CHAPTER-7

RESPONSE OF NUCLEAR CONTAINMENT UNDER CRASH INDUCED FIRE

7.1 GENERAL

According to the Nuclear Energy Institute (2009) guidelines, as a result of an aircraft crash over a containment structure, both external and internal fires can erupt. The fire has not been considered a design parameter for the structure of nuclear containment as of now. Therefore, the evaluation of fire resistance for nuclear safety related structures has not yet been developed.

In the present chapter, a real nuclear power plant TMIR outer containment structure has been considered for a safety check because till now the research has not been done on TMIR containment wall. The model has been simulated by ABAQUS/implicit software. Initially, the shape and size of TMIR is discussed. The deformation and stress of the wall is analysed for impact with induced fire effect under Boeing 707-320 aircraft crash. The high temperature after aircraft crash may cause scabbing of concrete at outer face of NPP containment wall but the induced fire does not affect the global behavior of containment.

7.2 THREE MILE ISLAND NPP CONTAINMENT GEOMETRY

Most of the nuclear containment structure has a cylindrical bottom and dome upper portion shape. The thermal stress analysis by coupling impact and fire did not consider in any type of analysis in available literatures. Here force-time curve for 707-320 has been considered to apply the impact load. In the current research, the fire region has been classified into three categories which are severe, moderate and low exposed region. As most of the fuel of aircraft fall down after impact of wings, the most severe zone is bottom of containment (up to 10m height from base). From 10m to 27.25m height was considered as low exposed zone and impact location was considered as medium exposed zone. The duration of fire for severe zone is 7200sec and for moderate zone is 900sec respectively, Jeon et al., 2012.

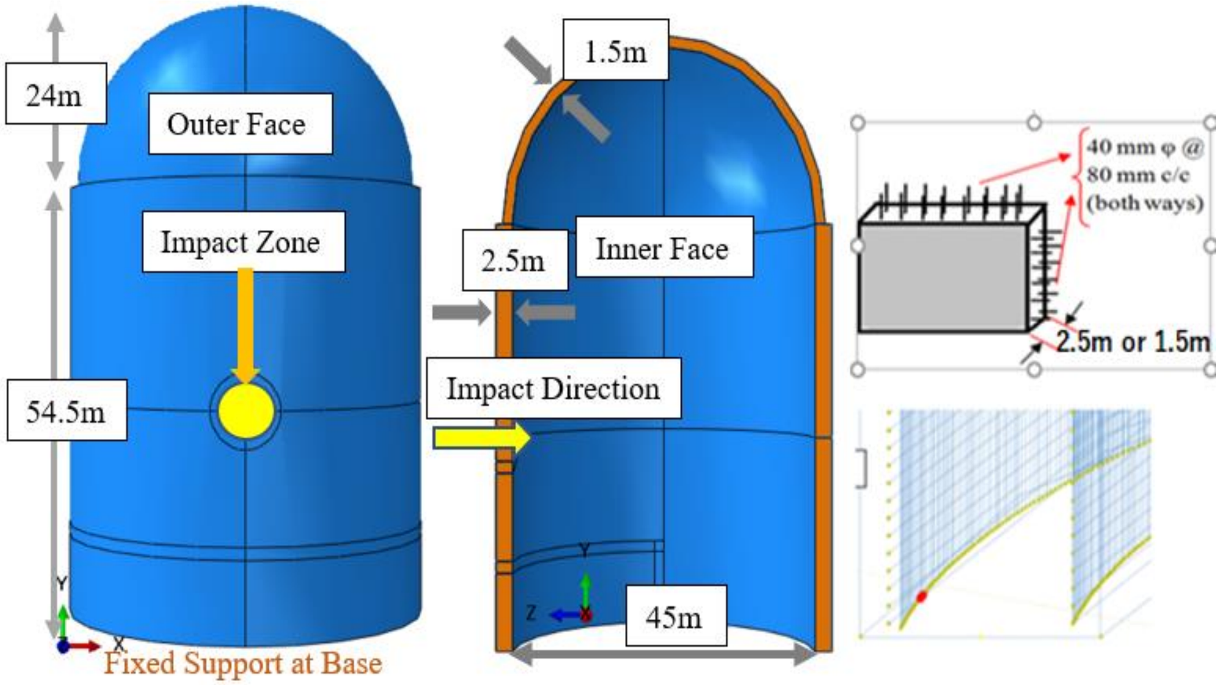


Fig. 7.1 Dimensions, reinforcement, impact location and meshing details

The Three Mile Island (TMI) NPP containment structure has been taken into consideration for the analysis. The structure was modeled and meshed using ABAQUS /

implicit. The structure dimension is 78.5m total height (54.5m cylindrical portion and 24m dome portion), 45m inner diameter as shown in Fig. 7.1. The containment thickness is not constant throughout the structure and the structure has fixed supports at the base. The cylindrical portion has 2.5m wall thickness and dome portion has 1.5 m wall thickness shown in Fig. 7.1. This NPP structure has 6 mm thick steel liner which is provided at the inner face of TMI containment wall. In this model 40 mm dia. rebar with 80mm centre to centre spacing was provided (both the faces inner and outer). The cover 100mm was provided in concrete. Reinforcement modeling and dimension of structure is shown in Fig. 7.1.

7.3 LOADING DETAILS

The behaviour of NPPs containment under the aircraft crash depends on an aircraft's speed, weight, length, fuselage area, wing span, impact location, fuel capacity, and weather conditions. Accurate determination for applying impact load due to aircraft crash is very complex. Material behaviour in impact region is totally different because of the high strain rate phenomena. Therefore, many researchers have tried to propose simplified impact load-time curves for easy application of impact load due to aircraft crash. The Boeing 707-320 airplane is considered in the current research, to strike the target at mid-height of the cylindrical part of TMI containment (27.25m from the base). The impact analysis has been conducted using Riera reaction-time methodology. Riera (1968) calculated reaction force history curve for Boeing 707-320 using deformable aircraft over a rigid target. Here the force-time history curve is used to apply the impact loading over the structure. Fig. 7.2 shows the force history curve for Boeing 707-320. Clearly, the reaction force due to impact is optimum when the aircraft's wings come into contact with objects (at 0.18sec). The time gap between the impact of plane's nose and plane's wing is kept 0.18 s. Most of the Aircraft have their fuel in the wings, Jeon et al., 2012. Boeing 707-320 aircraft has a fuel storage capability of 90.16m^3. The scattered fuel catches fire very fast. So, as to get the actual behaviour of an NPP containment structure for an aircraft crash, it is mandatory to consider the fire-induced stress with the stress due to impact. Heat transfer analysis has been performed after that time because fuel is stored in wings.

In the present study, A step-by-step analysis has been carried out to evaluate the stresses and deformations on the NPP wall due to aircraft crash with induced fire. At starting, the impact load 90 MN is applied to the NPP structure using force history curve of Boeing 707-320 aircraft and the angle of impact is considered as normal to the target. After impact, the nodal temperatures are applied to the model through heat transfer analysis using jet fuel curves due to fuel burning. Finally, the impact and heat transfer effect were combined to get thermal stress behaviour.

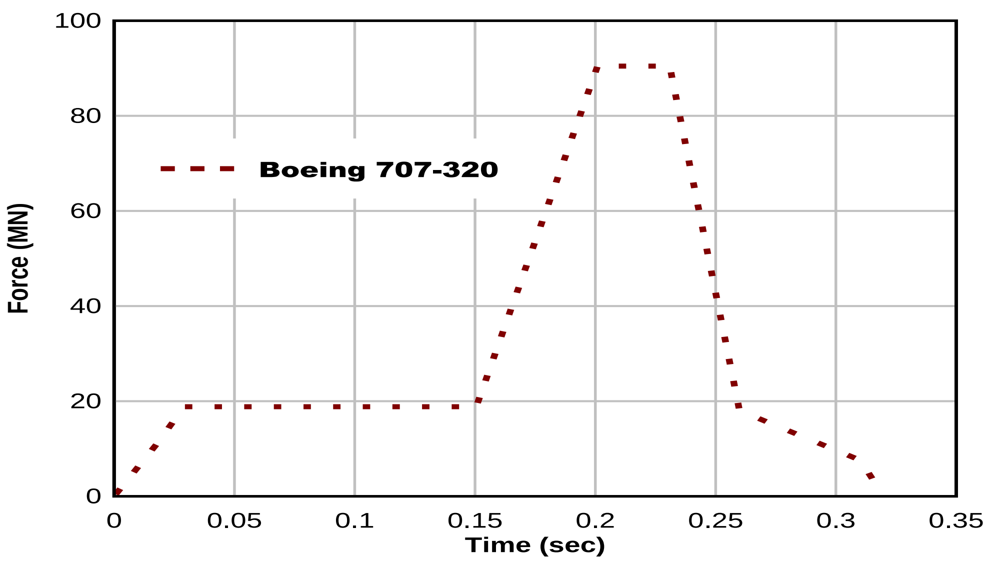
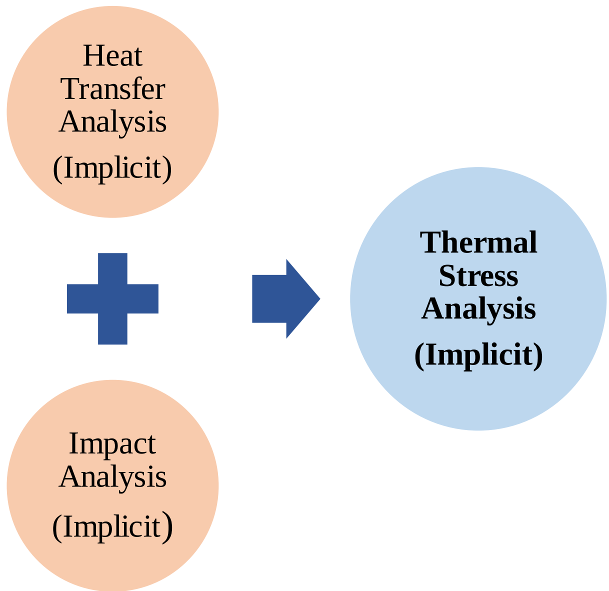


Fig. 7.2 Force-time history curve of 707-320

The obtained distorted shape through impact analysis is considered as an initial state in thermal stress analysis. Heat transfer analysis has been performed before thermal stress analysis to provide the nodal temperatures w. r. t. time in the containment model. All the analysis (impact, heat transfer, and thermal stress analysis) were performed by ABAQUS/implicit.



7.4 Results and Discussions

The results have been discussed in three sequential steps. Initially heat transfer analysis, then impact analysis and finally thermal stress analysis has been discussed.

7.4.1 Heat transfer analysis

When the aircraft's wings collision with the structure's wall, the fuel of aircraft falls at the base of containment after few seconds. The time duration and intensity of fire depends upon the fuel capacity of aircraft. Here the Boeing 707-320 aircraft has been considered for heat transfer analysis. The maximum temperature is predicted to be as much as 1300°C due to the aircraft fuel and hydrocarbon explosion in close space. But in this scenario the fire zone is open so the intensity of temperature is considered as 1200°C because of heat dissipation. The exterior face of the NPP structure is classified according to heat exposure intensity which has been shown in Fig. 7.3. The most severe region for the effect of fire is up to 10 m height from the foundation because the maximum fuel will flow to the lowermost of containment wall. As the fuel of aircraft flows down immediately after the impact, so the duration of fire for impact region is considered as very short (900sec). From 10m to 27.25m height is considered as very low intensity fire region with 7200sec time duration. The duration and intensity of heat for low and moderately exposed region is modified. Moderate exposed zone subjected to 1000°C temperature for 900 sec, low exposed zone subjected to 800°C for 7200sec and high exposed zone subjected to 1200°C has been considered. The fire intensity curves of 707-320 for different region are shown in Fig. 7.4. The unexposed region subjected to ambient temperature 20°C.

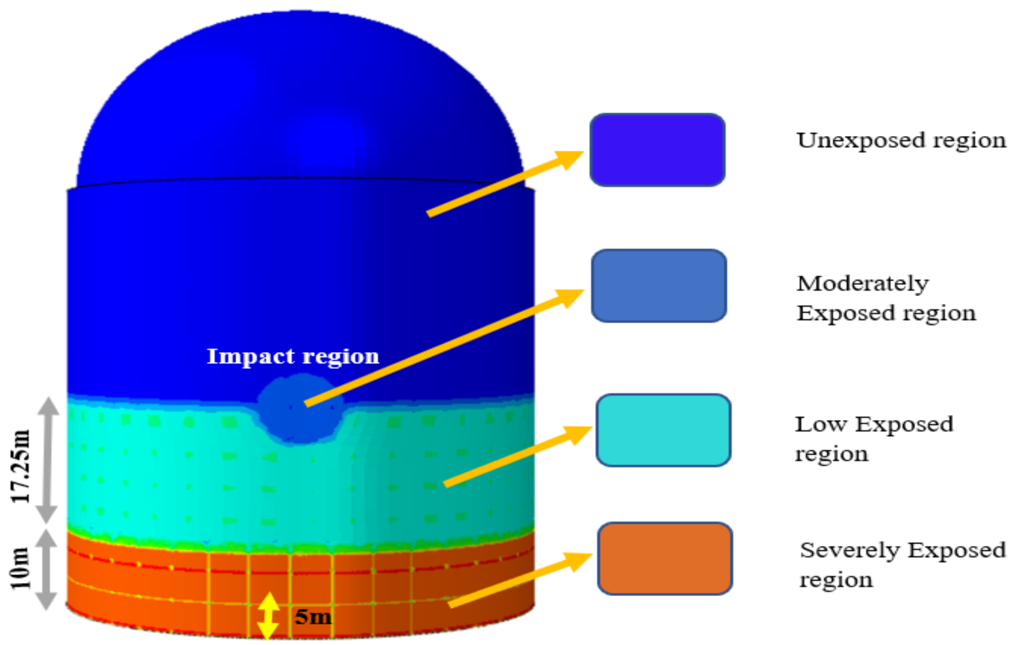


Fig. 7.3 NPP containment with different fire intensity

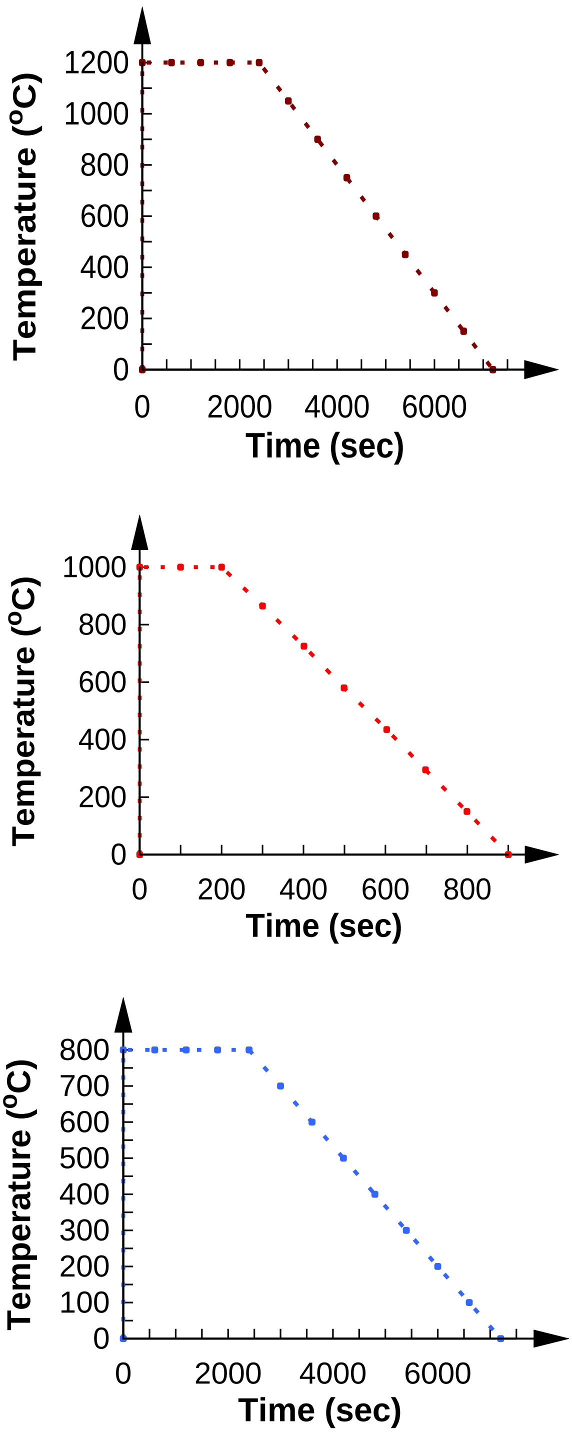


Fig. 7.4 Jet fuel curves for different fire zone (a) Severely (b) moderately (c) low exposed region

To evaluate the temperature gradient and thermal stress variation along the thickness of containment structure three paths A (at 5m height), B (at 10m height), and C (at 27.25m height) have been considered respectively (Fig. 7.5). The temperature variation for all three paths has been plotted in Fig. 7.6. It is found for all the cases that the average penetration depth of heat across the thickness of containment wall is around 250 mm. Temperature profiles of concrete, reinforcement steel bar and inner steel liner has been given at different time interval due to crash of Boeing 7070-320 aircraft, Fig. 7.7-7.10. The peak temperature 1062.04°C in concrete, 819.74°C in reinforcement bar and 23.94°C in inner steel liner reached at 2490 sec., 3640 sec., and 5140 sec. respectively (Fig. 7.9). When the maximum temperature in every part reached thereafter it began to decrease. The maximum temperature is reached in concrete faster than reinforcement bar and steel liner because the concrete is fully exposed to fire but steel bar and steel liner not exposed to fire directly. As the depth of wall is 2.5m, the maximum temperature in inner steel liner is noticed very less.

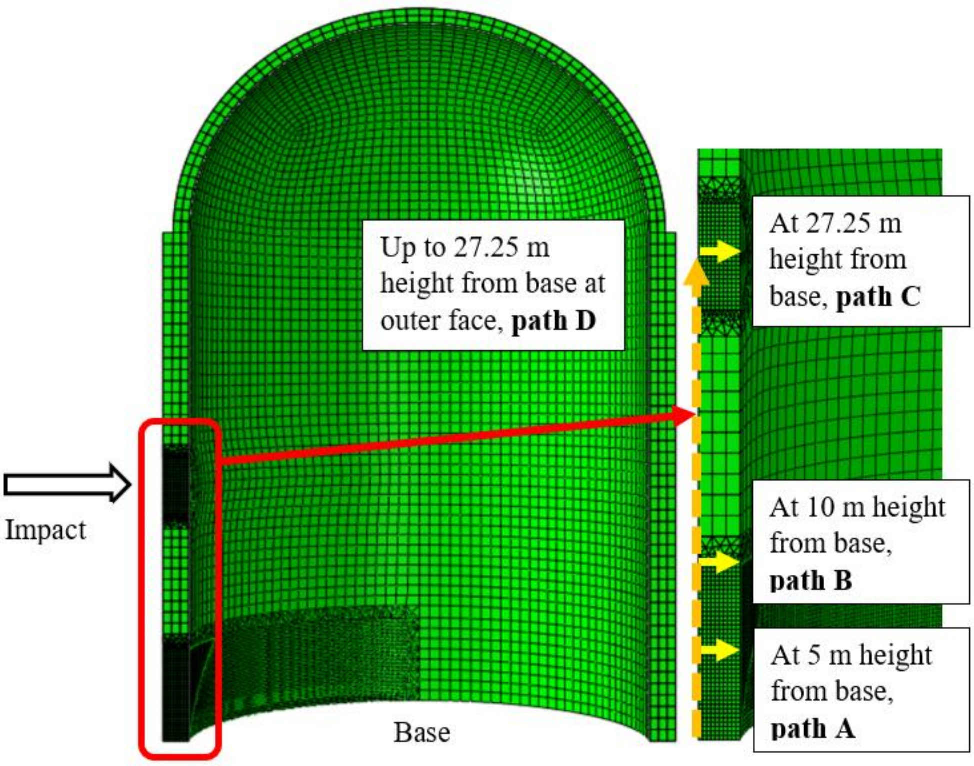


Fig. 7.5 NPP containment with Path-A, Path-B, Path-C and Path-D

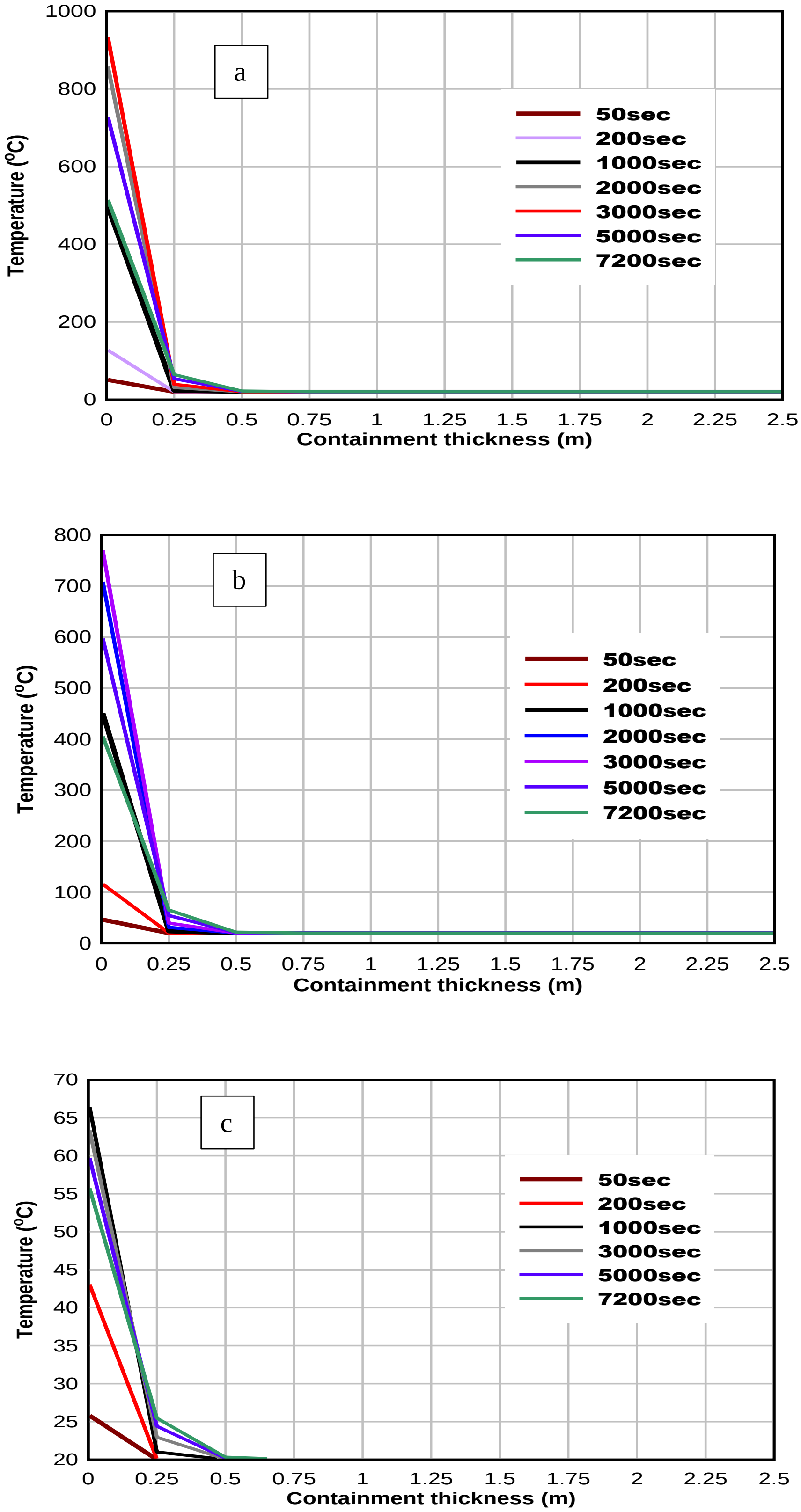


Fig. 7.6 Temperature gradient along (a) Path-A (b) Path-B (c) Path-C

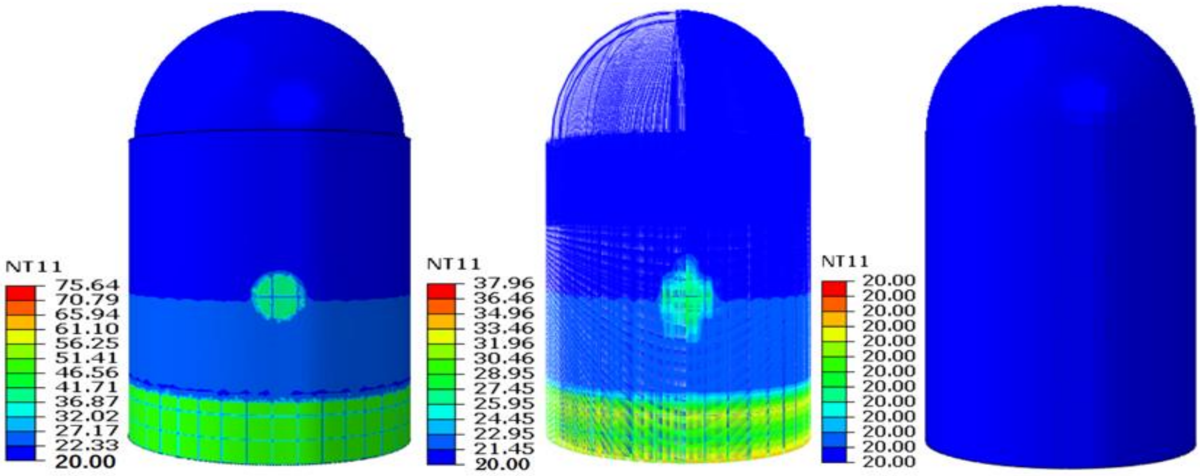


Fig. 7.7 Temperature profile at 50 sec. (a) concrete (b) reinforcement (c) inner steel liner

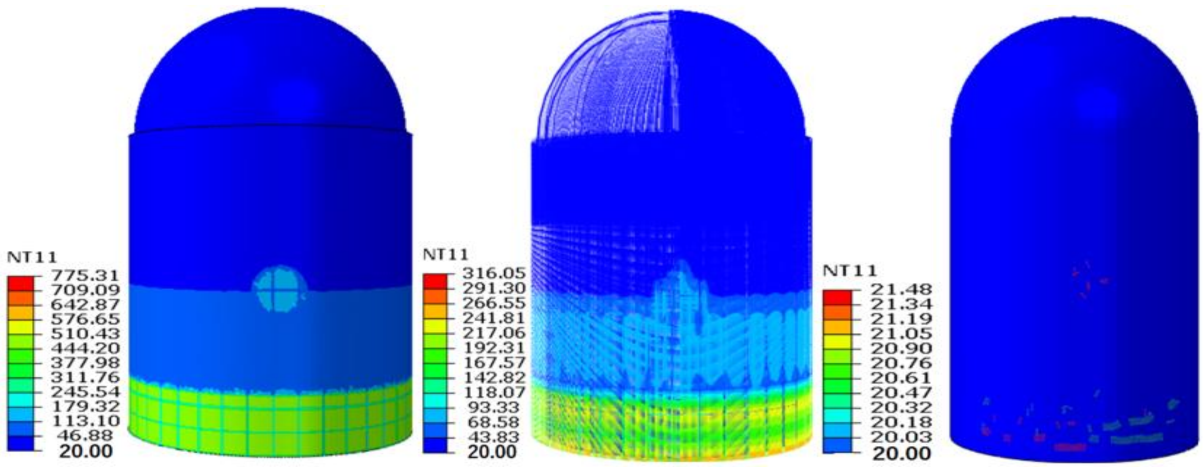


Fig. 7.8 Temperature profile at 1000 sec. (a) concrete (b) reinforcement (c) inner steel liner

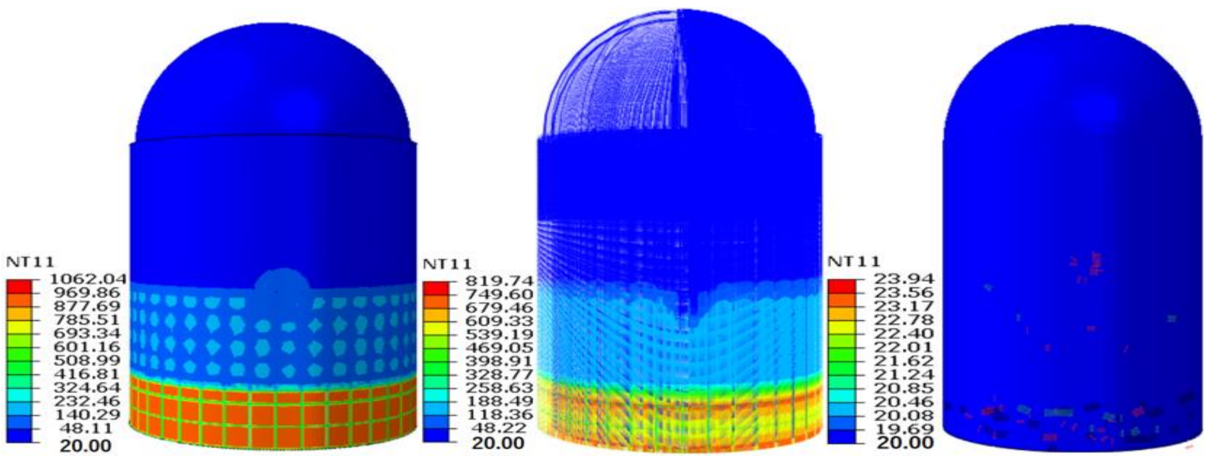


Fig. 7.9 Maximum temperature profile (a) concrete at 2490 sec. (b) reinforcement at 3640 sec. (c) inner steel liner at 5140 sec

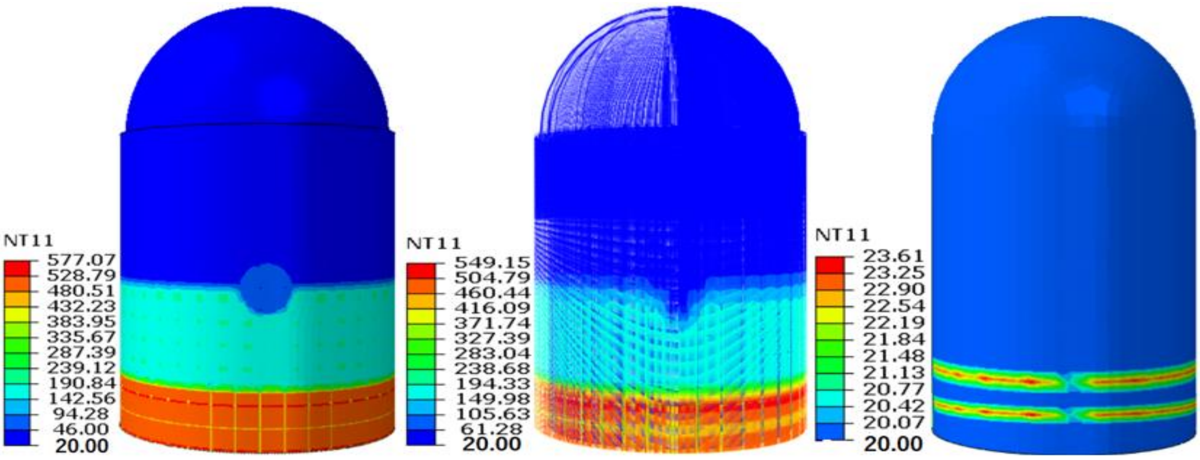


Fig. 7.10 Temperature profile at 7200 sec. (a) concrete (b) reinforcement (c) inner steel liner

A few element nodes have been selected in concrete body, reinforcement steel bar and steel liner to show the nodal temperature variation with time, Fig. 7.11. The nodal temperature in concrete body, steel rebar and inner steel liner are shown Fig. 7.12, 7.13 and 7.14 respectively. From these curves it can be concluded that the concrete body has experienced maximum temperature and steel liner has experienced minimum temperature among three bodies. It can be also observed that the rate of increase in temperature is more in concrete body and less in steel liner.

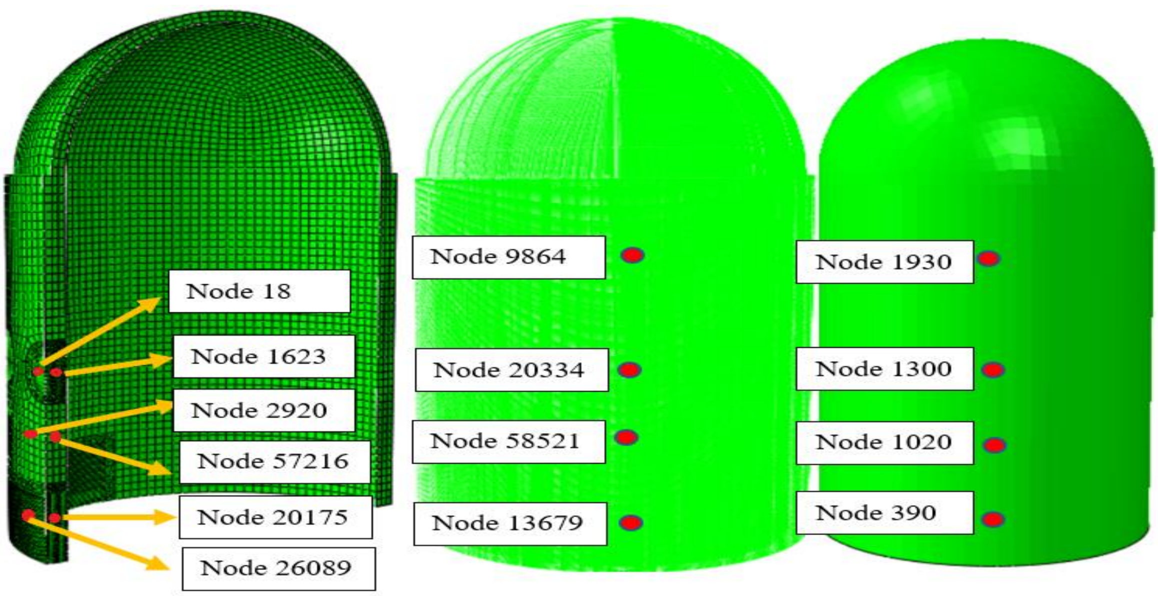


Fig. 7.11 Selective nodes in concrete, Steel reinforcement and steel liner

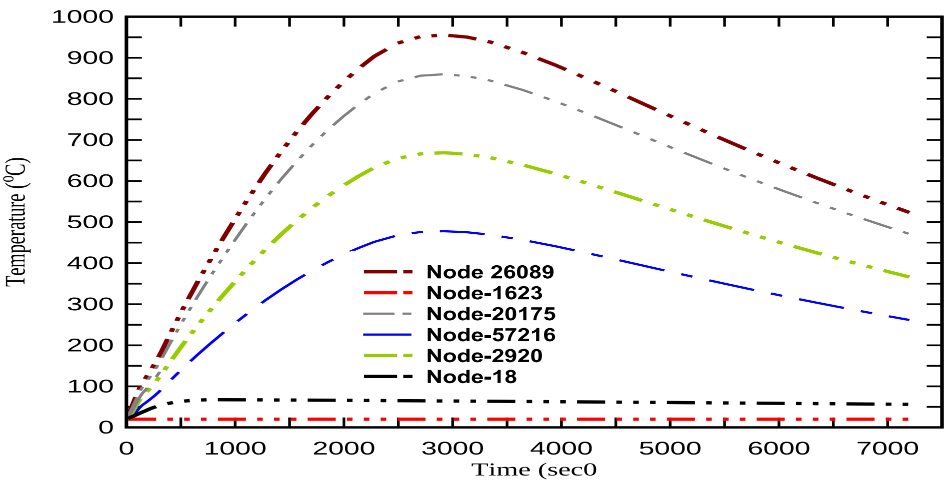


Fig. 7.12 Nodal temperature in concrete body

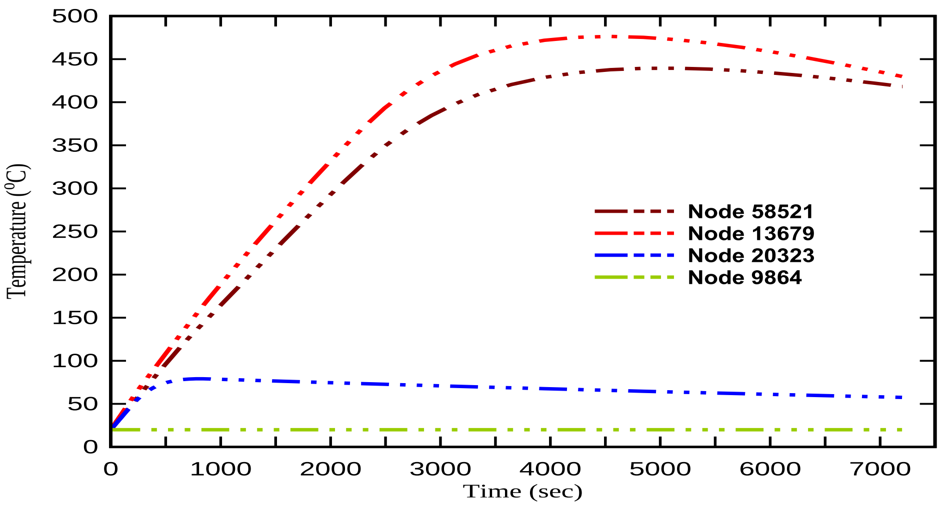


Fig. 7.13 Nodal temperature in steel reinforcement bar

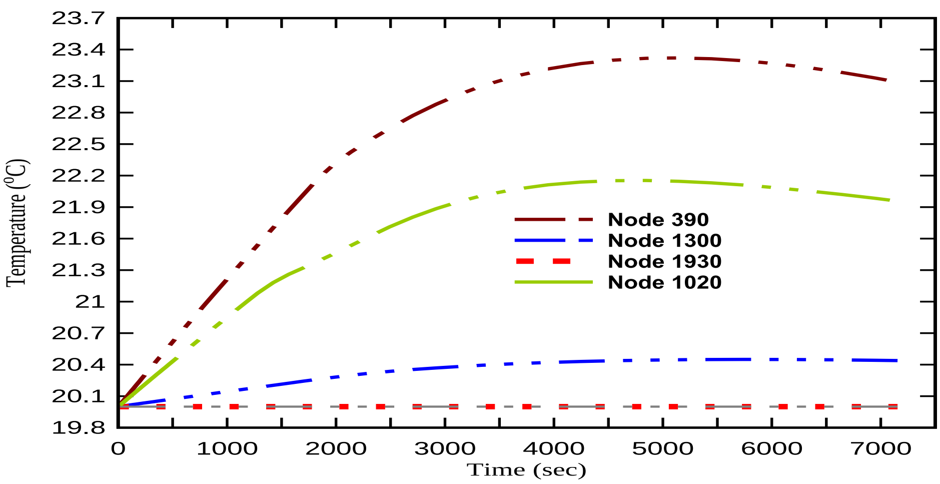


Fig. 7.14 Nodal temperature in inner steel liner

7.4.2 Impact analysis

The impact analysis on NPP containment structure is performed using ABAQUS/implicit. In the present analysis the fuel of aircraft is ignited at 0.18 sec. from starting time. Therefore, the impact analysis has been performed till 0.18 sec. and after that nodal temperatures are provided due to the burning of fuel. The distorted geometry through impact analysis is considered as an initial state in thermal stress analysis. In the simulation of model, the impact load is applied in the direction of Z (along the thickness of model). The maximum deformation in concrete body, reinforcement and steel liner of NPP containment is found to be same value of 15mm (Fig. 7.15). The maximum stress 9MPa in concrete, 37MPa in reinforcement and 63MPa in steel liner are observed in impact analysis (Fig. 7.16). It is also observed that the containment's outer face is under compression and inner face of containment is under tension in the analysis, Fig. 7.17.

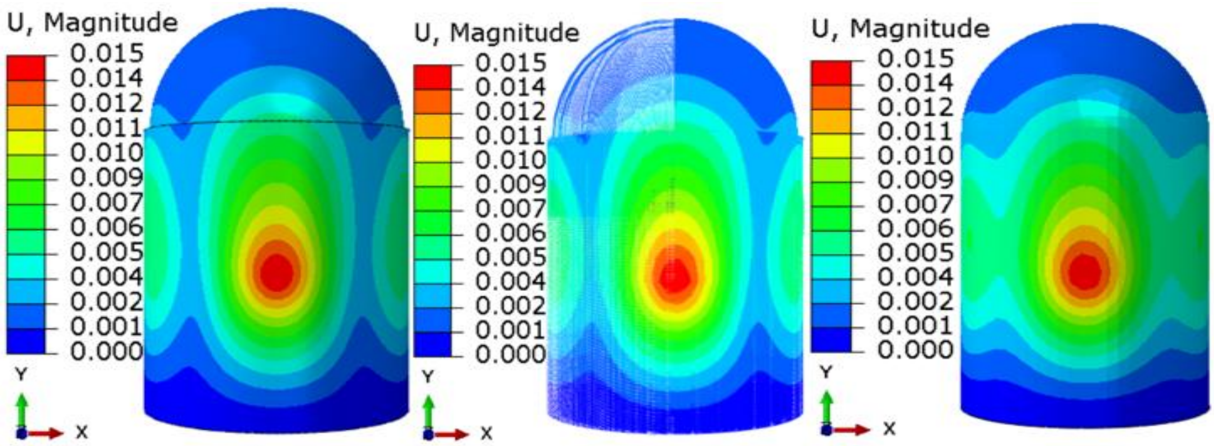


Fig. 7.15 Deformation contour at 0.18 sec. (a) concrete (b) reinforcement (c) inner steel liner

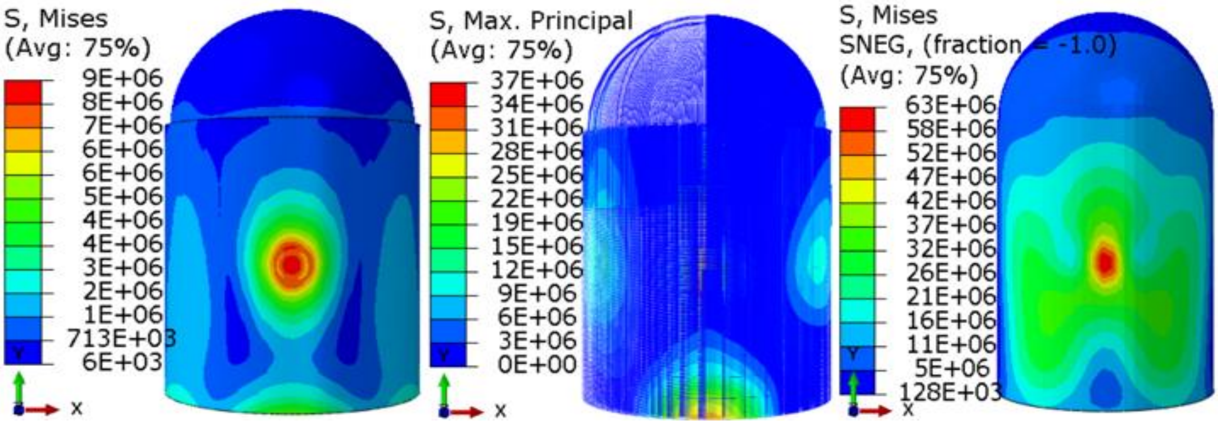


Fig. 7.16 Stress contour at 0.18 sec. (a) concrete (b) reinforcement (c) inner steel liner

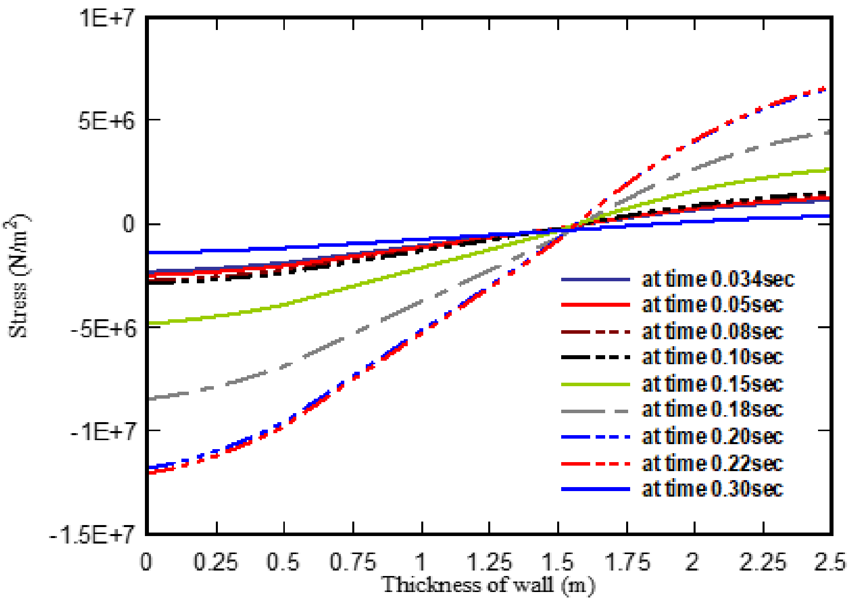


Fig. 7.17 Stress variation along the thickness of TMIR wall

7.4.3 Thermal Stress Analysis

After performing heat transfer and impact analysis, the thermal stress analysis should be performed. So, the thermal stress analysis is the third step of analysis where the impact and heat transfer results are coupled to get the resultant stresses. The thermal stresses are calculated at some suitable time interval (50sec, 400sec, 1000sec, 3000sec, 5000sec and 7200sec). The deformation contour in concrete body at different time interval have been shown in Fig. 7.18, 7.19 and 7.20. The thermal stress contour in steel rebar and steel liner has been shown in Fig. 7.21-7.26. The distribution of stresses along the thickness of structure is examined at various paths (A, B, C). The deformation variation along path-D has been shown in Fig. 7.27. The thermal stress variation in NPP containment structure has been plotted in Fig. 7.28-7.30. At the end of analysis, it is found that the direction of deformation is inward initially and outward finally (Fig. 7.27). Inward deformation is due to the impact whereas outward deformation was due to the burning of fuel. The maximum thermal stress at outer face of containment of 27MPa is found at 5m height, 25MPa is found at 10m height and 23MPa is found at 27.25m height. Finally, it is also observed that the thermal stress is increased initially but after certain time (after 3000 sec.) it is decreased.

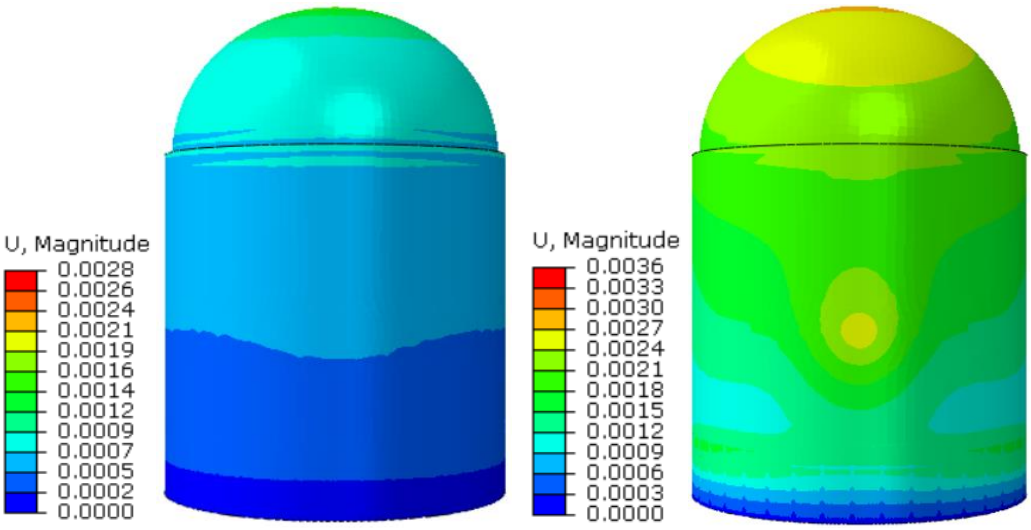


Fig. 7.18 Deformation profile in concrete body at 50 sec. and 400 sec.

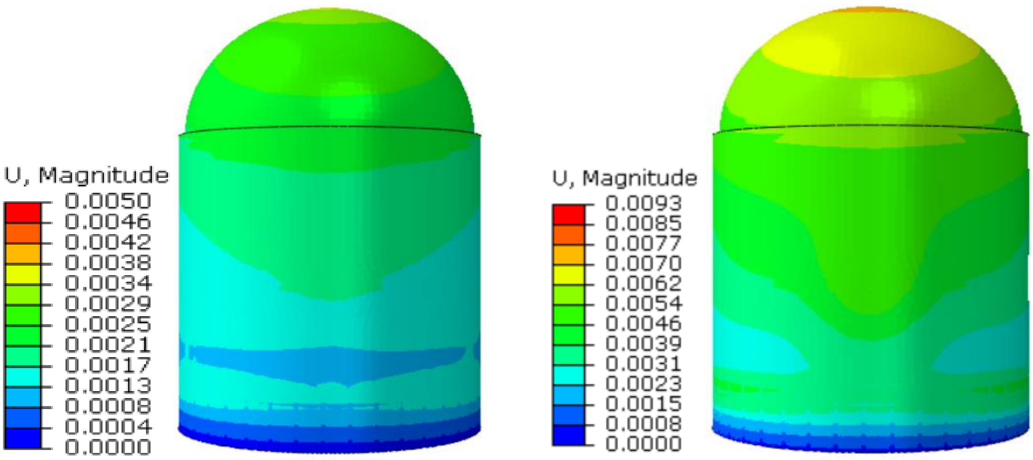


Fig. 7.19 Deformation profile in concrete body at 50 sec. and 400 sec.

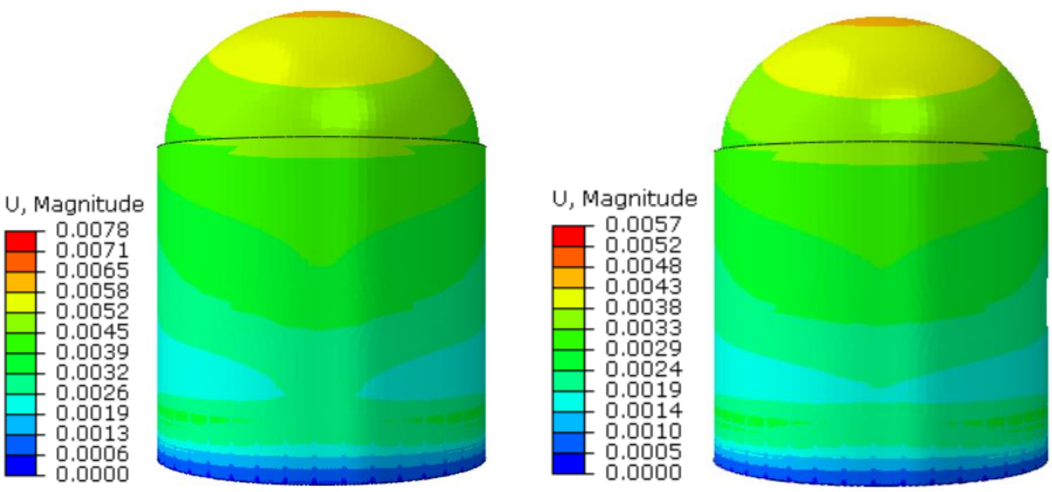


Fig. 7.20 Deformation profile in concrete body at 50 sec. and 400 sec.

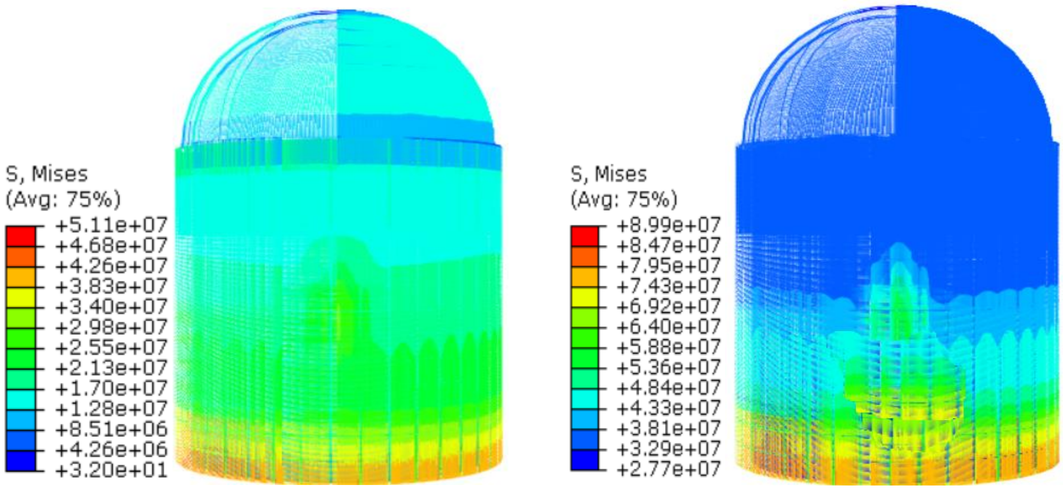


Fig. 7.21 Deformation profile in Steel rebar at 50 sec. and 400 sec.

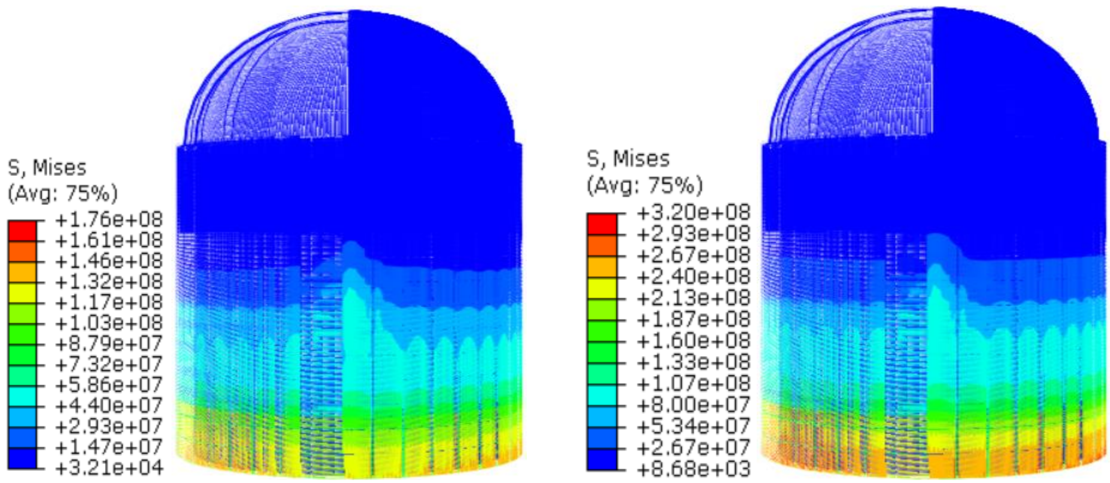


Fig. 7.22 Stress profile in Steel rebar at 50 sec. and 400 sec.

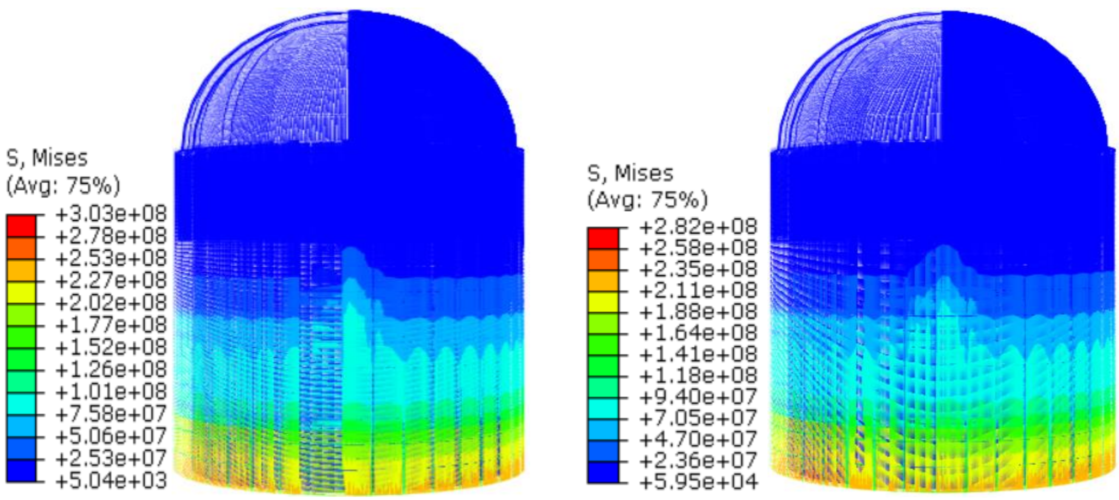


Fig. 7.23 Deformation profile in Steel rebar at 50 sec. and 400 sec.

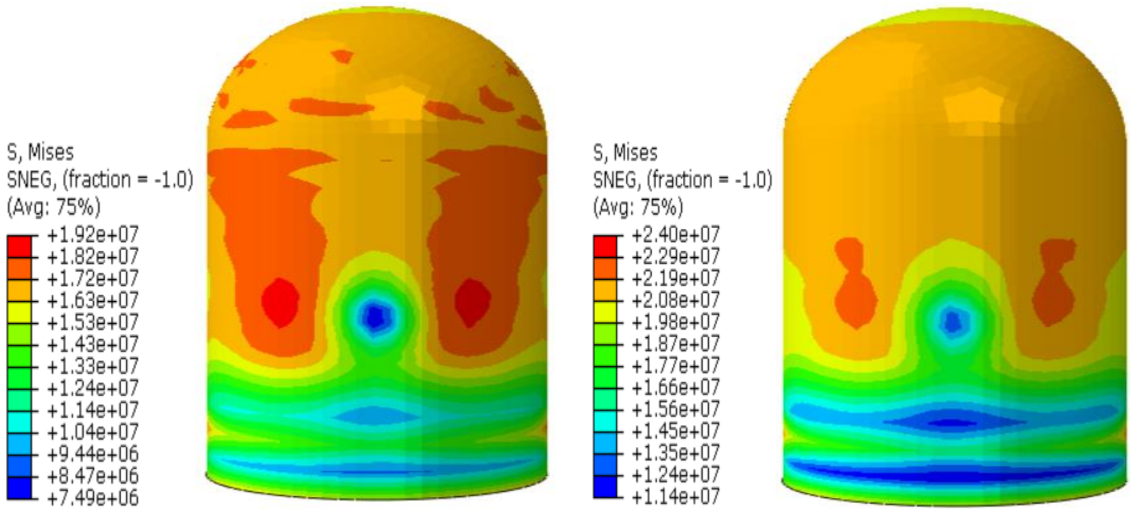


Fig. 7.24 Deformation profile in Steel liner at 50 sec. and 400 sec.

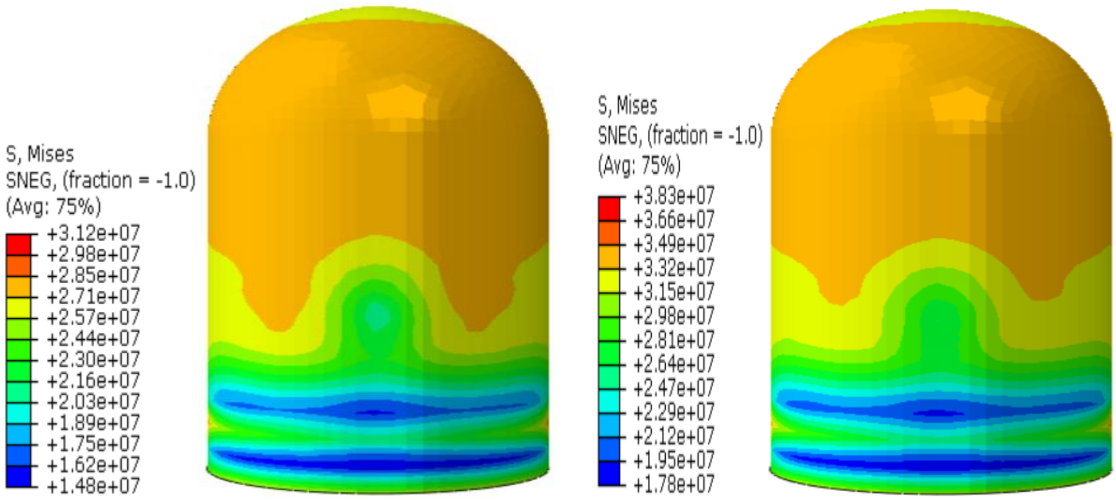


Fig. 7.25 Deformation profile in Steel liner at 50 sec. and 400 sec.

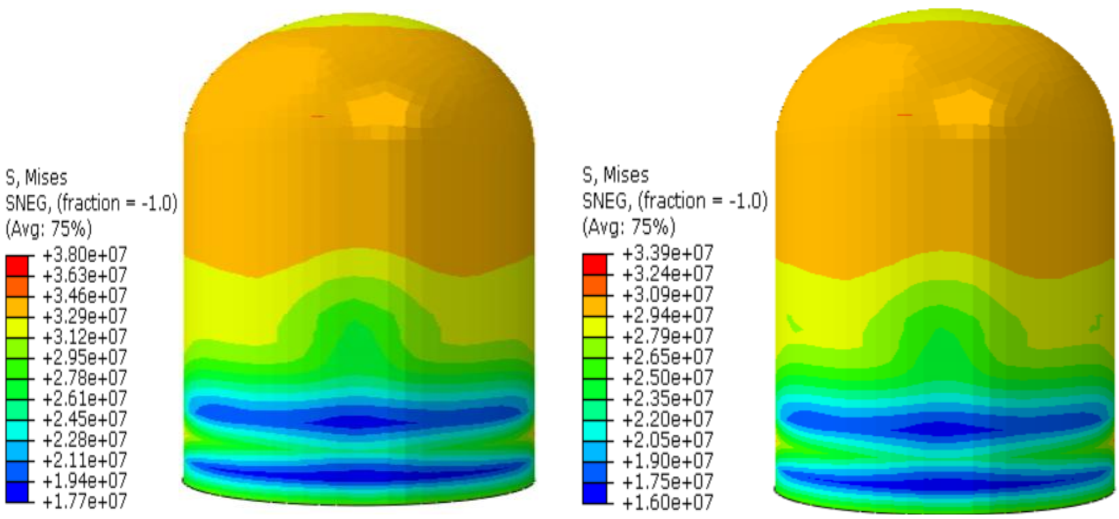


Fig. 7.26 Deformation profile in Steel liner at 50 sec. and 400 sec.

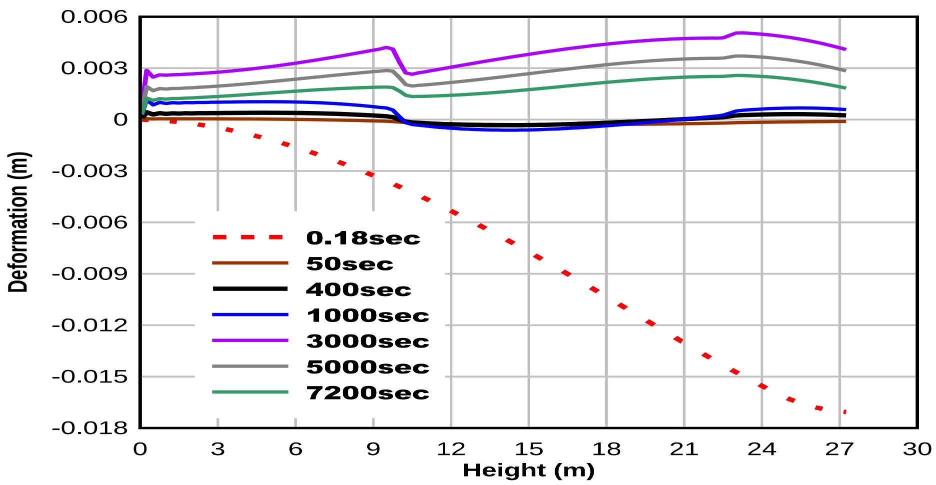


Fig. 7.27 Deformation variation along Path-D of the containment

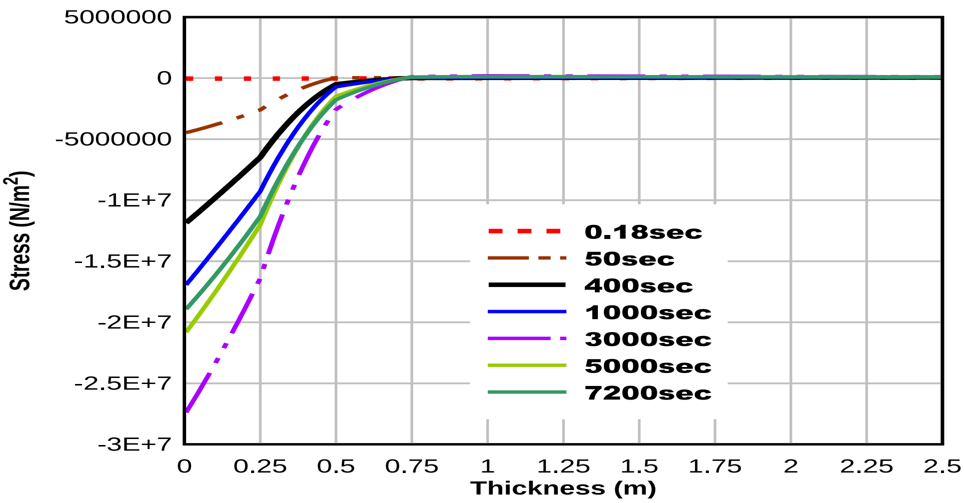


Fig. 7.28 Thermal stress variation against Boeing 707-320 crash along Path-A

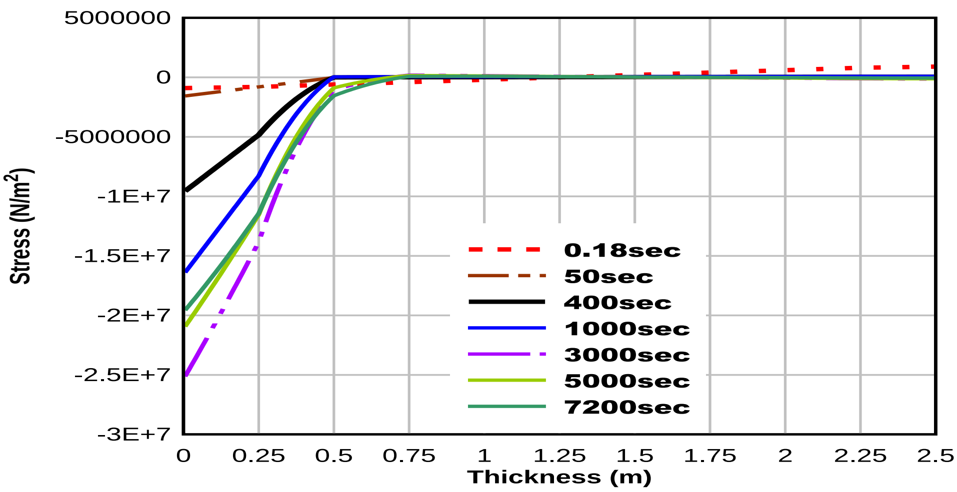


Fig. 7.29 Thermal stress variation against Boeing 707-320 crash along Path-B

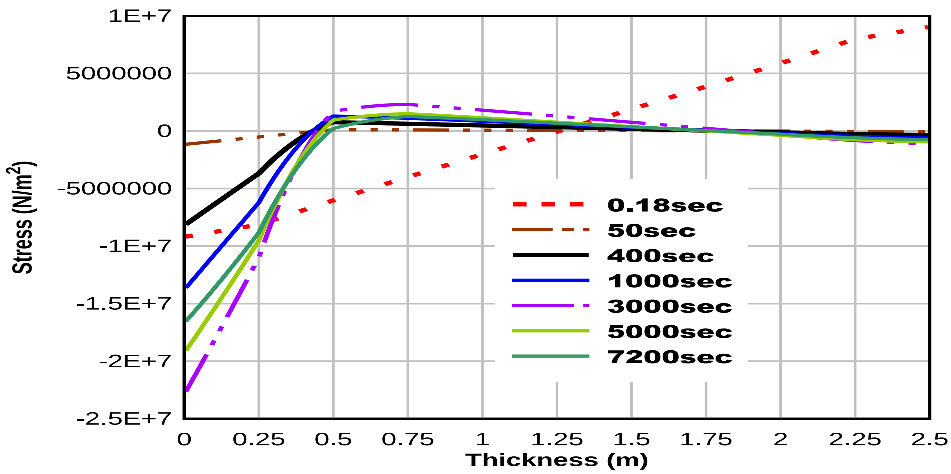


Fig. 7.30 Thermal stress variation against Boeing 707-320 crash along Path-C

7. 5 SUMMARY

In this study, an effort has been made to figure out the NPP containment structure (TMI) behaviour for an accidental aircraft (Boeing 707-320) crash and also its associated fire effects. This is done in three steps. In first step, impact analysis and in second step heat transfer analysis is done. In the third step, the thermal stresses are obtained by coupling the results due to impact as well as fire. From this analysis the following conclusions can be made:

- From heat transfer analysis, it is obvious that the average penetration of heat is 250mm and temperature of remaining depth is around 20°C (ambient temperature).
- From impact analysis, the maximum deformation of 15mm in the direction of loading has been observed at 0.18sec. The stresses due to impact are insignificant for short duration (9MPa in concrete, 37MPa in reinforcement and 64MPa in steel liner).

- From thermal stress analysis, it is clear that the outer face of containment is always under compression throughout the analysis.
- The maximum temperature of 1062^oC is found in concrete body during heat transfer analysis and this temperature may causes scabbing of concrete at outer face of NPP containment wall. The induced fire does not affect the global behavior of containment.
- The TMI containment structure is found to sustain its stability without any major damage for the impact of Boeing 707-320 aircraft.