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Prediction of thermal stress in concrete structures with various restraints using thermal stress device

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Abstract. Generally, thermal stress induced by hydration heat causes cracking in mass concrete structures, requiring a thorough control during the construction. The prediction of the thermal stress is currently undertaken by means of numerical analysis despite its lack of reliability due to the properties of concrete varying over time. In this paper, a method for the prediction of thermal stress in concrete structures by adjusting thermal stress measured by a thermal stress device according to the degree of restraint is proposed to improve the prediction accuracy. The ratio of stress in concrete structures to stress under complete restraint is used as the degree of restraint. To consider the history of the degree of restraint, incremental stress is predicted by comparing the degree of restraint and the incremental stress obtained by the thermal stress device. Furthermore, the thermal stresses of wall and foundation predicted by the proposed method are compared to those obtained by numerical analysis. The thermal stresses obtained by the proposed method are similar to those obtained by the analysis for structures with internally as well as externally strong restraint. It is therefore concluded that the prediction of thermal stress for concrete structures with various boundary conditions using the proposed method is suggested to be accurate.

Keywords: mass concrete; thermal stress; hydration heat; thermal stress device; degree of restraint

1. Introduction

Hydration heat is the resultant phenomena of the chemical reaction between cement and water, and responsible for the change in volume of concrete structures. During the construction of ordinary concrete structures, the heat is rapidly dissipated into the air, and temperature gradation inside the structure is not significant for cracking. However, this is not the case for mass concrete structures such as dams, containment buildings and mat foundations, as the release of heat is not

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rapid and thermal stress, which is the cause of thermal cracking, occurs (ACI 207.2R 2007, De Schutter 2002, ElSafty and Abdel-Mohti 2013, Klemczak and Knoppik-Wrobel 2014, Zhu 2014). Therefore, for the control of cracking, thermal stress must be accurately predicted.

Thermal stress is normally predicted by means of numerical analysis such as the finite element method. However, the accuracy of the stress predicted by numerical analysis is insufficient due mainly to the uncertainties involved in thermal and mechanical properties of concrete (Bažant *et al*. 1993, Deborst and Vandenboogaard 1994, Murthy *et al*. 2013, Ren *et al*. 2014). Much research works have been done to improve the accuracy of the prediction. Various experimental devices, therefore, were developed and verified by various analyses and experiments (Breitenbucher 1990, Kim *et al*. 2002). A thermal stress device (Amin *et al*. 2009) is one of the outcomes of these efforts. After the development of the device, (Chu *et al*. 2013) proposed a method to predict thermal stress in concrete structures considering the relationship between measured stress and strain. Though the method possesses the advantage of obtaining the stress without complicated calculation, strain in concrete structures must be measured in parallel. Additionally, the low prediction accuracy when the method is applied to concrete structures with internally strong restraint, of which the history of the degree of restraint is different from that of the device, is another restraint of the method.

In this paper, an enhanced method to predict thermal stress is proposed by considering the history of the degree of restraint to improve the prediction accuracy. In this method, an incremental thermal stress is predicted by comparing the degree of restraint to the incremental stress measured by the thermal stress device, and thermal stress is obtained by integrating the incremental stress. In addition, thermal stresses for the wall and foundation of mass concrete structures are predicted by the proposed method. Finally, the accuracy of the method is verified by comparing with those obtained by numerical analysis.

2. Prediction method for thermal stress in concrete structures

2.1 Limitaion of conventional method

The consideration of temperature change, mechanical properties of concrete, and the degree of restraint, influencing the amount of thermal stress, is significantly important for the prediction of thermal stress. The thermal stress device shown in Fig. 1 facilitates the measurement of thermal stress considering uncertain concrete properties and various degrees of restraint as concrete is placed in the middle of the device and restrained by constraint bars, the thicknesses of which are 10 mm, 20 mm and 40 mm (Amin *et al*. 2009). However, the measured stress obtained by the device should be adjusted according to the degree of restraint of structures due to there being a difference in the degree of restraint between the device and the structure.

This limitation of the device was overcome by introducing a means of predicting thermal stress in concrete structures using the relationship between the degree of restraint and stress obtained by the device based on that thermal stress due to restraint of volume change is proportional to the degree of restraint (Chu *et al*. 2013). In this method, the estimation of the degree of restraint is based on the measured strain in the field as well as the experiment. Thus, the method entirely relies on the verification in the field test. Furthermore, as shown in Fig. 2, the method can be applied only for concrete structures with restraint, which satisfies Eq. (1) as the stress in concrete structures is directly determined by comparing the degree of restraint and stress without consideration of the history of the degree of restraint. Therefore, the method should be modified with respect to the determination of the degree of restraint and consideration of the history of the degree of restraint.

$$\frac{R_{\delta_i}(t)}{R_{\delta_i}(t_0)} = \frac{R(t)}{R(t_0)} \tag{1}$$

where, R_{δ_i} represents the degree of restraint of the device with thickness δ_i, i represents each constraint bar, R is the degree of restraint of structures, and t_0 is the initial time.

2.2 Determination of the degree of restraint

In concrete structures, the volume change induced by hydration heat occurs at early age, and the volume change is restrained due to various factors. The restraint of the volume change is categorized into two kinds of restraints such as external and internal restraint according to the restraining factors. External restraint occurs when the whole or part of the boundaries of structures are restrained by rocks or foundations, whereas internal restraint occurs when volume change is restrained by the concrete itself owing to the temperature difference at each location inside concrete structures.

The degree of restraint changes over time as temperature and mechanical properties of concrete change drastically at early age. Accordingly, the histories of external and internal restraint gradually change following the variation of temperature and mechanical properties. More specifically, external restraint is similar to the perfect restraint condition at early age due to the small elastic modulus of concrete and it shows a gradual decrease over time due to the increasing properties. On the contrary, internal restraint is almost zero at early age due to the temperature change and elastic modulus of concrete being significantly small. However, a gradual increase in the temperature difference inside concrete and elastic modulus induces an increase in the internal restraint.

Therefore, it is significantly important to consider elastic modulus and temperature change estimating the degree of restraint. Furthermore, the degree of restraint should be estimated without field measurement.

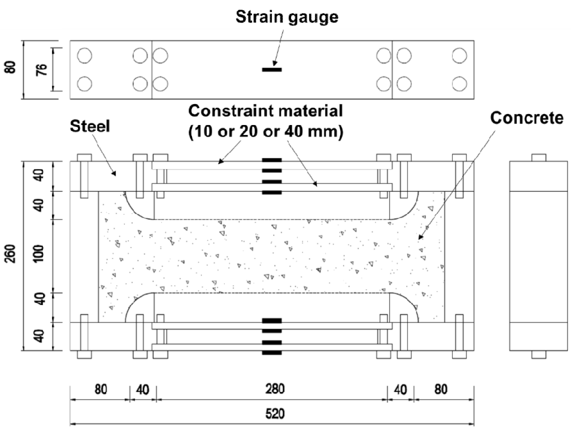


Fig. 1 The shape and dimensions of thermal stress device

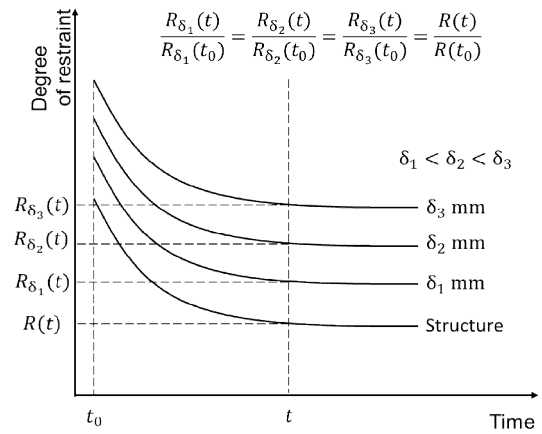


Fig. 2 The degrees of restraint of thermal stress device and structure with identical history

The degree of restraint can be defined in various ways. In this paper, the degree of restraint, however, is defined as the ratio of stress resulting from volume change to stress that would result if completely restrained shown as Eq. (2) (ACI 207.2R 2007).

$$R(t) = \frac{\sigma_c(t)}{\sigma_{c,fix}(t)} \tag{2}$$

where, $R(t)$ is the degree of restraint at time t, $\sigma_c(t)$ is the stress of a structure at time t, and $\sigma_{c,fix}(t)$ is the stress of the structure under complete restraint at time t.

As the degree of restraint is used to evaluate the relative amount of restraint of the device and the structure according to different boundary conditions, it can be obtained by elastic analysis without consideration of shrinkage and creep. Thus, $\sigma_c(t)$ and $\sigma_{c,fix,}(t)$ in Eq. (2) can be expressed with Eq. (3) and Eq. (4) respectively.

$$\sigma_c(t) = E_c(t)[\varepsilon_{total}(t) - \alpha_c(t)\Delta T(t)] \tag{3}$$

$$\sigma_{c,fix}(t) = E_c(t)\alpha_c(t)\Delta T(t) \tag{4}$$

where, $E_c(t)$ is the elastic modulus of concrete at time t, $\varepsilon_{total}(t)$ is the total strain of concrete at time t, $\alpha_c(t)$ is the thermal expansion coefficient of concrete at time t, and $\Delta T(t)$ is the temperature change of concrete at time t.

However, as shown in Eq. (3) and Eq. (4), the elastic modulus and thermal expansion coefficient should be accurately estimated because the degree of restraint changes with these properties. Discussion of these properties is expressed in clause 3.4.

2.3 Prediction of thermal stress in concrete structures considering the history of the degree of restraint

Fig. 3 shows the degree of restraint for the thermal stress device and a foundation with dimension of 4×3×1.2 m (length×width×height) by using input data shown in Table 1. Internal restraint was removed by equalizing the temperature of the whole structure to that at the center of the structure, and the bottom of the structure is completely restrained. So effectively, only the external restraint was simulated. On the other hand, internal restraint was simulated by keeping the bottom of the structure move freely to remove external restraint. As shown in Fig. 3, the degree of restraint of the structure with external restraint almost satisfies Eq. (1). Meanwhile, the internal restraint does not satisfy Eq. (1) as the thermal stress device can not simulate internal restraint because the volume change of the concrete in the device is restrained by external constraint bars and there is no temperature difference in the whole section of concrete in the device, of which the thickness is as thin as 80 mm. Therefore, the stress obtained by comparing the degree of restraint and stress is reliable only for structures with externally strong restraint as the history of the degree of restraint of the structures with internally strong restraint is different from that of the device.

This limitation can be overcome by using a step-by-step method. As incremental stress is proportional to the degree of restraint at any given time, incremental stress in a structure can be obtained by comparing the degree of restraint and incremental stress as shown in Fig. 4. In detail, incremental stresses, $\Delta\sigma_{\delta_1}(\bar{t}_i)$, $\Delta\sigma_{\delta_2}(\bar{t}_i)$ and $\Delta\sigma_{\delta_3}(\bar{t}_i)$ can be obtained by the stress measured by the thermal stress device (Fig. 4(a)), and the degree of restraint of the device and the structure, $R_{\delta_1}(\bar{t}_i)$, $R_{\delta_2}(\bar{t}_i)$, $R_{\delta_3}(\bar{t}_i)$ and $R(\bar{t}_i)$ can be calculated by elastic analysis (Fig. 4(b)). When the degree of restraint and elastic modulus of concrete are assumed to be constant between time $\bar{t}_i$ and time $\bar{t}_{i+1}$, the relationship between the degree of restraint at time $\bar{t}_i$ and variation of stress between time $\bar{t}_i$ and time $\bar{t}_{i+1}$ can be deduced. Thus, the incremental stress of the structure, $\Delta\sigma(\bar{t}_i)$ can be calculated by the degree of restraint of the structure $R(\bar{t}_i)$ (Fig. 4(c)). Since stress equals to the sum of incremental stresses, the stress of the structure can be calculated with Eq. (5) (Ghali *et al.* 2002). The whole procedure is shown in Fig. 5.

$$\sigma(\bar{t}_n) = \sum_{i=0}^{n-1} \Delta\sigma(\bar{t}_i) \tag{5}$$

where, $\sigma(\bar{t}_n)$ is the stress of a structure at time $\bar{t}_n$, and $\Delta\sigma(\bar{t}_i)$ is the variation of the stress of the structure between time $\bar{t}_i$ and time $\bar{t}_{i+1}$.

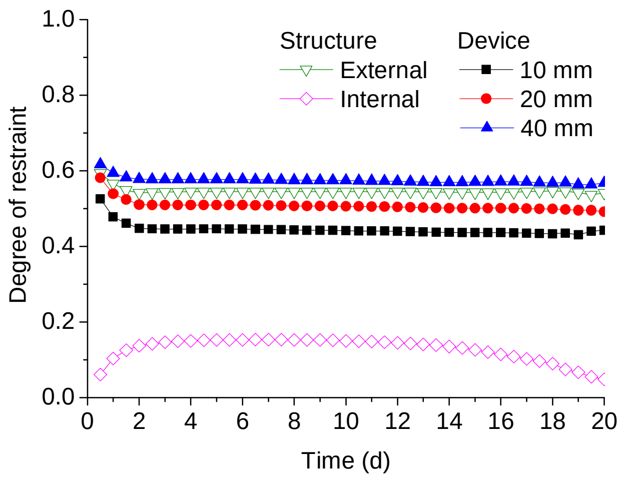
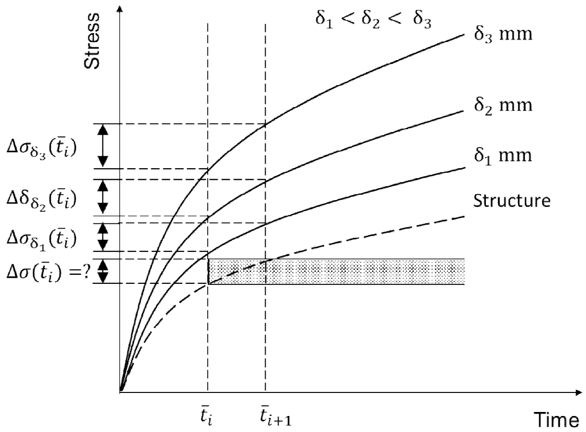
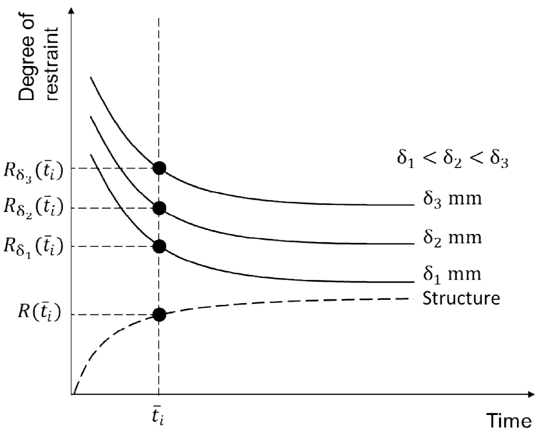


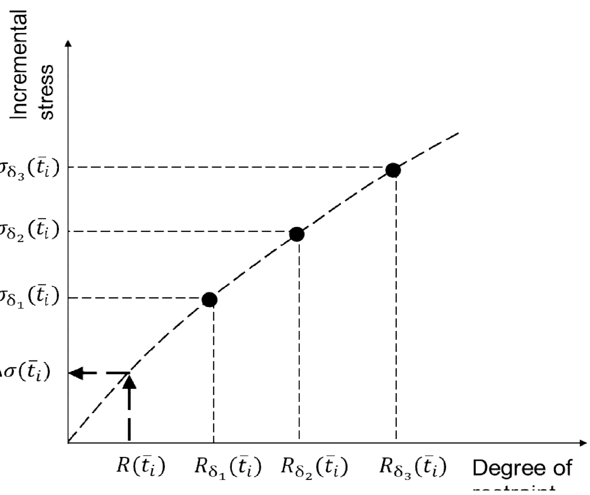
Fig. 3 Comparison of the degrees of restraint between device and structure



(a) Thermal stress



(b) The degree of restraint



(c) Relationship between incremental stress and the degree of restraint

Fig. 4 Prediction method for thermal stress in concrete structure

Table 1 Input data for example of the degree of restraint

Properties of concrete	
Thermal conductivity (W/(m·K))	2.1
Adiabatic temperature rise curve ($T(t) = K(1 - e^{-\alpha t})$)	$K = 70$, $\alpha = 1.0$
Casting temperature (°C)	20
Ambient temperature (°C)	20
Convection heat transfer coefficient (W/(m^2·K))	12
Elastic modulus (MPa)	ACI model (concrete) 1.4×10^5 (invar)
Thermal expansion coefficient (/°C)	1.0×10^{-5} (concrete) 1.3×10^{-6} (invar)

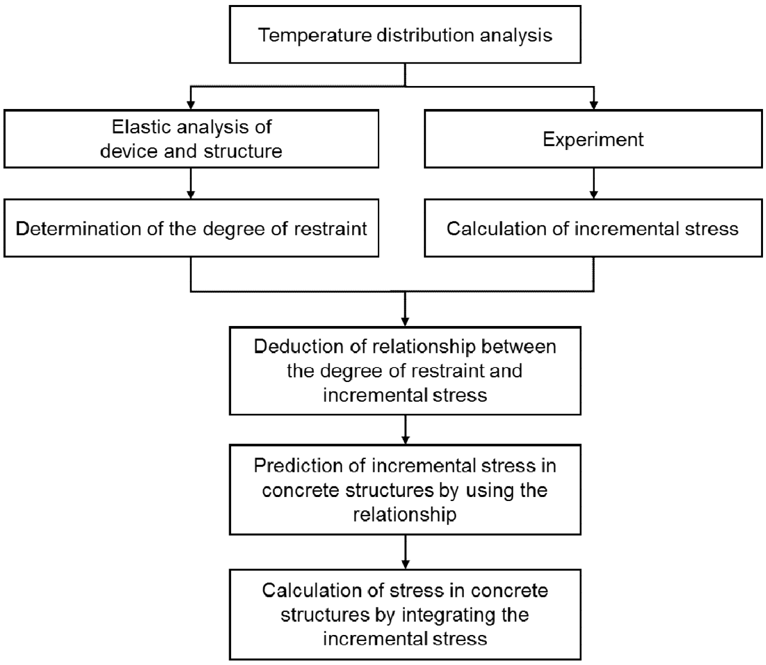


Fig. 5 Procedure of prediction of thermal stress in concrete structure

3. Verification of prediction results

3.1 Procedure of verification

The results of the proposed method can be verified by comparison with the stress measured in the field or obtained by analysis. Despite that comparing the stresses obtained by the proposed method to those measured in the field is deemed the most appropriate, the measurement of stress in mass concrete structures remains difficult. Meanwhile, the accuracy of analysis results is insufficient due to uncertain properties of concrete. To overcome this limitation, in this study, the stress obtained by the device is replaced with analysis results assuming the properties of concrete.

Therefore, stresses in concrete structures obtained by the proposed method and analysis can directly be compared to each other.

The details of the procedure are summarized as follows. First, hydration heat analysis for the thermal stress device was performed using assumed concrete properties, and the stress results from the analysis were used as the measured stress by the device. After that, the degrees of restraint of the device and structure were evaluated by elastic analysis, and the stress in the structure was calculated by the proposed method. Finally, hydration heat analysis of the structure was performed by using the identical properties of concrete for the device, and the stresses obtained by the proposed method and by hydration heat analysis were compared to verify the accuracy of the proposed method.

The stresses of a wall with internally strong restraint and a foundation with externally strong restraint, which is surrounded by rock, were predicted. CONSA/HS (Lee and Kim 2009) developed by the KAIST concrete laboratory was implemented for the hydration heat analysis. The ACI model (ACI 209R 2008) was used for elastic modulus (Eq. (6)) and creep (Eq.(7)), and the B3 model (Bažant *et al.* 1995) was used for autogenous shrinkage (Eq. (8)).

$$E_{ct} = g_{ct}[w^3(f_c')_t]^{1/2} \tag{6}$$

where, E_{ct} is the elastic modulus of concrete at time t, g_{ct} is 0.043, w is the unit weight of concrete, and $(f_c')_t$ is the compressive strength of concrete at time t.

$$\nu_t = \frac{t^{0.6}}{10 + t^{0.6}}\nu_u \tag{7}$$

where, ν_t is the creep coefficient at time t, and ν_u is the final creep coefficient.

$$\varepsilon_a(t) = \varepsilon_{a\infty}(0.99 - h_{a\infty})S_a(t); \qquad S_a(t) = \tanh\sqrt{\frac{t - t_s}{\tau_a}} \tag{8}$$

where, $\varepsilon_a(t)$ is the autogenous shrinkage at time t, $\varepsilon_{a\infty}$ is the final autogenous shrinkage, $h_{a\infty}$ is the final self-desiccation humidity, t_s is the time of final set of cement, and τ_a is the half-time of autogenous shrinkage.

3.2 Stress of structure with externally strong restraint

3.2.1 Stress by proposed method

As previously mentioned, the stress measured by the thermal stress device was replaced with that obtained by analysis. For simplification, only a quarter of the device was modelled as shown in Fig. 6(a) using an eight node isoparametric solid element. The total number of element was 2408 and the element size was 0.01 m. Assumed input data for the analysis is shown in Table 2. The results are shown in Fig. 6(b). The stress increased in compression until the age of approximately 2 days, when the maximum temperature appeared. The stress then decreased as the temperature decreased. Stress with 10 mm constraint bars was the lowest, while that with 40 mm constraint bars was the highest.

Elastic analysis was performed to evaluate the degrees of restraint of the device and the concrete structure. Elastic modulus and thermal expansion coefficient shown in Table 2 were adopted. Modeling and prediction location for the device and the concrete structure are shown in Fig. 6(a) and Fig. 7 respectively. The concrete structure is a foundation (diameter 26 m, thickness

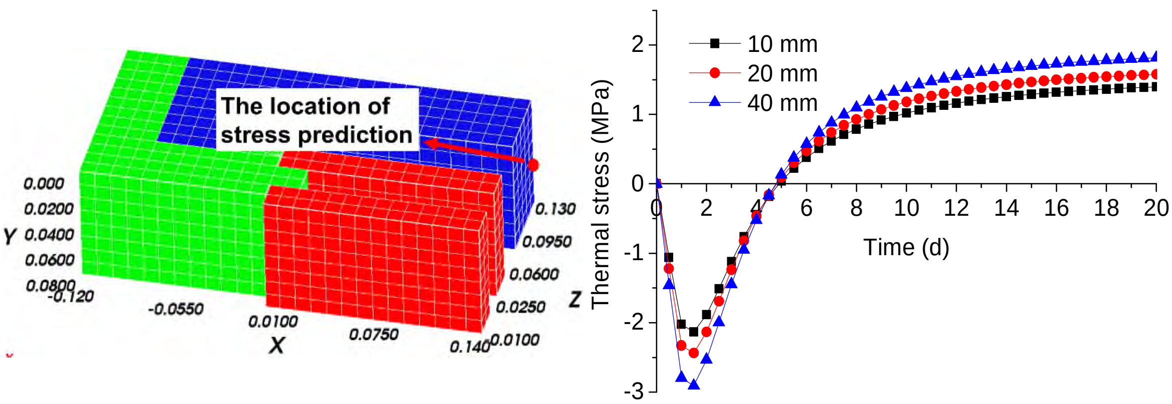
1.2 m) which has externally strong restraint due to the surrounding rocks. In the mesh modeling of the foundation, the total number of element was 3210 and the element size was from 0.15 to 2.0 m. The analysis results are shown in Fig. 8. As shown in Fig. 8, even though the foundation has externally strong restraint, the degree of restraint does not satisfy Eq. (1). This is attributed to the total degree of restraint being affected by internal restraint which decreased over time owing to the temperature change of the rock and concrete. However, as the history of the degree of restraint is similar to that of the device, the effects of internal restraint on the stress prediction can be neglected.

Regression analysis was carried out to deduce the relationship between the degree of restraint and incremental stress. The regression equation of the relationship is 2nd order polynomial, of which the *y* intercept is zero due to that no restraint indicates the stress in concrete would not occur as shown in Fig. 9.

The incremental stress in the foundation was calculated at an interval of 0.5 days by using the relationship. Thermal stress in the foundation was obtained by the integration of the incremental stress. The incremental stress and thermal stress in the foundation are shown in Fig. 10. As the foundation is externally strong restrained by the surrounding rocks and the location of stress prediction is at the center of the foundation, the stress of the foundation increased in compression until the maximum temperature was reached. It then gradually decreased and reached the maximum stress in tension.

3.2.2 Comparison of results

Hydration heat analysis was performed for the structure to verify the accuracy of the stress obtained by the proposed method. The input data was identical to that used for the device. The analysis results were compared to the stresses obtained by the method proposed by Chu and the proposed method based on the proposed degree of restraint. As shown in Fig. 11, the stress obtained by the proposed method was very similar to those obtained by the analysis. On the contrary, the stress obtained by the method proposed by Chu had a little difference from the stress by the analysis. However, the small difference is attributed to the history of the degree of restraint of the structure being similar to that of the device. Therefore, both methods can be applied to structures with externally strong restraint.



(a) Mesh modeling (b) Stress

Fig. 6 Hydration heat analysis for thermal stress device (Foundation)

Table 2 Input data for hydration heat analysis (Foundation)

Properties of concrete	
Thermal conductivity (W/(m·K))	2.1
Adiabatic temperature rise curve ($T(t) = K(1 - e^{-\alpha t})$)	$K = 65.0$, $\alpha = 1.1$
Casting temperature (°C)	20
Ambient temperature (°C)	20
Convection heat transfer coefficient (W/(m^2·K))	12
Elastic modulus (MPa)	ACI model (concrete) 1.4×10^5 (invar)
Thermal expansion coefficient (/°C)	1.0×10^{-5} (concrete) 1.3×10^{-6} (invar)

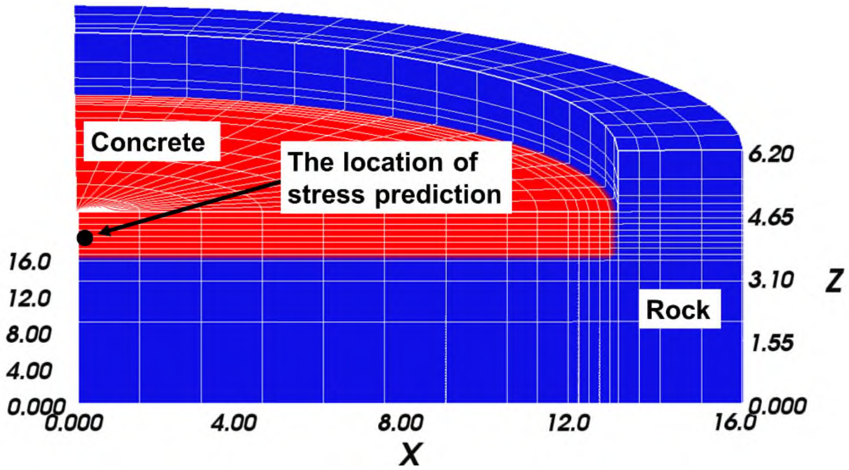


Fig. 7 Mesh modeling of foundation

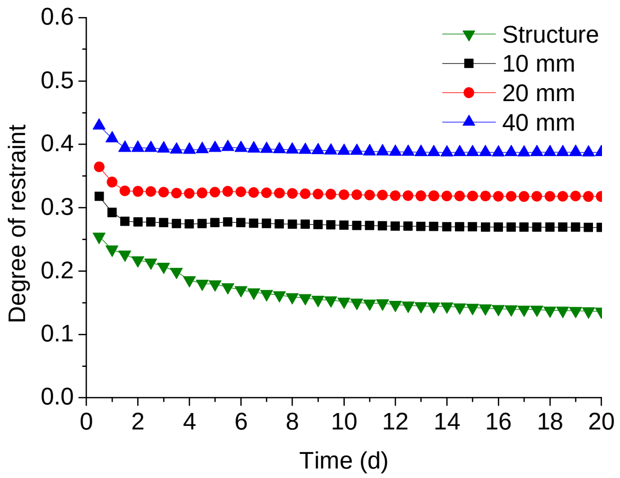


Fig. 8 The degrees of restraint of device and foundation

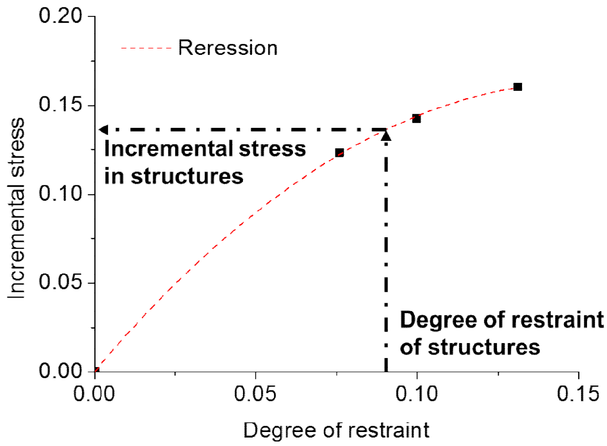
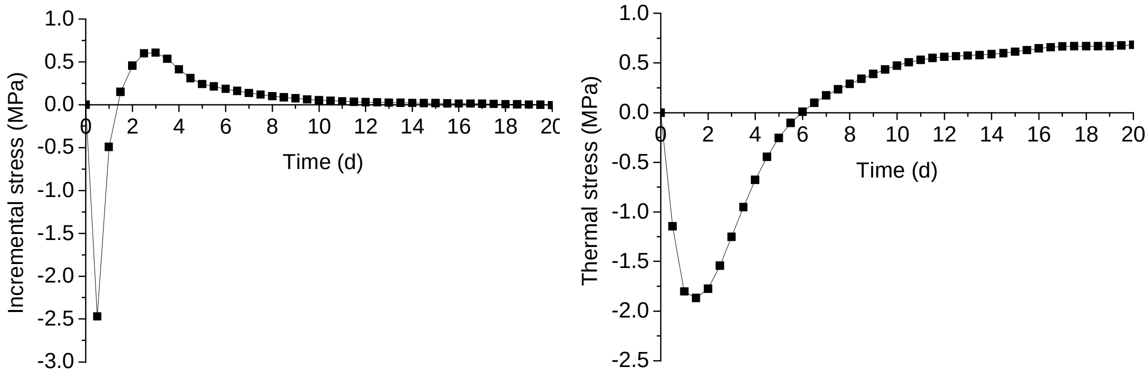


Fig. 9 Relationship between the degree of restraint and incremental stress



(a) Incremental stress (b) Stress

Fig. 10 Prediction results of foundation

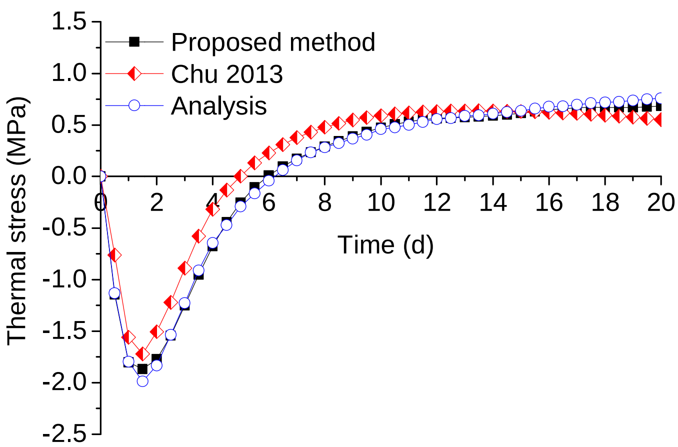


Fig. 11 Comparison of results (Foundation)

3.3 Stress of structure with internally strong restraint

3.3.1 Stress by proposed method

The stress measured by thermal stress device was also replaced with the stress results of the hydration heat analysis assuming uncertain properties of concrete. Input data for the analysis is shown in Table 3. The results are shown in Fig. 12.

Elastic analysis was performed to evaluate the degree of restraint. Modeling and prediction location for the device and structure are shown in Fig. 6(a) and Fig. 13 respectively. The structure is a wall (height 3 m, thickness 1.2 m). In the mesh modeling of the wall, the total number of element was 3540 and the element size was from 0.15 to 1.5 m. Elastic modulus and thermal expansion coefficient shown in Table 3 were used. The results are shown in Fig. 14. In contrast with the structure with externally strong restraint, the variation of the degree of restraint of the structure was significant due to internal restraint, which increased at very early age and decreased later, affecting the total degree of restraint.

Regression analysis was carried out to deduce the relationship between the degree of restraint and incremental stress. The regression equation of the relationship was 2nd order polynomial, of which y intercept is zero.

The incremental stress and thermal stress are shown in Fig. 15. As the location of stress prediction is at the center of the wall, the stress increased in compression until the maximum temperature was reached and then gradually decreased. The variation of the stress in tension is very small after 12 days because the degree of restraint is small.

3.3.2 Comparison of results

Hydration heat analysis was performed for the structure to compare the stress results. Input data was identical to that used for the device. As shown in Fig. 16, thermal stress obtained by the proposed method was similar to that obtained by analysis. However, thermal stress obtained by the method proposed by Chu had a large difference, especially in tension due to the fact that the degree of restraint changed drastically after 9 days. Therefore, the application of the method by Chu to structures with internally strong restraint is limited. Meanwhile, the proposed method can be applied to structures with internally strong restraint as well as externally strong restraint.

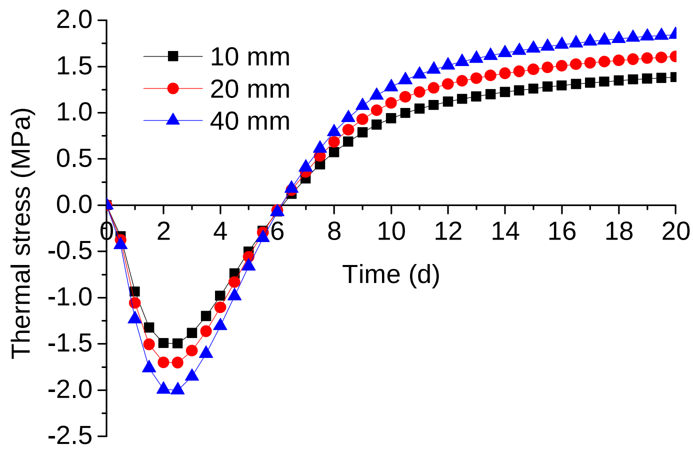


Fig. 12 Stress of thermal stress device by hydration heat analysis (Wall)

Table 3 Input data for hydration heat analysis (Wall)

Properties of concrete	
Thermal conductivity (W/(m·K))	2.1
Adiabatic temperature rise curve ($T(t) = K(1 - e^{-\alpha t})$)	K = 43.3 α = 0.57
Casting temperature (°C)	18.3
Ambient temperature (°C)	20
Convection heat transfer coefficient (W/(m^2·K))	10
Elastic modulus (MPa)	ACI model (concrete) 1.4×10^5 (invar)
Thermal expansion coefficient (/°C)	1.0×10^{-5} (concrete) 1.3×10^{-6} (invar)

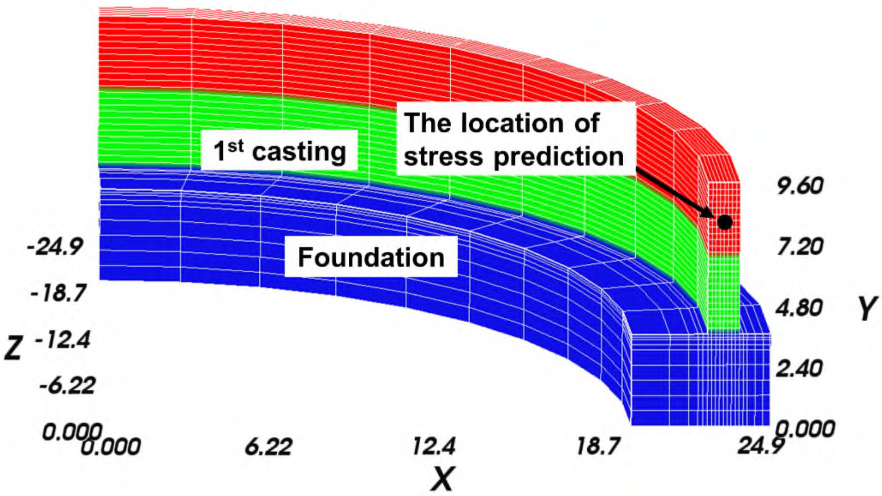


Fig. 13 Mesh modeling of wall

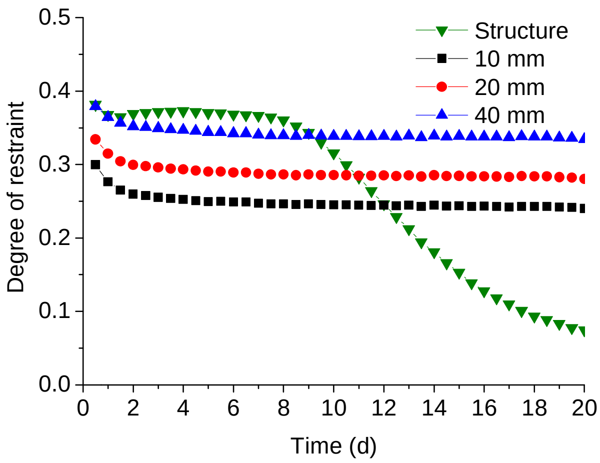
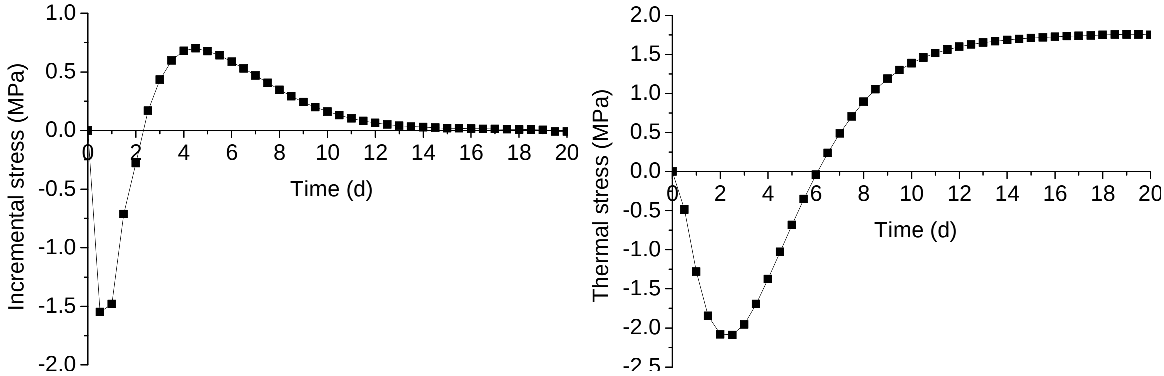


Fig. 14 The degrees of restraint of device and wall



(a) Incremental stress (b) Stress

Fig. 15 Prediction results of wall

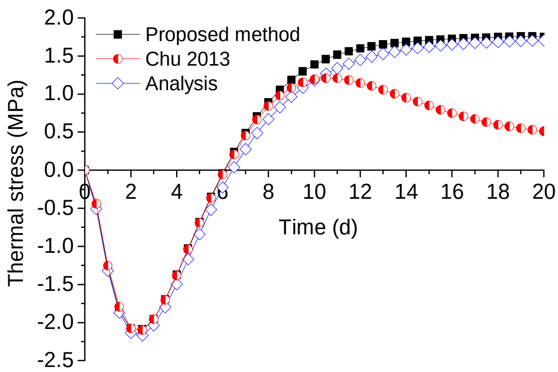
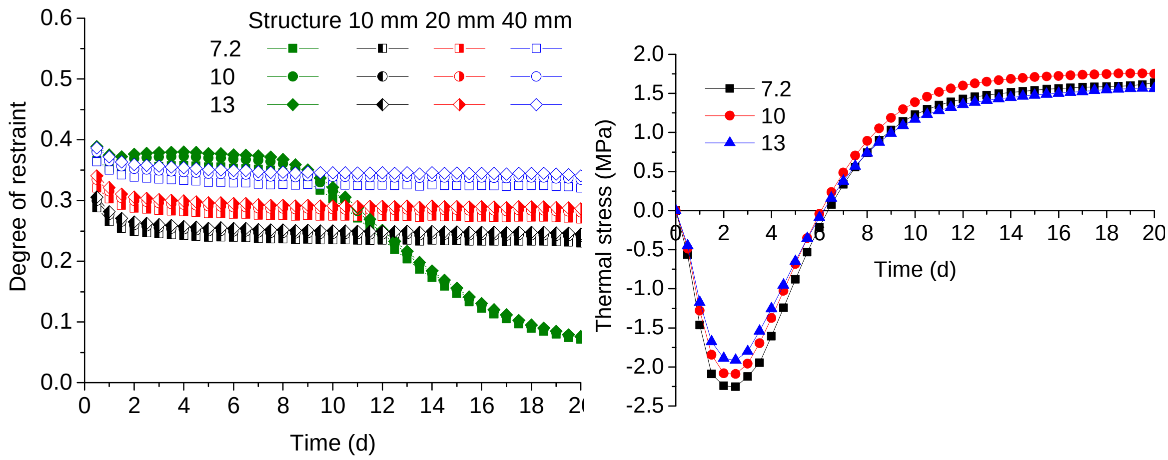


Fig. 16 Comparison of results (Wall)

3.4 Consideration of uncertain properties for elastic analysis

The degree of restraint by elastic analysis varies due to the uncertain concrete properties, which are elastic modulus and thermal expansion coefficient. Elastic modulus can be estimated by an elastic modulus test using specimens, which are made in the course of the experiment with the thermal stress device. On the contrary, it is difficult to estimate the thermal expansion coefficient as another specimen and equipment are required. However, as the range of thermal expansion coefficient of common portland-cement concrete is from 7.2×10^{-6}/°C to 13×10^{-6}/°C (ACI 207.2R 2007) and stresses under partial restraint and complete restraint are proportional to the thermal expansion coefficient, the effects of thermal expansion coefficient on the degree of restraint would be small.

Stresses of the wall in clause 3.3 were predicted with various thermal expansion coefficients including the maximum and minimum values to verify the variations. Fig. 17 shows the degree of restraint and stress results. The variation of the degree of restraint was about ±10 percent and the variation of the stress can be neglected as shown in Fig. 17(b). Therefore, the average thermal expansion coefficient value can be used to estimate the degree of restraint for common Portland-cement concrete.



(a) The degree of restraint (b) Stress

Fig. 17 The degrees of restraint and stress with various thermal expansion coefficients

4. Conclusions

The application method of the thermal stress device has been proposed, and the stress predicted by the proposed method was compared to the stress obtained by numerical analysis for the concrete structure. Based on the study, the following conclusions were reached.

• Stress in concrete structures can be more accurately predicted by adjusting the stress obtained by thermal stress device considering the history of the degree of restraint in concrete structures.

• The degree of restraint of mass concrete structures varies over time due to the effects of internal restraint. On the contrary, the degree of restraint of the thermal stress device is almost constant.

• To consider the history of the degree of restraint, incremental stress should be predicted by using the relationship between the degree of restraint and incremental stress based on the time history of the degree of restraint not the degree of restraint itself at a given time.

• Elastic modulus and thermal expansion coefficient should be accurately estimated as the degree of restraint varies due to the uncertainty of elastic modulus and thermal expansion coefficient of concrete. Elastic modulus can be easily estimated by an elastic modulus test. On the other hand, the average thermal expansion coefficient value can be used for common portland-cement concrete as the variation of the stress obtained by the proposed method is negligible.

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