Reduction of Thermal Cracking due to Heat of Hydration of Cement

1. Introduction

In concrete structures with very large member dimensions, such as concrete dams, etc., there can be problems of thermal cracking caused by the heat of hydration of the cement. On the other hand even in comparatively small structures, there have been cases where harmful cracking has occurred due to member constraint, environmental temperature, materials, mix proportion, and the construction conditions. In the JSCE Standard Specifications for Concrete Structures (hereafter referred to as the "Standard Specification"), concrete structures with thermal cracking due to the heat of hydration of cement are treated as "mass concrete", regardless of the dimensions of the members.

In the Standard Specification there are 2 methods of verification of thermal cracking: verification by thermal stress analysis, and verification by past construction experience. In this newsletter a summary of the control of thermal cracking in the Standard Specification and the method of verification by thermal stress analysis are presented, and in the next newsletter examples of the method of verification using construction experience is presented.

2. Summary of Control of Thermal Cracking in the Design of Mass Concrete

Thermal cracking is sensitive to the effects of construction and the environment, so it is a phenomenon whose occurrence and extent is difficult to predict. Therefore, in many cases evaluation based on experience will be more reliable than evaluation based on advanced analysis. In the Standard Specification verification must be carried out either by evaluation using experience or by evaluation using thermal stress analysis in cases where cracking caused by hydration of cement is a problem, as shown in Fig. 1.

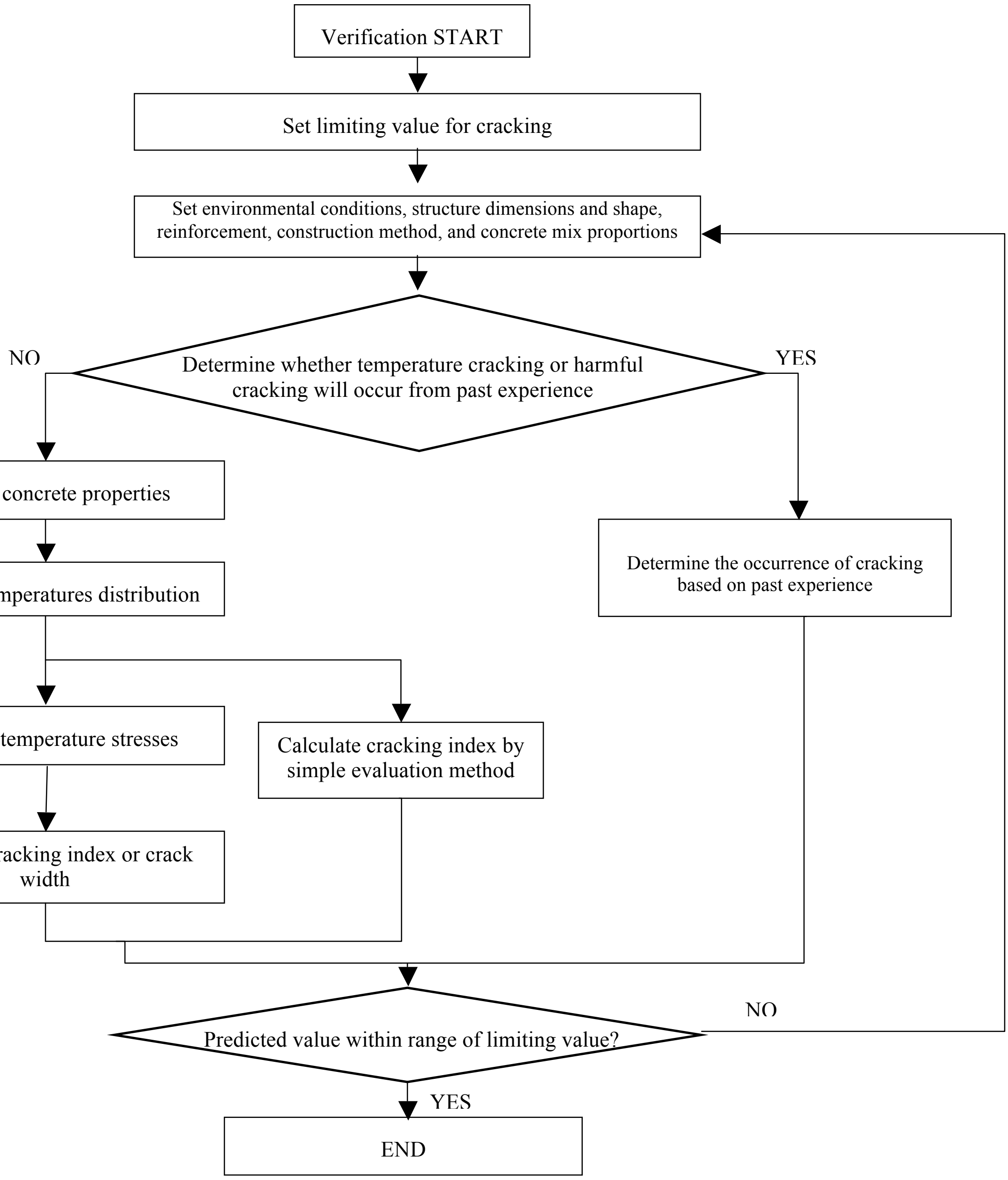

Fig. 1 Flow of temperature cracking verification

3. Verification by Thermal Stress Analysis using the 3-dimensional Finite Element Method

Concrete thermal stress analysis to date has mainly been based on 2-dimensional analysis by the CP method, but for structures with complex cross-sections in some cases the analysis results differ from the actual phenomena. Therefore in the JSCE Standard Specification 3-dimensional FEM is used in order to improve the analysis accuracy. In addition the relationship between the factor of safety and the probability of occurrence of cracking is varied, and the values of properties such as the concrete compressive strength and tensile strength, etc., are varied, as described below. Fig. 2 shows examples of analysis results by 3-dimensional FEM and the 2-dimensional CP method. The procedure for verification of thermal cracking using 3-dimensional FEM is described from Section 3.1 onwards.

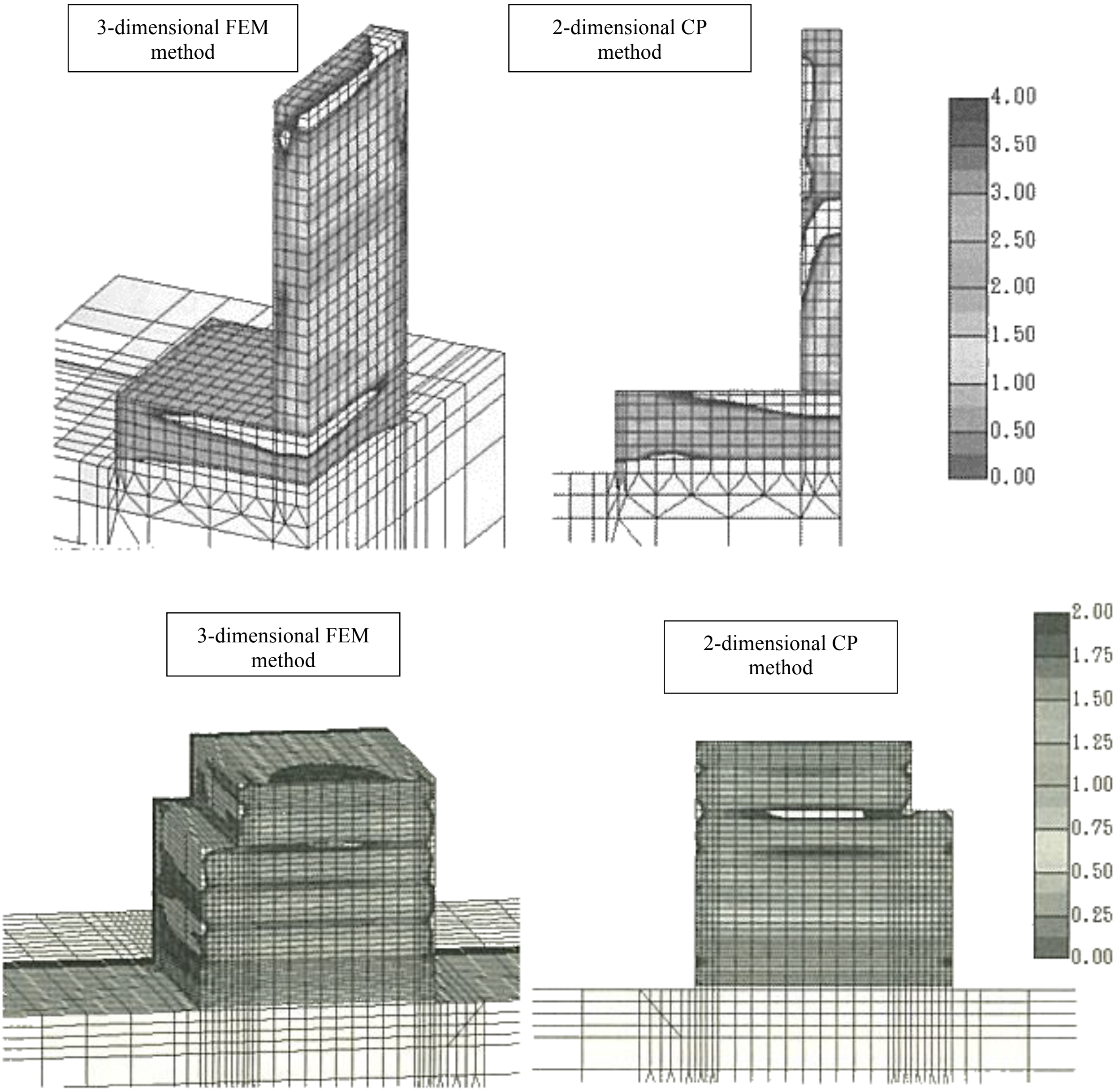

Fig. 2 Contour diagram of minimum crack width

3.1 Verification of the occurrence of cracking

For calculation of the probability of occurrence of cracking in cross-sections where the stresses change gradually, such as wall-like structures and slab-like structures, the following equations may be applied.

$$P(\gamma_{cr}) = \left[1 - exp\left\{-\left(\frac{\gamma_{cr}}{0.92}\right)^{-4.29}\right\}\right] \times 100P(I3_{rc}) = \left[1 - exp\left\{-\left(\frac{I3_{rc}}{0.92}\right)^{-4.29}\right\}\right] A?100$$

where the probability of occurrence of cracking: $P(\gamma_{cr})$, safety factor: γ_{cr}

Table 1 Standard crack occurrence indices and safety factor for normal reinforced structures

Countermeasure level	Probability of cracking	Safety factor γ_{cr}
When preventing occurrence of cracking	5%	1.85 or greater
When cracking is to be limited as much as possible	15%	1.40 or greater
When cracking is allowed, but crack widths are limited so that no problem is caused	50%	1.0 or greater

3.2 Verification of initial cracking

The following equation may be used for the relationship between the cracking index and the maximum crack width when external constraint is dominant.

$$w = \gamma_a \left(\frac{-0.071}{p}\right) \times (I_{cr} - 2.04)$$

where,

w: Maximum crack width (mm)

P: Reinforcement percentage (%), applicable range is 0.25 to 0.9%

γ_a: Safety factor for evaluating thermal crack width (normally 1.0).

3.3 Thermal stress analysis

The thermal conductivity used in concrete thermal analysis must take into consideration the presence or absence of formwork, its type, thickness, stripping time, and the curing time, etc. The following equation is used to define the thermal conductivity taking into consideration the formwork and the curing method, etc.

$$\eta = \frac{1}{\frac{1}{\beta} + \Sigma \frac{d_{Fi}}{\lambda_{Fi}}}$$

where,

η: Modified coefficient of heat transfer (W/m^{2o}C)

β: Coefficient of heat transfer at surface exposed to atmosphere (W/m^{2o}C) (generally taken as 12-14W/m2℃)

d_{Fi}: Thickness of curing material (m)

λ_{Fi}: Thermal conductivity of curing material (W/m^{2o}C)

3.4 Calculation of autogenous shrinkage

The autogenous shrinkage strain is obtained from tests with verified range of application and accuracy, or calculated from the following estimation equation.

$$\varepsilon_{ij,ag} = -\beta \varepsilon'_{as\infty}[1 - exp\{-a(t' - t_s)\}^b]$$

where,

β: Coefficient expressing the effect of the type of cement and admixtures (when ordinary portland cement or blast furnace cement type B only are used, 1.0)

t': Effective age (days)

t_s: Initial setting (days) (when ordinary Portland cement or blast furnace cement type B only are used, an effective age of 0.3 days may be used)

$\varepsilon'_{as\infty}$: Final value of autogenous shrinkage strain ($\times 10^{-6}$)

Ordinary Portland cement:

$$\varepsilon'_{as\infty} = 3070 exp\{-7.2(W/C)\} + \varepsilon'_{asT}$$
$$\varepsilon'_{asT} = 50[1 - exp\{-1.2 \times 10^{-6} \times (T_{max} - 20)^4\}]$$
$$a = 3.7 \times exp\{-6.8 \times (W/C)\}$$
$$b = 0.25 \times exp\{2.5 \times (W/C)\}$$

Blast furnace cement type B:

$$\varepsilon'_{as\infty} = 2350 exp\{-5.8(W/C)\} + \varepsilon'_{asT}$$
$$\varepsilon'_{asT} = 80[1 - exp\{-1.2 \times 10^{-6} \times (T_{max} - 20)^4\}]$$
$$a = 3.7 \times exp\{-6.8 \times (W/C)\} \times g$$
$$b = 0.25 \times exp\{2.5 \times (W/C)\} \times h$$
$$g = 0.060 T_{max} - 0.20$$
$$h = -0.0075 T_{max} + 1.15$$

where,

W/C: Water cement ratio
ε'_{asT}: Amount of increase in autogenous shrinkage due to constant temperature
T_{max}: Maximum temperature of the concrete (^oC)
a, b: Coefficients expressing autogenous shrinkage progression property
g, h: Coefficients expressing the effect of constant temperature

3.5 Concrete property values

Concrete tensile strength

$$f_{tk}(t') = c_1 \cdot f'_c(t')^{c_2}$$

where,

$f_{tk}(t')$: Tensile strength of concrete at an effective age of t' days (N/mm^2)
$f'_c(t')$: Compressive strength of concrete at an effective age of t' days (N/mm^2)
t': Effective age obtained from equation (2.2.7) in the 2012 JSCE specification [Design] (days)
c_1, c_2: Constant defined by the curing method, $c_1 = 0.13$, $c_2 = 0.85$ as standard.

Concrete compressive strength

$$f'_c(t') = \frac{t'}{a + b(t' - S_f)} f'_c(i)$$
$$f'_c(t') = \frac{t' - S_f}{a + b(t' - S_f)} f'_c(i)$$

where,

$f'_c(t')$: Compressive strength of concrete at an effective age of t' days (N/mm^2)

$f'_c(i)$:	Compressive strength of concrete at an effective age of i days (N/mm^2)
i:	Standard age for design standard strength (days)
a, b:	Constants corresponding to cement type and standard material age
S_f:	Effective age at the start of hardening corresponding to the type of cement (days)

3.6 Concrete Young's modulus

The following equation may be used to conveniently obtain an approximate value of the effective Young's modulus.

$$E_e(t') = \phi_e(t') \times 6.3 \times 10^3 f'_c(t')^{0.45}$$

where,

$E_e(t')$:	Effective Young's modulus at an effective age of t' days (N/mm^2)
$f_c'(t')$:	Compressive strength at an effective age of t' days (N/mm^2)
$\Phi_e(t')$:	Young's modulus reduction factor to take into consideration the effect of creep* *Up to the effective age at which the maximum temperature is reached: $\Phi_e(t') = 0.42$ Effective age on or after the effective age at which the maximum temperature is reached + 1 (days): $\Phi_e(t') = 0.65$