International Journal of Concrete Structures and Materials
Vol.5, No.1, pp.11~18, June 2011
DOI 10.4334/IJCSM.2011.5.1.011

Prediction of Durability for RC Columns with Crack and Joint under Carbonation Based on Probabilistic Approach

Seung-Jun Kwon[1)] and Ung-Jin Na[2)]

(Received August 16, 2010, Revised April 22, 2010, Accepted June 17, 2011)

Abstract Carbonation in RC (reinforced concrete) structure is considered as one of the most critical deteriorations in urban cities. Although RC column has one mix condition, carbonation depth is measured spatially differently due to its various environmental and internal conditions such as sound, cracked, and joint concrete. In this paper, field investigation was performed for 27 RC columns subjected to carbonation for eighteen years. Through this investigation, carbonation distribution in sound, cracked, and joint concrete were derived with crack mappings. Considering each related area and calculated PDF (probability of durability failure) of sound, cracked, and joint concrete through Monte Carlo Simulation (MCS), repairing timings for RC columns are derived based on several IPDF (intended probability of durability failure) of 1, 3, and 5%. The technique of equivalent probability including carbonation behaviors which are obtained from different conditions can provide the reasonable repairing strategy and the priority order for repairing in a given traffic service area.

Keywords: carbonation, crack, cold joint, PDF (probability of durability failure), Monte Carlo simulation.

1. Introduction

Carbonation is a phenomenon which usually occurs in underground structures or urban area. Damage of RC structures from carbonation is reported to increase due to increasing CO_2 concentration.[1,2] The service life prediction for carbonation has been widely researched through quantitative manner using durability limit state determined as the condition that induced carbonated depth proceeds to the nominal cover depth.[1,3,4] However, this prediction method in quantitative manner cannot consider the variables from uncertainties from design, material, and construction stages, so that several techniques based on probabilistic approaches are nowadays introduced.[5-13] Although the prediction techniques of carbonation can consider the effective parameters in great detail, it is almost impossible to predict the exact carbonation depth in non-homogeneous concrete exposed to spatially different environmental conditions. The uncertainties in prediction for carbonation depth can be summarized as Table 1.[14]

In the design concept based on probabilistic approach, a comparison between IPDF ($P_{f\max}$, intended probability of durability failure) and evaluated PDF (P_{fpre}, probability of durability failure) is performed instead of that between nominal cover depth and increasing carbonation depth with time. The IPDF which reflects the significance of RC structures should be established first, then maximum predicted probability is required to be lower than the IPDF within the intended service life.[5,6] In design method for RC structures exposed to chloride attack, probabilistic approach have been introduced for an evaluation of service life through MSC.[7,8,15] As for carbonation, similar approach is performed through utilizing probabilistic parameters like cover depth and proceeding carbonation depth. Keeping pace with the design trends, design parameters involving the safety index and IPDF are nowadays introduced to the Concrete Standard Specification.[16,17]

Several probabilistic models for carbonation have been proposed from 1980's,[1,18] however, they have dealt with sound concrete using probability distributions of concrete cover and ongoing carbonation depth with time. Recently, probabilistic designs considering cracked width, cover depth, and properties of mixture are attempted, but they are not obtained from field investigation so that it provides only simulation results.[19] Recently, some researches on spatial time-dependent reliability analysis are performed for cracking in RC structures[9-13] but they are only for the sound concrete without considering initially vulnerable condition like cracks and joint area.

Unlike the steel member, concrete are usually placed in situ and construction joints are installed for a comparably large concrete member for efficient construction process. Due to the imperfect integration of concrete, resistance to shear and flexural force is reduced in joint area, easily becoming vulnerable to intrusion of CO_2 or chloride ion.[20-23] In addition, cracks may be induced in early-aged concrete due to hydration heat and drying shrinkage in massive member like RC column. This crack is neither the progressive one nor critical to the structural safety, but generally becomes a main route of deteriorating agent, which may lead to the more rapid steel corrosion.[24-27] RC structures have unsound area with cracks and joint as well as sound one, so that the effects of weakened concrete should be considered for a reasonable ser-

[1)]Advanced Technology Team, Korea Conformity Laboratories, 137-707, Seoul Korea. E-mail: jjuni98@yonsei.ac.kr.
[2)]Busan Port Construction Office, Ministry of Land, Transport and Maritime Affairs, Busan 601-726, Korea.

Table 1 Uncertainties of carbonation prediction

Uncertainty type	Limitation
Physical	Inherent random nature of a basic variables - Concrete cover depth - Concentration of exterior CO_2 - Quality of concrete (diffusion coefficient of CO_2) - Local condition (cracks, joints)
Statistical	Assumption for probability density function. - Limited sample size
Model	Governing mechanism for carbonation - Simplified equation of carbonation without considering carbonic reaction. - Assumption of material properties (carbonatable and reactant material) - Assumption of non-correlated variables
Decision	Definition of durability failure criteria - The period that carbonation depth exceeds the cover depth

vice life prediction or determination of repair timing.

In this paper, field investigation for twenty seven RC columns exposed to carbonation in urban city is carried out, which have been used for 18 years. Through the investigation, carbonation depth, velocity, and its probability distributions are obtained for sound, cracked and joint concrete and each repair timing through Monte Carlo simulation is calculated respectively. The results of field investigation, procedures for calculation of repair timing, and exposure conditions of RC structures are discussed in this paper in detail. An averaging technique for equivalent PDF considering cracked and joint concrete is proposed as well.

2. Repair timing considering different conditions of RC structures

Durability limit state for carbonation usually means the condition that carbonation depth reaches cover depth.[1,3,4] But massive RC structures with joint area usually have cracks caused by hydration heat or drying shrinkage. The carbonation velocity in cracked or joint concrete are reported to be much faster than that in sound concrete.[21,28,29] The carbonation depth in cracked concrete is reported to increase in proportion to the square root of crack width[21,28,34] and more rapid carbonation velocity is measured in joint concrete which shows weakened resistance to the applied load.[23,28] In this paper, only the cracks which have occurred in early-aged condition, unlike the progressive ones due to external loading, are considered for the evaluation of carbonation behavior and its probabilistic analysis. The cracks caused in early-aged concrete are assumed to have constant depth and length from initiation because it is very difficult to consider the carbonation behavior with crack opening and closing due to rehydration.[24,25] The flow chart of this paper is provided in Fig. 1.

3. Carbonation in RC column through field investigation

3.1 Carbonation mechanism

Carbonation is a phenomenon that calcium compounds (in general, calcium hydroxide) in cement hydration products react with carbon dioxide to change into calcium carbonate. Carbonation is considered to be critical deterioration for its progress has a close relationship with embedded steel corrosion.[24,30] When pH value of pore solution filling the capillary pores falls below a certain critical value (= 10.5), the passive film around reinforcing steel is easily broken. The reaction of carbonation in concrete is written as Eq. (1) and shown in Fig. 2.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

The carbonated concrete has altered characteristics of porosity and saturation due to changed compound composition and surface tension.[24,30-32] A number of researches have been performed for more reasonable models on carbonic reaction,[30-32] or local condition of concrete surface with cracks.[24-26]

3.2 Outline of the field investigation

3.2.1 Environmental condition

The environmental conditions in the urban area where RC columns have built was investigated as [1] high concentration of CO_2 (average 353 ppm), [2] annually 25 days below -5^{o}C, [3] moderate annual temperature (12.2^{o}C), and [4] moderate annual relative humidity (69.0%). It is necessary to evaluate the repair timing for carbonation since carbonation progress is more severe under these

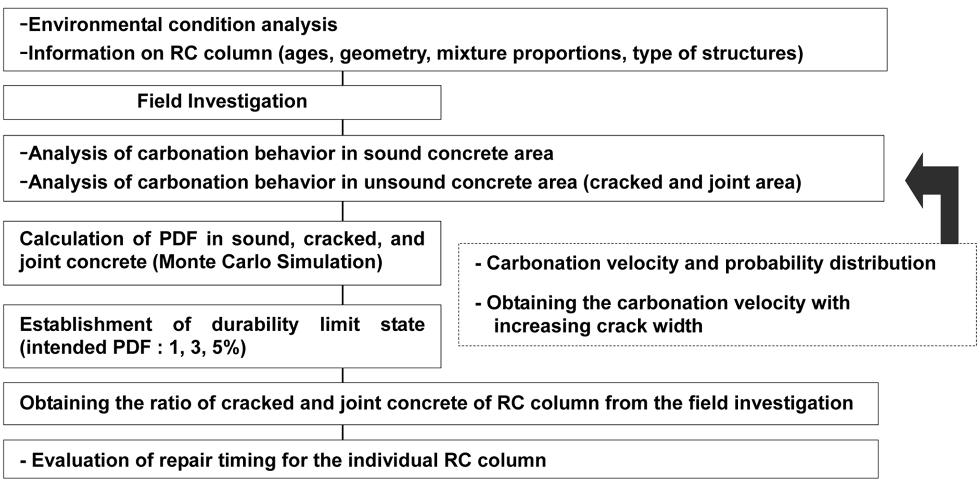


Fig. 1 Flow chart for this study.

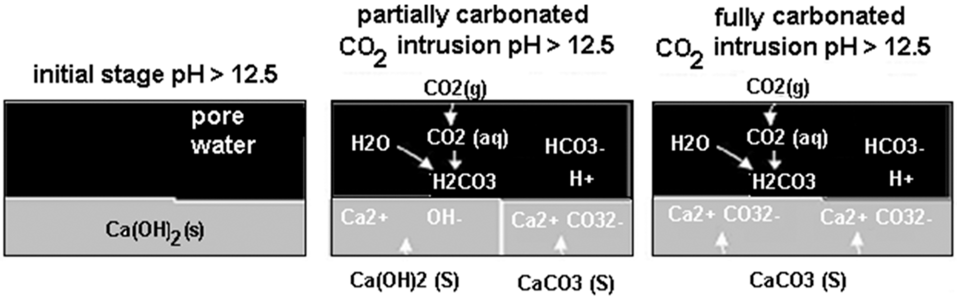


Fig. 2 Ion dissociation phenomena of carbonation.[24]

conditions. The exterior condition is listed in Table 2.

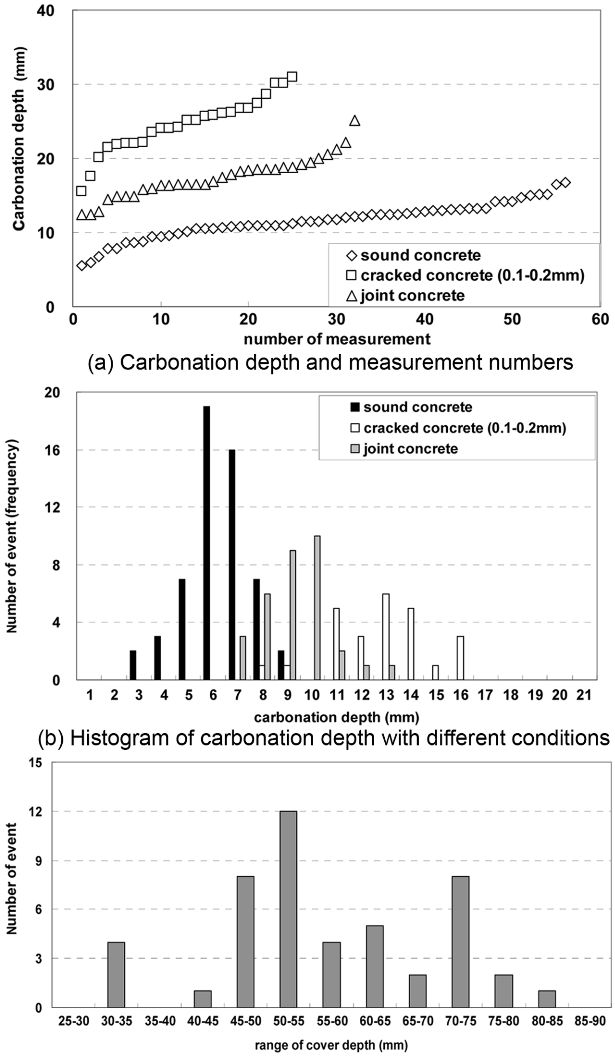
3.2.2 Actual assessment of RC structures

In this field investigation, several types of substructures are mixed as T-type and Rahmen-type. T type columns which has prestressed girder as superstructure and same cover depth are selected for this study. They have been used for 18 years and designed with strength of 24 MPa and 67.5 mm of cover depth. Crack width is evaluated to be almost within 0.1~0.2 mm from the field investigation since cracks over 0.3 mm are repaired through annual maintenance. In this paper, cracks in early aged concrete like drying shrinkage and hydration heat are considered from maintenance report. The concrete surface is pecked by chisel, and a phenolphthalein indicator of 1% concentration and digital calipers are used for measuring the carbonation depth based on JIS 1152.[33] Before measuring the carbonation depth in cracked and joint concrete, grinding is performed to remove unevenness on the surface of the concrete. The compressive strength in RC column is evaluated to be 26~30 MPa through rebound method,[34] which shows higher results than the design compressive strength (24 MPa).

3.3 Carbonation distributions in different conditions

3.3.1 Carbonation distribution for actual RC structures

The average carbonation depth is measured to be 11.7 mm taken from sound concrete in 56 data-set, 24.6 mm from cracked concrete in 24 data-set (0.1~0.2 mm of crack width), and 17.4 mm from joint concrete in 32 data-set. The results of carbonation depth from field investigation are shown in Table 3 and Fig. 3. In Fig. 3, (a) shows carbonation depth regarding number of measurement, (b) shows histogram of carbonation depth with different conditions, and (c) shows histogram of cover depth. Assuming that the carbonation depth is in proportion to the square root of the exposed time,[1,5,32,33] the carbonation depth for the different condi-



(a) Carbonation depth and measurement numbers

(b) Histogram of carbonation depth with different conditions

(c) Histogram of cover depth

Fig. 3 Result of measured carbonation distribution.

Table 2 Environmental condition of RC structures (annual average).

Concentration of carbon dioxide (ppm)	Average annual R. H. (%)	Average annual temperature (°C)	Note
353	69.0%	12.2	- RC columns are the lower structures so that they are sheltered from direct rain

Table 3 Results of carbonation depth from field investigation.

Condition	Number of sample	Carbonation depth after 18 years (mm)	Carbonation velocity (mm/year$^{0.5}$)	C.O.V. (%)
Sound	56	11.7	2.778	21
Cracked	24	24.6	5.808	15
Joint	32	17.4	4.092	16

Note) Measured cover depth : 57.5 mm, C.O.V. : 21.7%, COV: Coefficient of variation.

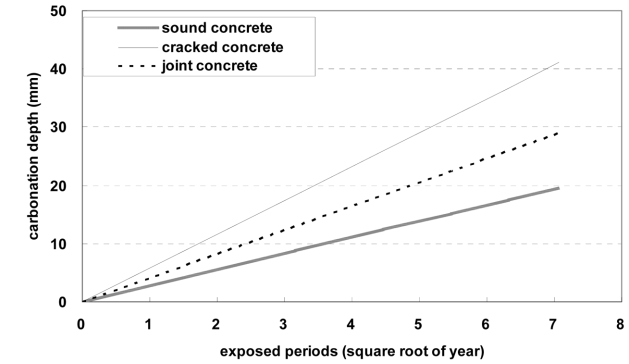


Fig. 4 Carbonation depth with exposed period.

tions can be plotted in Fig. 4, respectively.

The measured data from unsound concrete (with crack and joint) increase significantly compared to those from sound concrete. The regression results for carbonation depth in sound, cracked, and joint concrete in Fig. 4 are written as Eq. (2), Eq. (3), and Eq. (4), respectively.

Sound concrete: $C = 2.778\sqrt{T}$ (2)

Cracked concrete: $C = 5.808\sqrt{T}$ (crack width 0.1~0.2 mm)(3)

Joint concrete: $C = 4.092\sqrt{T}$ (4)

where C is carbonation depth (mm), T is exposed period (year).

3.3.2 Carbonation in cracked concrete

In cracked concrete, crack width can be the main channel for CO_2 intrusion so that carbonation depth is reported to increase with crack width. Several researches have dealt with the models[24-26] and field investigates[8,29] for quantitative evaluation of carbonation in cracked concrete. For an adaptation of suitable evaluation technique, carbonation depth considering crack width is studied as Eq. (5).[24]

$$D_{CO_2}^{eq} = \left[\frac{\phi(R)(1-S)^4 K_{CO_2}}{\Omega(1+N_K)} D_0^g + \frac{\phi(R)S^4}{\Omega} D_0^d + \frac{D_0^g K_{CO_2}\Omega[0.002\phi(R)S]^{-9.1952}}{R_a\phi(R)S}\right] \cdot \exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (5)$$

where $D_{CO_2}^{eq}$ is equivalent CO_2 diffusion coefficient in cracked concrete, $\phi(R)$ is porosity changing of carbonation rate, S is saturation, K_{CO_2} is equilibrium factor from Henry's Law, Ω is average torturity of single pore ($=\pi^2/4$), N_K is Knudsen number, D_0^d (1.0×10^{-9} m^2/s) and D_0^g (1.34×10^{-9} m^2/s) are basic CO_2 diffusivities for dissolved and gaseous state, respectively. The last term is for additional intrusion due to crack width. R_a is crack area factor considering crack width.[24] U is activity energy of CO_2 (8,500 Cal/mol K), R is universal gas constant, T_{ref} and T are reference temperature (298 K) and exterior temperature. From the field investigation, empirical equation has been proposed based on the assumption that carbonation depth is proportional to the square root of crack width.[28,29,34]

Figure 5 shows the comparison with analytical model with Eq.(5)[24] and regression results for carbonation depth from field in-vestigation.[28] The field investigation for Fig. 5 was performed for 21~24 MPa concrete exposed for 20~25 yeaars.[28] The mix proportions for the RC columns cannot be obtained since they were built in 1979 so that conventional mix proportions for 24 MPa are used for the analysis of carbonation depth in Fig. 5 and it is listed in Table 4.

As shown in Fig. 5, equation with $\sqrt{w}$ (crack width) which has 0.764 of determinant coefficient is more suitable than analytical equation. Several previous proposed models are consistent with the assumption that cracbonation depth is proportional to crack width , $\sqrt{w}$.[28,29,34]

In this paper, a regression equation with linear relation with $\sqrt{w}$ is employed for this reason. To apply this relation of crack to different crack widths, Eq. (3) can be modified to Eq. (6) considering averaged crack width (0.15 mm) since mostly 0.1 and 0.2 mm crack width are observed in this field investigation. The carbonation depth with different crack width can be plotted as Fig. 6 for the target RC structures.

$$C = (2.816\sqrt{w} + 1) \cdot A_1\sqrt{T} \quad (6)$$

where w and A_1 are crack width (mm) and carbonation velocity in sound concrete (= 2.778), respectively.

4. Evaluation of the repair timing in the RC structures

4.1 Repair timing considering different carbonation velocities

The equations along to Eq. (2)~Eq. (4) and Eq. (6) from field investigation are used for calculation of PDF. The durability limit state for carbonation can be determined as Eq. (7).

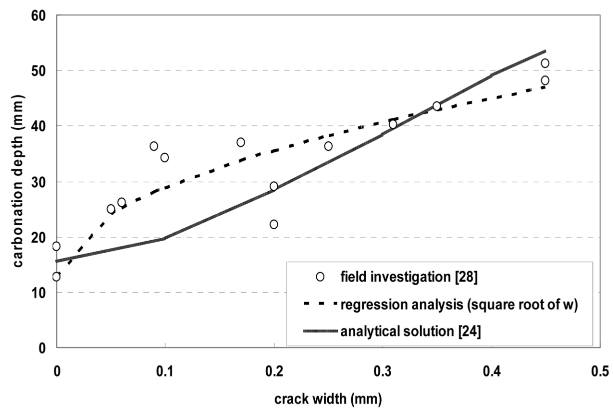


Fig. 5 Comparison of carbonation with previous researches.

Table 4 Mix proportions for analysis of carbonation depth in Fig. 5.

Strength (MPa)	Cement type	G_{max} (mm)	W/C (%)	W (kg/m^3)	C (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)
24	OPC	25	55	169	327	663	1,173

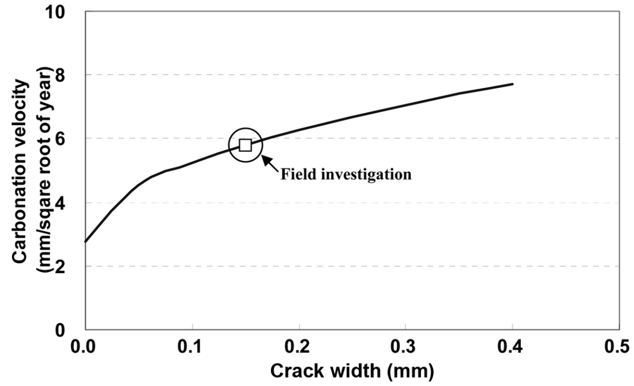


Fig. 6 Carbonation velocity with different crack width (18years).

$$D_{act} \le D(t)_{pre} \tag{7}$$

where D_{act} is the design cover depth, $D(t)_{pre}$ is increasing carbonation depth with exposed period, which can be calculated through using Eq. (2)~Eq. (4), and Eq. (6). For the 27 RC columns with same cover depth and type, PDF are obtained through Eq. (8). This assumes the equivalent probability simply considering unsound area (cracked and joint area) from the results of field investigation.

$$P(t)_{total} = P(t)_{sound}A_{sound} + P(t)_{crack}A_{crack} + P(t)_{joint}A_{joint} \tag{8}$$

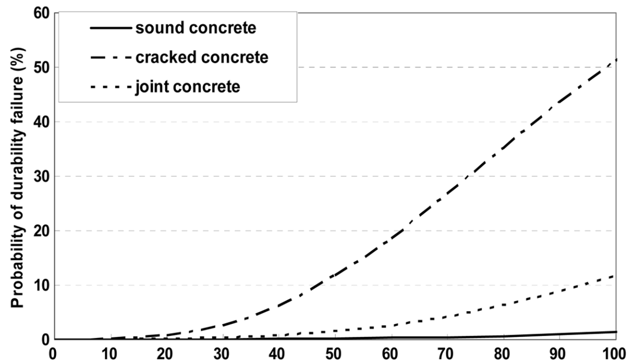


Fig. 7 Various PDFs in one RC columns considering different conditions.

where $P(t)_{total}$, $P(t)_{sound}$, $P(t)_{crack}$, and $P(t)_{joint}$ are calculated PDFs in total, sound, cracked, and joint concrete area with exposed period. A_{sound}, A_{crack} and A_{joint} are surface ratio of sound, cracked, joint area to total surface area of the RC column, respectively. For the calculation of the cracked and joint area, the effective width of them is assumed as 0.3 m, which is the normal width for the surface repairing of carbonation. In the area of aggregate segregation, carbonation depth is expected to increase. However, carbonation depth and its distribution are not measured in this field investigation so that it is assumed to be similar as that in the joint area.

In the Fig. 7, the calculated PDF in sound, cracked, and joint concrete are plotted, which show the PDFs in cracked concrete is most rapidly increasing with period. Regarding the simulation of PDF after 100 years, PDF in the cracked concrete is 58.4%, which are higher than those in sound concrete (2.0%) and joint concrete (7.4%) by 29.0 times and 7.4 times, respectively.

Using Eq. (6), carbonation depth with different crack width can be obtained and consequently PDFs with increasing crack width can be derived. PDFs in concrete with different crack width are shown in Fig. 8, where the same C.O.V (15%) obtained in carbonation distribution in cracked concrete is applied similarly. In the Fig. 9, representative mapping of field investigation is drawn including occurred crack width and joint. In Fig. 9, target area for calculatin PDF is shown in dot lines- only RC Column.

In the Table 5, the calculated PDFs in sound, cracked, joint concrete are listed with different crack width. The results are utilized

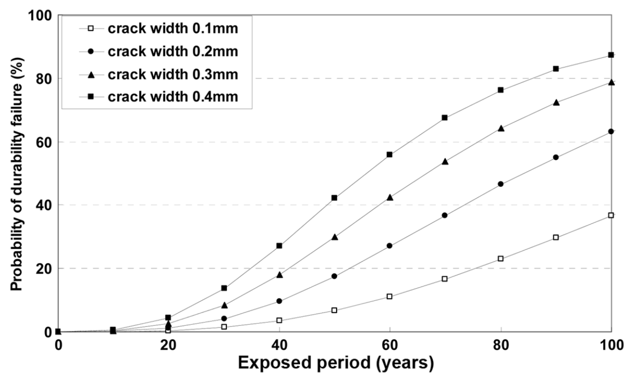


Fig. 8 Calculated PDFs with different crack widths.

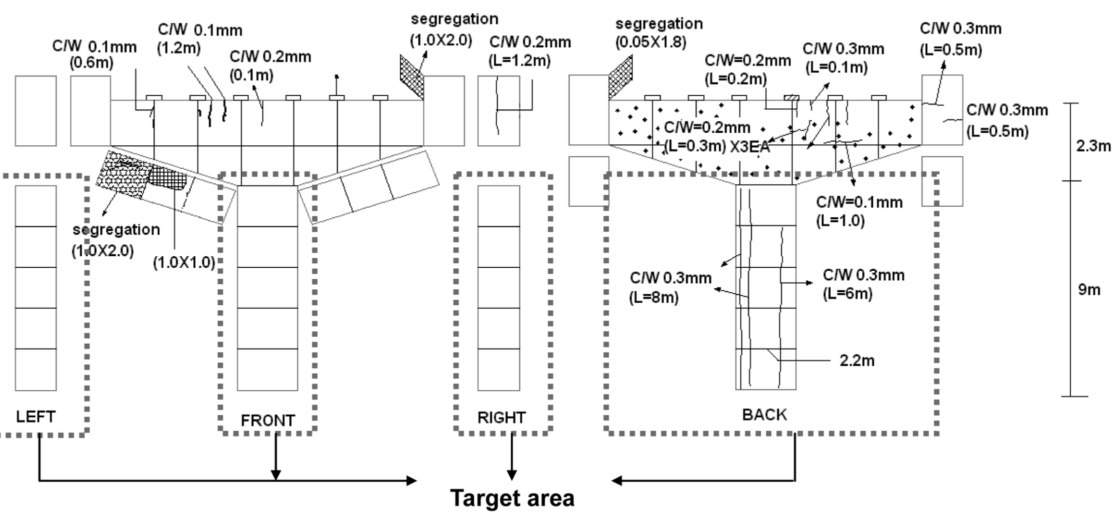


Fig. 9 Crack mapping in RC column (no. 27 column).

Table 5 Calculated PDFs with different crack widths.

Period (year)	Calculated PDF (%)					
	Sound concrete	Cracked concrete				Joint concrete
		0.1 mm	0.2 mm	0.3 mm	0.4 mm	
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.005	0.055	0.155	0.310	0.530	0.010
20	0.010	0.410	1.210	2.510	4.360	0.120
30	0.030	1.465	4.180	8.455	13.645	0.315
40	0.110	3.485	9.715	18.015	27.145	0.760
50	0.190	6.660	17.415	29.970	42.145	1.540
60	0.340	11.150	26.940	42.365	55.835	2.660
70	0.495	16.545	36.675	53.865	67.490	4.280
80	0.675	23.030	46.410	64.130	76.265	6.345
90	1.075	29.615	55.015	72.460	82.800	8.830
100	1.475	36.710	63.190	78.905	87.305	11.795
110	2.015	43.480	70.110	83.810	90.915	14.910

for total PDF considering different occurred crack width in Eq. (8).

When the period is extended to 110 years, PDF in 0.1 mm crack width shows 43.48% which is 21.6 times higher than PDF in sound concrete and 2.9 times higher than PDF in joint concrete. The calculated PDF increases significantly with crack width. When crack width reaches 0.4 mm from 0.1 mm, the PDF increases to 90.92% from 43.48%, of which the ratio is 2.1 times.

4.2 Evaluation of the repair timing for target structures

For the calculation of the repair timing for carbonation, IPDF which is allowed to be maximum probability within the intended service life should be determined. Some repairing work, the range of 0.5~1.5% is used based on the surface area showing visual signs of concrete damage due to steel corrosion.[11,35] Further studies are needed for the determining of IPDF. Actually, the range of 0.5~1.5% can be applied to criteria of spatial variation analysis since the probability is determined as damage percent which can be seen for entire surface of RC columc. Several Concrete Specifications[3-5,16] recommend the probability criteria but these are utilized for one determination which explains an expected deterioration exceeds the expected critical resistance like concrete cover depth or chloride threshold. In this paper, the changing repair timing is calculated considering several assumed IPDF (1%, 3%, and 5%). The results from 27 RC columns are plotted in Fig. 10, which shows different PDFs with increasing period due to individually different unsound area (crack width, length and so on). The repair timing for the each RC column can be obtained as Fig. 11 with different intended PDF.

From the results, the RC columns of No.2, 7, and 27 show less repair timing below 40 years in the condition of 1%-IPDF. In the condition of 3%-IPDF, 14 among 27 RC Columns have shown less repair timing below 80 years. This technique considering the carbonation in sound and unsound area can provide the repair timing for individual RC columns and also provide valuable information on the repairing strategy in a given service area.

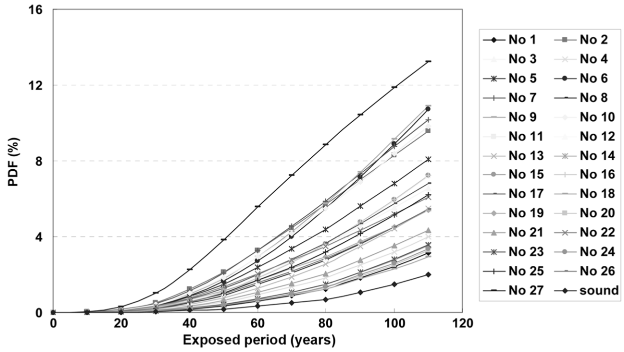


Fig. 10 Calculated PDF with time in individual RC column.

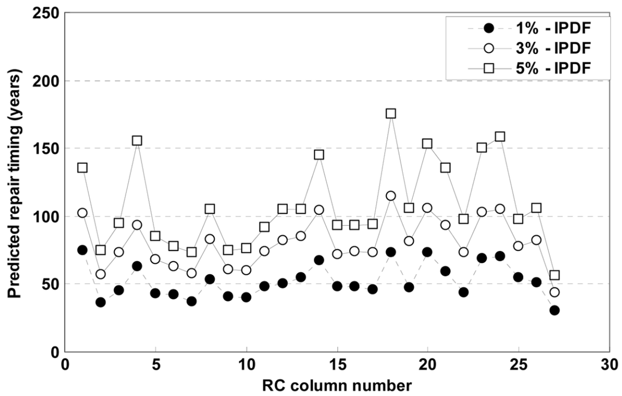


Fig. 11 Calculated repair timein each RC column.

5. Conclusions

The conclusions on prediction of repairing time for RC columns with crack and joint under carbonation based on probabilistic approach are as follows.

1) The field investigation for RC columns in urban area, exposed to carbonation is performed. Through the investigation, several different carbonation velocities in sound and unsound area

including cracks and joint are obtained. The carbonation velocity in cracked concrete (0.1~0.2 mm crack width) and joint concrete are evaluated to be more rapid than that in sound concrete by 2.10 times and 1.49 times, respectively.

2) Based on the equivalent PDF in each RC column, different repair timings for carbonation are derived for 27 individual RC columns in a given service area. The predicted timing varies at the range of 30~75 years (1%-IPDF), 44~102 years (3%-IPDF), 26~165 years (5%-IPDF), respectively. More rapid carbonation velocity and reduced repair timing are evaluated in the No.2, No.7, and No.27 RC column, which show less repair timing than 40 years in the condition of 1%-IPDF.

3) In the conventional techniques, the different carbonation characteristics in one RC column are not considered for prediction of the service life or repair timing. This proposed technique can provide the reasonable information on establishment of repairing strategy and the priority order for repairing in a given service area.

References

1. Izumi, I., Kita, D., and Maeda., H., *Carbonation*, Tokyo: Kibo press, 1986.

2 Chung, H., "Industrial Structure and Source of Carbon Dioxide Emissions in East Asia: Estimation and Comparison," *Energy and Environment*, Vol. 9, 1988, pp. 509~533.

3. CEB, *Durable Concrete Structures - CEB Design Guide*, Thomas Telford, UK, 1992.

4. JSCE-Concrete Committee, *Standard Specification for Concrete Structures*, 2002.

5. CEB Task Group 5.1 and 5.2, *New Approach to Durability Design-An Example for Carbonation Induced Corrosion*, Bulletin d' Information No. 238, Sprint-Druck, Stuttgart, 1997.

6. RILEM. *Durability design of concrete structures.*, Report of RILEM Technical Committee 130-CSL, E&FN, 1994.

7. Trocónis de Rincón, O., "Durability of Concrete Structures: DURACON, An Iberoamerican Project, Preliminary Results," *Building and Environment*, Vol. 41, 2006, pp. 952~962.

8. Ferreira, F., Arskog, V., and Gjorv, O.E., "Probability-Based Durability Analysis of Concrete Harbor Structures," *CONSEC04*, Vol. 1, 2004, pp. 999~1006.

9. Stewart, M. G., "Spatial Variability of Pitting Corrosion and Its Influence on Structural Fragility and Reliability of RC Beams in Flexure," *Structural Safety*, Vol. 26, 2004, pp. 453~470.

10. Stewart, M. G. and Rosowsky, D. V., "Time-Dependent Reliability of Deteriorating Reinforced Concrete Bridge Decks," *Structural Safety*, Vol. 20, 1998, pp. 91~109.

11. Stewart, M. G. and Mullard, J. A., "Spatial Time-Dependent Reliability Analysis of Corrosion Damage and the Timing of First Repair for RC Structures," *Engineering Structures*, Vol. 29, 2007, pp. 1457~1464.

12. Defaux, G., Pendola, M., and Sudret, B., "Using Spatial Reliability in the Probabilistic Study of Concrete Structures: The Example of a Reinforced Concrete Beam Subjected to Carbonation inducing Corrosion," *Journal of physics*, IV France, EDP Science, Les Ulis., Vol. 136, 2006, pp. 243~253.

13. Sudret, B., Defaux, G., and Pendola, M., "Time-Variant Finite Element Reliability Analysis - Application to the Durability of Cooling Towers," *Structural Safety*, Vol. 27, 2005, pp. 93~112.

14. Lounis, Z., "Probabilistic Modeling of Chloride Contamination and Corrosion of Concrete Bridge Structures," *Proceedings of the 4th International Symposium on Uncertainty Modeling and Analysis - ISUMA03*, 2003.

15. Gjorv, O.E., "Steel Corrosion in Concrete Structures Exposed to Norwegian Marine Environment," *Concrete International*, Vol. 16, 1994, pp. 35~39.

16. Korea Concrete Institute, *Standard Specification - Durability Part*, 2004, pp. 12~28.

17. CEB-FIP. *Model Code for Service Life Design, the International Federation for Structural Concrete (fib)*, Task Group 5.6, 2006, pp. 38~39.

18. Izumi, I., Kasami, H., and Oshida, F., "A Reliability Design of Cover Thickness for Reinforcement in Concrete Structures : On Case of Reinforcement Corrosion Caused by Concrete Carbonation," *Architectural Institute of Japan*, Vol. 384, 1988, pp. 58~67.

19. Kwon, S.-J., Song, H.-W., and Byun, K. J., "Durability Design for Cracked Concrete Structures Exposed to Carbonation Using Stochastic Approach," *Journal of KSCE*, Vol. 25, 2005, pp. 741~750.

20. Kyo, K., Komori, D., Kato, Y., and Utomo, T., "Effect of Mix Proportion and Working Conditions on Cold Joint in Concrete," *Proceedings of the Japan Concrete Institute*, Vol. 22, 2000, pp. 259~264.

21. Izumi, I. and Kasami, H., "Progress of Carbonation at Cracks, Construction Joints and Honeycombs of Concrete," *Cement and Concrete - Journal of Japan Cement Association*, Vol. 448, 1984, pp. 50~55.

22. JSCE, *Construction Guidelines for Concrete Tunnel Lining, Concrete Library of JSCE*, Vol. 102, 2000 (in Japanese).

23. JSCE, *Issues and Resolutions of Cold Joint in Concrete Structures, Concrete Library of JSCE*, Vol. 103, 2000.

24. Song, H.-W., Kwon, S.-J., Byun, K. J., and Park, C.-K., "Predicting Carbonation in Early-Aged Cracked Concrete," *Cement and Concrete Research*, Vol. 36, 2006, pp. 979~989.

25. Song, H.-W., Pack, S.-W., Lee, C.-H., and Kwon, S.-J., "Service Life Prediction of Concrete Structures under Marine Environment Considering Coupled Deterioration," *Journal of Restoration of Buildings and Monuments*, Vol. 12, 2006, pp. 265~284.

26. Isgor, O. B. and Razaqpur, A. G., "Finite Element Modeling of Coupled Heat Transfer, Moisture Transfer and Carbonation Processes in Concrete Structures," *Cement and Concrete Composites*, Vol. 26, 2004, pp. 57~73.

27. Song, H.-W., Cho, H.-J., Park, S.-S., Byun, K.-J., and Maekawa, K., "Early-Age, Cracking Resistance Evaluation of Concrete Structure," *Concrete Science Engineering*, Vol. 3, 2001, pp. 62~72.

28. Abe, Y., "Result of Reference Review on Crack Width Effect to Carbonation of Concrete," *Proceeding of Symposium on Rehabilitation of Concrete Structures*, Vol. 1, 1999, pp. 7~14.

29. Kwon, S.-J., Park, S.-S., Nam, S. H., and Cho, H. J., "A Study on Survey of Carbonation for Sound, Cracked, and Joint Concrete in RC Column in Metropolitan City," *Journal of Korea Structure Maintenance Institute*, Vol. 5, 2007, 116~122.

30. Ishida, T. and Maekawa, K., "Modeling of PH Profile in Pore Water Based on Mass Transport and Chemical Equilibrium Theory," *Concrete Library of JSCE*, Vol. 37, 2001, pp. 151~166.

31. Saeki, T., Ohga, H., and Nagataki, S., "Change in Micro-Structure of Concrete due to Carbonation," *Concrete Library of JSCE*, Vol. 18, 1991, pp. 1~11.

32. Papadakis, V. G., Vagenas, C. G., and Fardis, M. N., "Physical and Chemical Characteristics Affecting the Durability of Concrete," *ACI Materials Journal*, Vol. 8, 1991, pp. 186~196.

33. JIS-Japan Industrial Standard, *Method for Measuring Carbonation Depth of Concrete*, A-1152, 2002.

34. Schiessl, P., "Corrosion of Steel in Concrete," *Report of the Technical Committee 60-CSC RILEM*, Chapman and Hall, London, 1988.

35. Directoraat-Gerneraal Rijkswaterstaat, *Management and Maintenance System,* The Netherlands, 2000.