Preliminary Assessment of the Floor Response Spectra of Nuclear Structure against to Aircraft Impact Loading

Sang Shup Shin[1, 2], Daegi Hahm[1], and Min Kyu Kim[1]

[1] Korea Atomic Energy Research Institute, Daejeon, Korea
[2] Hanyang University, Seoul, Korea

This study is one of the categories on research to develop aircraft impact risk quantification technology by the Korea Atomic Energy Research Institute. This study has been performed to the preliminary assessment of the floor response spectra (FRS) of nuclear facilities against to aircraft impact (AI). The nuclear facility against to aircraft impact with high velocity may take a severe damage such as penetration, perforation, scabbing and spalling. Also, even if the integrity of structure is maintained from AI, the internal components may be damaged by shock vibration. Thus, in order to assess the damage on equipment and components by the shock vibration, it should be assessed the FRS on the structure subjected to AI. In this study, an aircraft impact analysis (AIA) for the primary auxiliary buildings (PAB) was performed using both of force-time history method and missile-target interaction method. In missile-target interaction methods, jet fuel modeling method was categorized by using added mass method and smooth particles hydrodynamics (SPH) method, respectively. From the AIA results, the severe damage of external wall at all cases was occurred by AI. Also, even if the response on the same location is calculated, the FRS results show different by analysis methods. The FRS results using added mass method is underestimated compared the results from the other methods.

I. Introduction

The safety assessment and protective design on nuclear power plants (NPPs) against the large commercial aircraft impact (AI) have been drawn significant attention around the world. The nuclear structure crashed by aircraft will be damaged by impact loads, shock vibrations, and fire. The aircraft impact assessment (AIA) is carried out by using a realistic analysis method which is to evaluate the physical and shock damages to structure, system and components (SSCs) from impact. A large commercial aircraft is made up of fuselage, wings, fuel tank, engine, and landing gear, which are semi-rigid components. During the crash of an aircraft, the fuselage mainly affects the out-of-plane bending and shock vibration behaviors in the structure, and the wings play the role of a knife to cut the structure. The shear failure and local punching damage of the structure may be occurred by a landing gears and engines. The fuel tank and jet fuel have a significant influence on the total AI loads as well as causing explosive fire, which affect the safety of the SSCs. If an AI occurs in a nuclear structure composed reinforced concrete, even if a perforation of the external wall is successfully protected, the internal system and components can be damaged by the extreme shock vibration. Thus, the shock vibration response of the floor on nuclear structure should be assessed carefully to secure the safety of the internal components and equipment (Ref. 4). Particularly, the safety assessment for the shock vibration of the internal components and equipment in the primary auxiliary buildings (PAB) should be performed, because most of the safety related components and equipment are located in the PAB. While the safety-related components and equipment in NPPs have been seismically qualified, the frequency spectrum associated with an aircraft impact is considerably higher than the spectrum associated with earthquakes (Ref. 5). The shock vibration responses of each component on the same floor level will be identical in case of the applied the seismic load. However, for the AI load, the magnitude of the shock vibration response may decrease as the distance from the impacted point increases.In this study, AIA of a PAB were carried out using both the force-time history method and the missile-target interaction method. In missile-target interaction analysis method, the added mass modeling and smooth particles hydrodynamics (SPH) method were applied to the fuel tanks with a large amount of jet fuel. Also, the initial aircraft impact velocity and weight were considered 150m/s and 200 ton, respectively. The structural integrity of the PAB and the floor response spectra (FRS) on the each floor subjected to AI were assessed. Also, the difference in the FRS at the location of the internal components on both sides of the bay was assessed for the AIA results with initial impact velocity 150m/s.

II. Aircraft Impact Analysis Methods

In AIA methods, we can categorize the analysis into two distinct types according to the method in which the aircraft impact force is applied. One of the methods is Force-Time History Analysis Method. It is generally referred to as the Riera methodology (Ref. 6, 7). Another method is the Missile-Target Interaction Analysis Method. The second method uses the finite element model to simulate the aircraft crash on the target structure and directly acquires a structural response.
The Force-Time History Analysis Method is an approximate method based on momentum principle and was developed for a head-on-type impact which allows the aircraft fuselage to progressively crush axially against a rigid target, resulting in the Force-Time History to which the target is subjected (Ref. 5).
The aircraft impact force equation is given by Eq. (1) which is the key formula used in the computation of the impact force-time history curve.

$$F(t) = P_c[x(t)] + \alpha_r \mu[x(t)](dx/dt)^2 \qquad (1)$$

where α_r is the mass coefficient determined experimentally and $\mu[x(t)]$ is the mass per unit length at location x. $P_c[x(t)]$ is the static force required to crush the shell of an aircraft axially located at the coordinate x. At the initiation of the impact to a rigid target, $V(=dx/dt)$, is equal to the initial velocity, V_1, of the aircraft.
The mass per unit length, $\mu[x(t)]$, can be divided as

$$\mu[x(t)] = \mu_s[x(t)] + \mu_e[x(t)] + \mu_f[x(t)] \qquad (2)$$

where $\mu_s[x(t)]$ is the airframe mass per unit length, $\mu_e[x(t)]$ is the weakly attached equipment mass per unit length, and $\mu_f[x(t)]$ is the fuel mass per unit length. The crushing force $P_c[x(t)]$ does not greatly affect the magnitude of the impact force (Ref. 7).

In AIA, an alternative to using the theoretical method called Riera's method is the Missile-Target Interaction Analysis Method. Missile-Target Interaction Analysis Method is developed by using a dynamic analysis model of the missile and target, and the dynamic response of target structure is drawn from an initial velocity, mass and stiffness etc. of missile. Because of using an initial velocity, mass and stiffness etc. of missile in Missile-Target Interaction Analysis Method, Missile-Target interaction method has various advantages more than Force-Time history method. For example, it should consider that missile impact area, impact angle, nonlinear behavior of missile materials, and the secondary effects from missile debris.

Ⅲ. Modeling of Aircraft and Primary Auxiliary Buildings

As shown in Fig. 1, the aircraft finite element (FE) model is developed by referring to EPRI report (Ref. 2) and Boeing website (Ref. 1). The aircraft fuselage, wings, fuel tank and engines are applied to shell elements, and the landing gear is modeled with beam elements. For the modeling of the jet fuel in the fuel tank, two alternative methods were introduced, an SPH method and an added mass method.

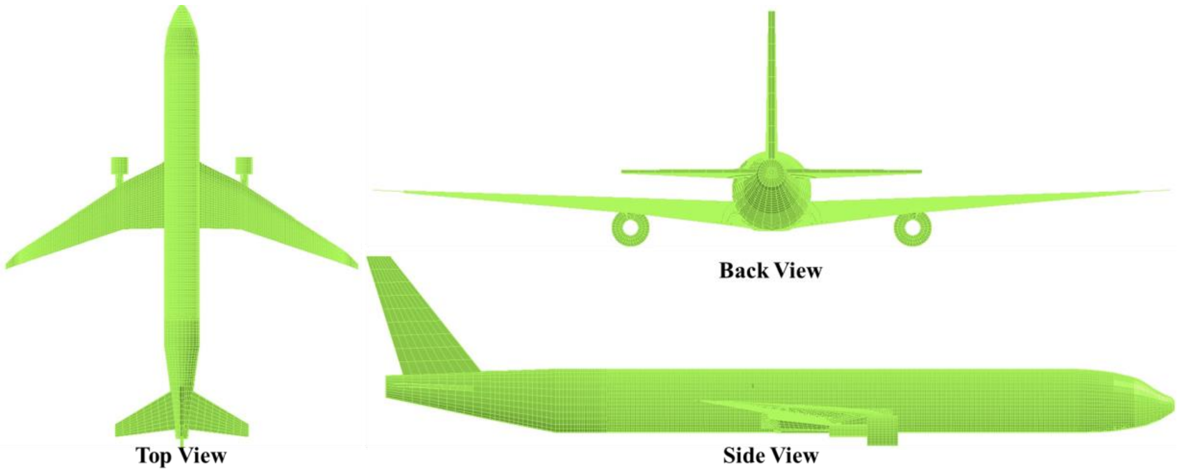


Fig. 1. Aircraft Finite Element Model

At AI, the sequence of aircraft failure is nose – fuselage – engine – main wing – tail. Since the consideration of all structures and non-structure components of an aircraft is inefficient in case of the AIA, an aircraft fuselage, wings, engines, a fuel storage tank and fuel were reflected in the aircraft FE model. The reference impact velocity 150 m/s was selected for an analysis of the vibration response spectra. Table 1 shows analysis cases with respect to the variation of analysis methods. The force-time and impulse-time history with respect to impact velocity 150 m/s were shown in Fig. 2. In the missile-target interaction method, a low-pass numerical filter (100Hz) was applied to eliminate the spurious structural response ("noise") in the AI force, in Fig. 2. The scales of vertical axes (force & impulse) in Fig. 2 have been normalized for safeguard sensitivity.

TABLE I. Analysis Cases with respect to the Variation of Analysis Methods

Case	Missile-Target Interaction Method		Force-Time History Method
	SPH Modeling Method	Added Mass Modeling Method	
Case 1	○		
Case 2		○	
Case 3			○

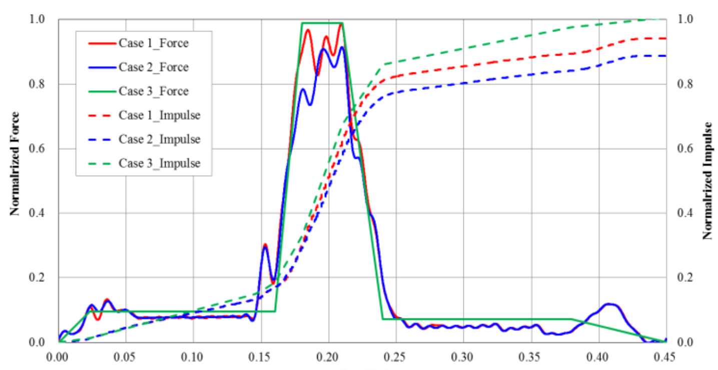


Fig. 2. Force-Time and Impulse-Time History

Fig. 3 shows the 3D FE model of the PAB with 6.79Hz of natural frequency. The plan dimensions are 67.7m×74.6m and the height is 37.9m, divided into six elevations. In the PAB FE model, we only considered the main bulkheads. The AI location is between the fifth and sixth floor slabs at the 67.7m wide wall, as shown in Fig. 3 and 4. The finer hexahedral solid elements were considered in the impacted side of the PAB. The floor and backside of PAB were considered with course hexahedral solid elements for the efficiency of the computational cost. The fixed boundary condition was applied to the restraining translations and rotations at the bottom of the PAB.

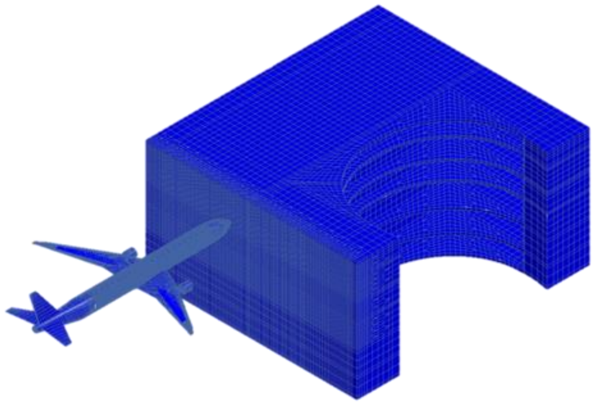


Fig. 3. Finite Element Model of the PAB

Ⅳ. Results of the Structure Damage

We assume that the aircraft will crash the external wall as shown in Fig. 3 and 4. In Fig. 4, P1 is 7m away from the external wall, and the space of each location is 8m. Since the maximum impact force occurs when the AI to the wall is normal direction, the normal direction impact to the wall is assumed. AI simulation was performed using LS-DYNA (Ref. 3).

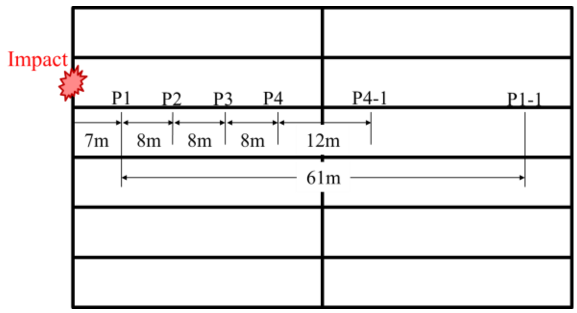


Fig. 4. The Measurement Location of Shock Vibration Response induced by AI

For the AIA of the PAB, the input force-time histories as cases 3were applied. The loading area in Fig. 5 was presumed based on the appropriate crushing features of the aircraft cross section used. The loading area is separated into the fuselage, wings, and engines.

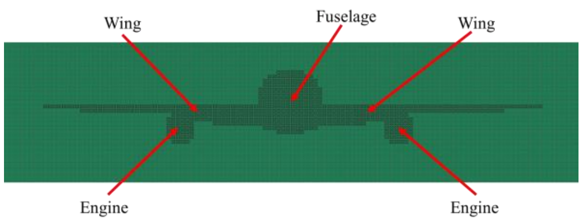
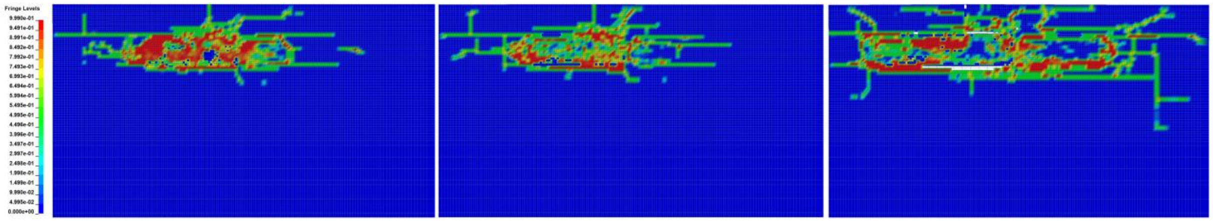


Fig. 5. Loading Area on the External Wall at PAB

In analysis case 3, the loading up to 0.150 seconds is only applied to the fuselage. At 0.150 seconds, the engine load is added to the fuselage load. At 0.160 seconds, the wing load is also added to the fuselage and engine load, and these three loads continue together until 0.240 seconds. The engine load is terminated at 0.180 seconds, and the wing load is terminated at 0.240 seconds, and after that, only the fuselage load is continued until reaching the end of the analysis.

The structural damage should be affected by the differences in jet fuel modeling methods. As shown in Fig. 6, the plastic strain contours on the external wall at the maximum force occurrence times are occurred at t=0.2s for Cases 1 through 3 (V=150m/s). The tension failure on external wall has been found to occur around the impact area in case 1 to 3.



Case 1 Case 2 Case 3

Fig. 6. Plastic Strain Contour on the Target wall Surface at 0.2 Second

Ⅴ. Results of Floor Response Spectra

Since a malfunction of the equipment to maintain the cooling system by shock vibration is one of the failure events for nuclear power plants subjected to AI, the safety of SSC to the maintenance of cooling system should be analyzed for a safety assessment and analysis from AI (Ref. 4). The FRS curves at P1 through P4 for the analysis methods were shown in Fig. 7. As shown in Fig. 7 (a), the maximum spectral acceleration response for case 2 at P1 is 54% and 58% smaller than those of case 1 and case 3, respectively. And, the tendency of the FRS in Fig. 7 (b) to (d) is close to the results in Fig. 7 (a). The case 2 results using the added mass method were underestimated in Fig. 7. Also, it can be seen that the result of case 1 using the SPH method is like to the Case 3.

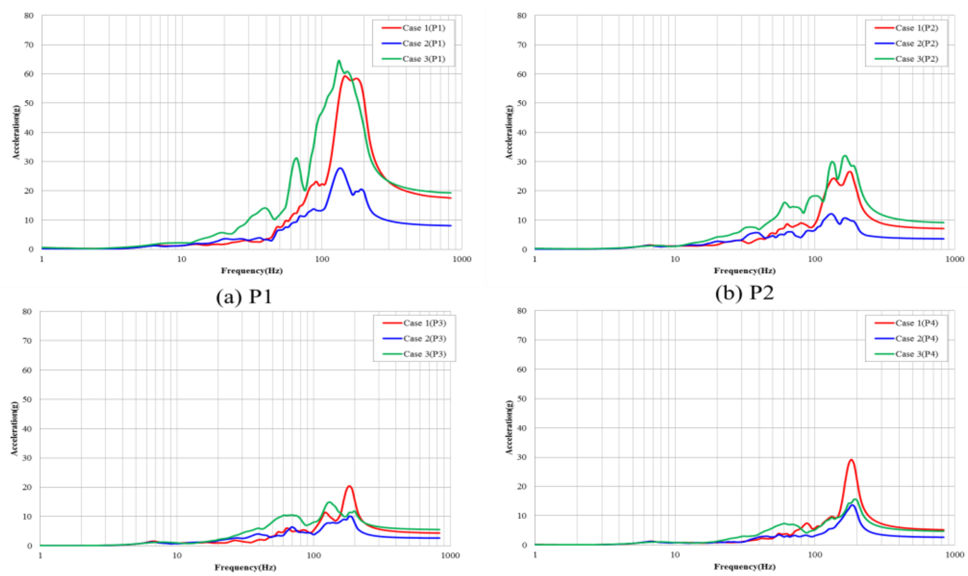


Fig. 7. Floor Response Spectra at P1 to P4 with respect to Case 1 to 3

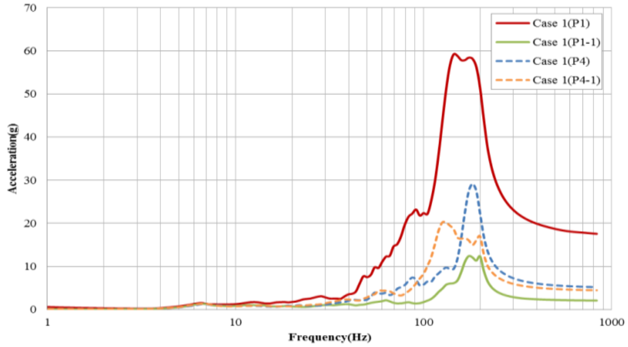


Fig. 8. Floor Response Spectra at P1, P1-1, P4 and P4-1 with respect to Case 1

So as to compare the FRS at P1, P1-1, P4, and P4-1 in Fig. 4, the FRS for case 1 was shown in Fig. 8. In Fig. 4, the space between P1 and P1-1 is 61m, and the location of P1 is 7m away from the impacted wall. And, the distance between P4 and P4-1 is 12m. As shown in Fig. 8, the maximum spectral acceleration response at P1-1 is decreased by 80% as compared to the response at P1. The tendency of FRS under 70Hz at P4 is similar to the response in P4-1. However, the FRS above 70Hz at P4 is different from P4-1.

Ⅵ. Conclusions

In this study, the structure damage and FRS at the specific locations caused by AI was analyzed using both the force-time history method and missile-target interaction method. For the identifying the difference of jet fuel modeling method, jet fuel was considered by using added mass method and smooth particles hydrodynamics (SPH) method, respectively. The FRS results using SPH method showed that the largest values in most of the frequency range compared to the other methods regardless of the response locations. From the FRS results, the maximum spectral acceleration response on the location on the opposite side (P1-1& P4-1) is decreased because of the absorption of impact energy by internal wall.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2012M2A8A4025985)

REFERENCES

1. Boeing website. http://www.boeing.com
2. Electric Power Research Institute (EPRI), Deterring Terrorism: Aircraft Crash Impact Analyses Demonstrate Nuclear Power Plant's Structural Strength (2002).
3. Hollquist, J., LS-DYNA Theory Manual, (2006).
4. IAEA, Safety Aspects of Nuclear Power Plants against Human Induced External Events: Margin Assessment, Draft Safety Report DD1086 (2014).
5. Nuclear Energy Institute (NEI 07-13 Rev. 8), Methodology for Performing Aircraft Impact Assessments for New Plant Designs (2011).
6. Riera, J.D., "On the Stress Analysis of Structures subjected to Aircraft Forces," Nuclear Engineering and Design, Vol. 8., p. 415-426 (1968).
7. Sugano, T., Tsubota, H., Kasai, Y., Koshika, N., Orui, S., Von Riesemann, W.A., Bickel, D.C., Parks, M.B., "Full-Scale Aircraft Impact Test for Evaluation of Impact Force," Nuclear Engineering and Design, Vol. 140., p. 373-385 (1993).