ESTIMATIOMN OF CARBONATION AND SERVICE LIFE OF BOX CULVERT FOR POWER TRANSMISSION LINE

S.K. Woo, J.H. Jo, Y.C. Song, Y.D. Choi (1), Y. Lee (2)

(1) Green Growth Laboratory, Korea Electric Power Research Institute, Korea
(2) Civil Engineering, Daejeon University, Korea

Abstract
The construction of underground structures such as box culverts for electric power transmission is increasing more and more, and the life extension of these structures is very important. Carbonation-induced corrosion in concrete may often occur in a high carbon dioxide environment. In this study, the risk of carbonation of two concrete box culverts in an urban area was evaluated by measuring the carbonation rate and concrete cover depth. Then, the carbonation-free service life at the depth of the steel was calculated, based on in situ information, by the Monte Carlo simulation. The service life of box culvert due to carbonation was estimated over 250 years via Monte Carlo simulation.

1. INTRODUCTION
Box culverts for electrical power transmission began to be constructed in the mid-1970s in Korea and are increasing in numbers recently due to power demand growth and underground installation of transmission lines. The amount of related maintenance work also continues to increase because of the increasing usage life of the constructed box culverts. Corrosion of steel due to carbonation usually occurs particularly in an urban area which has a high level of carbon dioxide, emitted from vehicles and industrial factories. Carbonation can be defined as the chemical reaction between carbon dioxide present in the air and cement hydration products such as mainly calcium hydroxide and the CSH gel phase, which results in the formation of calcium carbonate. Thus, the risk of carbonation is more severe in urban or/and industrial area. Carbonation of concrete itself does not do harm in view of the performance of structure, adversely a marginal enhancement of the compressive strength was observed. However, when carbonation reaches at the depth of the steel, the high alkalinity of the concrete pore solution is neutralized and hydration products are dissolved then to lower the buffering capacity of hydrations against a pH fall. At this moment, the passivation layer on the steel surface, which otherwise would protect the steel embedment from a corrosive environment, is destroyed, and steel is directly exposed to oxygen and water, eventually to corrode.
2. METHODOLOGY

2.1 Description of Carbonation Process

The limit state function is useful to render the risk/resistance of concrete carbonation, as being expressed into two parts: the resistance to carbonation and the carbonation risk, as given in Eq. (1).

\[ g(t) = R(t) - S(t) \]  

(1)

where \( R(t) \) and \( S(t) \) denote the carbonation resistance (concrete cover depth), and the carbonation risk (carbonation depth) with time.

The carbonation depth is usually calculated as a function of time, as given in Eq. (2), with the carbonation coefficient encompassing the concrete quality and the environmental conditions.

\[ x(t) = K \sqrt{t} \]  

(2)

where \( x(t) \) is the depth of carbonation, \( K \) for the carbonation coefficient and \( t \) for time of exposure to the atmosphere.

2.2 Monte Carlo Simulation

The safety factor method and the Monte Carlo simulation are representative techniques in modelling the risk of carbonation. However, for the safety factor method in predicting the risk of carbonation, the safety factor was not rationally determined with the reliability index in previous studies. The safety factor has been usually derived from an engineering judgment rather than calculated from in situ information, in order to compensate for the variance of the parametric values such as carbonation rate and concrete cover depth, which might happen arising from the difference in construction environments and construction quality. The safety factor has been conventionally regarded as being 1.2 in some standards and guidelines. Furthermore, the distribution type for the parametric values, although the carbonation rate and concrete cover depth are obtained from the corresponding in situ examination, is always determined to the normal distribution only, possibly leading to an error in calculating the safety factor. Thus, it can be said that the carbonation-free service life predicted by the safety factor method might be less convincible. The Monte Carlo simulation requires a number of empirical measurements from a field in terms of the average value and the standard deviation of the parametric values, in order to validate its probabilistic prediction.

Unlike the safety factor method, the carbonation resistance and risk factors are not required, when the probabilistic method is used, to consider the variance of the experimental information including the carbonation depth and concrete cover depth. Instead, the simulated deviation of the parametric values is taken into account in determining the carbonation resistance and risk. In the present study, the Monte Carlo simulation technique, as a probabilistic way, was used to assess the carbonation risk. For the simulation, mean value and standard derivation of the parametric values (i.e. carbonation depth and concrete cover depth) were obtained from underground field investigation. Then, 100,000 of random samples for the parametric value were generated by the Monte Carlo simulation. The probability for carbonation to reach the depth of the
steel can be calculated from the 100,000 random trials and is defined as the ratio of the number of carbonation, calculated by Eq. (1), at the depth of the steel to the number of total trials, as given in Eq. (3).

\[ P_t = \frac{n(g(t) < 0)}{N} \] (3)

where \( P_t \) is the probability of carbonation at the depth of the steel and \( n(g(t) < 0) \) denotes the number of carbonation at the depth of the steel out of \( N \) trials (100,000 trials in this study).

3. FIELD AND INDOOR INVESTIGATION

Two concrete box culverts in K- Box Culvert and G – Box Culvert in Seoul, as typically shown in Fig. 1, were examined for carbonation after 18 and 16 years, respectively. The concentration of carbon dioxide in the box culvert reached 508 ppm in K – box culvert and 629 ppm in G – box culvert, respectively.

Prior to measuring the carbonation depth, the concrete cover depth to the steel was measured using an ultrasonic cover meter in 84 points. After measuring the cover depth, 84 concrete core specimens were drilled out for durability test including carbonation depth investigation. In order to avoid further carbonation of the core specimen in later experiment, each specimen was sealed with plastic wrap up to indoor test. By splitting cylinder specimen in the laboratory, carbonation depth was measured in each specimen.

The measurement was done with a phenolphthalein pH indicator (i.e. <10 in the pH) to determine the carbonation depth. The carbonated concrete parts were not changed in color, whereas the sound ones turned purple by the indicator, as shown in Fig. 2.

(a) K- box culvert  (b) G – box culvert

Figure 1. Typical box culvert for power transmission

In this study, box culvert for power transmission in the metropolis was examined in terms of the risk of carbonation. Carbonation depth was examined with 17 core specimens.
using phenolphthalein indicator. The concrete cover depth and carbonation depth measured are given in Figs. 3 and 4, respectively.

The concrete cover depth measured ranged from 80 to 170 mm in K-box culvert, from 20 to 130 mm in G, respectively. The distribution of the concrete cover depth was best fitted to the lognormal distribution, determined by the goodness-of-fit tests. The average of the measured cover depth was 118.9 mm in K-box culvert and 72.9 mm in G-box culvert, respectively. The standard deviation was high, ranging from 22 to 32 mm, meaning that the quality of construction for concrete cover was not good in many parts of the box culvert in casting concrete.

The distribution of carbonation depth was best fitted to the lognormal distribution likewise cover depth, and ranged from 2 to 38 mm. Carbonation depth on average accounted for 19.6 mm and 14.2 mm for K and G-box culvert, respectively.

Figure 2. Carbonation test with phenolphthalein

Figure 3. Concrete cover depth distributions
The distribution of carbonation rate was best fitted to the lognormal distribution likewise cover depth, and ranged from 0.5 to 10 mm/year$^{0.5}$. Carbonation rate on average accounted for 4.6 and 3.5 mm/year$^{0.5}$ for K-box culvert and G-box culvert, respectively.
4. ESTIMATION OF SERVICE LIFE

The service life due to carbonation was calculated by the Monte Carlo simulation. Probability of corrosion was dotted with an increment of 1 year of time as shown in Fig. 6. The variation in the concrete cover depth and the rate of carbonation was taken into account by producing 100,000 samples considering the lognormal distributions of the parametric values.

![Figure 6. Probability of service life due to carbonation estimated by Monte Carlo simulation](attachment:image.png)

The service life of box culverts accounted for about 360 and 270 years for K – box culvert and G – box culvert, respectively, assuming that the limit state for carbonation at the depth of the steel is regarded as 10% of probability which is usually determined by engineers’ preference. Threshold value of 10% is crucial for the estimation of service life and it is noted that the obtained 360 and 270 years service life were estimated in the probabilistic sense, not in the deterministic way. Since internal relative humidity was measured over 40% throughout the year, the possibility of corrosion of internal reinforcement due to carbonation of cover concrete is open in both box culverts. Despite of rapid carbonation rate of G - box culvert, it was seen that the service life of K - box culvert was about 90 years longer than G - box culvert due to the large cover depth up to 120 mm.

5. CONCLUSIONS

The research results of this study are as follows.

1) In this study, the risk of carbonation of two concrete box culverts in an urban area was evaluated by measuring the carbonation rate and concrete cover depth. Then, the carbonation-free service life at the depth of the steel was calculated, based on in situ information, by the Monte Carlo
simulation. The service life of box culvert due to carbonation was estimated over 250 years via Monte Carlo simulation.

2) The distribution of the concrete cover depth and carbonation depth was best fitted to the lognormal distribution by the goodness-of-fit tests.

3) The service life of box culverts accounted for about 360 and 270 years for K-box culvert and G-box culvert, respectively, assuming that the limit state for carbonation at the depth of the steel is regarded as 10% of probability of steel corrosion.

4) It was seen that the service life of K-box culvert was about 90 years longer than G-box culvert due to the large cover depth up to 120 mm despite of rapid carbonation rate of K-box culvert.

ACKNOWLEDGEMENTS

This research program was funded by Korea Electric Power Corporation and its kind support is gratefully acknowledged.

REFERENCES