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Investigation of Concrete Cracking due to Hydration Heat of Reactor Containment Building in Hot and Cold Weather

*Yun Lee[1)], Ki Min Lee[2)], Yun Yong Kim[3)] and Jung Hwan Hyun[4)]

[1) 2)] *Dept. of Civil Engineering, Daejeon University, Daejeon, Korea*

[3) 4)] *Dept. of Civil Engineering, Chungnam National University, Daejeon, Korea*
[1)] *yunis@dju.ac.kr*

ABSTRACT

Prediction of concrete cracking due to hydration heat in mass concrete such as reactor containment building (RCB) in nuclear power plant is a crucial issue in construction site. In this study, the numerical analysis for heat transfer and stress development is performed for the containment wall in RCB by considering the severe weather conditions. Finally, concrete cracking risk in hot and cold weather is discussed based on analysis results. In analyses considering severe weather conditions, it is found that the surface cracking risk in cold weather is high due to the abrupt temperature difference between inside concrete and the ambient air in cold region. In hot weather, temperature differences between inner and outer face is relatively small, and accordingly the surface cracking risk is relatively low in contrast with cold weather.

1. INTRODUCTION

Thermal cracking problems due to the heat of hydration of cement in concrete structures were first noted in the many large-sized concrete dams that were constructed in the United States in the 1930s. Since this time, many studies concerning thermal cracking have been performed. In particular, a number of numerical tools using the Finite Element Method (FEM) have been developed. Currently, however, input data related to the thermal properties of the concrete have not been thoroughly investigated. For structures located at coastal regions or areas under the influence of strong winds, however, thermal damage by convective heat transfer may also be prevalent. In order to more accurately evaluate such thermal damage, it is necessary to consider thermal properties such as the convective heat transfer coefficient.

Fundamentally, concrete structures show various behaviors after being placed at construction sites due to the stress-inducing mechanisms of hydration heat,

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[1)] Assistant Professor
[2)] Graduate Student
[3)] Associate Professor
[4)] Graduate Student

autogenous shrinkage, and drying shrinkage. For the verification and prediction of concrete behavior, numerical schemes such as the finite element method (FEM) and the finite difference method (FDM) are considered powerful tools.

In this paper, the numerical analysis for heat transfer and stress development is performed for the containment wall in RCB by considering the severe weather conditions and construction sequences. From the analysis, the concrete cracking risk in hot and cold weather will be discussed based on thermal stress results.

2. Numerical Analysis

2.1 Modeling and Analysis Conditions

In order to investigate the cracking behavior of a RCB concrete wall, a numerical simulation for a representative portion in RCB concrete wall with a thickness of 1.2 m is carried out. The shape and configuration of the structure are shown in Fig. 1. Additionally, as boundary conditions for the numerical analysis, convection and restraint conditions are imposed by considering the ambient temperature and external constraint conditions.

In the mesh modeling of the structure, concrete is modeled as an eight node isoparametric solid, as shown in Fig. 1. For simplification, only a quarter of the structure is considered in this analysis. Input data for the thermal stress analysis of the concrete wall are shown in Table 1. To simulate the severe temperature conditions as predicted in construction sites, hot and cold temperature profiles based on annual monitoring estimates in UAE and Finland are considered in this analysis, as shown in Fig. 2. Two types of ambient temperature and casting temperature were considered, as tabulated in Table 1. For the adiabatic temperature rise curve of RCB concrete mix, the equation (i.e., Eq. (1)) of the Korea Concrete Institute (KCI) Code was used.

$$T = K\left\lfloor 1 - e^{-\alpha(t-t_0)} \right\rfloor \quad (1)$$

where T is the adiabatic temperature rise at time t (℃), *K* is the maximum adiabatic temperature rise (50.7℃), α is the temperature increasing velocity (1.24), and t_0 is the delayed time (0.168 day).

Table 1 Input data for thermal stress analysis of the concrete wall

Parameter		
Thermal conductivity (W/(m·K))	2.1	
Casting temperature (℃)	26.7 (UAE)	12.8 (Finland)
Ambient temperature (℃)	32 (UAE)	4.8, 13 (Finland)
Convection heat transfer coefficient (W/(m^2·K))	w/o form	14
	Steel form	14

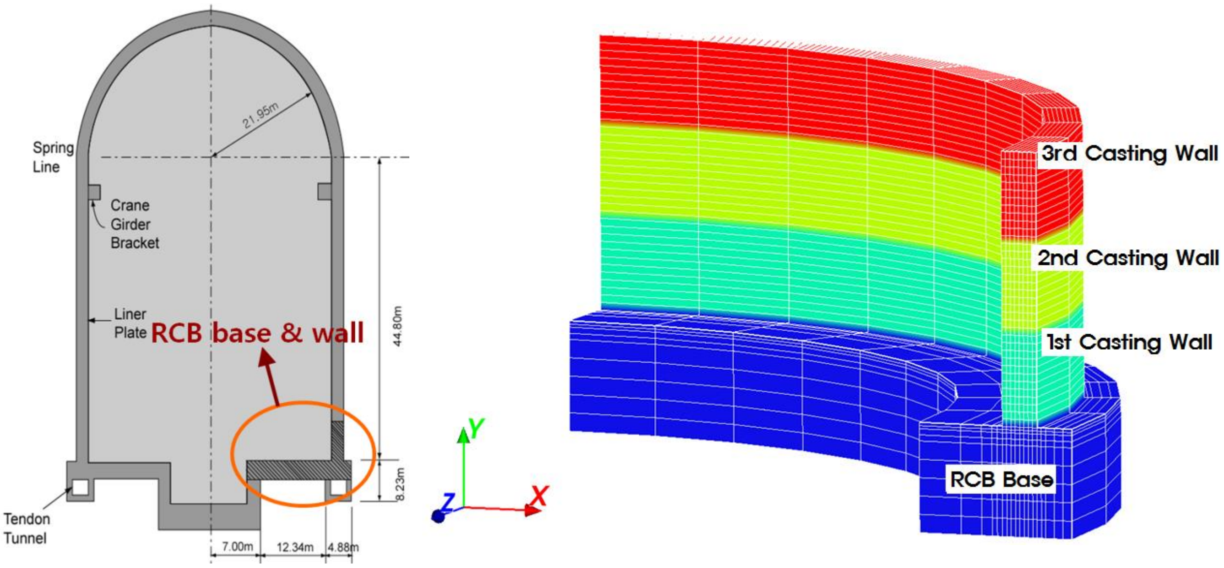


Fig. 1 Mesh Modeling of RCB Base Mat and Containment Concrete Wall.

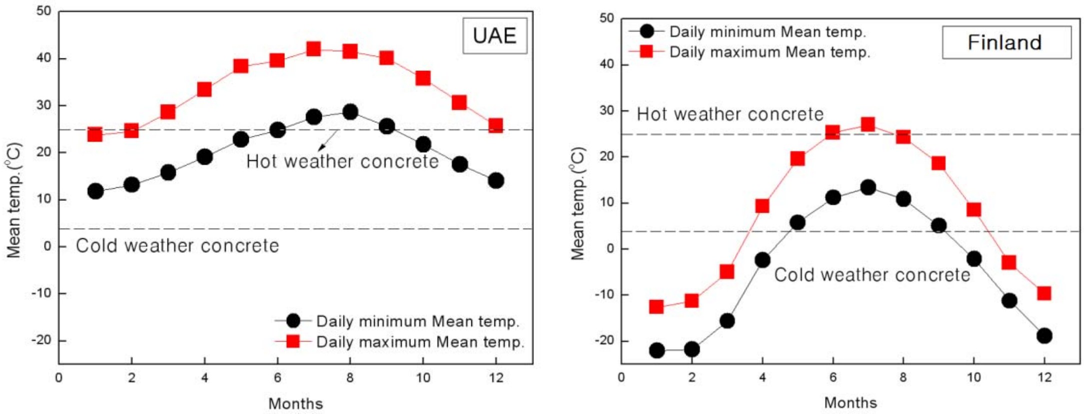


Fig. 2 Annual Ambient Temperature Profiles in Hot and Cold Region

2.2 Methodology of Thermal Stress Analysis

A numerical analysis for heat transfer and thermal stress is carried out using the finite element code CONSA V1.1, a 3D finite element analysis program developed at Korea Advanced Institute of Science and Technology (KAIST) for hydration heat transfer and the corresponding stress analysis.

To calculate stresses due to hydration heat and creep, the minimum potential energy principle is introduced. In an elastic body, potential energy can be expressed as given by Eq. (2).

$$\Pi_p = U - W_p \tag{2}$$

where Πp is the potential energy, U is the strain energy, and W_p is the energy due to external applied forces.

In Eq. (2), the strain energy and the energy due to external applied forces are as follows.

$$U = \int_V \left[\int_0^{\varepsilon} \{\sigma\} d\varepsilon \right] dV \tag{3}$$

$$W_p = \{F\}\{d\} \tag{4}$$

where {σ} is the internal stress, ε is the strain, {F} is the external applied force, and {d} is the displacement.

Considering only mechanical strain, which can be calculated by subtracting the strains produced by temperature and creep from total strain, the stress can be obtained by Eq. (5).

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon_C\} - \{\varepsilon_T\}) \tag{5}$$

where [D] is the stiffness matrix of the material, $\{\varepsilon_c\}$ is the creep strain, and $\{\varepsilon_T\}$ is the thermal strain.

Inserting Eq. (5) into Eq. (3), Eq. (6) is obtained.

$$\begin{aligned} U &= \int_V \left[\int_0^{\varepsilon} [D](\{\varepsilon\} - \{\varepsilon_C\} - \{\varepsilon_T\}) d\varepsilon \right] dV \\ &= \int_V \left[\frac{1}{2}[D]\{\varepsilon\}^2 \right] dV - \int_V \left[[D](\{\varepsilon_C\} + \{\varepsilon_T\} \right] dV \end{aligned} \tag{6}$$

Inserting Eq. (4), (5), and (6) into Eq. (2) and minimizing Πp, Eq. (7) can be obtained.

$$\frac{\partial \Pi_p}{\partial \{d\}} = \left\{ \int_V [B]^T [D][B] dV \right\} \{d\} - \int_V [B]^T [D][\{\varepsilon_C\} + \{\varepsilon_T\}] dV - \{F\} = 0 \tag{7}$$

Expressing Eq. (7) in a matrix form, Eq. (8) is finally obtained.

$$[K]\{d\} = \{F\} + \{F\}_C + \{F\}_T \tag{8}$$

In Eq. (8), [K], $\{F\}_C$ and $\{F\}_T$ are expressed by the following equations, respectively.

$$[K] = \int_V [B]^T [D][B] dV \tag{9}$$

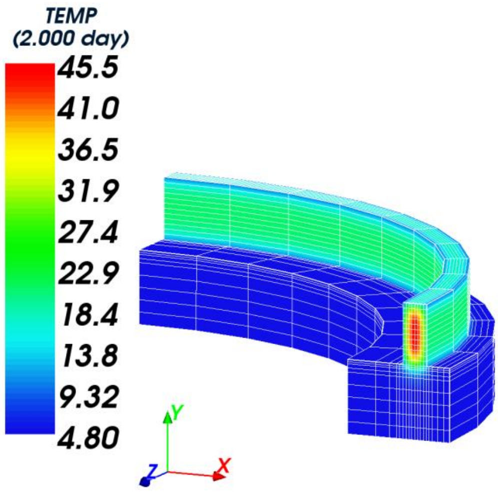
$$\{F\}_C = \int_V [B]^T [D]\{\varepsilon_C\} dV \tag{10}$$

$$\{F\}_T = \int_V [B]^T [D] \{\varepsilon_T\} dV \tag{11}$$

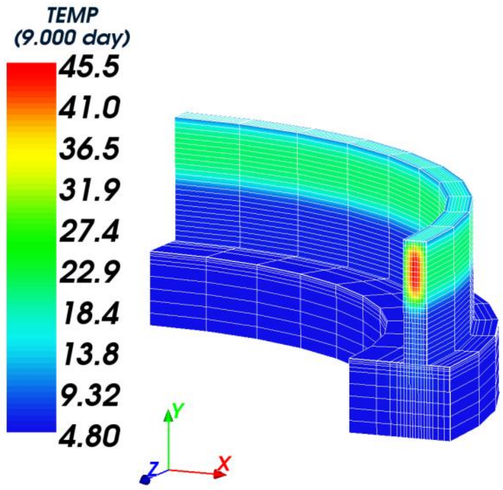
3. Results and Discussions

The temperature distributions for three stages of RCB wall at 2.0 days after casting are shown in Fig. 3. The fast release of heat at the surface of the concrete wall may cause the excessive tensile stress at the early age stage of concrete casting.

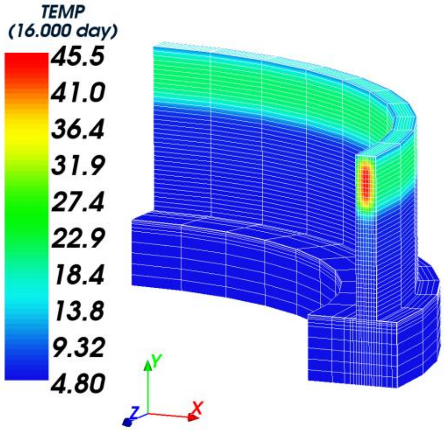
Fig. 4 shows the stress distributions for three stages of RCB wall at 2.0 days after casting. Fig. 4(b) shows that maximum tensile stress at 2 days is 4.69 MPa, which is the maximum value among three stages. The tensile stress due to the large temperature difference between the inner and outer locations can cause surface cracking if the tensile stress exceeds the tensile strength on the concrete surface.



(a) at 2 days after 1st casting

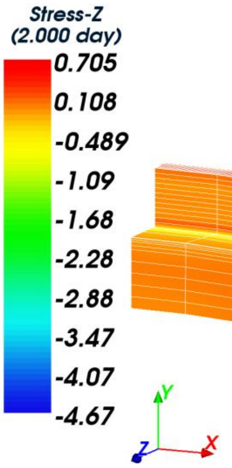


(b) at 2 days after 2nd casting

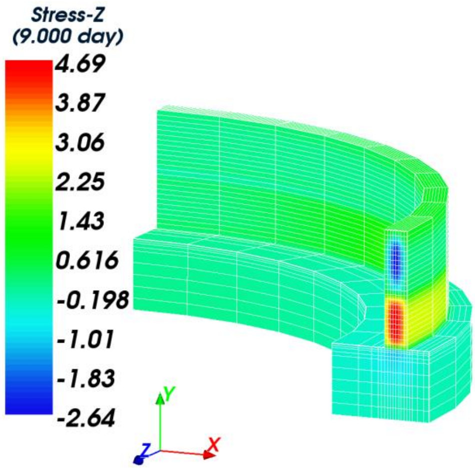


(c) at 2 days after 3rd casting

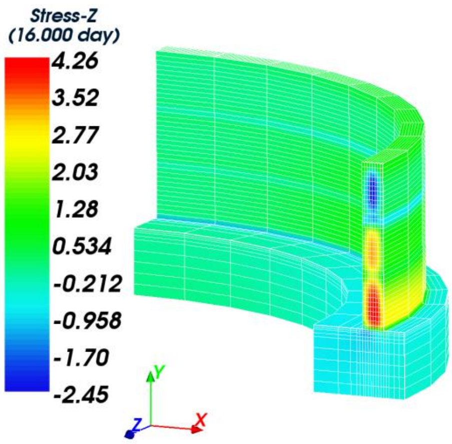
Fig. 3 Temperature Distributions in RCB Wall (Finland)



(a) at 2 days after 1st casting



(b) at 2 days after 2nd casting



(c) at 2 days after 3rd casting

Fig. 4 Stress Distributions in RCB Wall (Finland)

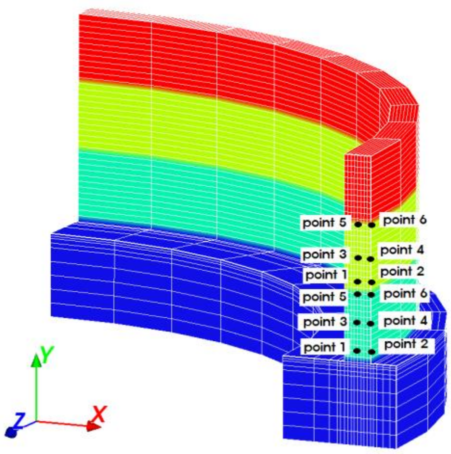
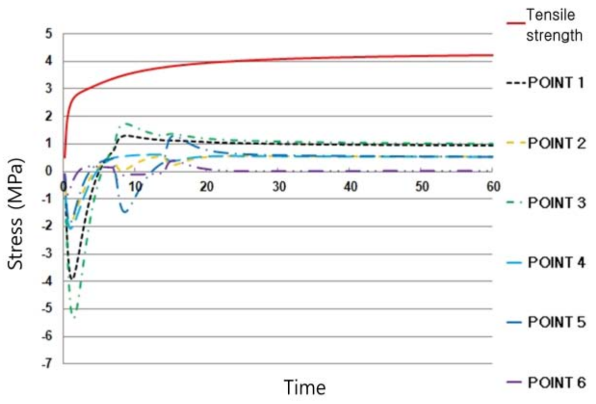
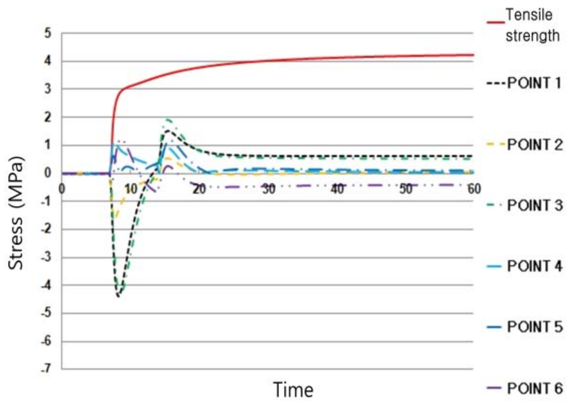


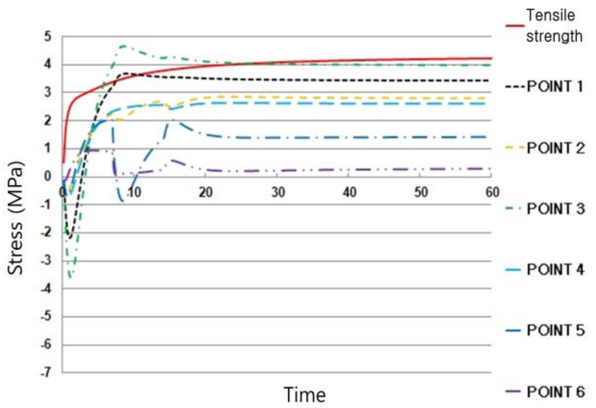
Fig. 5 Data Acquisition Points in RCB Wall



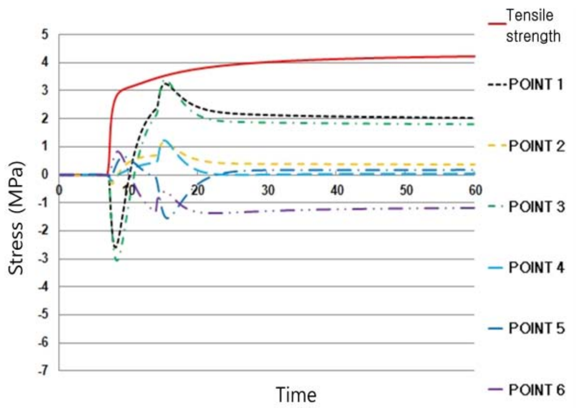
(a) 1st casting in UAE



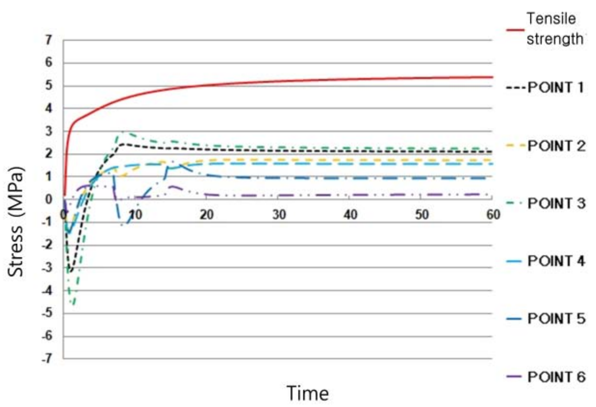
(b) 2nd casting in UAE



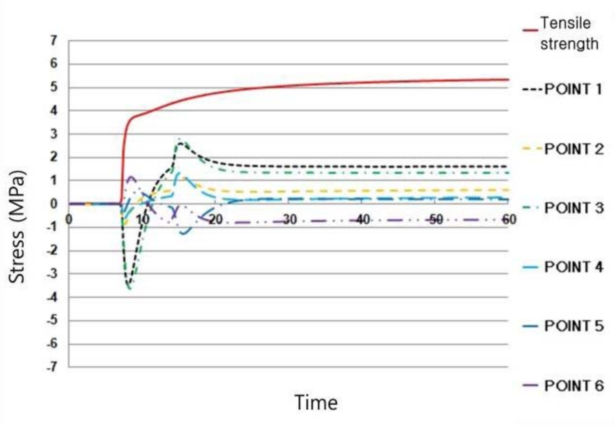
(c) 1st casting in Finland



(d) 2nd casting in Finland



(e) 1st casting in Finland (cured at 13℃)



(f) 2nd casting in Finland (cured at 13℃)

Fig. 6 Stress Histories at Successive Casting in RCB Wall

Fig. 6 shows the stress history at the six points displayed in Fig. 5. In Fig. 6, tensile strength evolution, which is influenced by concrete age and temperature variation, is shown at point 1, where the maximum temperature is predicted. As time increases after casting the concrete wall, the tensile stresses at points 1 and 3, which are representatives of wall center, develop and gain positive values. For the 1st casting in Finland shown in Fig. 6(c), tensile stress at point 3 exceeded tensile strength at around 5~6 days. The excess of tensile stress may cause tensile cracking on the concrete surface. In steam curing condition up to 13℃, tensile stress is lower than tensile strength, and, therefore, it is predicted that cracking in concrete wall will not happen as shown in Fig. 6(e) and Fig. 6(f).

4. CONCLUSIONS

In analyses considering severe weather conditions, it is found that the through-wall crack risk in cold weather is high due to the gradual large temperature difference between inside concrete and the ambient air in cold region. However, in ambient temperature up to 13℃, it is predicted that cracking in concrete wall will not happen in contrast with ambient temperature 4.8℃. In hot weather, temperature differences between inner and outer face is relatively small, and accordingly the cracking risk is relatively low in contrast with cold weather

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