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DESIGN OF ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE WASTE CONTAINER: THERMAL STRESS ANALYSIS

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ABSTRACT

Ultra-high performance fiber reinforced concrete (UHPC) is a relatively new generation of fiber cementitious composites, which has been developed to give a significantly higher material performance than other concrete classes. UHPC material can be considered a promising way to innovate in the management of radioactive waste storing industry. This study is part of an ongoing research project carried by the authors, which aimed to develop a new, efficient waste container using UHPC as an alternative to traditional steel-concrete-steel containers. The proposed design aims to overcome the drawbacks of existing concrete containers which are heavy in weight and difficult to fabricate.

This study focuses on the fire resistance rating for the new design (UHPC container) in comparison to existing container. The reinforced concrete dry storage container (DSC) that is typically in use at Canadian Nuclear Power Generation sites is selected to present the proposed design model. In the current study, the performance of containers is investigated numerically using ABAQUS finite element analysis software. The containers are subjected to a 30-minute thermal exposure at 800 ºC as specified by the Canadian Nuclear Safety Commission (CNSC). The finite element models are built in a detailed manner to get reliable and accurate results. The numerical analyses are carried out using complete calibrated mechanical materials models. The steel reinforcement, concrete and UHPC material models are coupled with temperature effect.

The numerical results showed that UHPC container with a wall thickness of 300 mm can replace the existing container of 550 mm wall thickness of composite concrete-steel section. At ambient temperature, the maximum stresses are of the same order for both designs under considered mechanical load. On the other hand, at elevated temperatures, the concrete core of the existing DSC (HSC with steel liner) experienced high level stresses which are spread over the walls. Steel liners have an adverse behaviour due to the high thermal conductivity which results in rapid heating of the concrete core. In comparison, UHPC container exhibits low thermal conductivity as a result the stresses in the walls are relatively lower than existing container.

INTRODUCTION

Nuclear waste containers must be constructed of material that should provide a high level of long-term isolation and containment without future maintenance. 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.

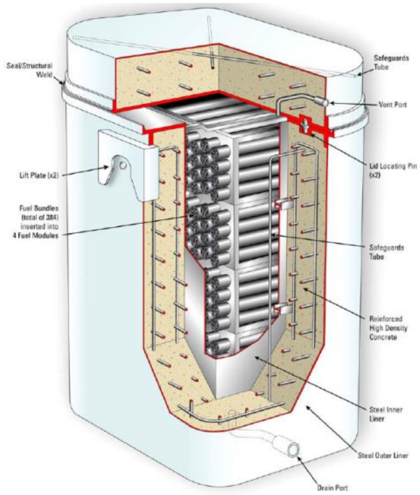
The application of UHPC in nuclear power plants and particularly in radioactive waste management structures seems possible and useful. UHPC is very appropriate in controlling local cracking and lose of tightness. The use of steel fibers enhances the ductility and stops the propagation of cracks by bridging action. The addition of relatively small amount of 0.7% by volume of polypylene fibers to UHPC mix is required in order to obtain fire resistance (Acker and Behloul, 2004; Wille et al., 2011). The polypylene fibers melt at approximately 165ºC to relieve the internal vapour pressure. The current investigation represents a continuation of the previous work by the authors (H. Othman et al., 2017; Othman et al., 2018). Previously, a structural design optimization of a reinforced concrete dry storage container (DSC) has been conducted by the research team to investigate the feasibility of using UHPC as an alternative to replace the traditional concrete-steel fabrication materials. The considered loading scenarios included, loading cases that arise during normal activities (e.g., waste conditioning, and transportation) and accidental collision events. The results of design optimization have shown that UHPC container with a wall thickness of 300 mm can replace the existing container of 550 mm wall thickness of composite concrete-steel section. The stiffness of the 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 (Othman et al., 2018).

The current research presents a comparative numerical study between the existing reinforced concrete DSC that is in use at Canadian Nuclear Power Generation sites and the new UHPC design. This study aims to investigate the effect of thermal stresses and deformations on the performance of the UHPC container (300 mm wall thickness) in comparison to existing reinforced concrete DSC (550 mm wall thickness). The two containers are exposed for a period of 30 minutes to a thermal load that corresponds to a heat flux of a hydrocarbon fuel up to 800°C. The thermal numerical analyses of the containers have been performed using ABAQUS finite element analysis software. In this study, the thermo-mechanical analysis of concrete containers under elevated temperature (i.e., fire loading) consists of two main steps. In the first step, the temperature distributions over the cross section are computed by implementing heat transfer analysis. Then in the next step, the mechanical responses are determined in which the temperature distributions from the heat transfer analysis are defined as thermal loading. The finite element models are built in a detailed manner to get reliable and accurate results. The numerical analyses are carried out using calibrated material models (H. Othman and Marzouk, 2018; Othman and Marzouk, 2017). Additionally, the steel reinforcement, concrete and UHPC material models are coupled with temperature effects. The degradations that occur in the material due to both mechanical and thermal loading are considered. In general, the effect of fire involves the thermal conductivity, specific heat and high thermal expansion of the concrete. This will cause the surrounding structure to respond against these effects and generate compressive forces in the structural member. Therefore, the container is analysed as free standing subjected to gravity loads of self-mass, the impact limiter, and waste weight. This load case introduces the maximum compressive stresses on the base and walls of the container. The results are invistgated under both ambient and elevated temperatures.

DESCRIPTION OF DSC CASE STUDY

Figure 1 presents the details and transportation of DSC used in the current study. The DSC has an 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.



a) Schematic design (Canada.ca, 2017) b) Indoor transporter vehicle (NWMD, 2009)

c) Transportation of DSC by road (Canada.ca, 2017)

Figure 1. Design and Transportation of DSC (the case study)

DEVELOPMENT OF 3D-FE MODEL FOR DSC CONTAINER

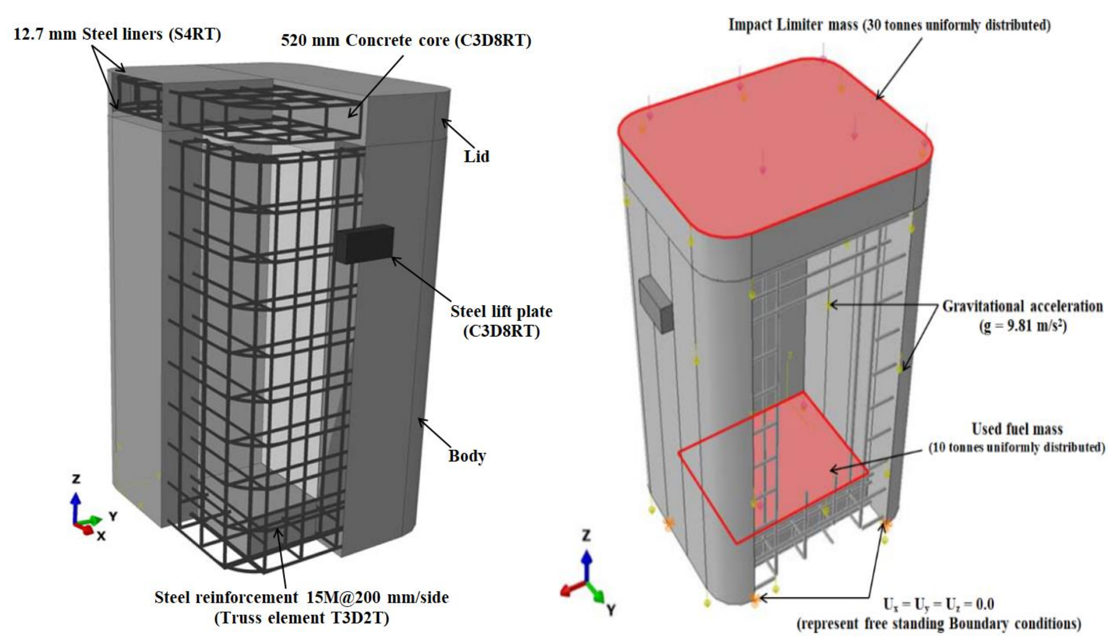
Geometric, boundary conditions and Loading Modeling of DSC Container

The container models are built, using ABAQUS version 6.14 (Simulia, 2016), in a detailed manner to get reliable results. The dimensions, boundary conditions, applied mechanical loads of generated finite element (FE) models are shown in Figure 2. Eight-node thermally coupled, trilinear displacement and temperature solid elements (C3D8T) are used to model the concrete of the lid and body. Steel reinforcement is modeled using two node 3-D thermally coupled truss element (T3D2T) with the same arrangement and concrete cover of the actual container as shown Figure 2. The concrete material of existing container is high-strength concrete (HSC) with a compressive strength of around 60 to 85 MPa. The external and internal steel liners of the first model (HSC/steel liners) are modelled using shell element (S4RT). Tie constraint 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 weight is modelled using thermal independent 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 sensitivity analysis was conducted by the authors to ensure the accuracy of the developed model and its convergence with mesh refinement in (Othman et al., 2018; Othman and Marzouk, 2017).

Fire is usually represented by a temperature–time curve, which gives the average temperature reached during a fire. As shown in Figure 3, three temperature curves can be used based on the type of fire (standard ISO 834, external fire, or hydrocarbon). In the current study, the temperature inside the containers are set equal to 50 ºC, throughout the entire simulation. For outer surface the heat transfer analysis is performed on the basis of a hydrocarbon fire curve that can be used for fires with a higher fuel energy content (ISO 834-1, 1999). For the hydrocarbon fire the gas temperature, *T*g, at a time *t*, in minutes, is given by:

$$Tg = 1080\times(1-0.325e^{-0.167t}-0.675e^{-2.5t}) + 20 \quad (1)$$

For applied mechanical load, the static loading scenario that takes place during the normal activity is considered. The container subjected to the weight of self-weight (60 tonnes), impact limiter (30 tonnes), and used fuel (10 tonnes). The loaded container is free standing during installation of the impact limiter before transportation. Figure 2-b shows the applied mechanical loads and boundary conditions considered in the current study.



a) Geometrical model b) Mechanical loading

Figure 2. Generated FE model for DSC container (Case study).

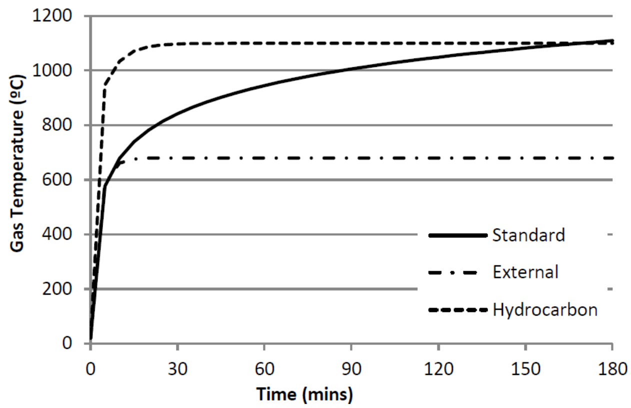


Figure 3. Temperature - time histories of the standard, external and hydrocarbon fires.

Mechanical Properties of Materials at Ambient Temperature

Concrete and steel reinforcement are represented by two separate ABAQUS built-in material models which are combined together to model the behaviour of the composite reinforced concrete materials. 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. 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: Mechanical properties of HSC, UHPC and steel reinforcement (at ambient temperature).

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

Thermal Properties of Materials

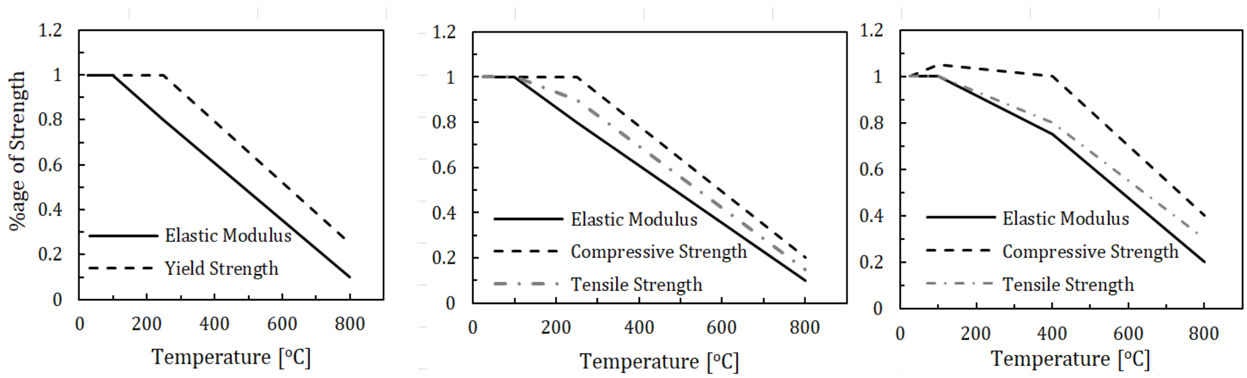
The thermal properties of the HSC, UHPC, and steel reinforcement materials are reported in Table 2. The values of the coefficient of thermal expansions, specific heat capacity and the thermal conductivity are selected in accordance with (Eurocode-2, 2005) and scientific studies (Hayhoe and Youssef, 2013; Li et al., 2017; Zhu et al., 2021) .

Table 2: Thermal properties of HSC, UHPC and steel reinforcement.

Material	HSC	UHPC	Steel
Thermal Expansions Coff. [/ºC]	10×10^{-6}	13.5×10^{-6}	10×10^{-6}
Specific Heat Capacity [J/kg.K]	900	1500	500
Thermal Conductivity [W/(m.K)]	1.6	3.0	40

Temperature Induced Degradation of Material Properties

Elevated temperatures experienced during a fire cause a significant degradation in material properties of reinforced concrete structures, including concrete compressive strength, concrete modulus of elasticity, yield strength of steel reinforcing bars. Figure 4 shows the degradation of material properties due to the effect of high temperatures that used as input for ABAQUS model. The material properties are presented at different temperatures as a normalized value relative to corresponding material property at ambient temperature. Reduction of steel and HSC concrete at elevated temperature are estimated per (Eurocode-2, 2005). While UHPC reductions are extracted from the experimental data reported in (JSCE, 2008; Li et al., 2017).



a) Steel b) HSC c) UHPC

Figure 4. Effect of elevated temperatures on reinforced concrete materials (Model input)

RESULTS AND DISCUSSION

Existing DSC (HSC with Steel Liners)

To show the development of stress with time, the contour plots are presented for two different times of fire exposure. Particularly at 50°C (initial temperature, approximately same as the used fuel temperature inside the container) and 800°C (temperature at the end of thermal loading). Figure 5 presents the contour plots of the stresses at 50°C for HSC container. As shown, the maximum compressive stress in concrete core is 0.27 MPa, and maximum absolute stress in steel liner is 1.74 MPa, which are significantly less than the design strength of concrete and steel.

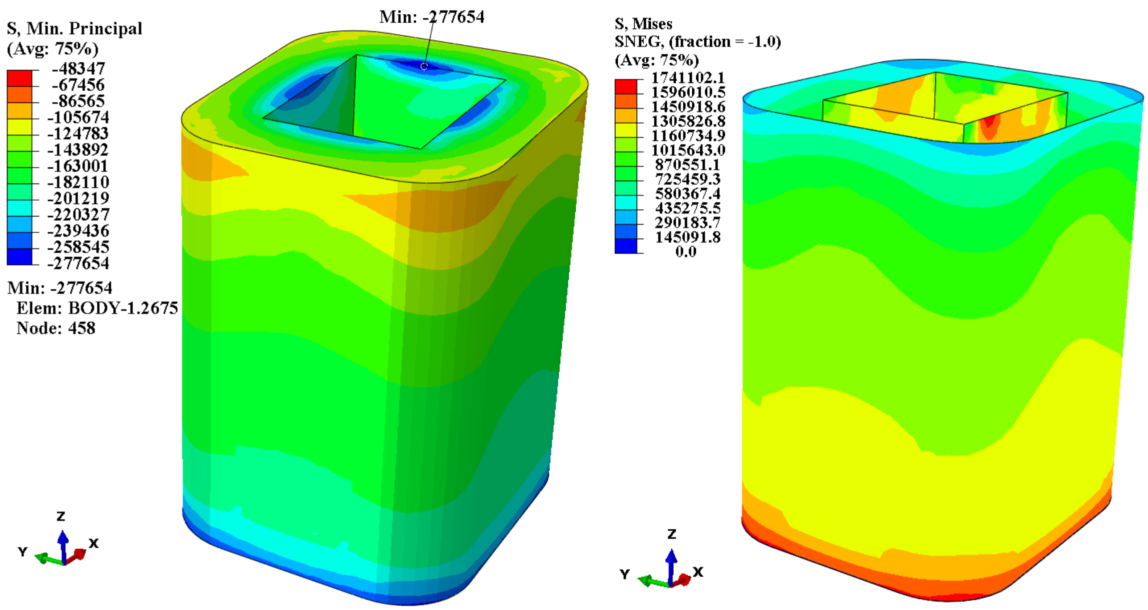


Figure 5. Maximum compressive stress at 50ºC (left: HSC core; right: steel liners).

Figure 6 presents the contour plots of stresses at 800ºC for HSC container. At elevated temperatures, the different heating conditions directly influence the mechanical behaviour and the developed stresses. The maximum compressive stress in concrete is 87.1 MPa, and maximum absolute stress in steel liner is significantly high (495.8 MPa). The thermal gradient between the temperature outside (800ºC) and inside (50ºC) the container is clearly shown in the stress change across the wall thickness.

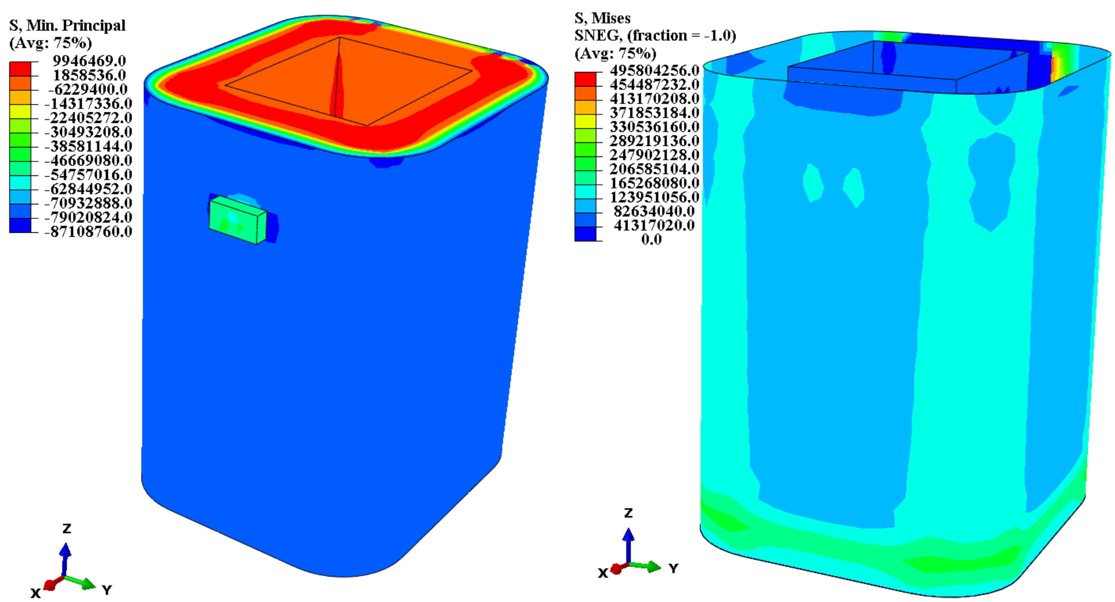


Figure 6. Stress distribution at 800ºC (left: HSC core; right: steel liners)

New DSC (UHPC)

Figure 7 shows the compressive stress distribution for the considered loading case at the room temperature. The maximum compressive stress in concrete is 1.35 MPa and in steel reinforcement is 2.60 MPa. It should be pointed out that the stress is uniformly distributed across the wall thickness and in the steel reinforcement as the temperature is almost the same both inside and outside the container (i.e., no thermal gradient). Figure 8 shows the compressive stress distribution due to mechanical and thermal loads. The maximum compressive stress in concrete is 89.5 MPa, and maximum absolute stress in reinforcement is 185.5 MPa.

Discussion

Comparing the performance of the two designs (Figures 5 to 8) under mechanical and thermal loads, the application of UHPC in radioactive waste management structures seems possible and useful. UHPC container with a wall thickness of 300 mm can replace the existing container of 550 mm wall thickness of composite concrete-steel section. At ambient temperature, the maximum stresses are of the same order for both designs under considered mechanical load. On the other hand, at elevated temperatures, the concrete core of the existing DSC (HSC with steel liner) experienced high level stresses which are spread over the walls. Steel liners have an adverse behaviour due to the high thermal conductivity which results in rapid heating of the concrete core. In comparison, UHPC container exhibits low thermal conductivity as a result the stresses in the walls are relatively lower than existing container. It should be mentioned that the high stresses in UHPC are localized on the base which mainly returns to the combined effect of thermal loads and the mechanical boundary conditions of the base. In reality, heating the bottom of container base is less likely to happen because the container will be resting on floor in the storage facility and will be covered by impactor during transportation scenario (Figure 1.C)

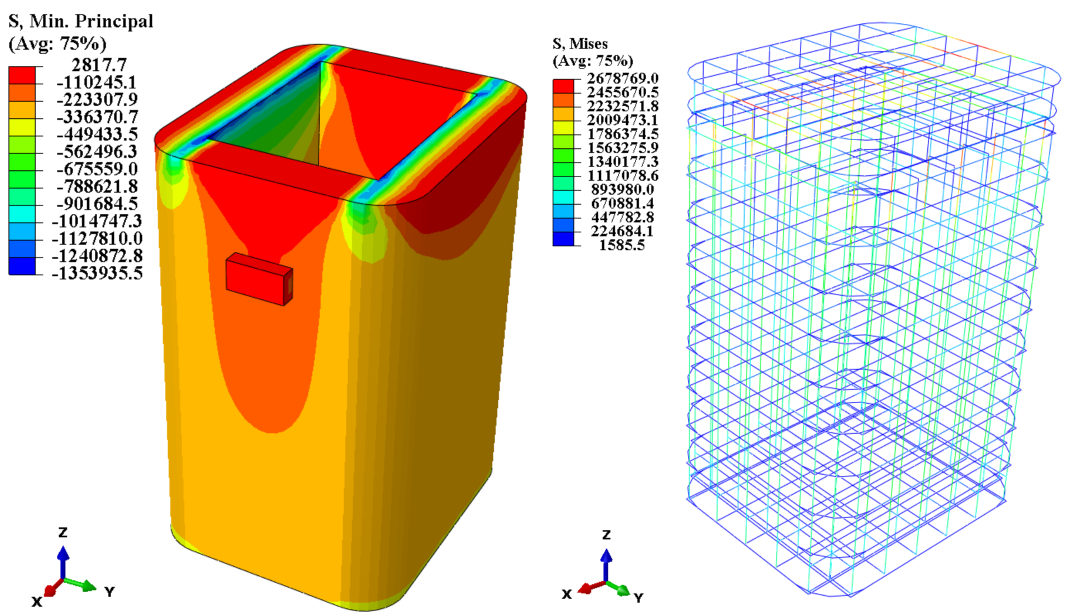


Figure 7. Stress distribution at 50°C (left: UHPC body; right: reinforcement)

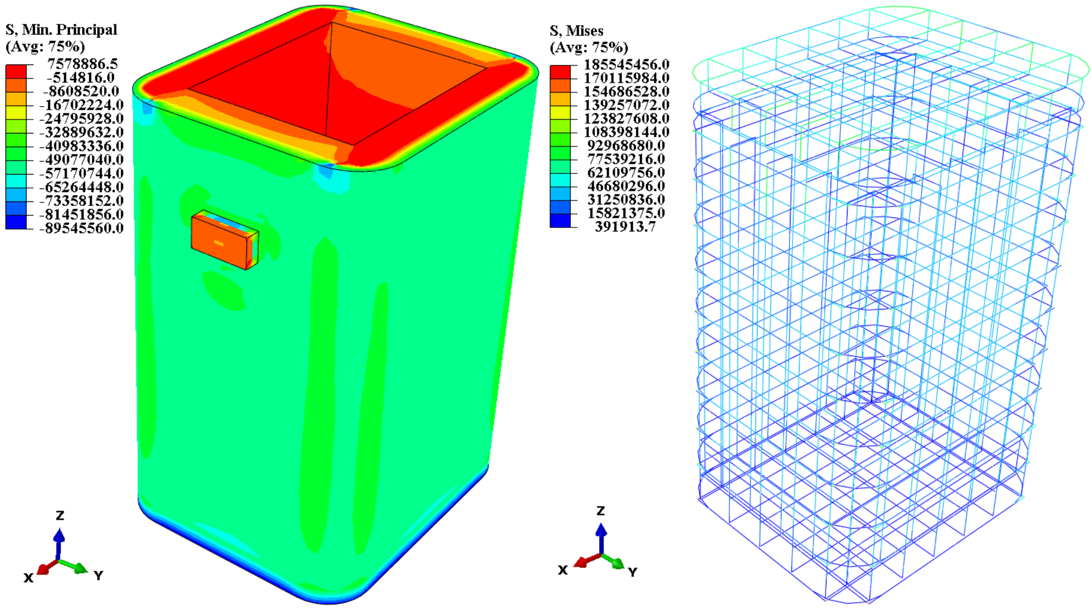


Figure 8. Stress distribution at 800°C (left: UHPC body; right: reinforcement)

CONCLUSION

This study is part of an ongoing research project carried out by the authors aimed to develop a new, efficient nuclear waste container using UHPC as an alternative to traditional steel-concrete-steel containers. This study focuses on the fire resistance rating for the new design (UHPC container) in comparison to existing DSC. The reinforced concrete DSC that is in use at Canadian Nuclear Power Generation sites is used in this numerical study. The performance of containers is investigated numerically using ABAQUS software. The containers are subjected to a 30-minute thermal exposure at 800°C as specified by the CNSC. The numerical results showed that UHPC container with a wall thickness of 300 mm can replace the existing container of 550 mm wall thickness of composite concrete-steel section. At ambient temperature, the maximum stresses are of the same order for both designs under considered mechanical load. On the other hand, at elevated temperatures, the concrete core of the existing DSC (HSC with steel liner) experienced high level stresses which are spread over the walls. Steel liners have an adverse behaviour due to the high thermal conductivity which results in rapid heating of the concrete core. In comparison, UHPC container exhibits low thermal conductivity as a result the stresses in the walls are relatively lower than existing container.

As part of a separate investigation, drop tests and fire tests will be performed for the validation of the numerical model and implementation of even more robust analyses of the proposed container behaviour.

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