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A numerical study of spent nuclear fuel dry storage systems under extreme impact loading

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ABSTRACT

The structural integrity of concrete dry storage systems under an impact loading caused by a simulated commercial airplane engine crash is evaluated in this study. A finite element model of a generic vertical dry storage system including the concrete overpack, multi-purpose canister, spent nuclear fuel (SNF) basket, and SNF assemblies was developed using a commercial finite element analysis software. The strain rate effect was considered for the steel parts of the cask via a rate dependent and nonlinear constitutive model. The modeling approach was first validated using experimental data available in literature on projectile impact of concrete and steel/concrete composite (sandwich) panels. Then, a comprehensive comparison in terms of strains, damage and deformations was performed for two configurations of reinforced and sandwich cask overpacks commonly used in the industry. Critical impact height was identified by an examination of the strains and accelerations in the SNF assemblies. Furthermore, the effect of boundary conditions for the two cases of free-standing and anchored configuration was investigated. The maximum deformation and stress as well as the peak acceleration were identified in the SNF basket to assess safety of the SNF assemblies. The minimum impact velocity causing tip-over from aircraft engine impact was determined.

1. Introduction

Free-standing concrete dry storage systems (casks) are widely used around the world to store spent nuclear fuel (SNF) due to their economic advantages compared to other alternatives. The resistance of nuclear containment structures to penetration or perforation has received considerable attention since September 11, 2001 terrorist attacks in the United States. Although the probability of such a crash is very small, the results of a leakage could be catastrophic as was observed in the recent 2011 Fukushima Daiichi incident. Therefore, evaluating the consequences of aircraft crash to an interim SNF storage facility is necessary.

The vertical SNF casks consist of a reinforced concrete (RC) or steel-concrete sandwich overpack and a canister that contains the SNF assemblies. The overpack protects the stainless steel canister from mechanical loads and also provides radiation shielding. The SNF assemblies are placed inside the canister at the fuel handling facility of the nuclear power plant. The canister is sealed and placed inside the cask, which is then transferred to an independent spent fuel storage installation (ISFSI) for temporary storage. General configuration of a vertical concrete cask is shown in Fig. 1, which consists of overpack, steel liner, canister, lid and a base plate. As mentioned above, there are two common overpack designs: a steel-concrete sandwich where concrete is filled between two steel plates and RC where steel reinforcing bars (rebar) are embedded in the concrete with only one steel plate on the inside surface. Vertical SNF casks sit on a concrete pad and they could be freestanding or bolted to the pad in seismic regions.

To prevent a leakage of radioactive material, an investigation of the structural performance of the casks in extreme conditions such as tip-over and projectile impact is critical. According to 10 CFR 50.150 by the United States Nuclear Regulatory Commission (NRC) [1], a safety evaluation of nuclear containment facilities against accidental impact by a large commercial aircraft is necessary. An impact loading might have local and global effects on structures [2]. Local effects, including penetration, cracking and spalling are caused by the impact of a hard projectile on to a relatively soft target. The local damage could be studied through experiments and the data could be used for the calibration and verification of finite element (FE) models. On the other hand, the global effects are related to the overall structural response of the target, i.e., displacement and deformation of the entire structure.

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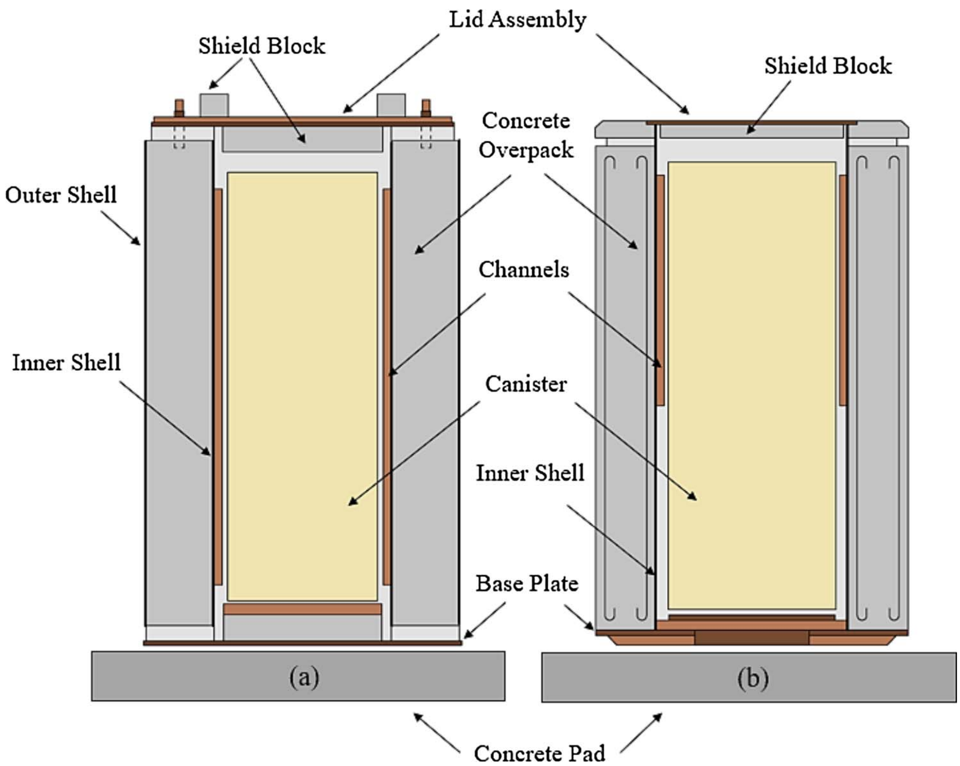

Fig. 1. Typical profile of vertical dry storage systems (a) sandwich, (b) RC cask.

The shock wave and acceleration caused by the impact may also damage the SNF assemblies. Due to excessive cost of large-scale impact experiments, global effects are commonly studied via FE simulations.

Several experimental and numerical studies have been carried out to investigate the reliability of steel storage casks to withstand extreme impact loads; while, studies on concrete casks have been limited. Sugano et al. [3] performed a full-scale impact testing of a F-4 Phantom fighter jet with 215 m/s velocity onto a rigid concrete block at Sandia National Laboratory to derive the impact force. The acceleration, velocity and displacement at the engine and fuselage were obtained. Lee et al. [4] investigated the safety of a concrete cask by performing experimental and numerical impact studies of a modified engine onto a concrete panel. It was concluded that for a precise simulation, proper calibration of the material model and eroding parameters is necessary. It was also found that the front steel liner in a sandwich configuration improves the impact resistance significantly in terms of penetration depth and deformation of the rear liner. In another study, Lee et al. [5] considered a dual-purpose metal cask in a simplified missile impact simulating a commercial aircraft engine designed for a horizontal impact with 150 m/s velocity. The simulation results were compared with experiments performed on a 1:3 scale model by the same authors. It was concluded that an accurate design of the projectile and load versus time function are needed for better prediction of the experimental results. It was also suggested that the subsequent events following the first impact, such as collisions with other casks and fire due to aircraft fuel, should be assessed.

Shirai et al. [6] evaluated the dynamic mechanical behavior and the leak tightness of a metal cask lid closure system using the finite element code LS-DYNA [7]. Two impact scenarios including horizontal hit to the overpack and vertical hit onto the lid were considered. A procedure for estimating the maximum leakage rate based on the pre-stress loss of the bolt, appearance of the plastic region and relative deformation of the lid seal was developed. The leakage rate was calculated for each case with the proposed procedure and it was concluded that the leakage rate is low and a pressure loss inside the cask could be avoided. Siefert and Henkel [8] compared the load-time function with the integral method using the crash analysis results of an Airbus Type A320 [9] on a simplified reactor building with velocities of 80 m/s, 120 m/s and 160 m/s as the basis. In the integral method, a detailed FE model of the aircraft was hit to the reactor building. As an alternative, the load-time function of the aircraft was obtained from impact to a rigid wall and then applied to the reactor building as a load time-history. It was determined that the maximum displacement in the load-time function method shows lower values than the integral method. It was also mentioned that the local stress concentrations could only be captured by the integral method.

There are analytical solutions to obtain the impact force; however, the estimation of the dissipated energy and the calculation of the canister deformation is not possible analytically. Therefore, detailed finite element models of the cask, canister and SNF assemblies were developed here to estimate the impact force and the dissipated energy. Riera [10] proposed an analytical approach to approximate the load time-history, $F_x(t)$, of an aircraft impact (soft object) to a rigid flat target. This derived equation for the total reaction force is

$$F_x(t) = P_c[x(t)] + \mu[x(t)]V^2(t) \tag{1}$$

where P_c is the static force required to axially crush a cross-section of the missile at location x, μ is the mass density of the projectile per unit length, V is the velocity of the remaining uncrushed portion of the aircraft, x is the crushed length of the missile and t is time. Full scale experiments have proven the reliability of the Riera method [11,12]. In this study, the Riera method is used for application of the impact load and validity of the procedure was confirmed by experimental results.

While there are several studies on aircraft impact on metal storage and transport casks, studies on concrete casks are very limited. Projectile impact analyses of concrete casks and their implications on the potential SNF damage and tip over using detailed finite element modeling is performed for the first time in this study. Two conventional configurations of vertical concrete cask (RC and sandwich) were developed and the results were compared in terms of local and global effects. Two different impact levels of top and middle were also considered to investigate the severity of damage and the worst loading scenario was identified. The effect of anchorage, which is commonly used in seismic areas to fix the cask on a foundation, was studied.