

Drying Shrinkage Cracking in RC Wall (Estimation by Bond Analysis)

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ABSTRACT: In this paper, to estimate drying shrinkage cracking behavior in RC wall of the concrete buildings, an improved analytical method on the basis of the bond analysis was proposed. And to verify the validity of the analytical method of crack width and number of cracks, the small-scale RC wall model were made, and the strains of reinforcing steel and concrete, the crack width, and the number of cracks were measured. In result, on the whole, good agreements were shown between the analytical values and the experimental values.

Keywords: drying shrinkage cracking, bond analysis, small-scale RC wall

1. INTRODUCTION

In South Korea and Japan, the concrete is poured into the wall, beams, and columns at the same time to resist the lateral force due to the earthquake. As a result, RC wall in the concrete building is restrained by the foundations, beams, columns, and RC wall is subjected to a direct tensile stress due to the restraint of volume change by drying shrinkage, and when the tensile stress is greater than the tensile strength of concrete, cracks occur. Then the tensile force transferred from the reinforcing steel to the concrete by bond stress, and the next crack occurs as well.

These cracks due to drying shrinkage are affected by the reinforcement ratio, the diameter of reinforcing steel, the concrete strength, the shrinkage of concrete, the creep of concrete, the restraint ratio, and the

length of member. However, because there is no established estimation method which can consider all these parameters, a quantitative crack control design of RC wall is impossible. Accordingly, to estimate shrinkage cracking behaviour (crack width, number of cracks) in RC wall, an improved analytical method on the basis of the bond analysis was proposed in this paper.

In order to confirm the validity of the analytical method, experimental study was carried out.

2. ANALYSIS METHOD OF DRYING SHRINKAGE CRACKING IN RC WALL

2.1 Assumption condition

Fig.1 shows the flow chart of program. The drying shrinkage cracking analysis is

carried out in the middle section of RC wall, and RC wall is considered as the uniaxial restraint condition. In this analysis, bi-linear bond-slip model under the long term age(see Fig.2) is used. Eq.(1) and Eq.(2) with two unknown quantities of the concrete strength and the diameter of reinforcing steel are used as the bond stiffness(K_0) and the bond strength(τ_{y0})[1][2]. To consider the bond-slip relationship under the long term aging, the reduction factors of bond stiffness and bond strength are used. Where reduction factor of the bond stiffness(K_1) is 0.6, and that of the bond strength(K_2) is 0.8. These factors were obtained from the experimental study [3].

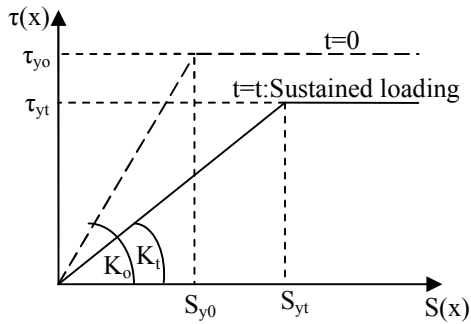


Figure 1: Bi-linear bond-slip model

$$K_0 = 116 \left(\frac{f_c}{24} \right)^{2/3} \left(\frac{13}{D} \right) \quad (1)$$

$$\tau_0 = 3.43 \left(\frac{f_c}{24} \right)^{2/3} \quad (2)$$

$$K_t = K_1 K_0 \quad (K_1 = 0.6) \quad (3)$$

$$\tau_{yt} = K_2 \tau_{y0} \quad (K_2 = 0.8) \quad (4)$$

where D is the diameter of reinforcing steel(mm), and f_c is concrete compressive strength(MPa)

2.2 Occurrence of first cracking

The shrinkage deformation of RC wall is restrained by the beams, and the index to reflect the restraint degree(restraint ratio(R)) is expressed as Eq.(5). Accordingly, tensile strain of concrete occurring in RC wall is

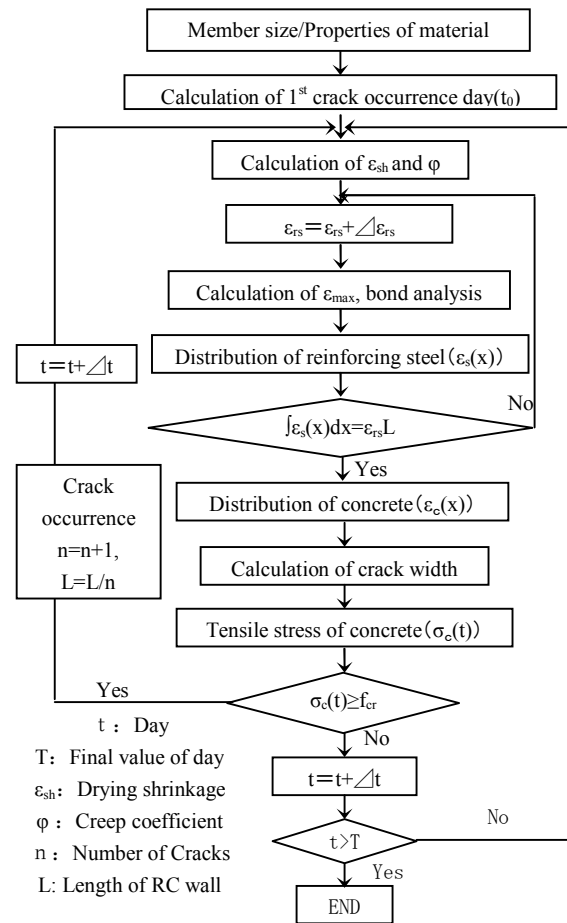


Figure 2: Flowchart of program

expressed as $R\epsilon_{sh}$, the tensile stress of the concrete in RC wall is calculated simply from Eq.(6), and the value of drying shrinkage when the crack occurs is obtained by Eq.(7). To consider the standard of the crack occurrence, the following Eq(8) is used, and this equation was proposed from the cracking behavior test of restrained RC axial members[4]. Where the reduction factor(k) is the value obtained from the experimental study that the tensile stress of the concrete, when the crack occurs, is about 60% of the split strength of concrete [4][5][6].

Eq. (9) means the restraint ratio of RC wall before the first crack occurs. Eq. (9) is obtained by applying the condition of force equilibrium (the compressive stress occurring in RC beam and the tensile stress occurring in RC wall) and Eq. (5).

$$R = (\varepsilon_{sh} - \varepsilon_R) / \varepsilon_{sh} \quad (5)$$

$$\sigma_t = R \varepsilon_{sh} E'_c \quad (6)$$

$$\varepsilon_{sh} = f_t / E'_c / RR \quad (7)$$

$$f_t = 0.291 f_c^{0.637} k \quad (8)$$

$$RR = \frac{A_{cb} \cdot E'_c + A_{sb} \cdot E_s}{A_{sb} \cdot E_s + (A_{cw} + A_{cb}) \cdot E'_c} \quad (9)$$

where f_t is the standard strength of the crack occurrence, $E'_c(E_c/(1 + \phi))$ is the effective Young's modulus, ϕ is the creep coefficient, A_{cb} is the sectional area of the concrete in the RC beam, A_{sb} is the sectional area of the reinforcing steel in the RC beam, A_{cw} is the sectional area of the RC wall, ε_{sh} is the free shrinkage, ε_R is the restrained shrinkage, and k is 0.6

2.3 After crack occurrence

After the first crack occurs, from the condition of force equilibrium of compressive stress occurring in the restraint member(RC beam) and tensile stress occurring in the reinforcing steel at the crack face of RC wall, following Eq.(10) can be obtained. And the deformation of reinforcing steel embedded in RC wall can be defined as the integral of the strain distribution of reinforcing steel, and because the shrinkage deformation of RC beam and reinforcing steel in RC wall are the same, following Eq.(11) can be obtained.

$$\varepsilon_{s \max} A_{st} E_s + \varepsilon_{rs} (A_{sb} E_s + A_{cb} E'_c) = 0 \quad (10)$$

$$\varepsilon_{rs} \cdot L = \int_0^L \varepsilon_s(x) \cdot dx \quad (11)$$

where ε_{rs} is the strain of RC beam, $\varepsilon_s(x)$ is the distribution of the reinforcing steel, $\varepsilon_{\max}$ is the strain of reinforcing steel at the crack, and L is the length of RC wall, A_{st} is the sectional area of reinforcing steel in RC wall

From Eq.(10), increasing the strain of RC beam(ε_{rs}), the tensile stress of reinforcing steel($\sigma_s = \varepsilon_{rs}(A_{sb} + A_{cb} E'_c) / A_{st}$) at the crack is obtained, and then the strain distribution of

reinforcing steel is obtained by the bond analysis. Next, until the condition of Eq.(11) is satisfied, this procedure is repeated. If this condition is satisfied, then the strain distribution of the concrete is obtained, and the crack width is calculated by Eq.(12). When the tensile stress is greater than the tensile strength of concrete, a new crack occurs.

$$w = \int_0^{L_{cr}} (\varepsilon_s(x) - \varepsilon_c(x)) dx \quad (12)$$

where, L_{cr} is the crack space

3. EXPERIMENTAL STUDY FOR SMALL-SCALE RC WALL TEST

In order to verify the validity of the cracking analysis method proposed, the small-scale RC wall specimens were made, and details are as follows.

3.1 Test outline

The mix proportion of the concrete is shown in Table I. The size of specimen is 2500mm in the length, 100mm in the thickness, and 990mm in the height, and these specimens were reinforced with two ($p_t=0.4\%$), three ($p_t=0.6\%$) reinforcing deformed bars(D10, yield stress:380MPa) as shown in Fig.3, and Table II. The sectional area of the restraint member(RC beam) is 250×250mm. In order to consider the uniaxial restrained condition, 70mm gaps were installed between the wall and beams. Restraint members were sealed with the aluminium waterproofing tape to prevent that the cracks occur in the restraint members due to the restraint of reinforcing steels embedded in restraint members, and the top and bottom of RC wall part were sealed as well. The unreinforced and reinforced dummy specimens of the wall were made to measure the drying shrinkage. Four faces of RC wall dummy specimen were sealed with the aluminium waterproofing tape. The creep specimen

(100×100×500) were made too. All specimens were stored in a controlled environment of 20±2°C and 60±5% relative humidity throughout the duration of the test.

In order to measure the strain distribution of reinforcing steel, strain gauges with a length of 1mm were installed on the reinforcing steel at intervals of 100mm, and strains were measured automatically at four-hour intervals. The contacting strain gauge (C.S.G) was used to measure the strain of concrete, and crack width. Fig.3 shows the gauge installed on the specimen. The creep specimen was subjected to a compressive stress of 6MPa at the age of 14days. The measurement of drying shrinkage was carried out at the age of 7 days. C.S.G with the gauge length of 300mm was used to measure the strain of drying shrinkage and creep.

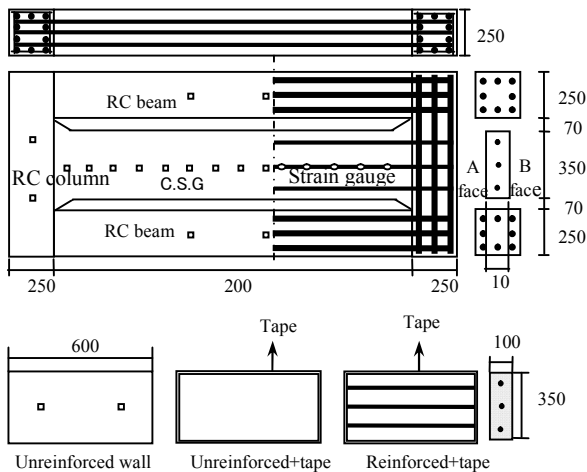


Figure 3: Details of specimen

Table I : Mix proportion of concrete

W/C (%)	s/a (%)	Proportion by unit weight(kg/m ³)				Slump (cm)	Air (%)
		Water	Cement	Sand	Gravel		
53	46	194	366	775	933	18	4.5

Table II : Details of specimen

Specimen	Reinforcing steel		
	Wall	Beam	Column
W1	2-D10(0.4%)	8-D22(5%)	10-D22(6%)
W2	3-D10(0.6%)	8-D22(5%)	10-D22(6%)

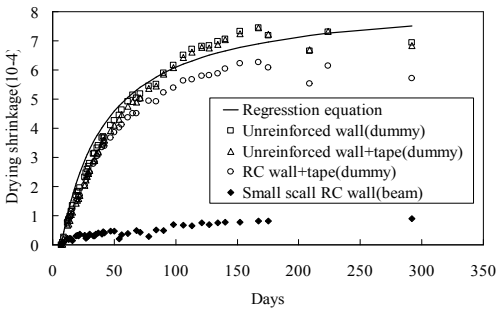
3.2 Test results

3.2.1 Properties of time dependent of concrete

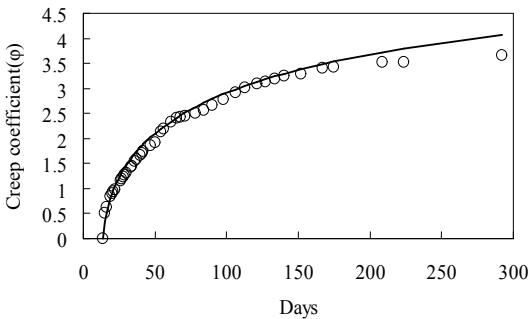
Table III shows properties of concrete, and Fig.4 shows drying shrinkage of dummy specimens and creep coefficient. The regression equation(Eq.(13)) of drying shrinkage of unreinforced wall dummy specimen with aluminium waterproofing tape was used for the analysis. In creep coefficient, $k(\tau)$ ($k(\tau) = 8.74/(5+\sqrt{\tau})$, τ : loading time, $k(14)=1$) was used to consider the effect of a loading time[7]. Eq.(15) [8] and Eq.(16) [4] was used to consider the properties of concrete compressive strength and Young's modulus in the analysis.

Table III: Properties of concrete

Days	Compressive strength (MPa)	Split strength (MPa)	Young's modulus (GPa)
7	18	1.43	20.4
14	22	1.70	20.5
28	26	1.95	21.0



(a) Drying shrinkage



(b) Creep coefficient

Figure 4: Drying shrinkage and creep coefficient

$$\varepsilon_{sh} = \frac{t-7}{7.5+0.11(t-7)} \quad (13)$$

$$\varphi = \frac{(t-14)^{0.6}}{3.26+0.12(t-14)^{0.6}} k(\tau) \quad (14)$$

$$f_c = \exp \left\{ s \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\} f_{c28} \quad (15)$$

$$E_c = 21000 \left(\frac{f_c}{20} \right)^{0.5} \quad (16)$$

3.2.2 Restraint ratio of specimen

Fig.5 shows the behavior of restraint ratio of small-scale RC wall specimens. The experimental value was predicted by Eq.(5). Where the drying shrinkage strain of the unreinforced wall dummy specimen was used as the free drying shrinkage strain(ε_{sh}), and the drying shrinkage strain of the restraint member(RC beam) of small scale RC wall specimen was used as the restraint shrinkage strain(ε_R). A good agreement is shown between the analytical value and the experimental value, and the restraint ratio is almost constant value.

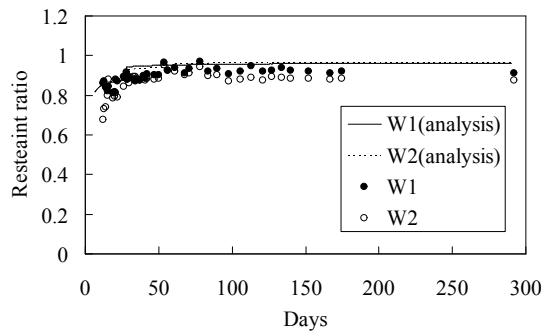


Figure 5: Restraint ratio of specimen

Fig.6 shows the strain distribution of the reinforcing steel and crack patterns of small-scale RC wall specimens. One crack occurred at the age of 24days in the specimen W1 ($p_t=0.4\%$), and the first crack occurred at the age of 23 days in the specimen W2 ($p_t=0.6\%$). These cracks penetrated the section of specimens. In case of W2, the second crack occurred approximately 700mm away from the first

crack. However, the progress of this crack stopped in the middle and didn't penetrate. The experimental value and the analytical value of the strain distribution at the age of 167days of the specimen W1 and W2 are shown in Fig.7, and there is a good agreement between the analytical values and the experimental values. Fig.8 shows the behavior of crack width until the age of 292days. The upper crack width is greater than other crack widths, because drying shrinkage in the upper place of the specimen is greater than that in the under place. A good agreement is shown between the analytical values and the experimental values of the specimen W2, but the analytical value is a little greater than the mean experimental value of specimen W1.

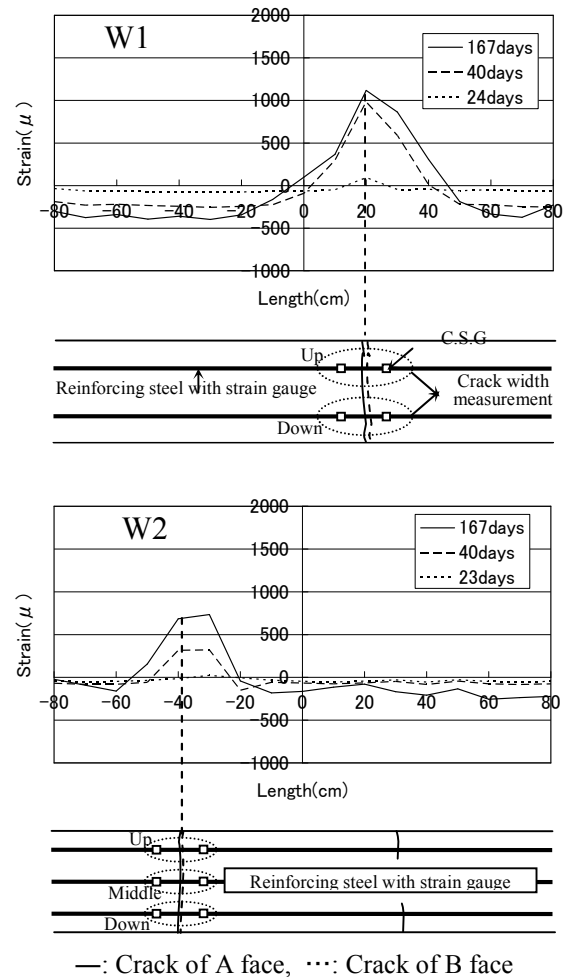


Figure 6: Strain distribution of reinforcing steel and concrete

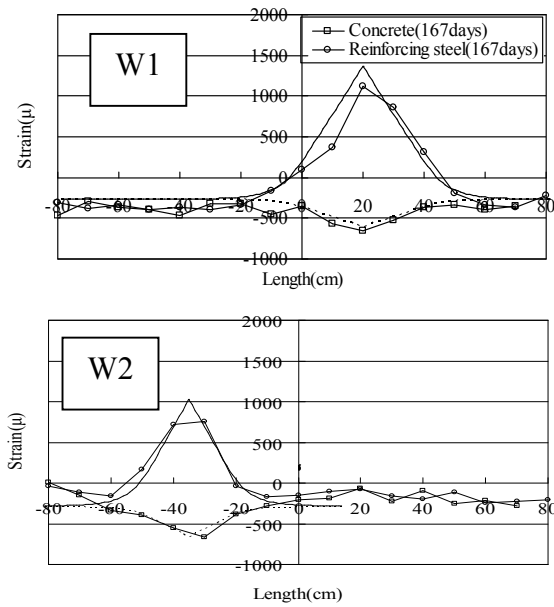


Figure 7: Comparison of analytical value and experimental value

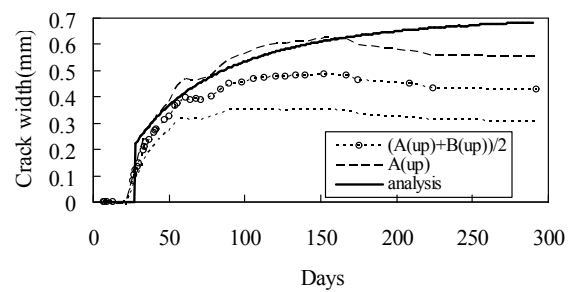
4. CONCLUSIONS

An analytical method based on the bond analysis was proposed in this paper, and the small-scale RC wall test was carried out to verify the validity of the cracking analysis method. The results of this study are summarized as follows.

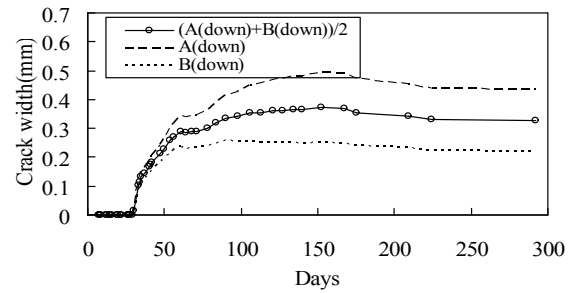
- (1) The restraint ratio was almost constant, and a good agreement was shown between the analytical value and the experimental value.
- (2) As the reinforcing steel ratio increased, the crack width decreased.
- (4) The strain distribution of reinforcing steel and concrete at the crack face could be predicted by the bond analysis.
- (5) It was confirmed that the behavior of cracks under the long term age could be predicted by the bond analysis method.

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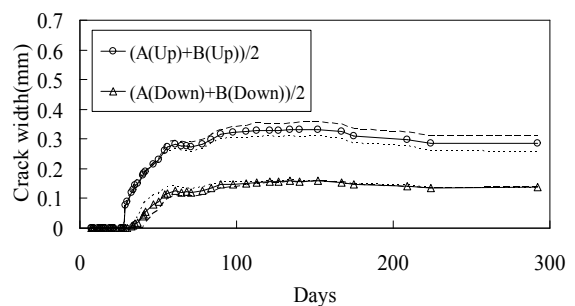
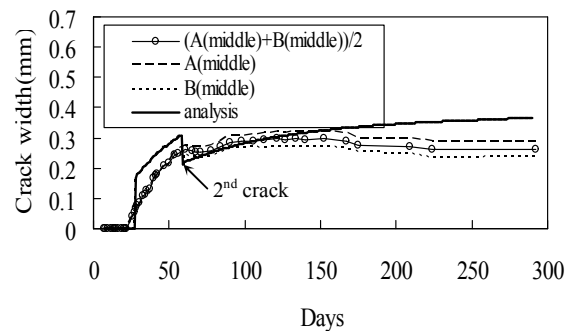
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(a) W1 specimen



(b) W2 specimen



Explanation of A, B, up, middle, and down(see Fig.6)

Figure 8: Behavior of crack width

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