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SAFETY ASSESSMENT OF APPURTENANCES OF CONTAINMENT STRUCTURE FOR DESIGN EXTENSION CONDITION

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ABSTRACT

The containment pressure boundary comprises of primarily the concrete shell. It also has several mechanical and electrical penetrations which have the potential to become a source of leak path during an accident scenario. In addition to evaluating the integrity of structure, i.e., concrete shell, integrity of penetrations needs to be established under pressure loading from the accident condition. Generally, assessment of ultimate capacity of concrete containment is carried out with assumption that shell failure will precede failure of appurtenances. However, to have a comprehensive study of ultimate capacity of the containment, it is worthwhile to investigate the validity of this assumption. Objective of this study is to assess the integrity of appurtenances at the ultimate load of concrete containment structure. In the case study, the containment of VVER 1000 reactor at Kudankulam, India (KKNPP) was adopted. This structure has three large appurtenances in the form of Airlocks. Global analysis indicated that a location near main air lock (MAL) is most critical with respect to structural failure and hence, the MAL was selected as the ‘appurtenance’ for the present study. The MAL consists of (a) lock body including doors, (b) embedded part in the containment wall and (c) rubberised seal around the door leaf in contact with the lock body. Airlock barrel is fixed to inner containment wall through the embedded part (EP). Safety assessment of MAL considering potential failure modes using numerical simulation established that integrity of this appurtenance is ensured at ultimate capacity (internal pressure) corresponding to concrete shell structure. Results of this assessment provide insight to the structural behaviour of the different components of MAL.

INTRODUCTION

Atomic Energy Regulatory Board (AERB) safety code on design (AERB/NPP-PHWR/SC/D, 2009) requires the containment to be designed taking into account all identified design basis accident scenarios as the containment structure is the last engineered barrier against release of radioactivity into public domain. One of the recommendations stemming from this requirement is evaluation of ultimate load capacity (ULC) of the containment structure considering pressure load. Elaborating the above requirement, AERB safety guide (AERB/NPP PHWR/SG/D-21, 2007) requires that the structural integrity of the containment structure including major appurtenances against collapse should be demonstrated by calculating ULC considering both pressure and temperature loads. This is in line with USNRC RG1.216 (2010) for defining the failure in terms of strain in containment material.

Kudankulam NPP (KKNPP) which is located at Kudankulam village in Tirunelveli district of Tamil Nadu, India, has adopted a double containment philosophy with a steel lined pre-stressed concrete inner containment structure and a reinforced concrete outer containment structure, both resting over a cellular raft (foundation system consisting of thick base slab connected to a mat foundation through a number of reinforced concrete cross walls). ULC of KKNPP was estimated in earlier studies by Chakraborty et al.

(2015), where assessment of ULC was carried out with an assumption that concrete-shell failure would precede failure of appurtenances. The appurtenances were not modelled explicitly and their failure modes were also not studied to optimize the computational efforts.

The objective of the present study is to assess the structural performance of appurtenances of containment structure for internal pressure load and study the breach of containment boundary leading to leakage through the pressure boundaries on items other than containment structure. The behaviour of large containment appurtenances are evaluated with respect to structural responses as well as separation of interfaces and strength of solid rubber seal which are potential leak paths under the loading case of internal overpressure in design extension condition.

MAJOR APPURTENANCES OF KKNPP-1&2: MAL

KKNPP-1&2 primary containment comprises of a pre-stressed concrete cylindrical structure capped with a hemi-spherical dome. It has a carbon steel liner on the inner surface as a hermitic boundary. It has three leak tight locks, which are the Transport Air Lock (TAL), the Main Air Lock (MAL) and the Emergency Air Lock (EAL) placed on circular openings in the cylindrical wall. TAL opening is the largest; whereas MAL and EAL openings are of the same size, see Figure 1.

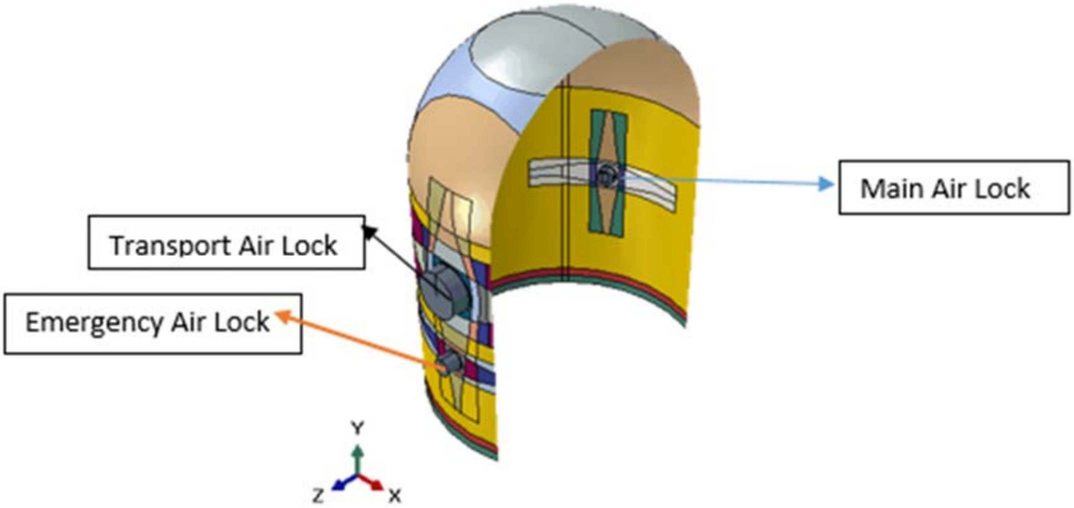


Figure 1. Containment structure with appurtenances (Air Locks)

These Air Locks are attached to the containment building through openings and provide controlled access to the primary containment (PC). Typically, Air Locks consist of a barrel, Embedded Part (EP) on the concrete section and doors with seals, which ensure leak tightness during operation as well as accident conditions. The cylindrical portion of the barrel is connected to the PC concrete section through the EP, which is the interface between the barrel and concrete section. EP details of MAL are shown in Figure 2. MAL is fixed at inner face of the PC. No constraints are present in the remaining portion of barrel.

Chakraborty et al. (2015) in their study of ULBC of PC, observed that the maximum radial displacement was near to the MAL opening. Accordingly, the MAL was chosen for the structural responses of its various components for design extension condition. Three types of structural failures are postulated for the MAL. These are (1) failure of barrel, (2) failure of EP-concrete section interface and (3) failure of the seals placed on the door leaf-barrel interface. All these probable failure modes are investigated separately and responses are reported.

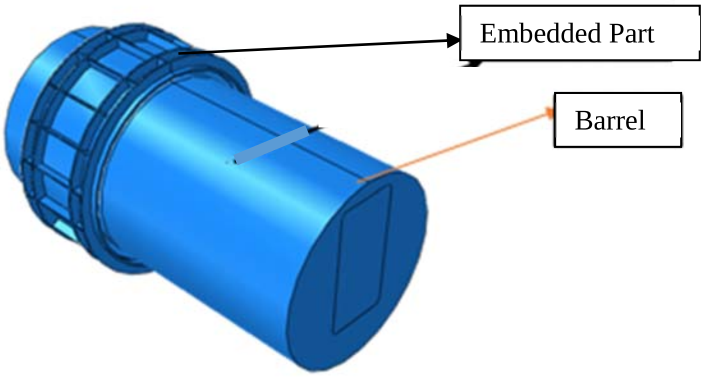


Figure 2. Typical arrangement of MAL

ASSESSMENT OF MAL BARREL

The cylindrical barrel is the main part of the MAL, which forms the body of the structure and the passage way. The strength assessment of the barrel is carried out for gravity load and internal pressure load. Two load cases have been studied, (1) barrel cylinder is subjected to internal pressure and (2) barrel is subjected to internal as well as external pressure at the portion at which it is a part of the hermetic boundary. It is assumed that the door on the inner face of the PC is not fully leak-tight and the barrel is subjected to the same pressure load as the PC. It is also assumed that the doors are structurally connected to the end plate (with a certain offset) whereas in actual case, this assumption may not be fully valid, as door is a separate component and there is a continuous seal in between the door and the end plate of the barrel.

Two different types of steels are used in the MAL; cylindrical portion and end plate including door. The density, Young’s Modulus, Poisson’s Ratio and ultimate uniaxial strain are considered as 7850 kg/m^3, 200E+9 N/mm^2, 0.3 and 10% respectively for both the steel materials. Yield strength and ultimate strength for the barrel are considered as 206 MPa and 392 MPa respectively, whereas 216 MPa and 363 MPa are considered for the door and the end plate. The barrel is connected to the EP using packing plates at the inner and outer faces of the containment wall.

Numerical simulation is carried out using nonlinear finite element analysis technique in ABAQUS/Standard (2014) using shell element with reduced integration technique. Two circular strips of packing are considered as fixed boundary condition. The system is analysed for gravity load and subsequently internal pressure. In another analysis, external pressure is applied on the barrel portion, inside the hermetic boundary.

ASSESSMENT OF EP-CONCRETE INTERFACE ZONE

A major objective of this study is to assess the EP-concrete interaction and EP stress/strain variation during pressure rise inside the PC. The global containment model is simulated using shell elements. Therefore, the 3D model of the EP cannot be simulated effectively by modelling the barrel in the global model of containment. An axi-symmetric analytical model was developed for this purpose. The analysis was carried out considering global displacements as the boundary condition. The global displacement history is collected by modelling the lock barrel at its location in the PC in a gross manner and the load history is applied. The displacement histories (radial as well as hoop displacements) with respect to the incremental pressure rise are extracted from the global model of the containment (see Chakraborty et al., 2015) at predefined location (in this case, at 2.0m radius from the edge of the circular MAL opening). These displacements are used as the boundary condition in the axi-symmetric model. The types of interactions, which are considered for EP-concrete interface are (1) EP is integrally fixed to the containment concrete section at all points along the edge of the circular EP, including the EP flanges, i.e., no relative slip is accounted between the EP and concrete section and (2) EP is integrally fixed to the containment section through the EP flanges alone, while the rest of the EP surface provides friction resistance to the relative displacements between the containment concrete section and the EP, i.e., slips of EP surfaces are allowed except at flange positions. The axi-symmetric model is developed based on the cross sectional details of the EP and the containment structure considering symmetry about longitudinal direction of the barrel. The containment wall portion is modelled for a radius of 2.0 m, whereas the reinforcing bars and prestressing tendons are modelled as equivalent steel area at its position in the cross section (see Figure 3).

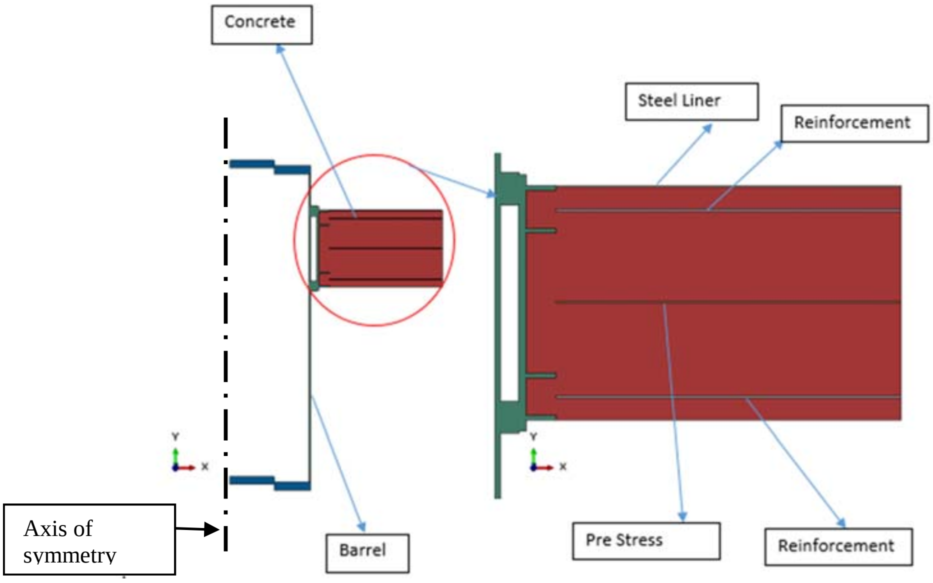


Figure 3. Axisymmetric model for assessment of EP-Concrete interface

For the containment cross section, properties of concrete, reinforcing steel and presstressing tendons are used similar to the global model (see Chakraborty et al., 2015). Material properties used for all of the steel components are reported in previous paragraphs. Displacement boundary conditions are considered at the boundary of containment wall (at a portion of 2.0m radius), which are extracted from the global model and are assigned to the concrete section in the global radial, i.e., Y direction in the axi-symmetric model. The displacements in the global hoop direction of the containment, i.e., X direction of axi-symmetric model, are given as shown in Figure. 4.

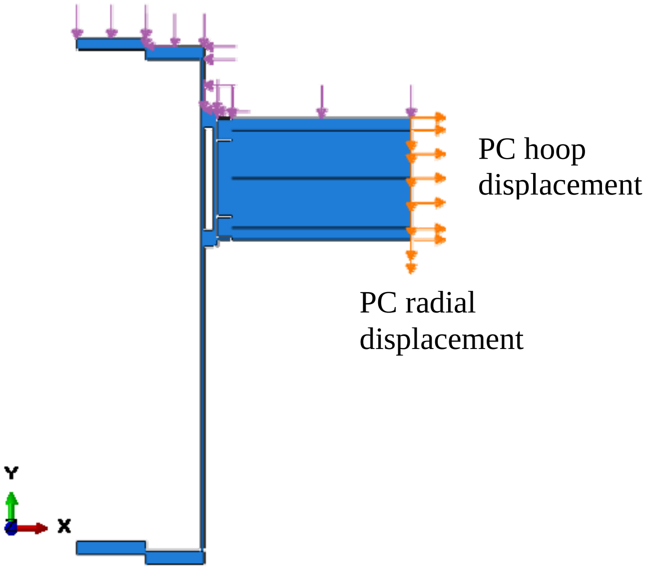
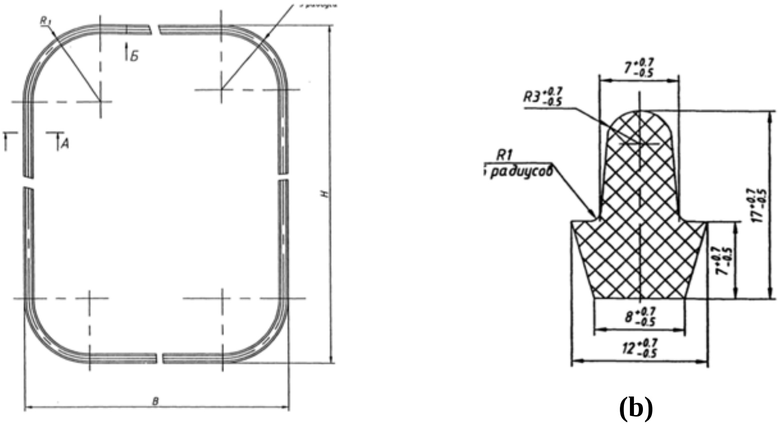


Figure 4. Boundary conditions and pressure load considered in the Axi-symmetric model

ASSESSMENT OF THE SOLID SEAL FOR THE DOOR

A seal is placed between the doors and end plates of the MAL barrel for ensuring air leak tightness. Under the containment internal pressure condition, the seal provides the barrel with required leak tightness. The profile/locii of the seal follows the geometry of the door, which is rectangular in shape with curved corners, vide Figure 5. Instead of modelling the total profile of the seal, only two portions of the seal are analysed, (1) straight portion and (2) curved portion, to optimize the computational efforts.



(b)

(a)

Figure 5. Geometric details of solid seal (a) Profile and (b) Cross-Section

Seal, door and end plates are considered as 3D solid elements. The seal is modeled using actual dimensions and scaled dimensions are used for the door and end plate. As the door is rigid and is used to transfer the applied pressure load, and the end plate is used to position the seal, this modelling approach is assumed to be sufficient. Frictionless contact condition is considered between the door and the seal as well as seal with its deformed surface (self-contact). The seal is assumed to be integrally connected with the end plate which does not allow it to slip in the grove of the plate. Assessment of seal is carried out for pressure loading only.

Various test results are required to simulate the solid seal silicone rubber material and all the test results are not shared due to proprietary nature of the items. The uniaxial strength of rubber is available and other data are adopted based on similar material to arrive at Mooney-Rivelin equation coefficients for the seal. The material properties are evaluated and the best fit for Mooney-Rivelin model is considered in ABAQUS (2014) as shown in Figure 6.

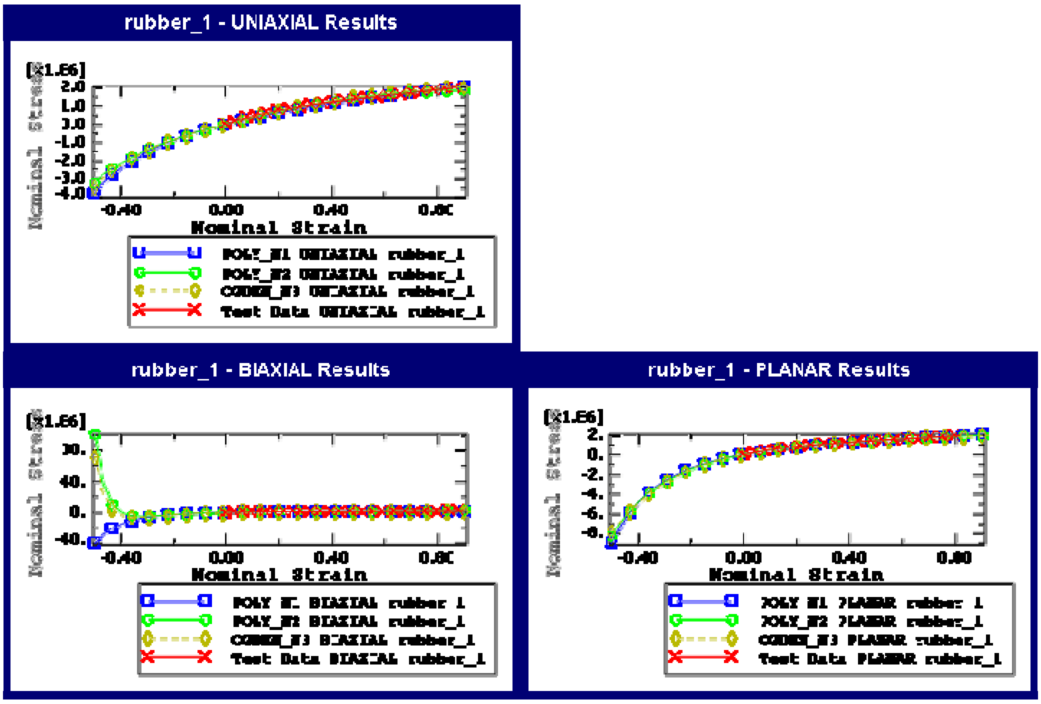
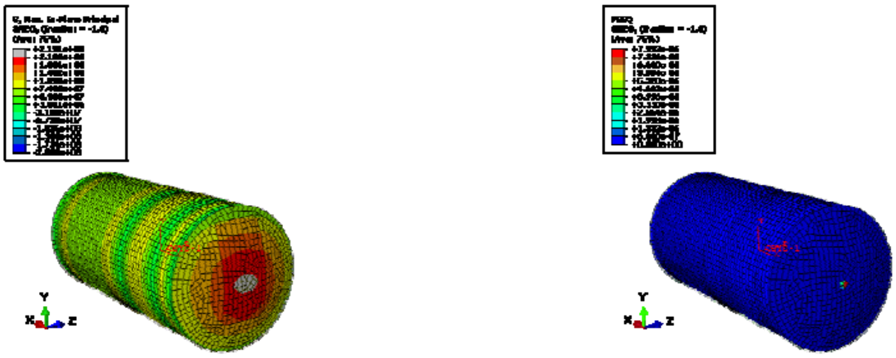


Figure 6. Material Properties of Rubber used in the analysis

ANALYSIS RESULTS

Results of assessment of barrel for internal pressure load

For the load case when the barrel is subjected to internal pressure load, the cylindrical portion as well as the end plates do not reach the failure strain till 2.0 MPa internal pressure ($5P_d$). Plastic yielding initiates at 1.66MPa, (4.15 P_d) on the outer door (assumed to be integrally connected with offset) of the barrel. Contours of the maximum principal stress and the plastic equivalent strain at 1.66 MPa internal pressure are shown in Figure 7. All these load steps are beyond containment structural failure of 3.0 P_d as reported in Chakraborty, et al. (2015).

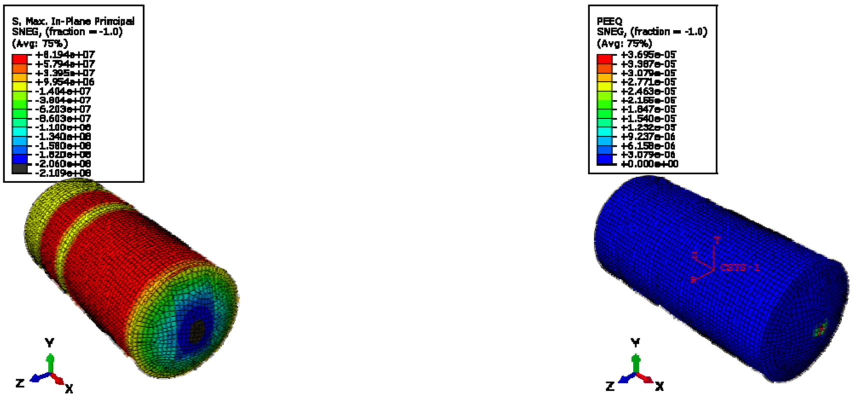


(a) (b)

Figure 7. (a) Maximum in–plane stress and (b) plastic equivalent strain (PEEQ) contour at 1.66 MPa (4.15 P_d) internal pressure; grey area in (a) and red area in (b) show yielding of material.

Results of assessment of the barrel for internal pressure as well as external pressure

When the lock barrel is subjected to pressure load on the inside as well as on the external portion exposed to the inside of the hermetic zone, the strains in the barrel and the end plates do not reach failure strain till 2.0 MPa pressure. Plastic yielding initiates at 1.66MPa, (4.15 P_d) on the outer door. Contours of maximum principal stress and the plastic equivalent strain at 1.66 MPa are shown in Figure 8. Therefore, failure of barrel is not envisaged before structural failure of primary containment.



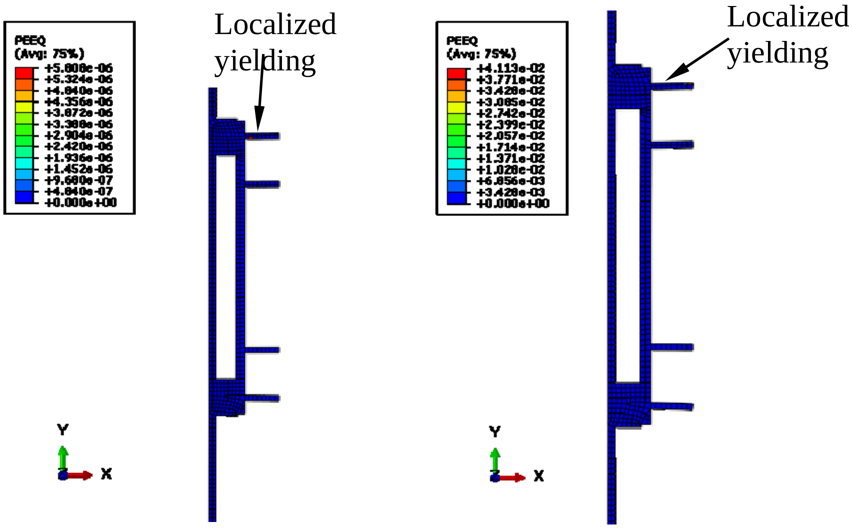
(a) **(b)**

Figure 8. (a) Maximum in –plane stress and (b) plastic equivalent strain contour at 1.66 MPa (4.15P_d) on the inside as well as on the external side (at the exposed side in the hermetic zone) ; grey area in (a) and red area in (b) show yielding of material.

Results of Axi-symmetric analysis for EP-Concrete Interface

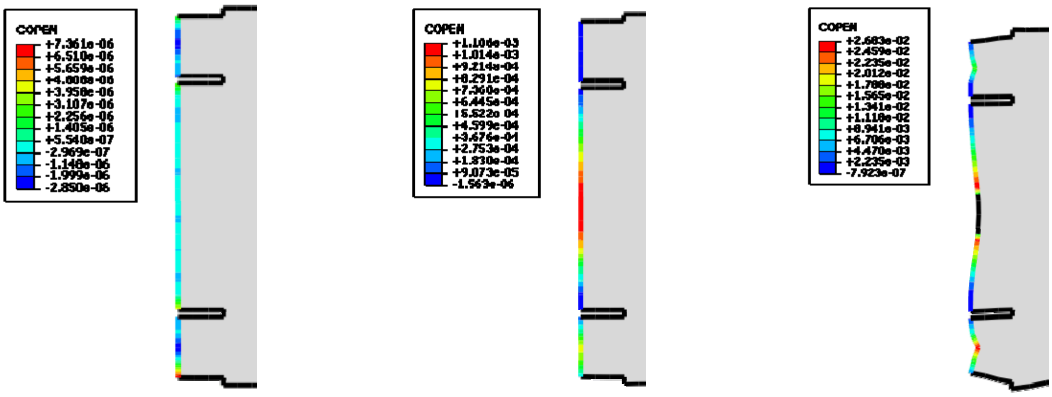
When the EP is considered to be integrally connected with concrete of containment (i.e., there is no relative slip), small localized yielding of EP is noted to be initiated at inner flange at 3.0 P_d. Similar localized yielding of EP flange is also observed at 2.0 P_d, when relative slip is allowed between the EP and concrete section, vide Figure 9. The strain in the EP does not reach ultimate strain/failure strain till 3.2 P_d in both the above mentioned cases.

From contact analysis of the axi-symmetric model, where relative slip is allowed between the EP and concrete section, an open contact condition is noted at middle part of the EP at $2.0P_d$. But through-the-wall contact opening of EP is not observed (i.e. no streaming of air). Through-the-wall contact opening is observed at $3.2P_d$, where EP is noted to be almost fully detached from the concrete section except at locations, where the flanges are present, vide Figure 10. This is beyond estimated containment failure pressure, ($3P_d$).



(a) (b)

Figure 9. Plastic equivalent strain (a) for no-slip at EP-concrete interface at 3.0 P_d and (b) for the case, where relative slip is allowed at EP-concrete interface at $2.0P_d$

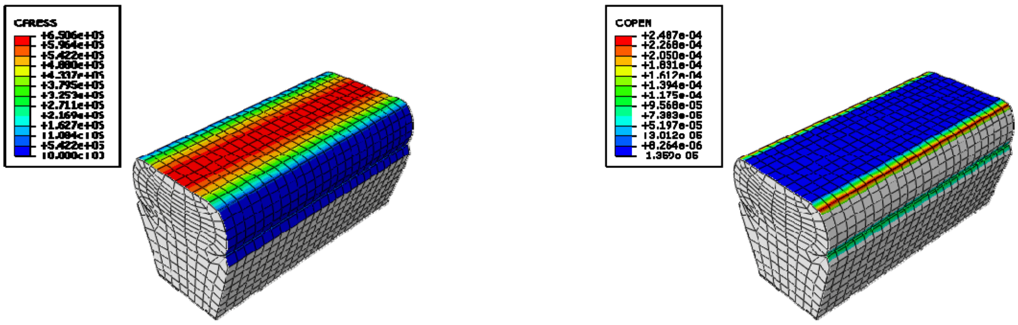


(a) (b) (c)

Figure 10. Contact Open condition at different Pressure Steps: (a) at $1.0P_d$, (b) at 2.0 P_d and (c) at 3.2 P_d (blue indicates no separation (-)ve value and red indicates maximum separation (+)ve value)

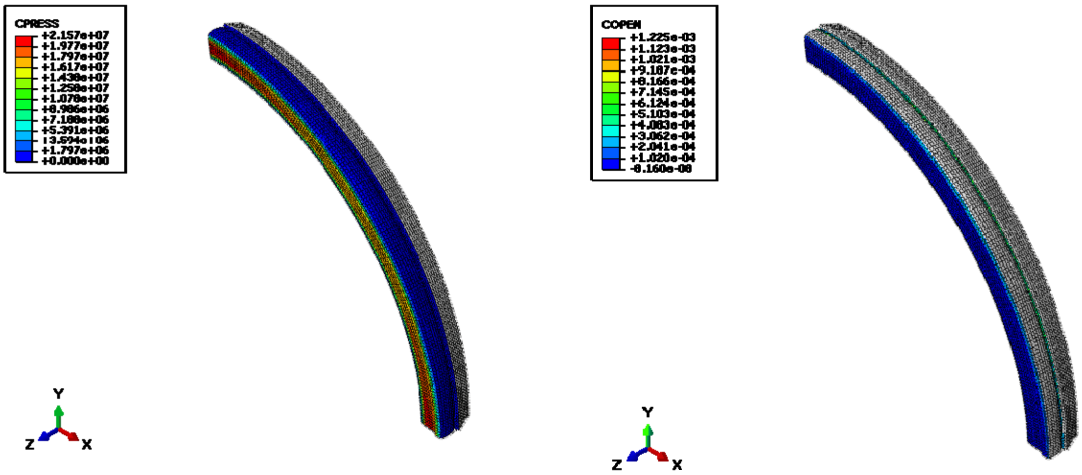
Results of Assessment of Seal

The door seal is noted to deform integrally with the door, i.e., there is no contact opening at a pressure value of 3.5 P_d between the top surface of the seal and the door for both locations; i.e., the straight and curved portions. In both load cases, the strain in the seal does not reach its failure limit till 3.5 P_d. Maximum contact pressures in both portions are also within the limit. Thus, functional (contact opening) as well as structural failure of solid seal is not expected before 3.5 P_d. Figures 11 and 12 show the contact stress and contact open condition contours for the straight portion and curved portion of seal, respectively.



(a) (b)

Figure 11. (a) Contact stress contours and (b) contact open contours for the straight portion of seal at 3.0 P_d (blue contour indicates no contact opening)



(a) (b)

Figure 12. (a) Contact stress contours and (b) contact open contours of curved portions of seal at 3.0 P_d (blue contour indicates no contact opening)

CONCLUSION

The assessment of MAL is carried out to check its functional as well as structural integrity capacities. It is observed that margins are present considering functional as well as structural integrity of MAL for the internal pressure load. It can be concluded that structural failure of the containment concrete section would precede the failure of large containment appurtenances such as the MAL. As the larger TAL is located at a thickened portion of containment wall cross section and as the structural response of EAL (global deformations) is noted to be much lower than MAL in the ULBC study (Chakraborty et al., 2015), it is concluded that these two appurtenances would not lead to a lower estimate than obtained through the present study. It is concluded that the ultimate structural load bearing capacities of KKNPP containment steel air locks are higher than the ULBC of the PC concrete structure.

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