Estimating the reliability of carbonated reinforced concrete bridges using particle filter

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Abstract: Many of our reinforced concrete structures today are ageing while subjected to the carbonation process. The process of carbonation in concrete is the leaching of the carbon towards the core of the concrete structure. It occurs when atmospheric carbon dioxide reacts with the components of the hydrated cement. This condition affects the strength of the concrete and thus its load carrying capacity is reduced. It is therefore necessary that the present state of the structure be estimated so that corrective / retrofit measures can be planned. In this regard, the authors estimated the reliability index (or the probability of failure) of the deteriorated reinforced concrete beams subjected to carbonation. In the reliability analysis, the resistance was modeled as a function of the concrete compressive strength, carbonation depth, relative humidity, carbon dioxide content and time while the load was modeled as a uniformly distributed load on a simply supported span. The results of the Monte Carlo Simulation from 0 to 100 years showed a decrease in the compressive strength and an increase in the probability of failure in the range of 0 to 86%. It was observed in the results of the simulation that the structures farthest from the shore generated a higher probability of failure compared to those that are near the shore and are on water. Using the observed hammer rebound test results for compressive strength of two bridges with life spans of 55 and 40 years respectively, the probabilities of failure were updated using Particle Filter. The filtered Probability of Failure was higher than that of the theoretical from simulation. The probability of failure increased from 60 to 63% and 48 to 61% for the two bridges respectively, meaning that the failure state is more delicate compared to the simulation.

Key Words: Carbonation; Deteriorated Structures; Probability of Failure; Reliability Index

1. BACKGROUND

1.1 Introduction

Studies have shown that the service life of concrete is affected by Carbonation (Saetta 2004, Liang 2013, Niu et. al 2013). Carbonation occurs when carbon dioxide from the atmosphere reacts with the component of hydrated cement. Specifically these components are calcium hydroxide, di-calcium silicate and tri-calcium silicate. Water also initiates carbonation process when carbon dioxide is not present which occurs in submerged foundations and underwater columns. Since the amount of carbonates is far less in water than of in the atmosphere, carbonation rate is significantly lower (Gode and Paeglitis, 2013).Although carbonation is a phenomenon that cannot be prevented and reinforced concrete members of a structure will in time be subjected to carbonation.

Chi et al (2002) suggested that the reliability of a concrete structure reduces when carbonation reaches the reinforcing steel of the structural element. Fortunately it does not do much damage to the concrete itself. The process of carbonation in concrete is the leaching of the carbon towards the core of the concrete structure. Factors affecting the rate of carbonation include many environmental factors. The process also shrinks the volume of the concrete.

Carbonation cannot be prevented because carbon dioxide is always present in the atmosphere surrounding the concrete structure; corrosion initiates when carbonation depth reaches the reinforcing steel (critical depth). However the corrosion of steel reinforcement is not only caused by carbonation, chloride induction and carbonation contributes to the corrosion of steel reinforcement according to Puatatson (2005). Though chloride induction creates a greater effect to the depassivation of steel, making it vulnerable to corrosion. Nevertheless, carbonation also creates effect on the compressive strength of the concrete structure. According to theory, carbonation depth has an inverse relationship with the compressive strength depending on the service life of the concrete (Brecolotti et al, 2013).

Though the dominant effect for corrosion is chloride induction, carbonation should not be neglected for it also contributes to phenomena. Due to the research gap regarding the effects of carbonation depth on the reliability of RC structure, this research attempts to quantify the reliability of a reinforced concrete structure due to a measured carbonation depth.

The research aims to clear the research gap regarding the effects of carbonation depth on the reliability of RC structure by contributing the results of this study to the literature of regarding the relation of carbonation depth and time. The study provides an estimate on the probability of failure and the reliability of deteriorated reinforced concrete structure subjected to carbonation especially when their compressive strength decreases. Although it is already known that compressive strength increases as concrete ages (ASTM), the study offers a new basis for changes in the compressive strength by taking consideration in the different environmental factors, environmental factors in the process such as temperature and relative humidity.

2. OPERATIONAL FRAMEWORKS

2.1 Conceptual Framework

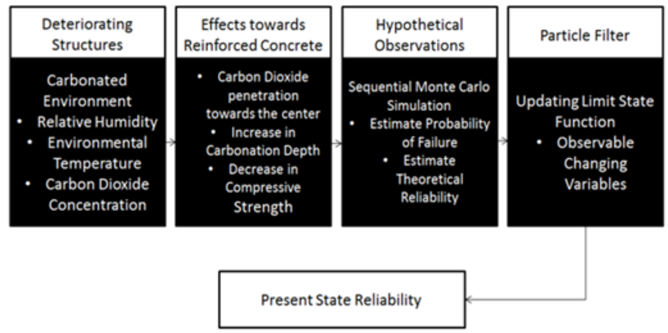

Fig. 1. Conceptual Framework

The carbonation process is the reaction of carbon dioxide in the environment with the chemical components of concrete. This lead to the deterioration of reinforced concrete. Figure 1 shows the visual representation of the conceptual framework, which consists of the concepts to be used in the development of the fragility curve along with its benefits. Moreover, it can lead to the deterioration of reinforced concrete by decreasing its compressive strength. There are environmental factors that lead to the carbonation of the structure such as the carbon dioxide in the environment, temperature, and the relative humidity. The carbonation process will lead to an increase in carbonation depth through the movement of carbon dioxide inside the RC. As time increases, the carbonation depth also increases leading to a decrease in the compressive strength of the RC.

Using the equations, the study will provide a limit state function for the probability of failure and the reliability of the carbonated RC structures with the use of hypothetical observations and Monte Carlo Simulation.

In order to update the limit state function from the hypothetical observations, the study will require other equations that relate the observable variables (RH, T, C_s) with the carbonation depth (x) and effective compressive strength due to carbonation (r). The study will involve on site observations regarding the observable variables. The process of the Monte Carlo Simulation will be repeated using the observed variables, and the limit state function will be updated with the use of particle filter. Using the updated limit state function, the present state reliability of the analyzed structure can be estimated.

2.2 Theoretical Framework

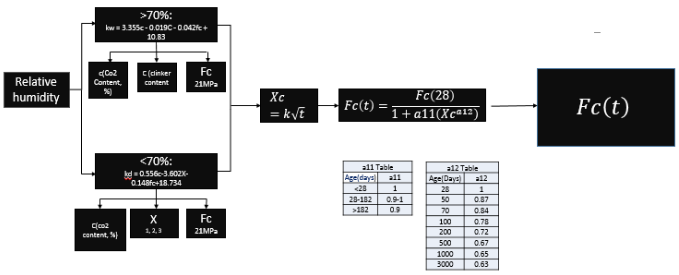

Fig. 2. Theoretical Framework

In the layout of the equations to be used, the initial part of the simulation involves the Carbonation Related Parameters.

2.2.1 *Carbonation related parameters*

In this study, the depth of carbonation in the reinforced concrete is affected by time *t* in days and the carbonation coefficient *k*. (Equation 1)

$$x = k\sqrt{t} \qquad \text{(Eq. 1)}$$

Where:

k = Carbonation Coefficient/Constant

t = Time(years)

X or X_c = Carbonation depth (millimeters)

The *k* was computed using either one the following equations depending on the percentage of the relative humidity RH:

$$k_d = 0.556c - 3.602X - 0.148f_c + 18.734 \qquad \text{(Eq, 2)}$$

$$k_w = 3.355c - 0.019C - 0.042f_c + 10.83 \qquad \text{(Eq. 3)}$$

Where:

k_d = value of k when the relative humidity is equal or less than 70% (mm/year$^{0.5}$)

k_w = value of *k* when the relative humidity is greater than 70% (mm/year$^{0.5}$). *c* is the carbon dioxide content of the concrete (%).

X = environment exposure class.

$X = 1$ when the concrete is either permanently dry (e.g. The interior of the building) or permanently wet (e.g., totally immersed);

$X = 2$ when the concrete is exposed or in contact with water for long period (e.g., rainwater drainage system);

$X = 3$ when the concrete is exposed to moderate humidity

$X = 4$ when the concrete is experiencing dry-wet cycles.

$f_c'(s)$ = 28-day compressive strength (MPa = N/mm^2).

C = clinker or mortar content of the reinforced concrete (kg/m^3).

C = Carbon Dioxide content of concrete front surface (%)

After obtaining the carbonation related parameters, the carbonation coefficient is now then applied to the equation,

$$Fc(t) = \frac{Fc(28)}{1 + a11(Xc^{a12})} \qquad \text{(Eq. 4)}$$

Where:

$F_c(t)$ = Effective compressive strength(MPa)

$F_c(28)$ = 28 day strength of concrete(MPa)

$a11$ = constant varying on life span of bridge as shown in table 1.

$a12$ = constant varying on life span of bridge as shown in table 2.

X_c = Carbonation depth(millimeters)

Table 1. *a11* values

Age(days)	a11
<28	1
28-182	0.9 - 1
>182	0.9

Table 2. *a12* values

Age(days)	a12
28	1
50	0.87
70	0.84
100	0.78
200	0.72
500	0.67
1000	0.65
3000	0.63

2.2.2 *Reinforced Concrete Capacity*

Depending on the amount of decrease on the effective compressive strength of concrete, this will vary the overall capacity of the reinforced concrete and as well as the type of interaction it experiences whether for it to be either over reinforced or under reinforced.

2.2.2.1 Under Reinforced

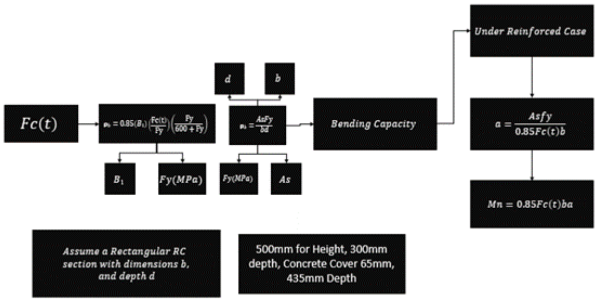

Fig. 3. Under Reinforced Case

Figure 3.2 shows the process in determining if the concrete beam is under reinforced. The balanced steel ratio (ρ_b) is a function of $F_c(t)$ and the state (whether under reinforced or over reinforced) depends on the value of $F_c(t)$.

$$\rho_b = .85(\beta_1)\left(\frac{F_c(t)}{F_y}\right)\left(\frac{F_y}{600+F_y}\right) \qquad \text{(Eq. 5)}$$

$$\rho = \frac{A_s F_y}{bd} \qquad \text{(Eq. 6)}$$

Where:

ρ_b = Balanced Steel Ratio

β_1 = 0.85

F_y = Yield Strength of Steel (MPa)

A_s = Total Area of Rebars(mm²)

b = base of cross section of reinforced concrete (mm)

d = depth of centroidal location of rebars from topmost fiber (mm)

ρ = steel ratio

The ρ_b from Eq. 5 is compared to the ρ of Eq. 6 to determine the state of the concrete beam. It is part of the assumption that the concrete beam has a height of 500mm, base of 300mm, concrete cover of 65mm, and a depth of 435mm. If ρ is less than ρ_b, then the following equations will be used in obtaining the capacity.

$$a = \frac{A_s F_y}{.85\,F_c(t)(b)} \qquad \text{(Eq. 7)}$$

$$Mn = 0.85Fc(t)ba(d - \frac{a}{2}) \qquad \text{(Eq. 8)}$$

Where:

a = Depth of the neutral axis (mm)

M_n = Nominal Capacity (N-mm)

2.2.2.2 Over Reinforced

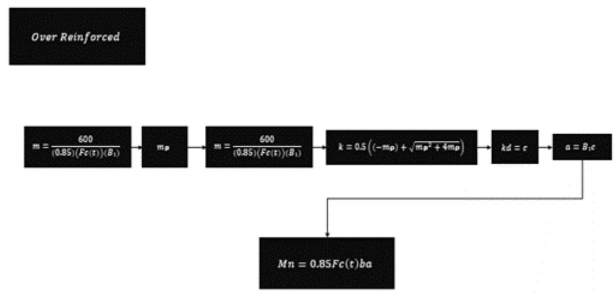

Fig. 4. Over Reinforced Case

In the over reinforced case, there is an increase in difficulty in obtaining the depth of the neutral axis of the cracked section because the yield strength of steel will not be equal to 415MPa because the concrete will first fail before the steel yields. Thus a few more equations are used in obtaining the depth of the cracked neutral axis of concrete.

$$m = \frac{600}{(0.85)(Fc(t))(B_1)} \qquad \text{(Eq. 9)}$$

$$k = 0.5\left((-m\rho) + \sqrt{m\rho^2 + 4m\rho}\right) \qquad \text{(Eq. 10)}$$

$$kd = c \qquad \text{(Eq. 11)}$$

$$a = \beta_1 c \qquad \text{(Eq. 12)}$$

In theory, m is merely a constant that needs to be applied into equation 10. After all equations have been applied, a value for a will be obtained, and thus the capacity can be solved using Equation 8.

2.2.3 Reliability Analysis

$$g(x) = R - S \qquad \text{(Eq. 13)}$$

$$S = \frac{WL^2}{8} \qquad \text{(Eq. 14)}$$

Where:

S = Load Induced

W = Uniformly Distributed Load on a Beam (kN/m)

L = Beam Span (meters)

In obtaining the performance of a Reinforced concrete beam, equation 13 is used in where the Resistance R is equal to equation 8.

3. METHODOLOGY

3.1 Monte Carlo Simulation

The simulation estimated the performance of concrete subdued to the carbonation process. With the use of the MATLAB software, the program generated realistic random values for the 28th day compressive strength (f_c), carbon dioxide content (c), and the clinker content (C). The values generated was used to generate the values of the relative humidity. The carbonation coefficient was computed using two equations. The equation to be used wasrely on the relative humidity of the area. The equation (RH <70%) used in solving had 3 cases depending on its distance from the shore or other large bodies of water.

The following were the steps used in the Monte Carlo Simulation:

1. The program produced 100 samples per increment of time for 100 years for each case thus producing four 100x100 matrices of the carbonation constant k.
2. The carbonation rate was then multiplied to the square root of time to get the carbonation depth. The carbonation depth was just an estimation based on theory of related literature. This produced four 100x100 matrices for the carbonation depth X_c.
3. Using the theoretical carbonation depth, the current compressive strength was solved using the equation shown above in the figure 2.1. This produced four 100x100 matrices for the values of the compressive strength $f_c t$.
4. The $f_c t$ matrices was used to generate the ρ_b which was then be compared to the ρ to determine if the case was in under reinforced or over reinforced.
5. Using the assumed dimensions, the program solved for the nominal moment M_n depending on the case it is under.

3.2 Particle Filter

The particle filter made use of the observed data from two bridges to generate the probability of failure of the selected bridge. With the use of equation:

$$f_c t = .032509\ x\ Rm^{1.94172}\ x\ 10^{-.00789*xc} \quad \text{(Eq. 15)}$$

Where

R_m = Rebound Number

The following were the steps used in the Particle Filter:

1. Create a linear observation equation based from equation 8.
2. Perform an on-site observation to determine the relative humidity of the site and the geographical location to determine the exposure class of the bridge.
3. Update the performance function from the Monte Carlo Simulation.
4. Observe if the Monte Carlo Simulation of the bridges has been over estimated or under estimated.

4. RESULTS AND DISCUSSION

4.1 Monte Carlo Simulation

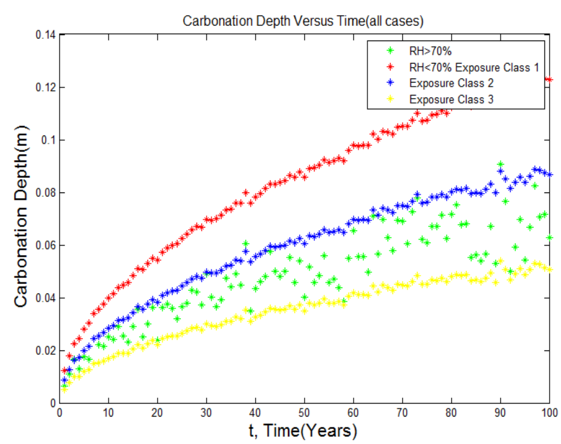

Fig. 5. Carbonation Depth Simulation

Figure 5 shows the trend of carbonation depth as time progresses. It can be observed that the rate of the carbonation depth increases as time progress in years. The level of carbonation depth depends on the relative humidity of its location and its distance from any significantly large body of water.

The exposure class 1 displayed the steepest degree of inclination among the four while the exposure class 3 showed the gentlest slope. Exposure class 1 *(XC1)* is classified as concrete exposed to permanently dry or permanently wet surrounding. Exposure class 2 *(XC2)* is classified as concrete exposed to wet surroundings for a long periods. Exposure class 3 *(XC4)* is submerged in water which reduces the amount of carbon dioxide reacting with the concrete thus reducing the carbonation depth.

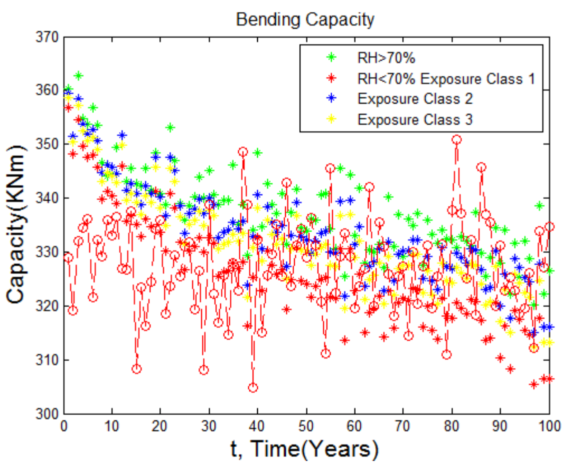

Fig. 6 Compressive Strength vs Time

Figure 6 shows the relationship of the compressive strength (*Fc*) in MPa and time in years. The increase in carbonation depth has been associated with the decline of compressive strength of concrete. The case which displayed the highest increase in carbonation depth (RH<70% - exposure class 1) also displayed the highest decrease in compressive strength and vice versa.

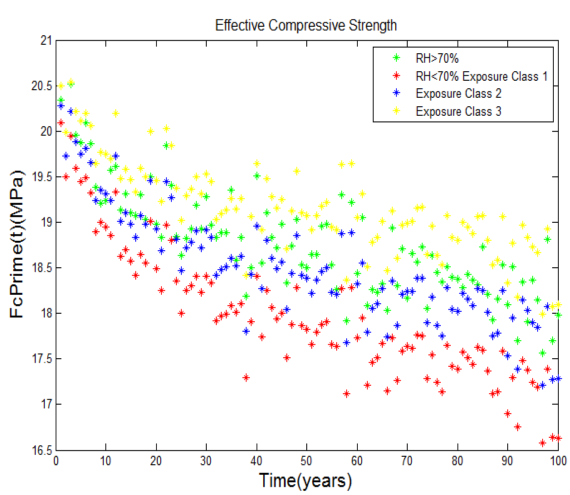

Fig. 7. Bending Capacity vs Time

In figure 7, it can be observed that the bending capacity also decreases over time. The case which shows the lowest decrease in bending capacity over time is the concrete with the relative humidity less than 70% (*RH<70%*) and exposed to the surrounding classified as exposure class 1.

4.2 Particle Filter

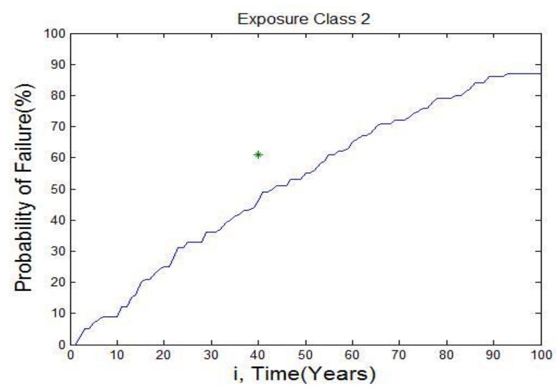

Fig. 8. Filtered Probability of Failure of Bridge 1

Figure 8 shows the updated probability of failure vs time of bridge 1. Bridge 1 is situated in a surrounding classified as Exposure class 2. The probability of failure increased from 48% to 61%.

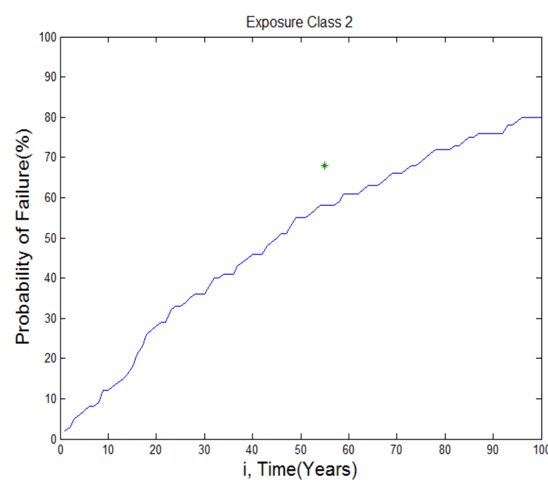

Fig. 9. Filtered Probability of Failure of Bridge 2

Figure 9 shows the updated probability of failure vs time of bridge 2. It can be observed that the result of the update is above the previously simulated probability of failure. The result is based from actual on site observation.

Both of the simulation of the two bridges proved to be underestimated.

5. CONCLUSION

The purpose of this paper is to estimate the reliability of the reinforced concrete bridges in Metro Manila using Monte Carlo Simulation and Particle Filter. The study used the MATLAB software in order to analyze the data collected. From the developed graphs obtained from the Monte Carlo Simulation, it can be observed that the carbonation depth increases as time progress. The increase depends on the condition of the surroundings and the location of the concrete structure from any body of water. The increase in carbonation depth yielded a decrease in the compressive strength of the concrete structure.

Based from the observed data and through the use of the Particle Filter, an update of the simulation curve can be seen. It can be observed if the simulation is over estimated or under estimated depending on where the produced result of the filter is located.

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