Transactions, **SMiRT-25**
Charlotte, NC, USA, August 4-9, 2019
Division VI (Design Issues, Codes & Standards)

DESIGN OF ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE CONTAINER FOR HIGH-LEVEL WASTE

Hesham Othman[1], Tamer Sabrah[2], and Hesham Marzouk[3]

[1] Research Engineer, Ryerson University, Toronto, ON, Canada (hesham.othman@ryerson.ca)
[2] Technical Director, Master Peers Ltd., Milton, ON, Canada (tsabrah@masterpeers.com)
[3] Professor, Department of Civil Engineering, Ryerson University, Toronto, ON, Canada

ABSTRACT

Ultra-high performance fiber reinforced concrete (UHPC) material can be considered a promising way to innovate in the management of radioactive waste storing industry. UHPC exhibits exceptional mechanical, serviceability and durability characteristics in comparison to its traditional concrete counterparts. However, there are few information on the application of UHPC in the nuclear industry. The main focus of this paper is to design a new, efficient waste container using UHPC as an alternative to traditional steel-concrete-steel containers. In general, the existing concrete containers are heavy in weight, difficult to fabricate, and expensive. The proposed design aims to overcome these drawbacks. The reinforced concrete dry storage container (DSC) that is in use at Canadian Nuclear Power Generation sites is selected to present the proposed design. The design of UHPC waste container has been performed such that the new UHPC alternative has at least equivalent structural stiffness of the exiting container under various loading scenarios that would arise during the service life. The considered loading scenarios include, loading cases that arise during normal activities (e.g., waste conditioning, and transportation). Thereafter, the integrity of the new design is evaluated against accidental collision events.

Based on the results of stress analysis and design optimization, UHPC container 300 mm wall thickness is proposed to replace the existing container with a 550 mm wall thickness of composite steel-concrete-steel section. The stiffness of the proposed UHPC container is being in the range of 1.35 to 1.75 times the stiffness of the existing container under considered static loading scenarios. The use of UHPC resulted in decreasing the container weight by more than 60 %, which would be resulted in more waste weight capacity considering a gross weight restriction. Additionally, stresses and damage levels at lid to body interface are substantially improved in case of using UHPC.

INTRODUCTION

For over 40 years, nuclear generation has provided a clean source of electricity in Canada and worldwide. There are 19 power reactors currently operating at four nuclear generating stations in Canada (NWMD 2009). These power reactors provided about 16.6% of Canada’s electricity and over 50% of Ontario’s demand of electricity. It has an excellent safety record. And it’s reliable, affordable power with virtually no greenhouse gas emissions. However, nuclear generations produce a radioactive waste that has to be managed (Husain and Choi 2003).

Waste containers must have long-term isolation and containment without future maintenance. During such long service life waste containers may be subjected to accidental impact loads resulting from the high incident of heavy objects falling during waste packaging operation, intermediate storage, or during transportation of waste containments to storage facilities. The material that used to construct those containers should provide a high level of long-term isolation and containment without future maintenance. Additionally, it should also have superior impact resistance properties. In general, concrete is overwhelmingly the choice for shielding material in a large number of storage container designs. It is a strong and inexpensive material. 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 deep geological repositories (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 concrete option.

UHPC material can be considered a promising way to innovate in the management of radioactive waste storing industry. UHPC 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, dimensional stability, durability, impermeability, corrosion resistance, and abrasion resistance. Additionally, UHPC 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. Previously, a comparative numerical study has been conducted by the research team to investigate the feasibility of using UHPC material as an alternative to replace the traditional fabrication materials. Three different finite element (FE) models of a typical waste container with identical dimensions and steel reinforcement detailing are developed. The cross section (high-strength concrete [HSC], HSC with steel liners, UHPC) is varied parametrically to study its effect on principal stresses, damage distribution, and plastic deformation. Figure 1 shows the damage extend in the three containers under two different drop-impact scenarios. As shown, UHPC container suffered the least damage level and stress concentration. On the other hand, traditional containers suffered high damage levels aligned between lid and container's body which might lead to an opening of the container. More details and discussions regarding this investigation can be found in (Othman et al. 2017).

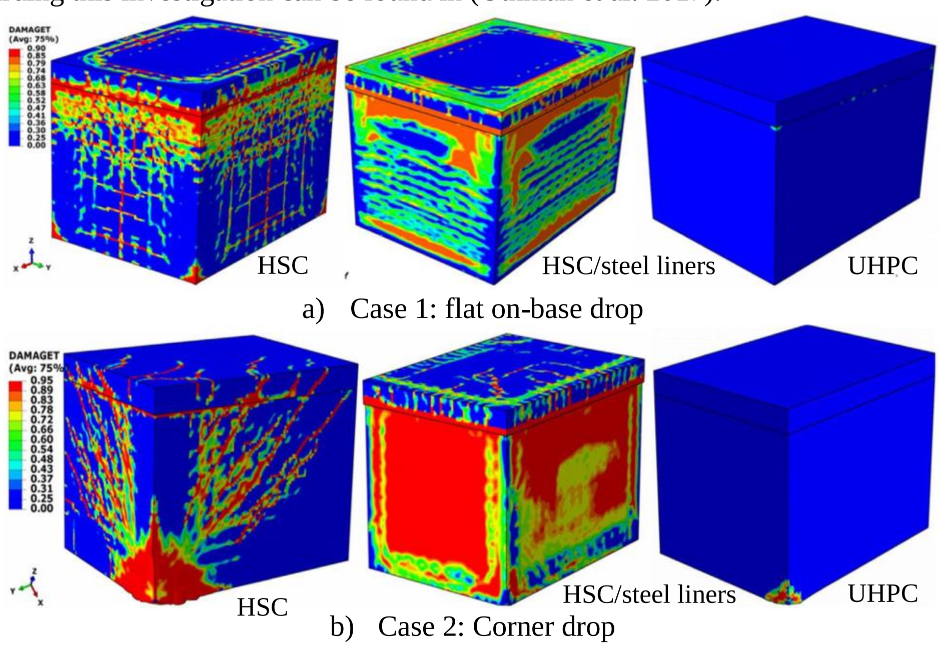


Figure 1. Advantage of using UHPC in nuclear waste management (Othman et al. 2017).

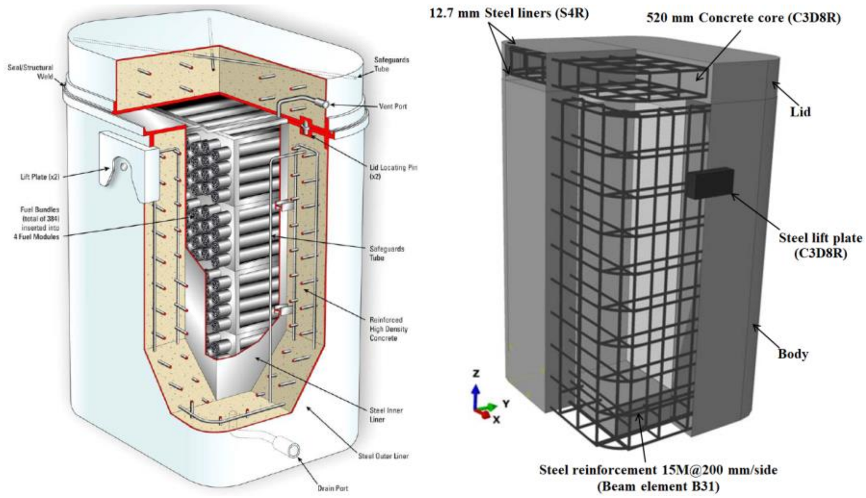
The current study is motivated and built upon the previous comparative numerical investigation discussed before. UHPC exhibits superior mechanical, serviceability and durability characteristics. The use of steel fibres enhances the ductility and stops the propagation of cracks by bridging action. The addition of relatively small amount of 0.7 % by volume of polypylene fibres to UHPC mix is required in order to obtain fire resistance UHPC (Acker and Behloul 2004; Wille et al. 2011). The polypylene fibres melt at approximately 165 ^{o}C to relieve the internal vapour pressure. It should be pointed out that the radiation sheielding of UHPC is out of the scope of current publication and still under investigation by the research team. However, some remarks can be reported here, UHPC has higher density and less voids in comparison to traditional concrete. Therefore, UHPC is effective in shielding radiation. Additionally, the use of polypylene fibres allow to reduce neutron radiation, however the influence on gamma radiation is less effective (Salimi et al. 2013).

In the current study, the reinforced concrete dry storage container (DSC) that in use at Canadian nuclear facilities is used to present the proposed design approach. The design approach described in this study is demonstrated as a general concept and is suitable for other types of nuclear waste containers. The structural design of UHPC container has been optimized based on all loading scenarios that DSC container may be subject to during its service life. The design optimization has been performed such that the new UHPC alternative has a structural stiffness greater than the exiting (HSC/steel liners) container under considered loading cases. For this purpose, two different FE models with identical geometry and steel reinforcement ratio are generated. The cross section of the first model represents the existing DSC container (high strength concrete with internal and external steel liners). This model is used to evaluate the structural stiffness and stresses of HSC/steel liners container under different load cases. The cross section of the second model is UHPC. Obtained responses of the first model (HSC/steel liners) are used to constrain design optimization of the second model (UHPC model). The details of container geometry, Structural element types, and material constitutive modelling, considered loading scenarios, design optimization are presented in the following sections.

CHARACTRISTICS AND MODELING OF DSC (CASE STUDY)

Figure 2 presents the details of DSC used in the current study side by side with the generated FE model. The DSC is of box shape with internal capacity of 3.5 m^3. The container consists of a box body with large fillet corners and a lid. The container walls consist of high density concrete of 520 mm thick placed lined inside and outside with steel plates. The DSC weights approximately 60 tonnes when empty and 70 tonnes when fully loaded. Lift plates on the outer shell of the DSC are designed for use with a dedicated lifting beam or a transporter. With impact limiters placed on each end of the DSC (for off-site transportation), the overall transportation package weighs approximately 101 tonnes. The DSC is carried at a low lift height (about 250 mm) during the transfer.

The model is built, using ABAQUS version 6.14 (Simulia 2016), in a detailed manner to get reliable and accurate results. Eight-node solid elements with reduced integration (C3D8R) are used to model the concrete core of the lid and body. Tie constraint is used to simulate a full sealing between the lid and the body. Steel reinforcement is modeled using two node beam element (B31) using same arrangement and concrete cover of the actual container as given Figure 2. The external and internal steel liners of the first model (HSC/steel liners) are modelled using shell element (S4R). Tie constrains is used to simulate full bond between steel liners and concrete core. On the other hand, the UHPC alternative is modeled as reinforced concrete section without considering steel liners. The waste mass is modelled using C3D8R elements. The height of waste filling is taken less than the container's internal height by 100 mm. The assumed material properties of waste content are: elastic modulus = 77.0 GPa, Poisson's ratio = 0.2, and a mass density = 3000 kg/m^3. The density is evaluated by dividing a waste mass of 10 tonne by the fillable internal volume of the waste container.



a) Schematic design (Canada.ca 2017) b) Generated FE model

Figure 2. Details of DSC container (Case study).

Concrete and steel reinforcement are represented by two separate ABAQUS built-in material models which are combined together to describe the behaviour of the composite RC material. Concrete Damage Plasticity (CDP) model is adapted to consider nonlinearity and stiffness degradation. The classical metal plasticity model is used to define the full response of the steel reinforcement. Table 1 provides the input data of HSC, UHPC, and steel reinforcement materials that are extracted from previous materials investigation tests conducted by the authors. Additionally, the complete details of the calibration process and the influence of each parameter on the analytical results are reported in (Othman and Marzouk 2017; Othman and Marzouk 2018; Othman et al. 2017).

Table 1: Material properties of HSC, UHPC and steel reinforcement.

Concrete	Density [kg/m^3]	Compressive strength [MPa]	Elastic modulus [GPa]	Flexural strength [MPa]	Splitting strength [MPa]	Fracture energy [N/m]
HSC	2,540	83.1	30.2	8.0	3.6	160
UHPC	2,650	162.4	48.8	19.2	11.11	18,000
Steel rebar size	Diameter [mm]	Mass [kg/m]	Elastic modulus [GPa]	Yield stress [MPa]	Yield strain ε_y	Ultimate strength [MPa]
15M	15.95	1.56	204.24	435.0	20×10^{-3}	618.30

STRUCTURAL DESIGN OF THE NEW UHPC WASTE CONTAINER

The new design approaches have increasingly relied on simulation-based design coupled with optimization techniques. In the current study, size optimization technique is used with the aim of maximizing stiffness, and minimizing the cost while satisfying both the design stresses and construction requirements. Size optimization refers to the optimization of the size of structural elements, i.e., wall thickness. The other variables, such as, dimensions, steel reinforcement ratio, are kept constant. It should be noted that other optimization techniques like material and shape optimizations are already obtained by using UHPC material and large fillets at corners of the container (refer to Figure 2) that optimize the stress concentration during corner drop loading scenarios.

The first objective of maximizing the stiffness is attempted by minimizing the sum of the strain energy of the waste container model. The strain energy of all elements of the FE model is estimated using ABAQUS/Implicit. On the other hand, the second objective of minimizing the cost has been achieved by minimizing the concrete volume (i.e., minimizing material usage) and using minimum steel reinforcement ratio. The optimization process of the container is constrained to the requirements of Canadian design standards and construction practices: concrete stresses are limited by the design strengths of UHPC; the effective stress of steel reinforcement is limited by the design yield stress of steel reinforcement. Additionally, as a geometrical constraint the wall thickness is limited to 200 mm according to the construction practice of liquid tightness structures. This thickness is normally sufficient to limit crack widths. However, for no leakage permitted class structures an internal thin liner must be used in the final design to meet the liquid tightness requirements (IAEA 1972). The design of reinforced concrete in important structures, like nuclear waste containers, is based on uncracked sections without redistribution of moments associated with plastic damage. Therefore, only elastic material properties of UHPC and steel reinforcement are considered in this analysis.

The design optimization of UHPC waste container has been performed considering two static loading scenarios that may be rise during normal activities (e.g., waste conditioning, transportation, and handling). In both scenarios, the container subjected to its self-weight (60 tonnes), impact limiter (30 tonnes), and used fuel (10 tonnes). The ultimate load combination of National building code of Canada is considered in both load cases. A load factor of 1.5 is used for live load (Impact limiter and used fuel weight) and a load factor of 1.25 is used for the dead load (container own-weight). In this first loading case (Static 1), the loaded container is free standing during installing the impact limiter before transportation. This load case introduces the maximum compressive stresses on the base and walls of the container. In the second considered load case (Static 2), the loaded container is hanged from the lift plates by a dedicated lifting beam or a transporter during the transportation. This loading case introduces the maximum tensile stresses on the walls of the container.

ANALYTICAL RESULTS OF THE EXISTING DSC (HSC WITH STEEL LINERS)

This section reports the numerically estimated structural stiffness of the DSC (Model: 1, HSC/steel liners). It should be recalled that this model is used to evaluate the structural stiffness and stresses of HSC/steel liners container in order to constrain the new UHPC container. Figure 3 presents the contour plots of the minimum principal stress (i.e., maximum compressive stresses) for the first load scenario (Static 1). As shown, the maximum compressive stress in concrete core is 0.27 MPa, and in steel liner is 1.58 MPa. Which are significantly less than the design strength of concrete and steel. This means that all sections of the container are satisfied for strength check. No buckling is observed for wall members under the considered gravity loads. The total strain energy output of the FE models is reported in this section. The total strain energy of the container under considered loading case (Static 1) is equal to 8.25 J.

The maximum principal stress plots (i.e., maximum tensile stresses) of the hanged container loading scenario during the transportation (Static 2) are presented in Figure 4. As shown, the maximum tensile stress in concrete core is 3.5 MPa, and in steel liner is 22.9 MPa. Which are less than the design tensile strength of concrete and steel. The total strain energy of the container under considered loading case (Static 2) is equal to 29.99 J.

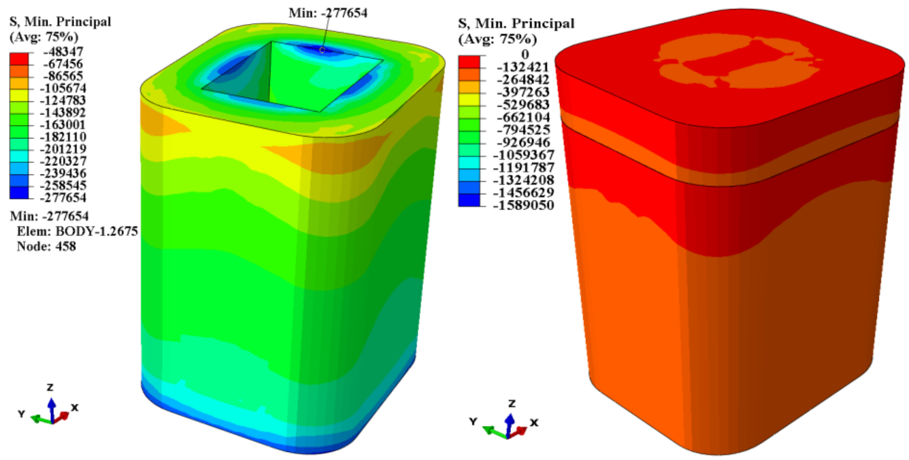


Figure 3. Static 1: Maximum compressive stress (left: concrete core; right: steel liners).

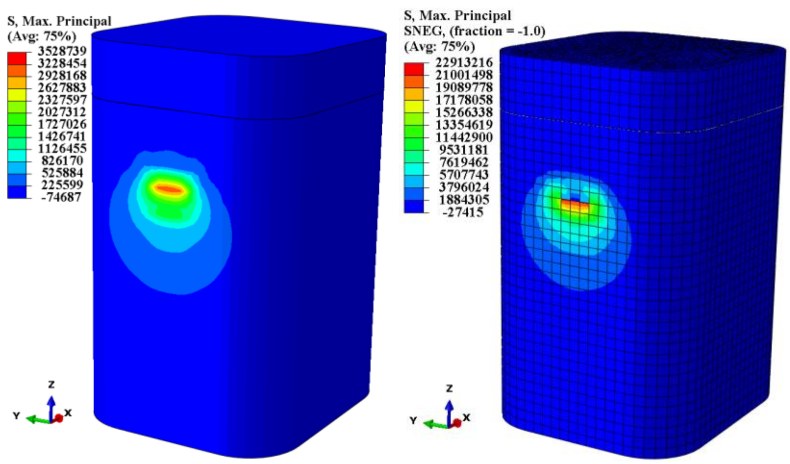


Figure 4. Static 2: Maximum tensile stress (left: concrete core; right: steel liners).

DESIGN OF THE NEW UHPC DSC CONTAINER

Tables 2 and 3 report the change in the design responses with increasing the wall thickness under the two considered load cases. The design characteristics of the existing HSC/liners DSC are included as well. As shown, The maximum and minimum principal stresses are almost the same among the alternatives. Such results are expected because all models subjected to same loading conditions. The principal stresses are within the design capacities of both alternatives HSC and UHPC. It is evident from Tables 2 and 3, the use of UHPC material enhances the structural stiffness significantly. Comparing the stiffness of UHPC container to HSC/liners that have same wall thickness and are constructed using same steel reinforcement ratio, the stiffness of UHPC container is being in the range of 1.05 to 1.25 times the stiffness of sandwiched HSC/steel liners section under free standing and hanging loading scenarios, respectively. Additionally, the use of UHPC resulted in decreasing the container weight by more than 45 % for the same wall thickness of HSC with steel liners which would be resulted in more waste weight capacity considering a gross weight restriction of 60 tonnes. In terms of cost, a single material is more desirable and normally concrete is preferred rather metal. Using UHPC material as an alternative of traditional sandwich section can reduce material consumption greatly, save time and resources, and reduce the energy consumption of production, transportation, and construction. It can be observed that increasing UHPC wall thickness has no significant effect on the total strain energy of the container under free standing loading conditions. The enhancement in stiffness is counterparted with increasing the container mass which results in the almost same deformation (i.e., total strain energy). On the other hand under the hanging loading condition, increasing the wall thickness enhances the total strain energy (i.e., structural stiffness) up to 300 mm thickness after that the increase in wall thickness overcome by the increase in the container weight.

Table 2: Results of the optimization process for free standing loading scenario (Static 1).

Container	HSC/Liners	UHPC [wall thickness in mm]			
		200	**300**	400	500
Total strain energy [Joule]	8.25	6.12	**5.97**	5.85	6.10
Concrete volume [m^3]	13.10	4.00	**6.50**	9.50	13.00
Mass of empty container [kg]	60,000	13,260	**17,027**	24,807	33,942
Maximum principal stress [MPa]	0.65	3.67	**2.01**	0.78	0.61
Minimum principal stress [MPa]	- 1.27	- 3.51	**- 1.35**	- 1.90	- 1.95

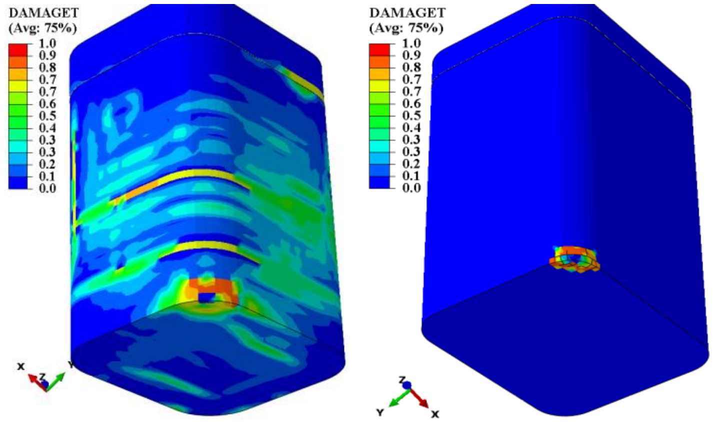
Table 3: Results of the optimization process for hanging loading scenario (Static 2).

Container	HSC/Liners	UHPC [wall thickness in mm]			
		200	**300**	400	500
Total strain energy [Joule]	29.99	18.86	**17.28**	20.26	28.07
Maximum principal stress [MPa]	3.5	4.70	**4.86**	5.80	7.23
Minimum principal stress [MPa]	- 3.13	- 4.05	**- 4.11**	- 6.44	- 7.75

According to the above analysis results for the effect of wall thickness and the rule of maximum stiffness and minimum construction cost, the wall thickness of 300 mm is proposed to be a basic cross section for the UHPC waste container. As reported in Table 2 and 3, the maximum compressive stress and the maximum tensile stresses are significantly less than the design strength of UHPC and steel. This means that all sections of the container are satisfied for strength check.

ACCIDENTAL DROP PERFORMANCE OF UHPC CONTAINER

Since HSC/liner and UHPC materials have different design capacities. It is difficult to address the advantage of using UHPC instead of traditional steel-concrete-steel section in the construction of waste containers based on stress analysis. Therefore, in this section the comparison between the performance of two design options is presented based on damage characteristics under drop-impact accidental load. The drop simulations are performed using dynamic ABAQUS/Explicit solver and nonlinear dynamic material properties. A drop orientation in the corner is considered in this study. As a quality check, all the predicted damage patterns presented on the following subsections are visually compared with the crack patterns of related experimental drop tests reported in Refs. (Tholance 2010; Kramar, Sinur, and Gams 2016; NDA 2010; Quercetti et al. 2014) and the comparisons indicate that the cracking configurations and extents are very realistic. The tension damage contour plots of the HSC with steel liners containers in comparison with the new UHPC alternative are presented in Figure 5. As can be seen, HSC with steel liner container shows limited corner damage. However, moderate to high damage levels in the range of 50 to 90 % are spread over walls, base, and at closure contact surfaces. Such high damage level indicates a large amount of absorbed energy by the external liner are transferred by the composite action between the concrete and steel liner. On the other hand, the tension damage of UHPC container is only a limited to the region of impacted corner. Complete details of the dynamic drop analysis are reported in (Othman et al. 2017).



a) HSC with steel liners b) UHPC

Figure 5. Predicted damage of waste containers under corner drop scenario.

CONCLUSION

This research is an essential stepping stone that provides a new innovative alternative to the nuclear waste management industry in Canada and elsewhere by introducing the UHPC. The application of UHPC in various constructions in nuclear power plants and particularly in radioactive waste management structures seems possible and useful. UHPC exhibits superior mechanical, serviceability and durability characteristics. UHPC is very appropriate in controlling local cracking and lose of tightness. This paper has presented a structural design of UHPC waste container under all expected loading scenarios. Based on the results of the current design optimization, UHPC container of 300 mm wall thickness is proposed to be the optimum cross section, the stiffness of the optimized UHPC container is being in the range of 1.35 to 1.75 times the stiffness of sandwiched HSC/steel liners container of 550 mm wall thickness under free standing and hanging static loading scenarios, respectively. The use of UHPC resulted in decreasing the container weight by more than 60 %, which would be resulted in more waste weight capacity considering a gross weight restriction. Based on the results of damage comparative study, the UHPC container suffered less damage level and distribution than the existing HSC/steel liner design under considered drop loading case. Additionally, HSC/steel liners container suffered high damage levels aligned between lid and container's body which may lead to an opening of the container. On the other hand, stresses and damage levels at lid to body interface are substantially improved in case of using UHPC.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Mitacs Canada (Mitacs Accelerate program) in partnership with Master Peers Ltd., which have funded this and related research.

REFERENCES

Acker, P., and Mouloud, B. (2004). "Ductal® Technology: A Large Spectrum of Properties, a Wide Range of Applications." In *International Symposium on Ultra High Performance Concrete*, 11–24. Kassel, Germany.

Canada.ca. (2017). "Canadian Nuclear Safety Commission." *Government of Canada*.

http://nuclearsafety.gc.ca/eng/reactors/power-plants/nuclear-facilities/.

Habel, K., and Gauvreau, P. (2008). "Response of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) to Impact and Static Loading." *Cement and Concrete Composites* 30 (10). Elsevier Ltd: 938–46.

Hill, S. (2016). "The Corrosion of Carbon Steel under Deep Geologic Nuclear Waste Disposal Conditions." Ph.D. Thesis, The University of Western Ontario, Canada.

Husain, A., and Kwansik C. (2003). "Status of Storage, Disposal and Transportation Containers for The Management of Used Nuclear Fuel." In *Nuclear Waste Management Organization (NWMO)*. Ontario, Canada.

IAEA. (1972). "Storage Tanks for Liquid Radioactive Waste: Their Design and Use." In *International Atomic Energy Agency (IAEA) - Report No. 135*. Vienna, Austria.

International Atomic Energy Agency (IAEA)-Report No. 355. 1993. "Containers for Packaging of Solid and Intermediate Level Radioactive Wastes." Vienna, Austria.

Kramar, Miha, Franc Sinur, and Matija Gams. (2016). "Drop Test Simulation and Analysis of Reinforced Concrete Disposal Container." In *25th International Conference Nulcear Energy for New Europe*, (604) 1-8. Portorož, Slovenia.

NDA. (2010). "Geological Disposal: Waste Package Accident Performance Status Report." In *Nuclear Decommissioning Authority-Report No NDA/RWMD/032*. Didcot, Oxon, UK.

NWMD. (2009). "Technical Support Document: New Nuclear–Darlington Environmental Assessment." In *Nuclear Waste Management Division (NWMD) -Report No.NK054-REP-07730-00027 Rev 000*. Ontario, Canada.

Othman, H, and Marzouk, H. (2017). "Finite-Element Analysis of Reinforced Concrete Plates Subjected to Repeated Impact Loads." *Journal of Structural Engineering* 143 (9): 1–16. doi:10.1061/(ASCE)ST.1943-541X.0001852.

Othman, H, and Marzouk, H. (2018). "Applicability of Damage Plasticity Constitutive Model for Ultra-High Performance Fibre Reinforced Concrete under Impact Loads." *International Journal of Impact Engineering* 114 (August 2017). Elsevier: 20–31. doi:10.1016/j.ijimpeng.2017.12.013.

Othman, H, Sabrah, T., and Marzouk, H. (2017). "Feasibility of Using Ultra-High Performance Fiber Reinforced Concrete for Radioactive Waste Containers : Drop Test Simulation." *Nuclear Engineering and Design* 325 (April). Elsevier: 113–23. doi:10.1016/j.nucengdes.2017.09.019.

Othman, H, Sabrah, T., and Marzouk, H. (2019). "Conceptual Design of Ultra-High Performance Fiber Reinforced Concrete Nuclear Waste Container." *Nuclear Engineering and Technology* 51 (April). Elsevier: 588–599. doi: https://doi.org/10.1016/j.net.2018.10.014.

Quercetti, T., Karsten Müller, Tino Ne., Bernhard D., Holger Völzke, Uwe Z., and Günter W. (2014). "Methodology and Experiences of Experimental Drop and Fire Testing of Radioactive Waste Containers for Final Disposal." In *Waste Management Conference*, 1–14. Phoenix, AZ, USA.

Salimi, M., Eskandar A., Nima G. and Gholam R. (2013). "Design and Simulation of Concrete Reinforced with Fiber as a Shield to Gamma and Neutron Radiations." *International Science and Investigation Journal* 2 (July): 60–71.

Simulia. (2016). "ABAQUS 6.14 User's Manuals." *Dassault Systèmes Simulia Corp.* France.

Tholance, S. (2010). "Drop Test Behaviour of a Low Radioactive Waste Package in Concrete." In *4th European Hyperworks Technology Conference*. Versailles, France.

Wille, K., Antoine E. N., El-Tawil, S. and Gustavo J. Parra-Montesinos. (2011). "Ultra-High Performance Concrete and Fiber Reinforced Concrete: Achieving Strength and Ductility without Heat Curing." *Materials and Structures* 45 (3): 309–24.