Study on the Optimization of APC (Air Plane Crash) Countermeasures for Nuclear Power Plants Using Finite Element Analysis

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ABSTRACT

This study aims to establish a numerical simulation framework based on the finite element method (FEM) using an interaction-based approach, under the scenario of an airplane crash (APC) into a nuclear power plant. After verifying the concrete material models and confirming the validity of the aircraft model, a realistic and high-fidelity impact analysis was successfully performed. The ultimate goal is to propose a design guideline that ensures sufficient structural resistance with minimal reinforcement. This will be achieved by quantifying damage zones, evaluating residual capacities, and defining threshold criteria for reinforcement.

I. Background and Motivation

Since the terrorist attacks in the United States in 2001, deliberate airplane crashes (Airplane Crash: APC) have been recognized as a serious threat to critical infrastructure. Nuclear power plants, in particular, are considered high-risk targets due to their nature, and structural countermeasures to enhance safety have been internationally demanded. Conventional APC impact assessments often rely on simplified load models, but these are frequently criticized as being either overly conservative or lacking realism when applied to actual plant designs.

II. Objective

The objective of this research is to clarify the necessary and sufficient conditions for cost-effective APC countermeasures through numerical simulations of aircraft impacts on nuclear power plant buildings. As a first step, the study focuses on establishing a high-fidelity FEM-based impact analysis methodology and validating its accuracy.

III. Analysis Methodology

The analysis was conducted using the explicit dynamic impact analysis code “Ansys LS-DYNA,” employing an interaction-based approach. In this method, both the aircraft (as the projectile) and the target building are modeled in detail, and an initial velocity is applied to the aircraft to simulate the collision. A Boeing 767 was selected as the impacting object, with an initial velocity of 150 m/s against a reinforced concrete (RC) structure. The aircraft model was created using CAD, with components such as the fuselage, wings, engines, and tail represented by shell elements, and each part assigned individual densities and stiffnesses. The impact velocity of 150 m/s was chosen based on international safety guidelines (e.g., IAEA-TECDOC-624) [4], which suggest typical velocities for large commercial aircraft impacts range from 150 to 200 m/s. The Boeing 767 represents a conservative assumption of a large aircraft impact, consistent with prior safety evaluations (e.g., NRC guidelines) [5].

IV. Material Model Evaluation and Validation

Accurate representation of the mechanical properties of materials is essential for appropriately reproducing the behavior of target structures in impact analyses. In this study, which targets RC structures, it is especially important to capture the complex response of concrete—such as nonlinearity, cracking, crushing, and shear failure. Two widely used concrete models implemented in LS-DYNA—the Karagozian & Case Concrete (KCC) model and the Continuous Surface Cap (CSC) model—were considered. These models are commonly adopted for high-velocity, large-scale impact simulations.

To evaluate their validity, numerical simulations were performed to replicate full-scale RC wall impact tests conducted by the Central Research Institute of Electric Power Industry (CRIEPI). The analysis model employed solid elements for the concrete and beam elements for the reinforcement, replicating the dimensions, reinforcement layout, and boundary conditions of the test specimens. Figure 1 shows the finite element model of the RC wall used in the simulations. A rigid body with mass was collided at a constant velocity at the center of the model to observe structural responses[3].

The results showed that the analysis using the CSC model (Figure 2) clearly reproduced perforation from the impact face through to the rear surface, consistent with experimental observations. In contrast, the KCC model (Figure 3) captured a failure mode involving rear-face spalling, which also aligned with the experimental results. Both models were found to be capable of reproducing typical impact responses of RC structures. While the KCC model offers more functionalities and incurs higher computational costs, the CSC model is characterized by easier parameter setup and higher numerical stability. Therefore, considering the applicability to multiple cases and feasibility of repeated simulations, the CSC model was adopted as the standard model for further analyses in this study.

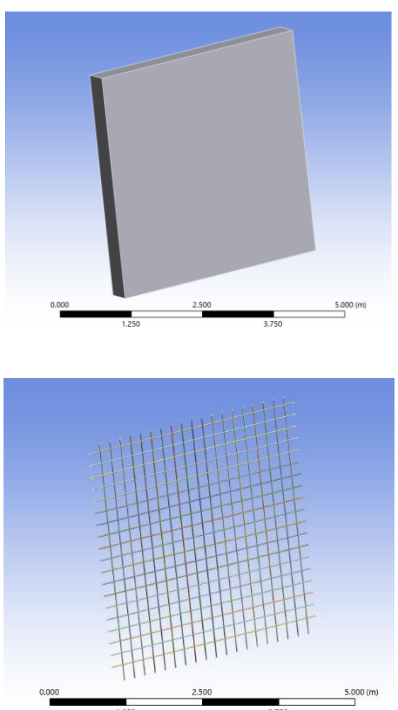

FIGURE 1. CAD MODLE

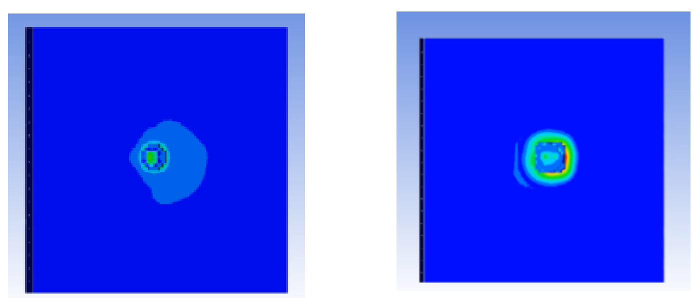

FIGURE 2.CSC MODEL ANALYSIS

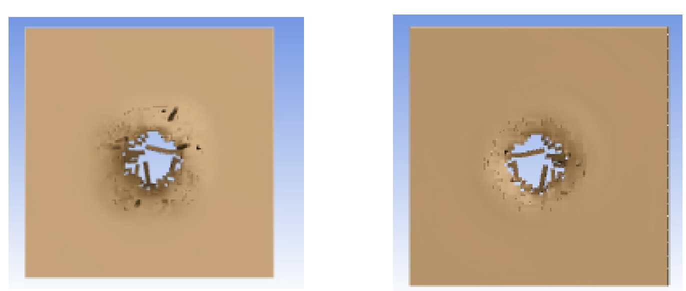

FIGURE 3. KCC MODEL ANALYSIS RESULTS

V. Development and Validation of the Aircraft Model

Based on previous studies, a Boeing 767 aircraft model was independently developed by representing major components—including the fuselage, main wings, engines, and tailplane—using shell elements. Each component was assigned individual density and stiffness properties to accurately replicate the structural characteristics of the actual aircraft.

To address convergence issues frequently encountered in contact analyses within the finite element method, the initial Boeing 767 model was refined. Specifically, the model was subjected to a contact analysis involving collision with a solid-element concrete wall using the same simulation code intended for later applications. Errors caused by the aircraft model geometry during this analysis were identified and addressed by optimizing the geometry of the model, thereby improving the convergence behavior of the simulation.

Finally, to validate the credibility of the developed Boeing 767 model, an impact analysis against a rigid wall was conducted, as shown in Figure 4. The resulting impact force history, presented in Figure 5, was compared with previously validated data from earlier studies (Figure 6) [1]. The comparison showed that the force-time history generally matched well with the reference data, confirming the reliability of the developed aircraft model[1].

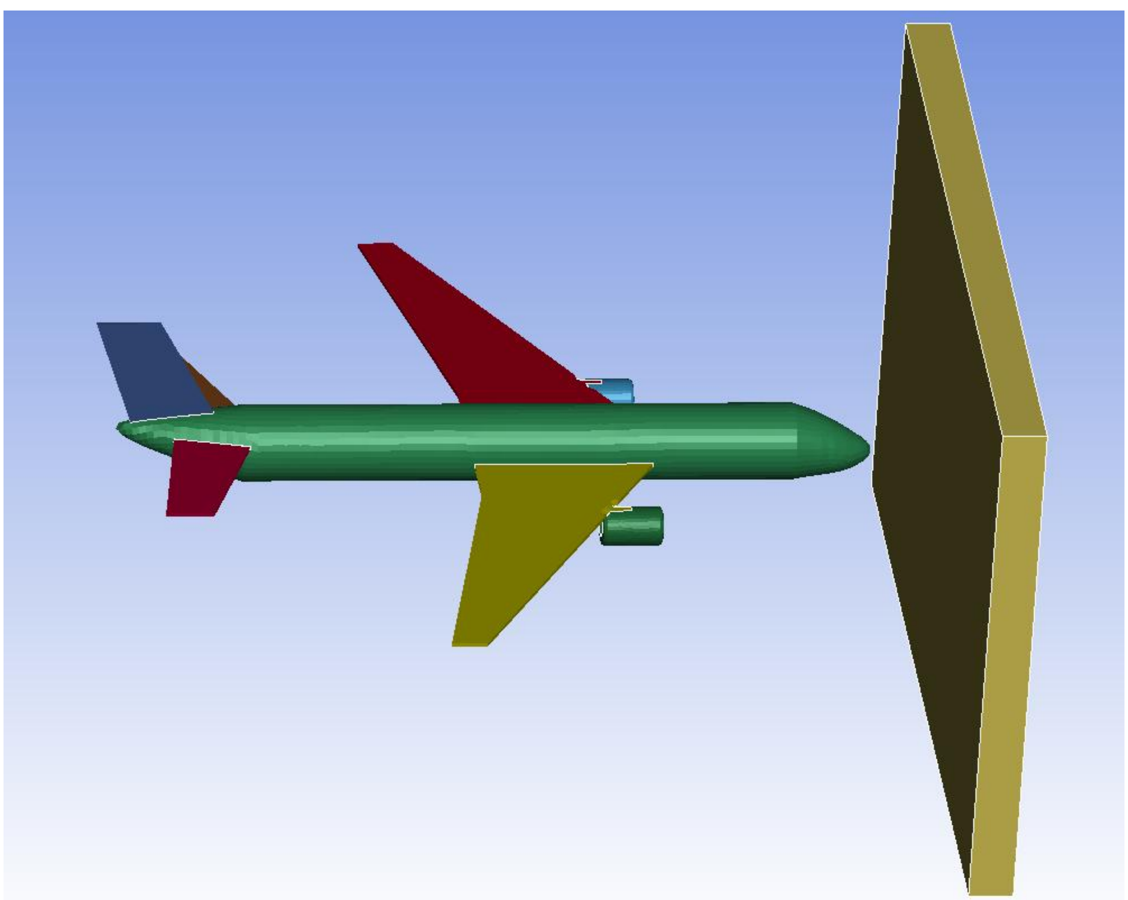

FIGURE 4. AIRCRAFT MODEL

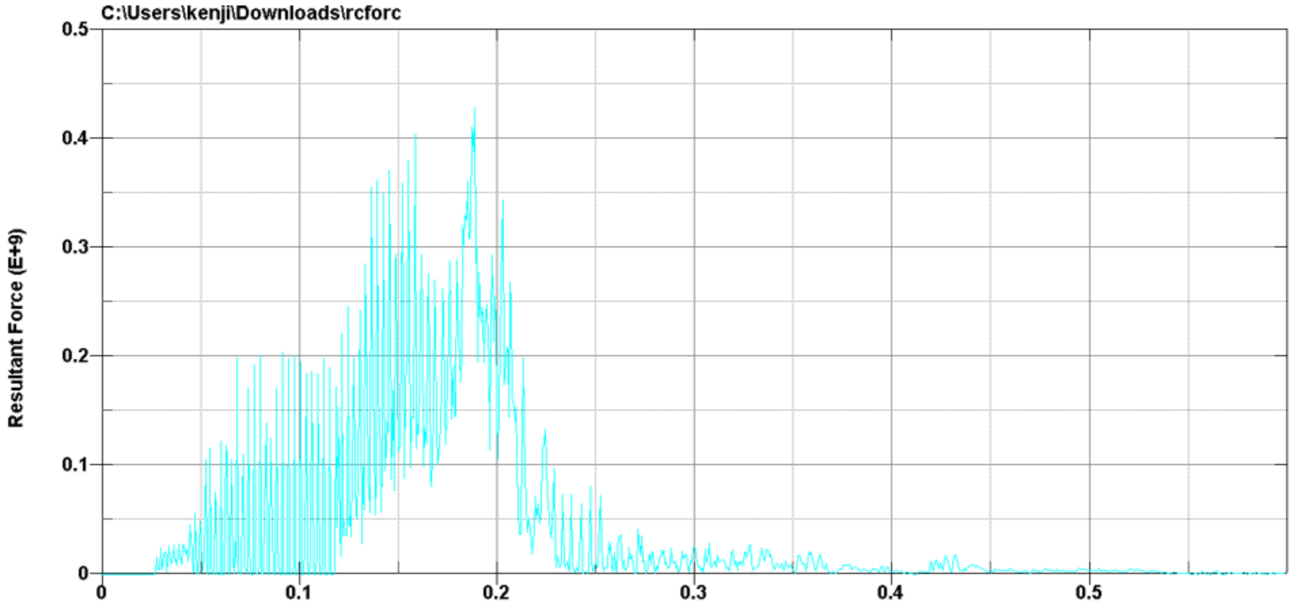

FIGURE 5 . DYNAMIC LOAD-TIME HISTORY OF THE AIRCRAFT IMPACT AT 150 M/S (CURRENT STUDY)

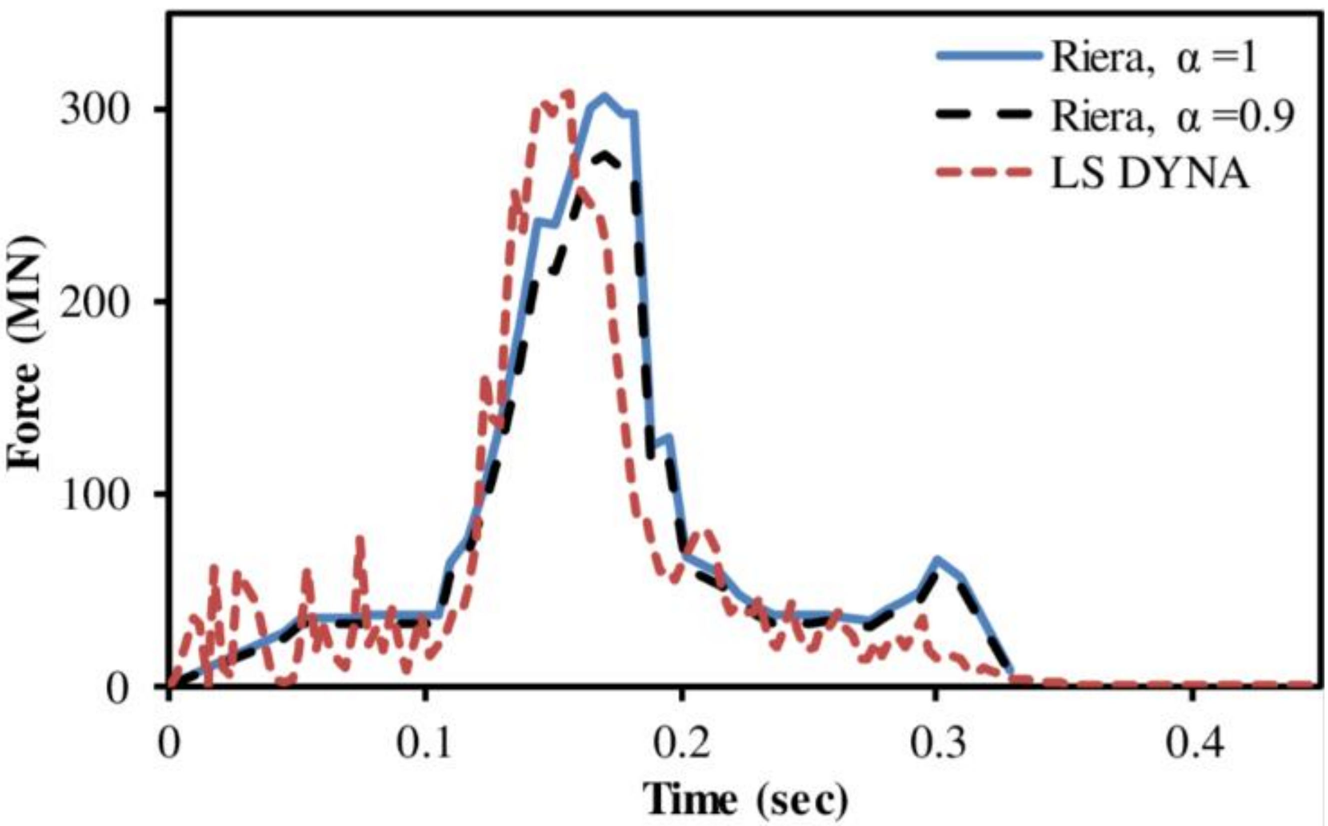

FIGURE 6. DYNAMIC LOAD-TIME HISTORY OF THE AIRCRAFT IMPACT AT 150 M/S (PREVIOUS STUDY) [1]

VI. Interaction Method and Associated Challenges

As previously described, the actual simulation was conducted using the interaction method. The interaction method involves explicitly modeling both the projectile (aircraft) and the target structure as FEM models and simulating their direct collision through contact analysis. Due to the extensive computational time required, this method is rarely employed in practical plant analyses and is primarily adopted in academic research.

Compared to the "force time-history method," which is commonly used in practical applications—where a prescribed time-history load is applied to a limited region of the target structure—the interaction method offers the advantage of reproducing more realistic impact scenarios. Following this methodology, a direct impact analysis on an RC building was performed using the CSC material model in conjunction with the validated aircraft model. Figure 7 shows the FEM model setup prior to analysis.

The analysis successfully converged, as illustrated in Figure 8. However, abnormal failure behavior of shell elements on the side wall of the building was observed immediately after impact. This phenomenon was attributed to non-physical stress wave propagation, most likely caused by numerical diffusion due to coarse mesh resolution. Efforts are currently underway to enhance numerical stability through mesh refinement. Ultimately, the goal is to use the improved simulation results to propose design guidelines that ensure sufficient APC resistance with minimal reinforcement.

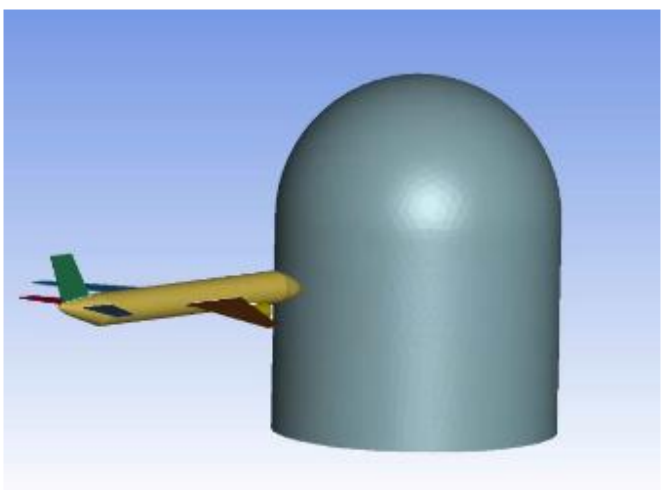

FIGURE 7. INTERACTION METHOD ANALYSIS

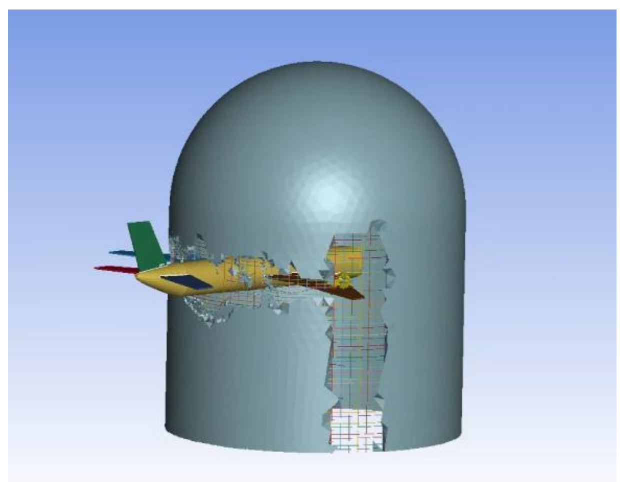

FIGURE 8. INTERACTION METHOD ANALYSIS RESULT

VII. Conclusion and Future Outlook

This study aimed to optimize protective measures against aircraft impact (APC) on nuclear power plants, focusing on the development of a fundamental numerical analysis framework as a prerequisite. The interaction method, in which both the projectile and the target building are modeled using the finite element method (FEM), was adopted in order to reproduce structural responses that closely resemble real-world behavior.

In the investigation of material models, numerical simulations using both the Karagozian & Case Concrete (KCC) model and the Continuous Surface Cap (CSC) model successfully reproduced experimentally observed failure modes—namely, rear-face spalling and perforation—thus validating their applicability. Considering ease of implementation and numerical stability, the CSC model was selected for subsequent analyses.

An aircraft model representing the Boeing 767 was then constructed and validated. The resulting impact force history showed good agreement with validated data from previous studies, confirming the model's reliability. While the initial interaction analysis achieved convergence, some numerical instability was observed in the form of non-physical sidewall failure. This issue is presumed to be caused by numerical diffusion resulting from a coarse mesh, highlighting the need for mesh refinement as a key area for improvement.

Moving forward, the established simulation framework will be applied to evaluate the effectiveness of various proposed APC countermeasures implemented on a simulated plant structure. The ultimate objective is to identify the necessary and sufficient conditions for cost-effective and robust APC protection strategies.

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