Annals of Nuclear Energy 110 (2017) 126–139

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Added mass effect for tip-over analysis of dry cask composite structures at two different scales

Masoud Dehghani Champiri [a],*, Amir Mohammadipour [a], Reza Mousavi [a], Kaspar J. Willam [a], Bora Gencturk [b]

[a] Department of Civil and Environmental Engineering, Cullen College of Engineering, University of Houston, TX, USA
[b] Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, CA, USA

ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 10 June 2017
Accepted 16 June 2017

Keywords:
Dry cask
Tip-over analysis
Impact analysis
Mass effect
Dynamic similitude

ABSTRACT

Safety of dry-cask storage structures, containing spent nuclear fuel, has always been an important concern for the nuclear industry. Detailed investigations of the mechanical response of these important composite structures due to hypothetical accident conditions have been the subject of many studies. In this paper, a tip-over induced impact of a dry cask is numerically analyzed at two different dimensional scales, i.e., a full-scale “prototype” and a 1/3-scale “model cask”. The latter is considered to study the accuracy of similitude laws because most experiments are done at the reduced scale. The added mass technique is applied to the model cask using the dynamic similitude concept in order to represent the behavior of the prototype cask. The effects of this added mass are also studied in terms of damage parameters, time histories of strains, stresses and accelerations to compare these two models. The results demonstrate that the added mass is able to predict the behavior of the model cask compared to that of the full-scale prototype.

1. Introduction

All U.S. nuclear power plants store used nuclear fuel in “spent fuel pools.” These pools are robust containment structures made of thick reinforced concrete protected by steel liners. The water is typically about 12 meters deep, and serves both to shield the radiation and to cool the spent fuel rods. As the pools reach their capacity, utilities started to move the older spent fuel bundles into “dry cask” storage. The used fuel is typically cooled at least 5 years in the fuel pool before being transferred to dry casks. While the Nuclear Regulatory Commission (NRC) has authorized the transfer as early as 3 years, the industry norm is about 10 years (NEI 07-06, 2007). Currently, the licensure of dry casks is 40 years. However, in view of the absence of a permanent storage repository their life may be extended further after appropriate condition evaluations.

Dry storage casks are composite structures made of an inner steel liner and a concrete outerpack housing the basket of the spent nuclear fuel bundle inside a canister. The main purpose of the cask structures is to provide safe storage of spent nuclear fuel elements of low level radiation and temperature. Consequently, the upright storage cask structures are mainly subject to self-weight and environmental aging besides experiencing hazards of potential overturning in case of severe seismic events and man-made hazards like missile or aircraft impact. NRC guidelines state that tip-over events should be prevented for the dry cask structures (NUREG-1536, 1997 and NUREG-1567, 2000).

In order to evaluate the resulting damage due to overturning of the dry cask, a numerical study has been performed here. A 1/3-scale model cask has been modeled and its behavior has been investigated. The main focus is on the similitude between the model cask and the prototype.

Many researchers worked on the tip over impact behavior of dry cask structures with different shapes and types. Gupta (1997) proposed an analytical approach for tip-over simulation. He considered simple assumptions such as a rigid pad and a single degree of freedom mass–spring system. Others employed the finite element method to conduct more detailed simulations. Since the implicit time integration schemes cannot simulate this contact-impact problem due to the convergence issues with regard to the large deformations and high nonlinearity, explicit time integrations are generally used. Witte et al. (1997) performed impact tests of a solid steel billet onto concrete pads, and applied to a generic independent spent fuel storage installation (ISFSI) cask for tip-over simulation. They showed that the maximum deceleration test results were within 20 percent of the simulated analytical results. NUREG-6608 (1998) presented an example using an explicit time integration for tip-over simulations of casks. Teng et al. (2003)

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* Corresponding author at: Department of Civil and Environmental Engineering, 110 Engineering Building 1, University of Houston, Houston, TX 77204-4003, USA.
E-mail address: mdehghanichampiri@uh.edu (M.D. Champiri).

http://dx.doi.org/10.1016/j.anucene.2017.06.028
0306-4549/

used a dynamic explicit FEA code, named DYTRAN (2008), to perform an edge impact analysis of a cask structure and showed that the plastic strain does not exceed the yield strain of the cask material. They also performed a simulation to evaluate the penetration resistance using DYNA2D (Whirley and Engelmann, 1992) in order to optimize the design of the containment structures in nuclear power plants (Teng et al., 2005). Lee et al. (2005) simulated the drop impact of a cask using LS-DYNA (Hallquist, 2006) and ABAQUS (Hibbitt et al., 2002) and compared the results in the form of energy and effective stress. Shah (2005) conducted a tip-over simulation for a specific type of cask, named HI-STORM, using LS-DYNA (Hallquist, 2006). He studied the relationship between the cask response and the impact velocity and the foundation stiffness. Kim et al. (2007) studied the shock-absorption characteristics of a cask pad using the explicit finite element analysis (FEA) feature in ABAQUS (Hibbitt et al., 2002). They investigated the effect of the pad structure from the drop tests and analyzed an optimized pad with greater shock-absorption characteristics. Huang and Wu (2009) presented a tip over simulation with cases of element erosion, de-bondable interface, glued interface, nonlinear material and large deformation behavior. They emphasized the importance of interface de-bonding and concrete fragmentation in the vertical concrete casks. Champiri et al. (2015a, 2015b, 2016) investigated the performance of dry-cask structures under different dynamic loading scenarios including end-drop test and tip-over analysis. They showed the main failure modes for each scenario, investigating different load cases such as the long term performance in the form of creep, shrinkage and alkali-silica-reaction.

In this paper, the tip-over induced impact of the casks is assessed using the commercial code LS-DYNA version 970 (Hallquist, 2006). The paper focuses on simulate issues and added mass effect and only the concrete outerpack of the casks has been modeled.

In the following sections, the geometry of the cask structure and material properties are first presented. An explanation of the theory of dynamic similitude is then followed by the calculation of the added mass, which has to be applied to the model cask, and the results of the tip-over simulation in LS-DYNA (Hallquist, 2006). The paper concludes with a discussion of the results and possible future studies.

2. Geometry and material properties

2.1. Geometry

A dry cask structure is made of different parts including reinforced concrete, steel liner, base plate, lid assembly (lid-top, lid-bottom, concrete) and the canister. The dimensions of the model and the prototype cask are summarized in Table 1. The prototype cask is about 2.8 times larger than the selected model cask.

Furthermore, the following assumptions are made in this work:

- The air outlet and inlet of the cask outerpack are not considered in this study.
- The base plate is modeled as a solid cylinder. The equivalent thickness of this cylinder is calculated based on the weight of the actual base plate.
- The canister is modeled as a rigid part.

2.2. Material models and properties

Plasticity material models are applicable if the cracks in concrete are small enough and can be homogenized to satisfy the basic assumption of continuum mechanics (Fung, 1993; Chen, 1982). Two material behaviors were considered for the cask structure analyzed here. Elastic-perfectly plastic behavior was used for the steel liner with the properties shown in Table 2. Due to triaxial effects in concrete, continuous surface cap model (CSCM-MAT_159) (Murray, 2007) was used for the mechanical behavior of cask and the pad in LS-DYNA (Hallquist, 2006). Isotropic elastic material behavior was assumed for the soil foundation. The modulus of elasticity, Poisson's ratio, and density of soil were taken as 34.474 MPa, 0.3, and 1500 k g/m^3, respectively.

In this section, first the constitutive equations of CSCM model is presented and then the behavior of this material model under uniaxial loadings is examined. CSCM correlates the shear yield cone and the hardening cap with a smooth intersection as illustrated in Fig. 1. The plastic yield surface corresponds to the initial damage surface and the viscoplastic overstress formulation of Duvaut-Lion is applied to account for the rate effects (Murray, 2007).

Table 1
Dimensions of 1/3-scale (model) and prototype casks.

Part	Type	Height (mm)	Length (mm)	Width (mm)	Internal radius (mm)	External radius (mm)	Thickness (mm)
Rectangular concrete pad	Model	381	3810	3810	–	–	–
	Prototype	1143	11430	11430	–	–	–
Subgrade soil	Model	2540	5080	5080	–	–	–
	Prototype	7620	15240	15240	–	–	–
Steel liner	Model	1962.2	–	–	355.6	371.5	15.9
	Prototype	5557.5	–	–	1009.7	1054.1	44.5
Concrete cask	Model	1962.2	–	–	371.5	609.6	238.1
	Prototype	5557.5	–	–	1054.1	1727.2	673.1
Lid-Top	Model	–	–	–	–	431.8	6.4
	Prototype	–	–	–	–	1117.6	19.1
Lid-Bottom	Model	–	–	–	–	352.4	3.2
	Prototype	–	–	–	–	1003.3	7.9
Lid-Rib	Model	50.8	–	–	349.3	352.4	3.2
	Prototype	145.7	–	–	995.4	1003.3	7.9
Concrete lid	Model	50.8	–	–	–	349.3	349.3
	Prototype	145.7	–	–	–	995.4	995.4
Base plate	Model	–	–	–	–	609.6	63.5
	Prototype	–	–	–	–	1727.2	146.1
Canister	Model	1905	–	–	349.3	352.4	3.2
	Prototype	5397.5	–	–	995.4	1003.3	7.9