EVALUATION OF ULTIMATE LOAD BEARING CAPACITY OF CONTAINMENT STRUCTURES:

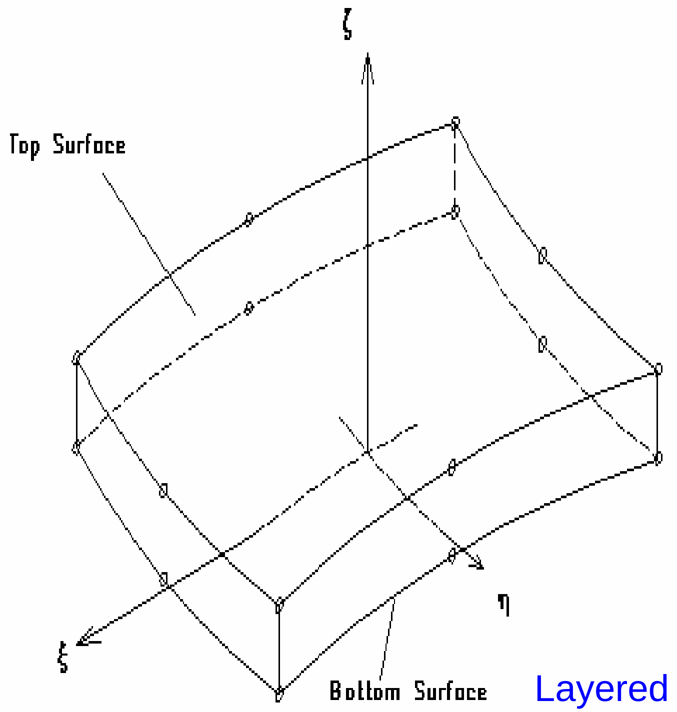
INDIAN PERSPECTIVE

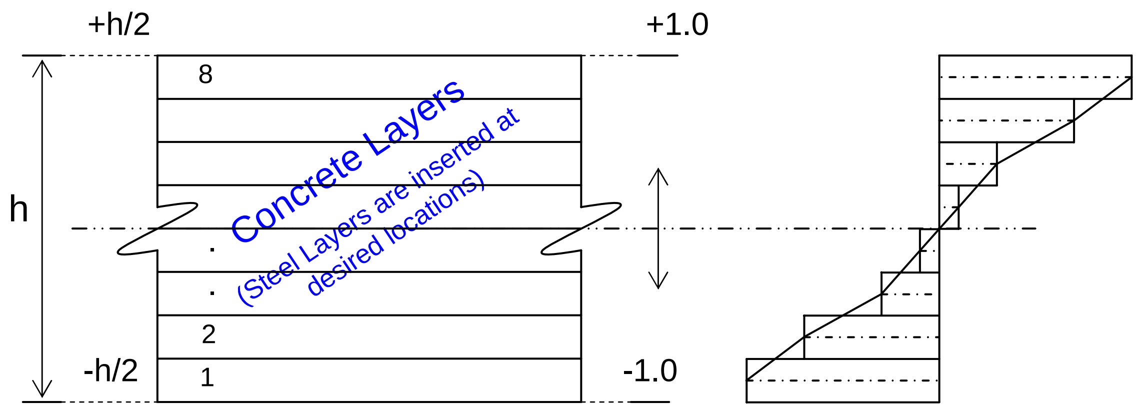
Nuclear Power Corporation of India Limited
Mumbai, India

Methodology of Analysis

ELEMENT USED

- 3D ANALYSIS USING 8-NODED LAYERED SHELL ELEMENT
  - DEGENERATE QUADRATIC SHELL ELEMENT with *SMEARED* LAYERS of concrete, reinforcement & prestressing steel
    - Layering System used for Tracing the progress of cracking through the Thickness of the section





Layered Shell Element with Stress Distribution across Thickness of Shell

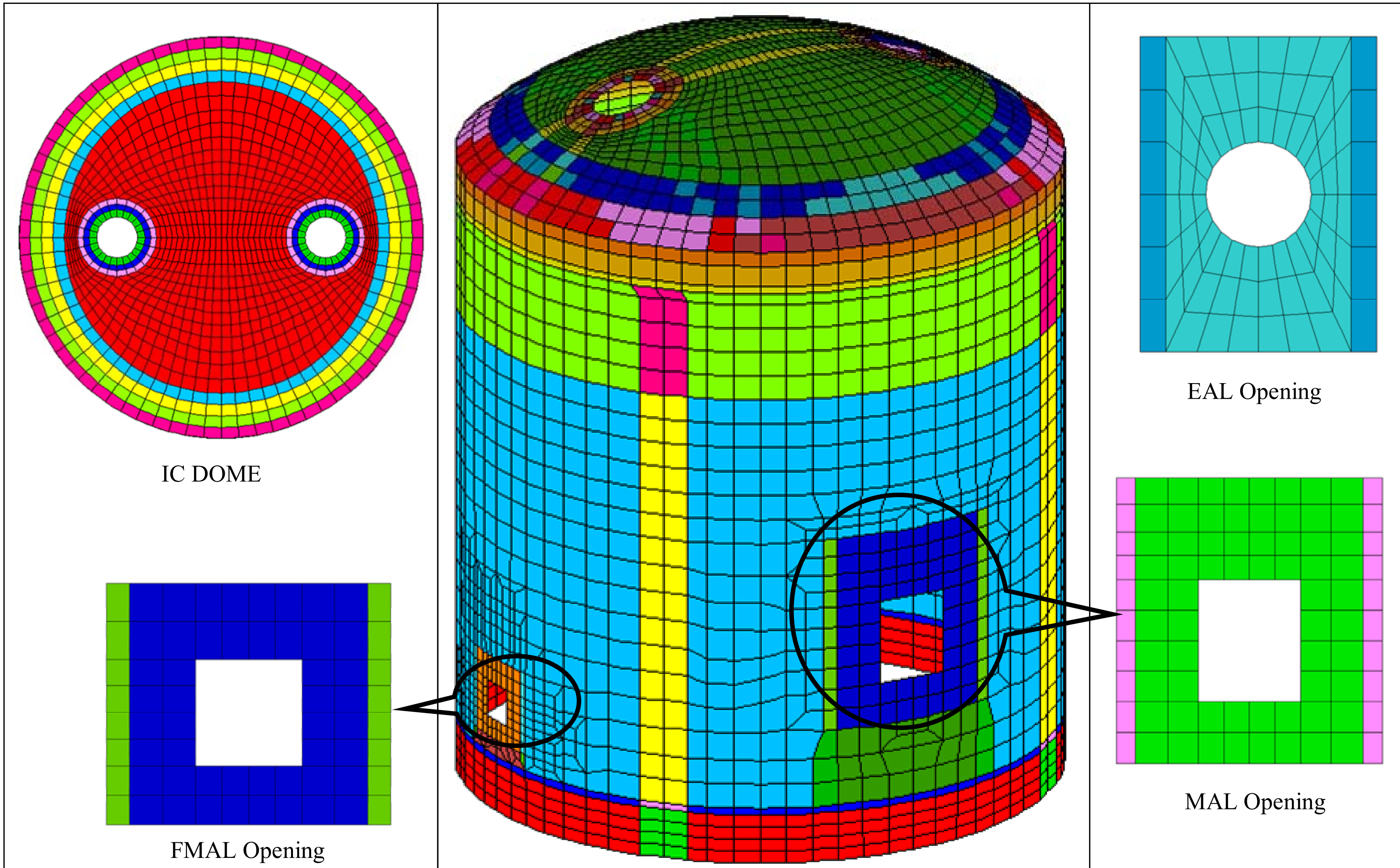
Modelling of Containment Structure

- Geometric Modelling
- Material Modelling

Geomteric Modelling

- **ZONING OF THE STRUCTURE BSAED ON**
  - **VARIATION IN GEOMETRY**
    - **Thickness**
  - **VARIATION IN REINFORCEMENT LAYOUT**
    - **Reinforcement Zoning**
  - **VARIATION IN PRESTRESSING LAYOUT**
    - **Prestress Zoning**

TYPICAL F.E. Model for ULBC Studies



Loads Considered

- Constant Loads
  - Dead Load
  - Prestress
  - With & Without Temperature Variation under DBA condition
- Variable Load
  - Internal Pressure

Material Modelling

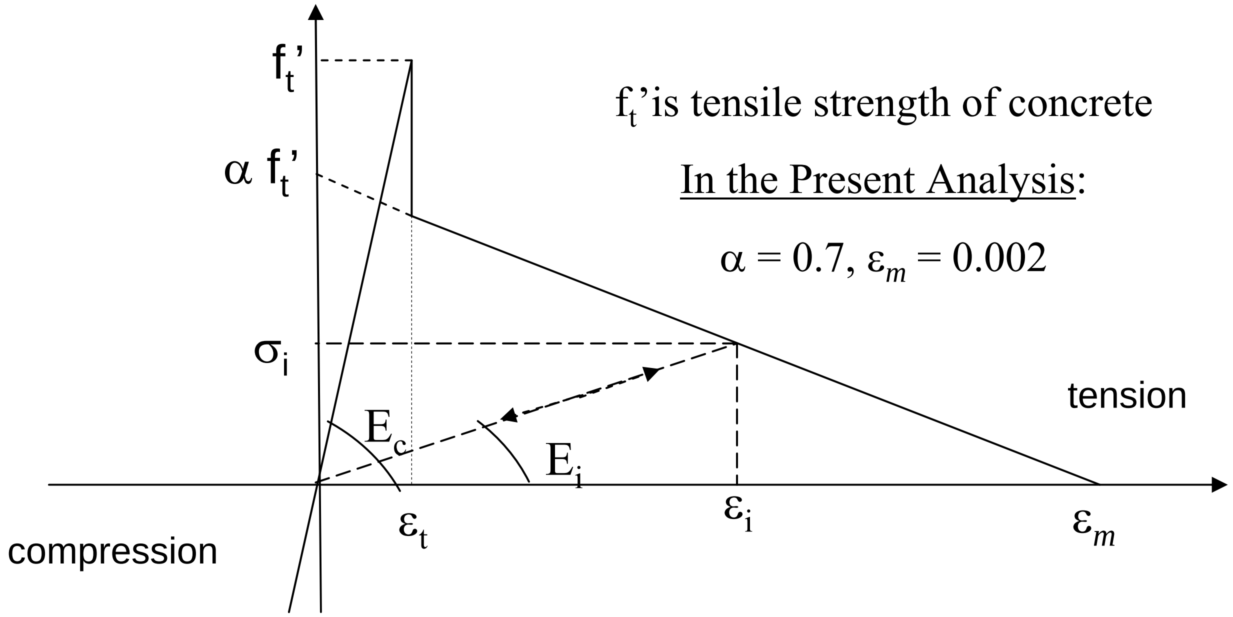
- MATERIALS SIMULATED
  - Concrete under
    - Tension
    - Compression
  - Reinforcing & Prestressing Steel

MATERIAL MODELLING

➢BEHAVIOUR OF CONCRETE UNDER TENSION

- Concrete behaves linearly up to tensile strength
- There is a sudden drop in strength on cracking
- Thereafter tensile strength of concrete gradually reduces to zero with increase in strain

  ⇨ Due to Aggregate Interlock & Dowel Action



$f_t'$is tensile strength of concrete

In the Present Analysis:

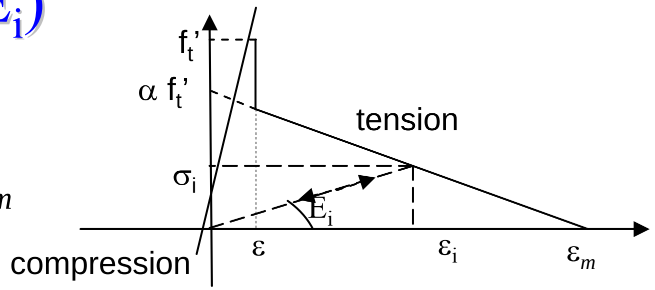
$\alpha = 0.7,\ \varepsilon_m = 0.002$

Loading and Unloading behaviour of Cracked Concrete illustrating Tension Stiffening Behaviour

BEHAVIOUR OF CONCRETE UNDER TENSION (Contd…)

- Process of loading – unloading of cracked concrete by fictitious linear elasticity Modulus (E_i)

$$E_i = \alpha\left(1 - \frac{\varepsilon_i}{\varepsilon_m}\right) \Big/ \varepsilon_i\,, \quad where\ \ \varepsilon_t \le \varepsilon_i \le \varepsilon_m$$



- Concrete is assumed to Crack in the Perpendicular *Direction of Maximum Principal Stress (‘1’ or/and ‘2’)* , when it reaches corresponding Tensile Strength ($f_t^{'}$)

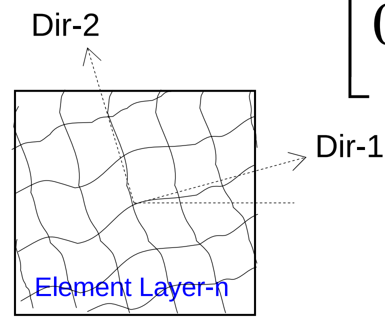
- If the crack closes, the un-cracked shear modulus is restored in the corresponding direction
    - o Maximum tensile strain & the direction of the crack is stored

Un-cracked Concrete

$$\begin{bmatrix} E & 0 & 0 & 0 & 0 \\ 0 & E & 0 & 0 & 0 \\ 0 & 0 & G_{12} & 0 & 0 \\ 0 & 0 & 0 & G_{13} & 0 \\ 0 & 0 & 0 & 0 & G_{23} \end{bmatrix}$$

Cracked: perpendicular to Dir-1

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & E & 0 & 0 & 0 \\ 0 & 0 & G_{12}^{C} & 0 & 0 \\ 0 & 0 & 0 & G_{13}^{C} & 0 \\ 0 & 0 & 0 & 0 & \dfrac{5G}{6} \end{bmatrix}$$



Concrete cracked in Dir.-2

$$G_{12}^{C} = \frac{1}{4}G\left(1 - \frac{\varepsilon_1}{0.004}\right); \quad G_{12}^{C} = 0 \ if \ \ \varepsilon_1 \geq 0.004$$

$$G_{13}^{C} = G_{12}^{C}, \quad G_{13}^{C} = \frac{5G}{6}$$

Cracked: perpendicular to Dir-1 & Dir-2

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & G_{12}^{C}/2 & 0 & 0 \\ 0 & 0 & 0 & G_{13}^{C} & 0 \\ 0 & 0 & 0 & 0 & G_{23}^{C} \end{bmatrix}$$

Concrete cracked in Dir.-1

$$G_{13}^{C} = \frac{1}{4}G\left(1 - \frac{\varepsilon_1}{0.004}\right); \quad G_{13}^{C} = 0 \ if \ \ \varepsilon_1 \geq 0.004$$

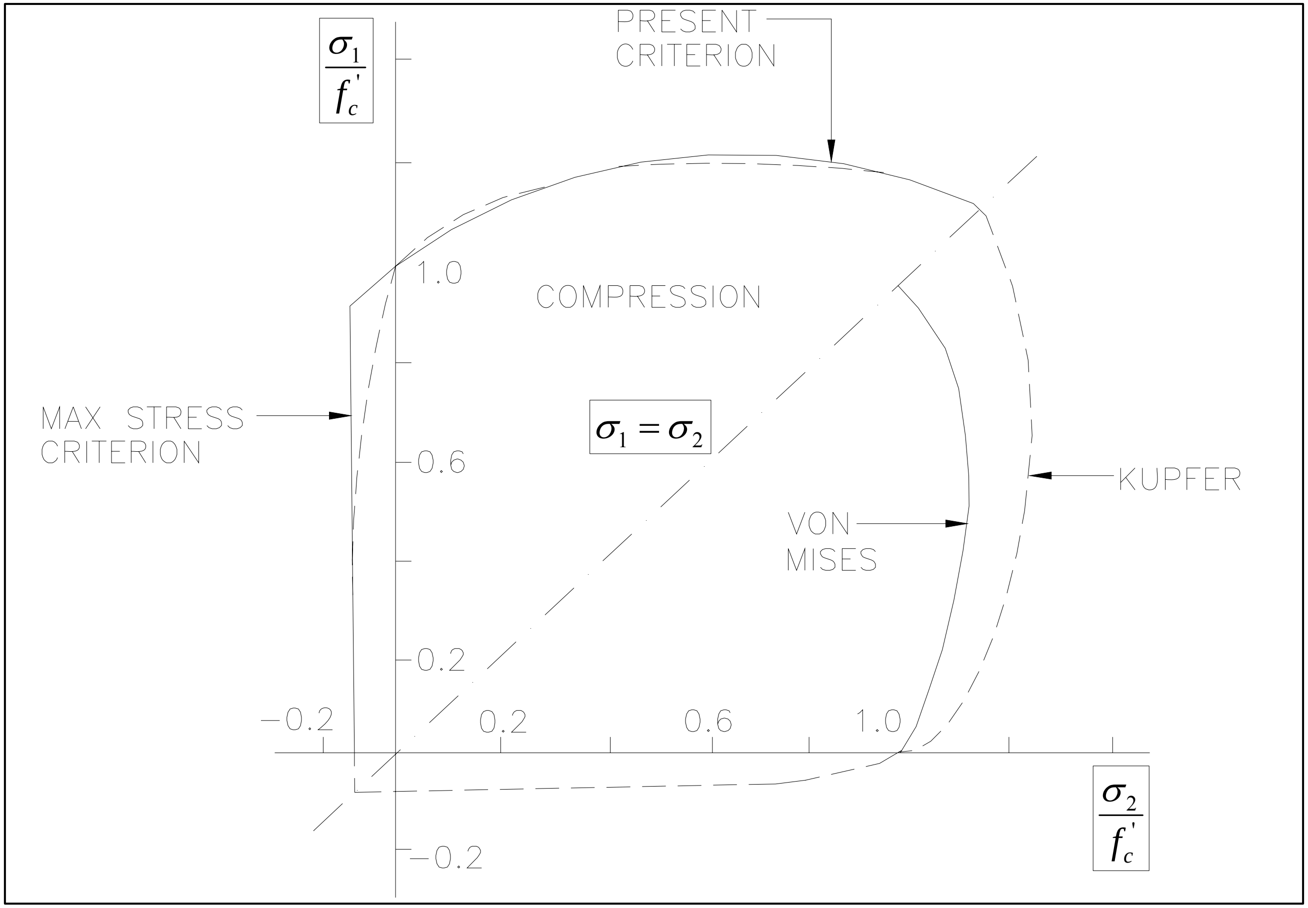
$$G_{23}^{C} = \frac{1}{4}G\left(1 - \frac{\varepsilon_2}{0.004}\right); \quad G_{23}^{C} = 0 \ if \ \ \varepsilon_2 \geq 0.004$$

$$G_{12}^{C} = \frac{1}{2}G_{13}^{C}; \quad G_{12}^{C} = \frac{1}{2}G_{23}^{C} \ if \ \ G_{23}^{C} < G_{13}^{C}$$

BEHAVIOUR OF CONCRETE UNDER COMPRESSION

- Formulation Required to Capture Elasto-Plastic Behaviour of Structure
  - Before Yielding
    - *Stress based criterion*
      - *$\sigma - \varepsilon$ 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

BEHAVIOUR OF CONCRETE UNDER COMPRESSION



TWO DIMENSIONAL STRESS SPACE REPRESENTATION OF CONCRETE CONSTITUTIVE MODEL

➢BEHAVIOUR OF CONCRETE UNDER COMPRESSION

- Yield Criterion – Stress Based

$$f(I_1, J_2) = \left[\beta(3J_2) + \alpha I_1\right]^{0.5} = \sigma_o$$
$$\beta\left[\left(\sigma_1^2 + \sigma_2^2 + \sigma_3^2\right) - \left(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1\right)\right] + \alpha\left(\sigma_1 + \sigma_2 + \sigma_3\right) = \sigma_o^2$$
$$f(\sigma) = 1.355\left[\left(\sigma_x^2 + \sigma_y^2 + \sigma_x\sigma_y\right) + 3\left(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2\right)\right] + 0.355\sigma_o\left(\sigma_x + \sigma_y\right) = \sigma_o^2$$

- 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

➢BEHAVIOUR OF CONCRETE UNDER COMPRESSION

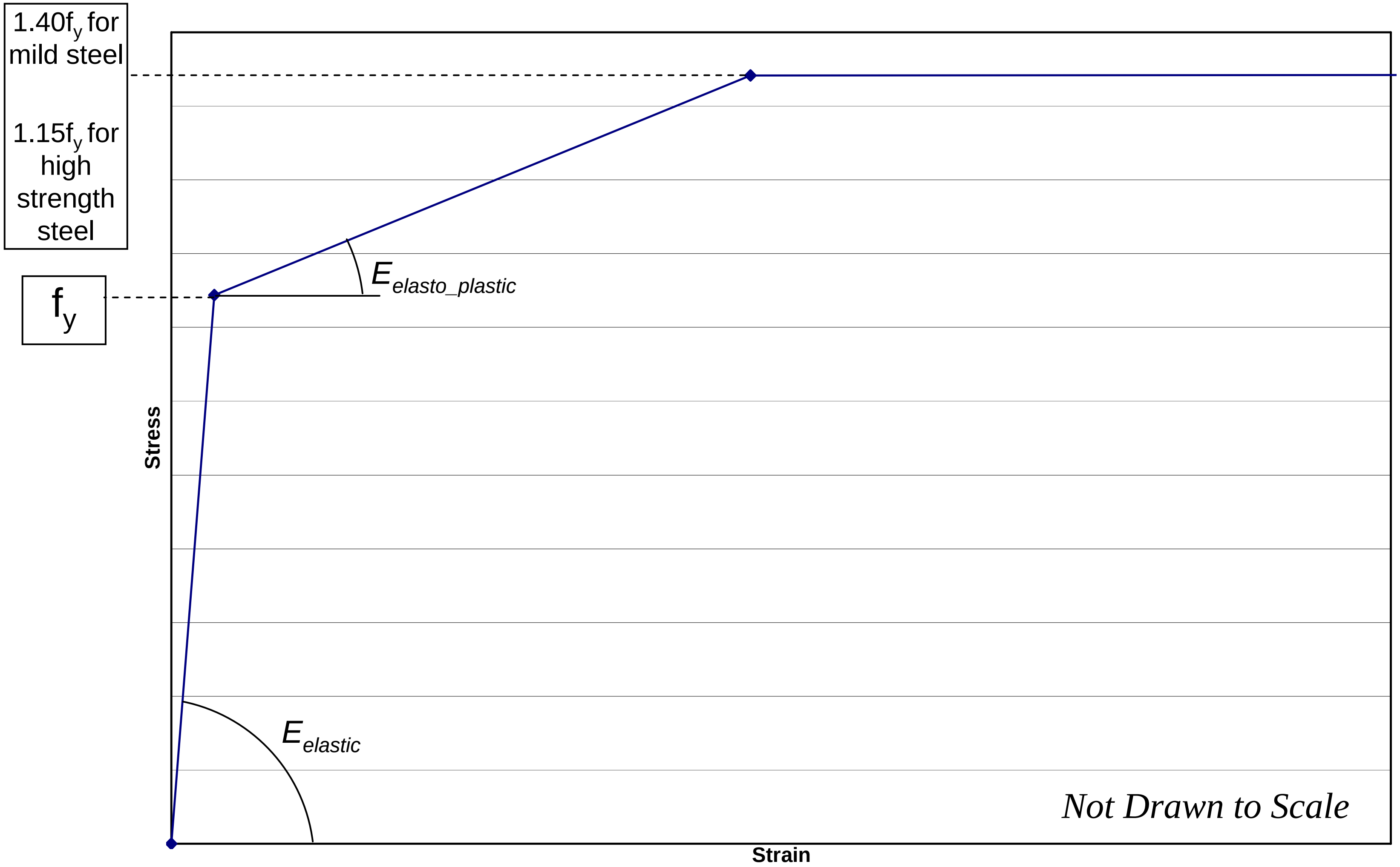
- Crushing Condition – Strain Based

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

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

➢REINFORCING AND PRESTRESSING STEEL

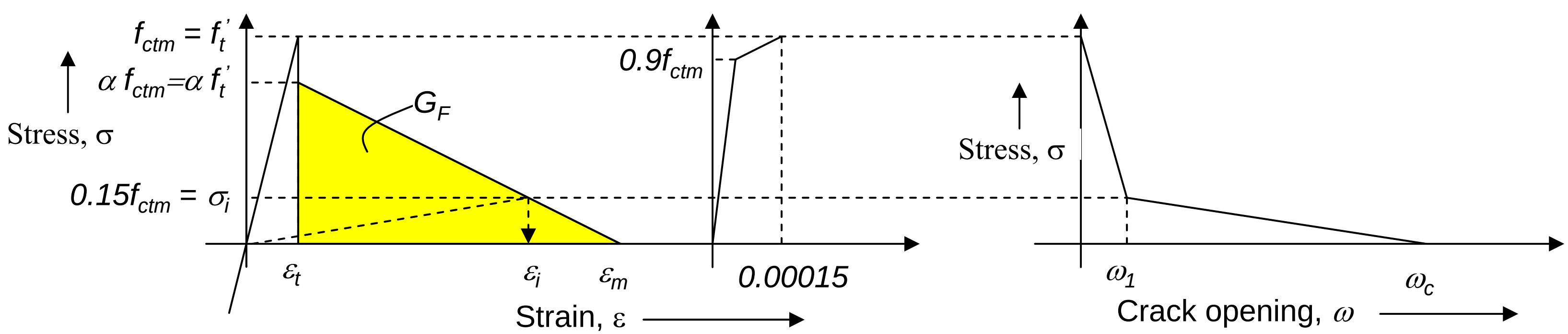
- Considered as smeared layer of equivalent thickness
  - Uni-axial Behaviour in Bar Direction
- Linear Elastic and Plastic Hardening behaviour is modelled



σ–ε Curve of Prestressing & Reinforcing Steel as Adopted in Analysis

STRESS-CRACK OPENING RELATIONSHIP

- No "*Leakage – Crack Opening*" Relationship available
- CEB-FIP Model Code 1990 Methodology is adopted along with Tension Stiffening Model
  - To obtain crack width based on Fracture Energy Formulation



$$\omega_1 = \left[\frac{G_F - 22 w_c \left(\frac{G_F}{\alpha} \right)^{0.95}}{150 \left(\frac{G_F}{\alpha} \right)^{0.95}} \right], \quad where\; \omega_c = \alpha \left(\frac{G_F}{f_{ctm}} \right)$$

ε_{TOTAL}	Crack Opening (mm)	Tensile Strength (MPa)
0.00015	No Cracking	f_{ctm}
0.00157	w_1	$0.15 f_{ctm}$
0.002	w_c	0

Assumption

- Smeared Cracked Model
  - Cracking over a finite area
    - Appropriate Representation of cracking in concrete

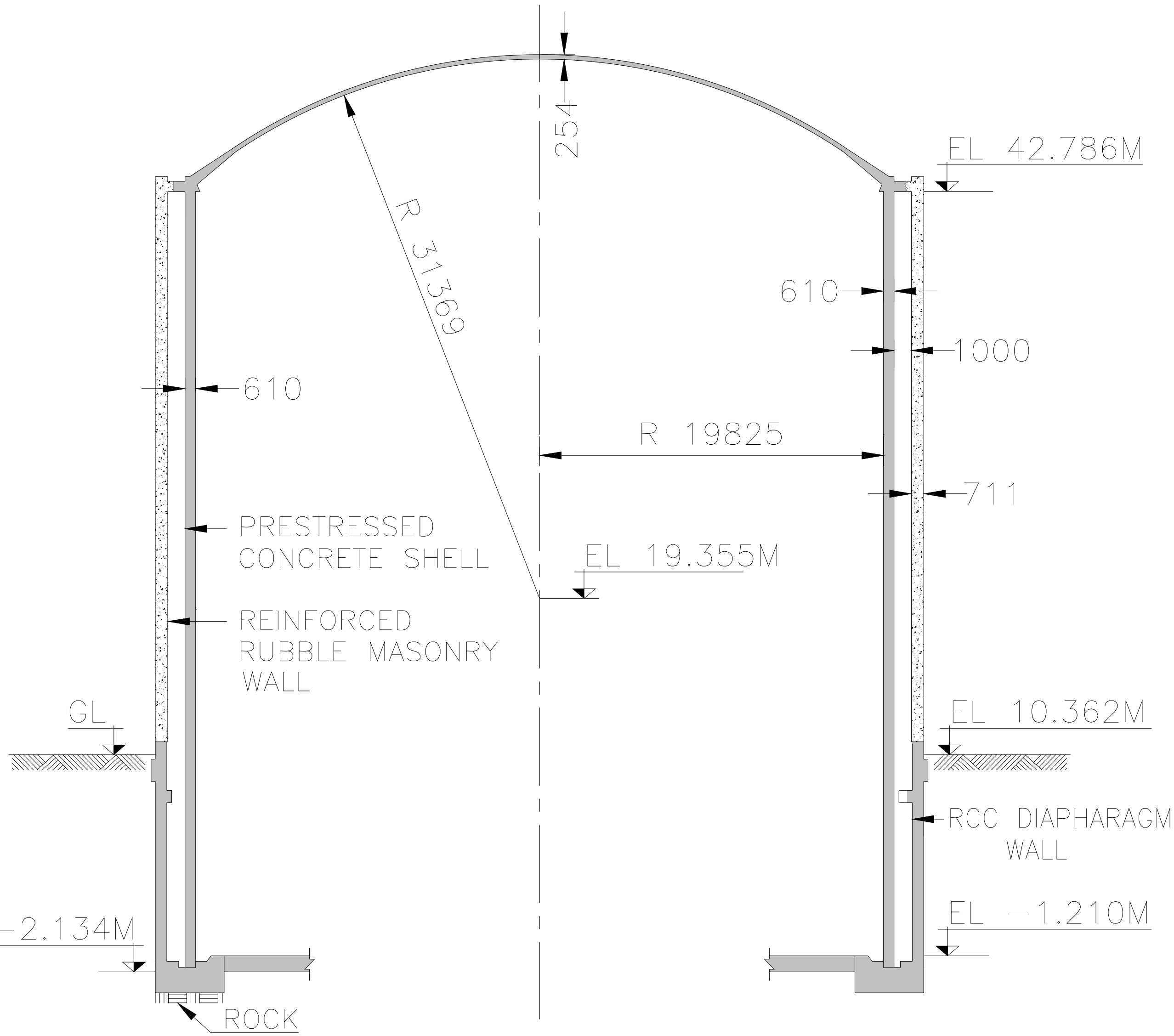
Limitations

- Shell Model
  - Contribution of Radial Reinforcement Can not be Considered
- Perfect bonding between layers
  - Inter-laminar shear failure can not be predicted
  - De-bonding of prestress cables & relative movement can not be modelled
- Above limitations leads to *Lower Bound* Prediction of ULBC
  - Conservative

Road Map to ULBC Studies of Indian Containment Structures

- Analytical Evaluation of Ultimate Load Bearing Capacity (ULBC) of all Types of Indian Containments have been carried out
  - *Madras Atomic Power Station, Unit-1&2* (MAPS-1&2)
    - First Generation 220MWe Atomic Power Station
      - *Partial Double Containment System*
  - *Narora & Kakrapara Atomic Power Station* (NAPS-1&2 / KAPS-1&2)
    - Second Generation 220MWe Atomic Power Stations
      - *Double Containment System with Cellular Slab connected to OC Structure*
  - *Kaiga Generating Station, Unit-1to4* (KGS-1to4) / *Rajasthan Atomic Power Station, Unit-3to6* (RAPS-3to6)
    - Third Generation 220MWe Atomic Power Stations
      - *Independent Double Containment System*
  - *Tarapur Atomic Power Station, Unit-3&4* (TAPS-3&4)
    - 540 MWe Atomic Power Stations
      - *Independent Double Containment System*

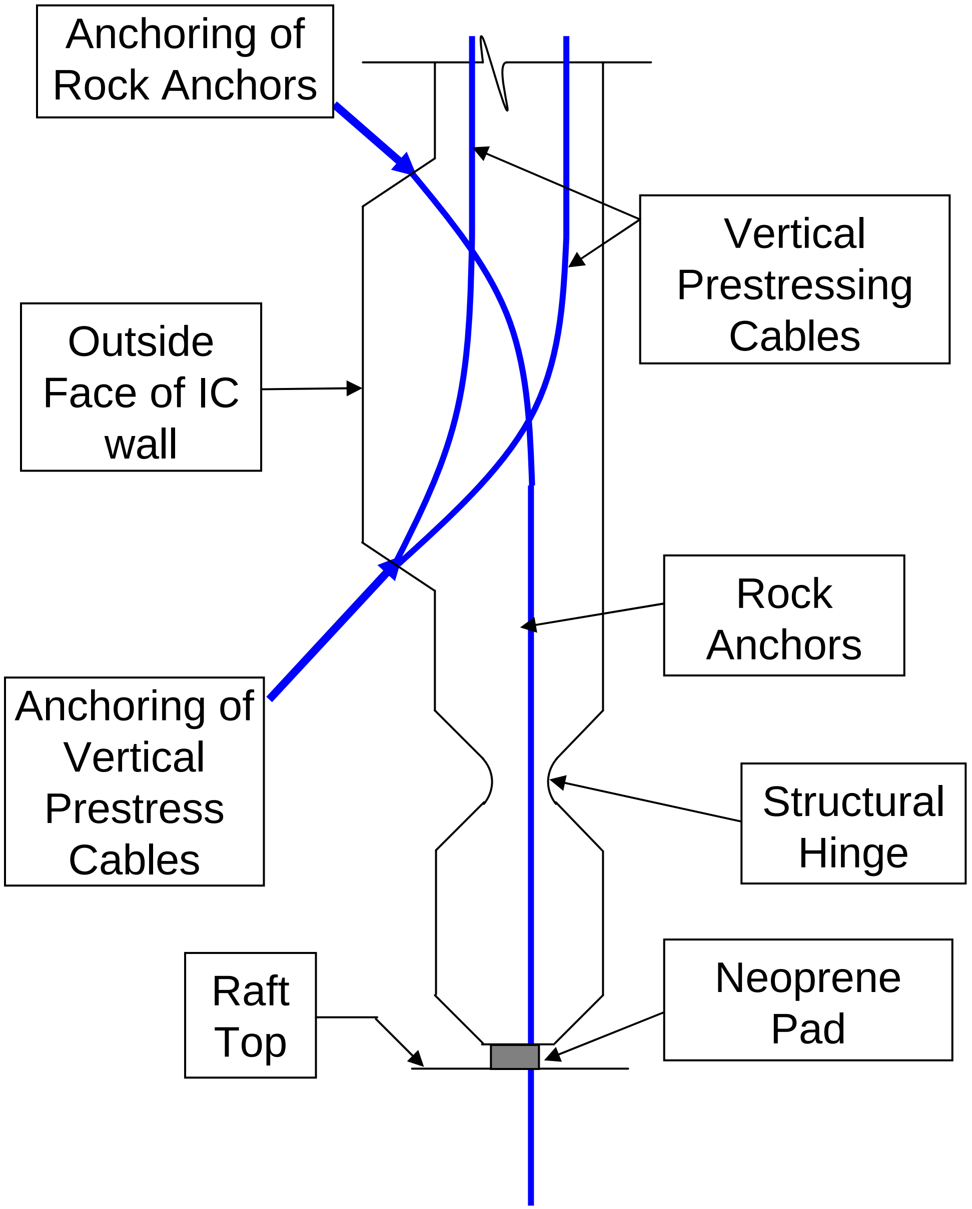
Salient Features
of
Different Containment Structures



CONTAINMENT STRUCTURE OF MAPS-1&2

MAPS-1&2 : Unique Features

- The IC Wall on Neoprene for Radially Sliding Boundary Condition
  - For Effective prestress Transfer
- Structural Hinge above Neoprene Pad
  - For Hinge Behaviour to avoid transfer of moment to structure
- Rock Anchors are Anchored in the IC wall
  - Has direct impact on ULBC



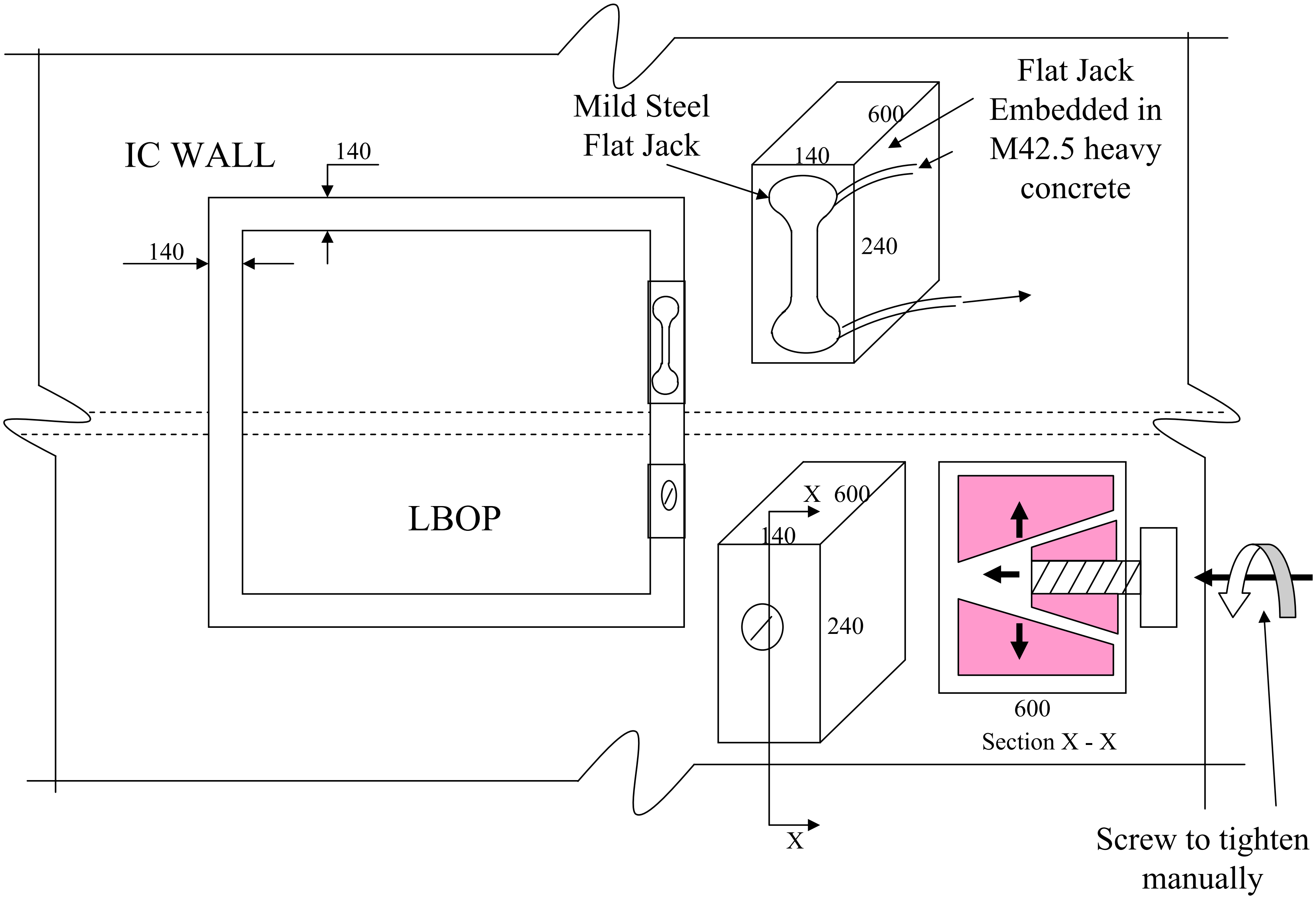
Unique Features

- Large Break Out Panel (LBOP : size -10.05m x 7.772m)
  - Provided in IC wall during construction to take in equipments
    - Closed almost after two years of construction of parent IC wall
  - Designed as Independent Panel & not Cast Monolithically with IC wall
  - Made Structurally Integral with IC wall
    - Using Flat Jacks & Steel Wedges
      - To compensate Differential Shrinkage after construction
    - Providing Grease Filled Prestressing Cables – Horizontal & Vertical
      - Facility to Re-open, if Required
  - Independent Panel Design of LBOP to avoid
    - Local thickening
    - Extra requirement of reinforcement

    to cater for bending effect around LBOP

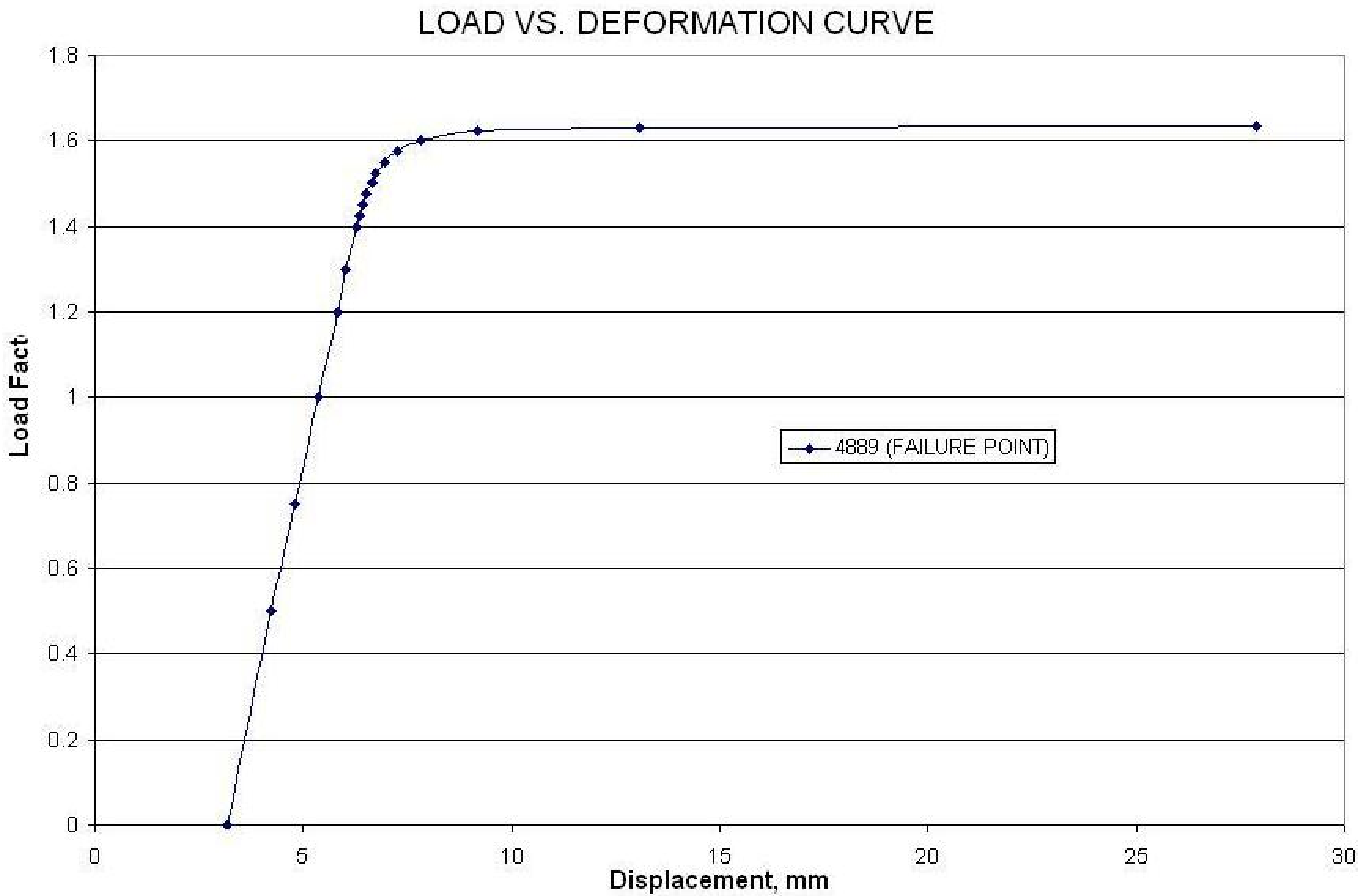
The behaviour of disjointed interface of IC wall & LBOP has direct bearing on ULBC of the Structure

SCHEMATIC DETAILS OF FLAT JACKS & STEEL WEDGES



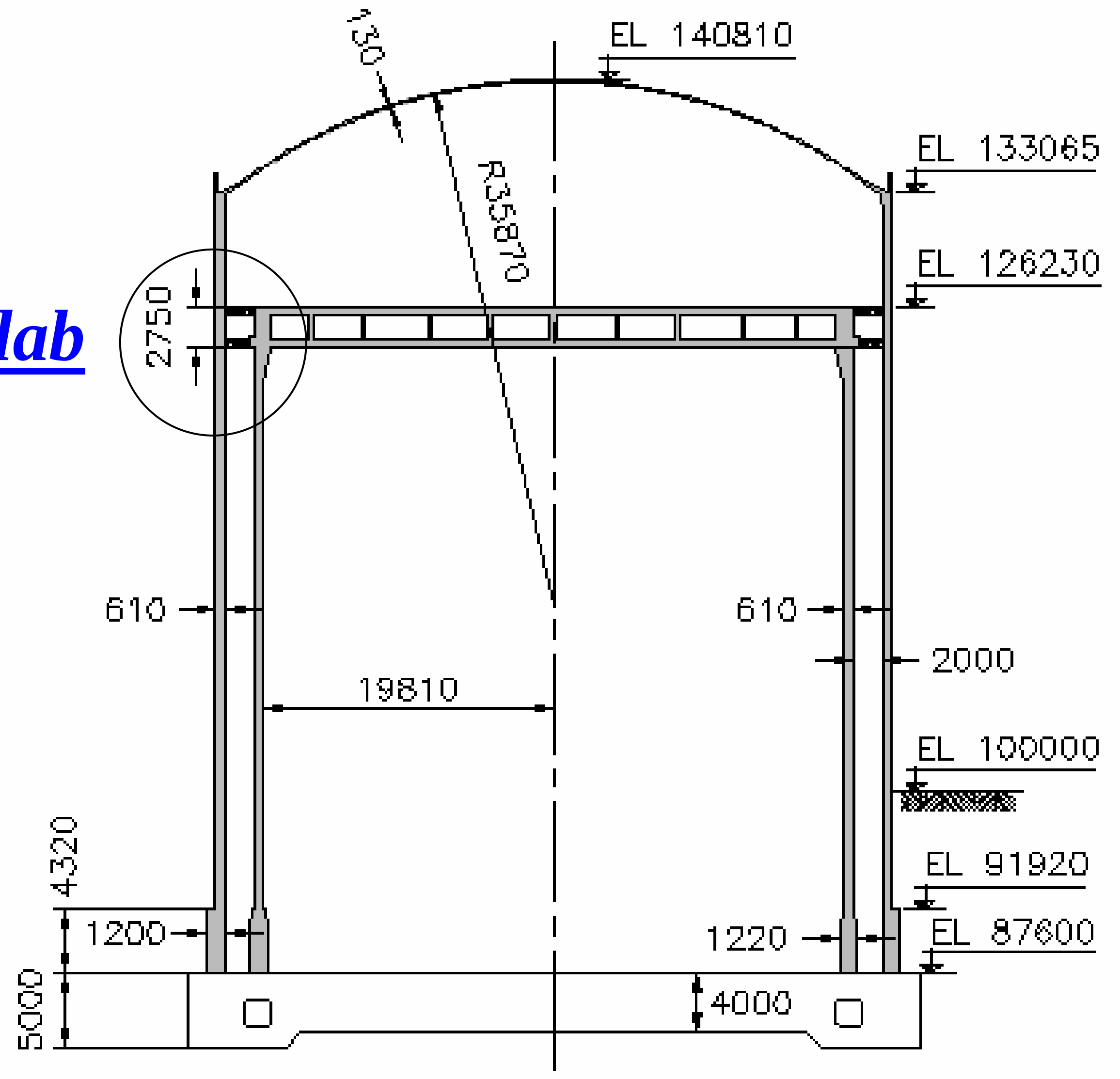
MAPS-1&2

TYPICAL RESPONSE OF STRUCTURE

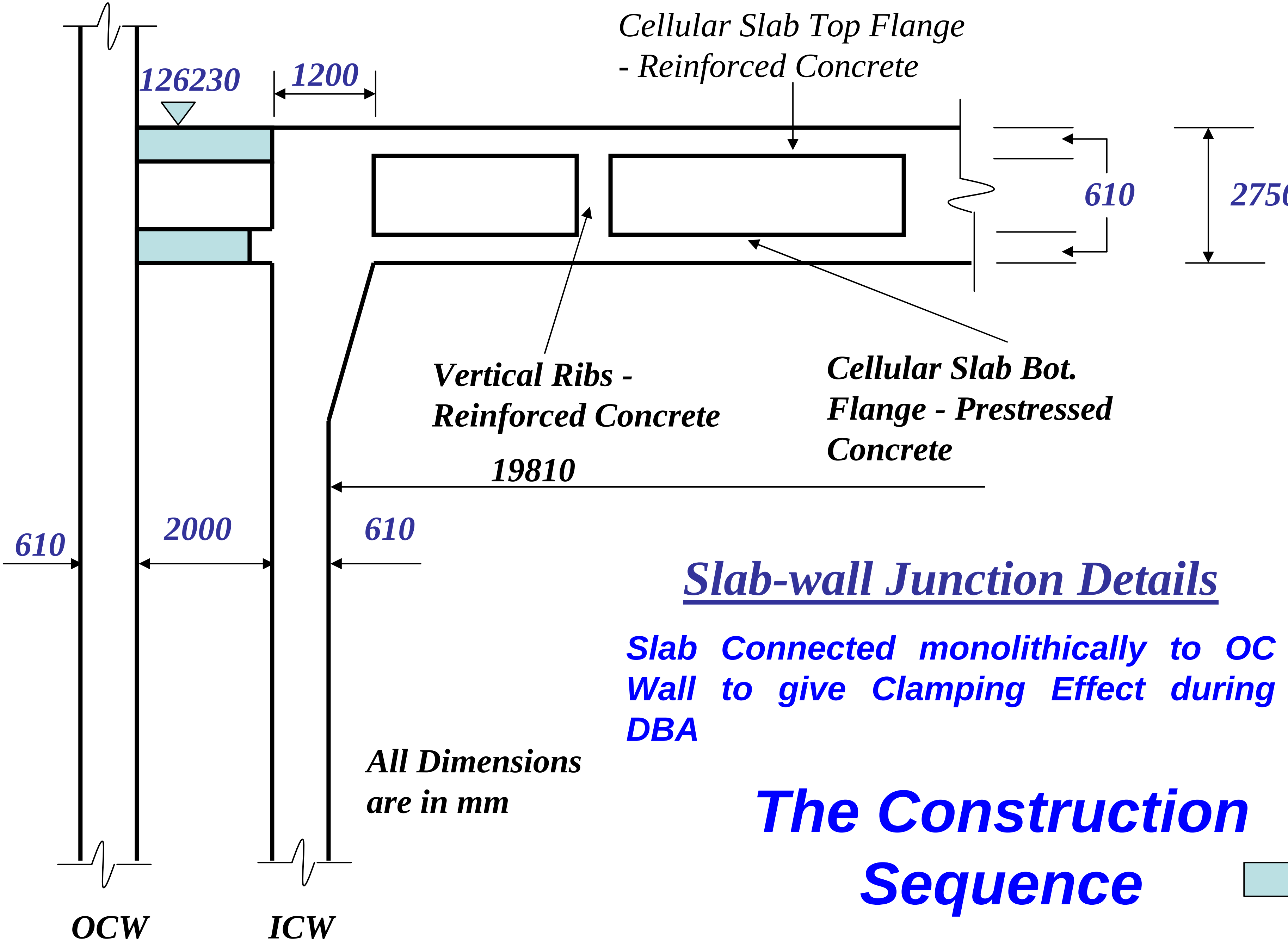


NAPS-1&2 / KAPS-1&2: Unique Feature

Cellular Slab



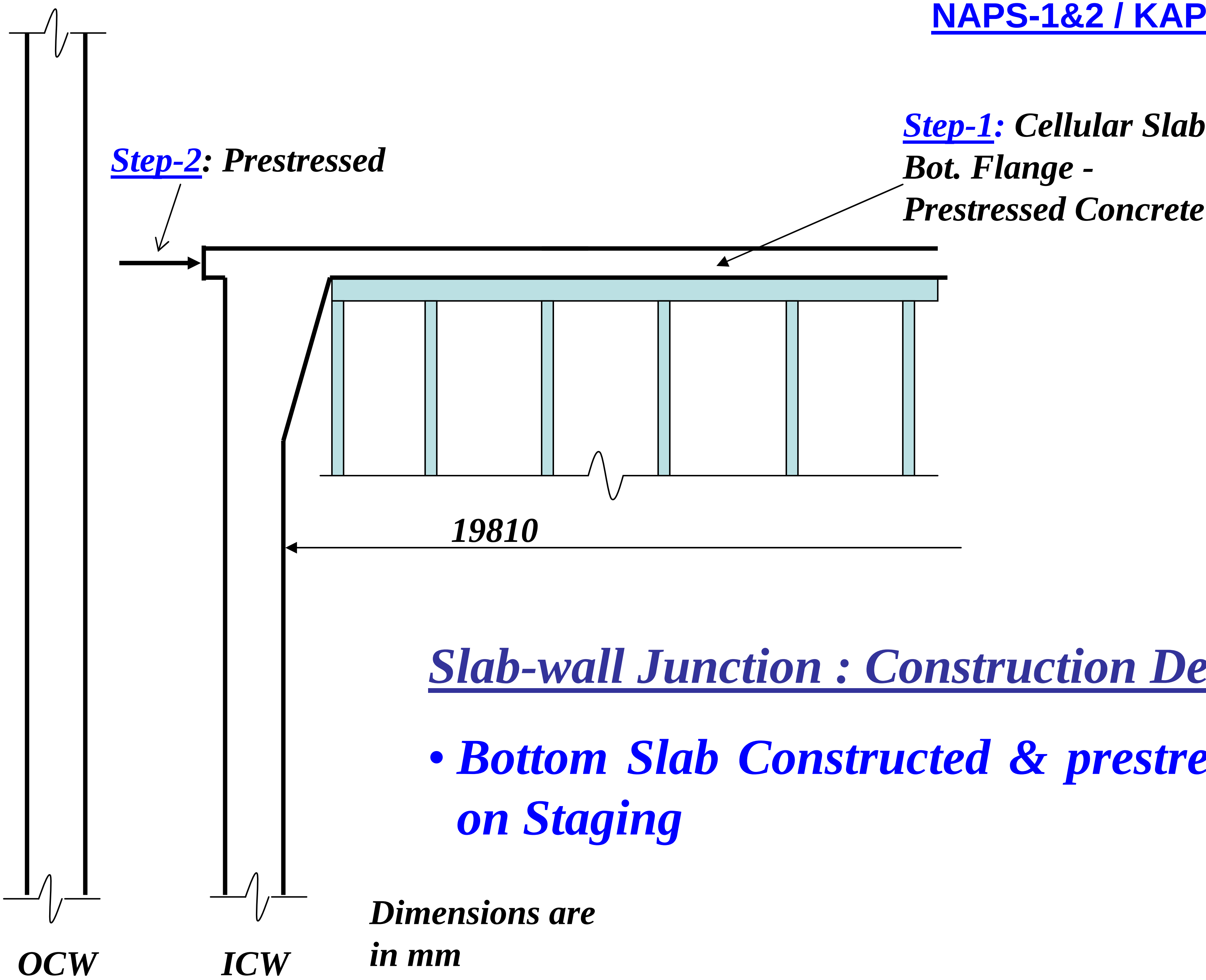
CONTAINMENT STRUCTURE OF TYPICAL FIRST GENERATION INDIAN PHWRs



Slab-wall Junction Details

Slab Connected monolithically to OC Wall to give Clamping Effect during DBA

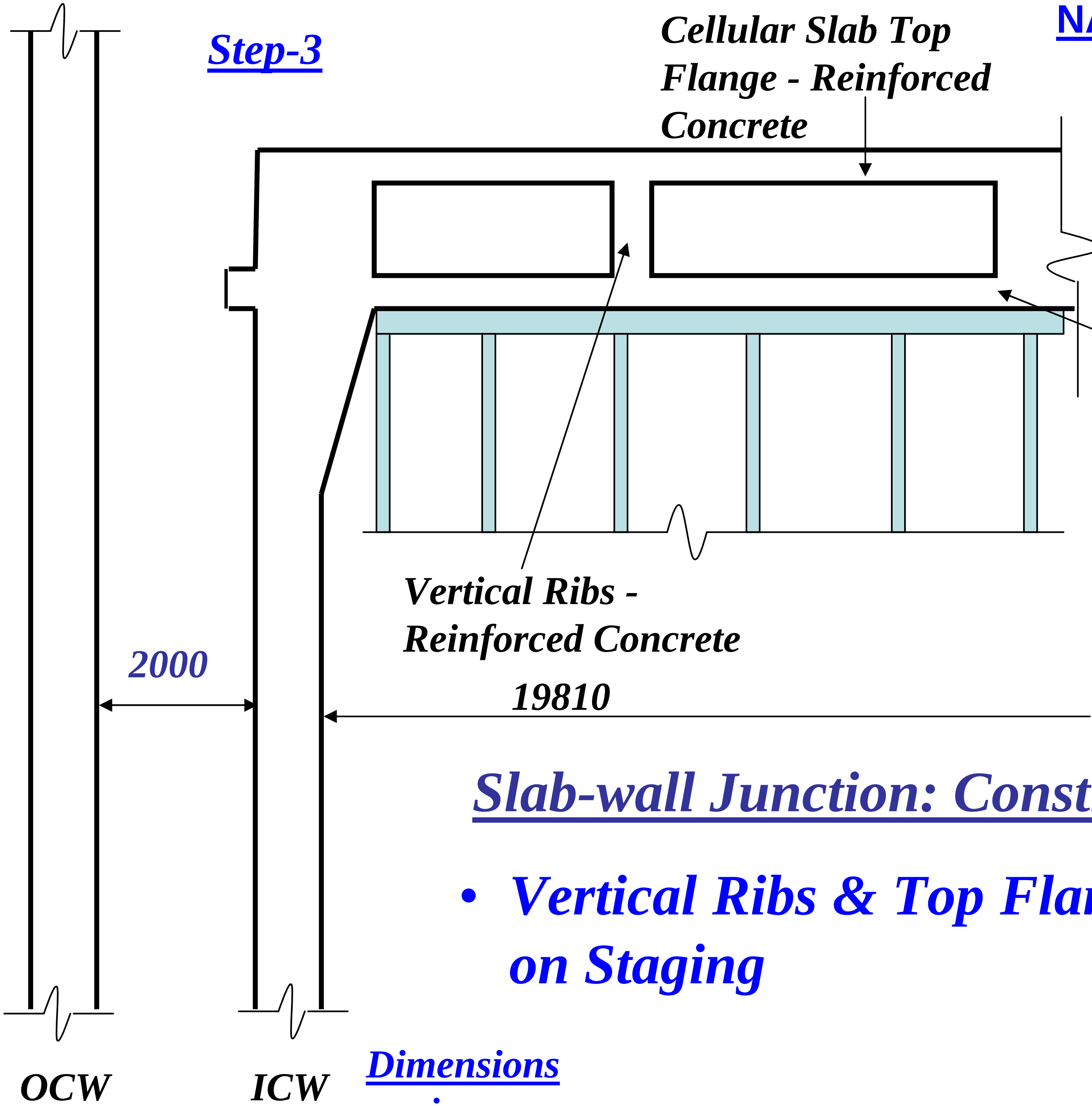
The Construction Sequence



Slab-wall Junction : Construction Details

- ***Bottom Slab Constructed & prestressed on Staging***

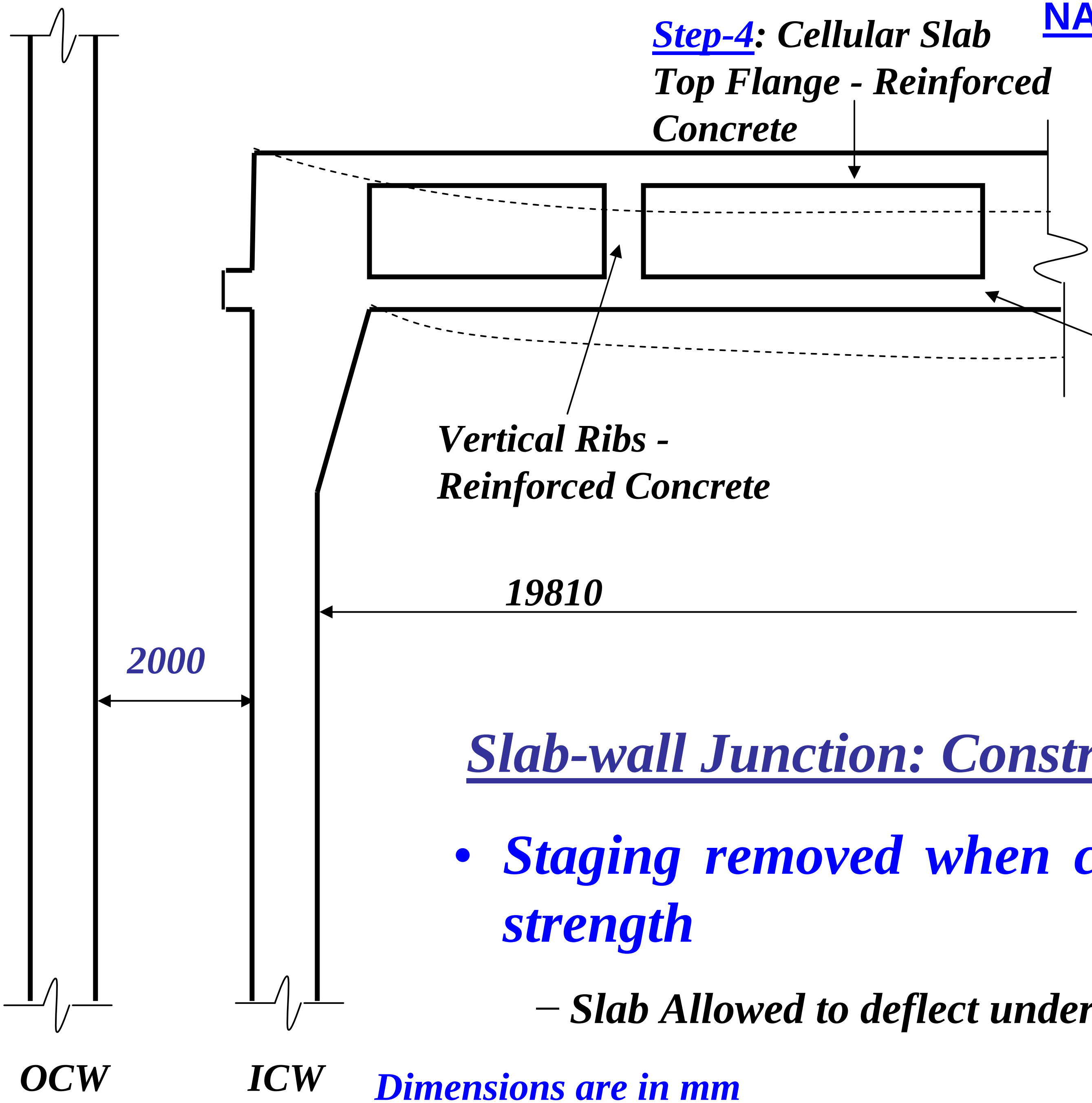
Step-3



Slab-wall Junction: Construction Details

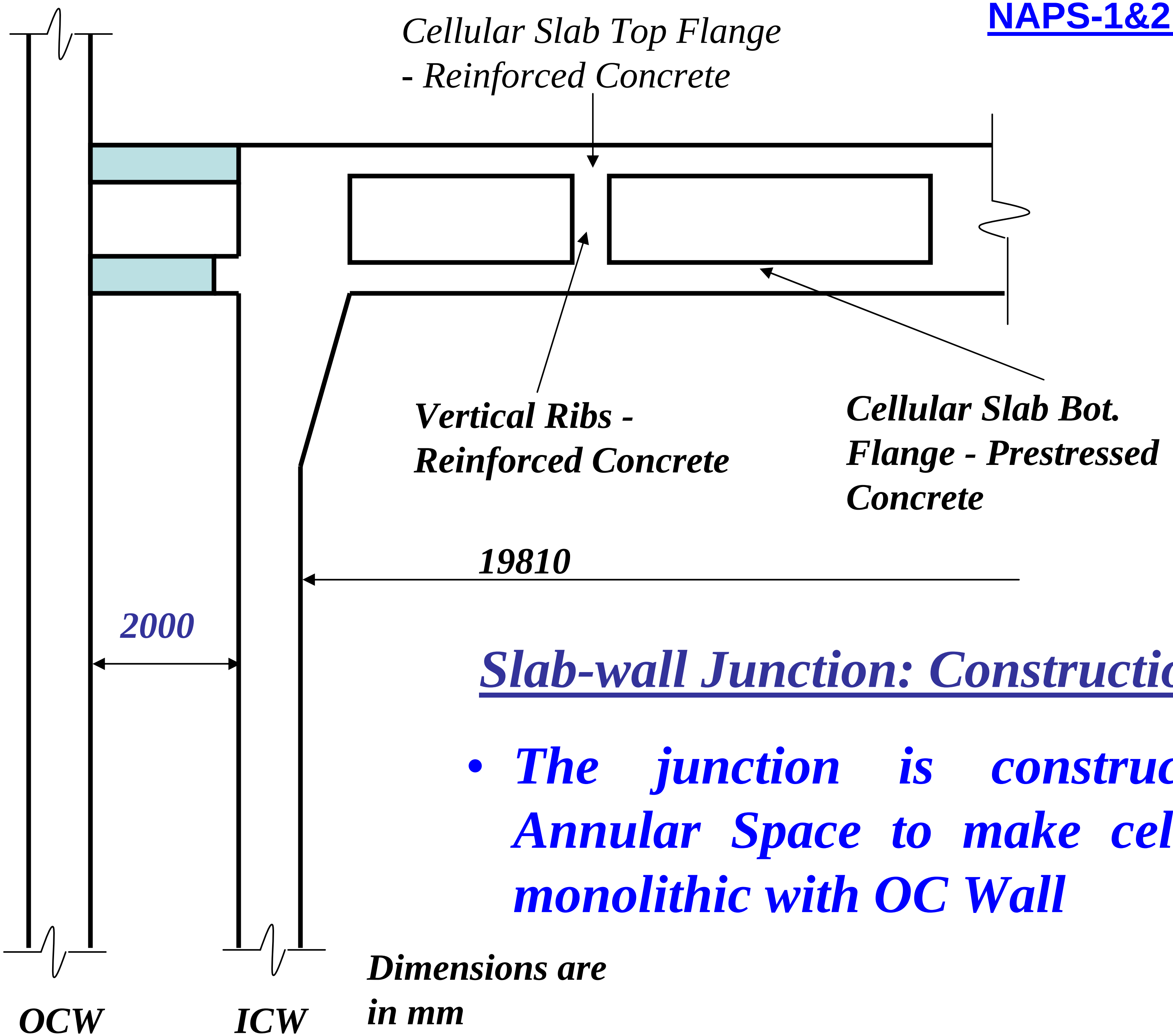
- ***Vertical Ribs & Top Flange Constructed on Staging***

Dimensions are in mm



Slab-wall Junction: Construction Details

- ***Staging removed when concrete gained strength***
  - ***Slab Allowed to deflect under Self-weight***



Slab-wall Junction: Construction Details

- *The junction is constructed over Annular Space to make cellular slab monolithic with OC Wall*

ANALYSIS

- In Two Steps
- Step-1
  - Calculation of Residual Stresses in the structure
    - Due to *CONSTRUCTION SEQUENCE* of cellular slab
- Step-2
  - Non-linear Analysis

SIMULATION OF CONSTRUCTION SEQUENCE OF CELLULAR SLAB IN ANALYSIS

- ***First Step*** of analysis
  - Full prestress of the bottom slab is considered
  - OCS and the connection between OC wall & cellular slab and the vertical webs & top slab of ICS are made inactive by specifying a very low value of Young's Modulus
  - Self-weight of IC wall is considered
    - Self weight of Bottom Slab is not considered
      - As Supported by staging

SIMULATION OF CONSTRUCTION SEQUENCE OF CELLULAR SLAB IN ANALYSIS

- ***Second Step*** of analysis
  - The self-weight of entire cellular slab is considered
  - The connection of cellular slab with OC is not considered

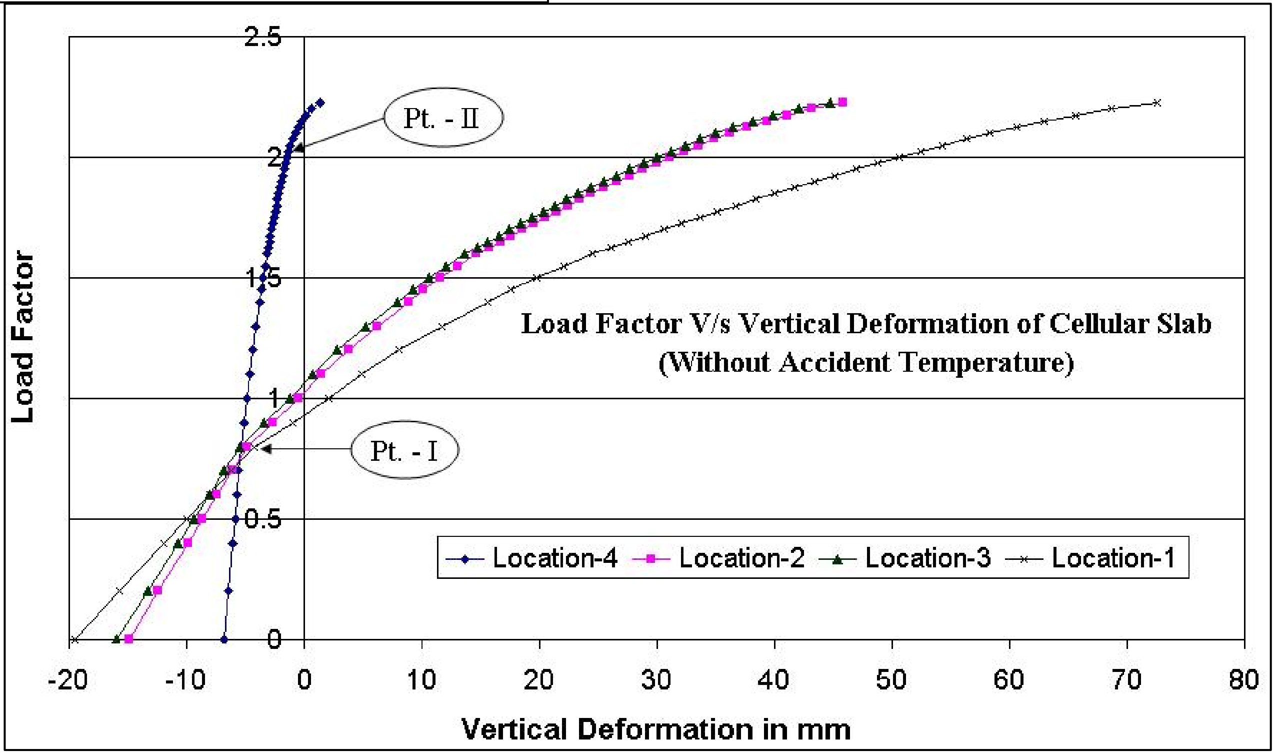
- ***Third Step*** of analysis
  - The full Structure is considered

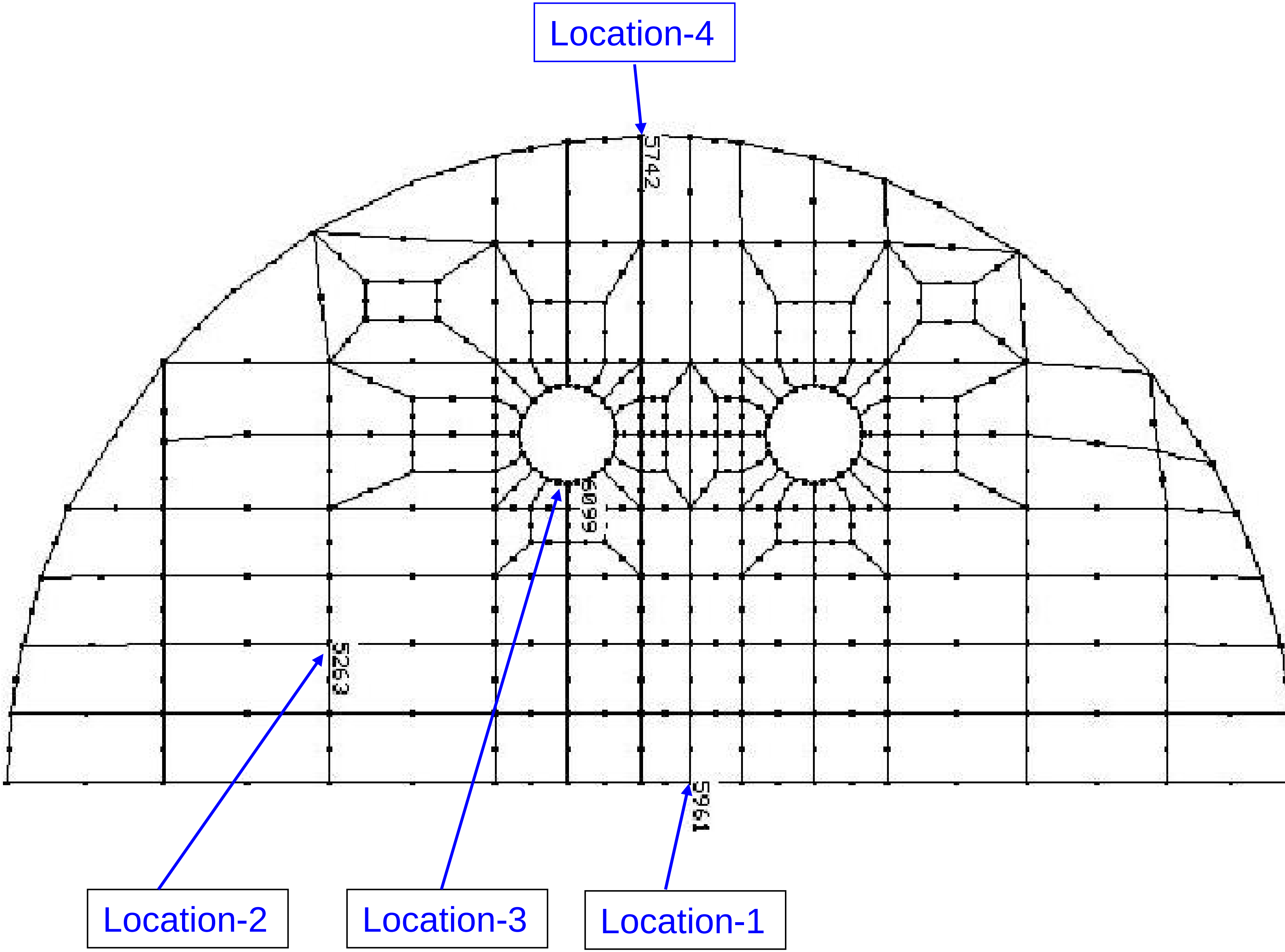
- **The stresses in all these 3 steps are cumulated and stored as residual stress**

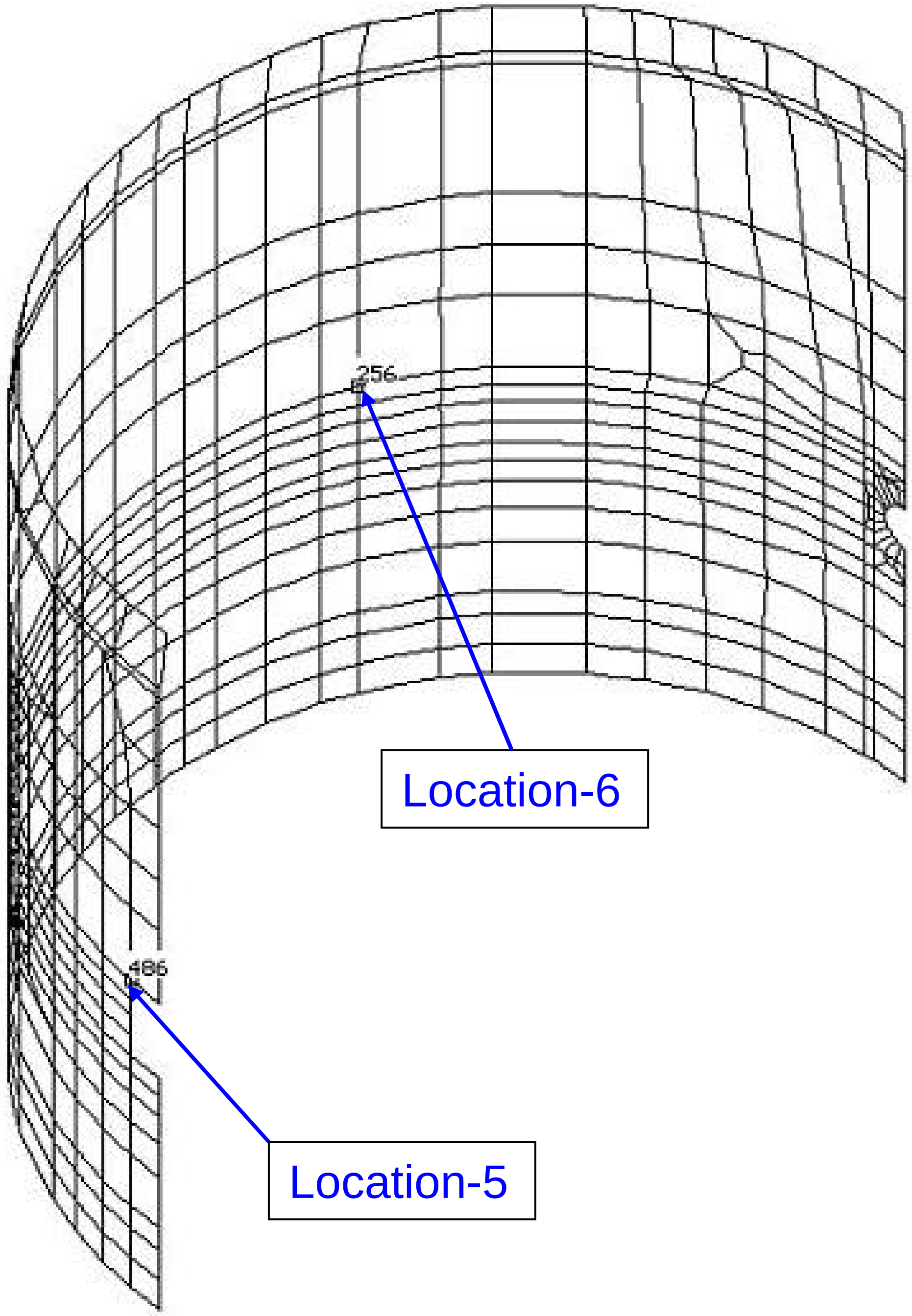
The Internal Pressure is incremented after third step

RESPONSE OF STRUCTURE

RESPONSE		LOAD FACTOR W/O Acc. Temp	LOAD FACTOR With Acc. Temp
Linear	Cellular Slab	0.800	0.72
Linear	IC Wall	1.500	1.59
Yielding of Steel		1.824	1.77
Functional Failure		1.900	1.875
ULBC		2.3	2.3



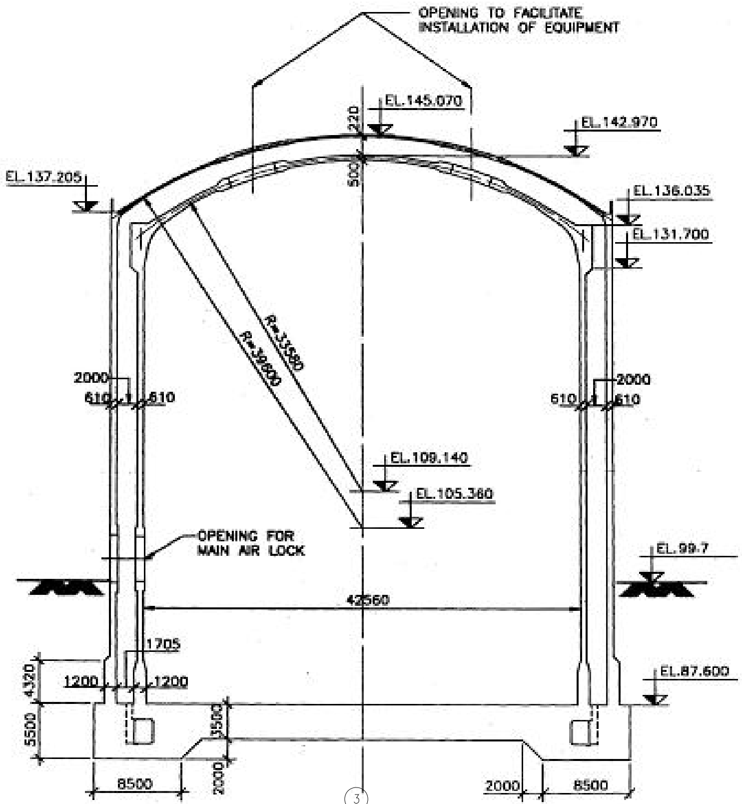

Location-4
5742
5263
5961
Location-2
Location-3
Location-1

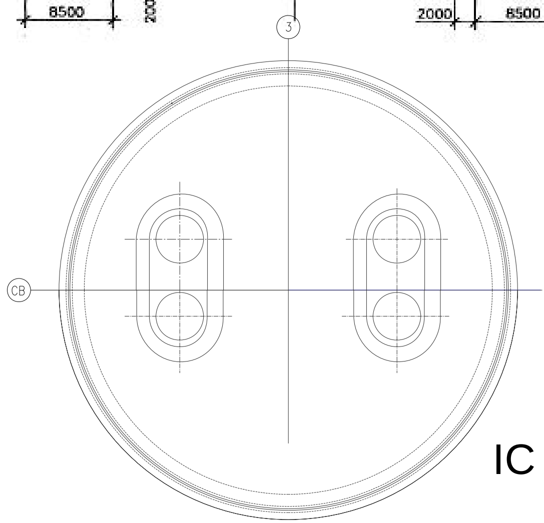


256
466
Location-6
Location-5

RESPONSE OF STRUCTURE

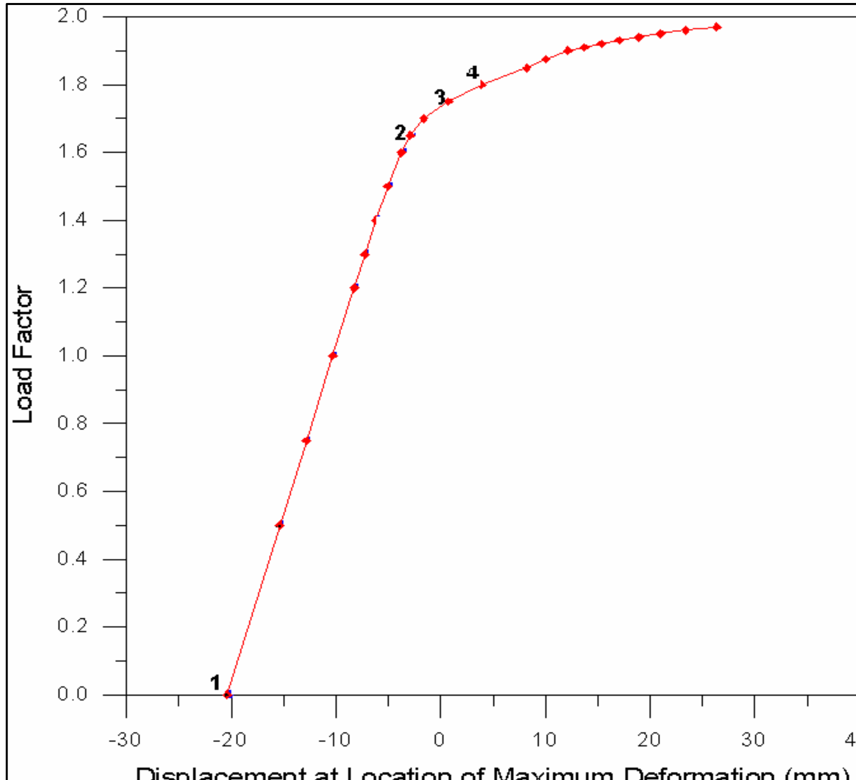
220MWe: RAPP-3-6 / KGS1-4





IC Dome

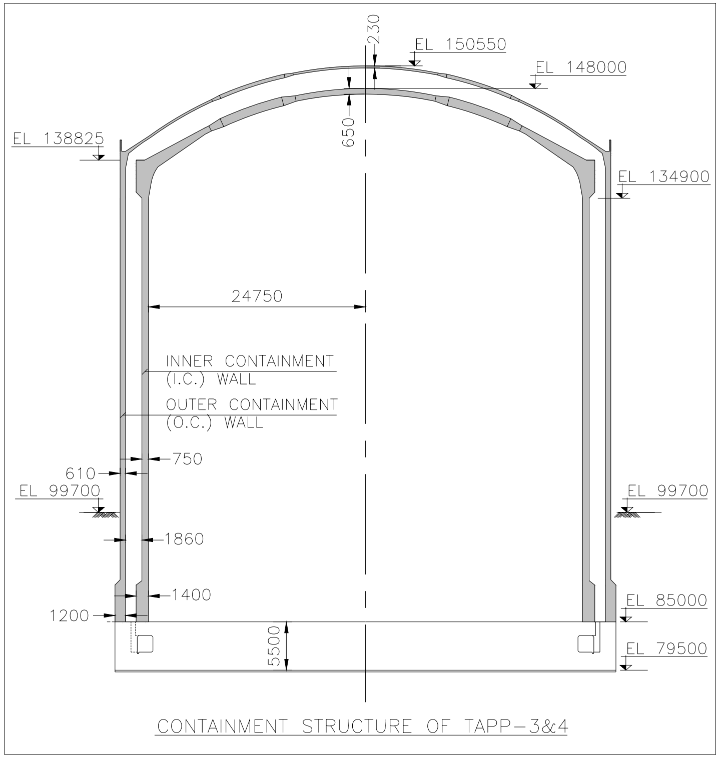
RESPONSE	LOAD FACTOR
Yielding of Steel	1.75
Functional Failure	1.85
ULBC	1.97



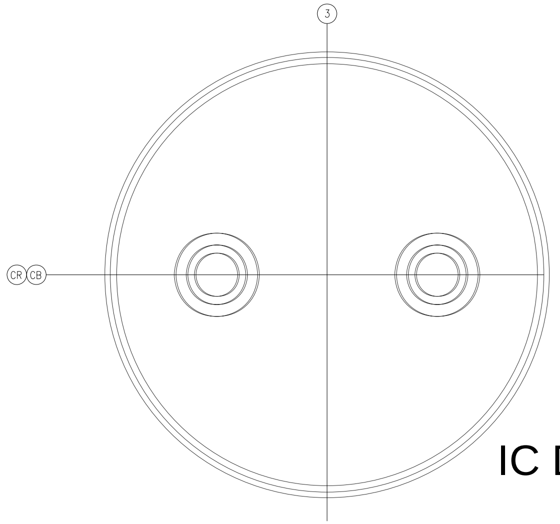
(Around Steam Generator Opening in IC Dome)

RESPONSE OF STRUCTURE

540MWe: TAPS-3&4

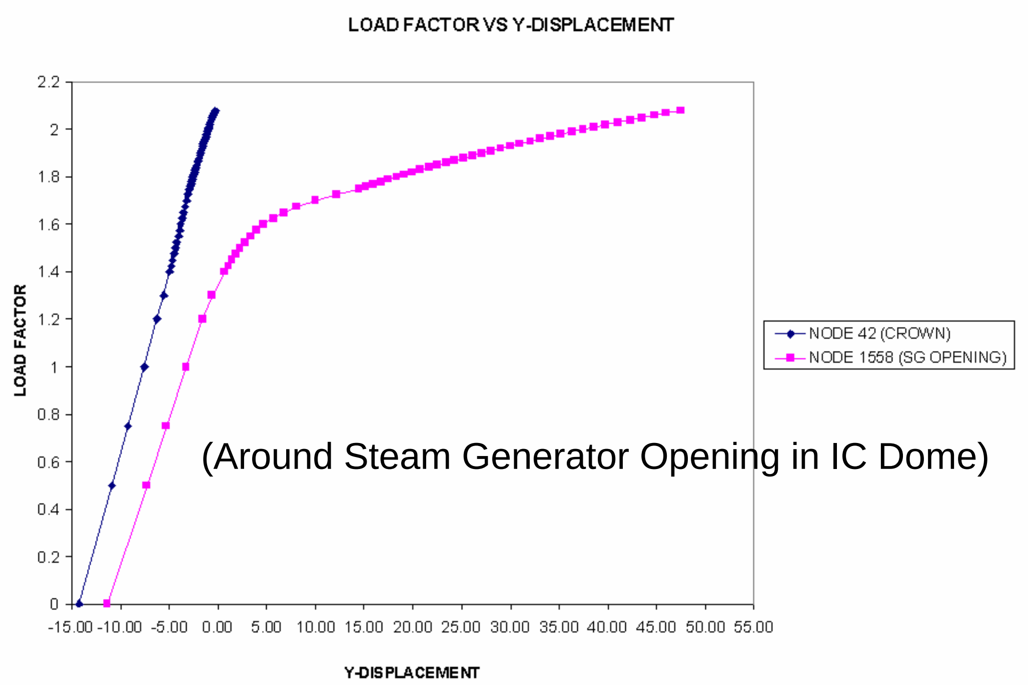


CONTAINMENT STRUCTURE OF TAPP-3&4



IC Dome

RESPONSE	LOAD FACTOR W/O Acc. Temp	LOAD FACTOR With Acc. Temp
Linear	1.4	1.25
Yielding of Steel	1.75	1.475
Functional Failure	1.88	1.55
ULBC	2.08	1.9



(Around Steam Generator Opening in IC Dome)

Summary

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

Thank You