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CONCEPTUALIZATION, DESIGN AND ENGINEERING OF INNER CONTAINMENT DOME LINER OF INDIAN 700 MWe PHWR

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ABSTRACT

The 700 MWe IPHWR is first of its kind in the Indian PHWR programme and as a part of major improvements, 6 mm thick metallic liner has been introduced on the inner surfaces of Inner Containment (IC). The liner is a non-structural member provided as an additional leak-tight barrier under all operating, design basis and design extension conditions. However, the metallic liner and its anchorage system are designed as a structural member during erection and concreting of IC. For the dome portion, the liner and its anchorages have been engineered to be self-supporting during it construction and also to be lifted as a single unit of 355 MTon with the help of heavy-duty crawler crane. The engineering of the self-standing IC dome liner has been conceptualized based on detailed sequential analyses simulating the stage-wise concreting of IC dome. The analysis and design of this self-supporting structure has been based on the stress and strain criterions as per ASME Section III Division 2 under construction and different service loading conditions. The major challenges in the design of the 8 m high and 46 m diameter, double curvature segmental spherical dome liner system, with two large openings (of 6 m diameter) for steam generator (SG) replacement was the control of the deformation and stresses while lifting it as a single unit and stage-wise concreting of IC dome. This paper brings out the salient features adopted during the conceptualization, design and detailed engineering of the IC dome of 700 MWe IPHWR.

INTRODUCTION

The 700 MWe Indian Pressurized Heavy Water Reactor (IPHWR) has evolved after forty years of design, construction, commissioning and operating experiences gained from earlier 220 MWe and 540 MWe NPPs. As a part of major improvement in the functional and structural design of the Inner Containment (IC), 6 mm thick metallic liner has been introduced on its inner surfaces along with use of 500 MTon capacity-prestressing cables. The IC structure is of prestressed concrete consisting of 850 mm thick cylindrical wall, capped with a segmental dome of 850 mm thickness. Ring beam has been provided between the two to form a smooth transition that serves the structural role in resisting forces due to geometrical discontinuity and functional role of housing pre-stressing anchorages.

6 mm thick liner has been provided as an additional leak-tight barrier that will reduce the radioactive release through the containment in case of design basis accidents and design extension conditions as well as improve the leak tightness during normal operating condition. As such the liner has been engineered as a non-structural member during service life of the IC structure, taking no advantages of its strength and stiffness on the IC design. However, the metallic liner and its anchorage system are designed as a structural member during construction phase where it has been used as a self-supporting formwork capable to resist all construction phase loads including green concrete pressure.

For the dome portion, the engineering of the liner-backing member system has been performed in three stages: ability to resist all handling related stresses when lifted as a single unit of 355 MTon with the help of heavy-duty crawler crane during the process of installation, ability to resist construction related stresses during pour-wise concreting of IC dome and ability to resist all service and design basis accidents strains during the operating life of the reactor. However, the final configuration of the liner-backing member system including the sizes of various pours and its sequence is evolved based on various trials of the stage-wise sequential analyses simulating the exact boundary conditions after each pour of concrete.

Analysis of the system and design of the same is based on scheme, wherein the locked-in-responses in the liner-backing member system due to previously concreted pours are carried forward and added to the response analysis of further pours. This way IC dome liner system has been engineered to be self-supporting during construction of IC dome and also to be lifted as a single unit. State-of-art modularization technique for the erection and installation of the entire dome liner has been implemented. This has not only eliminated the requirement of structural steel IC dome shuttering assembly, conventionally used for dome construction, but has also led to a considerable saving in construction time along with optimum use of resources. Fabrication of the IC dome liner system panels at workshop and assembly of the same on ground lead to better quality control.

This is a First-of-Its-Kind attempt in the world as the 8 m high and 46 m diameter, double curvature segmental spherical dome, with two large openings (of 6 m diameter) for steam generator (SG) replacement was a challenge to be lifted as a single unit. This thin-shelled segmental structure becomes unique due to its combined membrane and flexure behaviour due to geometrical discontinuity posed by these two large SG openings. This paper brings out the salient features adopted during the conceptualization, design and detailed engineering of the IC dome liner for all the three stages of its engineering.

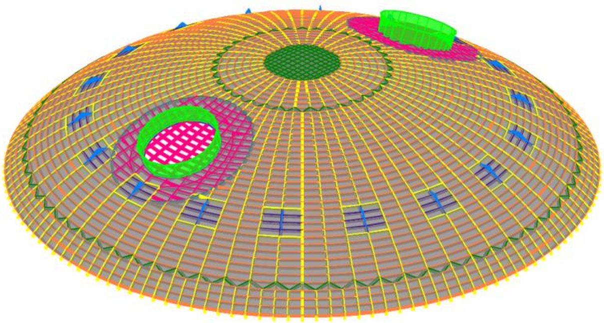
IC DOME LINER DESCRIPTION

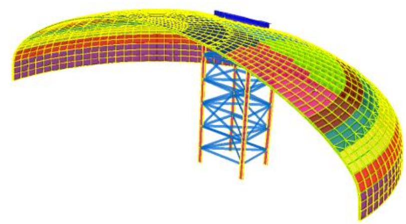
The 6 mm thick liner conforms to low alloy carbon steel plate, cold rolled to the desired curvature and stiffened by a grid work of structural backing members. The structural backing member systems consists of a continuous meridional-circumferential grid work of rolled structural steel of ISHB150-3, welded to the liner plates and are spaced at an angle of 10˚, 5˚ and 2.5°. Wherever, there is a change in the angle, bracings have been used. All circumferential members are spaced at a curved distance of 600 mm centre-to-centre and are placed between two consecutive meridional members. A central compression panel of diameter 3 m consisting of orthogonal backing members has been provided at the crown.

Due to two large 6 m diameter circular openings provided in the IC dome and complex geometry around the opening area, a SG trestle has been provided around the opening area to limit the deformation during the process of construction. The SG trestle transfers the loads to 800 mm thick reinforced concrete walls. The SG trestle is trapezoidal in geometry with the four columns braced vertically and horizontally along diagonal for additional torsional stiffness. The arrangement of IC dome liner along with the SG Trestle is shown in Figure 1.

Material

The dome liner-backing member system conforms to IS 2062 (2011). The material for the dome concrete is M45 having a characteristic strength of 45 MPa. In the sequential, stage wise analysis of the IC dome, four different properties of the same concrete has been assumed based on the age of the pour viz., 7 day, 14 day, 21 day and 28 day to simulate the strength and stiffness gain of already poured concrete. The development of modulus of elasticity and strength of concrete have been verified with respect to actual values obtained from concrete laboratory for grade of concrete used in actual construction of IC structure.





Part sectional view showing SG Trestle

Figure 1. General Arrangement of backing members on the IC dome

The time variation of the modulus of elasticity of normal weight concrete is calculated as per ACI 349 (1985):

$$E_c = 4734\sqrt{f'_{cj}}\ \text{(MPa)} \qquad (1)$$

The variation of the compressive strength of concrete has been assumed as per the French code BAEL (1983) as:

$$f'_{cj} = \frac{j}{4.76+0.83\,j} f'_{c,28} \qquad (2)$$

Where, E_c = modulus of elasticity of concrete, f'_{cj} = compressive strength at j[th] day, $f'_{c,28}$ =28-day compressive strength

Allowable stresses and strains

The IC dome liner has been designed as per provisions of ASME, Section III, Division 2 (2015). The allowable stresses in liner-backing member system for construction load combinations and allowable strains for service and factored load combinations are given in Table 1.

Table 1: Allowable Stresses and Strains as per ASME Section III Division 2

Category	Stress-Strain Allowable [(1), (2)]	
	Membrane	Combined Membrane and Bending
Construction	$f_{st}=f_{sc}=2/3\ f_{py}$	$f_{st}=f_{sc}=2/3\ f_{py}$
Service	$\epsilon_{st} = \epsilon_{sc} = 0.002$	$\epsilon_{st} = \epsilon_{sc} = 0.004$
Factored	$\epsilon_{sc} = 0.005$	$\epsilon_{sc} = 0.014$
	$\epsilon_{st} = 0.003$	$\epsilon_{st} = 0.010$

(1) Types of strains limited by this table are strains induced by other than construction related liner deformation. (2) Strain in in./in. or mm/mm.
f_{py} = yield stress of steel=166.67 MPa, ϵ_{st}, ϵ_{sc}= tensile & compressive strain, f_{st}=f_{sc}= tensile & compressive stress

Strain based allowable are used under service and factored load combination as the liner is designed as a non-structural member and allowed to deform beyond its elastic limit, leading to absorption of strain energy. However, the limits are specified so that the liner does not tear apart leading to functional failure.

Handling arrangement as a single unit

The entire IC dome liner system was fabricated into 53 panels at workshop and later assembled on the ground near the Nuclear Building area to form the required geometry. While lifting the entire IC dome liner as a single unit, the design concern was to control the deformation behaviour and stresses around the lifting locations within the linear elastic range. A number of options were planned and scrutinized to lift the IC dome liner as a single unit. The final option implemented at site consists of lifting it using 18 numbers of 54 mm diameter steel crane cables having a tensile strength of 1960 MPa and a minimum breaking load of 207 MTon. The angle of inclination of these crane cables were kept 55° to the horizontal keeping in mind the interferences of cables with the IC dome liner and the maximum height of the crane configuration finalized based on the capacity assessment of heavy duty crawler crane (safe working load = 373 MTon at 44 m radius). The loading plane has been made co-incident with the plane of centre of gravity of the IC dome liner. As per the requirement of the crane operation, the maximum permissible wind speed during operation of crane was restricted to be at 9 m/sec.

Seating arrangement

A seating arrangement was provided at 144 locations on the meridional ISHB150-3 members. The seating arrangement in the assembly area was an exact replica of the seating arrangement provided on the concreted ring beam to simulate the actual installation process and is shown in Figure 2.

Assembly area

Part IC dome liner

Figure 2. Seating arrangement in the assembly area and part view IC dome liner seating arrangement

Strengthening arrangement around lifting and Embedded Parts locations

At locations where the crane cable is connected to the IC dome liner, local strengthening has been provided at lifting locations and the same has been shown in Figure 3. Since, the IC dome liner was to be lifted along with the Containment Spray System (CSS), its inspection platform and the Hydrogen and Steam Condensation Monitoring System (HSCMS), the Embedded Parts (EPs) provided for these systems were also strengthened and is shown in Figure 4.

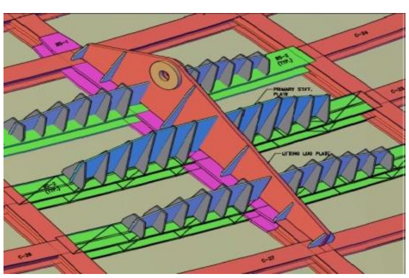


Figure 3. Strengthening arrangement near lifting locations

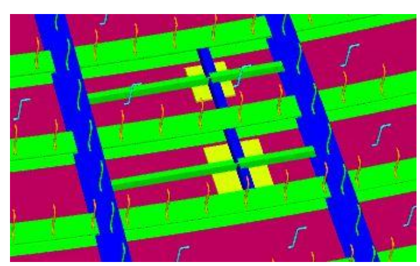


Figure 4. Strengthening arrangement at EP locations

Crane hook connector

A crane hook connector has been provided that connect all the 18 crane cables to the crane hook. The cables are connected to the crane hook connector using bow and shackle arrangement. The crane hook connector has been designed for the worst case of snapping of one crane cable. The crane hook connector was load tested 1.25 times the design working load.

ANALYSIS AND DESIGN METHODOLOGY FOR HANDLING STAGE

Analysis and design of the IC dome liner has been carried out during the process of lifting and installation at the specified location on ring beam. The IC dome liner has been analyzed for all applicable dead loads and wind load during lifting process and stresses have been limited to allowable stress value. To envelop all possible scenarios during its lifting and installation, following cases considering accidental snapping of one crane cable and misfit of the 18 crane cables have been analyzed:

- Case-1: No snapping of crane cable and all cables are equally stressed
- Case-2: No snapping of crane cable but cables are unequally stressed due to misfit of length
- Case-3: Snapping of one out of 18 crane cables @ SG opening area along N-S axis
- Case-4: Snapping of one out of 18 crane cables in IC dome general area near E-W axis
- Case-5: Snapping of one out of 18 crane cables near SG opening area

Proper arrangement, in the form of turnbuckle installed at each crane cable, is made to ensure that each crane cable is stressed as per the design requirement. However, to account for any unsolicited misfit, parametric analysis has been carried out such that the cables are unequally stressed due to misfit of length. This analysis has been covered under Case-2 mentioned above. The deformed shape of the IC dome liner for Case-2 and Case-5 are shown in Figure 5 and Figure 6, respectively. Load carried by each of the 18 crane cables have been measured through load cells installed for each of the crane cable. Load cells measurements have been used to adjust the stresses in the cable by use of turnbuckle such that the stresses are as per the design requirements.

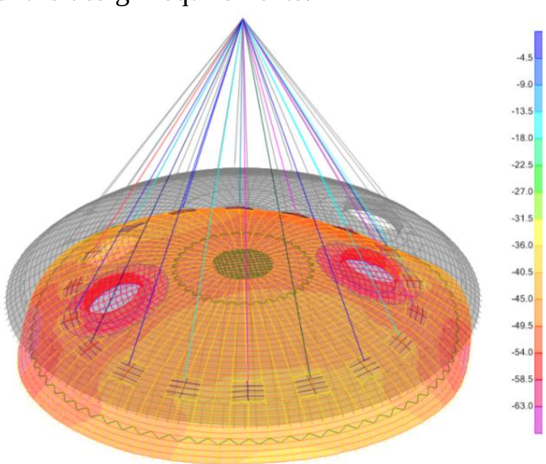


Figure 5. Deformed shape of IC dome liner Case-2 (Scale factor for deformation 1:100)

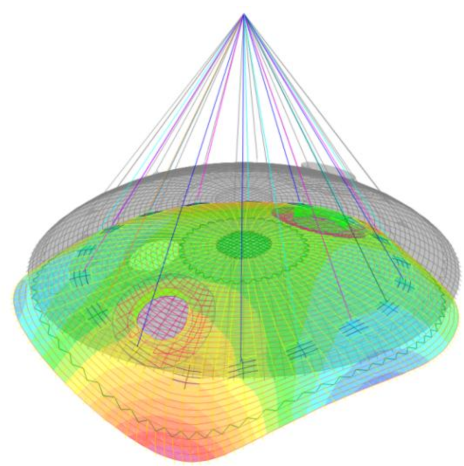


Figure 6. Deformed shape of IC dome liner Case-5 (Scale factor for deformation 1:100)

The analysis of IC dome liner during lifting and installation has been carried out using 3D FE models developed in FE software SAP2000. The global displacements and forces/moments in the liner plate and its backing members are extracted from the FE analyses for all the five cases mentioned above and are post-processed to evaluate the stress level in liner plate, backing members and crane cables. The stresses are higher near lifting point and gradually reduce with distance away from it. All circumferential and meridional members above lifting plane are in compression. All circumferential members below the lifting plane are in compression and meridional members are in tension except few circumferential rings around loading plane. Additionally, the entire single unit has also been checked for resonance effect due to wind-induced vibration and it ensured that the structural frequency under lifted condition is far away from the frequency of the fluctuating component of the measured wind speed.

ANALYSIS AND DESIGN METHODOLOGY AFTER ERECTION PHASE

The IC dome liner is also checked for its adequacy to resist wind load during liner erection and installation and temperature effect due to solar radiation once the IC dome liner has been installed at its intended location. The temperature load due to solar radiation has been calculated using the empirical ASHRAE (2013) formulations which have been validated using actual temperature measurement using a laser interferometer.

Loading conditions

As per the erection sequence, the entire IC dome liner is placed at 144 seating locations provided on the ring beam. After alignment and welding with the 144 ring beam bearing plates, the IC dome liner is connected to the SG trestle at 60 locations (30 each for the North and South side). The IC dome liner assembly will be subjected to the temperature load due to solar radiation and wind loading under both of these boundary conditions as mentioned below. As such, analysis for temperature loading due to solar radiation and wind loading and subsequent design adequacy of IC dome liner has been performed considering both the two boundary conditions:

- **Condition-I:** Dome assembly seated at 144 locations on the ring beam and locked.
- **Condition-II:** Dome assembly seated and connected at 144 locations on ring beam and 60 locations of SG supporting trestle and locked.

Analyses for temperature load due to solar radiation have been performed considering the following conditions: **Case A:** Summer **and Case B:** Winter

Similarly, analyses for wind load have been performed considering the following wind pressures: **Case C:** Suction pressure and **Case D:** Lateral thrust along the horizontal directions

Once the dome liner has been installed at its seating location and before concreting the first pour of dome, design adequacy of already cast ring beam concrete and IC dome liner have been checked for the following loading conditions:

a) Shear check of ring beam concrete due to thermal expansion of IC dome liner due to solar radiation that will induce shear on the ring beam concrete due to the lateral thrust.
b) Shear check of ring beam concrete due to lateral thrust of IC dome liner due to wind loading for both the N-S and E-W directions.
c) Design adequacy of the ring beam concrete for shear friction, at construction joint, has been carried out for the maximum thrust induced by dome liner due to concreting of Pour-1 of IC dome.
d) Design adequacy of IC dome liner for thermal loading due to solar radiation.
e) Design adequacy of IC dome liner under wind loading condition.

During the process of placement of the seating plate of the IC dome liner on the bearing plate of the ring beam, frictional resistance between the two seating plates may not allow for elastic rebound of the IC dome liner at these 144 seating locations. The frictional resistance developed, will induce locked-in response in the dome liner system. The same has been evaluated separately and is later added to the induced response of IC dome liner due to temperature and wind loadings. FE analyses have been performed for all above loading and boundary conditions and from the design adequacy check, it is concluded that the IC dome liner will perform satisfactorily under all the applicable loading conditions.

ANALYSIS AND DESIGN METHODOLOGY DURING CONSTRUCTION PHASE

Pour Sequence for IC Dome

The pour sequence was the most important parameter for finalizing the optimum configuration of the liner-backing member system such that the entire assembly acts as self-supporting formwork during construction phase. Several iterative trial analyses were carried out and the following parameters were finalized based on the optimization study: pour sequence, arrangement of backing members, SG Trestle support requirements and geometrical properties of backing member system. The pour sequence adopted for the construction of IC dome is shown in Figure 7.

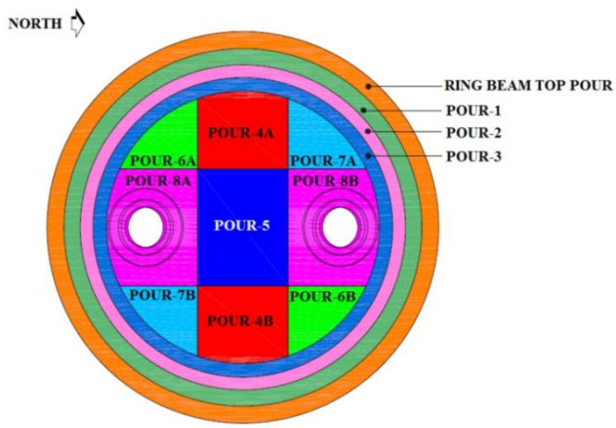


Figure 7. Pour sequence for the IC dome

The entire dome has been designed to be cast in eight pours, with the first three circular pours starting from the ring beam level towards the crown. This reduces the span of the dome as concreting progresses. The pour sequence has been designed such that a central arch is formed in the E-W direction, after the fourth and fifth pour is cast, that bears the load of subsequent pours. Pour number 8A and 8B are each of nearly 450 MTon and separate support arrangements, in the form of SG Trestles, have been provided to control deflection.

Loads and basis for load combination

The IC dome liner is designed to resist all applicable loads and their combinations during construction phase including self-weight, reinforcement, prestressing tendons and sheathing loads, live load, green concrete pressure (CIRIA, 1985), incidental and top formwork load. The self-weight includes all structural members of the IC dome liner system, CSS and its access staircase and maintenance platform, HSCMS, along with EPs of CSS and HSCMS. As the pour progresses, the concrete that has already been poured will achieve stiffness and strength value depending upon its age. Solid elements, representing the already concreted pour, are used to simulate the effect of the stiffness on the response analysis of the liner-backing member system. These are simulated using eight FE models, each representing the state of ICS after each pour. These solid elements in the FE model are assigned geometric properties as per the dome thickness and material properties as per the age of casting. 7-day gap between each pour has been assumed in the analysis for assigning material properties.

The basis of load combination for the sequential analysis, corresponding to all the eight FE models, is based on scheme wherein the locked-in-responses in the liner-backing member system due to previously cast pours are carried forward and added to the response analysis of the new FE model. For each stage, various loads are classified into those imposing locked-in response and those that will be relieved after the completion of a particular pour. As the dome concreting progresses, locked-in responses from previous pours are carried forward and added to response from the new pour. These locked-in-responses are any response parameter viz., the liner stress, frame element forces, displacements, etc.

FE model details and analysis methodology

The IC dome liner has been analyzed using a combination of classical method and mathematical approach using FEM. Eight detailed 3-D finite element model has been developed to analyze the exact behaviour when used as a self-supporting formwork during construction stage. The 3-D FE model that serves as the base model for the sequential analysis is shown in Figure 8. The FE model developed for Pour-5, Pour-6 and Pour-7 are shown in Figure 9, Figure 10 and Figure 11, respectively (only the part above ring beam shown). Similar models have been developed for other pours, each depicting the physical state of the IC structure after each pour.

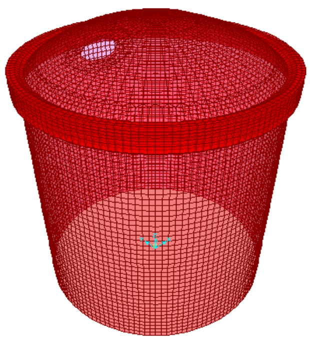


Figure 8. 3D FE Model for IC post Ring Beam Construction

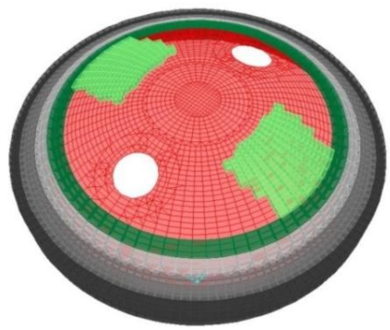


Figure 9. FE Model for Analyzing IC structure during Pour-5 concreting

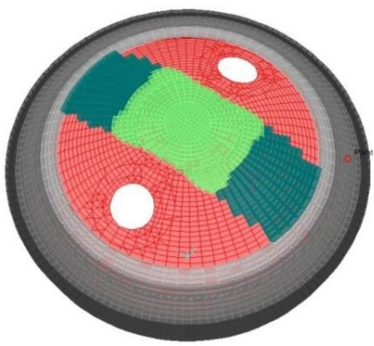


Figure 10. FE Model for Analyzing IC structure during Pour-6 concreting

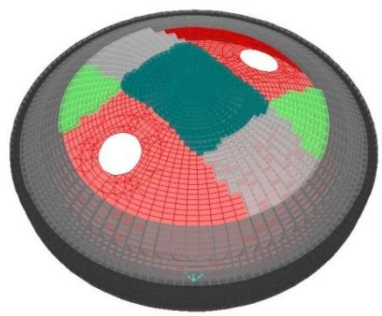


Figure 11. FE Model for Analyzing IC structure during Pour-7 concreting

In all the multiple models that have been developed for the sequential analysis, the finite elements representing the cylindrical wall, ring beam, dome liner plate and its supporting frameworks have been kept as same. The change is only in the progressive addition of solid elements depending upon the pour sequence and material properties for these elements depending upon the age of casting. The IC is considered fixed at the raft wall junction. The SG opening supporting framework is supported on the SG enclosure wall and is considered fixed at that elevation.

Analysis results and design of liner-backing member system

The backing members of the IC dome liner get embedded in the concrete in a sequential manner depending upon the pour sequence adopted for the dome construction. These backing members and liner plates are checked for its design adequacy in bending, compression and tension and the stresses are limited to their allowable values. The peak vertical displacement is -20.39 mm, peak N-S direction horizontal displacement is -3.90 mm and the peak E-W direction horizontal displacement is -7.43 mm. The stresses due to combined action of biaxial bending and axial forces in the backing members are extracted from each of the analyses and are post-processed for response after each pour. The maximum stresses in the circumferential and meridional members are within two-third of the yield stress. The stress in liner has been checked as per classical formulation for a rectangular plate fixed at all ends subjected to normal pressure given by Young (1989). The stress in the liner panels are within the permissible limit of two-third yield stress.

Anchor design

The normal pressure on a pour area being concreted will induce a tearing effect at the top flange plate-concrete interface of the already poured concrete. This splitting will induce compression in the bottom part and tension on top part of the cross-sectional area. Anchors have been provided along the thickness direction of the IC dome that is designed to provide resistance against tearing/fracture at the interface between adjacent concrete pours. These anchors are checked for development length in compression below the splitting plane and tension above the splitting plane as shown in Figure 12.

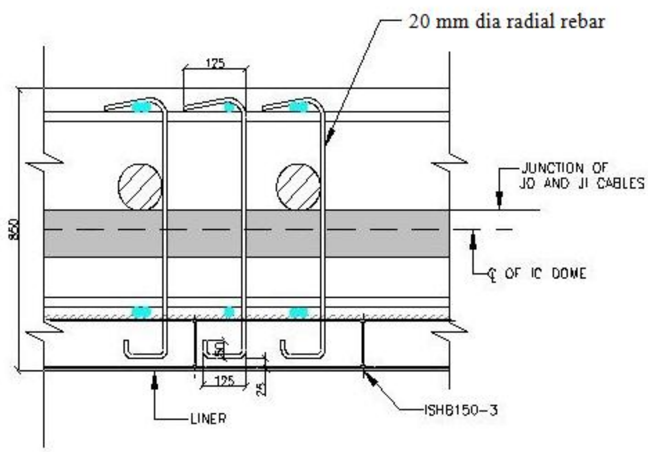


Figure 12. Arrangement of radial reinforcement at a typical liner backing member-concrete interface

Stresses in the solid elements

The tensile stress in the IC dome concrete during the process of its construction has been evaluated after each pour. Concrete has been modelled using eight noded solid elements with incompatible bending mode formulation that are able to capture the bending behaviour even with single solid element across the thickness of the IC dome. The element formulation has been validated and the maximum tensile stresses in cast concrete for all the groups due to sequential pouring of concrete of IC dome is found to be 1.34 MPa which is less than the modulus of rupture of concrete.

ANALYSIS AND DESIGN METHODOLOGY DURING SERVICE LIFE PHASE OF IC

Analysis and design of IC liner has been carried out for load combinations specified in ASME Section III Division 2 (2015). The normal and shear stresses and strains at the inner face of concrete of IC structure are calculated from the stress resultants for each element and for each load combination using Hookean formulation. As liner is integrated with inner face of IC structure, the strains on the liner is same as that of inner face of IC structure at the location where it is connected to concrete through its backing members. Strain compatibility is considered at the connection points between liner and concrete. The strain in the liner plate at the junction of the backing member is worked out by combining the strains obtained from the IC analysis. Additional strains on account of shrinkage and temperature effect are taken into account. The principal strains and maximum shear strain of concrete on inner face of IC structure are calculated and limited as per requirements. The design of liner is checked for buckling within a panel under all service load combinations.

CONCLUSIONS

- The IC dome liner has been designed as a self-supporting formwork during the construction process, capable of resisting all construction and environmental loads and the system has been engineered to be installed as a single unit with the help of heavy-duty crawler crane.
- The presence of the two large openings in the IC dome has made the dome liner assembly a very unique in the world in view of its complicated geometry around these openings.
- Implementation of state-of-art modularization technique in Nuclear Power Plant construction has been demonstrated. This has not only eliminated the requirements of the IC dome shuttering assembly conventionally used for dome construction, but also led to saving of nearly 180 MTon of structural steel and has led to nearly three months saving in construction time, better quality and optimum use of site infrastructure.
- With this installation, parallel work fronts are opened up, which has significantly accelerated the construction and erection activities of the project

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