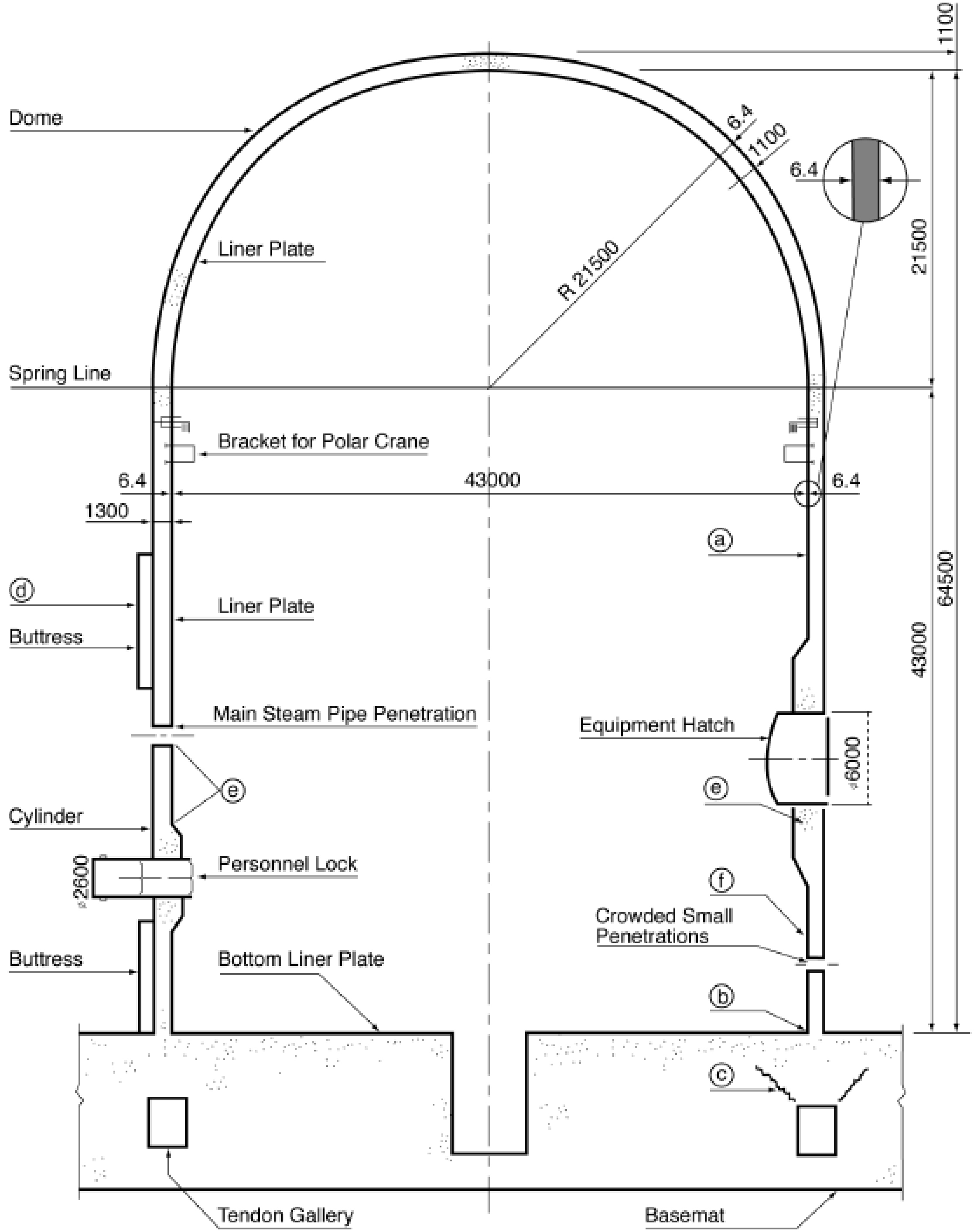
* Design Pressure ** Factor over Design pressure

Note: Functional Failure: Through-and-through crack with minimum width of 0.2mm

Structural Failure: Excessive cracking and spreading of rebar yielding zone

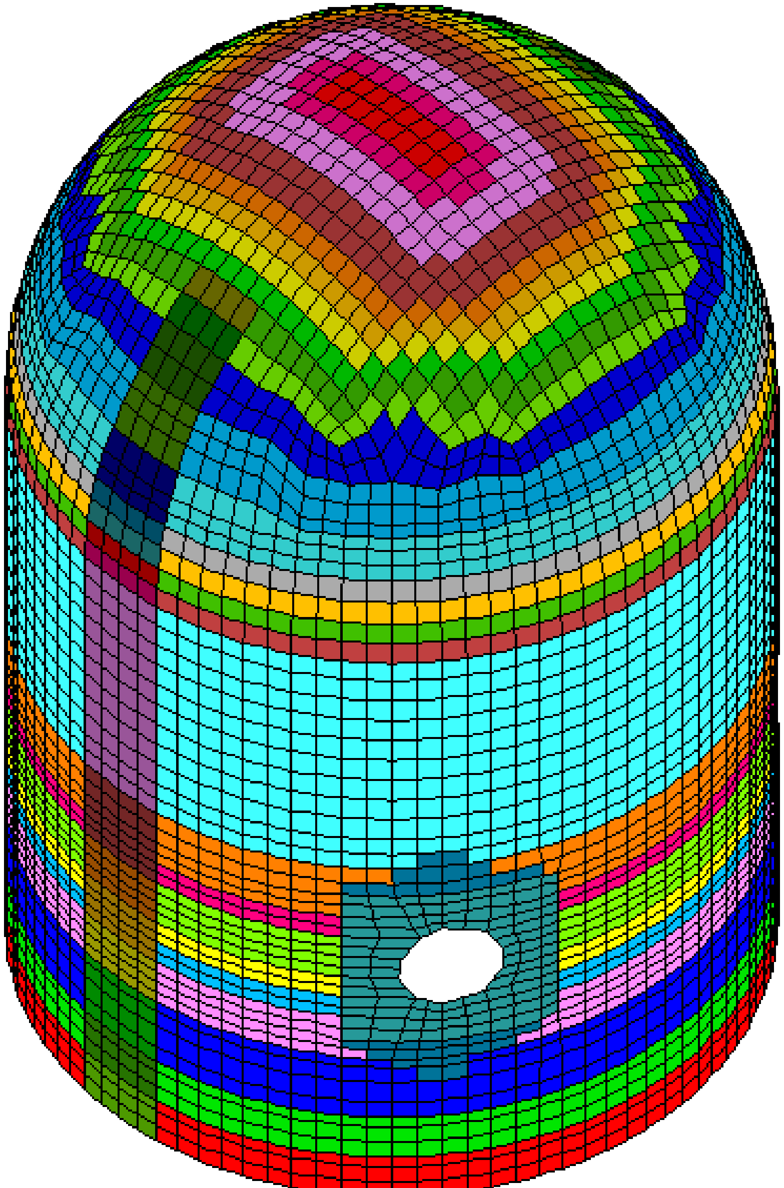
- Based on the Experience Gained, Analysis of 1:4 PCCV of SANDIA Laboratory has been taken up
  - Basic Differences with respect to Indian Containment Structures
    - Metallic Lined Structure
    - Pre-stressing System Un-bonded
  - Limitations
    - Liner could not be modeled (Limitation of the program)
  - Objective
    - To study global behavior

– Geometry



Dome
Liner Plate
Spring Line
R 21500
6.4
1100
6.4
21500
1100
Bracket for Polar Crane
6.4
43000
6.4
1300
ⓐ
ⓓ
Liner Plate
Buttress
64500
43000
Main Steam Pipe Penetration
Equipment Hatch
ⓔ
ⓔ
6000
Cylinder
Personnel Lock
2600
ⓕ
Crowded Small Penetrations
Buttress
Bottom Liner Plate
ⓑ
ⓒ
Tendon Gallery
Basemat

- Finite Element Discretisation



FULL STRUCTURE CONSIDERED

Degrees of freedom per Node :

3 Translations and 3 Rotations

Fixity BC along the raft-wall Junction

Model Statistics

Element: 5553

Node:16790

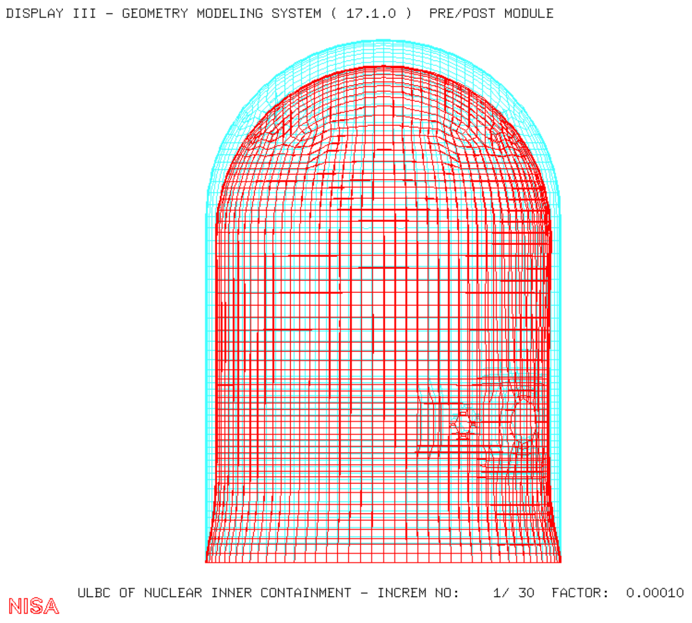
F. E. DISCRETISATION CONSIDERS

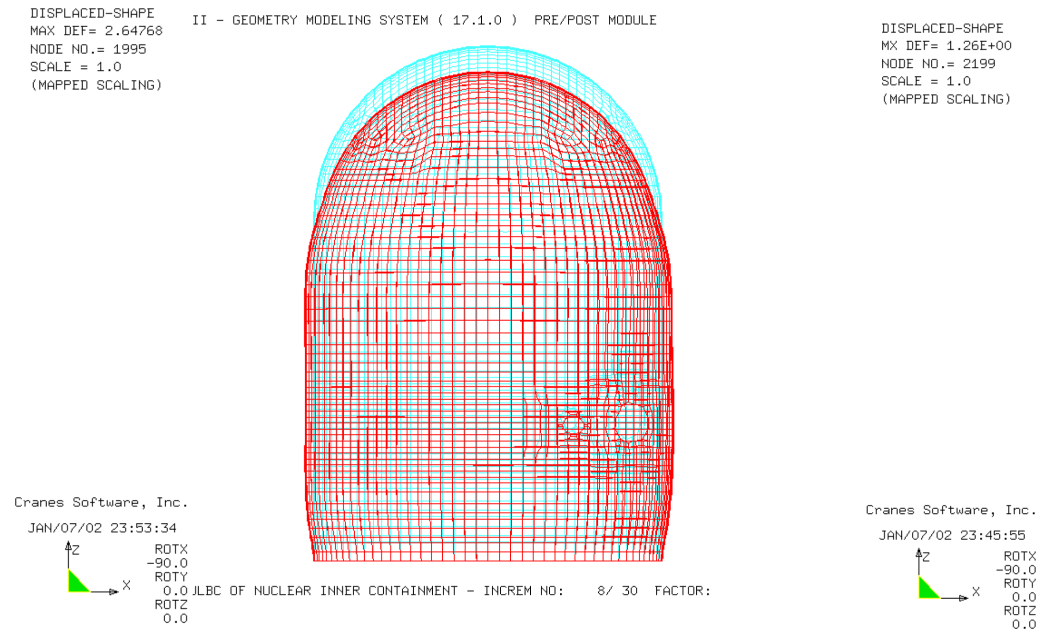
- GEOMETRIC VARIATIONS (THICKNESS)
- VARIATION IN AREA OF REINFORCEMENT STEEL AND ITS DISPOSITION
- PRESTRESSING SIMULATED AS EQUIVALENT PRESSURE

RESULTS

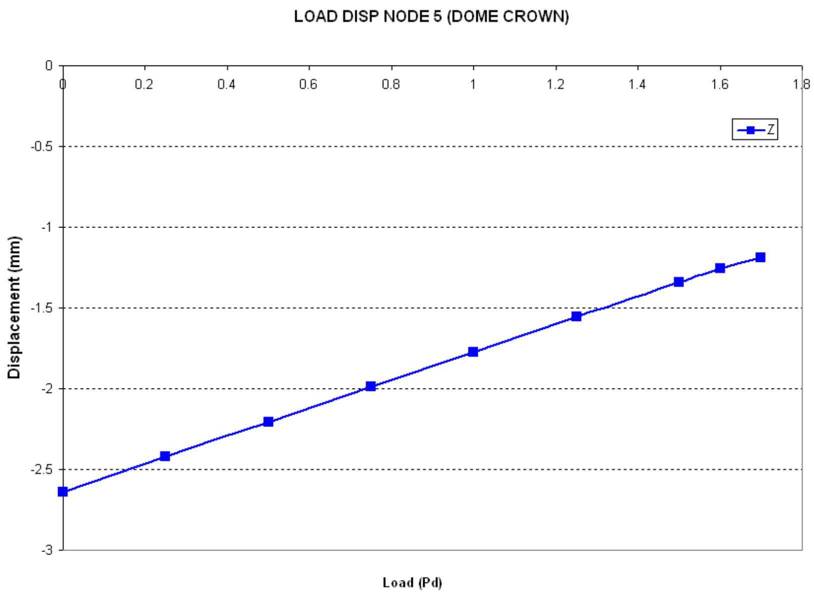
- ANALYSIS PROGRESSED UPTO LF 1.70
- DISPLACEMENTS ARE LINEAR BOTH IN DOME & WALL UPTO LF 1.70
- DEFORMATION
  - UNDER PRESTRESS
  - UNDER 1.0 Pd (0.39 MPa)
- LOAD-DEFORMATION CHARACTERISTICS
  - DOME CROWN
  - WALL GENERAL AREA

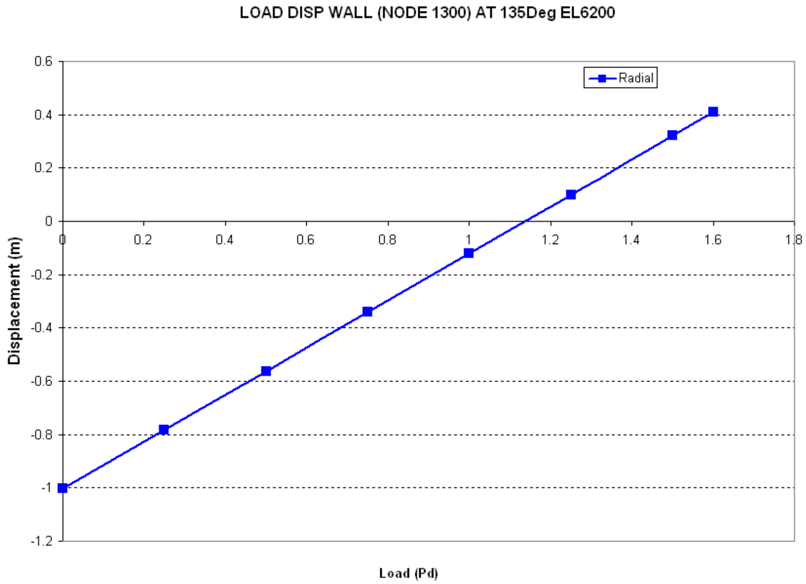
DEFORMATION UNDER PRESTRESS LOADING
&
UNDER PRESSURE 1.7 P_d)





LOAD-DEFORMATION CHARACTERISTICS





FUTURE PLAN

- COMPLETION OF THE PRESENT ANALYSIS AFTER FINE-TUNING THE ANALYSIS/SOLUTION PARAMETERS (UNDER PROGRESS)
- SWITCHING OVER TO SOFTWARE HAVING BETTER CAPABILITY TO ADDRESS ALL RELEVANT ISSUES
- IMPLEMENTATION OF OUTCOME OF PRESENT DISCUSSION FOR EVALUATION OF ULTIMATE LOAD CARRYING CAPACITY OF CONTAINMENT STRUCTURE

Thank You