CREEP AND SHRINKAGE ANALYSIS FOR CONCRETE SPENT FUEL DRY STORAGE MODULE

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Abstract

CANDU® reactors are designed in Canada and are built and operated worldwide to produce electricity economically with no emission of green house gases. This paper presents creep and shrinkage analysis for a concrete spent fuel dry storage module of a CANDU® nuclear power plant. Creep and shrinkage analysis was performed using a method outlined in American Concrete Institute (ACI) code (references [1] and [2]), and then the creep and shrinkage strains were analyzed in a finite element model to obtain the structural behavior of the concrete module. This demonstrated that the creep and shrinkage analysis for concrete spent fuel dry storage is reasonable. AECL's spent fuel dry storage module is adequate to resist the time-dependent effects due to creep and shrinkage of concrete.

1. Introduction

The operation of CANDU® reactors yields spent fuel bundles that are removed from the reactor core by means of unique remote mechanisms. Spent fuel bundles coming out of the reactor are kept spent fuel bays for several years to allow their heat production to drop sufficiently to enable dry storage in specially designed and built concrete modules. The function of a spent fuel dry storage facility is to provide safe, economical, reliable and retrievable medium term storage for spent fuel from CANDU® reactors.

The spent fuel dry storage operations consist of removing the spent fuel bundles from the storage trays that are stacked in the spent fuel bay, placing them in stainless steel baskets, removing the baskets from the spent fuel bay, and transferring them to a shielded work station. Inside the shielded workstation, the basket is dried and seal welded. It is then transferred to the storage site and placed in a concrete module for storage.

As large volumes of reinforced concrete are used to build the storage module, creep and shrinkage is one of the load cases that must be analysed to meet performance requirements of the structure.

2. Description of the structure

The reinforced concrete structure has dimensions of 21.93-m in length, 12.93-m in width, and 7.67-m in height and holds 40 storage cylinders. Each storage cylinder is capable of holding 10 irradiated fuel storage baskets. The module structure is built directly on top of a 1-m thick

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lean concrete pad that extends approximately 0.5-meter below the module. The top slab is 1.08-m thick and the sidewalls are 0.985-m thick.

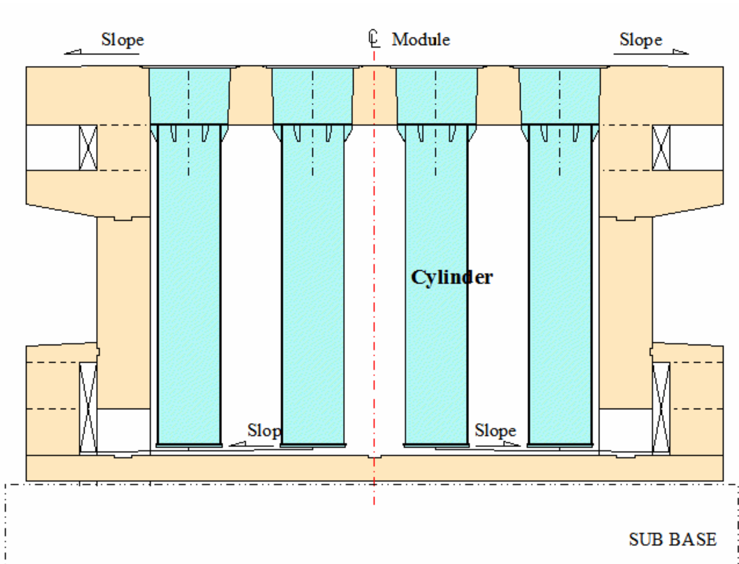

Figure 1 Elevation view of a module.

The steel storage cylinders are encased in the upper deck with the portion holding the fuel hanging within the plenum. The encased portion of the storage cylinder in the upper deck contains the shielding plug. The shielding plug is removable to allow fuel basket loading operations. The bottom section of the storage cylinder is laterally supported by seismic restraints that allow thermal expansion of the storage cylinder in the vertical direction, while restraining movements in the horizontal direction.

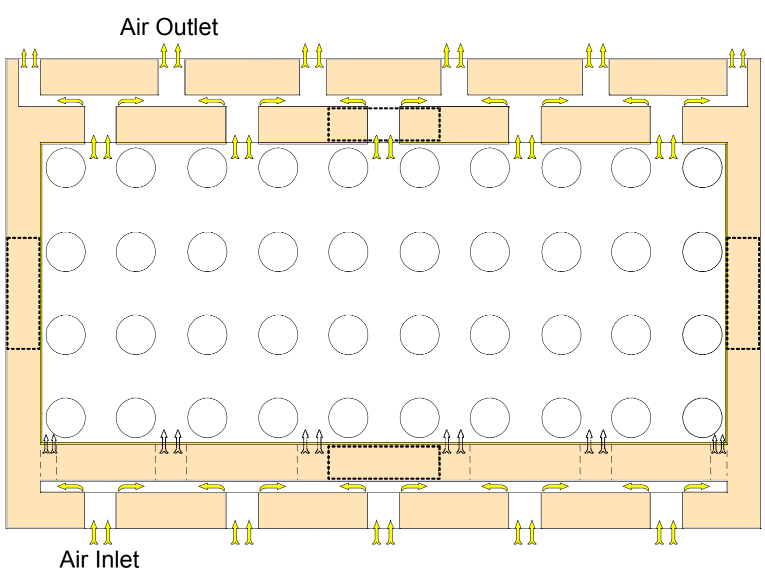

Figure 2 Plan view of a module.

3. Finite element model

A full size finite element model was developed to represent the real structure. An ANSYS program was used in the analysis. The units used in the model are kilogram (kg) for mass, Newton (N) for force, and meter (m) for length.

The Y-axis of the model is perpendicular to the base slab upward. The X-axis is in the short wall direction of the model and the Z-axis is in the long wall direction of the model. The reinforced concrete structure was modelled using Solid elements. The element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The cylinder and fuel are modeled using Mass elements.

The cylinders are treated as masses added to the top and bottom slab of the module. The total weight of one cylinder including 10 baskets is about 30,000 kg. Since all the cylinders are suspended from the top, free in vertical direction and restrained laterally at bottom, the total cylinder mass in Y direction is added to the top slab. Half of the cylinder mass is added horizontally on both the top and bottom slab in the X and Z directions.

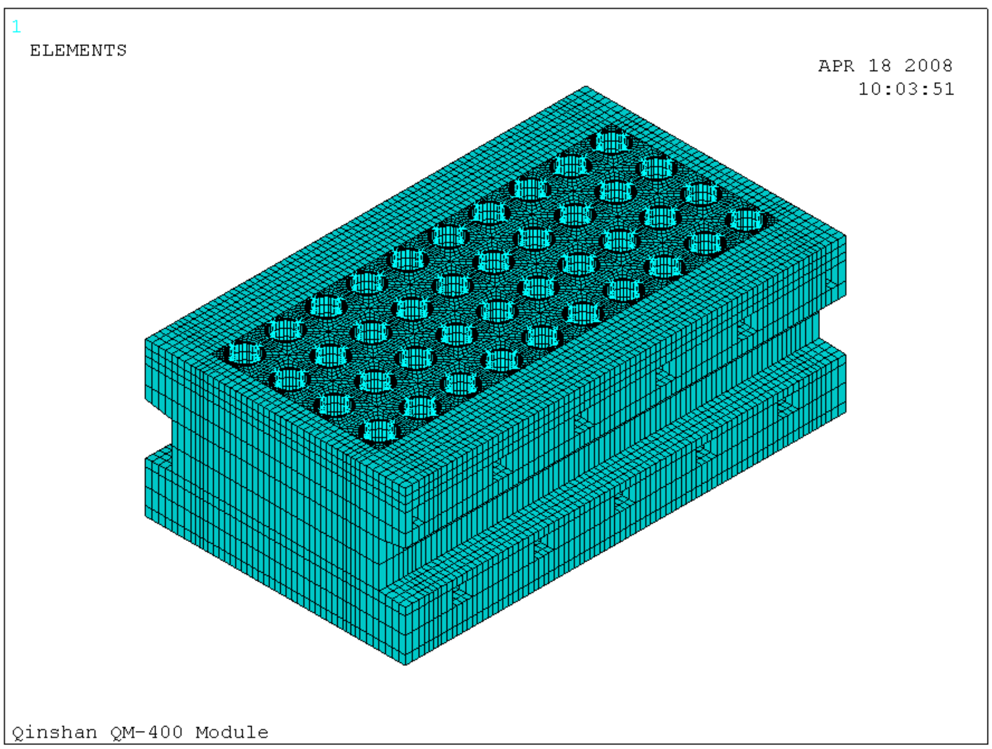

Figure 3 Finite element model of the structure.

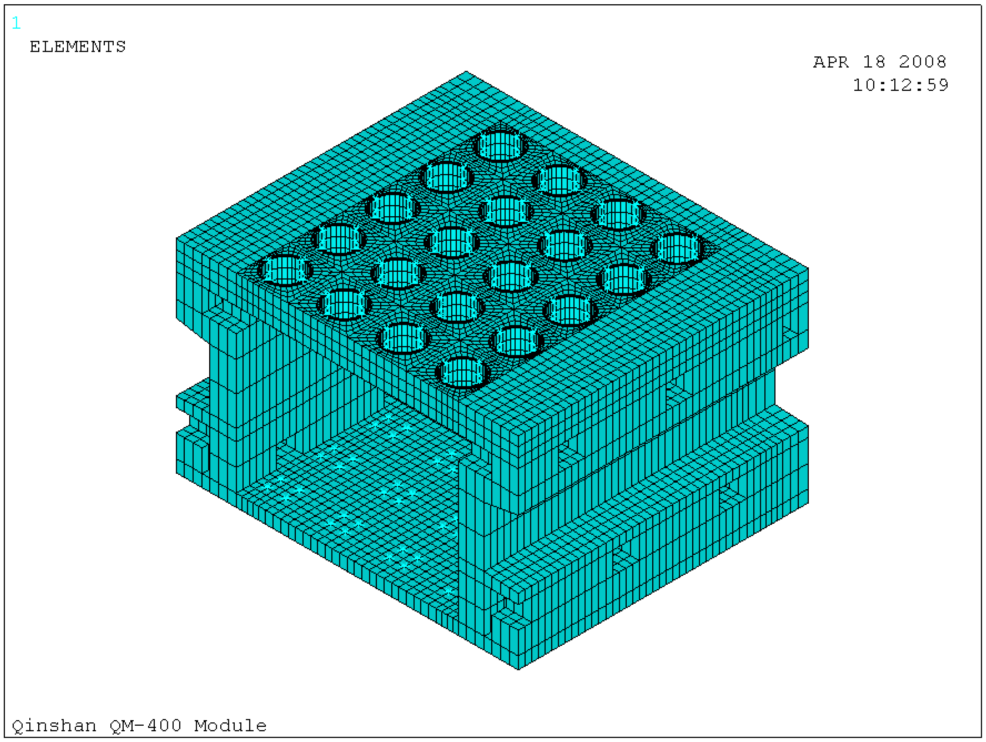

Figure 4 Sectional view of finite element model.

4. Creep and shrinkage analysis using ACI methods

Figure 5 shows sections through the end wall and side wall of the storage module. The following formulas from References [1] and [2] were used to analyse the creep and shrinkage of each section.

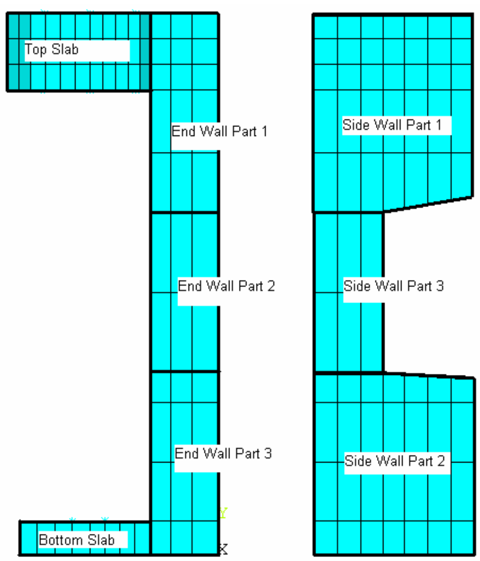

Figure 5 Structure sections of the model

The ACI committee 209 suggests the use of the following equations for prediction of creep and shrinkage strain:

Creep coefficient: $\nu_t = \dfrac{t_c^{0.60}}{10 + t_c^{0.60}} \nu_u$ for loading age of 7 days of moist cured concrete. $t_c =$ time in days after loading.

Unrestrained shrinkage strain: $(\varepsilon_{sh})_t = \dfrac{t_s}{35 + t_s} (\varepsilon_{sh})_u$ after aging 7 days for moist cured concrete. $t_s =$ the time after shrinkage is considered, that is, after the end of initial wet curing.

In the absence of specific creep and shrinkage data for local aggregates and conditions, the average values suggested for ν_u and $(\varepsilon_{sh})_u$ are: $\nu_u = 2.35\gamma_c$ and $(\varepsilon_{sh})_u = 780\gamma_{sh} \times 10^{-6} m/m$, where γ_c and γ_{sh} represent the product of the applicable correction factors in Section 2.5 and 2.6 of Reference [1] from equations (2-12) to (2-30) as shown in section 4.1 in this paper.

Creep strain for small cross section: for structures which are allowed to lose their moisture and have cross sections which are not too massive (6 to 12 in., 150 to 300 mm), $\varepsilon_c = \varepsilon_t \nu_t = \dfrac{t^{0.60}}{10 + t^{0.60}} \nu_u \varepsilon_i$, $\nu_u = 2.35\gamma_c$, ratio of ultimate creep strain to initial strain. γ_c is product of correction factors.

Creep strain for massive cross section: for structures such as nuclear reactor containment which are insulated, or submerged in water, or are so massive they can not lose much of their moisture during their lifetime, $\varepsilon_c = \dfrac{1}{E_O} + \dfrac{\psi_1}{E_O} (t_{la})^{\left(\frac{-1}{3}\right)} \left(t^{\frac{1}{8}} \right)$, is the sum of instantaneous strain and creep strain caused by unit stress. $\psi_1 = 0.97\nu_u$, $\dfrac{1}{E_O} = \dfrac{0.84}{E_{ct}}$, $E_{ct} =$ modulus of concrete which does not undergo drying. $E_{ct} = g_{ct} \left[w^3 (f_c')_t \right]^{1/2}$, for the unit weight of concrete w in pcf and the compressive strength $(f_c')_t$ in psi. $g_{ct} = 0.043$ for w in kg/m^3 and compressive strength $(f_c')_t$ in MPa. $g_{ct} = 33$ for w in pcf and compressive strength $(f_c')_t$ in psi. $(f_c')_t = \dfrac{t}{\alpha + \beta t} (f_c')_{28}$, is the ranges of α and β for the normal weight, sand lightweight, and all lightweight concretes (using both moist and steam curing, and Type I and III cement), the detail values of α and β are given in Table 2.21 of Reference [1].

4.1 Correction factors for creep and shrinkage

Correction factor for age of loading:

$\gamma_{la} = 1.25(t_{la})^{-0.118}$, where t_{la} = age of loading (days) for moist cured concrete.

Correction factor for ambient relative humidity:

Creep: $\gamma_{\lambda} = 1.27 - 0.0067\lambda$, for $\lambda > 40$

Shrinkage: $\gamma_{\lambda} = 1.40 - 0.0102\lambda$, for $40 \le \lambda \le 80$ or

$\gamma_{\lambda} = 3.00 - 0.030\lambda$, for $80 < \lambda \le 100$

Correction factor for thickness:

Creep: $\gamma_{vs} = \frac{2}{3}\left[1 + 1.13\exp^{\left(-0.54\frac{v}{s}\right)}\right]$

Shrinkage: $\gamma_{vs} = 1.2\exp(-0.12\, v/s)$, where $\frac{v}{s}$ is the volume-surface ratio of the member in inches.

Correction factor for concrete composition:

Slump: creep $r_s = 0.82 + 0.067s$

Shrinkage $r_s = 0.89 + 0.041s$, where s is the observed slump in inches.

Fine aggregate percentage: creep $\gamma_{\psi} = 0.88 + 0.0024\psi$

Shrinkage $\gamma_{\psi} = 0.90 + 0.002\psi$, where ψ is the ratio of the fine aggregate to total aggregate by weight expressed as percentage.

Correction factor for cement content:

Shrinkage $\gamma_c = 0.75 + 0.00036c$, where c is the cement content in pounds per cubic yard.

Correction factor for air content:

Creep $\gamma_{\alpha} = 0.46 + 0.09\alpha$, but not less than 1.0

Shrinkage $\gamma_{\alpha} = 0.95 + 0.008\alpha$, where α is the air content in percent.

4.2 Creep and shrinkage analysis results

Creep and shrinkage for each part of the structure were analysed. Figures 6 and 7 show the creep and shrinkage in its 50 years design life for one of the Side Wall Part 2. The results indicate that the creep strain continues to develop during the design life of the structure but most shrinkage strain was developed in first 5 years. Finally, total strain of each part was converted to equivalent temperature drop according to coefficient of expansion of concrete 10 x 10^{-6} /°C [3]. Figure 8 shows the temperature drops for simulation creep and shrinkage of the structure.

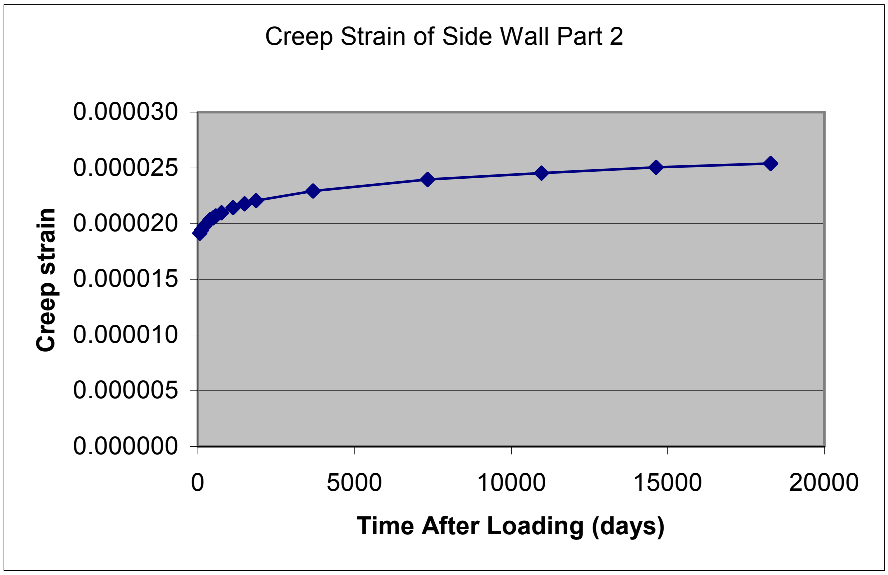

Figure 6 Total creep strain of side wall part 2 changes with time ($unit : mm / mm$)

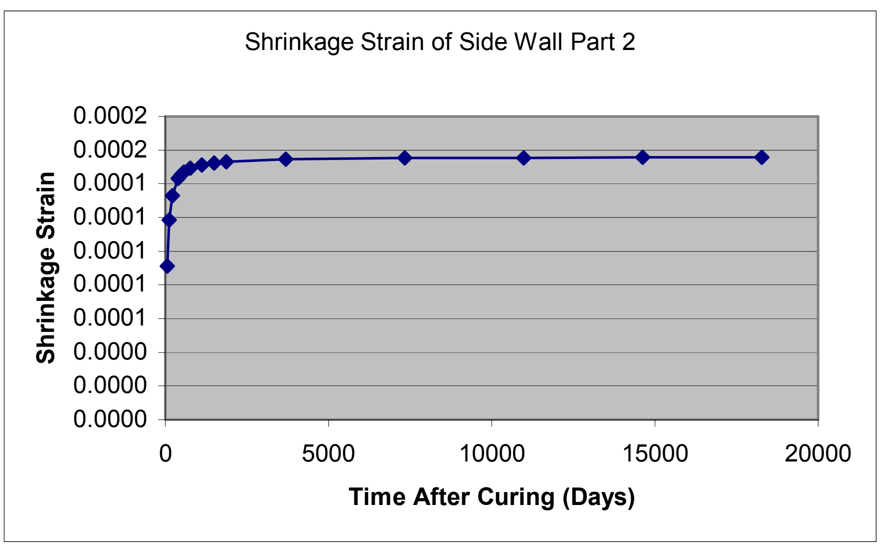

Figure 7 Total shrinkage strain of side wall part 2 changes with time ($unit : mm / mm$)

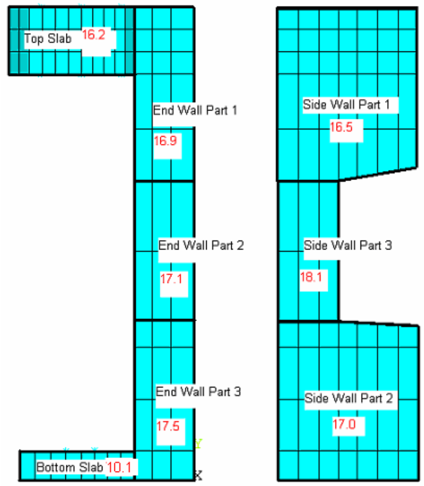

Figure 8 Temperature drops for simulation creep and shrinkage ($unit : °C$)

5. Numerical simulation of the structure subjected to creep and shrinkage

A coupled thermal stress analysis was performed with a temperature drop applied at each node of the finite element model. Figure 9 shows the temperature distribution on the whole structure which indicates higher creep and shrinkage strain at the thick wall part and lower creep and shrinkage strain at the bottom slab because of the effects from the constraints. Figure 10 shows Von Mises stress distribution on the structure subjected to creep and shrinkage in its 50 years design life, which produces about 10% stress contribution to the total stress effect on the structure in normal load combinations.

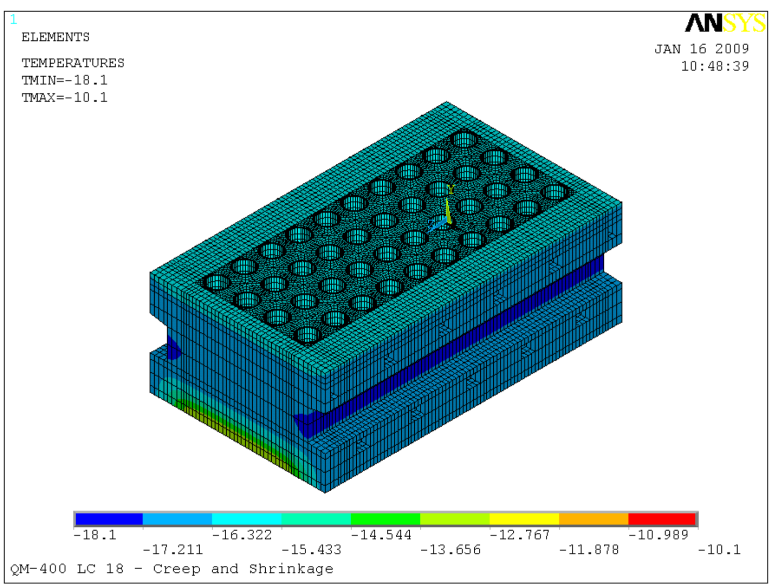

Figure 9 Creep and shrinkage simulation of the structure in finite element model ($unit : °C$)

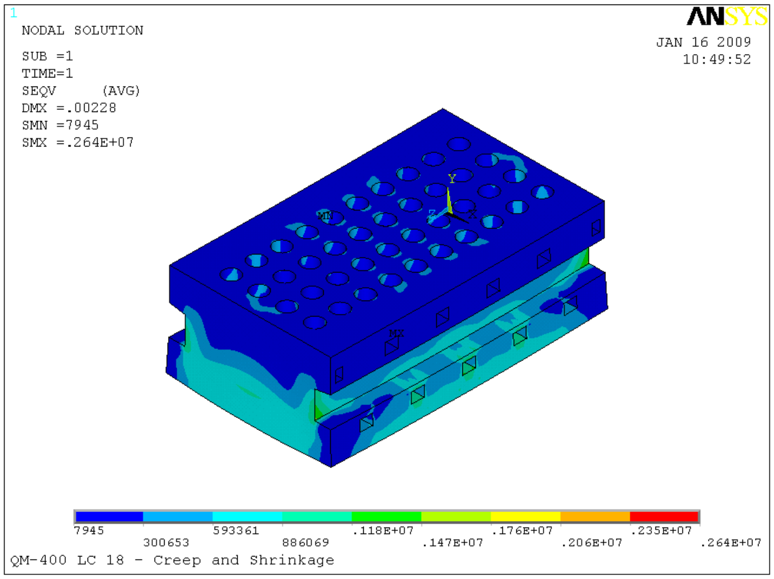

Figure 10 Von Mises stresses of the structure subjected to creep and shrinkage (*unit* : *Pa*)

6. Conclusion

The design of the spent fuel dry storage module is adequate for the given time-dependent effects of creep and shrinkage of concrete as demonstrated through analysis. This analysis was completed using America Concrete Institute (ACI) guides to analyse the creep and shrinkage strain of reinforce concrete structure at specified environment and construction conditions, and a finite element model to analyse the structural behaviour of the module subjected to creep and shrinkage in its 50 years design life. It was further demonstrated by an numerical simulation method through equivalent temperature drop, that creep and shrinkage stress distribution on the structure is approximately 10% of the total stress effect on the structure in normal load combinations.

7. References

[1] America Concrete Institute, ACI 209R-92, “Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures”, 1997.

[2] America Concrete Institute, ACI 207.2R-95, “Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete”, 1995.

[3] Canadian Standard Association, A23.3-04, “Design of Concrete Structures”, 2004.

Acronyms

ACI = America Concrete Institute