Impact Analyses and Tests of Metal Cask Considering Aircraft Engine Crash - 12308

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ABSTRACT

The structural integrity of a dual purpose metal cask currently under development by the Korea Radioactive Waste Management Cooperation (KRMC) is evaluated through analyses and tests under a high-speed missile impact considering the targeted aircraft crash conditions. The impact conditions were carefully chosen through a survey on accident cases and recommendations from the literature. The missile impact velocity was set at 150 m/s, and two impact orientations were considered. A simplified missile simulating a commercial aircraft engine is designed from an impact load history curve provided in the literature. In the analyses, the focus is on the evaluation of the containment boundary integrity of the metal cask. The analyses results are compared with the results of tests using a 1/3 scale model. The results show very good agreements, and the procedure and methodology adopted in the structural analyses are validated. While the integrity of the cask is maintained in one evaluation where the missile impacts the top side of the free standing cask, the containment boundary is breached in another case in which the missile impacts the center of the cask lid in a perpendicular orientation.

INTRODUCTION

The safety assessment against an aircraft crash has been an important issue in the design of facilities with hazardous materials such as nuclear power plants [1]. For an accidental aircraft crash, the probability of a crash is calculated and its consequences are selectively evaluated for those facilities with a significant crash probability. Since the 9/11 terrorist attacks, greater emphasis has been placed on the case of a targeted aircraft crash than on accidental crashes. In many aspects, the requirements for a targeted aircraft crash are different from those for accidental crashes and tend to be more severe. Recently, the US Nuclear Regulatory Commission (NRC) revised 10 CFR 50.150 to include the safety assessment requirements against a targeted aircraft crash for the licensing of newly introduced nuclear power plants [2]. In addition to nuclear power plants, many countries have performed safety assessments of spent nuclear fuel storage systems against a targeted aircraft crash using numerical simulations and tests [3-5].

In Korea, the safety assessment of a nuclear power plant against an aircraft crash has been performed using numerical simulations, but not many efforts have been made on the safety assessments of spent nuclear fuel storage systems. In addition, efforts to verify the simulation results for an aircraft crash using tests have yet to be reported. In this research, the safety assessment of a dual purpose metal cask (DPMC) under development by the KRMC is performed using numerical simulations and tests. A scenario of a targeted aircraft crash is set from a literature survey, and the impact conditions are derived from the scenario. Through a comparison of the test and simulation results, the methodology used in the numerical simulation is verified. However, it should be noted that the results of the assessment in this paper are not conclusive since the cask is under development and the design is subject to change.

TARGET SYSTEM

The spent nuclear fuel storage system considered in this research is a DPMC, which is under development by the KRMC. It consists of a welded canister with a spent fuel basket and a metal cask with a lid. Fig. 1 shows the concept drawing of the DPMC without impact limiters. To ease the simulation and tests, a simplified scale model of the original cask was designed as shown in Fig. 2. The scale factor is 1/3, and the spent fuel basket is replaced by a dummy weight with the same mass and similar stiffness. The neutron absorbers are omitted in the design of the simplified model. The cask and dummy weight are made of carbon steel A516 Gr. 70, and the canister is made of stainless steel A240 Type 304. The total weight of the 1/3 scale model is 3578 kg.

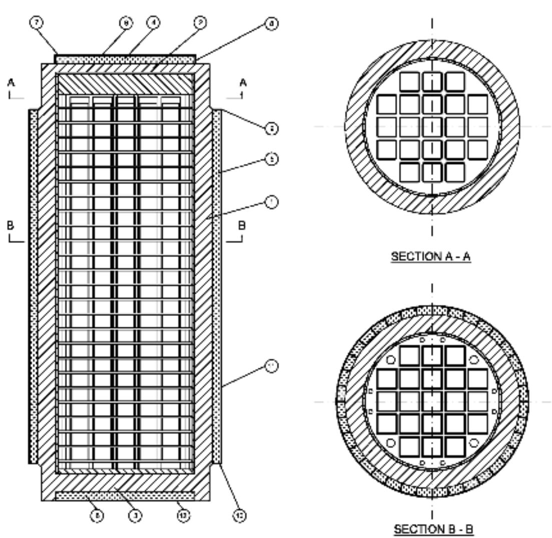

Fig. 1. Concept drawing of DPMC

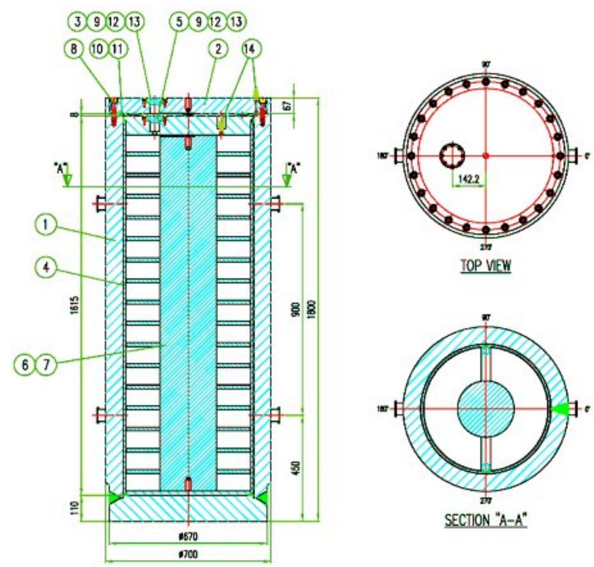

Fig. 2. Simplified scale model of DPMC

IMPACT CONDITIONS

The scenario of a targeted aircraft crash has been made based on 10 CFR 50.150 [2] and NEI report [3]. A Boeing 747, a large commercial aircraft frequently flown over Korea, is considered as the impacting aircraft, and the impact velocity is set at 150 m/s, which is the measured velocity of the airplane that struck the Pentagon during the 9/11 terrorist attacks. The impact velocity should be determined considering the maneuverability of the aircraft based on the size of the target system, topography around the site, skill of the pilot, and so on. Since the topography of Korea is not the same as that near the Pentagon, an impact velocity of 150 m/s might not be realistic. However, it is the only available data of a real targeted aircraft crash into a low profile building. The impact orientation is another important factor to be determined in an aircraft crash scenario. As mentioned in [3], the size of the DPMC is much smaller than the aircraft, and the most severe impact condition is the direct impact of the aircraft engine with the DPMC. In our research, two orientations are considered. In one case, the engine of the B747 hits the upper part of a DPMC, which is free standing on a concrete pad. In the other case, the engine of the B747 hits the center of the lid of DPMC perpendicularly, which implies that the airplane has flown vertically downward. While the second case is more unrealistic considering the maneuverability of the aircraft, this orientation is expected to cause very severe damage to the containment boundary of the cask and was selected as a candidate orientation to remain on the conservative side. Figs. 3 and 4 show the impact orientations considered in this research.

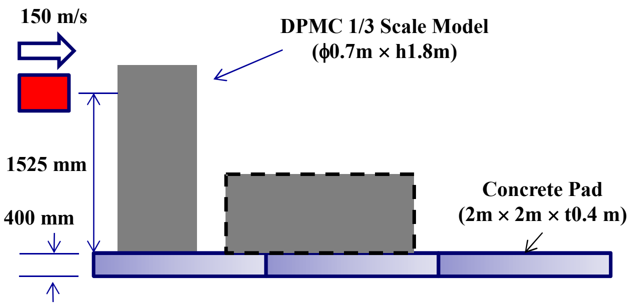

Fig. 3. Impact orientation (Case 1)

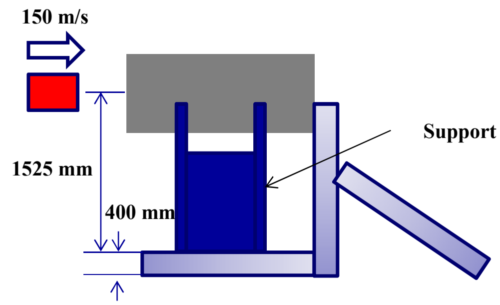

Fig. 4. Impact orientation (Case 2)

MISSILE DESIGN

A simplified missile simulating the engine of a B747 was designed. The engine weighs about 4.5 tons and the effective impact diameter is about 1.4 m [4]. The impact load history curve proposed in [4] and the scale theory are utilized in the design of the simplified scale model of the engine. The impact load history provided in the literature is from an impact at a velocity of 60 m/s onto a rigid wall. Firstly, the reference load history curve is scaled down based on the scale theory. The dimensions of the simplified missile are then determined such that the load history of the designed missile from an impact onto a rigid wall at a 60 m/s velocity is as close to the reference curve as possible. The procedure is depicted in Fig. 5. The simplified missile, which weighs 167 kg and has a diameter of 355 mm, is made of carbon steel.

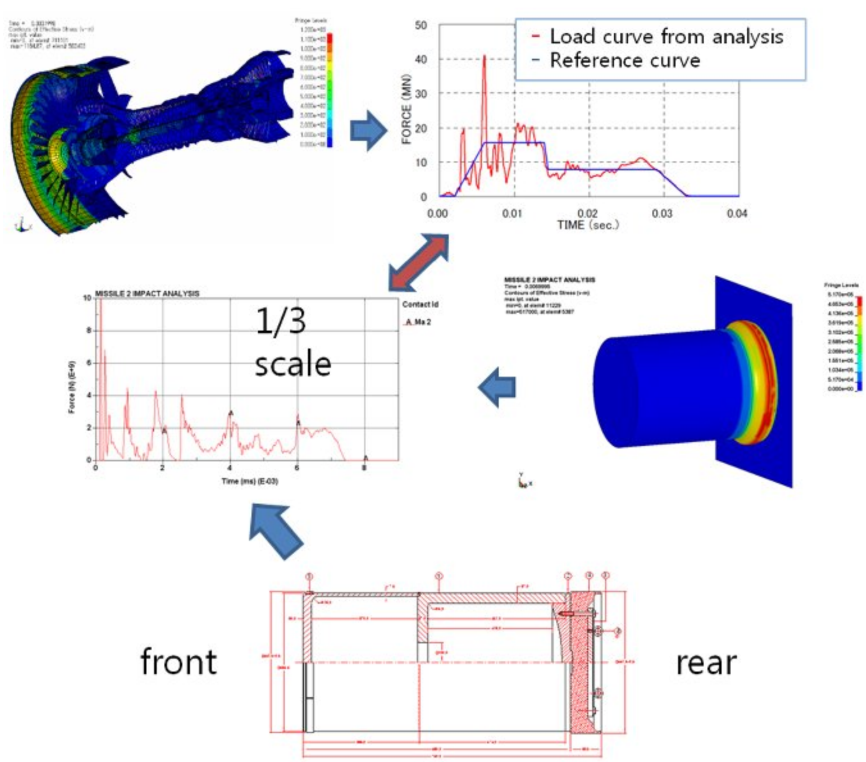

Fig. 5. Design of simplified missile

EVALUATION CASE 1

Numerical Simulation – Case 1

The numerical simulation for Case 1 assessment is done in two steps. Since the cask is not firmly supported but free standing on a concrete pad, a very dynamic impact behavior of the cask is expected. Thus, the first step of the simulation utilizes a simple model to examine the impact behavior of the cask for a long duration of up to 2 seconds, which is very important when the subsequent impacts of the cask are of concern, for example, collisions with the other casks. However, the evaluation considering the secondary impacts is not covered in this paper. The concrete pad and foundation are modeled using rigid elements. The simulation results show that the cask gains significant angular velocity as well as translational velocity in the direction of impact, as shown in Fig. 6. It is expected that the cask will land on the concrete pad after traveling about 11 m in the air.

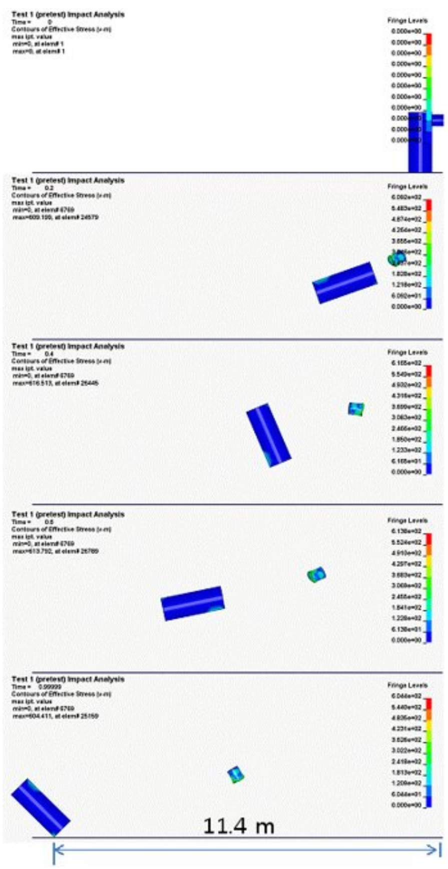

Fig. 6. Dynamic behavior of cask after impact

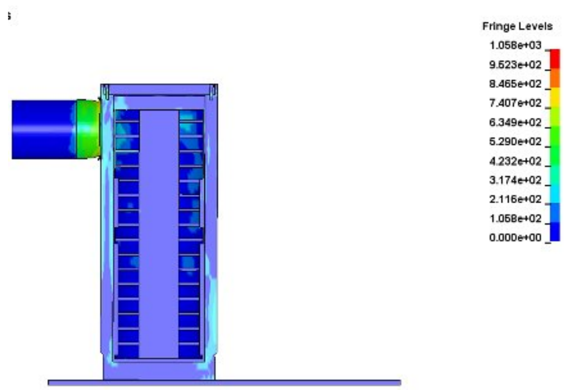

Fig. 7. Stress contour after impact (Case 1)

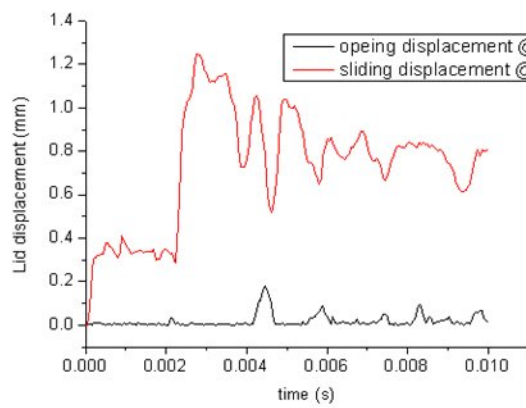

Fig. 8. Lid opening, sliding displacement history (Case 1)

The second step of the simulation utilizes a detailed model to evaluate the structural response of the cask components at the moment of the missile impact. The half model of the DPMC was constructed using 300,000 finite elements and the containment boundary was modeled with sufficient accuracy. The main focus of the evaluation is to examine the integrity of the containment of the cask. Dynamic material properties considering the strain rate effect are utilized in the simulation, and bolt pretention is applied using a dynamic relaxation. Fig. 7 shows the stress contour at 3 ms after impact, and Fig. 8 shows the history of the cask lid opening and sliding displacements. It turns out that the cask suffers significant shear deformation in the lid-cask connection, but the lid opening displacement remains within quite a small range and the bolt failure stress is not reached. Thus, we can conclude that the containment is damaged in the first impact by the missile but that the containment integrity is maintained. The evaluation of the containment integrity follows the procedure proposed in NUREG/CR-6672 by Sandia National Laboratory [6].

Test – Case 1

The test was performed at the testing site of the Agency of Defense Development (ADD). The missile was fired using a Counter Mass Gun (CMG), and the velocity of the missile was measured at 148 m/s. The behavior of the cask after impact is shown in Figs. 9 and 10. The first landing point of the cask on the concrete pad is about 3.3 m away from the initial standing point, which is much smaller than 11 m, which is expected from the simulation. This discrepancy comes from the modeling error of the concrete pad and the foundation (soil and sand). While the actual foundation has considerable flexibility and can absorb a significant amount of impact energy by itself, during the numerical simulation it is modeled as a rigid body. This will be compensated for in our future research. After the test, the containment integrities of the cask and canister were checked using a He leak tester. It was shown that the cask lid closure suffered considerable damage, but the leak rate was kept under the allowable range. Thus, the conclusions from the simulation are verified with the test results. The physical quantities measured during the test such as the accelerations and strains at important locations on the cask also show very good agreement with the predicted history based on the numerical simulation.

Fig. 9 Impact moment (Case 1, 3 ms)

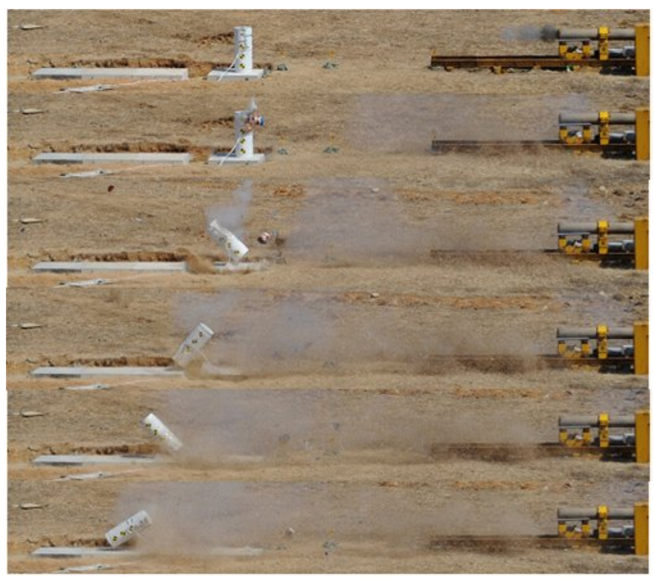

Fig. 10. Dynamic behavior after impact

EVALUATION CASE 2

Numerical Simulation – Case 2

The numerical simulation of the Case 2 assessment is done in one step using a detailed model.

As in the Case 1 assessment, a half model of the DPMC using 300,000 finite elements is utilized and the support structure for the cask is replaced by a rigid wall at the bottom of the cask. Dynamic material properties considering the strain rate effect are utilized. The simulation results show that the cask lid suffers from a significant amount of plastic deformation, and also causes a large impact force exerted on the upper part of the canister, as shown in Fig. 11. Due to the deformation of the cask lid, the lid bolts suffer large bending moments and bend inward about 0.5 degrees. Checking the lid opening and sliding displacement history (Fig. 12), it turns out that the lid opening is larger than the allowable range, and a breach of the containment boundary is highly probable. While stress at the canister weld zone is also significant, the evaluation of the canister is not covered in this paper.

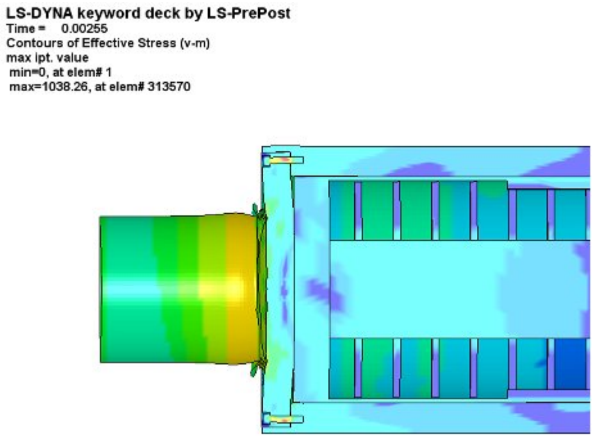

Fig. 11. Stress contour after impact (Case 2)

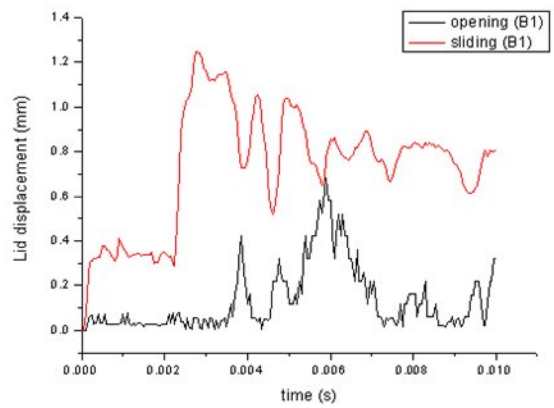

Fig. 12. Lid opening, sliding displacement history (Case 2)

Test – Case 2

Testing was performed at the ADD testing site using CMG as in the Case 1 evaluation. The missile velocity was measured as 155 m/s, and the behavior after the impact is shown in Fig. 13. It can be seen that the support structure for the cask is detached from the concrete pad due to the impact force, and is pushed backward about 40 cm. It should absorb some of the impact energy and may mitigate the severity of impact results from the cask side. After the impact, the cask lid was deformed into almost the same shape predicted by the simulation, and the bolts were bent inward at up to 1.5 degrees. In the He leak test, the cask showed a significant level of leakage, which means that the containment boundary is bleached due to the missile impact. Thus, it is shown that the test results agree well with the simulation results.

The impact condition in the Case 2 evaluation is rather unrealistic since the impact orientation is almost impossible, especially considering the topography of South Korea. However, the conclusion of this evaluation is that the current design of a dual purpose metal cask cannot survive under a 150 m/s impact from an aircraft engine perpendicular to the center of the lid.

CONCLUSION

A safety assessment using a numerical simulation of an aircraft engine crash into spent nuclear fuel storage systems is performed. A commercially available explicit finite element code is utilized for the dynamic simulation, and the strain rate effect is included in the modeling of the materials used in the target system and missile. The simulation results show very good agreement with the test results. It is noted that this is the first test considering an aircraft crash in Korea.

Fig. 13. Impact moment (Case 2, 2.5 ms)

Fig. 14. Behavior after impact (Case 2)

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