Local Damage Analysis of Dry Storage Facility under Aircraft Engine Impact

Belal Almomani, Tae-Yong Kim, Yoon-Suk Chang*
Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si,
Gyeonggi-do 17104, Republic of Korea
**Corresponding author: yschang@khu.ac.kr*

1. Introduction

Aircraft crash on nuclear facilities is considered as an interesting human-induced external event that is required to be implemented in safety analysis as one of BDBAs [1]. Many studies focused on aircraft crash analysis for NPP containment using different modeling techniques; however, few studies were implemented to evaluate the aircraft crash on interim storage facilities. Nevertheless, the previous studies are mainly limited to global damage response which refers to the overall building behavior under the entire aircraft impact load but not much considered on the local damage response that refers to the penetration of the concrete shield caused by a stiff element impact such as the jet engines. Thus, proposing further numerical analyses is necessary to evaluate the local damage response analysis caused by a jet engine impact on an interim storage facility.

In this paper, local damage analysis of a postulated spent fuel storage facility impacted by a jet engine is presented using LS-DYNA code with considering the influence of erosion factor.

2. Modeling procedure

2.1. Jet engine model

A 3D solid element-based model of a large conceptual civil aircraft engine has been developed and verified using the impact force-time history curve created by the Riera function. The engine mainly consists of a diffuser, turbofan, and core which includes complex parts such as low and high-pressure compressor, combustor, turbine sections, and exhaust cone. Considering the purpose of this study, a dummy solid body representing the interior structures of the core was made and a mass distribution was implemented as illustrated in Fig. 1 and 2.

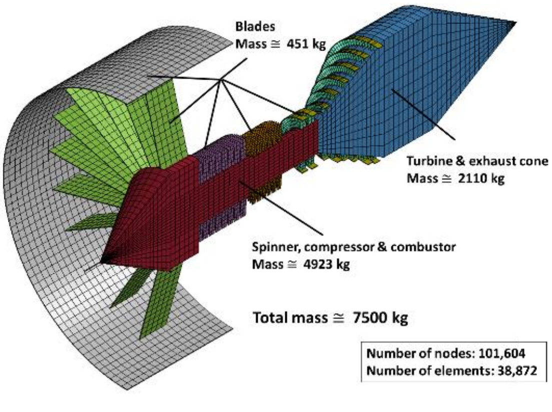


Fig. 1. A cross-sectional view of the jet engine FE model

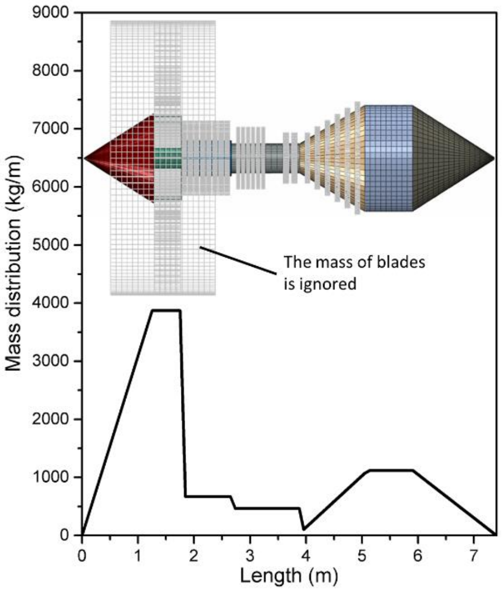


Fig. 2. Engine mass distribution

Riera's approach is being a one-dimensional ideal-plastic model to predict the normal force of a missile impact on a rigid flat target. The applied force of the rigid target is based on the time interval corresponding to the momentum change. Accordingly, the engine core is modeled as a compressible part using the modified honeycomb model available in LS-DYNA to simulate a soft impact. The deceleration from destruction is assumed to be 0 m/s^2 as such deceleration arises in most numerical tests above 0.05s from the beginning of the impact. The influence of the crushing force, which depends on the deceleration from destruction, is neglected and the mass coefficient is assumed as 1. Thus, the following simplified Riera formula is used to calculate the engine force in the subsequent analysis that only depends on mass distribution and initial impact velocity.

$$F(t) = \mu[x(t)]v(t)^2 \qquad (1)$$

Figure 3 displays the impact force and impulse-time history obtained from the theoretical calculation and FE analysis. As shown in the figure, the filtered curve with a cut-off frequency of 200 Hz showed good agreement with the theoretical curve. Besides, the maximum impulse values derived from theoretical and simulation curves were 1.055 MN-s and 1.048 MN-s, respectively, which matched within a difference of less than 0.7%. Thus, the confidence of the proposed FE analysis procedure was gained. It is should be noted that the blades are not considered in the loading function since not yielding a significant contribution to the impact load.

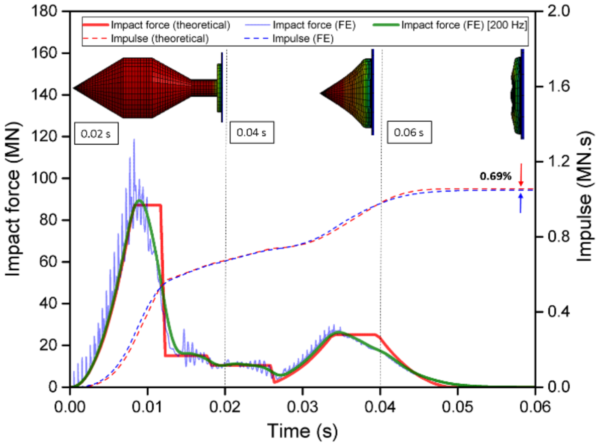


Fig. 3. Impact force-time histories

2.2. Postulated storage facility model

Figure 4 depicts the details of postulated storage facility model and impact location of the engine. The building is composed of reinforced concrete (RC) structure and two-layers of steel rebar arrangement. The wall thickness at the impacted area is 98cm and the reinforcement ratio is 1.4%. The concrete wall was generated by using solid elements and the rebar was embedded using the constrained Lagrange option. Continuous Surface Cap Model (CSCM) considering damage and strain-rate in LS-DYNA was used for the concrete elements. The tensile and compressive failure phenomena can be demonstrated by applying adequate values to the erosion parameters. The element erosion happens when the erosion parameter is greater than 0.99 and the maximum principal strain is greater than a user-supplied input value. The rebar was modeled using beam elements and a plastic kinematic model was adopted to implement elastic-plastic behavior and strain rate effect. The rebar has a yield strength of 414MPa and a failure strain of 20%.

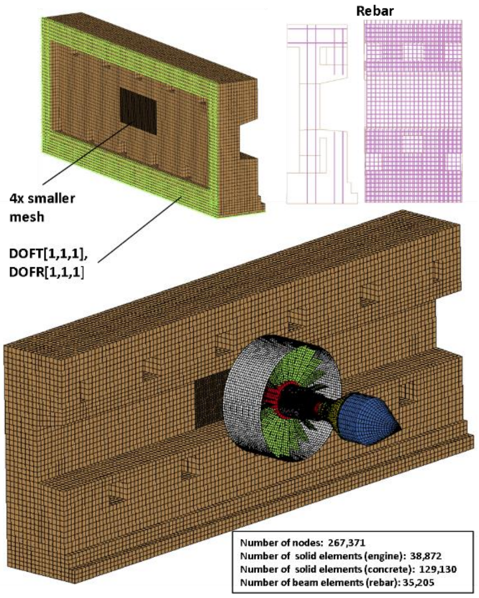


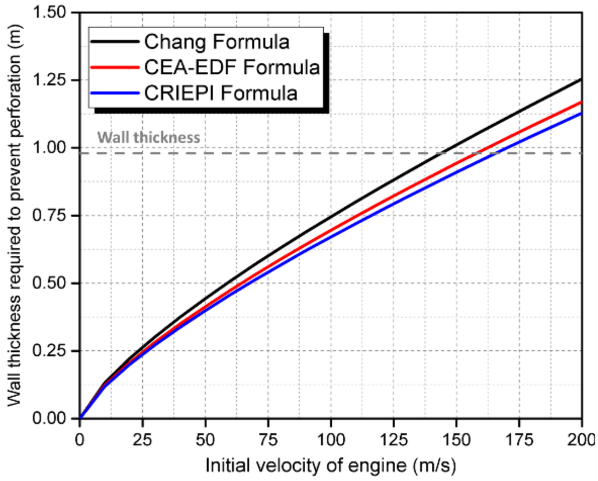
Fig. 4. FE model of dry storage facility and jet engine

A sensitivity assessment is carried out for the erosion values of the concrete wall. The common erosion thresholds to probably predict the damage of RC are ranged from 1.1 to 1.4. Accordingly, examined erosion values in this study are 1.1, 1.2, 1.3, 1.4 as well as two extra cases of 1.05 and 1.5 to provide a wide-ranging analysis. The mesh density of concrete at the location of engine impact was made 4-times higher than the global facility mesh to accurately evaluate the local damage response. The element mesh size in this area is around 50mm. The local damage effect of interest is an eventual perforation transporting the engine completely through the RC shield with exit velocity. The impact velocity of the engine was set at 150m/s, which was the measured velocity of the airplane that struck the Pentagon.

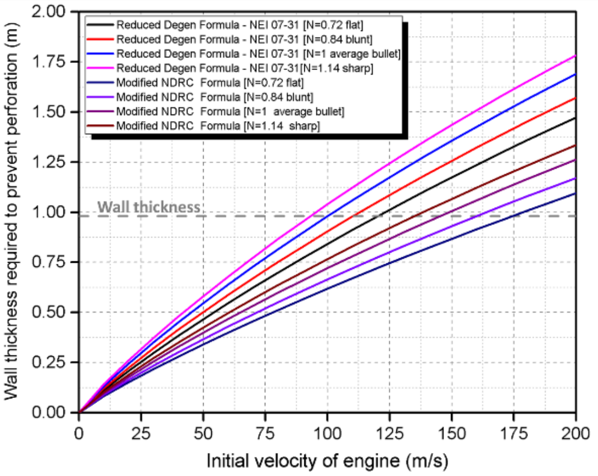
3. Empirical formula evaluation

Applicable widely-used empirical formulas for predicting the required thickness to prevent the perforation of hard projectiles impacting the RC target are used to compare it with the engine impact analysis. The used formulas are not presented in this paper for brevity but detailed explanations can be found in [2, 3]. The commonly required input parameters in these formulas are engine weight, average outer diameter, velocity, concrete compressive strength, missile shape factor, penetration, and perforation coefficients. The coefficients are assumed to be 0.5 for the penetration depth calculation and 0.6 for the perforation limit calculation as suggested in reference [4]. Figure 5a shows the relationship between the impact velocity and the required thickness to prevent perforation using Chang, CEA-EDF, and CRIEPI formulas. It is found that the average required thickness to prevent perforation at 150m/s is 96cm, which is close to the wall thickness of the facility. However, these formulas are not considered the missile shape factor. Thus, the Reduced Degen and Modified NDRC formulas are used with applying several shape factors as illustrated in Fig.5b. These formulas indicate that the perforation phenomenon would probably occur at impact velocity 150m/s for the presented engine specifications.

The residual velocity, or exit velocity of the engine after complete perforating, is another parameter that could verify the modeling procedure presented in this work. The residual velocity is the engine velocity that exceeds those required to perforate a given wall thickness. Kar formula was applied to estimate the residual velocity using the procedure described in NEI 07-13 report [2] with assuming that the engine velocity of the missile and ejected concrete are same. Figure 6 shows the relationship between the exit velocities concerning the initial impact velocities with several shape factors. From the formula calculations, it is expected that the exit velocity would be ranged from 53 to 70m/s corresponding to the missile shape factors. These obtained exit velocities will be compared with the numerical simulation for various erosion values of concrete as discussed in the next section.



(a) Empirical formulas with no missile shape factor consideration



(b) Empirical formulas with missile shape factor consideration

Fig. 5 Empirical formulas for predicting perforation thickness

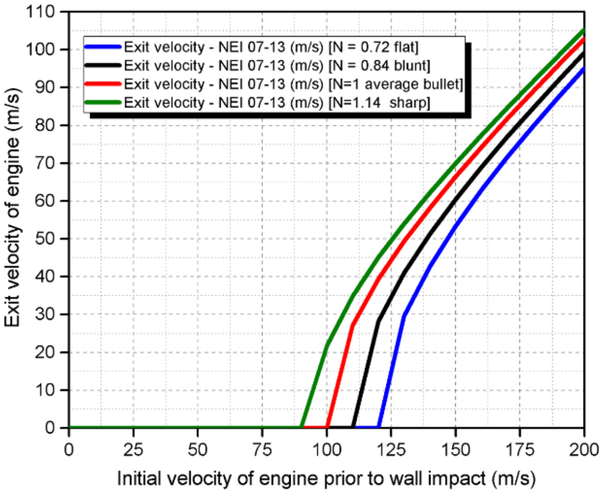
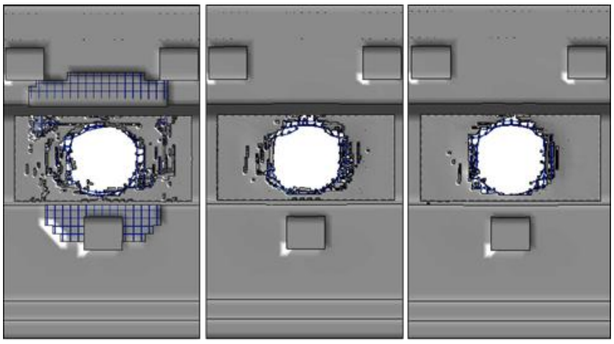


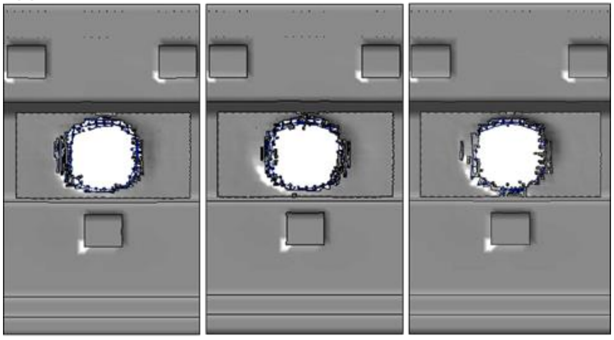
Fig. 6. The relationship between the initial velocity and the existing velocity with various missile shape factors

4. Analysis results

The analysis results of concrete damage considering several erosion values were investigated, as presented in Fig.7. In general, the amount of failed elements was increased with decreased erosion value. The impact interaction between the engine core and the facility wall approximately begins at time 0.1s and ends at 0.4s where the engine perforates the shield and continues to fly freely with a reduced exit velocity. The front part of the engine at time 0.4s is mostly destroyed (≈ 60% of the engine) due to elastoplastic behavior, which is consistent with the assumed perforation reduction coefficient that is used in the empirical formulas. Despite increasing the erosion value, the perforation phenomenon is observed in all the cases at impact velocity 150m/s as predicted by the empirical formulas.



(a) Erosion value 1.05 (b) Erosion value 1.1 (c) Erosion value 1.2



(d) Erosion value 1.3 (e) Erosion value 1.4 (f) Erosion value 1.5

Fig. 7. Illustration of concrete wall damage at the front face with various erosion values from engine impact at 150 m/s

Figure 8 shows the velocity-time histories of the engine model during the impact. The range of exit velocity for all the cases is ranged from 58.9 to 70.8m/s, which is slightly higher than the predicted exit velocities from the Kar formula for various missile shape factors. Nevertheless, the estimated exit velocity from the numerical simulation at erosion value 1.4 is 61.1m/s while the predicated exit velocity for blunt-nosed shape from the Kar formula is 60.5m/s. The difference between these two values is 0.98%, which represents the least difference among the other cases. Hence, using erosion value of 1.4 with CSCM model in the numerical analysis would provide the best matching results in comparison of Kar formula results with using the shape factor of 0.84 for the blunt-nosed body as the most representative shape for the proposed engine.

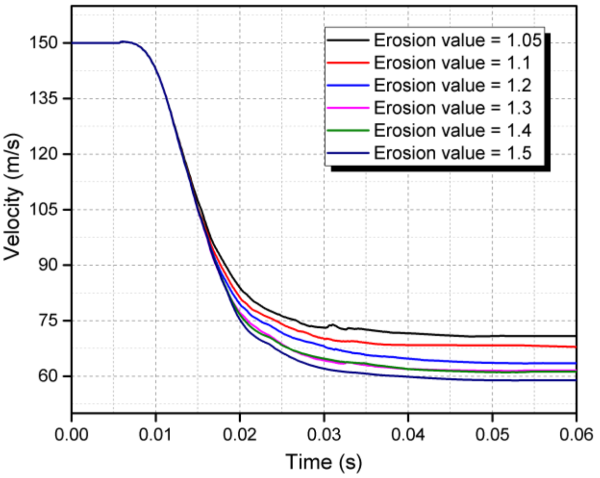


Fig. 8. Velocity time-histories of engine for various erosion values of concrete

It should be pointed out that the probability of the applied scenario (velocity, impact location) in this study might be very small and not realistic due to several technical issues related to piloting skill in the maneuvering of a large civil aircraft near to the ground and to successfully hit a small size target such as an interim storage facility. Therefore, the probabilistic risk assessment needs to be conducted as in the author's previous work [5] to provide an efficient and reasonable analysis using the data acquisition from validated numerical analyses and tests to investigate storage facility capacity to withstand an aircraft impact and thereby protect public health.

5. Conclusions

This paper presented an interesting case study of local damage analysis for a postulated storage facility under jet engine impact. Advanced modeling procedure of engine and storage facility building was developed. A severe impact scenario was implemented considering the most critical location with high initial velocity (150 m/s) of a large civil engine to demonstrate the perforation phenomenon. A sensitivity assessment was performed according to erosion values of the concrete using the CSCM model. The exit velocity of the engine was increased to 18.5% when increased the erosion value from 1.05 to 1.5. It concludes that erosion is a very important factor to get a responsible behavior of local damage. Overall, the analysis results agree well with the calculations of empirical formulas and it was found that the erosion value of 1.4 is the most appropriate value to be implemented in the numerical analysis.

This study will be expanded using different material models of concrete and further local damage response phenomena will be evaluated.

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