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Fragility Assessment Method of Concrete Wall Subjected to Impact Loading

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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, for the one example of the probabilistic safety assessment approach, a method to estimate the failure probability and fragility of concrete wall subjected to impact loading caused by missiles or engine parts of aircrafts will be introduced. This method and the corresponding results will be used for the total technical roadmap and the procedure to assess the aircraft impact risk (Fig.1).

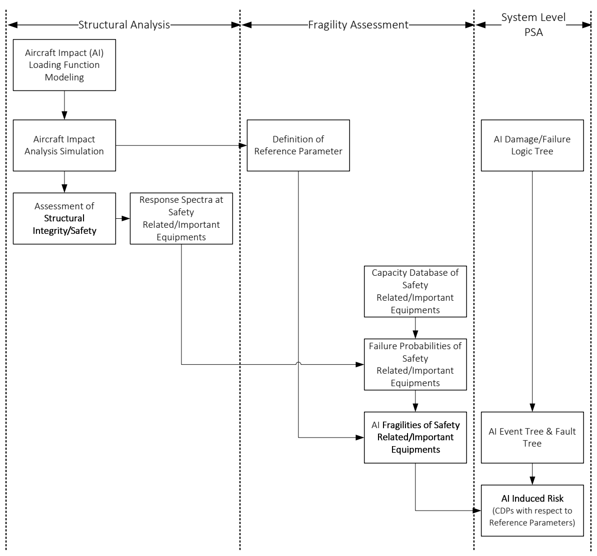

Fig. 1. Schematic diagram for the assessment procedure of the aircraft impact event induced risk of NPPs.

2. Methods and Results

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. With this method, we selected a maximum force variable for the reference parameter of aircraft impact risk assessment [10].

To detect the response and the damage of the target structure, both of analytical method and numerical simulation method, including missile-target interaction method and Riera's time-history analysis method, can be used. In this study, basically we adopted analytical method using three equations recommended by NRC [7], and verified the results by using the numerical simulation method.

The sequence of localized loading effects consists of three stages – missile penetration into the target; spalling and scabbing of the target; and, potentially, missile perforation completely through the target. These terms are defined as follows:

· Penetration – the displacement of the missile into the target. It is a measure of the depth of the crater formed at the zone of impact.

· Spalling – the ejection of target material from the front face of the target (i.e., the face on which the missile impacts).

· Scabbing – the ejection of material from the back face of the target (i.e., opposite the face of impact).

· Perforation – the missile fully penetrates and passes through the target. The term "perforation velocity" refers to the initial missile velocity, which is just sufficient to fully penetrate the target without exiting. The term "residual velocity" refers to the exit velocity of missile that has an initial velocity greater than the perforation velocity.

Such local damage modes would not, in general, result in structural collapse, but instead are considered because of their potential to damage safety-related systems or components. The induced velocity of the scabbed material or the residual velocity of the perforating missile could potentially cause equipment/system failures. Most technical references consider the engines of an aircraft as the critical missiles that can result in local structural damage. Although there are other stiff elements on an aircraft, the engines – while absorbing energy due to crushing during impact – are generally considered to have the greatest potential to cause local damage, since they are external appendages of the aircraft that can become independent missiles during aircraft impact. In this study, we considered two failure mode of concrete wall, i.e., scabbing, and perforation, with an assumption that the penetration and scabbing damage of wall may not cause a significant damage to safety related equipments in primary auxiliary building or reactor containment building.

Actually, for the realistic case, the regulation committee will provide each NSSS vendor (or their appointed representatives) with the aircraft engine parameters necessary to apply the formulas. In this paper, we assumed the information of the aircraft engine parameters by using an ideal engine, and it is considered safeguard information (SGI), so that it is not contained in this paper.

For the analytical estimation of the concrete wall damage subjected to impact loading, first, the penetration depth (or concrete damage depth) (x_c) of the crushed mass of the engine casing should be defined. NRC recommended the modified NDRC (National Defense Research Committee) equation for large diameter missiles such as aircraft engine parts:

$$x_c = \alpha_c \{4K \cdot W \cdot N \cdot D\,(V/(1000D))^{1.8}\}^{1/2},$$
$$\text{for } x_c/\{\alpha_c D\} < 2$$

where x_c is the crushed casing penetration depth in inches, V is the engine velocity in ft/sec, D is the average outer diameter of the engine casing in inches, W is the total engine weight (in lbs), K=180/(f_c\`)$^{1/2}$, $N$=0.72 (flat-nose missile), $f_c$\` is the concrete strength in psi, and α_c = 0.5 is the penetration reduction factor to account for missile deformability and other factors as suggested in Reference [11].

For the scabbing failure mode, the formula of wall thickness required to prevent scabbing (t_s), known as reduced Chang formula [12], is used:

$$t_s = \alpha_s 1.84(200/V)^{0.13}(MV^2)^{0.4}/(\{D/12\}^{0.2}\{144f_c`\}^{0.4})$$

where $M = W$/g and g = 32.2 ft/sec2. The factors of 12 and 144 used in this equation are used to convert the units of casing diameter (inches) and concrete compressive strength (psi) to the units (ft, psf) used in the empirical Chang formula. The recommended value for α_s is 0.55.

For the perforation failure mode, the reduced Degen formula [12] is used to calculate the wall thickness criteria to prevent perforation (t_p):

$$t_p = \alpha_p D\,\{2.2(x_c/\{\alpha_c D\}) - 0.3(x_c/\{\alpha_c D\})^2\},$$
$$\text{for } x_c/\{\alpha_c D\} \leq 1.52$$

The recommended value for α_p is 0.60.

For the estimation of the wall thickness criteria to prevent scabbing and perforation, we assumed the median value and their probabilistic distribution coefficient of f_c\`, D, and M. Then, we estimated the probabilistic distribution of wall thickness criteria, t_s & t_p, with respect to the variation of the impact velocity, V. Finally, we can evaluate the failure probability of the target concrete wall which has a thickness of t_0, and compose a fragility curves for each failure mode, scabbing and perforation, respectively. The detailed probabilistic parameter information of the target concrete wall in NPP, and the example aircraft engine model is considered safeguard information (SGI), and is not contained in this paper. Fig.2 shows a schematic diagram for failure probability estimation method, and Fig.3 represent an example of the fragility curves for each failure mode. Because the failure probability and fragility results of concrete wall subjected to impact

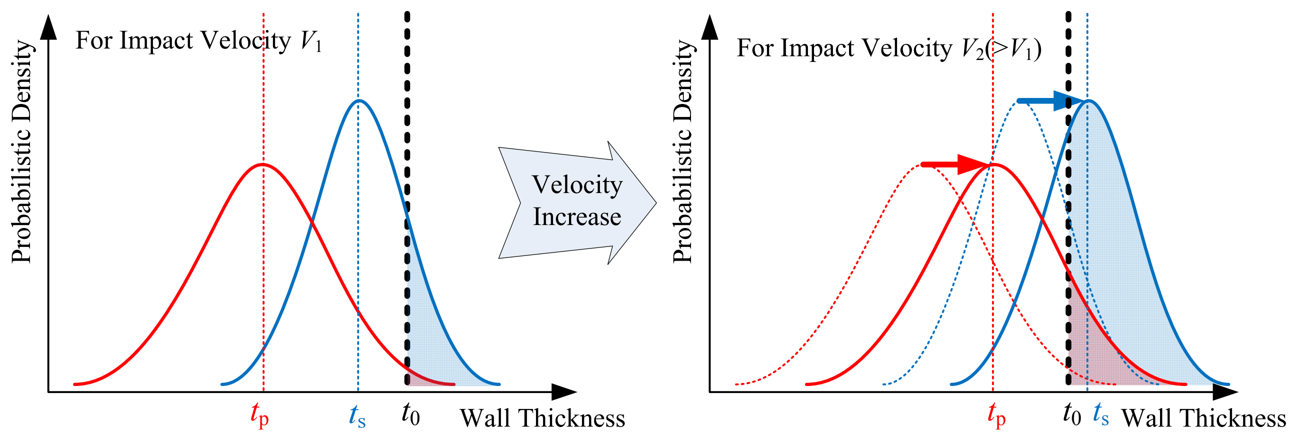

Fig. 2. Schematic diagram for failure probability estimation method.

loadings are very sensitive information for the vendors, the values in horizontal axis of fragility curves, i.e., the representative parameter, are normalized to unit value.

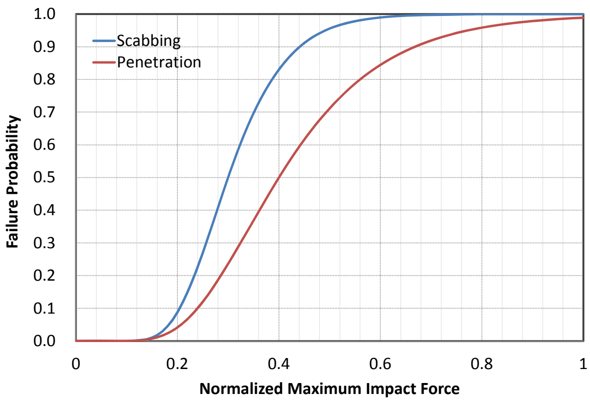

Fig.3 Example of the fragility curves for each failure mode.

3. Conclusions

A method and corresponding results of the estimation of the failure probability and fragility for a concrete wall subjected to impact loadings caused by missiles or engine parts of aircrafts was introduced. The detailed information of the target concrete wall in NPP, and the example aircraft engine model is considered safeguard information (SGI), and is not contained in this paper. However, the trend of the failure probability and fragility results will be presented in the Korean Nuclear Society Autumn Meeting at October 30-31. The method and the results introduced in this paper will be used for the probabilistic approach of the aircraft impact risk assessment.

Acknowledgement

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