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Multi-hazard performance of reinforced concrete dry casks subjected to chloride attack and tip-over impact

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ABSTRACT

Vertical concrete dry storage systems (or dry casks) are circular containers made of steel and/or reinforced concrete, specifically developed for storing spent nuclear fuel (SNF). In the United States, dry casks have an intended life of 40 years; however, in the absence of a permanent repository for storage of SNF, it is expected that dry casks will remain in service for a significantly longer period of time. Tipping-over is considered as one of the hypothetical accident conditions. The consequence of such an incident may be more severe if the structural integrity of the dry cask is compromised during the extended service life due to steel corrosion and related material degradation. In this study, structural performance of a 1/3-scale vertical concrete cask is evaluated under combined corrosion-induced damage and tip-over impact. The results are compared with those from a control cask, which is only subjected to impact but no corrosion-induced damage. The impact response of both casks in terms of acceleration, velocity, and strain was measured and compared. The damage after testing is investigated in terms of cracking and deformation to identify the failure modes for each cask and the effects of aging on the structural performance.

1. Introduction

Dry cask storage systems are intended to provide temporary onsite storage of spent nuclear fuel (SNF). The SNF assemblies, composed of several fuel rods, are placed in SNF pools for cooling and radiation shielding for several years after being removed from the nuclear reactor. As SNF pools started to reach their capacities in the early 1980s, utilities began looking for alternatives to increase the on-site storage capacity of SNF. Dry cask systems emerged as a convenient temporary storage option. After a minimum of one year storage in the SNF pool (U.S. NRC, 2016), the fuel temperature and radioactivity decreases sufficiently for the SNF to be removed from the pool and placed in a dry cask. The first cask installation was licensed by the United States Nuclear Regulatory Commission (NRC) in 1986 at the Surry Nuclear Power Plant in Virginia. Since then, the cask sites have constantly increased exceeding 60 sites around the United States at the time of writing of this paper. In the canister-based cask designs, the SNF is sealed in a cylinder filled with an inert gas, called the canister, and then the canister is placed in the cask with a thick outerpack made of steel, concrete, or both, to provide further radiation shielding and protection against mechanical loading. There also exists non-canistered cask designs where the SNF assemblies are directly inserted into the cask without a separate sealed canister. Both horizontal and vertical cask configurations are used in the United States. In this paper, a vertical, canister-based configuration is investigated for its vulnerability to tip-over impact event. A typical configuration of a vertical concrete storage system is shown in Fig. 1.

A tip-over event is a hypothetical accident which may happen during the regular handling or in the case of an extreme event such as a strong earthquake, tornado or an explosion. Based on the standard review plans developed by the U.S. NRC, the structures should be evaluated under normal and off-normal environmental conditions as well as under hypothetical accidents (NUREG, 2000). Most vertical casks are freestanding on a concrete pad. This leads to stability concerns in terms of sliding and tipping-over in seismic areas which threatens the safety of the canister and the fuel rods. The most important parameter for SNF integrity under impact loading is the induced g-load, which could be used as a measure for performance evaluation and canister design.

Over the past three decades, several impact tests have been performed mostly on the transfer casks (used to transfer the canister from a storage to a transportation cask). In the United States, the first series of testing including impact and fire tests were performed in 1970s at Sandia National Laboratories (Shappert,

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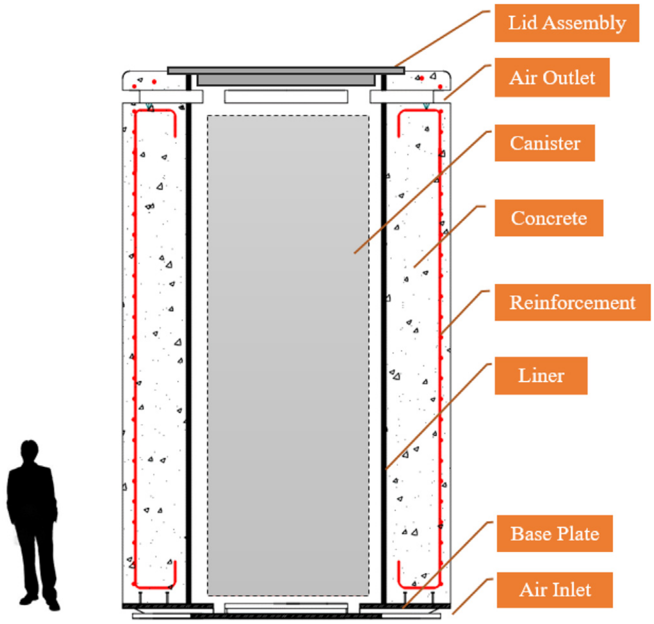

Fig. 1. Typical configuration of a vertical dry storage system.

1970). The Oak Ridge National Laboratory built an impact pad at the Tower Shielding Facility, which has a large lift capacity, sufficient to elevate a 75-ton weight to a height of about 60 m. In 1974, the first cask specimens weighting from 2700 kg to 5400 kg were dropped from a height of 9 m onto a steel impacting surface (Shappert and Ludwig, 2004). Vecchio and Sato (1988) performed free drops from 9 m onto a ridged surface and 1 m onto a steel pin of a half-scale concrete cask weighting 6.6 tons. They observed significant cracking in the impact area and rupturing of hoop reinforcement in the 9 m drop test. Several full-scale impact tests were performed from 2004 to 2008 consisting of drop and aircraft crush test on steel storage casks by the Central Research Institute of Electric Power Industry in Japan (Kato and Saegusa, 2001). Furthermore, a series of drop tests were performed on 1/3 scale models of steel dual purpose casks produced by Hitachi in 2000s (Shimizu and Hoshikawa, 2004). The results from these studies were used for improvements toward an optimal design. To the knowledge of the authors, the only published tip-over test on a concrete cask (in this case, a 1/3 scale model) is presented by Kim et al. (2006) in which the structural integrity of the canister was also investigated via liquid penetrant testing and an ultrasonic method. Further, the tip-over impact performance of vertical concrete casks subjected to environmental degradation has not been investigated before.

Corrosion damage is a major concern for reinforced concrete structures, which in the long-term can cause deterioration of the reinforcing steel (rebar), concrete and the steel-concrete interface. The rebar is initially protected by alkalinity of the concrete pore solution, which results in a passive film on the surface. The presence of the chloride ions could suppress the passive film and produce corrosion products (iron oxide and hydroxides), which have a volume twice to four times that of steel. The expansion from the development of the corrosion products initiate tensile stresses and eventually grow cracks on the concrete surface. This issue becomes more significant for structures located in coastal environments such as nuclear power plants. The corrosion may reduce the area of steel reinforcement, deteriorate the bond between the rebar and surrounding concrete and also result in surface cracks and spalling of the cover concrete. Corrosion results in a reduced service life and structural integrity. The effect of steel corrosion on the service life of the reinforced concrete structures has been extensively studied (Song and Saraswathy, 2007; Spencer et al., 2014; Ahmad, 2003; Liu and Weyers, 1998; Schießl and Raupach, 1997; Ann and Song, 2007; Ghazanfari and Manafpour, 2016). However for casks, the studies have mostly focused on the corrosion of the canister (Tani et al., 2009; Spencer et al., 2014; Marsh and Taylor, 1988; Shoesmith, 2006). In this study, reinforcement corrosion in concrete is considered as the main source of material degradation and the structural integrity in the case of tip-over accident is assessed. To our knowledge, no prior research investigated the multi-hazard performance of dry casks subjected to environmental aging followed by a tip-over impact, which is now more seriously considered as a potential scenario due to extended use of dry casks in the absence of a permanent facility for storage of commercial SNF in the United States. In order to address this issue, first a concrete mixture was developed to accelerate the long-term aging of reinforced concrete due to corrosion. Two scaled cask model were fabricated, one using normal concrete (control cask) and another one using the corrosive mixture (aged cask). Corrosion progression of the aging specimen was monitored over a two year period. After the two years, the two specimens were subjected to tip-over events and a comparative structural performance evaluation was performed.

2. Experimental Program

Two 1/3 scaled cask models were designed and fabricated. Calcium chloride was added to one of the concrete mixtures (here called corrosive concrete) to simulate the long-term steel corrosion. A normal concrete mixture was used for the second (control) specimen. The aging was monitored via destructive and non-destructive methods over a two year period. The details on the non-destructive testing of the casks are provided in a previous publication (Attar et al., 2016). Three tip-over tests were performed after two years followed by damage evaluation of the specimens.

2.1. Design and fabrication of the specimen

A detailed review of the most commonly used cask in the United States was performed. Table 1 summarizes the main dimensions of the casks commonly used by the United States nuclear power industry. Typical values were chosen for the weight and dimensions of the cask model using a scaling factor of 2.83. More realistic behavior of the structure may be obtained from full-scale tests; however, the specimen dimensions and weight are in most cases limited due to the cost of fabrication and capabilities of the testing facilities. Reduced-scale models are commonly used for experimental investigation of large structures. The main objective of the scaling procedure is to reduce the size and weight of the specimen without losing the main structural characteristics. The average values were scaled using the geometric scaling factor of 2.83 and the final dimensions were determined for the cask height, liner thickness, outer diameter and concrete thickness with due consideration given to constructability issues (e.g., available discrete steel plate thicknesses and rebar sizes). The scaled dimensions used in the physical model casks are provided in Table 1.

In order to represent the SNF canister inside the cask, an assembly of eight solid steel rods packed inside a steel tube was used. The individual components of the model cask are illustrated in Fig. 2. The fabrication process of the scaled physical cask models is shown in Fig. 3. The key dimensions for each component of the model are summarized in Table 2. The lid was fixed in place using six high strength bolts once the tube is placed inside the overpack. The steel reinforcing cage was made of U.S. designation No. 3