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Behavior of Critical RCC Structures under Crash Induced Fire

M.R. Sadique[1], P. Bhargava[2], A. Rawsan[3] and M.A. Iqbal[4]

[1]Department of Civil Engineering, ZHCET, Aligarh Muslim University
[2,4]Civil Engineering Department, Indian Institute of Technology Roorkee, India
[3]Civil Engineering Department, Graphic Era University, India
E-mail: [1]rehan.sadique@gmail.com, [2]bhpdpfce@iitr.ac.in, [3]rawsance@gmail.com, 4iqbalfce@iitr.ac.in

Abstract—*The The nuclear power is considered to be an efficient, reliable and cheapest source of energy, however, due to the associated risk of nuclear radiation, the production of nuclear energy is considered to be highly controversial throughout the globe. In view of the previous incidents of missile and aircraft attacks on important structures and the associated very high risk of failure the present study has been designed to evaluate response of nuclear containment structure against aircraft crash. The outer containment of a typical BWR nuclear power plant has been modeled. The numerical simulations have been carried out using the implicit and explicit integration schemes of ABAQUS finite element code. The effect of fire induced due to aircraft crash has been studied against Boeing 707-320 aircraft. The Concrete Damaged Plasticity model for concrete and Johnson-Cook elastic-visco plastic model for reinforcement were employed to predict the behavior under impact loading, while for heat transfer and thermal stress analysis, the concerned material properties have been taken at elevated temperature form Eurocode 2. The impact of aircraft was considered to occur up to the point the engines came in contact. Thereafter the fire was assumed to have spread out since majority of the aircraft fuel is stored in and around the wings. The fire effect was considered to be most severe at the bottom of containment up to 10 m height from the base. After 15 mint of exposure to fire the temperature in the concrete element at the height of 10 m from the base of the containment has been noticed to be 1094 °C against the selected fire scenario. However, due to sharp fall in the thermal gradient across the thickness of the containment, the damage has been limited to few centimeters depth only.*

1. INTRODUCTION

As of now the fire is not considered a design parameter for the nuclear containment structure. Hence, the assessment of fire resistance has not been established yet for nuclear safety related structures. As such the temperature limits have been well established for the normal operation and the shutdown conditions during a test. However, the most sever temperature in case of an internal accident such as loss of coolant and main line break (175 ºC) is significantly lesser than the fire spread due to an aircraft crash. According to Nuclear Energy Institute (2009) guideline both external and internal fires may be erupted as a result of an aircraft crash over a containment structure. The response of the containment structure exposed to the external fire due to an aircraft crash will depends upon the size, velocity and fuel capacity of aircraft as well as the strike location and weather conditions.

Although the fire spread in a containment structure due to aircraft crash has been studied earlier (Contri et al., 2005; Jeon et al., 2005 & 2012) however, a coupled analysis of aircraft crash and the induced fire effect has not been dealt in the literature. The crash induced fire will be ignited as a result of the breach of the fuel tank as soon as the wings come in contact. Therefore, in order to obtain a more realistic response of containment for the crash induced fire the effect of impact loading must be considered. In the present study therefore initially the Boeing 707-320 and Boeing 747-400 aircrafts have been considered to hit the containment at the mid height of the cylindrical wall (23 m from the base) and the fire has been assumed to break out as soon as the wings come in contact. The impact analysis has been carried out using the reaction-time response approach discussed in the previous chapter. The deformed state of the containment obtained through the impact analysis has been considered as the initial state for the thermal stress analysis. Before performing the thermal stress analysis however, the heat transfer analysis has been carried out in order to obtain the nodal temperature variation with respect to time in the containment structure. It should be noted however, that the heat transfer analysis is not supported by the ABAQUS/Explicit. Therefore the impact analysis performed in the previous chapter was repeated using the ABAQUS/Implicit. Thereafter the heat transfer analysis and thermal stress analysis was carried out using ABAQUS/Implicit.

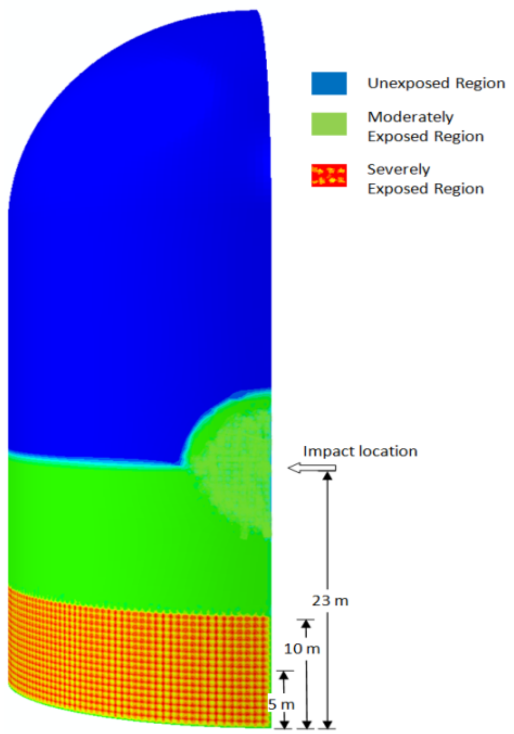


Fig. 1: Containment surface subjected to varying intensity of fire exposure

2. 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 not more than a few minutes. Therefore the impact location has been considered to be less important in terms of aircraft induced fire analysis, Fig. 1. On the other hand, the fuel flew down through the wall of the containment will accumulate at the base and result severe inflammation and fire pool effect up to 10 m height. Hence, the wall of the containment up to 10 m height from the base has been assumed to have severe exposure, Fig 1.

The intensity and time duration of the fire is another important factor affecting the response of the containment. The ignition of the aircraft fuel (jet fuel) is highly rapid such that the resultant fire immediately attains the peak temperature. The fire curve of Boeing 707-320 is shown in Fig. 2. The maximum temperature in the jet fuel and hydrocarbon fire is known to be as high as 1300ºC in an enclosed space for example inside a tunnel (Promat Tunnel, 2011). However, in open space the maximum temperature will not increase beyond 1100°C due to dissipation of heat. Hence, in the present study the increase in the fire temperature has been assumed to be up to 1100ºC while the ambient temperature considered 20ºC.

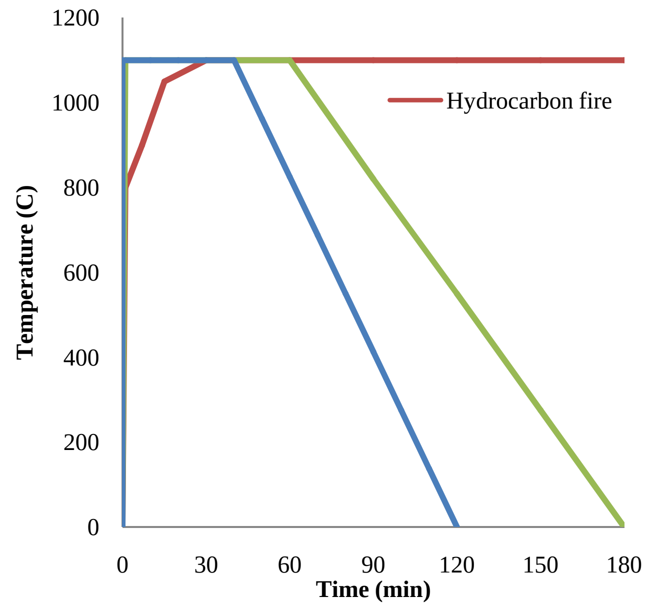


Fig. 2: Proposed fire curves

As such the time duration of the induced fire will be dependent up on the pool depth of the jet fuel accumulated at base of the containment. The pool depth on the other hand will be dependent on the fuel capacity of the given aircraft. Generally, irrelevant to the pool depth, 3-4 hours duration may be considered sufficient to start the fire fighting action. Hence, this time duration is often referred to as fire endurance time required for important structures (CES 2002, NRC 2003). The fuel carrying capacity of Boeing 707-320 is 61000 kg. For Boeing 767 aircraft, which carries approximately 90,000 kg fuel, Jeon et al., (2012) assumed fire duration of 3 hours. In the present study therefore, the fire duration of 2 hours respectively has been assumed for Boeing 707-320, see Fig.2. For simulating the fire at impact region however, these curves have been modified by lowering the fire intensity to 700ºC and reducing the time duration to 15 minutes.

2.1. Heat Transfer Analysis for BOEING 707-320 Aircraft

The heat transfer analysis has been performed on the BWR containment for the proposed fire curve of Boeing 707-320 aircraft. In order to plot the thermal gradient across the containment thickness, the path A, B and C have been identified as shown in Fig. 3 at 5 m, 10 m and 23 m height from the base respectively. The thermal gradient at "path A" and "path B" has been found to be almost same at different time duration, Fig. 4 (a) and (b). However, the magnitude of the nodal temperature at "path A" is slightly higher than that of "path B". Both of these points were lying under severe fire zone, however, the vicinity of moderate fire zone may be the reason of the slightly reduced magnitude at "path B". Moreover, at "path C" the maximum temperature has been found to be very low, 43°C, as a result of the decrease in fire intensity as well as the time duration. It can be noticed from

Fig. 4 (a) and (b) that after 1 hour time duration the temperature at the exposed face has been found to reduce. In the inside elements however, the temperature has been found to further increase, see the curve corresponding to 2 hours time duration. Similar trend can also be noticed in Fig. 4(c), however, in this case the temperature started decreasing just after 30 minutes.

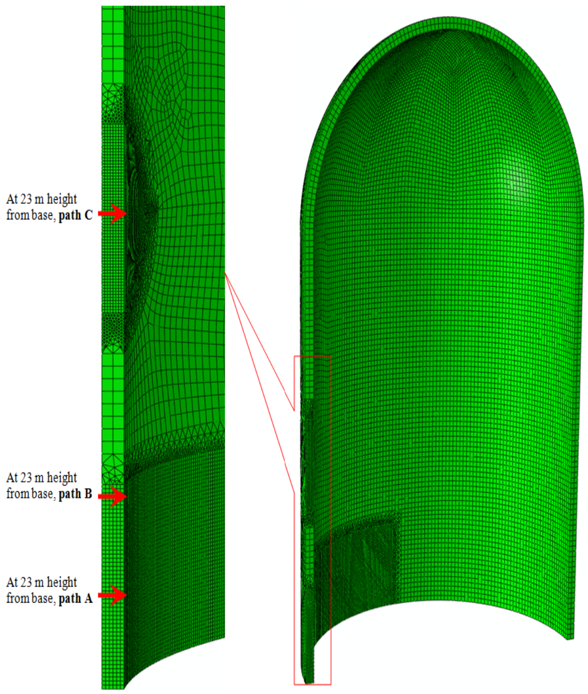
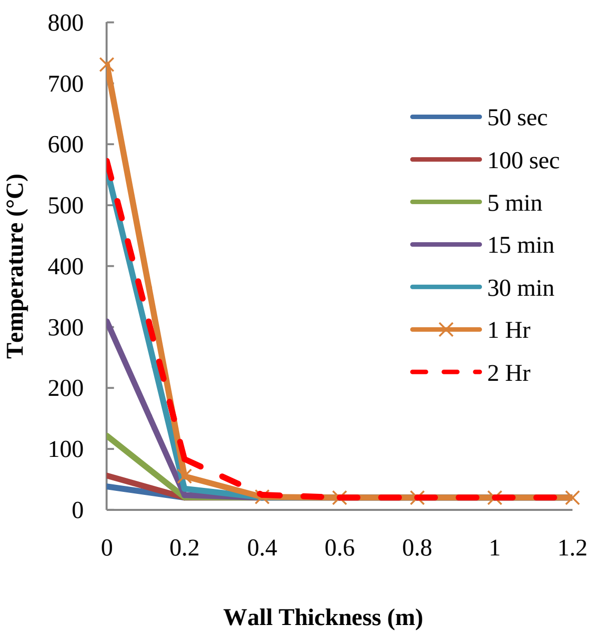
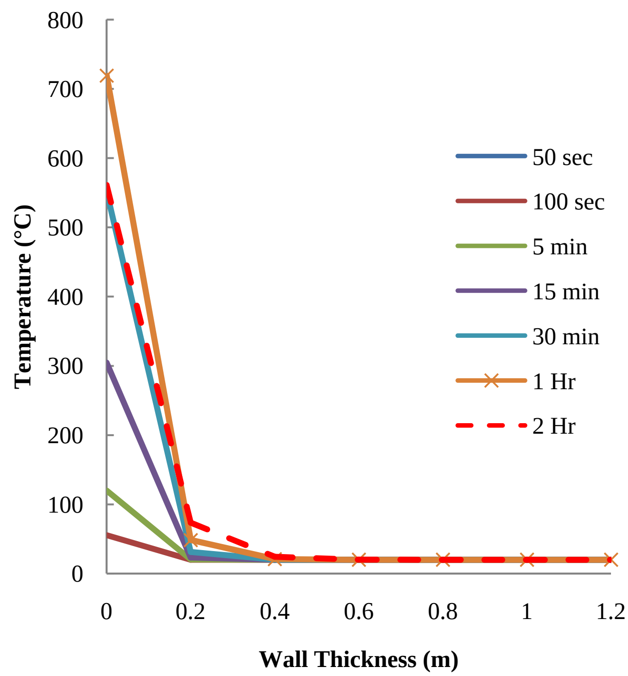


Fig. 3: Locations identified for plotting the temperature gradient across the thickness





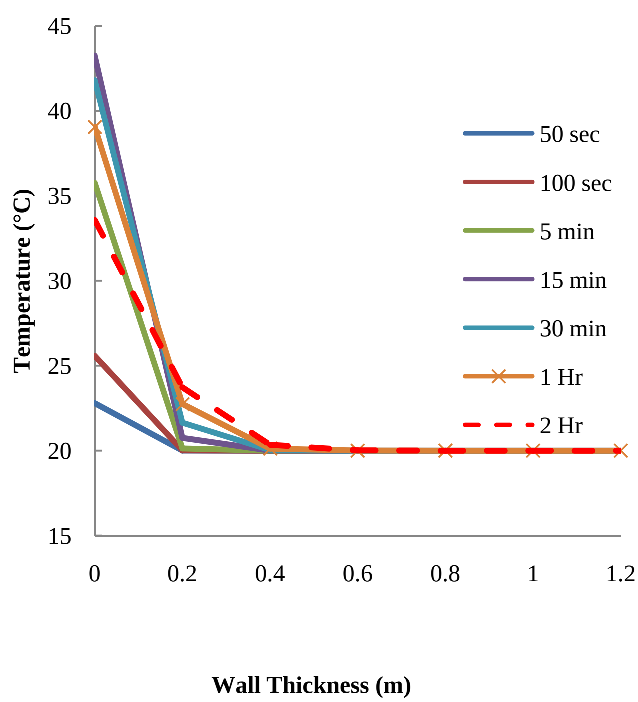


Fig. 4: Temperature gradient in concrete across the thickness of containment for Boeing 707-320 aircraft (a) at path A (b) at path B (c) at path C

3. IMPACT ANALYSIS

The main Impact analysis on BWR Mark III containment has been carried out using ABAQUS/Implicit scheme since ABAQUS/Explicit does not support the heat transfer analysis. Hence, the deformed profile of the containment obtained from the impact analysis and the nodal temperature obtained from the heat transfer analysis have been considered input for the thermal stress analysis. However, the constitutive model and the meshing characteristics of the containment have been considered identical to what have been employed in Sadique et al.(2013). It should also be noted that the loading has been assigned through the corresponding reaction-time curves of Boeing 707-320 aircrafts. Further, the average area approach has been employed for assigning the loading through the reaction-time curves.

3.1 Impact Response Against Boeing 707-320 Aircraft

In general majority of the aircraft fuel is contained in and around the wings (Jeon et al., 2012). Hence, in the present study it has been assumed that the fire will break out as soon as the wings come in contact. The wings of Boeing 707-320 aircraft have been seen to contact the containment after 0.2 sec. of the onset of strike. Hence, the break out of fire has been assumed to occur after 0.2 sec. of initial contact.

The implicit impact analysis has therefore been carried out until 0.2 sec. and the deformation obtained has been considered to be the input for the thermal stress analysis. The maximum deformation in the containment at 0.2 sec. has been found to be 38.35 mm at the impact location, Fig. 5 (a). A nominal outward bulging has also been noticed on the surface of the containment beyond the impact zone. The maximum displacement in the inner reinforcement has been found to be slightly higher than that of the outer reinforcement. The maximum displacement in the outer and inner reinforcement was 37.31 mm and 37.70 mm respectively, see Fig. 5 (b) and (c) respectively.

4. THARMAL 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 deformation and the stresses at the end of impact analysis have been considered as the initial state to evaluate the further damage of the containment due to the induced fire.

4.1 Fire due to BOEING 707-320 Aircraft

The variation of stresses across the thickness of the containment has been plotted at three different locations identified for plotting the temperature gradients (path A, B and C), Fig. 3. The deformation of the containment has also been plotted along path D highlighted Fig. 7. Along "path A", the exposed face of the containment was under nominal tension throughout the fire duration, Fig. 6.(a). However, the elements in the middle of the thickness have been found to be under compression. This behaviour may be due to the fact that the elements at the exposed face had a tendency of expanding while the

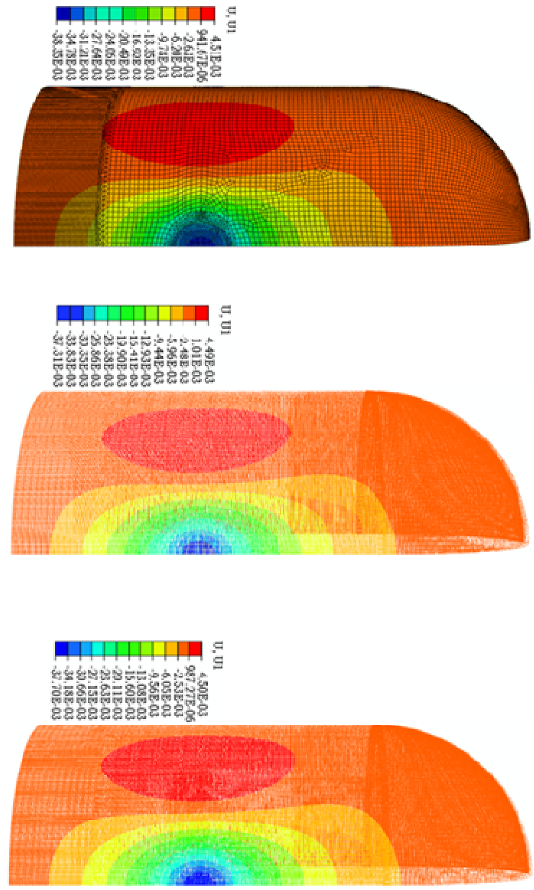
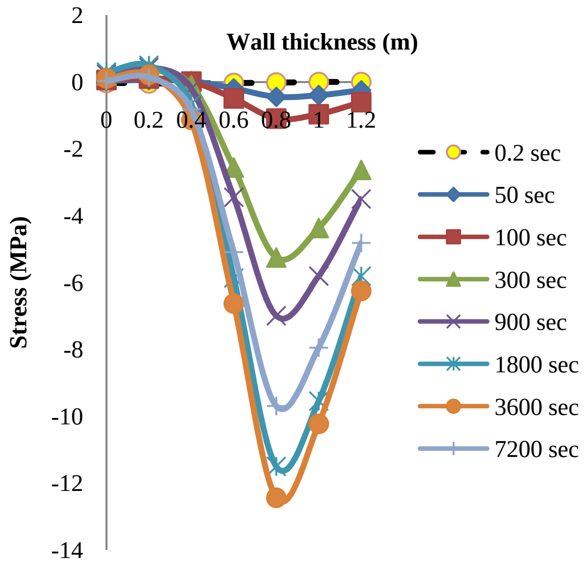


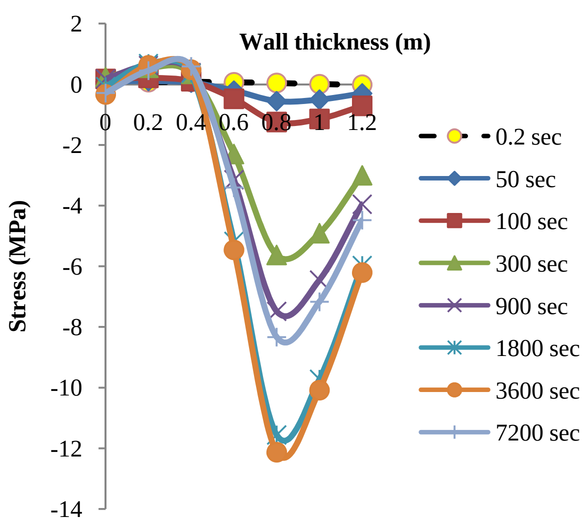
Fig. 5: Deformation contour before break out of fire against Boeing 707-320 aircraft (a) concrete (b) outer reinforcement (c) inner reinforcement

inner elements are restraining their expansion. The compressive stress has been found to increase with increase in temperature. After 1 hour of fire however, the temperature starts decreasing and hence the stresses. A similar pattern of stress variation has been found along "path B", however, the rate of stress decrement has been was found to be higher at this location, Fig. 6 (b). After 2 hours the maximum compressive stress was 9.6 MPa and 8.3 MPa along path A and B respectively. The variation of stresses along path A and B during the cooling face may be due to the fact that path B is located near the moderate exposed region. The pattern of stress gradient observed in the present study has a close agreement with the results of Jeon et al. (2012). However, due to the higher wall thickness (1.5 m), Jeon et al. (2012) found negligible stresses at the inner face of the containment.

The stress variation along path C has been plotted in Fig. 6 (c). It should be noted that path C is located at the impact region.

Before the application of fire the outer face of the containment was under predominant compression while the inner face under predominant tension. A maximum compressive stress of 4 MPa was noticed at the outer face of the containment along path C. At the corresponding inner face along path C, a maximum tension of 1MPa has been noticed. Due to the elastic recovery however, the trend of stresses has been found to have reversed. The complete elastic recovery has occurred within 100 seconds of the analysis. It should be noted that the fire effect in this region is insignificant. However, after half an hour of fire duration, nominal compressive stresses have been noticed at the front as well as inner face of the containment. The nominal compressive stresses at the front face might have been developed due to the loss of moisture content.





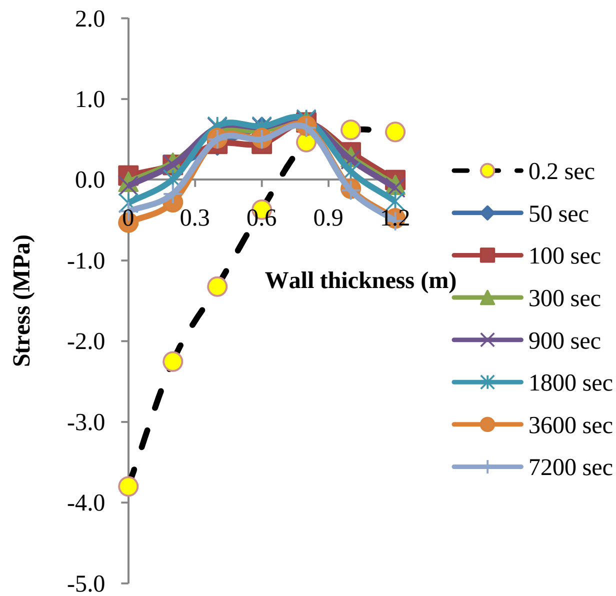


Fig. 6: Stress gradient in concrete across the thickness of containment for Boeing 707-320 (a) at path A (b) at path B (c) at path C

At the inner face however, a nominal compressive has been noticed. The elevation of temperature at the front face will cause a overall expansion at the this face, hence the entire opposite inner face will be under nominal compressive stress.

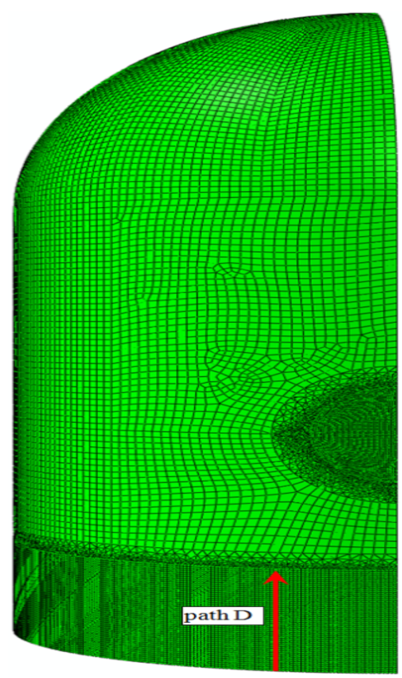


Fig. 7: Locations identified for plotting the displacement up to 10 m height from

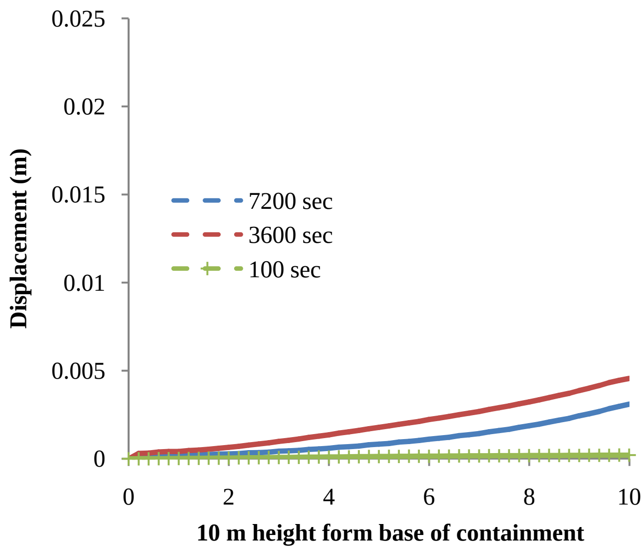


Fig. 8: Displacements in concrete along "path D" for Boeing 707-320 aircraft

The nodal displacement along path D has been plotted at selected time intervals in Fig. 8. An outside bulging can be noticed when moving up from the base of the containment. The displacement near the base is zero due to the fixidity of the containment. At a height of 10 m from the base a maximum displacement of 4.5 mm has been noticed after 1 hour of fire. Thereafter however, the recovery in deformation has been noticed due to gradual decrease in surface temperature.

5. CONCLUSIONS

Heat transfer, Impact and thermal stress analyses have been carried out using finite element code ABAQUS/Implicit. The effect of fire induced due to aircraft crash has been studied against Boeing 707-320 aircrafts. The impact of aircraft was considered to occur up to the point the engines came in contact. Thereafter the fire was assumed to have spread out since majority of the aircraft fuel is stored in and around the wings. The fire effect was considered to be most severe at the bottom of containment up to 10 m height from the base. At the impact region however, moderate fire effect has been considered. However, due to sharp fall in the thermal gradient across the thickness of the containment, the damage has been limited to few centimetres 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.

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