A Linear Finite Element Three-Dimensional Analysis of A Prestressed Concrete Containment Dome With Large Openings

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Abstract- *The containment design of Indian PHWR (Pressurized Heavy water Nuclear Reactor) based Nuclear Power Plant has been developed using a complete double containment philosophy. The principal design criteria for containment arise out of Design Basis Accidents (DBA) such as Loss of Coolant Accident (LOCA) and Main Steam Line Break (MSLB). The prestressed concrete inner containment dome has got four major circular (in plan) openings; these openings are called steam generator (SG) openings. PHWR dome is considered in this study and it is composed of a hemispherical dome supported on ring beam. To simplify the analysis, the structural geometry is assumed to be axisymmetric. At the dome, the prestressing tendons are placed in the circumferential direction and the directions parallel to x and y-coordinates. In the numerical simulation, eight-node shell elements (six degrees of freedom per node) are used to model the parts of the dome and ring beam.*

Keywords- Nuclear Double Containment, Prestressed concrete, Dome, Design, SAP 2000

I. INTRODUCTION

Nuclear Reactor Technology has found potential in this era where innovation and development are keys to build a brighter future. The massive abundance of energy released through the process of fission, as well as fusion, are being harnessed and used at constantly increasing efficiencies. The first artificial nuclear reactor, called the Chicago Pile-1, was constructed at the University of Chicago, by a team led by Enrico Fermi, in late 1942. This was the seed that led to the growth and understanding of nuclear energy technology all over the world, utilizing newer and better ways to increase the efficiency and safety of the Nuclear Reactors as a world. The total installed capacity for electricity generation in our Indian country has increased from 16,271 MW as on 31.03.1971 to 206,526 MW as on 31.03.2012. (Energy Statistics, 2013). Nuclear power is the fourth-largest source of electricity in India. As of 2010, India has 20 nuclear reactors in operation, in six nuclear power plants, generating 4,780 MW while seven other reactors are under construction and are expected to generate an additional 5,300 MW. A nuclear reactor is modeled and analyzed using SAP 2000 (Computers and Structures 2007)

II.PRESSURIZED HEAVY WATER NUCLEAR REACTOR (PHWR)

By moving to greater levels of enrichment of U235, it is possible to tolerate a greater level of neutron absorption in the core (that is, absorption by non-fissile, non-fertile materials) and thus use ordinary water as both a moderator and a coolant. The two commercial reactor types based on this principle are both American designs, but are widely used in over 20 countries.

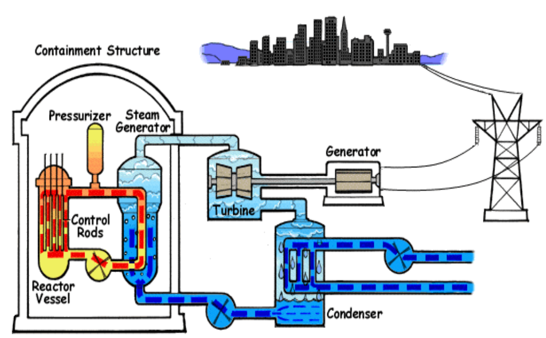

Fig. 1: Pressurized Heavy Water Reactor (PHWR)

2.1 The Containment Vessel

The containment vessel is a structure of double containment reactor building. The containment design of Indian PHWR based NPP has been developed using a complete double containment philosophy. The principal design criteria for containment arise out of Design Basis Accidents (DBA) such as Loss of Coolant Accident (LOCA) and Main Steam Line Break (MSLB).

The structural arrangement of a reactor building of a typical Indian PHWR consists of two containments. The containments are,

1. Outer Containment
2. Inner Containment

2.1.1 Outer Containment

The outer containment (OC) structure is made of reinforced concrete (RC). The outer Containment structure has vertical cylindrical wall and segmented spherical dome as cap and cylindrical wall rest on a common reinforced concrete base raft. The RC outer containment (OC) dome has got four major circular (in plan) openings, which are called steam generator (SG) openings. The OC is designed against aircraft, missile impact, seismic, wind loads and a small overpressure or under pressure due to accident conditions.

2.1.2Inner Containment

The inner containment (IC) structure is made of prestressed concrete (PSC). The inner containment is designed to withstand pressure and temperature conditions during accidents and seismic effects, with specific leakage provisions. The main components of the inner containment are,

1. PSC cylindrical wall,
2. PSC spherical dome and
3. PSC ring beam.

The Inner Containment structure has vertical cylindrical wall and segmented spherical dome as cap and cylindrical wall rest on a common reinforced concrete base raft. The prestressed concrete inner containment dome has got four major circular (in plan) openings; these openings are called steam generator (SG) openings. The prestressed concrete ring beam, at the springing level of the dome (i.e. at the junction of dome and wall).

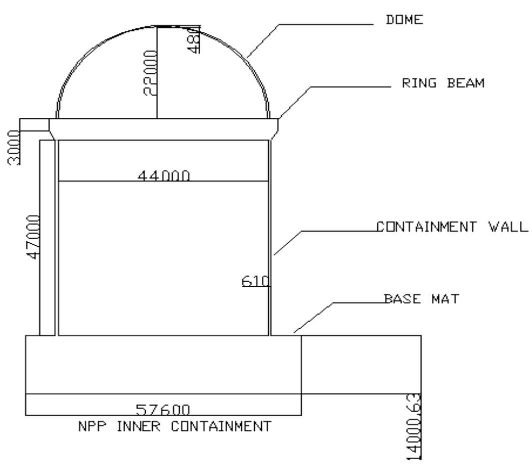

Fig. 2: Typical section of Inner Containment Structure

III. ANALYSIS SOFTWARE

The development of software for applications in engineering was foreseeable as soon as the complex computer system had come into being early last century. Fast and accurate analysis and design, provides a large reduction in cost and time. The Analysis software involved in this thesis includes SAP2000.

IV. GEOMETRY

A prestressed concrete nuclear containment dome is considered for this study, and is shown in figure 4.1. It is a prestressed concrete structure which is axisymmetric form. The prestressed anchorages are located in orthogonal direction. It rests on a flat slab. The structure is located in the seismic zone III, as per IS 1893-2002. The typical cross section of containment vessel is shown in Fig 4.1. This model has been prepared as per the following design details.

- Diameter of dome = 44.00 m
- Height of dome = 22.00 m
- Thickness of dome wall = 0.48 m
- Height of ring beam = 5.00 m
- Radius of ring beam = 22.96 m
- Thickness of ring beam = 2.00 m
- Diameter of SG openings = 4.10 m
- Thickness of dome near
- SG opening = 1.22 m

The Indian PHWR program has been emphasizing on the double containment philosophy, the structural configuration of the containment of Indian NPP double wall concept ensures the desired safety levels for effective accident mitigation, by branching the main operation requirements in the following manner.

1. The IC is designed to withstand pressure and temperature conditions during accidents and seismic effects, with specific leakage provisions.
2. The OC is designed against aircraft/missile impact, seismic/wind loads and a small overpressure or under pressure due to accident conditions.
3. The annular space between the two walls is used to collect and filter residual radioactive leakage (especially for highly hypothetical situations not yet covered by design conditions).

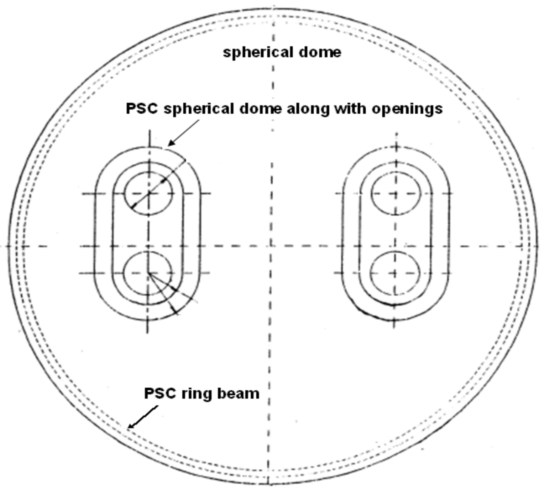

Fig. 3: Plan view of Inner Containment Dome

4.1FINITE ELEMENTS

4.1.1 3D Thick Shell Element

3-D thick Shell Element includes membrane, bending and transverse shear deformation effect (i.e. thick shell element), having six degrees of freedom per node (UX, UY, UZ, ROTX, ROTY, ROTZ). The element can be shaped as a four, eight or twelve noded quadrilateral, or a three or six noded triangle depending on the order of the element. The element configuration, node location and face numbering convention for top and bottom surfaces are as shown in Figure 4.1.

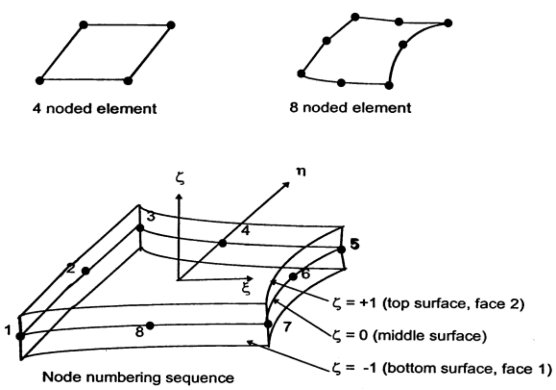

Fig.4.1 3-D shell Element configuration

The element can be shaped as a four, eight or twelve noded quadrilateral, or a three or six noded triangle depending on the order of the element. The element configuration, node location and face numbering convention for top and bottom surfaces are as shown in Fig. 4. The element may be oriented anywhere in the space, but the connectivity must be given in the order shown in Fig. 4, in which node numbering sequence starts at a corner node and proceeds along the perimeter of the element. For pressure loading, the pressure is integrated over the area of the loaded face. Stresses can be determined in both local and global systems, at the centroidal and or Gauss points, for the top, middle and bottom surfaces. B) 3-D Beam Element, this is a two node prismatic element including stretching, bending and torsion effects. It has six degrees of freedom per node (UX, UY, UZ, ROTX, ROTY, ROTZ). The local x-axis of the element is along the centroidal axis.

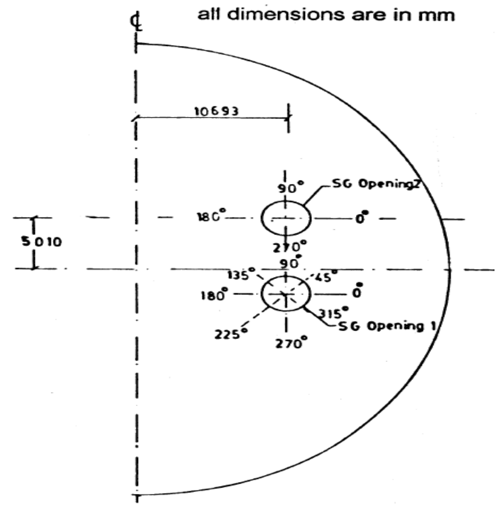

Fig. 4.2: Plan showing Angular locations at the Edge of SG Openings

4.2 Material Properties

The present study beam model is fully based on layer concept. Material number for each material is numbered as

1. Steel linear
2. Rebar
3. Pre stressing tendon
4. Concrete

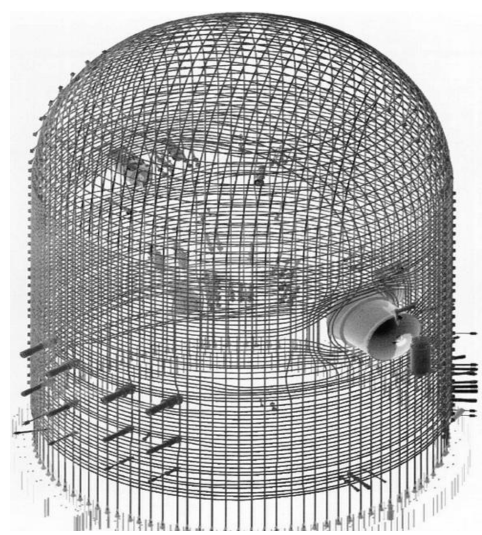

Fig.4.3. Configuration of tendons in meridian and hoop directions

4.3 LOADS

The following loads are predominantly acting during accidental condition. Therefore, these four load cases are used in this analysis

- Dead load
- Prestress
- pressure
- Temperature

4.4 LOAD COMBINATIONS

Material properties obtained from the literature by NOH et al., Analysis of Prestressed Concrete Containment Vessel (PCCV) under Severe Accident Loading.

Table 1 Load combination for pressure with temperature cases

load case	Load combination
Case 1	Dead load + prestress
Case 2	Dead load + prestress + pressure + temperature

V. MATERIAL NON LINEAR ANALYSIS

5.1 Non linear finite element analysis

Finite Element non-linear analyses are carried out by using the SAP2000N finite element program to predict the ultimate pressure capacity and the failure mode of the PHWR prestressed concrete containment dome nuclear power plant.

5.1.1 Geometric non linear analysis

a) Large deflection and rotation
b) Stress stiffening

5.1.2 Material non linear analysis

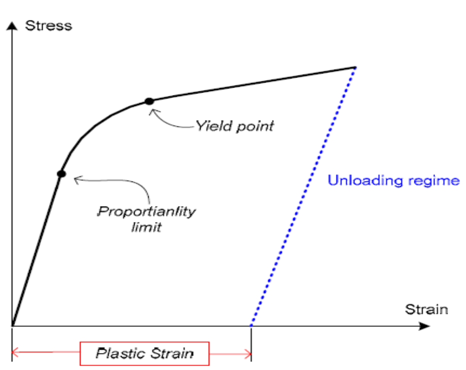

Fig.5. Typical Elasto-Plastic Behaviour

5.2 Analysis result

5.2.1 Deformed Shape

When a prestressed concrete containment dome is subjected to various types of loadings such as dead, prestress, pressure and temperature, stresses are induced in the structure which leads to corresponding strains and deformations in the structure. SAP2000 can show the vertical(y-component) deformation of the structure for an applied load.

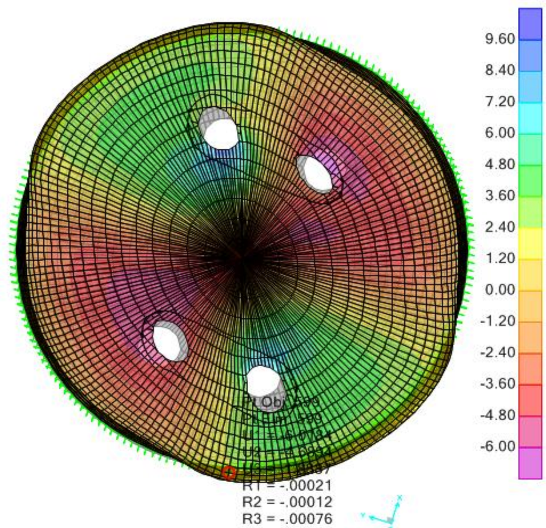

Fig.5.2. Deformation due to dead + prestress + pressure + temperature

VI. CONCLUSION

1. The deformation of the IC dome is mainly due to vertical displacement components.
2. The response of the dome is well within elastic limits.
3. The dome is predominantly under compression excepting for some local regions.
4. The interface zone adjacent to the cylindrical plates of the SG openings is predominantly under compression excepting for the indicated possible transverse slip over symmetrically disposed regions.
5. Maximum vertical displacement of the dome under DL+prestress is: 45% higher than that under DL+prestress+pressure.
6. The magnitude of maximum compressive principal stress is within the linear elastic limits of the material, except for some high values in the case of DL+prestress occurring at cable anchorage locations.
7. Significant tensile principal stress has been observed to occur in some specific locations at the edges of SG openings.
8. Variation of stresses at top and bottom layers of all the load cases of the ring beam.

9. Both vertical displacement and stress contours have been found to be almost identical for two types of mesh. There are differences in stress values only at the locations of hatch connection near the edges of SG openings in the case of Dead Load+prestress+pressure+temperature. This comparison is well indicative of the trend of linear behavior of the PSC IC dome within the framework of assumptions made.
10. The analysis also shows significantly more shear stress in the dome with openings. These shear stresses are largest along the edges of the opening; however the magnitude of the shear stresses is very low and will not cause delaminating (even locally).

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