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BEHAVIOUR OF OUTER WALL OF NUCLEAR POWER PLANT SUBJECTED TO AIRCRAFT CRASH AND SUBSEQUENT FIRE EFFECTS

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ABSTRACT

In view of the recent nuclear disasters, safety concern in nuclear structures is on the rise. In this study, safety analysis of 1.2m thick outer containment of a typical Nuclear Power Plant has been carried out using ABAQUS/Implicit finite element code. Areal nuclear containment BWR Mark III has been considered in the present study. The heightanddiameterof the containment wall is 46m and 42m respectively.First, the impact load is applied on the containment using Iliev et al.force history curve of Boeing 747-400, after 0.2 secnodal temperatures were increased following the proposed jet fuel curve to imitate fire as a result of fuel burning. Combined effect of impact and heat has been used to study thermal stress variation.

As the fuel is stored in the wings of the plane, the effect of fire is assumed to trigger as soon as the wings hit the outer face of containment wall. From Iliev et al. force history curve, time delay between plane's first contact and wing contact with the containment wall was assumed to be 0.2 second.The impact location of the aircraft was considered at mid-height of the containment wall as more deformationwas observed in this location.The fire effect was considered to be most severe near the base of the containmentas the most of the fuel will immediately flow down to the bottom of containment after impact. The behaviour of concrete and reinforcement has been incorporated using Concrete Damaged Plasticity model and Johnson Cook elastic-visco plastic model respectively. The material parameters for concrete and reinforcement at elevated temperature have been taken from Eurocode 2. From the study it may be concluded that there was no global damage in the containment wall due to impact, heat and thermal stress, but some local damage on the outer face of the containment wall has been occurred.

Keywords: Impact, Aircraft crash, Nuclear containment, Fire resistance, Fire endurance time, Thermal stress, Heat transfer.

INTRODUCTION

The safety assessment of important structures such as a nuclear power plant under the crash of a large commercial aircraft has been performed worldwide after the terrorist attack that occurred in the U.S. on 11th September, 2001. However, many important studies on this subject were carried out much before these attacks in order to study the effect of accidental crash of various aircraft on important structures (Riera [1], Iliev et al. [2], Abbas et al. [3], Arros and Doumbalski [4], M. R. Sadique et al. [5], A. Rawsan et al [6]). An analysis of an aircraft crash on an outer containment of a nuclear power plant using the reaction time history curve was done by Abbas [7]. Kukreja [8] analysed outer nuclear containment using time history curve for Boeing 747-400 and other aircrafts. Similarly, Jeon et al. [9] evaluated the fire resistance of a nuclear power plant subjected to a large commercial aircraft crash. The present study is about the behavior of an outer nuclear containment wall of 1.2 m thick concrete with 46m height and 42m diameter (cylindrical) against the impact of an aircraft and its subsequent fire induced stresses.Theconcrete properties at elevated temperature have taken from Eurocode 2 [10]. In the first step impact analysis was done for force-time history of Boeing 747-400 aircraft on the model. This was followed by a heat transfer analysis. Finally, a thermal stress analysis was performed by importing the deformed state of the model as initial condition in the thermal stress analysis. For heat transfer analysis, fire is assumed to continue for 3 hours at bottom level of the containment up to a height of 10 meters from base and for 15 minutes at 10 meters to 23meters with impact region by Jeon et al. [9].

NUMERICAL METHODOLOGY

The concrete structure of the nuclear containment has been modeled as three dimensional deformable solid whereas the reinforcement as three dimensional deformable wire. The geometric model of the containment has been considered identical to BWR Mark III type reactor. The containment has a circular cylindrical wall of inner diameter 42 m and the total height of the containment was 46 m. The wall thickness has been assumed to be constant throughout the containment. The base of the containment has been assumed to be fixed with respect to all degrees of freedom. The containment structure is doubly reinforced with 40 mm diameter bars placed at 80 mm c/c both ways at the inner and outer faces of the cylindrical wall. The effective cover to concrete was assumed to be 100 mm. The reinforcement modeled as 3D wire was placed in the structure. The modeling of reinforcement in the outer face of the containment structure is shown in Fig. 1.

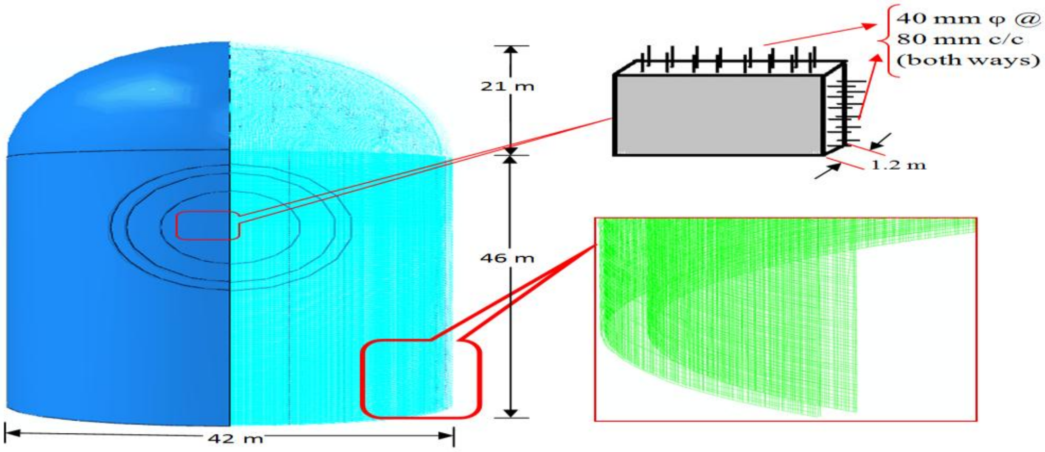


Fig. 1: Outer containment structure with reinforcement detailing

Iliev et al. [2] calculated the reaction force for the deformable aircraft over the target area and plotted the response as the force history curves. In the present model, this force history curve was used on the containment wall for Boeing 747-400 aircraft as shown in Fig. 2. The application of load for impact of Boeing 747-400 aircraft on target is shown in Fig. 3.

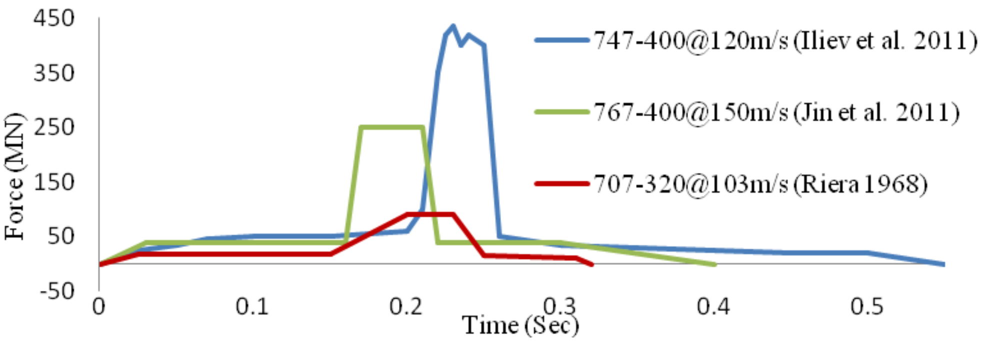


Fig. 2:Reaction time response of Boeing 747-400 Airbus

The geometry of the containment was divided into various regions for an appropriate meshing. The detail of meshing for the containment is shown in Fig. 3. To minimise no of elements in model, the half of cylindrical was simulated with symmetric boundary conditions on cutting plane.

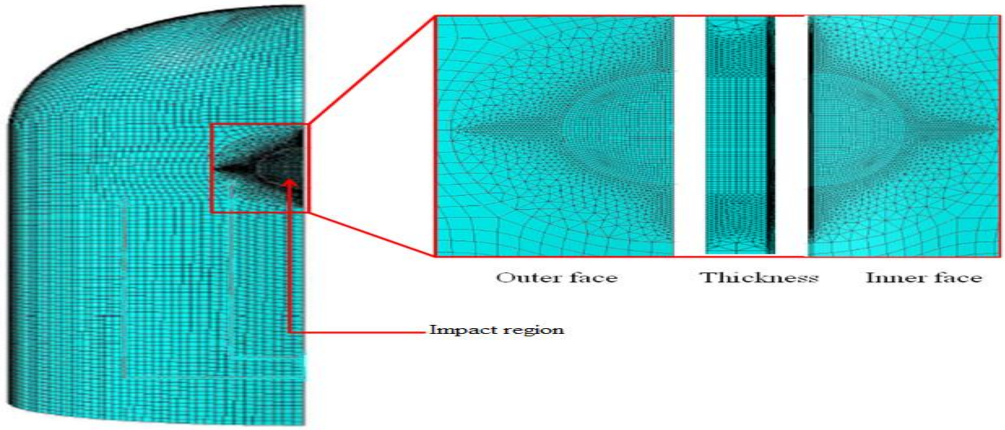


Fig. 3: Meshing detail of containment structure and plate

CONSTITUTIVE MATERIAL MODEL AND PROPERTIES

Concrete damage plasticity model of Abaqus 6.8 [11] material library was used for the simulating the behaviour of concrete in the containment structure. Fig. 4(a) and (b) shows the stress-strain curves for the concrete material under uniaxial loading in tension and compression respectively. In the present study the response of concrete under compression was incorporated using the stress-strain curve of Sinha et al. [12] and Grote et al.[13]. The behavior of concrete under tension was incorporated from the analytical study carried out by Lu and Xu [14].

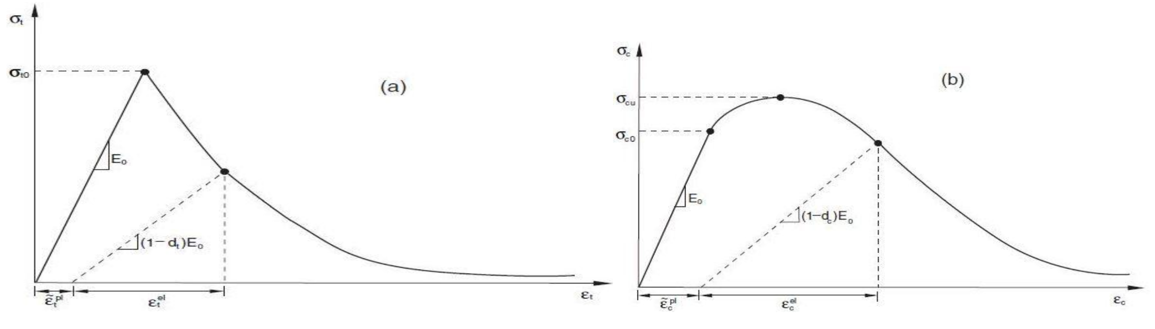


Fig. 4: Response of concrete to uniaxial loading in (a) tension (b) compression

The behavior of concrete under the elevated temperature is quite different from that of observed at ambient temperature. In the present study, however the material properties of the concrete have been adopted with reference of Eurocode 2 [10].The material behavior of the steel reinforcement was incorporated using the well-known Johnson-Cook elasto-viscoplastic material model. The material parameters of reinforcing steel were considered identical to those of the Weldox 460 E steel obtained by Borvik et al. [15].

RESULTS AND DISCUSSIONS

The response of the containment structure exposed to the external fire due to an aircraft crash depends upon the size, velocity and fuel capacity of aircraft as well as the strike location and weather conditions.

In the present study, the Boeing 747-400 aircraft has been considered to hit the containment at the mid height of the cylindrical wall (23m from the base).

1. Heat transfer analysis

The external surface of the containment structure has been categorized based on the intensity of heat exposure. The aircraft fuel scattered on the containment will flow down immediately after the impact. Hence, the impact region will be exposed to intensive fire for not more than a few minutes. Therefore the impact location has been considered to be less important in terms of aircraft induced fire analysis and the wall of the containment up to 10 m height from the base has been assumed to have severe exposure.

The fire curves of Boeing 747-400 aircraft are shown in Fig. 5 (a) and (b). In order to plot the thermal gradient across the containment thickness, the path at 5 m and 23 m height from the base has been selected respectively. The temperature gradient for different path has been plotted in Fig. 6.

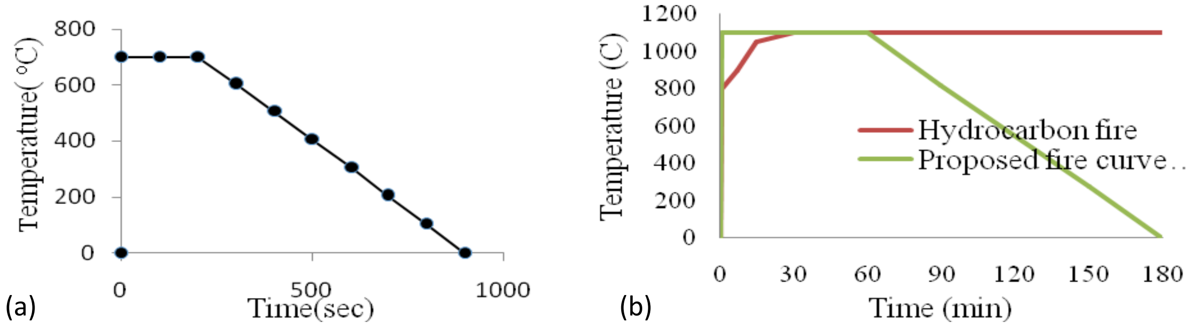


Fig. 5: Proposed jet fuel curves for (a) Impact region (b) High exposed area

The maximum temperature in the concrete reached 1078.89◦C after 3680 seconds and thereafter it started decreasing. In the outer set of reinforcement the maximum temperature was found to be 1045.71◦C at 3870 sec. No significant increase in temperature beyond the ambient was noticed at the inner set of reinforcement (Fig. 7)

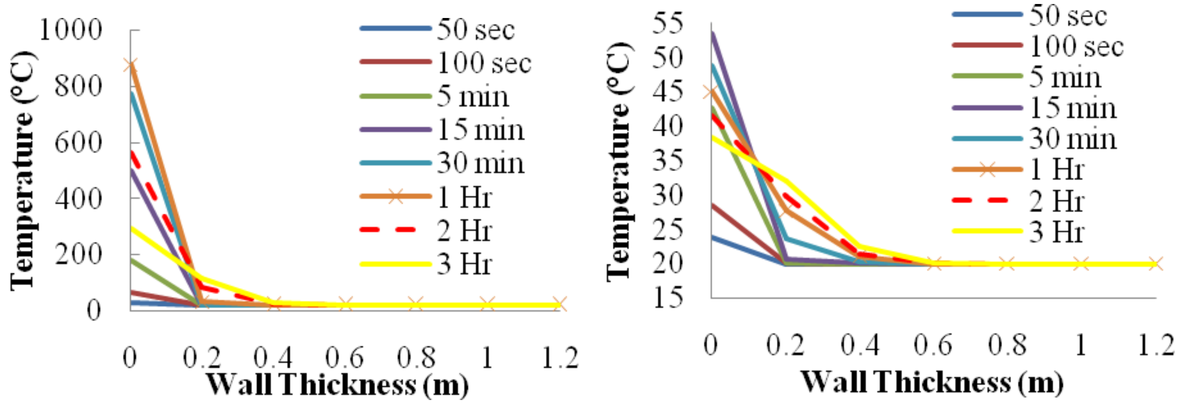


Fig. 6: Temperature gradient in concrete across the thickness at 5m and 23m

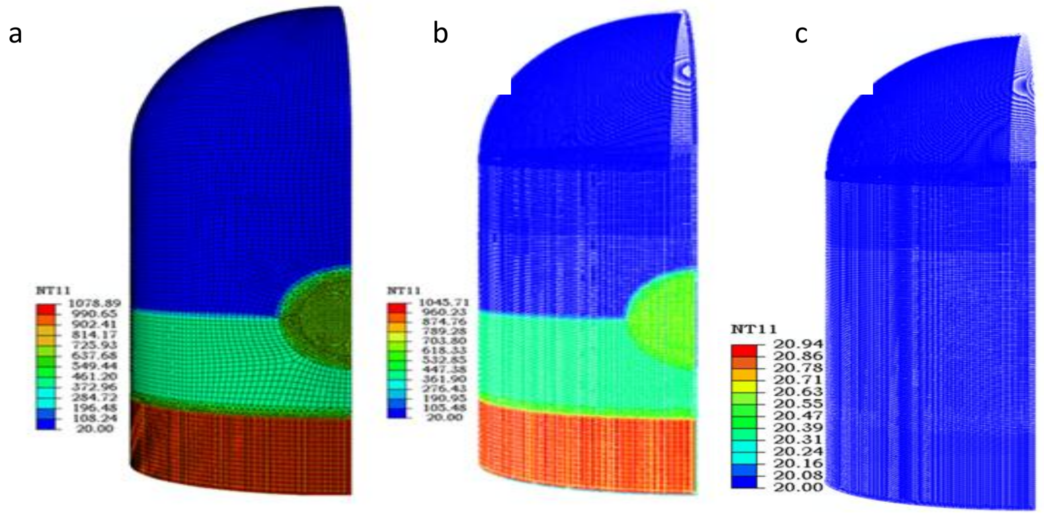


Fig.7: Thermal profile with maximum nodal temperature (a) concrete (time t = 3680 sec.), (b) outer reinforcement (t = 3870 sec.) and (c) inner reinforcement (time t = 4190 sec.)

2. Impact analysis

In the present study it has been assumed that the fire will break out as soon as the wings come in contact with the containment. Hence, the fire is assumed to start 0.2 sec after the initial contact. The implicit impact analysis has therefore been carried out until 0.2 sec and the deformation state obtained considered as the input for the thermal stress analysis.

In this case, the impact load was applied along the X direction (thickness). The maximum deformation in the containment at 0.2 sec. has been found to be 50.47 mm at the impact location (Fig. 8). The maximum compressive stress in concrete was found to be 8.32 MPa at the outer face of containment in the impact region. The inner face has been found to be under tension with a maximum stress 2.9 MPa in the impact region. The maximum compressive stress has been noticed to be 406 MPa. The inner set of reinforcement subjected to tensile stress of 349.6 MPa has been observed under the impact zone (Fig. 9).

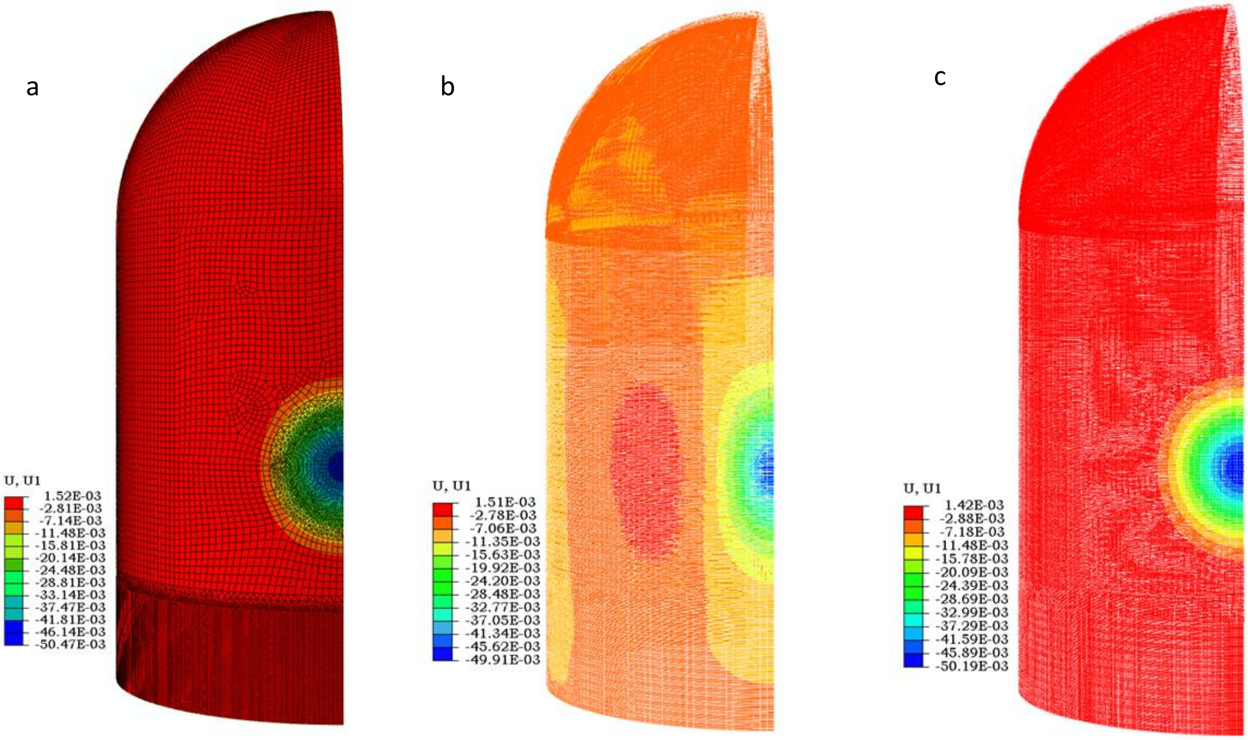


Fig. 8:Deformation contour at 0.2 sec (a) concrete (b) outer reinforcement (c) inner reinforcement

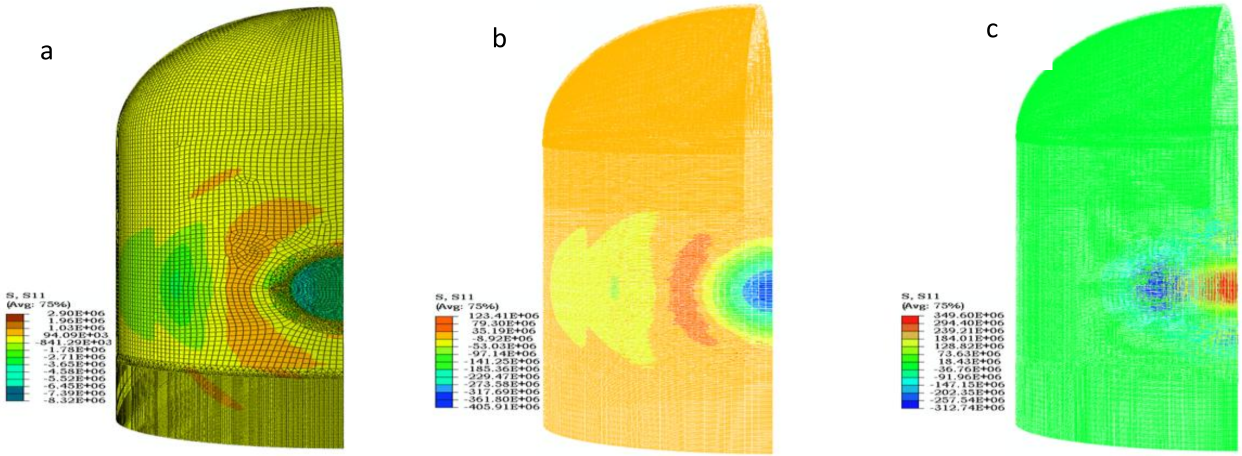
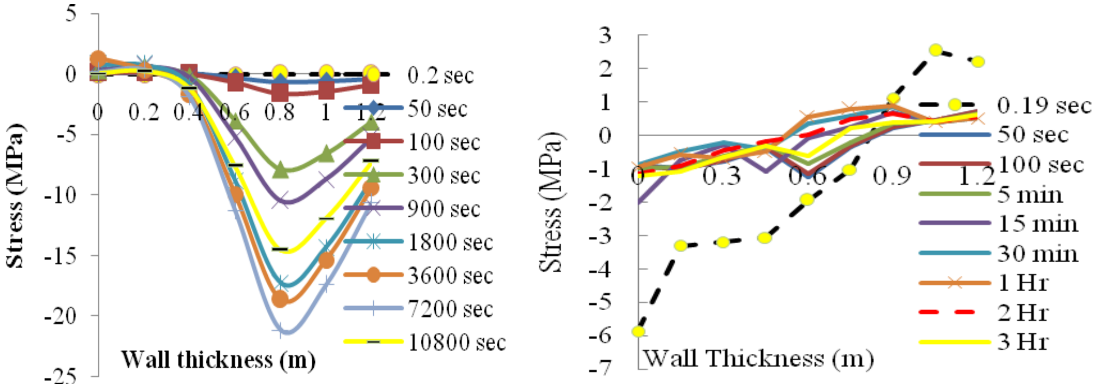


Fig. 9: stress contour before break out of fire (a) concrete (b) outer reinforcement (c) inner reinforcement

3. Thermal Stress Analysis

The thermal stress analysis is the third step of the analysis wherein the impact and the heat transfer responses have been coupled together to obtain the resultant thermal stresses. The thermal stresses were obtained for some selected frames of the heat transfer analysis results. The variation of stress across the thickness of the containment has been investigated at different paths. The stresses variation for cylindrical containment has been plotted in Fig. 10.



(a) (b)

Fig. 10: Stress gradient in concrete across the thickness of containment (a) at 5m (b) at 23m

CONCLUSIONS

In the present study an attempt has been made to find out the behavior of the RC containment for an aircraft crash and its subsequent fire effects using finite element code. This was done in two steps. In the first step impact analysis was done for force-time history of Boeing 747-400 aircraft crash on the model. This was followed by a heat transfer analysis. Finally, a thermal stress analysis was performed by importing the deformed state of the model as initial condition in the second step. The following conclusions were drawn from the analysis:

1. From the heat transfer analysis it is clear that due to sharp fall in the thermal gradient across the thickness of the containment, the damage has been limited to few centimeters depth only. Hence, it can be concluded that the containment suffers severe local damage due to the fire resulting in scabbing of the concrete however; the global behaviour of the containment will not be affected. The same was also noticed through the mesh convergence studies.
2. Impact analysis showed a maximum displacement of 50.47 mm (in the direction of impact) for an applied load at 0.2 sec. The stresses induced along the thickness were nominal for such a small duration of load.
3. Thermal stress analysis showed that the outer face (subjected to impact load) of the containment at the impact region is under compression throughout the analysis.
4. Peak temperatures in excess of 1079^0C were observed during thermal analysis. At such high temperatures, thermal stresses produced due to crash induced fire may cause scabbing of concrete leading to exposure of reinforcement. However, the induced fire does not pose a threat to the global behavior of the containment structure.
5. A maximum tensile stress of 2.9MPa was observed in M30 grade of concrete in RC containment. However, the structure was found to maintain its integrity with no visible damage in the containment.

REFERENCES

1. Riera, J.D., 1968. On the stress analysis of structures subjected to aircraft impact forces, Nucl. Eng. Des. 8, 415-26.
2. Iliev, V., Georgiev K., Serbezov V., 2011. Assessment of impact load curve of Boeing 747-400. MTM Virtual J. 1, 22-25.

3. Abbas, H., Paul, D.K., Godbole, P.N., Nayak, G.C., 1996. Aircraft crash upon outer containment of nuclear power plant, Nucl. Eng. Des. 160, 13-50.
4. Arros, J., Doumbalski, N., 2007. Analysis of aircraft impact to concrete structures, Nucl. Eng. Des. 237, 1241–49.
5. Sadique M.R., Iqbal M.A., Rawsan A., Gupta N.K., (2017). Response of outer containment of an NPP against aircraft crash and induced fire, Thin-Walled Structures (in press).
6. Rawsan A., Sadique M.R., Iqbal M.A., (2015). Safety Analysis of Nuclear Containment Structure against Aircraft Crash and Induced Fire, Jounal of Basic and Applied Engineering Research, 2 (9), 778-785.
7. Abbas, H., Paul, D.K., Godbole, P.N., Nayak, G.C., 1995. Reaction-time response of aircraft crash, Comp. Struct. 55, 809–17.
8. Kukreja, M., 2005. Damage evaluation of 500 MWe Indian Pressurized Heavy Water Reactor nuclear containment for aircraft impact, Nucl. Eng. Des. 235, 1807–17.
9. Jeon, S., Jin, B., Kim, Y., 2012. Assessment of the Fire Resistance of a Nuclear Power Plant Subjected to a Large Commercial Aircraft Crash, Nucl. Eng. Des. 247,11-22.
10. Eurocode 2 (2004), "Design of concrete structures: Part 1-2: general rules-structural fire design", European Committee for Standardisation, Brussels, BS EN 1992-1-2, 2004.
11. Abaqus Explicit user manuals Version 6.8.
12. Sinha, B. P., Kurt, H., Tulin, L. G., 1964. Stress-Strain Relations for concrete Under Cyclic loading, J. Am, Concrete Inst. 2 (61), 195–210.
13. Grote, D. L., Park, S. W., Zhou, M., 2001. Dynamic behaviour of concrete at high strain rates and pressures, International Journal of Impact engineering 25, 869-886.
14. Lu, Y., Xu, K., 2004. Modeling of dynamic behavior of concrete material under blast loading, International Journal of Solid and Structures 41, 131-143.
15. Borvik, T., Hopperstad, O.S., Berstad, T., 2002. On the influence of stress triaxiality and strain rate on the behaviour of a structural steel. Part II. Numerical simulations, Eur J Mech A:Solids , 22, 15–32.