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EVALUATION OF METHODS FOR ANALYZING EARLY-AGE CRACKING RISK IN CONCRETE WALLS OF TUNNEL STRUCTURES

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Abstract: This paper is concentrated on investigating the modern methods to evaluate the probability of cracking in urban tunnel structures during construction. The study considers the current standard methods for assessing reinforced concrete walls of an urban tunnel, which experienced early-age cracking. The results obtained using guidelines were compared with actual observations of crack widths in the urban tunnel wall. Examples of using specifications in wall design were also described. The proper method is highlighted with suggestions for a possible path for considering early-age thermal and shrinkage effects in urban reinforced concrete tunnel walls.

Keywords: early-age concrete, early-age cracking, temperature, shrinkage, tunnel walls.

1. INTRODUCTION

Currently, in big cities, urban tunnel structures have been built to meet the increasing traffic demand. However, there are many urban tunnels after construction, especially the structure of the tunnel walls, which have detected many cracks, such as cracks in the open tunnel walls of Thanh Xuan (Hanoi), Trung Hoa closed tunnel (Hanoi), etc. These initial cracks may not directly damage the structure, however if they develop over time, they will lead to detrimental influences on the structure such as decreases in concrete strength and durability.

Some of the predictable objective reasons are those concrete structures that are affected by heat and early-age shrinkage [1]. The early-age thermal-shrinkage effects prompt cracks that can be observed in the first days after casting. This cracking is a big problem when the crack width exceeds the critical value, which reduces the durability and usability of the structure [2-8]. Moreover, after the end of concrete hardening, the cracking caused by volume changes due to changes in temperature and moisture during the hardening process and may also develop as a result of the temperature changes (daytime and seasonally), then concrete continues to shrink and at the same time be subjected to mechanical loads. In addition, cracks – even of insignificant width – may still lead to corrosion of reinforcement in the concrete [1]. These factors particularly affect structures such as bridge abutments' walls and tunnels in urban areas.

In countries around the world (such as the US, Japan, Europe, etc.), there have been studies on cracking in concrete structures at the construction phase, as well as existing and improving standards and regulations to control and ensure anti-cracking for construction works. Currently, there are many standards used to evaluate cracks such as Eurocode 2 [9], CIRIA C660 [10], JCI's Guidelines for control of cracking of mass concrete 2016 [11], the standard of ACI committee 207.2R-07 [12].

In Vietnam, the construction standard TCXDVN 305:2004 [13] has also been applied to the construction and acceptance of concrete structures and mass concrete. This standard only gives two criteria: the temperature difference between the core and the surface of mass concrete must not exceed 20^{o}C and the module of the temperature difference between points in mass concrete exceeds 50^{o}C/m. However, in the hot and moist climate of Vietnam, the effect of the environment on the temperature in early-age mass concrete (even during the construction period) is significant. For example, there are urban tunnel construction projects that must be constructed in the summer to ensure the construction schedule, with an ambient temperature of up to 35-37^{o}C. Besides, many other factors that affect the early-age cracking of these structures that needs to be considered. Vietnamese standards do not specify particular and appropriate methods for cracking identification and calculating crack width and crack spacing.

Therefore, it is necessary to evaluate modern methods for analyzing risk of early-age cracking in tunnel walls during construction phase in order to take measures to control and prevent crack formation in such structures thus improving the durability and sustainability.

2. REVIEW OF METHODS

2.1. Eurocode 2 [9, 14] and CIRIA C660 [10]

The British guidelines were published in 2007 as supplement to Eurocode 2 standards [9, 14], which describe early-age volume changes in the concrete to a limited extent. According to the instructions provided in [10], the risk of cracking is assessed by comparing tensile strains, ε_r, induced in the wall structure after 3 days of concrete hardening with corresponding ultimate strains, ε_{ctu}. Therefore, the risk of cracking occurs when the following condition is fulfilled:

$$\varepsilon_r > \varepsilon_{ctu} \tag{1}$$

The tensile strain, ε_r, in early-age concrete may be calculated from the following formula:

$$\varepsilon_r = K_1 R(\alpha_T \Delta T + \varepsilon_{ca} + \varepsilon_{cd}) \tag{2}$$

where:

ΔT - the temperature difference, which in case of concrete walls with a predominant contribution of restraint stresses [10, 15], is taken as the difference between the maximum self-heating temperature and the ambient temperature after finishing the cooling phase. CIRIA C660 includes diagrams enabling direct determination of the temperature difference, ΔT, for the wall depending on its thickness, the type and quantity of used cement, and the type of formwork;

α_T - the coefficient of thermal expansion for concrete, dependent on the type of aggregate;

ε_{cd} - the strains due to drying shrinkage determined according to [9], the development of drying shrinkage strain with time as follows:

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s).k_h.\varepsilon_{cd,0} \tag{3}$$

where:

$\varepsilon_{cd,0}$ - Nominal unrestrained drying shrinkage (in $^0/_{00}$) [9].

k_h - coefficient depending on the notional size h_0,

$$\beta_{ds}(t, t_s) = \frac{t - t_s}{(t - t_s) + 0.04\sqrt{h_0^{\,3}}} \tag{4}$$

where:

t – the age of concrete at the moment considered, in days

t_s – the age of concrete (days) at the beginning of drying shrinkage (or swelling). Normally this is at the end of curing.

h_0 – the notional size (mm) of the cross-section.

$h_0 = 2A_c/u$. Where:

A_c – the concrete cross-sectional area

u – the perimeter of that part of the cross section which is exposed to drying

ε_{ca} - the strains due to autogenous shrinkage determined according to [9];

$$\varepsilon_{ca}(t) = \beta_{as}(t).\varepsilon_{ca}(\infty) \tag{5}$$

where:

$$\varepsilon_{ca}(\infty) = 2.5(f_{ck} - 10).10^{-6} \tag{6}$$

$$\beta_{as}(t) = 1 - \exp(-0.2t^{0.5}) \tag{7}$$

where t is given in days and f_{ck} is concrete compressive strength at the age of 28 days (MPa).

K_1- the coefficient of stress relaxation due to creep under sustained loading; the recommended value is K_1 = 0.65 or 1.0 when the R factor is taken based on [14].

R- the restraint factor reflecting the degree of limiting deformation freedom. In the case of walls cast on the existing foundation, R may be assumed according to [14] or based on equations enclosed in ACI [12], which is described later. Values of the R factor corresponding to the simplest case of a wall with limited deformation freedom along the lower edge are visible in Figure 1.

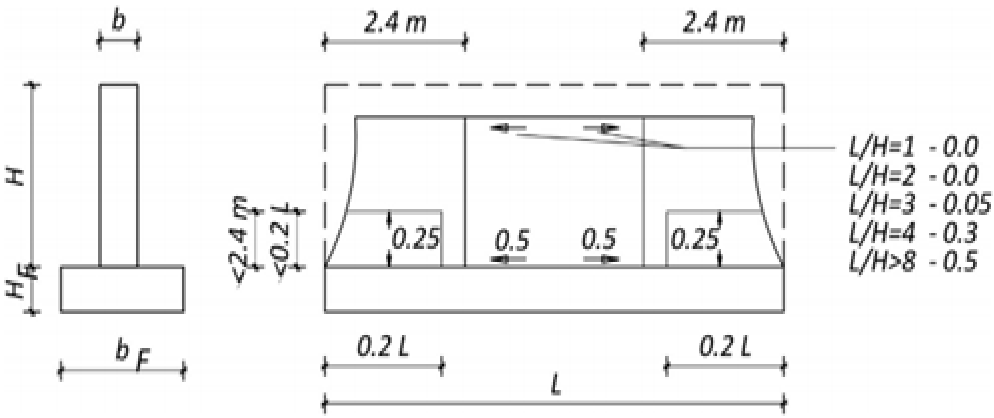

Figure 1. The restrain factor R for a wall with limited deformation freedom along the lower edge [12].

Guidelines provide values of the ultimate strains, ε_{ctu}, for concrete class C30/37 with various types of aggregate (Table 1). When the concrete class differs from class C30/37, the values given in Table 1 should be recalculated according to the formula:

$$\varepsilon_{ctu} = \varepsilon_{ctuC30/37}[0.63 + (f_{ck,cube}/100)] \tag{8}$$

where $f_{ck,cube}$ is concrete compressive strength of cubic samples at the age of 28 days (MPa).

The thermal-shrinkage crack width in an element restrained along one edge may be calculated according to the expression:

$$w = S_{r,\max}\varepsilon_{cr} = [3.4c + 0.425\frac{k_1\phi}{\rho_{p,eff}}]\varepsilon_{cr} \tag{9}$$

where: c – is the cover to reinforcement (m),

ϕ - is the bar diameter (m),

ε_{cr} - is given in Eq. (10),

k_1 - a coefficient which take account of the bond properties of the reinforcement; [9]

recommends 0.8 for high bond bars and 0.7 for standard bars, however [10] suggests the higher value to be used for early-age thermal cracking, k_1=0.8/0.7=1.14, due to the inability to guarantee sufficient anchorage of reinforcing bars in the hardening concrete.

$\rho_{p,eff}$ - is the ratio between the area of reinforcement and the effective area of concrete, calculated as $\rho_{p,eff} = \frac{A_s}{A_{c,eff}}$.

$A_{c,eff}$ - the effective area of concrete in tension around the horizontal reinforcement to a depth of $h_{c,eff}$, calculated from $h_{c,eff} = \min\begin{Bmatrix} B/2 \\ 2.5(c+\phi/2 \end{Bmatrix}$, where B is the thickness of the wall.

A_s - the area of horizontal reinforcement, m^2.

Strain ε_{cr} is lower than strain ε_r due to the decrease in tensile force after cracking in the wall:

$$\varepsilon_{cr} = \varepsilon_r - 0.5\varepsilon_{ctu} \tag{10}$$

Table 1. Ultimate strain, ε_{ctu}, for concrete class C30/37 [10].

Coarse aggregate applied in concrete[1]	ε_{ctu} after 3 days 10^{-6}	ε_{ctu} after 28 days 10^{-6}
Basalt	63	90
Flint gravel	65	93
quartzite	76	109
granite	75	108
Lime stone	85	122
Sandstone	108	155
[1] in case of no information about the applied type of aggregate, the recommended value of ε_{ctu} should be assumed as for quartzite		

2.2. JCI guidelines for control of cracking of mass concrete 2016

The guidelines [11] developed by the Japan Concrete Institute (JCI) are the latest version of Japanese standards concerning the design process and reducing cracking risk in mass concrete structure. According to the current guidelines, numerical methods are recommended for the design process and cracking risk assessment. Nevertheless, the simplified method has also been provided in [11], resulting from comprehensive numerical simulations. In this regard, the guidelines propose the special thermal cracking index for cracking risk assessment, generally defined as a ratio between the tensile strength, $f_t(t_e)$, of concrete and the generated principal tensile stresses, $\sigma_t(t_e)$:

$$I_{cr} = \frac{f_t(t_e)}{\sigma_t(t_e)} \tag{11}$$

where t_e is the equivalent concrete age. If $I_{cr} \geq 1{:}85$, the probability of the cracking is 5%. Otherwise, when $I_{cr} < 1{:}85$, the probability of cracking $P(I_{cr})$ may be estimated from:

$$P(I_{cr}) = \left[\left\{1-\exp\left\{-(\frac{I_{cr}}{0.92})^{-4.29}\right\}\right\}\right].100 \tag{12}$$

In detail, the thermal cracking index is given by:

$$I_{cr} = (\alpha_1^{\eta}.\alpha_2^{\varsigma}\alpha_3^{\xi})^{\beta}.I_{cr0} - I_b \tag{13}$$

with the following coefficients:

α_1 – considers the influence of the shape and stiffness of the structure and is calculated from: $\alpha_1 = a_0 + a_1(\frac{1}{D/D_0}) + a_2(\frac{1}{L/L_0}) + a_3\ln(\frac{H}{H_0}) + a_4(\frac{1}{\frac{E_c/E_r}{E_{c0}/E_{r0}}})$ (14)

α_2 – considers the influence of the material and mix composition and is calculated from a formula depending on the type of cement:

- For high early-age strength Portland cement:

$$\alpha_2 = b_0 + b_1 e^{(\frac{T_a}{T_{a0}})} + b_2 e^{(-\frac{Q_{\infty 0}}{Q_\infty})} + b_3 e^{(-\frac{\gamma_{AT0}}{\gamma_{AT}})} + b_4 e^{(\frac{f'_c}{f'_{c0}})} + b_5(\frac{S_{AT}}{S_{AT0}}) \tag{15}$$

- For other cements:

$$\alpha_2 = b_0 + b_1 e^{(\frac{T_a}{T_{a0}})} + b_2(-\frac{Q_\infty}{Q_{\infty 0}}) + b_3(-\frac{\gamma_{AT0}}{\gamma_{AT}}) + b_4(\frac{f'_c}{f'_{c0}})^{0.45} + b_5(\frac{S_{AT}}{S_{AT0}}) \tag{16}$$

α_3 – considers the influence of the curing method and is calculated from:

$$\alpha_3 = c_0 + c_1\log_e(\frac{T_a}{T_{a0}}) + c_2(\frac{h}{h_0}) + c_3(\frac{t}{t_0}) + c_4 e^{\left(\frac{T_{at}+\Delta T}{T_{at}}\right)} \tag{17}$$

Additionally, the following coefficients are used in Eqs. (12) through (17):

$\eta, \varsigma, \xi, \beta$ – coefficients representing the influence factor of each cement on the thermal cracking index, coefficient values correspond to the type cement are provided in [11],

I_{cr0} – the basic thermal cracking index; the recommended value is I_{cr0} = 1.0, I_b – the safety factor to ensure estimates comply with numerical results; the recommended value for wall structures is I_b = 0.2,

a_0–a_4, b_0–b_5, c_0–c_4 – constants provided in [11], depending on the cement type, D – the wall thickness; D_0 – the reference value,

L – the wall length; L_0 – the reference value, H – the wall height; H_0 – the reference value,

E_c/E_r – the ratio of the modulus of elasticity for the wall and the foundation; E_{c0}/E_{r0} – the reference value,

T_a – the placing temperature, T_{a0} – the reference value,

T_{at} – the ambient temperature, Tat – the reference value,

Q_∞ – the ultimate adiabatic temperature rise, $Q_{\infty 0}$ – the reference value,

γ_{AT}, S_{AT} – constants related to the temperature rise, γ_{AT0}, S_{AT0} – the reference values,

f'_c – the concrete compressive strength, f'_{c0} – the reference value,

h – the heat transfer coefficient, h0 – the reference value,

t – the time until formwork removal, t_0 – the reference value.

The applicable ranges of parameters listed above, as well as their reference values, are generally determined by the type of cement and are given in corresponding tables or detailed formulas found in [11]. The maximum thermal crack width is calculated based on the thermal cracking index as follows:

$$w = \gamma\left(\frac{-0.141}{\rho_{eff}} + 0.0938\right)(I_{cr} - 1.965) \tag{18}$$

Where:

γ - a safety factor depending on the performance requirements and assumed from the range 1–1.7;

ρ_{eff} - the degree of reinforcement in the horizontal direction; %

2.3. ACI Committee 207.2R-07 [12]

According to American guidelines ACI 231.R-10 [16], numerical methods are recommended for the cracking risk assessment of early-age concrete. Nevertheless, former guidelines ACI 207.2R- 07 [12] present an analytical method based on the comparison of the tensile stresses, $\sigma(t)$, with the actual value of the tensile strength of concrete, $f_t(t)$. Thus, cracking occurs if the following condition is fulfilled:

$$\sigma(t) > f_t(t) \tag{19}$$

The guidelines recommend controlling the above condition after 7 days of concrete curing (t = 7 days). The tensile stress, σ(t), can be calculated from the following expression:

$$\sigma(t) = K_R K_F (\alpha_T \Delta T + \varepsilon_{cd}) E_{cm,eff}(t) \tag{20}$$

Generally, coefficients K_R and K_F reflect the degree of structure restraint. A change of restraint at the height, H, of the wall with the limited deformation freedom along the bottom edge is considered by coefficient K_R, which can be calculated based on the following formulas:

- For L/H≥2.5

$$K_R = \left(\frac{L/H - 2}{L/H + 1} \right)^{y/H} \tag{21}$$

- For L/H<2.5

$$K_R = \left(\frac{L/H - 1}{L/H + 10} \right)^{y/H} \tag{22}$$

where y is the distance from the joint. For y=0, coefficient K_R takes a maximum value of 1.0.

Coefficient K_F refers to the degree of restraint in the contact layer between the restrained and restraining members. Its value is dependent on the ratio between the corresponding values of stiffness for these members:

$$K_F = \frac{1}{1 + n\frac{A_C}{A_F}} \tag{23}$$

where:

A_C - the cross-sectional area of the restrained member (wall), influenced by thermal-shrinkage effects,

A_F - the cross-sectional area of the member restraining the member influenced by thermal-shrinkage effects (foundation),

N - the ratio between the modulus of elasticity for the concrete in the restrained element (wall) and the modulus of elasticity for the concrete in the restraining element (foundation); the recommended value is taken from the interval 0.6–0.8. Lower values correspond to longer gaps between the casting of the restraining element (foundation) and the casting of the restrained element (the wall).

The difference between the self-heating temperature and the external temperature is calculated from the expression:

$$\Delta T = (T_{pl} + T_{adiab}) - T_z \tag{24}$$

where:

T_{pl} - the initial temperature of the concrete,

T_{adiab}- the adiabatic temperature rise of the concrete,

T_z - the external temperature after 7 days from casting.

The adiabatic temperature rise, T_{adiab}, is estimated based on diagrams provided in [12].

Reference [12] presents a simplified method for determining the drying shrinkage, expressed by the equivalent temperature change:

$$\Delta T_{DS} = (30 - \frac{12V}{S})(\frac{W_u - 125}{100}) \tag{25}$$

and the shrinkage strains:

$$\varepsilon_{cd} = \alpha_T \Delta T_{DS} \tag{26}$$

Similar to the temperature determination, the units implemented in the formula (25) hinder its application, i.e. Wu – the water content in the concrete mix, expressed in lb/yd^3, V - the volume of the member, in yd^3, S - the area of the surface exposed to drying, in yd^2.

Generally, the guidelines recommend experimentally determining the modulus of elasticity, E_{cm} (t); nevertheless, two formulas enabling analytical calculation of its value are provided:

$$E_{cm}(t) = \sqrt{\frac{t}{a+bt}} E_{cm} \tag{27}$$

Where E_{cm} is the modulus of elasticity of concrete after 28 days, a=0.4, b=0.85, or:

$$E_{cm}(t) = 0.043\rho^{1.5}\sqrt{f_c(t)} \tag{28}$$

where:

ρ , the volume density of the concrete, kg/m3,

f_c(t), the compressive strength of the concrete at age t

The compressive strength, f_c(t), may be determined from the formula:

$$f_c(t) = \frac{t}{a+bt} f_c \tag{29}$$

where f_c is the compressive strength of concrete after 28 days, a=0.4, b=0.85.

Creep effects can be considered by using the effective modulus of elasticity, E_{cmeff}(t), instead of the modulus of elasticity, E_{cm} (t) [17]:

$$E_{cm,eff}(t) = \frac{E_{cm}(t)}{1+\phi(t,t')} \tag{30}$$

The creep coefficient $\phi(t,t')$ for typical curing conditions is calculated according to:

$$\phi(t,t') = 2.35\frac{(t-t')^{0.6}}{10+(t-t')^{0.6}} \tag{31}$$

where t’ is the loading time

The tensile strength of concrete f_t (t) may be determined from the following formulas:

$$f_t(t) = 0.0069\left[\rho f_c(t)\right]^{0.5} \; f_t(t) = \frac{t}{a+bt} f_t \quad (32)$$

where f_t is the tensile strength of the concrete after 28 days, a=0.4, b=0.85.

Furthermore, the following formula is provided for determining the width of a thermal-shrinkage crack, expressed in mm:

$$w = 0.00145\sigma_s \sqrt[3]{a_1 A_{c,eff}} \quad (33)$$

where:

σ_s - the stress in the reinforcement, MPa;

a_1 - the distance from the surface to the center of gravity of the reinforcing bars, m;

$A_{c,eff}$ - the effective cross-sectional area of the member in tension, m^2.

The average spacing between cracks is calculated from the expression:

$$s_r = \frac{w}{K_F \alpha_T \Delta T - F_t(t)/E_{cm,eff}} \quad (34)$$

3. REAL WALL DATA AND COMPARISION BETWEEN METHODS

3.1. Examples of real wall

A real wall sample is taken from actual cracking survey data for the U6B segment of open tunnel walls of Thanh Xuan (Hanoi) project. The plan view and the typical cracking types are shown in Figures 2 and 3, respectively.

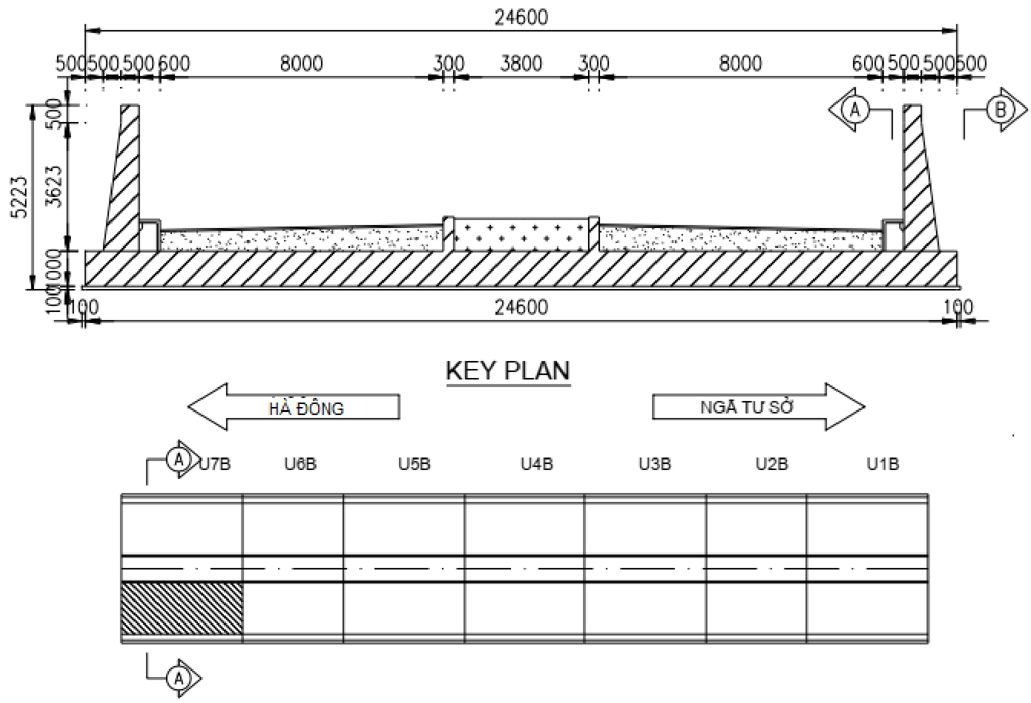

Figure 2. Cross- section and plan view of tunnel segment U6B.

The properties of materials used for segment U6B are shown in Table 2.

Table 2. Material properties of real urban tunnel wall.

Material data	
Concrete class	C25/30
Cement type	CEM I 42.5 R
Cement content	380 kg/m^3
Water content	180 kg/m^3
Aggregate type	gravel
Concrete density	2400 kg/m^3
28-day compressive strength f_{cm}	33 MPa
28-day tensile strength f_{ctm}	2.6 MPa
Module of elastic E_{cm}	31 GPa
Horizontal reinforcement	6 ϕ 14 / 0.9m at each surface
Technological data	
Ambient temperature	22.5^{o}C
Initial concrete temperature	30.9^{o}C
Dimensions	
Basic dimensions	Fig. 3
L/H	4

The actual cracking survey data is shown in Table 3 and Figure 3.

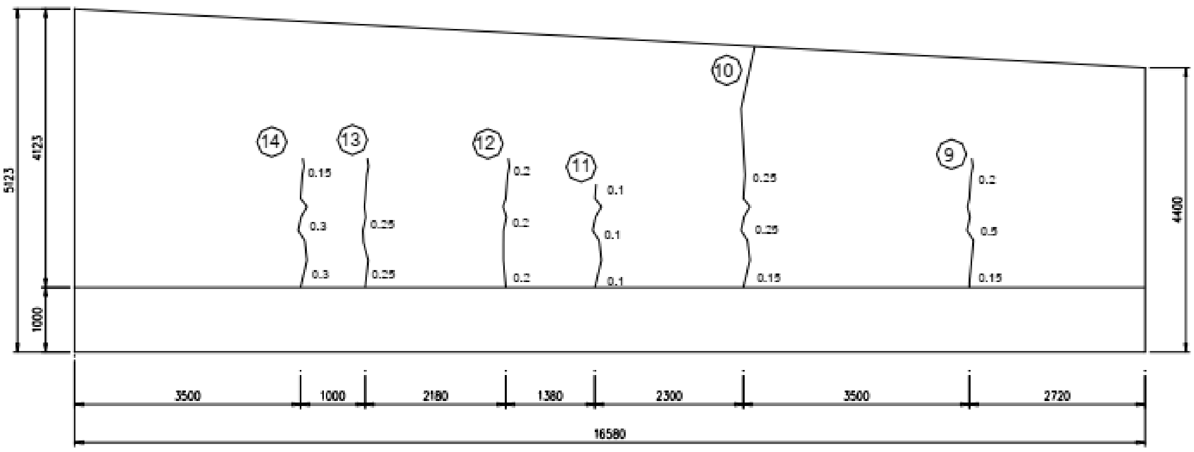

Figure 3. Side view - typical cracking types (units: mm).

Table 3. Actual cracking survey data for Segment U6B.

Segment	Name of crack	Length (m)	Crack width (mm)		
U6B	9	2.00	0.15	0.5	0.2
	10	4.00	0.15	0.25	0.25
	11	1.60	0.10	0.10	0.1
	12	2.00	0.20	0.20	0.2
	13	2.00	0.15	0.25	-
	14	2.00	0.30	0.30	0.15

3.2. The results of calculation

The results obtained from the three procedures are presented in Tables 4 – 6, while Table 7 summarizes the results for comparison purposes.

Table 4. Evaluation of cracking risk based on CIRIA C660.

Calculated value	For example of wall
ΔT	39.8^0C
α_T	12×10^{-6}
R	0.3
K_1	1
ε_{ca}	44×10^{-6}
ε_{cd}	523.575×10^{-6}
ε_r (h=0)	1727.2×10^{-6}
ε_{ctu}	65×10^{-6}
Cracking risk	Yes
ε_{cr} (h=0)	1694.73×10^{-6}
k_1	1.14
ϕ	14 mm
Concrete cover c	60 mm
A_s	83×10^{-4} m^2
$A_{c,eff}$	0.1675 m^2
$\rho_{p,eff} = \frac{A_s}{A_{c,eff}}$	4.96 %
$S_{r,\max}$	0.205 m
w	0.35 mm

Table 5. Evaluation of cracking risk based on JCI.

Calculated value	For example of wall
I_{cr0}	1.0
I_b	0.2
$T_{adiab}(\Delta T)$	41.9^0C
α_1	1.193
α_2	0.755
α_3	1.120
β	0.8
η	1.4
ς	0.5
ξ	0.3
I_{cr}	0.99
Cracking risk	yes
P	51.5%
ρ_{eff}	0.63%
γ	1-1.7
w	0.13-0.22 mm

Table 6. Evaluation of cracking risk based on ACI.

Calculated value	For example of wall
T_{adiab}	33
ΔT	38
A_T	12×10^{-6}
K_F	0.91
$E_{cm}(t)$	26471MPa
$E_{cm,eff}(t)$	16844 MPa
σ_t	7 MPa
$f_t(t)$	3 MPa
Cracking risk	Yes
w	0.32 mm
$S_{r,\max}$	0.85 m

Table 7. Final comparison between CIRIA C660, JCI, and ACI methods.

Value	CIRIA C660	JCI	ACI	Real value
ΔT °C	39.8	41.9	38	No data
Cracking	Yes	Yes	Yes	Yes
Cracking spacing, m	0.2	-	0.85	2.07
Crack width, mm	0.35	0.13-0.22	0.32	0.1-0.5

From the analysis results and the comparison (Table 7), it can be seen that the crack widths calculated by CIRIA C660 and ACI are close. In addition, these two methods propose calculation of cracking spacing while the JCI standard does not.

4. CONCLUSIONS

The clearest description of the early-age cracking assessment procedure for reinforced concrete walls is CIRIA C660 among the 3 methods outlined in this paper. The procedure is described thoroughly in the JCI guidelines but uses a number of coefficients making it difficult to calculate. Additionally, the JCI procedure does not provide the computation of spacing of potential cracks. The ACI method is difficult to use because of the imperial units although it yields similar crack width compared with that using CIRIA C660.

The preliminary investigation in this paper shows that the calculation procedure proposed by CIRIA C660 is the method that gives results close to the real wall cracking survey data and is a very practical method for the design stage, which can reduce the workload and time. The CIRIA C660 method needs further verifications on other tunnel walls' cracking data before final implementation can be included in the design process.

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