FLOOR RESPONSE SPECTRA IN THE INTERNAL STRUCTURE DUE TO AIRPLANE IMPACT

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ABSTRACT

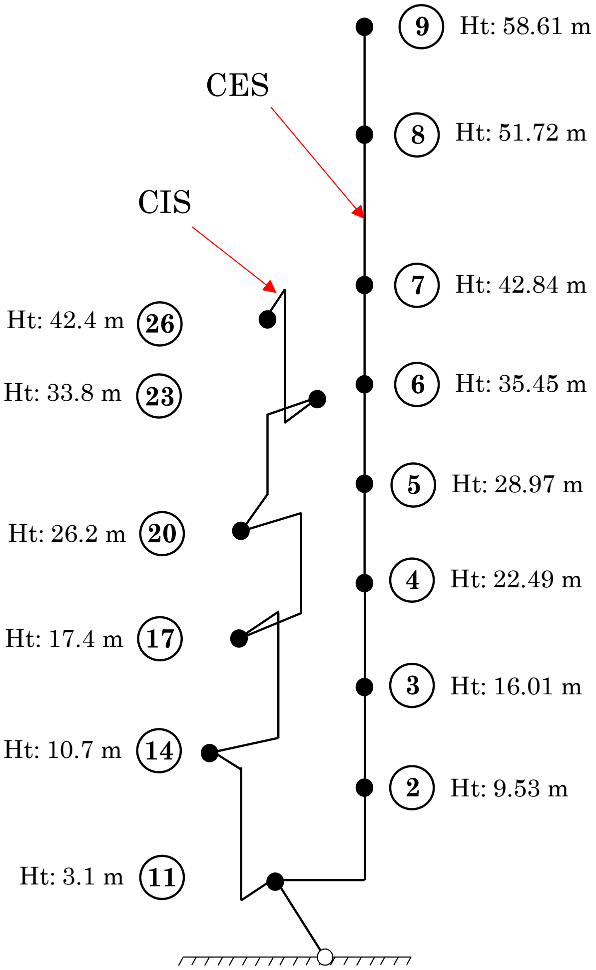
The scenario of an airplane crashing into the containment building is a critical external hazard considered in the design and safety evaluation of nuclear power plants (NPPs). While numerous studies have assessed the structural resilience against such impacts, it is equally important to ensure the integrity as well as continued functionality of safety-significant electrical systems to maintain the safe operation or shutdown of the plant. Safety-related electrical equipment such as relays may be vulnerable to high-frequency vibrations due to airplane crash (APC) impact that could compromise the continued functionality of the control systems. Simulations of APC impact scenarios on a nuclear containment building model are presented in this paper to evaluate the acceleration time-histories and their corresponding response spectra at various floors of the internal structure of an NPP. The frequency content of these floor motions is analyzed to understand the vibrations characteristic to which the electrical systems are subjected as a result of an airplane crash.

INTRODUCTION

Safety against external hazards is essential for nuclear power plant designs to protect the public and environment from the consequences of potential accidents. One such scenario involves an airplane crash (APC) on a nuclear containment building, which houses the reactor pressure vessel and other corresponding systems. Although the potential impact of airplanes has been considered in design since the 1970s, the events of September 11, 2011, have accelerated the development of more realistic and comprehensive approaches for assessing beyond-design-basis conditions (Ghadimi Khasraghy et al., 2024b; Henkel and Klein, 2007). Many studies have focused primarily on analyzing and ensuring the structural integrity of containment buildings under airplane impact (Frano and Forasassi, 2011; Kostov et al., 2014; Sadique et al., 2013). One aspect that has not received enough attention is related to ensuring safe operational conditions for nuclear power plants which also requires a continued functionality of digital control systems and other essential electrical equipment (Gupta et al., 2019). Ghadimi Khasraghy et al. (2024a) reviewed available experimental studies, design methods, and practices for safety-related components subjected to high-frequency impact-induced accelerations.

An APC on a nuclear containment structure generates substantial vibrations that can propagate from the impact location to the internal structure where critical equipment is mounted, potentially impairing their functionality. A seismic design and performance assessment of such devices ensures a certain degree of safety against floor vibrations. However, earthquake ground motions typically have frequencies below 10 Hz (EPRI, 2014). In many instances, electrical systems and equipment have exhibited operational failure when subjected to high-frequency motions. Furthermore, Moussallam et al. (2022) conducted shake table testing of relays, demonstrating that the capacity of relays to resist chatter or functional failure diminishes at higher frequencies. Therefore, it is essential to understand the nature of vibrations generated and transmitted to the internal structure following an airplane impact, as these vibrations have the potential to influence the continued functionality of the electrical systems.

In this study, APC scenarios are simulated using a simplified model of the containment structure (both external and internal) of an existing NPP. The APC impact load is applied to the containment model, and vibrations (accelerations and their corresponding response spectra) at different floor levels within the internal structure are obtained. The generated floor response spectrum (FRS) curves are analyzed to study the frequency content of these vibrations.



(a)

Significant Eigenmodes

Mode No.	Frequency (Hz)
1	4.86
2	4.94
4	11.56
5	11.76
7	15.52
10	22.63
11	22.89
20	36.61
21	36.86

(b)

Figure 1. (a) Lumped-mass-stick model of CES and CIS of the NPP; and (b) significant eigenmodes of the model

CONTAINMENT STRUCTURE MODEL

For this study, a simplified lumped-mass-stick model of the containment building, comprising both the containment internal structure (CIS) and the containment external structure (CES), is used for airplane impact simulations. This model is constructed to represent an existing NPP to relate the results obtained to a realistic scenario. The stick model simulates the foundation employing translational and rotational springs in the two orthogonal horizontal directions at the foundation node, while the vertical direction is constrained. The lumped masses and their respective heights from the foundation node are shown in Figure 1(a). The significant modes of the model are listed in Figure 1(b). The APC load is applied to the stick model of the CES. The CES and the CIS do not have any connections at higher elevations and are connected solely at the foundation level. Therefore, vibrations propagate only through the foundation into the CIS. The lumped masses in the stick model of the CIS correspond to various floors.

AIRPLANE IMPACT LOADS

Two airplanes, a commercial plane and a military jet, are selected to investigate the effects of impact on the containment structure. The commercial airplane has an approximate weight of $150{,}000\,\mathrm{kg}$, while the military airplane weighs approximately $28{,}000\,\mathrm{kg}$. The crash of each airplane is simulated by applying the corresponding impact load time-history to the model of the containment structure, followed by a dynamic time-history analysis. The Riera (1968) approach, which employs the momentum theorem, is utilized to determine the impact load-time functions for these airplanes (Kamath et al., 2016). This approach considers the mass distribution and velocity of the airplane used in the analysis. As this method is widely adopted, the load-time functions of some commonly used airplanes are documented in IAEA (2003).

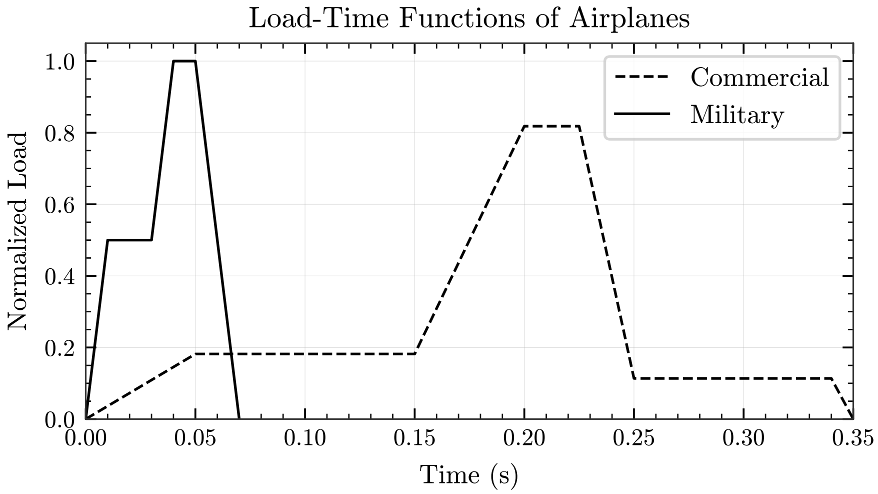


Figure 2. Impact load-time functions of the commercial airplane @ $100\,\mathrm{m/s}$ and the military airplane @ $215\,\mathrm{m/s}$

The impact load-time function for the chosen commercial airplane is calculated at a typical velocity of $100\,\mathrm{m/s}$ during landing and takeoff, whereas the load-time function for the military airplane is considered at a higher velocity of $215\,\mathrm{m/s}$, assuming accidental conditions. These load-time functions (normalized curves) are illustrated in Figure 2. Upon comparison, it is evident that the load duration for the commercial airplane is significantly longer than that of the military one. However, the military airplane exerts a greater force during impact, reaching a peak value $22\,\%$ higher than that of the commercial airplane impact. This is due to the higher impact velocity, despite the smaller weight.

Typically, the impact force is applied over a circular area (impact area) on the 3D model of a containment structure as a pressure function derived from the load-time function (Rawsan, 2021). In some cases, a complete coupled analysis is conducted by modeling the airplane; however, this approach is computationally intensive. In this study, for the stick model, the simplified loads are assumed to be distributed uniformly over the specified lengths of impact, as illustrated in Figure 3. The considered lengths of impact for the commercial and the military airplanes are $6\,\mathrm{m}$ and $3\,\mathrm{m}$, respectively, corresponding to the average areas considered for their impact. The impact location is specified at the mid-height of the CES, positioned $30.83\,\mathrm{m}$ from the foundation. The impact load is directed along the X-axis, with X and Y representing the two orthogonal horizontal directions and Z indicating the vertical direction.

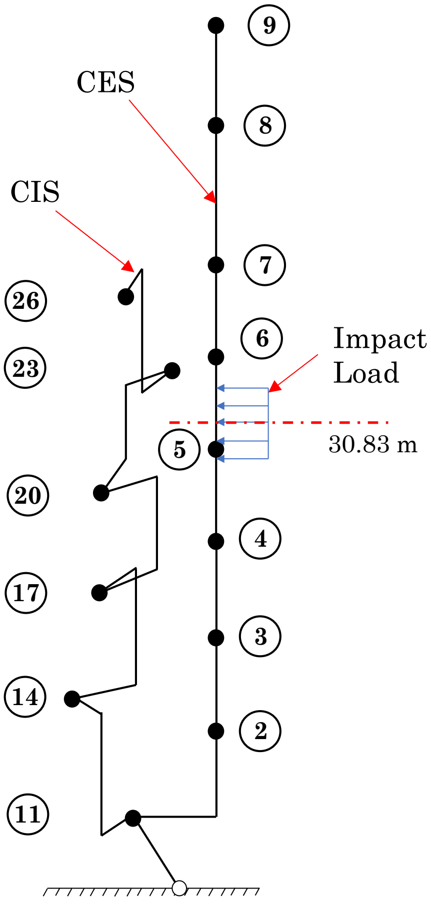
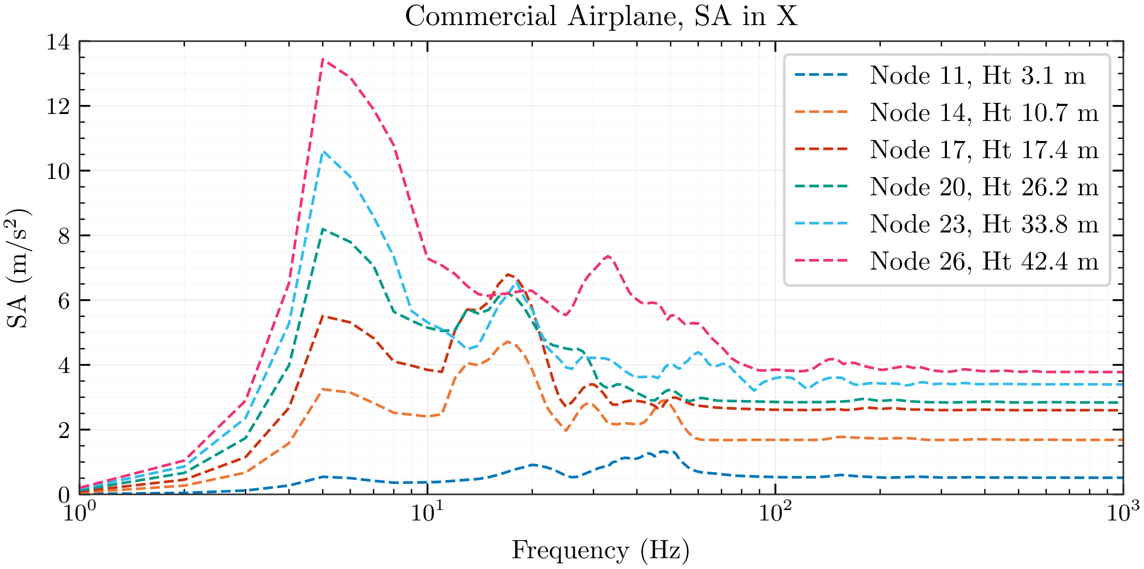


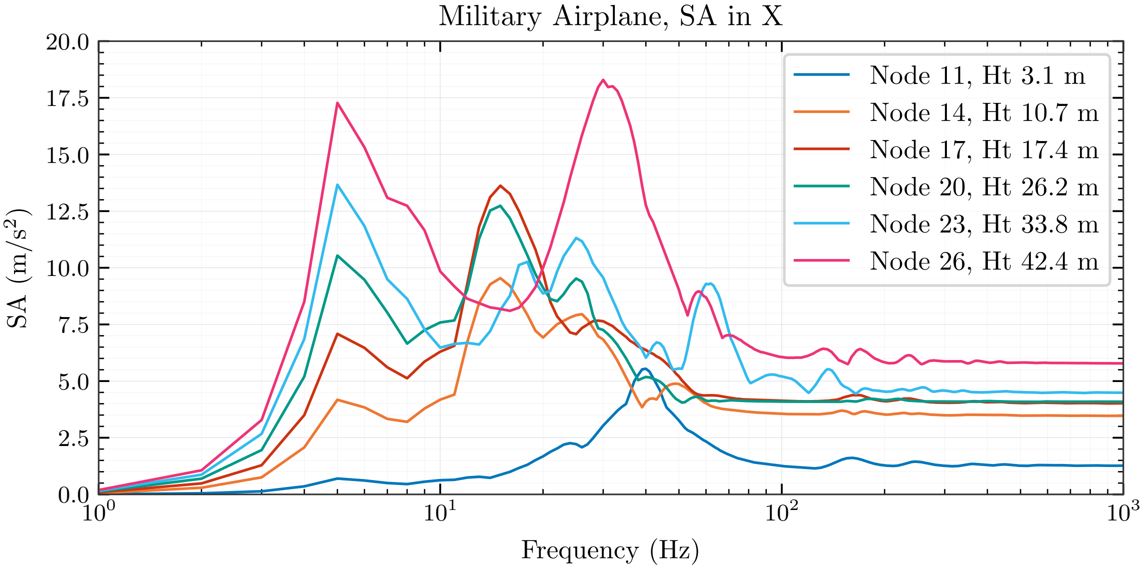
Figure 3. Airplane impact load applied as uniformly distributed load on the stick model

RESULTS

Results are obtained using implicit dynamic time-history analyses performed in SAP2000, wherein the acceleration time-histories at the lumped masses across various floor levels in the CIS are obtained. The locations examined are Nodes 11, 14, 17, 20, 23, and 26, at elevations of 3.1, 10.7, 17.4, 26.2, 33.8, and 42.4 m from the foundation, respectively. Acceleration time-histories obtained at different floor levels from the time-history analyses are then used to generate the FRS curves in terms of spectral acceleration (SA) values.



(a)



(b)

Figure 4. FRS at different heights in the CIS in X direction for impact with (a) the commercial airplane and (b) the military airplane

It is observed that the response is predominantly significant in the X direction, while it is negligible in the Y and the Z directions. This observation can be attributed to the application of the APC force in the X direction. Figure 4 presents a comparison of the responses in the X direction at various heights.

Analysis of the results shown in the figure indicates that the FRS plots predominantly exhibit peaks around 5 Hz, corresponding to the models fundamental low-frequency modes. In addition, the FRS curves exhibit significant responses in the higher frequency range above 10 Hz. The most pronounced peak at Node

11 occurs between 40 Hz and 50 Hz, although the maximum SA at this location is low. In contrast, other locations exhibit higher spectral accelerations, with Node 26, the topmost node in the CIS, showing the highest values for both considered APC cases. The FRS consistently show at least one significant peak in the high-frequency region, with some plots displaying multiple peaks. Peaks can be observed near 20 Hz, 30 Hz, and even 60 Hz. In most instances, these peaks exhibit higher values than those in the low-frequency region (below 10 HZ), indicating that the higher frequency modes govern the floor acceleration responses in those cases. A comparison of the FRS from the two airplanes reveals that the impact with the military jet has more prominent peaks in the high-frequency region as compared to the commercial plane case. Figure 4 illustrates that an airplane impact on a nuclear containment building induces substantial high-frequency motions on various floors within the internal structure.

CONCLUSIONS

Studying the effects of an airplane crash on a nuclear containment building is essential for ensuring safety against such hazardous scenarios. While various studies have evaluated the structural integrity of containment structures, it is also important to investigate the nature of vibrations transmitted to internal structures, given that critical electrical systems are sensitive to high-frequency motions. In this paper, APC impacts on a nuclear power plant are simulated using a simplified stick model of the containment building, containing both the external and the internal structures. Impact loads from two planes, a commercial and a military airplane, are applied at the mid-height of CES as load-time functions derived from the Rieras approach. Accelerations at different floor levels within the internal structure are obtained, and their FRS are compared to examine the frequency content of the floor motions.

The FRS plots indicate that the responses have significant high-frequency content above 10 Hz. Multiple peaks are observed in the high-frequency region following impacts from both considered airplanes. In some cases, although the magnitude of peaks in the responses at higher frequencies is lower than those at lower frequencies, the SA values remain considerably high. In most cases, the spectral accelerations in the high-frequency range dominate the floor response across different heights in the CIS. The findings of this study have shown that in the event of an APC impact, a significant amount of high-frequency vibrations can reach the internal structure and may compromise the integrity and/or functionality of mounted electrical systems. Furthermore, APC impact at a higher velocity (military jet case) induces more pronounced high-frequency vibrations as compared to impact at a lower velocity (commercial plane case). Consequently, impact-induced vibrations from smaller, high-velocity aircraft may pose a greater concern for the continued functionality of these systems. It is, therefore, important to study the effects and potential mitigation measures for high-frequency vibrations on safety-critical electrical equipment in nuclear power plants.

It must be noted that the simplified model presented herein has inherent limitations. The complex wave propagation phenomena can only be modeled approximately with the stick model. For this reason, in the next phase, a realistic 3D (shell or volume) model for the containment external structure should be developed. Subsequently, the base raft and internal containment structure should also be modeled in detail. With a step-by-step approach, the influence of the model simplifications can be better understood.

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REFERENCES

EPRI (2014). “High frequency program: High frequency testing summary.” Technical Report 3002002997, Electric Power Research Institute.

Frano, R. L. and Forasassi, G. (2011). “Preliminary evaluation of aircraft impact on a near term nuclear power plant.” *Nuclear Engineering and Design*, 241(12), pp. 5245–5250.

Ghadimi Khasraghy, S., Szczesiak, T., Gupta, A., Rangelow, P. and Wilding, B. (2024a). “Impact Induced High Frequency Vibrations: Options for a Unified Approach for the Design of Components.” *Transactions, SMiRT-27*.

Ghadimi Khasraghy, S., Tarallo, F., Szczesiak, T., Rangelow, P., Darraba, A., Välikangas, P. and Pfeiffer, N. (2024b). “Proposal for Improvement of Airplane Crash and Impact Resistance Design Provisions in RCC-CW Code.” *Transactions, SMiRT-27*.

Gupta, A., Cho, S.-G., Hong, K.-J. and Han, M. (2019). “Current state of in-cabinet response spectra for seismic qualification of equipment in nuclear power plants.” *Nuclear Engineering and Design*, 343, pp. 269–275.

Henkel, F.-O. and Klein, D. (2007). “Variants of analysis of the load case airplane crash.” *Transactions, SMiRT-19*.

IAEA (2003). *External Events Excluding Earthquakes in the Design of Nuclear Power Plants*. Number NS-G-1.5 in Safety Standards, International Atomic Energy Agency, Vienna.

Kamath, A. S., Gundlapalli, P., Ranjan, R. and Neeraja, D. (2016). “Study, simulation and analysis of aircraft crash on concrete containment structure.” In *International Conference on Emerging and Sustainable Technologies for Infrastructure Systems*.

Kostov, M., Henkel, F. and Andonov, A. (2014). “Safety assessment of A92 reactor building for large commercial aircraft crash.” *Nuclear Engineering and Design*, 269, pp. 262–267, ISSN 0029-5493.

Moussallam, N., Dennerlein, J., Graf, C., Goth, M., Liebig, K. D. and Darraba, A. (2022). “Development and Implementation of a Qualification Methodology for I&C Components to Airplane Crash Induced Vibrations.” *Transactions, SMiRT-26*.

Rawsan, A. (2021). *Response of nuclear containment wall subjected to impact and thermal loads*. Ph.D. thesis, IIT (BHU) Varanasi.

Riera, J. D. (1968). “On the stress analysis of structures subjected to aircraft impact forces.” *Nuclear Engineering and Design*, 8(4), pp. 415–426.

Sadique, M., Iqbal, M. and Bhargava, P. (2013). “Nuclear containment structure subjected to commercial and fighter aircraft crash.” *Nuclear Engineering and Design*, 260, pp. 30–46, ISSN 0029-5493.