Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Probabilistic Assessment Method of Turbojet Engine Impact on an Interim Dry Storage Facility

Belal Almomani[a], Sanghoon Lee[b], Hyun Gook Kang[a*]
[a]*Dept. of Nuclear and Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Korea*
[b]*Dept. of Mechanical and Automotive Eng., Keimyung University, Dalgubeol-daero 1095, Dalseo-gu, Daegu, Korea*
[*]*Corresponding author: hyungook@kaist.ac.kr*

1. Introduction

In the process of developing an aircraft crash scenario onto an interim dry storage facility, the shield wall of the facility building is considered as a first barrier of protecting the internal spent fuel storage casks. In order to evaluate the aircraft risk model on the interim storage facility, it is important to use a probabilistic safety assessment approach for investigating the probable realistic and severe impact conditions from the aircraft crash. This paper describes an analytical method of structural analysis for an interim storage facility subjected to aircraft jet engine based on a probabilistic approach. This method will be employed in the process of aircraft risk model for the interim storage facilities.

2. Methods and Assumptions

The local response mechanism of a concrete shield is initiated with spalling and subsequently can result in penetration, scabbing of the shield material from the back face, and eventual perforation transporting the missile through the shield as illustrated in Fig 1 [1].

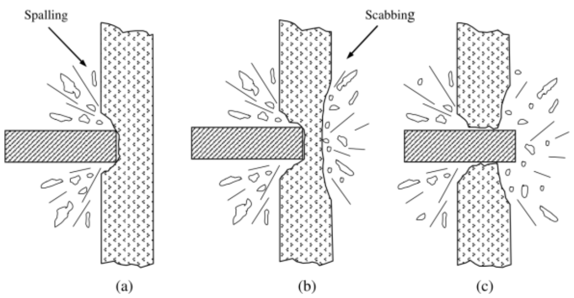

Fig. 1. Local response of a shield: (a) penetration and spalling, (b) scabbing, and (c) perforation.

The primary local damage effect of interest is an eventual perforation of the shield that the missile fully penetrates and passes through the target since this study concentrates on the safety of the internal storage casks during a direct high-speed impact from a heavy component. The direct impact on the storage casks happens when the initial velocity of the missile is greater than the perforation velocity that is sufficient to fully penetrate the target without exiting. The exit velocity of the missile is called a “residual velocity”. The residual velocity of the perforating missile is an important parameter that could potentially cause casks to be damaged.

The engines of an aircraft were considered from many references as the major critical missiles that can result a significant local structural damage. Regardless of other stiff elements on an aircraft, the jet engine is assumed as a potential independent missile normally impacting towards the reinforced concrete wall slab for this study.

The analytical formulation of the engine impact and the perforation to find the required thickness of concrete to protect the equipment inside the structure is an enormously complex impact phenomenon. Therefore, all the available formulas describing perforation phenomena are empirical and based on experimental data. In this study, the assessment of structural integrity for the local loading on concrete walls is based on a simplified approach using empirical formulas that were recommended in NEI 07-3 report [2].

2.1 Perforation mode of damage

The term perforation thickness is used especially when the projectiles just passes through the target completely with zero exit velocity. Two empirical formulas have been used to determine the limit state of the perforation depth and to define the concrete wall thickness criteria to protect the storage casks inside the facility. The Modified NDRC (National Defense Research Committee) eq. (1) obtains the penetration depth, and the reduced Degen eq. (2) calculates the wall thickness required to prevent perforation.

$$x_c = \alpha_c \sqrt{4KNWD\left(\frac{V_i}{1000D}\right)^{1.8}} \quad \text{, for} \quad \frac{x_c}{\alpha_c D} < 2 \qquad (1)$$

$$t_p = \alpha_p D\left\{2.2\left(\frac{x_c}{\alpha_c D}\right) - 0.3\left(\frac{x_c}{\alpha_c D}\right)^2\right\} \quad \text{, for} \quad \frac{x_c}{\alpha_c D} < 1.52 \qquad (2)$$

where t_p is the wall thickness to prevent perforation (inches), x_c is the crushed casing penetration depth (inches), W is the missile weight (Ibs), α_c is the reduction factor for penetration and α_p is the reduction factor for perforation, K is the concrete penetrability factor defined as $180/(f_c)^{1/2}$, f_c is the compressive strength of concrete (psi), D is the effective diameter of the engine (inches), V_i is the original missile velocity (ft/sec). For the missile shape factor N, 0.72 is assigned for flat-nosed, 0.84 for blunt-nosed, 1.00 for spherical end, and 1.14 for very sharp-nosed projectiles.

The conditional probabilities of perforation of a structural concrete slab are functions of aircraft engine characteristics, impact speeds, and target specifications. It is presumed that the aircraft engine characteristics are given in this study. Large turbojet engine type CF6-80C2, commonly used for B747s and Air-Bus 300, was chosen for this analysis. This engine could be one of the acceptable ideal model provided by the regulatory body due to its dimensions and weight represents the upper boundaries among other commercial aircrafts engines. The engine has an effective averaged diameter of 1.4 m, 4.3m length, a weight of 4.4 tons, and has a flat-nosed body [3]. The engine is assumed to be a deformable missile with a reduction factor α_c = 0.5 for the penetration depth calculation and α_p = 0.6 for the perforation limit calculation as suggested in reference [4].

Aircraft impact speeds and concrete strength parameters are considered as the major sources of uncertainty in the perforation calculations. The aircraft impact speed depends on many factors such as the size of the target, topography around the site, weather, payload, pilot skills, etc. The concrete wall varies in property during fabrication batch to batch and according to age factor. Table 1 shows the typical airplanes speeds in different flight modes and the recorded impact velocities during September 11 attacks. From Table I, aircraft impact speed, V_i, is assumed to be normally distributed with a mean value of 155 m/s and a standard deviation 35.24.

Table I: The estimated aircraft speeds during typical normal flight and during September 11 attacks. [5], [6]

Item	Values km/h (m/s)
At optimal flight altitude	990 (275)
Flight close to ground	650 (180)
Average normal landing speed	468-576 (130-160)
Minimum landing speed	324 (100)
Attack on the north tower of WTC	691 (192)
Attack on the south tower of WTC	810 (225)
Attack on Pentagon building	555 (154)

The compressive strength of concrete f_c is modeled as a logarithmic normal distribution, which is usually used in the civil engineering applications. The mathematical model of probability density function of the concrete strength is, as reported in reference [7]:

$$f(f_c;\ \mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma f_c} e^{-\frac{1}{2}\left(\frac{\ln f_c-\mu}{\sigma}\right)^2} \quad (3)$$

$$\sigma = \sqrt{\ln\left(1 + \frac{28.11}{{f_{ck}}^2}\right)} \quad (4)$$

$$\mu = \ln(1.28143 f_{ck}) - \frac{1}{2}\ln\left(1 + \frac{28.11}{{f_{ck}}^2}\right) \quad (5)$$

where f_c is defined as the strength of a single sample, and f_{ck} is the characteristic strength as defined the value of strength of material below which not more than a minimum acceptable percentage of the test results are expected to fall. μ and σ can be called the location parameter and the scale parameter, respectively. Fig. 2 shows the distribution curves for various concrete strength classes.

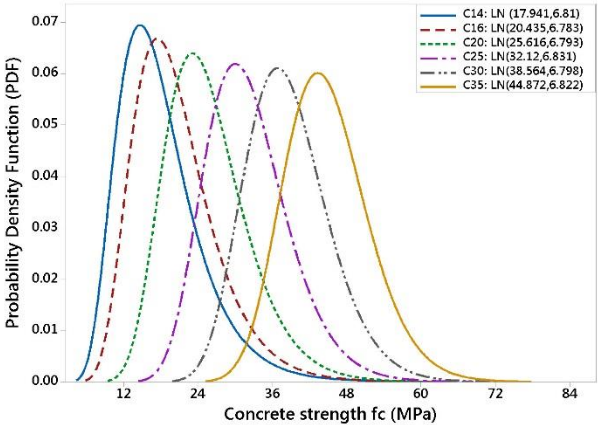

Fig. 2. Logarithmic normal distribution model for uncertainty in concrete compressive strengths.

2.2 Exit velocity of the missile

The second stage is computing the residual velocity of the missile after penetrating into the concrete wall. The residual impact velocity is the engine velocity that exceeds of those required to perforate a given wall thickness. Fig. 3 shows the geometers for the concrete conical plug. Kar equation (6) was applied to estimate the residual velocity using the procedure described in NEI 07-13 report with assuming that the engine velocity of the missile and ejected concrete are the same [8]:

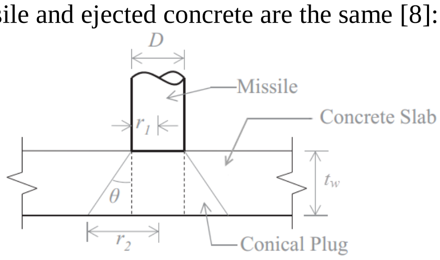

Fig. 3. Conical plug geometry.

$$V_R = \left[\frac{V_i^2 - V_p^2}{1 + \frac{W_{cp}}{W}}\right]^{0.5},\ for\ (V_i > V_p) \quad (6)$$

$$W_{cp} = \pi\,\rho_c \left(\frac{t_w}{3}\right)({r_1}^2 + r_1 r_2 + {r_2}^2) \quad (7)$$

$$r_2 = r_1 + t_w(\tan\theta) \quad (8)$$

$$\theta = 45°/(t_w/\mathrm{D})^{1/3} \quad (9)$$

where V_R is the residual velocity (ft/sec), W_{cp} is weight of the concrete plug ejected by the perforating missile with weight, W (lbs), r_1 is the minor radius of cone (inches), r_2 is the major radius of cone (inches), t_w is the wall thickness (inches), ρ_c is the weight density of concrete (Ib/in^3). The concrete wall perforation velocity V_P, that just initiates perforation, is combined into individual equation (10) to solve V_P directly instead of doing multiple steps of calculations [9].

$$V_p = 1000.D\left(\frac{D}{1.44K.W.N}\left(2.2-\sqrt{4.84-1.2\left(\frac{t_w}{\alpha_p D}\right)}\right)^2\right)^{5/9}, \quad \text{for } \frac{t_w}{\alpha_p d} \le 2.65 \qquad (10)$$

From the current existing design concepts of interim storage facilities, the wall thickness is around 0.7 to 1.2 m [10]. Two samples of the residual velocity calculations are shown in the results section; one is estimated for 70 cm wall thickness with various concrete strength classes, and the another one is estimated for a concrete class C25 with six selected wall thicknesses, which are 70, 80, 90, 100, 110, 120 cm.

3. Results

The conditional probability of perforation of a given thickness was estimated by using a simple Monte-Carlo technique. Frequency distributions were assigned only to impact velocity and concrete strength from a random sampling, then a perforation thickness was calculated. From 10000 trials, the cumulative distribution function for perforation thickness was generated as shown in Fig. 4.

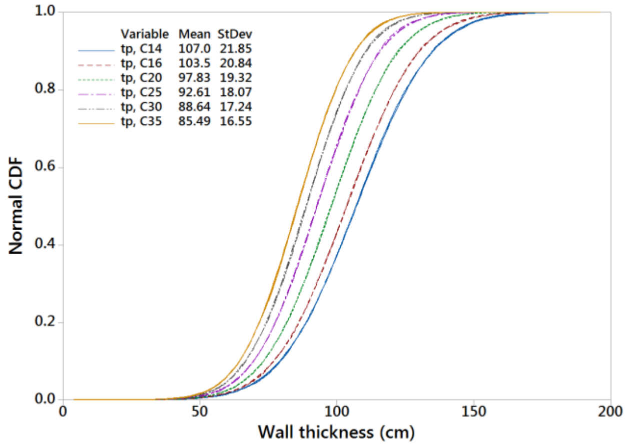

Fig. 4. Cumulative distribution curve for perforation thickness.

The local failure probability (perforation) of a given wall thickness t_w can be calculated from the complementary cumulative distribution function (ccdf) of Fig. 4. The estimated local failure probabilities of perforation for several concrete wall thicknesses are shown in Table II.

Table II: The estimated conditional local failure probability of perforation for various concrete wall thicknesses.

Concrete class	70 cm	80 cm	90 cm	100 cm	110 cm	120 cm
C14	0.95	0.89	0.78	0.62	0.44	0.27
C16	0.94	0.87	0.74	0.56	0.37	0.21
C20	0.92	0.82	0.65	0.45	0.26	0.125
C25	0.89	0.75	0.55	0.34	0.16	0.06
C30	0.86	0.69	0.46	0.25	0.10	0.03
C35	0.82	0.63	0.39	0.19	0.06	0.018

Table II may help for selecting a suitable concrete wall characteristics during the design stage with concern about the safety margins to protect the inside storage casks from the aircraft crash hazard.

The obtained distribution curves for the residual velocity variables are shown in Fig. 5 for wall thickness 70 cm with respect of various concrete classes, and Fig. 6 for concrete strength class C25 with respect of various wall thicknesses through using the equations (6)~(10). The reasons of selecting the Weibull distribution curve modelling of $V_R$is because it shows a good fit based on a normality test (Anderson Darling), also because the value of random variable of the residual velocity is positive (0< V_R<∞).

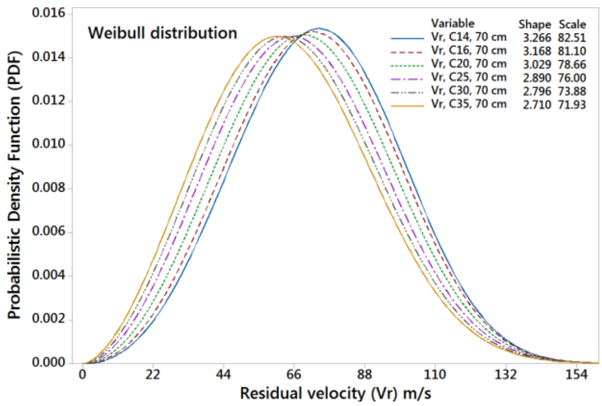

Fig. 5. Probabilistic density function curve of engine residual velocity for wall thickness 70 cm and various concrete classes.

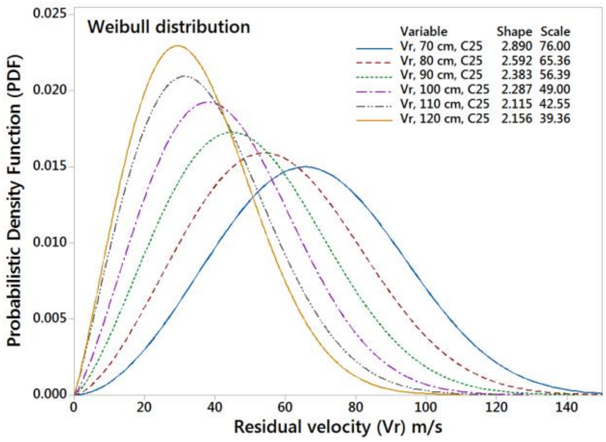

Fig. 6. Probabilistic density function curves of engine residual velocity for concrete strength C25 and various wall thicknesses.

The 95% confidence interval values for residual velocity was selected, which can representative of a lower and upper limit on the variable. In Fig. 5, the mean value of V_R is 74.062 m/s with lower limit 26.778 m/s and upper limit 120 m/s for concrete class C14, and the mean value equals 64.083 m/s with lower limit 18.53 m/s and upper limit 116.4 m/s for concrete class C35. Same in Fig 6, the mean value of V_R is 67.862 with lower limit 21.3 m/s and upper limit 120 m/s for wall thickness 70 cm, and the mean value equals 34.858 m/s with lower limit 7.154 m/s and upper limit 72.11 m/s for wall thickness 120 cm. It can be noted that a wide spread between the lower and the upper bounds. This happens due to the considerable uncertainty in the aircraft impact velocities. However, applying impact velocities higher than the upper limits on the storage cask body would over-predict the effects of the aircraft impact. Therefore, Fig. 5 and 6 indicates to reasonable impact velocity ranges that could be applied on the storage casks. Through applying engine impact loading for several impact velocities within the proposed range in Fig. 5 and 6 into the cask body, the failure criteria of the cask can be defined for a purpose of continuing the risk assessment process of aircraft impact.

4. Conclusions

In this paper, a method with sample results to determine the local failure probability of the facility's wall and the probable residual velocities after passed through the target by applying a probabilistic approach was proposed. Normal engine impact on the wall shield using applicable empirical formulas provides a best estimation of perforation depth and residual velocity with intent of producing conservative outcomes. The most influential factors in the calculations are the engine impact velocity, wall thickness of target, and concrete strength. Subsequent engine impact loads into the internal storage casks depend on the estimated residual velocity range after the engine penetrated the facility's wall. The introduced method in this study can be used for the probabilistic risk assessment of the aircraft crash on an interim storage facility.

REFERENCES

[1] US-DOE Standards, Accident Analysis For Aircraft Crash Into Hazardous Facilities, DOE- STD-3014, 2006.
[2] NEI 07-13, Methodology for Performing Aircraft Impact Assessments for New Plant Designs, NEI, 2011.
[3] K. Shirai, K. Namba, and T. Saegusa, Safety Analysis of Dual Purpose Metal Cask Subjected to Impulsive Loads due to Aircraft Engine Crash, Journal of Power and Energy Systems, Vol.3, No.1, pp.72-82, 2009.
[4] Sugano, et al., Local Damage to Reinforced Concrete Structures Caused by Impact of Aircraft Engine Missiles part 2. Evaluation of the Test Results, Nuclear Engineering and Design, Vol.40, pp. 407-423, 1993.
[5] Kausel, 2002, Speed of Aircraft [internet]. Available from: http://web.mit.edu/civenv/wtc/.
[6] Kessler, G. et al., 2014. The Risk of Nuclear Energy Technology. New York: Springer, ISSN: 2213-1965.
[7] A. Ö ztemel, et al., Mathematical Model for the Probability Distribution of In-Situ Concrete Compressive Strength in North Cyprus, 29th Conference on our World in Concrete & Structures, pp. 387-395, 2004.
[8] Anil K. Kar, Residual Velocity for Projectiles, Nuclear Engineering and Design, Vol. 53, pp. 87- 95, 1978.
[9] Bruhl, J., et al., Design of composite SC walls to prevent perforation from missile impact, International Journal of Impact Engineering, Vol. 75, pp.75-87, 2015.
[10] Thomauske, B., Realization of the German Concept for Interm Storage of Spent Nuclear Fuel-Current Situation and Prospects. Tucson, WM'03 Conference, 2003