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Development of Probabilistic Risk Assessment Procedure of Nuclear Power Plant under Aircraft Impact Loadings

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1. Introduction

Research on aircraft impacts (AI) has grown gradually in a theoretical and experimental way since the Riera method was first introduced [1]. Most of these studies have been mainly focused on global and local damage of the structures subjected to an aircraft impact [2-6]. In addition, these studies have been aimed to verify and ensure the safety of the targeted walls and structures especially in the viewpoint of the deterministic approach.

However, recently, the regulation and the assessment of the safety of the nuclear power plants (NPPs) against to an aircraft impact are strongly encouraged to adopt a probabilistic approach, i.e., the probabilistic risk assessment of an aircraft impact [7-9]. In Korea, research to develop aircraft impact risk quantification technology was initiated in 2012 by Korea Atomic Energy Research Institute (KAERI). In this paper, the total technical roadmap and the procedure to assess the aircraft impact risk will be introduced.

In the first year of the research project, 2012, we developed aircraft impact accident scenario and performed preliminary fragility analysis of the local failure of the targeted wall by aircraft impact. An aircraft impact event can be characterized by the appropriate load parameters (i.e., aircraft type, mass, velocity, angle of crash, etc.). Therefore, the reference parameter should be selected to represent each load effect in order to evaluate the capacity/fragility of SSCs using deterministic or probabilistic methods. This is similar to the use of the peak ground acceleration (PGA) to represent the ground motion spectrum of the earthquake in the seismic probabilistic risk assessment (SPRA) approach. We developed the methodology to decide on the reference parameter for the aircraft impact risk quantification among some reasonable candidates, which can represent many uncertain loading parameters.

To detect the response and the damage of the target structure, missile-target interaction method and Riera's time-history analysis method have been used primarily in the aircraft impact research area. To define the reference loading parameter, we need to perform repetitive simulations for many analysis cases. Thus, we applied a revised version of Riera's method, which is appropriate for a simplified impact simulation. The target NPP to determine the reference parameter and evaluate the preliminary assessment of aircraft impact risk was selected among the typical Korean PWR NPPs. The response has been calculated for pre-stressed concrete containment buildings subjected to aircraft impact loading, and the responses according to each reference parameter have been analyzed.

Recently, we also evaluated the floor response spectra for the locations of important components for the estimation of the failure probabilities and fragility functions of structures and equipments. Some representative floor response spectra for primary auxiliary building were presented in this paper. With the conceptual technical roadmap proposed in this paper to assess the aircraft impact risk of NPP and the previous results of the project in KAERI, we expect that the aircraft impact risk of the NPPs can be estimated in terms of the core damage probability (CDP) in near future. In the presentation at the Korean Nuclear Society Spring Meeting in May, 2014, the feasibility of proposed aircraft impact risk assessment procedure will be proved by the preliminary risk assessment the core damage probability estimation for the most simplified case of aircraft impact induced accident scenario.

2. Aircraft Impact Risk Assessment Procedure

Fig. 1 is a schematic diagram for the assessment procedure of the aircraft impact event induced risk of NPPs. The total procedure composed by three stages; 1) structural analysis to obtain structural responses and evaluate the structural safety, 2) fragility assessment to estimate the aircraft impact fragility functions of safety-related equipments, and 3) system level probabilistic safety assessment (PSA) to quantify the aircraft impact induced risk.

The previous studies on the aircraft impact analysis of NPPs were mainly focused on the structural analysis stage, i.e., the numerical and experimental studies to assess the structural integrity/safety of protecting barrier structures (such as walls, roof, and other barriers). To evaluate the fragilities and the risk induced by aircraft impact, further studies including probabilistic analysis and plant level system analysis are should be performed.

In seismic PSA approach, the seismic failure probability and seismic capacity (in another word, fragility) can be described by one of the reference parameters, peak ground acceleration (PGA). To assess the aircraft impact induced risk, the reference parameter which takes similar roll of PGA in seismic PSA should be selected.

For the fragility assessment stage, on the other hand, the structural response spectrum in specific location point of each safety related equipment should be evaluated from the aircraft impact simulations. Then the failure probability of each equipment can be estimated from the relationship between the response spectrum and capacity data of each equipment. The fragility, i.e., the median capacity and uncertainty parameters, can be evaluated with respect to the reference parameter.

From the research project in KAERI during the first two year, preliminary studies for each stage were performed. Response spectra at the location points of safety related equipments and important SSCs were estimated in structural analysis stage. A method to select the reference parameter of aircraft impact loading was developed for the fragility assessment. Logic trees of damage/failure sequences for important SSCs under aircraft impact event were also developed to perform the plant level system analysis. In the conference presentation, each interim result of the studies will be introduced briefly.

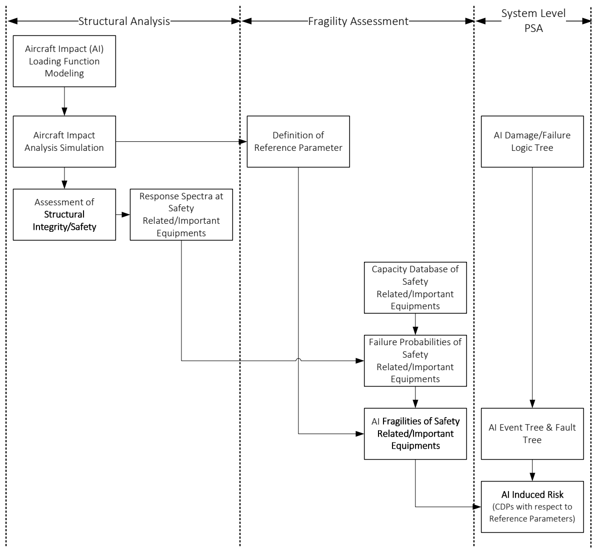


Fig. 1. Schematic diagram for the assessment procedure of the aircraft impact event induced risk of NPPs.

3. Fragility Evaluation & Preliminary Risk Assessment

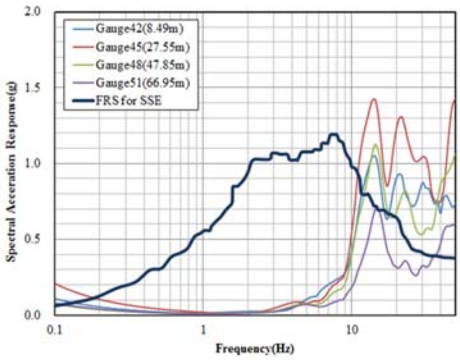
To prove the feasibility of proposed aircraft impact risk assessment procedure, we performed the preliminary risk assessment and estimated the core damage probability for the most simplified case of aircraft impact induced accident scenario. To do this, firstly, aircraft impact simulation for the auxiliary building was implemented and acceleration response spectra at the selected safety related components were developed. The failure mode of components will be a functional or a structural failure according to an excessive acceleration responses. For the fragility evaluation of selected components, since that the vibration capacity database of such components are very difficult to establish, the information of seismic capacities were used. Fig. 2 (a) and (b) depict the acceleration response spectra at the level of 77' and 100' level of auxiliary building subjected to aircraft impact loading compared with floor response spectra for safety shutdown earthquake (SSE). Most of important safety related components have a natural frequency larger than 10 Hz, and the response spectra by aircraft impact at that region are higher than those by SSE. Therefore, we estimated fragility of selected components by using its natural frequency information and seismic fragility database.

In this study, as mentioned previously, we only considered the intentional aircraft crush case. Therefore, the aircraft impact risk will be introduced in terms of a core damage probability. To perform the plant level system analysis and estimate the core damage probability, the logic trees of damage/failure sequences for important SSCs under aircraft impact event were developed. To develop the logic trees of damage/failure sequences for important SSCs under aircraft impact event, firstly, we select a target NPP. The target NPP is one of typical Korean PWR NPP. Fig. 3 shows the placements of safety-related important SSCs of the target NPP. Then, we performed screening out procedure based on intervening structures and near field topography. With these results, we only considered the survived possible directions and SSCs in the development of logic tree. The scattered particles of aircraft and structures after impact can cause the secondary damages on the SSCs which are opened in the yard. The effects of the secondary damages are also included in the logic tree. Fig. 4 depicts an example of the damage/failure sequence logic tree for impact on the primary auxiliary building. We developed also five another logic trees for important SSCs such as containment building, primary auxiliary building, secondary auxiliary building, access control building, and intake building.

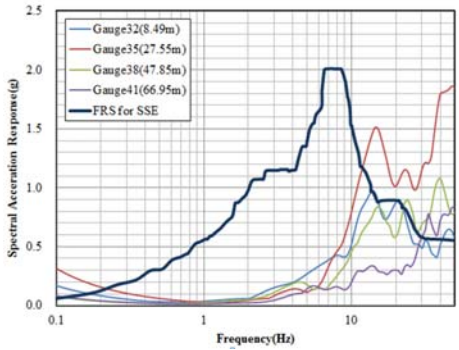
These logic trees are required in the development of the plant level event tree (ET) and fault tree (FT) of the aircraft impact induced accidents. With the fragility database of safety related equipments and critical SSCs, we estimated the plant level aircraft impact risk by solving the Boolean equations in ET & FT. The whole results of this preliminary risk assessment will be presented at the Korean Nuclear Society Spring Meeting, in May, 2014.

4. Conclusions

In this study, the probabilistic risk assessment procedure of nuclear power plant under aircraft impact loadings is developed and introduced. To prove the feasibility of proposed aircraft impact risk assessment procedure, the preliminary risk assessment was performed and probabilistic risk of plant was estimated in terms of the core damage probability for the most simplified case of aircraft impact induced accident scenario. In the further research project, the fragility database of selected safety related components will be fully developed and the ET & FT for the quantification of the aircraft impact induced risk will be established comprehensively.

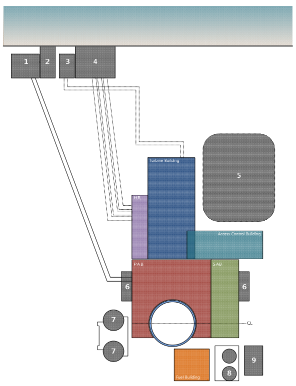


(a) 77ft Level



(b) 100ft Level

Fig. 2. Acceleration response spectra at auxiliary building subjected to aircraft impact loading.



1. CCW HX Bldg.
2. ESW Intake Structure
3. TBCCW HX Room
4. CW Intake Structure
5. Offsite Power
6. Diesel Oil Storage Tank
7. Condensate Storage Tank
8. Reactor Make-up Water Storage Tank
9. AAC Diesel Generator Bldg.

Fig. 3. Placements of safety-related important SSCs in the target nuclear power plant.

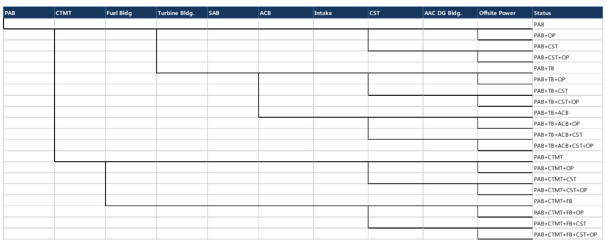


Fig. 4. Example of damage/failure sequence logic tree (primary auxiliary building)

Acknowledgement

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