Nuclear Containment Wall under Aircraft Crash

A. Rawsan, P. R. Maiti

Abstract*: *The safety analysis of important structure such as nuclear power plant against commercial aircraft has been studied. In the present study, a stepwise sequential analysis has been performed to determine the stresses on the nuclear containment wall under aircraft crash and induced fire effects. ABAQUS/Implicit finite element code was followed to get the response of the nuclear containment. First, the impact load is applied on the containment using Riera force history curve of Boeing 707-320, after 0.16 sec nodal 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 Riera force history curve, time delay between plane's first contact and wing contact with the containment wall was assumed to be 0.16 second. The effect due to fire was considered to be most severe at 10 m height from the base of containment structure. This is due to the fact that post-impact most of the fuel will immediately flow down to the bottom of containment. In the impact region, moderate fire for 15 minutes has been considered. The fire duration has been considered for 2 hrs at severe zone. The deformed geometry of model in impact analysis is then assumed to be the initial state for the thermal stress analysis. The concrete damaged plasticity model for concrete and Johnson-Cook elastic-visco plastic material model for reinforcement have been taken to predict the behavior of concrete and steel. For heat transfer and thermal stress analysis, the material properties have been taken at elevated temperature form Eurocode 2. The containment has a circular cylindrical wall of inner diameter 42 m and thickness 0.85m excluding 6mm steel plate which was provided at the inner face of containment. The total height of the containment was assumed to be 60 m. The impact location of the aircraft was considered at the mid-height of the containment as more deformation was observed in this location.

Keywords* : *Reinforced concrete with steel liner, Impact, Aircraft crash, Nuclear containment, Heat transfer, Thermal stress.

I. INTRODUCTION

The safety analysis of important structures, like a nuclear power plant under a large commercial aircraft crash has been performed internationally after the terrorist attack in the U.S. on 11th September, 2001. Now a various important studies were performed on this topic to get the effect of accidental aircraft crash on important structures (Riera [1-2], Abbas et al. [3], Arros and Doumbalski [4], M. R. Sadique et al. [5], A. Rawsan et al [6]). Generally there are two types of nuclear containment wall, one is inner and other is outer. The function of the inner containment wall is to control the leakage of radioactive radiation while the outer containment wall provides the safety against external hazard. Through experiments it is very difficult to get the response of the nuclear containment wall for impact and thermal due to the massive cost.

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So, a lot of researchers have simulated the model of containment wall numerically to get the response of containment through an aircraft crash. Abbas [7] and Kukreja [8] analysed the outer containment wall using load versus time history curve for Boeing 707-320 and many aircrafts. After that, Jeon et al. [9] evaluated the response of a nuclear containment wall against fire resistance for a large commercial aircraft crash. The present study focuses on the studying the behavior of a nuclear containment of outer concrete layer 0.85 m thick with 6 mm thick steel liner and 60m high against the impact of an aircraft and its subsequent fire induced stresses. Some work has already been done on this type of problem where the force history curves obtainable by many authors or an actual/ arbitrary model of an aircraft was made to hit on the containment wall to see the behavior of the wall and its failure. It has also been observed by many researchers that the concrete material exhibits dissimilar behavior under different conditions of loading such as compressive or tensile loading, rate of loading, strain rate variation, temperature etc. Aircraft crash on the containment is a complex subject where such kind of concrete behavior is encountered. Many materials like Concrete exhibits elasto-plastic behavior with plastic hardening (or softening). In the present study concrete damaged plasticity model has been incorporated for the behavior of the concrete available in Abaqus/Implicit which is finite element analysis software. The rate of change of loading makes variation in strain rate in the concrete material and these effects have been included for the concrete using the strain rate dependent data. It is understandable that after the impact of aircraft on containment wall, the heat will be formed due to the fuel scattered at the bottom surface of the containment and the heat produces the temperatures as high as 1200 degrees Celsius. For this phenomenon the thermal stresses will be generated in the structure wall along with the impact stresses. Hence, the material properties at elevated temperature for concrete and reinforcement bar have been taken from Eurocode 2 [10]. In the first step impact analysis was done for force-time history of Boeing 707-320 aircraft on the model. This was followed by a heat transfer analysis. Finally, an analysis due to thermal stress was performed by importing the distorted shape of the model as initial form in the thermal stress analysis. For heat transfer analysis, fire is assumed to continue for 2 hours at bottom level of the containment up to a height of 10 meters from base and for 15 minutes at impact region by Jeon et al. [9].

II. NUMERICAL METHODOLOGY

The nuclear containment wall has been modeled as 3D deformable solid elements whereas the reinforcement bar was modelled as 3D deformable wire elements. The geometrical dimension of the model of nuclear containment has been considered identical to Creys-Malville reactor.

The cylindrical containment wall has 42 m inner diameter and 0.85m thickness excluding 6mm steel liner which was provided at the inner face of containment shown in Fig. 1.The total height of the containment was 60 m. The thickness of wall is constant throughout the containment and the base of the containment structure has fixed supports. The containment wall is doubly reinforced section with 40 mm dia bars which are placed at 80 mm c/c at the inner as well as outer surface of the cylindrical containment wall and the effective cover for concrete is 100 mm. The rebars are modeled in the structure using radial / linear pattern option which is available in ABAQUS/CAE. The reinforcement details in structure have been shown in Fig. 1.

Riera [1] calculated the reaction force for the deformable aircraft over the target area and plotted the response as the force history curves. These force history curves for Boeing 707-320 aircraft have been used for applying the loading over the target structure. In the present model, 90 MN load was applied over an area of twenty eight square meters in the form of force history curves for Boeing 707-320 Airbus as shown in Fig. 2. The application of load for normal impact of Boeing 707-320 aircraft on target area is shown in Fig. 1.

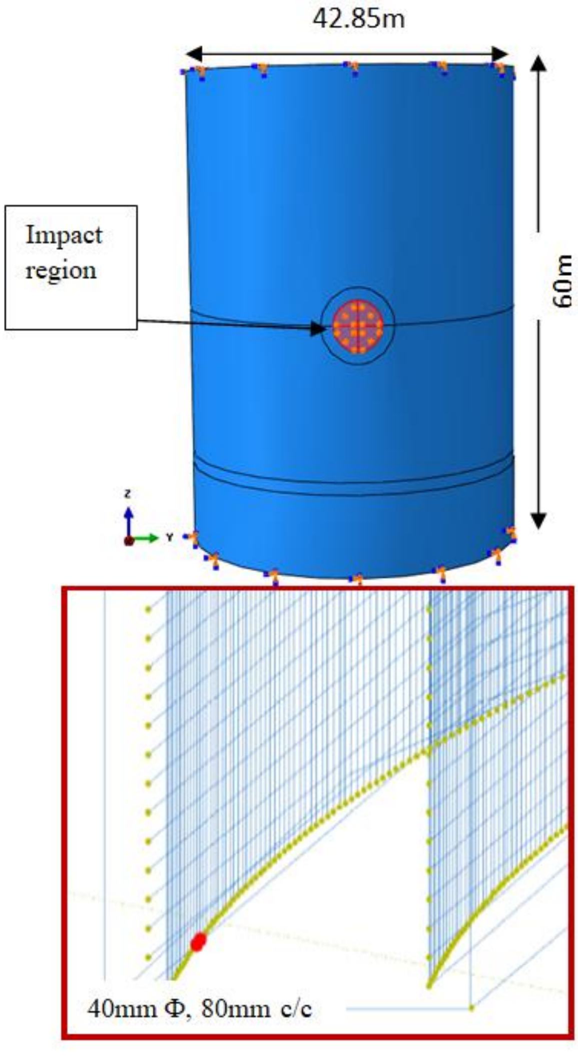


Fig.1. Outer containment structure with impact region and Reinforcement details

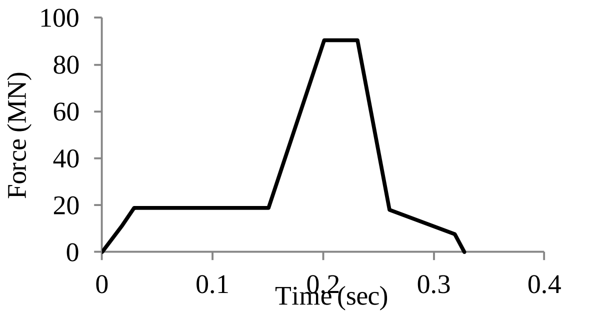
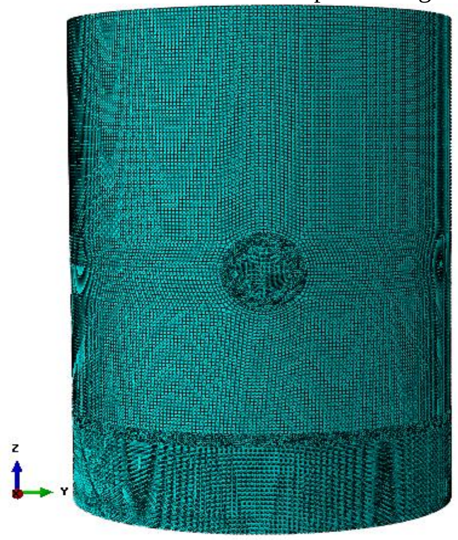


Fig.2. Force versus time curve of Boeing 707-320 Airbus

The containment wall was separated into different regions for a suitable meshing. The model was meshed for the simulation with lot of care to overcome the unnecessary distortion of the elements. The meshing details for the structure have been shown in Fig. 3. The diameter of impact region was considered 6 m for Boeing 707-320. The impact region was meshed with 3D, reduced integration, 8 noded brick elements with size 212.5 mm x 212.5 mm x 212.5 mm which give 4 elements at thickness of the containment. The outer region of containment wall was meshed with 425 mm x 425 mm x 425 mm and in-between region was meshed with tetrahedral elements of different size [varying from 212.5 mm (at the inner edge) to 425 mm (at the outer edge)]. The bottom section which is 10 m height from the base of containment was meshed with four elements along the thickness. The reinforcement was meshed with two noded 3D truss element of size 600 mm throughout the containment in the meridonial as well as circumferential directions. The size of reinforcement was considered same throughout the containment. The steel plate was also modeled with 425mm eight noded brick element. The total elements in the structure was found 552325 (C3D8R), 41455 (C3D4) and 322560 (T3D2).

The containment structure has also been simulated to get the response for the fire induced effects due to aircraft crash. The meshing details in heat transfer analysis are almost same to the mashing of impact analysis; however there is minor modification in type of element. The element types were taken as DC1D2 for reinforcement, DC3D8 for whole concrete model and DC3D4 for transition zone. The size of reinforcement elements was kept unchanged.



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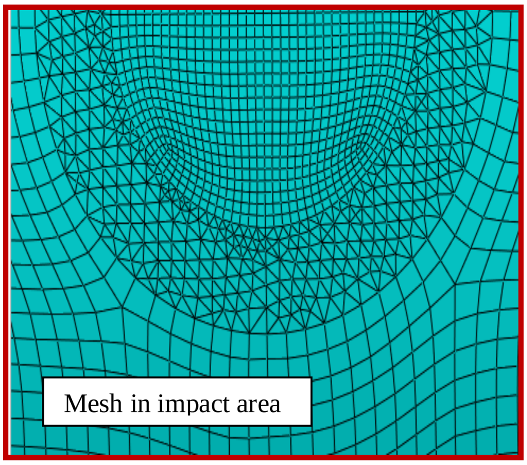


Fig.3. Meshing detail of containment wall

In the current study, the interaction between the elements of reinforcement and concrete has been assigned using embedded constraint option in impact as well as thermal stress analysis. It was considered that the reinforcement as the embedded and the concrete as the host element. However, embedded constraint is not used for heat transfer analysis. Then a surface-based tie constraint was used in heat transfer simulations.

III. MATERIAL MODEL AND ITS PROPERTIES

The behaviour of concrete has been incorporated using concrete damage plasticity model which is available in the library of Abaqus and the material properties for reinforcement behaviour, the Johnson cook model was used. The material properties under compression and tension have been considered damage plasticity model because it has the scope for using strength rate strain rate behaviour of material. It was also assumed that the material may fail under tension or compression cracking. The stress strain curve for concrete under tension and compression has been shown in Figure 4 (a) and 4 (b). The mathematical equation to draw stress and strain curve for different damage parameters are given in the below equation.

$$\sigma_t = (1-d_t)E_0(\varepsilon_t - \tilde{\varepsilon}_t^{\,pl}) \quad \sigma_c = (1-d_c)E_0(\varepsilon_c - \tilde{\varepsilon}_c^{\,pl})$$

Where d_t and d_c are the damages variable and can be represented by the given equations.

$$d_t = d_t(\tilde{\varepsilon}_t^{\,pl}, \theta, f_i)i \qquad d_c = d_c(\tilde{\varepsilon}_c^{\,pl}, \theta, f_i)i$$

Where $\tilde{\varepsilon}_t^{\,pl}$ and $\tilde{\varepsilon}_c^{\,pl}$ are the equivalent plastic strains under the tension and compression. In the current research the behaviour of concrete under compression has been taken from Sinha et al. [12] and Grote et al. [13]. The behaviour of concrete at very low strain rate under cyclic load was performed by Sinha at al. Analysis of nuclear containment wall under impact load should consider the material behaviour at the varying strain rate and which are taken from Abaqus material library. The properties of concrete under tension have been taken from Lu and Xu [14]. The property of material for concrete behaviour has been shown in Table 1.

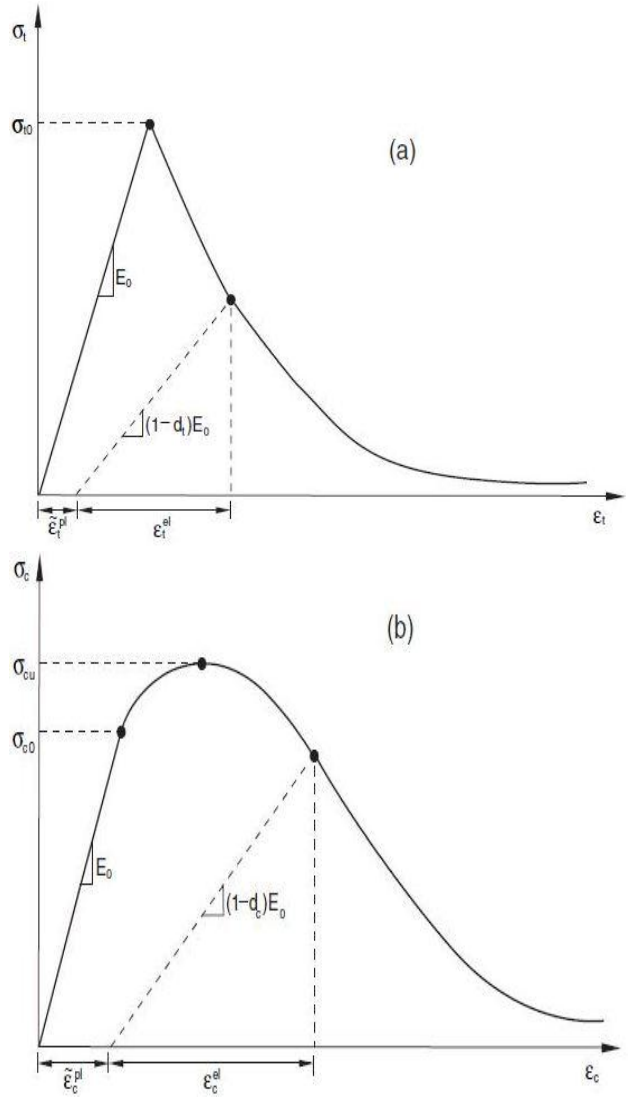


Fig. 4 Stress-strain curve of concrete under (a) tension (b) compression

The behaviour of concrete at high temperature is fully different from normal temperature. When the temperature increases the strength of concrete gradually decreases and that is obtained from Eurocode. The stress strain curve for concrete at elevated temperature has been plotted from Eurocode and shown in figure 5. The grade of concrete was M30 for the stress strain diagram. Von Mises stress incorporates the combined result of strain rate and temperature which is given in the below equation.

$$\bar{\sigma}(\bar{\varepsilon}^{pl}, \dot{\bar{\varepsilon}}^{pl}, \hat{T}) = \left[A + B(\bar{\varepsilon}^{pl})^n\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \hat{T}^m\right]$$

Where B is hardening constant, n is hardening exponent, A is yield stress, C is strain-rate parameter, m is temperature parameter, $\bar{\boldsymbol{\varepsilon}}^{\mathbf{pl}}$ is equivalent plastic strain, $\dot{\bar{\boldsymbol{\varepsilon}}}^{\mathbf{pl}}$ is equivalent plastic strain rate, $\dot{\boldsymbol{\varepsilon}}_{\mathbf{0}}$ is reference strain rate.

Thermal expansion coefficient of steel was taken 1.35×10-5 per degree C and it was also assumed that value of coefficient is constant throughout the analysis and varying temperature. The properties of steel for this model have been shown in Table 2.

Table 1 Properties of concrete

Modulus of elasticity(N/m^2)	2.7386E+10
Poisson's ratio	0.17
Dilation angle	30
Eccentricity	1.0
Density (kg/m^3)	2400
Bulk Modulus, K	0.666
Fracture Energy (N/m)	720
Uniaxial Failure Stress under Tension(MPa)	10.8
Cracking displacement (m)	0.0001332
Tensile strength (MPa)	3.86
Compressive Strength (MPa)	30

Table 2 Properties of steel reinforcement bar

Young's modulus (N/mm^2)	$2x10^5$
Poisson Ratio	0.33
Density (Kg/m^3)	7850
Yield stress (N/mm^2)	490
B- strain hardening parameter (N/mm^2)	383
n (strain rate parameter)	0.45
Reference strain rate (s^{-1})	$5x10^{-4}$
C (strain rate sensitivity)	0.0114
m (adiabatic thermal softening parameter)	0.94
T_{melt} (K)	1800
T_0 (K)	293
Specific heat (J/ Kg K)	452

At elevated temperature, the stress strain curve for steel bar has been plotted from Eurocode and shown in Figure 6.

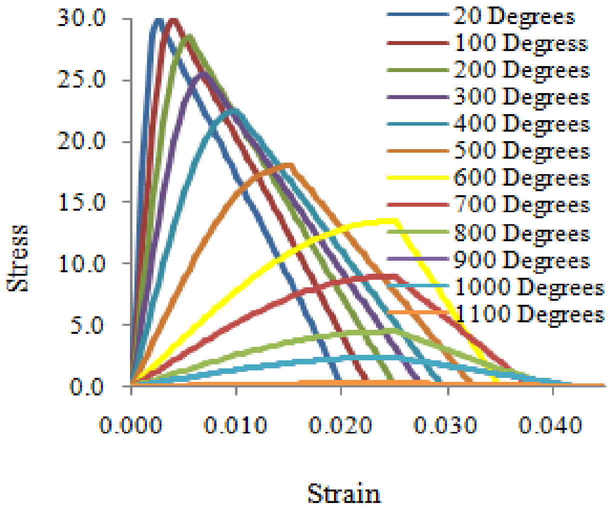


Fig.5. Stress-strain curves of concrete at elevated temperature from Eurocode

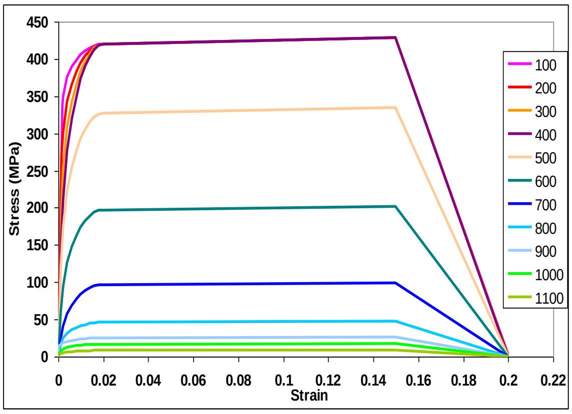


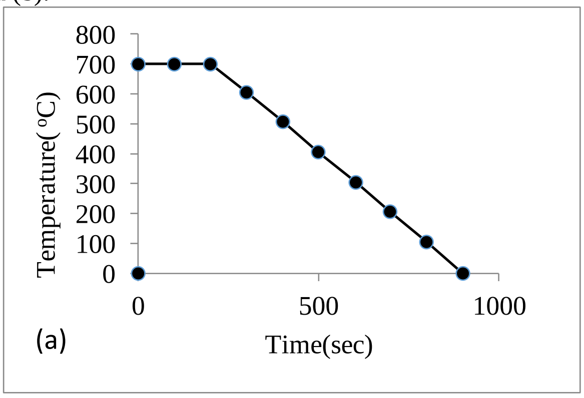
Fig.6. Stress-strain curves steel rebar at elevated temperatures from Eurocode

IV. RESULT AND DISCUSSION

The behavior of the containment wall under the induced fire due to an aircraft crash depends upon fuel capacity of an aircraft and conditions of the weather. The induced fire will be generated when the fuel tank of aircraft come in contact with the containment. To get the best response of containment wall the thermal stress has been considered after impact analysis. In the current study, the impact location for the Boeing 707- 320 aircraft has been considered at the mid height of containment structure (30 m from the base). The distorted shape of the structure which is obtained from the impact analysis has been considered as the initial state for the thermal stress analysis. The heat transfer analysis has been performed to get the nodal temperatures in the elements of containment structure.

A. Heat transfer analysis

When the aircraft crash on nuclear containment wall occurred, the fuel which is stored in wings of aircraft spread and flows down immediately at the base of containment. So, Fire was applied on the impact location of structure for few minutes and the 10 m height from the base of containment structure was assumed to be severe condition. The jet fuel curves of Boeing 707-320 aircraft are shown in Fig. 7 (a) and (b).



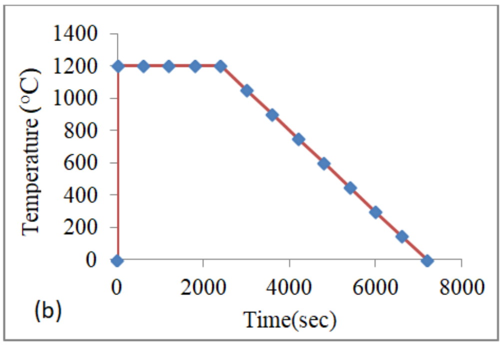


Fig.7. Proposed jet fuel curves for (a) Impact region (b) High exposed area

Variations of temperature along the thickness at 5m, 10m, 15m and 30m from the base of containment have been shown in Fig. 8 for 1000 sec, 3000 sec and 7200 sec respectively. The thermal profile of concrete and reinforcement due to the crash induced fire has been plotted for maximum temperature in Fig. 9. It was observed that the maximum penetration of heat along the thickness was 200 mm approximately for all the cases. No significant increase in temperature beyond the ambient was noticed at the steel liner.

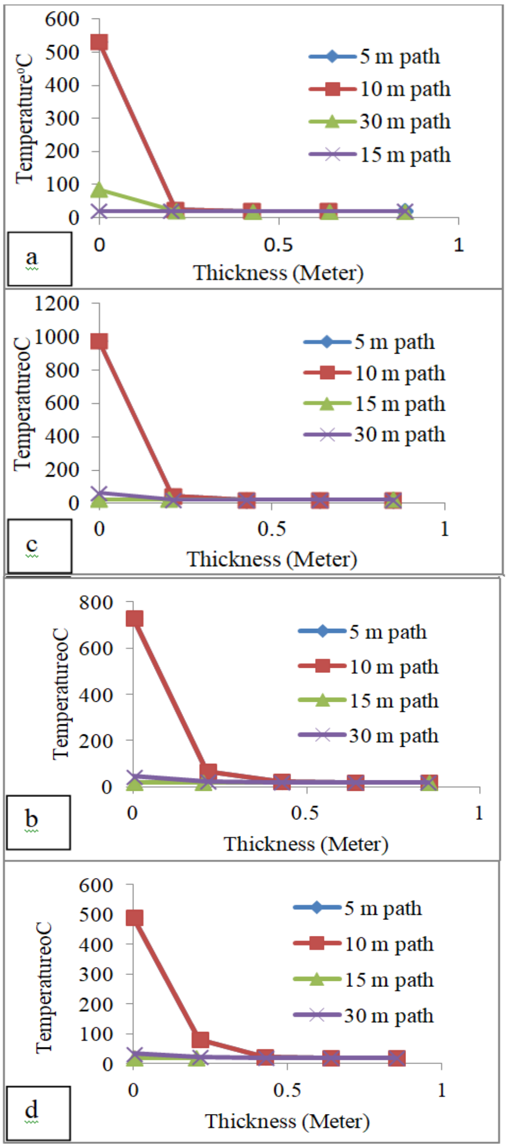


Fig.8. Variations of temperature along the paths at (a) 1000 sec (b) 3000 sec (c) 5000 sec (d)7200 sec

B. Impact analysis

The deformed shape of the structure which is obtained from the impact analysis and the nodal temperature which is obtained from the heat transfer analysis has been incorporated in the thermal stress analysis. The average area approach was used for assigning the loading through the reaction-time curves.

Most of the cases, in or around the wings of the aircraft contains the fuel (Jeon et al. [9] Hence, the fire is assumed to start 0.16 sec after the initial contact (M. R. Sadique et al. [5] and A. Rawsan et al. [6]). The implicit impact analysis has therefore been carried out until 0.16 sec and the deformation state obtained considered as the input for the thermal stress analysis.

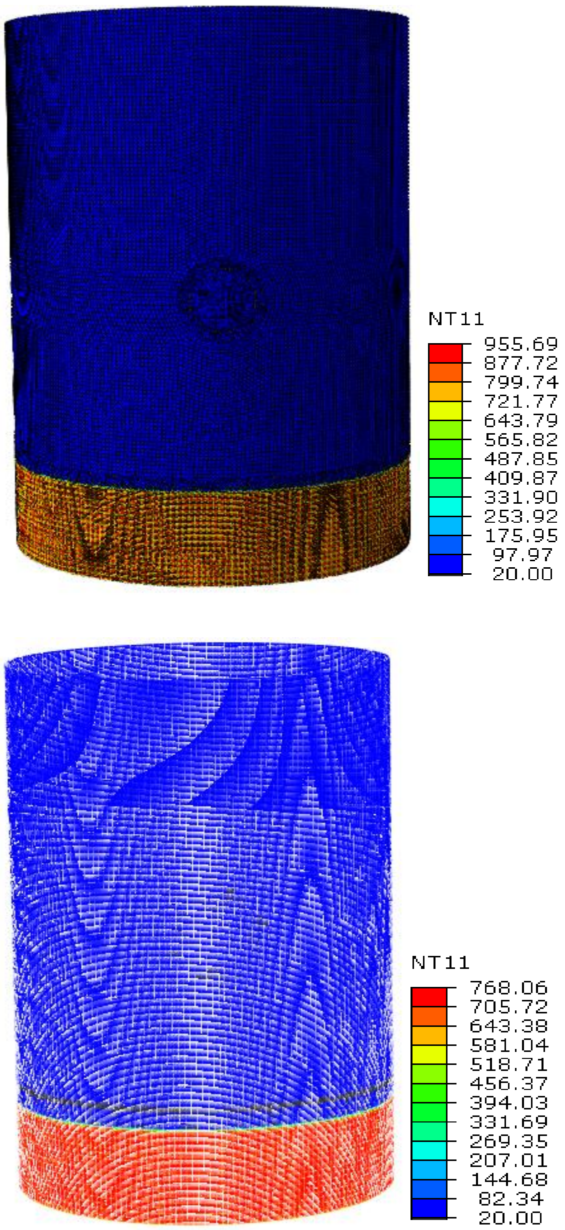


Fig.9. Thermal profile at 3000 sec. (a) concrete (b) reinforcement

In this case, the impact load was applied along the X direction (thickness). The maximum deformation in the containment at 0.16 sec. has been found to be 24.9 mm at the impact location shown in Fig. 10. The maximum compressive stress in concrete was observed 12.8 MPa at outer face and tensile stress in concrete was observed 5.7 MPa at the inner face of containment as shown in Fig. 10. A maximum stress 77.9 MP has been found in reinforcement while the peak stress in steel liner of 66 MPa has been noticed at impact region, Fig. 11.

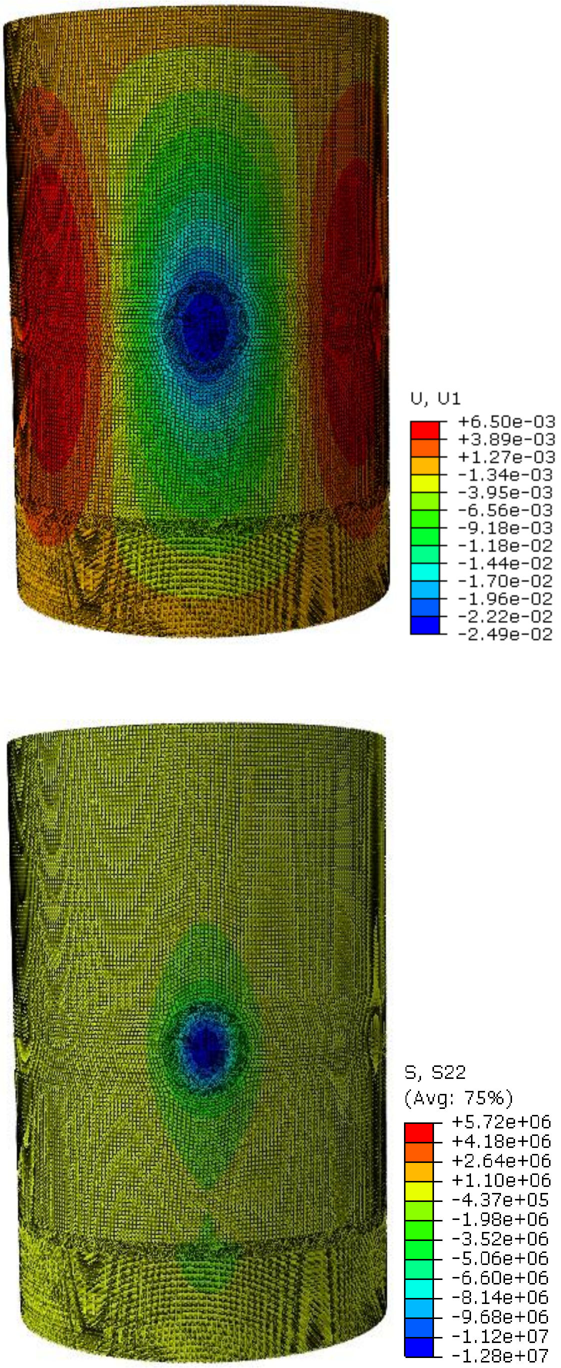


Fig.10. Deformation profile at time 0.16 sec and Stress profile at time 0.16 sec for Concrete

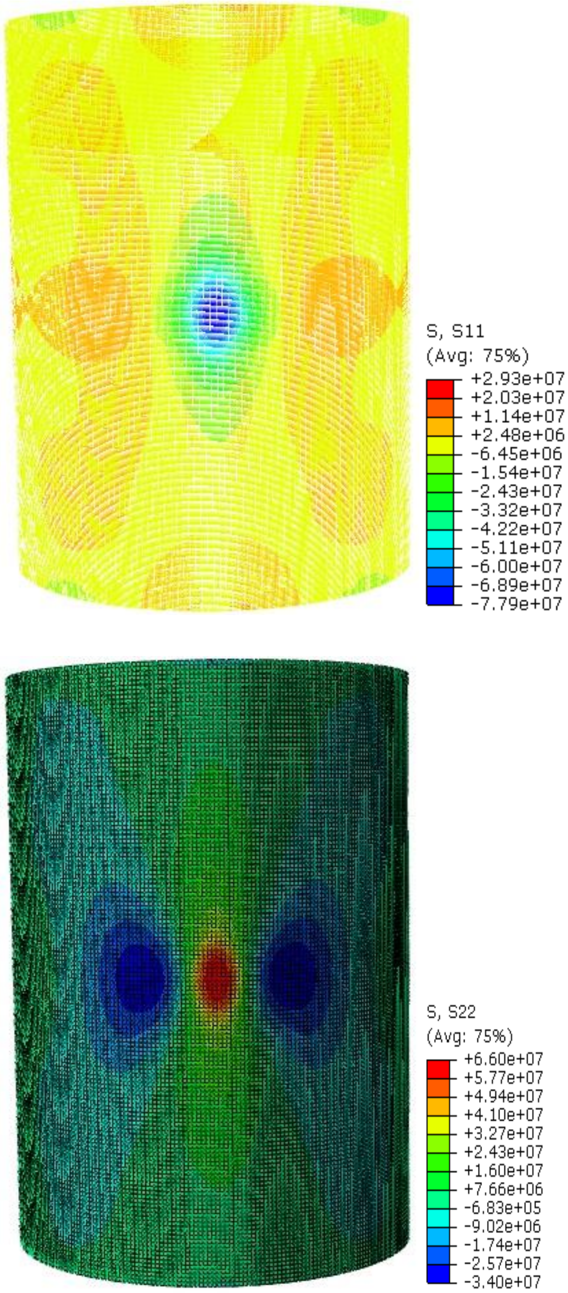


Fig. 11 Stress profile at time 0.16 sec for (a) Reinforcement (b) Steel Liner

C. Thermal Stress Analysis

After performing the impact as well as heat transfer analysis, the thermal stress analysis were carried out to get the resultant stress on the structure by coupling the results. The thermal stresses were obtained for some selected frames of the heat transfer analysis results.

The variation of stresses along the thickness of the wall has been investigated at impact region (Fig. 12) and 5m height (Fig. 13).

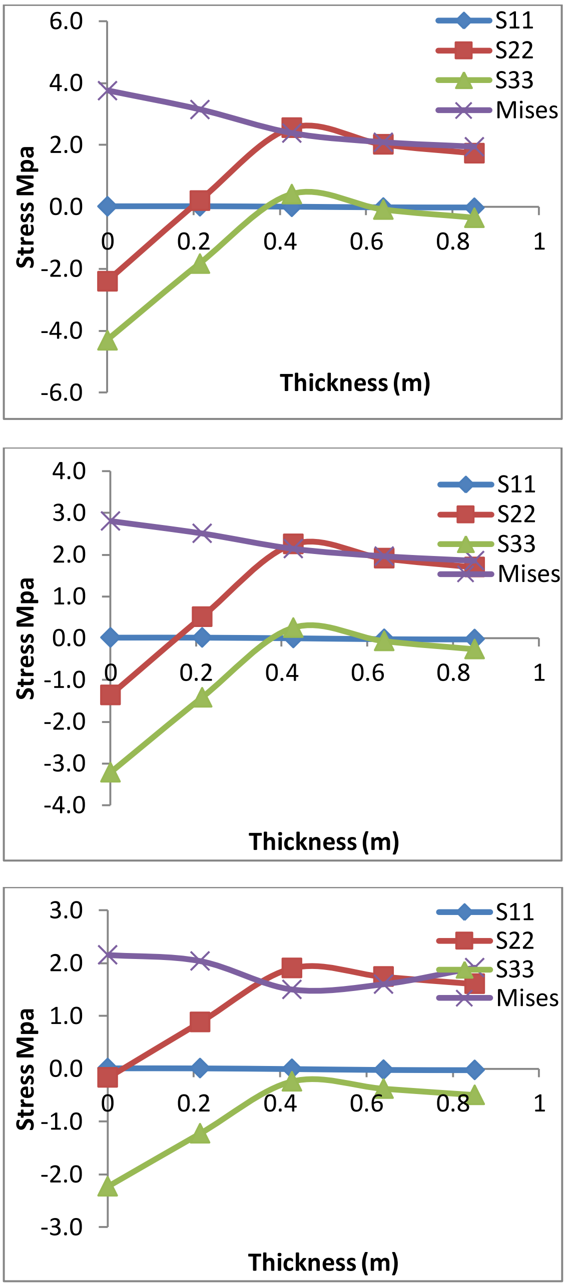
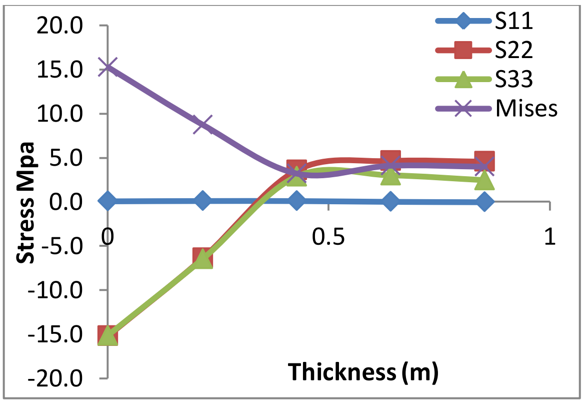


Fig.12. Thermal stress along the thickness at impact region for 1000, 3000, 5000sec



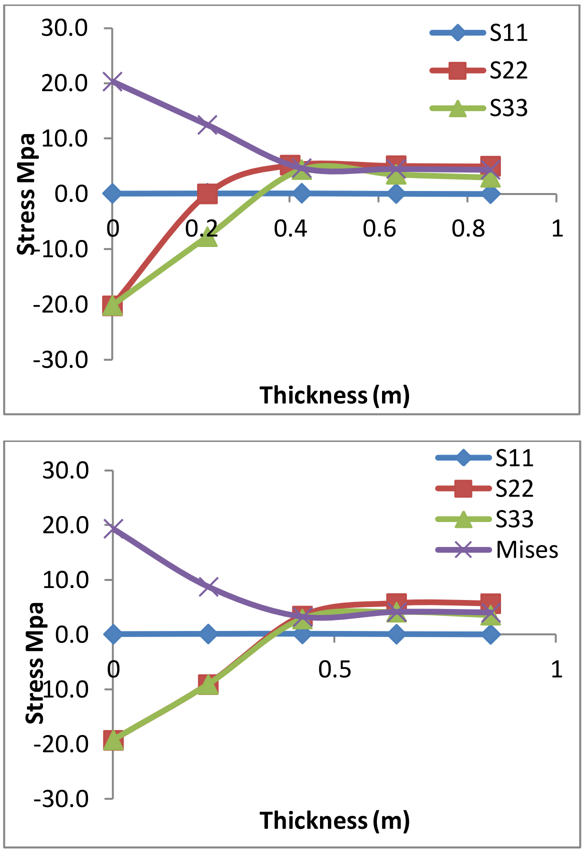


Fig.13. Thermal stress along the thickness at 5m height from base for 1000, 3000, 5000sec

V. CONCLUSION

In the present study an attempt has been made to find out the behavior of the RC containment with a solid steel liner 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 707-320 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 clearly observed that the maximum penetration of heat along the thickness of containment wall is 200mm and rest of the depth remains at ambient temperature of 20^{0}C. The same matter was also noticed through the mesh convergence studies also.
2. Impact analysis showed a maximum displacement of 24.9 mm (in the direction of impact) for an applied load for 0.16 sec for reinforced cylindrical containment with steel liner. 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 955^{0}C were observed during thermal loading in the 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 5 MPa was observed in M30 grade of concrete in RC containment with steel liner. However, the structure was found to maintain its integrity with no visible damage in the containment. This indicates that the steel liner may arrest the tensile cracking otherwise possible in concrete due to high tensile stress.

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