Nuclear Engineering and Design 325 (2017) 113–123

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Feasibility of using ultra-high performance fiber reinforced concrete for radioactive waste containers: Drop test simulation

H. Othman[a,b,*], T. Sabrah[b], H. Marzouk[a]

[a] *Department of Civil Engineering, Ryerson University, Toronto, ON M5B 2M2, Canada*
[b] *Master Peers Ltd., 101-2275 Upper Middle Road E, Oakville, ON L6H 0C3, Canada*

ARTICLE INFO

Keywords:
Ultra-high performance fiber reinforced concrete
Nuclear waste container
Explicit finite element
Accidental drop dynamic load
Damage plasticity model

ABSTRACT

A comparative numerical study has been conducted to investigate the advantage of using ultra-high performance fiber reinforced concrete (UHP-FRC) material as an alternative to replace traditional cross sections of nuclear waste container. Three different finite element (FE) models of a typical waste container with identical dimensions and steel reinforcement detailing are developed. The cross section (HSC, HSC with steel liners, UHP-FRC) is varied parametrically to study its effect on mass, principal stresses, damage distribution, and plastic deformation. The current investigation considers the worst load case scenario by simulating accidental drops of the containers from a full stack height of 5.00 m. Two different accidental drop scenarios are considered (flat on-base and corner drop). The detailed 3D-FE models have been built considering nonlinear material properties and the simulations are performed using ABAQUS/Explicit. The material constitutive models have been calibrated based experimental tests.

Based on the results of numerical comparative study, the UHP-FRC container suffered the least damage level and distribution among the three designs under considered loading cases. Both HSC, HSC with steel liners containers suffered high damage levels aligned between lid and container's body which might lead to an opening of the container. On the other hand, stresses and damage levels at the lid to body interface are substantially improved in case of using UHP-FRC.

1. Introduction

Low and intermediate level radioactive wastes (LILW) are generated at different phases of the nuclear power generation, medical and industrial applications of radiation. Commonly, LILW such resins, filters, material used for decontamination processes, etc., solidified with cement or bitumen and packaged in metal or concrete containers then intermediately stored above ground, then eventually to be stored in a deep geologic repository (DGR) until the final decay of radioactivity. Waste containers must have long-term isolation and containment in order to avoid any potential risks to the public health and the environment. During such long service life waste containers may be subjected to accidental impact situations, as a result, for example, of dropped loads or collisions during handling at the site of the waste producer or at DGR. The full details regarding transport in public are given in International atomic energy agency (IAEA) Transport Regulations (IAEA, 2012). However, potential drop heights and orientations of waste containers during handling, lifting and stacking at storage facility are more critical in comparison to that during the transportation process.

In general, the strength and the ductility of container's material are important parameters in enhancing the impact resistance of the container. In case of using steel, special consideration should be given of any reduction in container impact resistance as a result of material corrosion, either internal or external, of the container material (IAEA, 1993). It should be pointed out that carbon steel should not be used in the fabrication of waste containers that would be disposed at DGR. The environmental conditions inside DGR could accelerate corrosion rate of carbon steel after short period of container emplacement in the repository (Hill, 2016). In such cases it is recommended to use concrete or galvanized steel. However, galvanized steel is expensive in comparison with the concrete option. Commonly, a wall thickness of about 150–200 mm is used in reinforced concrete (RC) container. Increasing the wall thickness of a reinforced concrete (RC) container increases its impact capacity (Kishi et al., 1997). Dry storage containers currently used in Canada are typically 510 mm thick made of high density concrete and are lined with a steel liner 12.7 mm thick inside and outside. The thickness of the concrete provides the effective barrier against

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[*] Corresponding author at: MON 208 – Department of Civil Engineering, Ryerson University, Toronto, ON M5B 2M2, Canada.
E-mail address: hesham.othman@ryerson.ca (H. Othman).

http://dx.doi.org/10.1016/j.nucengdes.2017.09.019
Received 20 April 2017; Received in revised form 22 September 2017; Accepted 24 September 2017
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radiation. However, thick concrete section led to higher gross weight and cost. Additionally, there is a gross weight restriction on such packages in respect of road, rail and sea transport and handling at the repository (IAEA, 1993). Fiber reinforced concrete (FRC) can be used to increase impact capacity. FRC waste containers constructed with a wall thickness of about 50–100 mm have been used in France since 1990 (IAEA, 1993). Additionally, Slovak Republic developed a RC container of 2.9 m^3 internal capacity and wall thickness of 125 mm. The concrete material used in this container is long durable high performance fiber reinforced concrete with a maximum compressive strength of 90 MPa at 90 days (Hudoba, 2007).

Ultra-High Performance Fiber Reinforced Concrete (UHP-FRC) seems to be a suitable alternate choice to fit evolving static, dynamic and durability properties required in high integrity waste containers. The current research provides a new innovative alternative to the nuclear industry in Canada and elsewhere by introducing the UHP-FRC in the design of nuclear waste storage containers. UHP-FRC exhibits exceptional mechanical, serviceability and durability characteristics in comparison to its traditional concrete counterparts. Such properties include: ultra-compressive strength exceeding 150 MPa, enhanced tensile strength, toughness, high post-cracking capacity, fracture energy of several times traditional concrete, dimensional stability, impermeability, corrosion resistance, and abrasion resistance. Additionally, UHP-FRC has enhanced performance under dynamic properties especially impact/blast resistance (Habel and Gauvreau, 2008). It has high resistance to spalling, scabbing, and fragmentation and high energy absorption capacity (Othman and Marzouk, 2016b).

Commonly, the impact performance and integrity of waste containers are demonstrated by experimental drop testing. Waste containers are filled with a representative simulant waste, dropped from a defined height. The drop height and orientation of the container are mostly derived from the requirements of maximum damage based on a handling incident in the storage facility. Details, methodologies and experiences in experimental drop testing of radioactive waste containers performed by United Kingdom Nirex Limited in (NDA, 2010) and by the German Federal Institute for Materials Research and Testing (BAM) can be found in Quercetti et al. (2014). These experimental investigations have revealed that: damage level increases with the increase of drop heights (Davis et al., 1989; NDA, 2010). Using container with body flange exhibits superior performance of lid to body interface (NDA, 2010; Quercetti et al., 2014). However, there are several scenarios in which a waste container could experience an impact including different orientation angles, drop height and the nature of the target surface. Therefore, the use of FE to predict the structural response of waste containers under impact loads is inevitable due to the limitation of empirical equations and expensive experimental tests. Generally, FE analysis is combined with small-scale testing in order to generate accurate input data for material constitutive models. Additionally, the final design resulted from numerical modeling must be verified by actual drop test of critical cases (Kramar et al., 2016).

In the current investigation, the second approach of combined FE analysis with small-scale testing has been selected to address the feasibility of using UHP-FRC as alternative of currently used containers. Two experimental tests have been conducted to facilitate the numerical simulation of waste containers under accidental drop load. The first testing program focuses on the dynamic response of reinforced HSC and UHP-FRC plates. The second testing program is material investigation aims to generate accurate input data for HSC, UHP-FRC and steel reinforcement constitutive models. In this research, FE analysis is performed using FE program ABAQUS/Explicit, version 6.14 (Simulia, 2016). Explicit analysis is suitable for dynamic events with strong discontinuous geometrical and/or material responses.

2. Experimental program

Two concrete materials are used in this investigation. First matrix is a plain HSC with target 56-day compressive strength of 80 MPa. HSC mix is based on the composition developed and used previously in Marzouk (1991), Marzouk and Hussein (1992), Marzouk and Chen (1995). While, the UHP-FRC matrix are proprietary product Ductal® specified by Lafarge North America (Lafarge, 2016). The UHP-FRC matrix has target 28-day compressive strength of 150 MPa. The manufacturer supplied the Ductal® constituents in three separate groups: premix, fibres, and superplasticizer. The batched premix consists of a blend of all cementitious, fine sand, and silica fume materials. The superplasticizer is a high-range water reducing admixture (HRWA). Short straight steel fibers with 2% volume content are used in UHP-FRC mix, as this volume content is a common fiber percentage for UHP-FRC in industry, and is recommended by manufacturer. Table 1 reports the mix proportions of HSC and UHP-FRC materials used in the current study.

Table 1
Mixture proportions of concrete materails (by weight: kg/m^3).

High strength concrete (HSC)	
Cement	440
Silica fume	30
Fine sand (0.5)*	550
Coarse aggregate (12)*	1100
Super-plasticizer	20
Water	220
UHP-FRC	
Premix**	2195
HRWA	30.0
Water	130
Fibres (2% by volume)	156

* Maximum nominal size (mm).
** Proprietary mixture designs.

Two reinforced concrete (RC) plate specimens of identical geometry and steel reinforcement are constructed and tested under drop-weight low-velocity impact loading conditions. One specimen is cast using HSC, while the other is cast using UHP-FRC. Specimens are 1950 mm square with a thickness of 100 mm and 15 mm clear cover. The two plates are doubly reinforced with equal top and bottom orthogonal steel reinforcement mats. 10 M standard Canadian deformed steel bars with spacing of 100 mm are used as longitudinal reinforcement (CSA A23.3, 2004).

Specimens are subjected to hard impact at their midpoint and simply supported at their four corners. A special tie-down steel frame is used to prevent uplift of specimen corner. Specimens are subjected to multi-impact tests by dropping a steel mass of 475 kg from a height of 4.15 m. It has been decided to conduct the impact testing till cumulative residual midpoint displacement of 65 mm is reached under repeated impact loads, or severe punching damage took place with probability of instrumentation damage. The deflection limit of 65 mm is approximately equal to 8 times the serviceability deflection limit specified by Canadian code (CSA A23.3, 2004). In order to conduct precision impact testing, the experimental investigation is equipped with sophisticated instrumentation to monitor applied impact force, reaction forces at the four corners, midpoint displacements and steel reinforcement strain at the midpoint specimen. The impact force excited in the falling steel weight is determined based on the average reading of two ± 20,000 g accelerometers mounted to the drop-weight (where g is the Earth's gravitational acceleration). The reaction forces at the four corners are measured using quartz load cells of 650 kN capacity. Midpoint displacement is measured using a contact-less laser sensor with a wavelength of 655 nm and a measuring range of 290 mm. Two strain gauges are glued to the bottom surface of steel reinforcement at the midpoint of specimens in order to determine the magnitude and rate of strain in the steel reinforcement at central zone. The raw collected data are sampled at rate of 100 kHz using a digital dynamic data acquisition.

The final cracking patterns of tested specimens are presented in

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