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I, **Alim Rawsan**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. Pabitra Ranjan Maiti** from *July-2016 to February-2021*, at the *Department of Civil Engineering*, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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ABSTRACT

Nuclear power is considered as a reasonable, cheapest and effective energy source, however, there is an associated risk of nuclear radiation. There is always a chance that exposure to some amount of ionizing radiation from the nuclear plant that can harm cells or tissues. Leakage of nuclear radiation can cause cancer and other health problems in human being and these effects continue for a long time. The matter of NPP safety and sustainability against aircraft crash is more worried after 9/11 terrorist attack and aircraft crash with Twin Towers in the United States. The aim of the NPP containment structure is to isolate radioactive materials. To avoid the release of radiation in the case of any internal failure, the innermost structure consists of either steel or high-strength RC concrete. To protect the internal containment structure from any external threat, the outer containment is designed as a thick RC concrete structure. Furthermore, it offers a final protective layer to prevent the exposure of radioactive radiation to the atmosphere. The nuclear containment systems are typically designed in two layers, taking into account the associated risk.

In the present study, the impact due to aircraft crash on RCC outer containment wall of nuclear power plants (NPPs) has been studied. The outer most containment of four well-known NPP structures i.e. Creys-Malville Reactor (CMR), Fessenheim and Bugey Reactor (FBR), Boiling Water Reactor (BWR Mark-III) and Three Mile Island Reactor (TMIR) containment have been considered and impacted by fighter and commercial aircrafts to determine the most vulnerable location or most susceptible to damaged prone zone on the outer wall. The dimension of each containment structure is

different in size and shape.

Th material of the NPP containment structure is made up of concrete and steel rebar. For the actual behaviour of concrete material, the Concrete Damaged Plasticity (CDP) model is used. CDP model that based on combined fracture mechanics and plasticity mechanics is used to evaluate the failure mechanism of the concrete structure. This model defines the significant features of the concrete failure mechanism subjected to multi-axial loading. The behaviour of material for the aircraft as well as the steel rebar has been taken using the Johnson-Cook (J-C) material model that is capable to predict the fracture and flow nature of the ductile materials. In general, the material strength decreases with increasing in temperature. Therefore, in heat transfer and thermal stress analysis, the parameters of the material properties (steel and concrete) at different temperatures are taken from Euro-code 2.

The numerical analysis of NPP structure has been carried out using explicit and implicit integration scheme available in ABAQUS finite element solver software. Initially, simple PCC, RCC flat plate and RCC cylindrical wall have been analyzed under different impact loads due to aircraft crash. Thereafter, real NPP structures have been analyzed numerically subjected to different aircraft crash. The aircraft Boeing 707-320, Boeing 767-400, Airbus A320, and Phantom F4 have been considered to impact the containment wall. Out of these four, the Phantom F4 is a fighter jet whereas all other three aircrafts are commercial aircrafts. The heaviest aircraft is Boeing 767-400 and high-speed aircraft is Phantom F4 among considered aircrafts.

At first hypothetical PCC and RCC flat plate has been analyzed under the impact of Boeing 707-320 and Phantom F4. It is observed that the aircraft Boeing 707-320 has less damaging potential than Phantom F4 fighter jet. Thereafter a hypothetical cylindrical RCC wall similar to cylindrical portion of BWR mark-III is impacted under Boeing 707-320 aircraft. In this model both ends are fixed supported whereas BWR containment has one end fixed and upper end is fixed with dome roof. For the case of both end fixed cylindrical wall the most damage prone zone is observed at the mid height of the wall. When the real BWR subjected to same impact load shows the maximum deformation lies above mid height of the wall. It may be due to the different boundary condition (dome roof) at the top of the cylindrical wall in real condition.

TMIR has not been analyzed previously by any researcher. An effort has been made to perform the detail analysis of the outer containment wall subjected to different impact and thermal loads due to different aircraft crash. The minimum tension damages are observed in TMIR due to more thickness of the containment. It is seen that the Boeing 767-400 aircraft has more damaging potential among all considered aircrafts. As the velocity of aircraft impact load is very high, strain rate is an important parameter on the material behavior of the containment. The containment wall is also studied for different strain rate to get the most suitable value of strain rate that gives best results. The parametric study has been carried out for different thickness of NPP wall, % of steel reinforcement in wall, radius of curvature of wall, impact angle of aircraft and velocity of aircraft.

The results showed the most damage prone containment is Creys-Malville and less damage prone is Three Mile Island due to impact load of Boeing 707-320 aircraft. The maximum tension damages are observed at impact location in CMR due to less thickness of the containment. The damage due to aircrafts crash over the containment structure is not a global failure. It was also observed that when the wings of aircraft came in contact with NPP containment, the deformation and stress developed in the structure is maximum.

The aircraft's reaction time curve can be used effectively to reliably predict the response of the containment structure. The current approach is used to determine aircraft reaction-time response curves against a rigid target and non-rigid target. Many authors used the reaction time response curve on rigid target but in real the target is non-rigid. In present study, the target is assumed as flexible. The geometric model of the aircraft Boeing 707-320 is therefore developed and the associated response time curve is achieved assuming non - rigid and rigid targets of varying curvatures. It was found that the curvature and rigidity of the target has a major impact on the aircraft's reaction-time response. With increasing target curvature, a decrease in the peak reaction force has been developed. The reaction magnitude for same curvature given by the deformable target is smaller than the non-deformable target. The reaction-time curves therefore generated are compared with the results obtained by the analytical expressions available in literature.

The influence of the contact area using two separate approaches for the application of the reaction-time curve has been investigated. In the first method, for the application of the curve, an average of the total aircraft contact area is considered. The method of trifurcation is considered in the second technique. It was found that the average area approach for the loading application overestimated the local deformation and stress while the trifurcation approach is more precise.

The reaction-time curves and the subsequent contact area thus obtained are idealised and used to find the containment's response. The aircraft's geometric model developed numerically is used to hit the containment at the most damaging zone. The containment response has been found in terms of local deformation, global deformation, stresses developed in concrete and steel reinforcement and the subsequent material degradation. The results that are obtained are compared and discussed in accordance with the reaction-time curve and the geometric model. It is found that the containment response against the reaction-time curve and the approach of the aircraft geometric model with the trifurcation method are in close agreement.

The influence of fire due to crash of aircraft Boeing 707-320 has been studied. A step-by-step analysis was carried out to evaluate the stresses on the NPP wall due to aircraft crash with induced fire. First, the impact load was applied to the structure using force history curve of Boeing 707-320 aircraft and the angle of impact was considered as normal to the target. After impact the nodal temperatures were applied to the model through heat transfer analysis using jet fuel curves due to fuel burning. Finally, the impact and heat transfer effect has been combined to get thermal stress variation. The time gap between the impact of plane’s nose and plane’s wing is 0.18sec. So, heat transfer analysis has been performed after that time because fuel is stored in wings. The NPP containment wall along the height is segmented into three heat intensity regions i.e., severe, moderate and low intensity. The most severe region for the effect of fire is upto10 m height from the foundation because the maximum fuel will flow down to the bottom of structure. The analysis of heat transfer has been performed to get the nodal temperature in the steel reinforcement as well as concrete elements. For Boeing 707-320, the fire period has been considered to be 2hrs. Thermal stress analysis is subsequently carried out considering the

deformed geometry of the containment as the initial state due to the impact of the aircraft. From heat transfer analysis, it is observed that the average penetration of heat is approximately 250 mm along the thickness of the wall. The stresses caused by the induced fire have been observed to induce local concrete damage (scabbing). The induced fire due to Boeing 707-320 aircraft crash has no global effect on the TMIR NPP containment structure.

Keywords: Nuclear Containment Structure, Impact loading, Aircraft crash, Boeing 707-320, Water Reactor Mark-III NPP, Three Mile Island NPP, Thermo elastic analysis