APPLICATION OF A FULL PROBABILISTIC MODEL FOR PREDICTING THE ADVANCE OF CARBONATION FRONT IN CONCRETE STRUCTURES

Enson de Lima Portela

enson@usp.br

Department of Civil Engineering, University of São Paulo,
Av. Prof. Almeida Prado, travessa 2271
05508-900, São Paulo-SP,Brasil

Túlio Nogueira Bittencourt

tbitten@gmail.com

Department of Civil Engineering, University of São Paulo,
Av. Prof. Almeida Prado, travessa 2271
05508-900, São Paulo-SP,Brasil

André Teófilo Beck

atbeck@sc.usp.br

Dept. of Structural Engineering, University of São Paulo,
Av. Trabalhador São Carlense, 400
13566-590, São Carlos-SP, Brazil.

Abstract. The high elevation of CO2 in our atmosphere can generate deeper carbonated layers in concrete structures; this fact has a direct impact on the lifetime of RC structures, mainly reducing their durability. For the past 70 years, carbonation has been studied and a large literature on this subject exists. In general, those works agree that the most important variables influencing concrete carbonation are relative humidity, CO_2 concentration, curing of concrete and water/cement ratio. This paper presents an alternative methodology to predict the advance of carbonation front inside concrete structures. The methodology presented in this work uses the model adopted by the Model Code in 2010 and results from phenolphthalein test. Historical data from both local environment and concrete structures are incorporated into the proposed model, in order to perform a reliability analysis of concrete carbonation. The proposed methodology is applied to some bridges in Brazil as case studies.

Keywords: Carbonation, Deterioration, Concrete, FORM, ISMC.

1 INTRODUCTION

According to Parrot (1987) the high elevation of CO_2 in urban environments can generate deeper carbonated layers in concrete structures, with a direct impact on the lifetime of RC structures, mainly reducing the durability and consequently the performance of such structures. In 1987, when Parrot published his article, the CO_2 concentration in our atmosphere was 15% lower that it is in 2015. In 2014, the Mauna Loa Observatory in Hawaii reported that, for the first time in human history, the global concentration of carbon dioxide in the atmosphere had reached 400ppm, as can be seen in Figure 1, and it is increasing by almost 2ppm per year.

Adding this climate change to the fact that penetration of the carbonation front depends on the concentration of CO_2 in our atmosphere, carbonation of concrete has started to attract more and more attention recently (Yoon et al. 2007). Moreover, following the FIB Model Code (FIB, 2010), the exposure of RC structures to atmospheric CO_2 results in the carbonation accompanied by a cutback in pH values of the pore solution, which can cause corrosion of the steel.

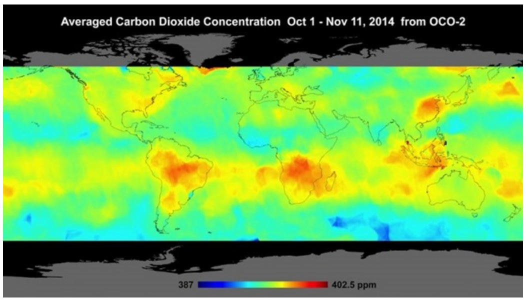

Figure 1- CO2 concentration in the Globe (Source: NASA, 2104).

The occurrence of carbonation initiates whenCO_2in the air penetrates the RC structure and reacts with hydroxides, mainly calcium hydroxide - $Ca(OH)_2$, but also sodium hydroxide 2NaOH and potassium hydroxide 2KOH, forming carbonates (Papadakis *et al.*1991, Ishida and Maekawa, 2000). Equation (1) shows the three chemical processes:

$$\begin{gathered} Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \\ 2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \\ 2KOH + CO_2 \rightarrow K_2CO_3 + H_2O \end{gathered} \tag{1}$$

Since carbonation depends on CO_2 concentrations, it may be expected that it is more intense where air pollution takes place, as reported by Khunthongkeaw *et al.* (2006).Nevertheless, it is hard to obtain data of carbon dioxide concentrations in urban areas where a particular structure is located; because, in general, this variable is not monitored. Even though the presence of carbon dioxide is essential to start the carbonation process, there are a series of other variables involved in the process. Taking into account these variables, in theory, may improve predictions about the behavior of carbonation front.

Important models to estimate carbonation front, such as the models by Smolczyk (1969), Schiessl (1976) and Tuuti (1982), do not clearly take into account all those parameter related to carbonation. Indeed, it is hard to find a feasible and computationally affordable model capable of considering all variables correlated to carbonation. Nevertheless, the model proposed by the Model Code (FIB, 2010) could be considered viable because it gathers a considerable number of variables correlated to carbonation and it is not very difficult to solve. This model is used only to predict carbonation, not corrosion, and will be deeply discussed in this paper.

Liang et al. (2013) argued that, although a significant amount of research has been done on service life prediction of RC structures, not enough work has been done on service life prediction of existing RC structures due to concrete carbonation. With that in mind, the main objective of this article is to determine the carbonation evolution of existing structures using information from both field data and the original design. A fully probabilistic model is applied in order to compute the reliability index and failure probability over time. A point-in-time approach will be considered to perform analysis over time. This approach takes the time effects successively into account at many points in time. Each calculation gives the probability of failure specific to the point in time considered.

2 MODELING OF CARBONATION

The most common deterioration process in reinforced concrete structures is corrosion (Vu and Stewart, 2000; Du et al 2013, Zhou et al. 2014,Toongoenthong et al. 2005). However, the initiation of this deterioration process has in the steel depassivation its primary condition. It is well-known that steel-concrete interface creates a sort of protective film around the reinforcements, this layer has a high pH value, about 12, which prevents the initiation of the corrosion process. Therefore, it is necessary that an external agent causes a reduction of pH (below 9.5) in order to start corrosion.

The two major agents which cause the reduction of alkalinity are the chlorides and carbon dioxide. The second will be discussed in this paper, since carbonation is a premise condition for steel corrosion in concrete under general atmospheric environment (Liang *et al* 2013). In Figure 2 and Figure 3 the carbonation process is explained step by step.

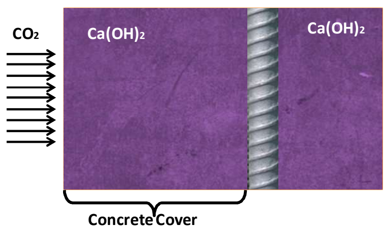

Figure 2 - Representation of the initial state of concrete in relation to carbonation.

Initially, the uncarbonated concrete has a pH around 12-13 (alkaline). As the diffusion of CO_2starts, the reaction described by Equation (1) will happen and, of course, the alkalinity of concrete will change due to the reduction of pH. As time goes by, the carbonation front advances (Figure 3) until it reaches the neighborhood of rebar. When this takes place it is said that the steel is depassivated. Usually, a threshold pH value of 8 to 9 is necessary to reach depassivation of the reinforcement (De Schutter, 2012). Therefore, the advancement of carbonation front is directly linked to the easiness that CO_2 finds when penetrating the concrete cover.

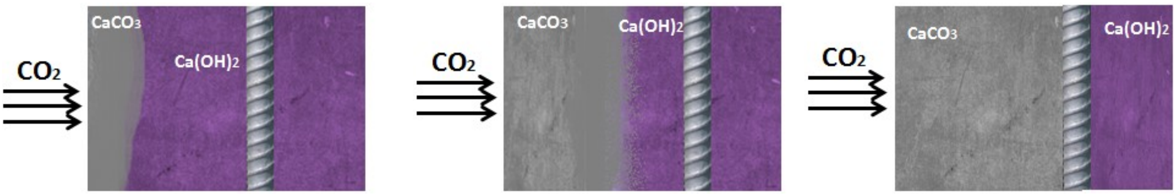

Figure 3 - Representation of Carbonation front advancement.

A considerable effort in modeling the carbonation of RC, in order to predict service life of structures has been made from a variety of authors and projects (e.g., Smolczyk 1969, Schiessl 1976, Tuuti 1982, Papadakis *et. al.* 1989, DuraCrete 1999, Jiang 2000, Hyvert 2009). Fagerlund (1985) mentioned that a service life estimate demands an extensive amount of data concerning the functional requirements, environment, deterioration mechanism and material properties. The problem when modeling such a complex phenomenon is the trade-off between the number of variables (extensive amount of data) to be considered and the difficulty to perform an analysis by obtaining those data.

For the past 70 years, carbonation has been studied and a large literature on this subject exists (Smolczyk 1969, 1976, Hamada 1969, Nepomuceno 1992, Helene 1981, 1986, Ho and Lewis 1987, Parrot 1987, Papadakis et al 1989, Bary and Sillier 2004, etc). Table **1** shows some of the most important models to predict the carbonation depth in RC structures. In general, these works agree that the most important variables influencing concrete carbonation are relative humidity, CO_2 concentration, curing of concrete and water/cement ratios.

Table 1 - Optimal *RH* for carbonation penetration.

Author	Model	Variables
Smolczyk (1969)	$e_c = k\sqrt[n]{t - t_0}$	e_c = carbonation depth (mm) k = coefficient of carbonation t = exposure time (year) n = paramenter related to the type of cement
Schiessl (1976)	$e_c = \left(\frac{2D(\Delta c)}{a}\right)^{1/2}\sqrt{t}$	D = Diffusion coefficient (m^3/s) Δc = diference of CO_2 on air and structure
Parrot (1994)	$e_c = 64\left(\frac{t^n K^{0,4}}{c^{0,5}}\right)^{1/2}$	c = CaO concentration (mol/kg) n = depend on relative humidity K = specific permeability of oxygen
CEB (1997)	$e_c = \sqrt{\frac{2D_{CO_2}}{a}tC}$	a = CO_2 to complete carbonatioin C = atmospheric CO_2 concentration (gcm^{-3})
Yoon (2007)	$e_c = \sqrt{\frac{2D_{CO_2}(RH,t)}{a(C_{CO_2})}C_{CO_2}(t)t\left(\frac{t_0}{t}\right)^m}$	a = CO_2 to complete carbonatioin n = age factor C = atmospheric CO_2 concentration (gcm^{-3})
Model Code (2010)	$e_c = \sqrt{2k_e k_c R_{NCC,0}^{-1} C_s \sqrt{t} W(t)}$	k_e = environmental function k_c = execution transfer parameter W = weather function $R_{NCC,0}^{-1}$ = carbonation resistance ((mm^2/years)/(kg/m^3)) C_s = atmph. CO_2 concentration (kg/m^3)
	Common variables	e_c = carbonation depth (mm) t = exposure time (year) D_{CO_2} = diffusion coefft. (cm^2sec^{-1})

3 MODEL CODE - FIB34

In 1999, a joint project between 12 different partners, companies, institutes and universities in the EU member states formulated a model to estimate the carbonation induced corrosion of uncracked concrete. This model was slightly revised in the research project DARTS and a full probabilistic approach of this method is the basis of the model described in the Model Code (FIB, 2010).

Commonly, when carbonation is the deterioration mechanism, the depassivation probability is computed having concrete cover as "capacity" and carbonation depth as "demand". The same approach is used in the Model Code (2010). According to this model, the carbonation depth is based on the following equation:

$$x(t) = \sqrt{2k_e k_c (k_t R_{ACC,0}^{-1} + \varepsilon_t) C_s} \sqrt{t} \; W(t) \tag{2}$$

and, consequently, the limit state equation is given by:

$$g(t) = cover - \sqrt{2k_e k_c (k_t R_{ACC,0}^{-1} + \varepsilon_t) C_s} \sqrt{t} \; W(t) \tag{3}$$

where:

- *cover* is the concrete cover [mm]
- $x(t)$ is the carbonation depth at the time t [mm]
- t is time [years]
- k_e is the environmental function which takes into account the relative humidity
- k_c is the execution transfer parameter
- k_t is regression parameter
- $R_{ACC,0}^{-1}$ is the inverse effective carbonation resistance [(mm²/years)/(kg/m³)]
- ε_t is the error term
- C_s is the CO_2 concentration [kg/m³]
- W is the weather function.

This equation is based on Ficks's first law of diffusion and it is assumed that the diffusion coefficient for CO_2 is a constant material parameter. It is clear that one of the main reasons that makes this model relatively complicated is the amount of data which is required to compute Equation (3). Depending on where the structure is located and how old it is determine, for example, the k_e or $R_{ACC,0}^{-1}$ values can be impossible. On the other hand, what is the theoretically weakness of the model it is also its strength. Since the model consider a large number of parameter such as: relative humidity, number of days with considerable precipitation, concentration of CO_2 and also number of days of concrete curing, it is supposed that the model is capable of taking into consideration a reasonable amount of information that directly influence the penetration of CO_2 inside the concrete. A short description of how the Model Code computes these variables are now presented.

3.1 Estimation of parameters

- Environmental function k_e

The relative humidity (*RH*) is one of the main causes for carbonation of concrete. In order to consider its effect the environmental function is given by:

$$k_e = \left[\frac{1-\left(RH_{real}/100\right)^{f_e}}{1-\left(RH_{ref}/100\right)^{f_e}} \right]^{g_e} \tag{4}$$

where RH_{real} is the relative humidity of carbonated layer, RH_{ref} is the reference relative humidity taken equal to 65%, f_e and g_e are exponents equal to 5 and 2.5, respectively. These exponents are independent of exposure conditions. Since it is very difficult to determine the RH_{real}, as results for carbonated area would be necessary, a justifiable approximation can be made: to use relative humidity data from the ambient air around the structure. Therefore, data from the nearest weather station can be used.

In 2015 the total number of weather stations in Brazil was almost 500. As it can be seen in Figure 4 and in Figure 5 the most important regions have stations. Accessing information from these station is quite a easy task, all one has to do is to go to the National Meteorological Institute website. Normally, the NMI provides data enough to make any kind of analysis.

Figure 4 - Automatic Weather stations in Brazil.

Figure 5 - Manual Weather stations in Brazil

From the NMI website, one can gather data such as daily precipitation, relative humidity, temperature, wind speed and direction, pressure and radiation. With the daily average measurements of relative humidity Table 2 was constructed in order to show some mean values of that parameter throughout Brazil.

Table 2 - Statistical data for *RH* in Brazilian cities.

City	Mean	Stand. Deviation	Max	Min
Fortaleza/CE	77,46	6,49	97	58
Guaramiranga/CE	87,11	6,51	100	41
Boa Vista/RR	73,69	10,43	100	42,75
Caratinga/MG	75,9	9,6	99,75	32,25
Bento Gonçalves/RS	76,02	12,31	98,75	31
Guarulhos/SP	74,19	9,24	99	32,75
Crateus/CE	60,23	16,07	97,25	30

Even though there is no consensus on which percentage of *RH* is the one that will lead to the deepest carbonation, most authors consider values between 50% and 80%, as can be seen in Table 3:

Table 3 - Optimal *RH* for carbonation penetration.

Authors	*RH(%)*
Helene (1986)	65 - 85
Parrot (1987)	50 - 70
Papadakis, Vayenas e Fardis (1989)	50 - 65
Andrade (1992)	50 - 80
Neville (1997)	50 - 75
Russell et al. (2001)	55 - 75

The Model Code does not completely agree with Table 3, since the behavior of k_e with respect to *RH* clearly shows that, for small values of humidity, the environment function has the highest values. In fact, for all values of relative humidity lower than 50%, k_e displays the maximum values of 1.4.

- Execution transfer parameter k_c

As the curing of concrete has a great impact on permeability and porosity of concrete structures, it is coherent that the curing time also has a considerable influence on the effective carbonation resistance (Uomoto *et al.*, 1993; Neville, 1997). The execution transfer parameter takes this influence into account through Equation (5). According to Model Code (2010), b_c is the dimensionless exponent of regression and t_c is the period of curing in days. The Model Code (FIB, 2010) quantifies the exponent of regression as a normal distribution with mean of -0.567 and standard deviation of 0.024. Figure 6 shows the average values of k_c considering t_c ranging from 0 to 30 days. The figure also shows that, after 7 days of curing, the values of k_c are smaller than 1, which means that, for a curing time greater than 7 days, the execution parameter actually cooperates to decrease the carbonation depth.

$$k_c = \left(\frac{t_c}{7}\right)^{b_c} \tag{5}$$

In Brazil, a common number of curing days (t_c) is around 2 or 3. The average variation of k_c in this case is around 25%. It means that the simple fact that instead of curing the concrete for 2 days the constructor decides to cure the concrete for 3, this one extra day is responsible for lowering average result of k_c from 2.03 to 1.62. Since carbonation depth has a square root relation with this parameter, it is straightforward that the carbonation depth is reduced in almost 12% when curing the concrete for one more day.

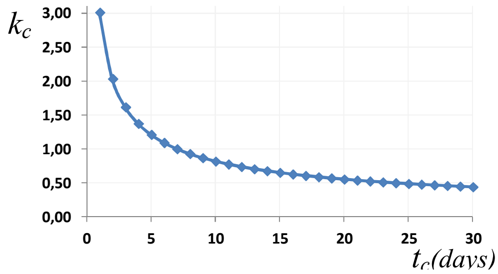

Figure 6 -Average values of execution transfer parameter x t_c.

- Environment impact C_s

The ambient air concentration of CO_2 expresses a direct impact on the carbonation depth of concrete structures. Figure 7 shows that CO_2 concentration has reached more than 400ppm. This is equivalent to 0.00072 kg/m³.

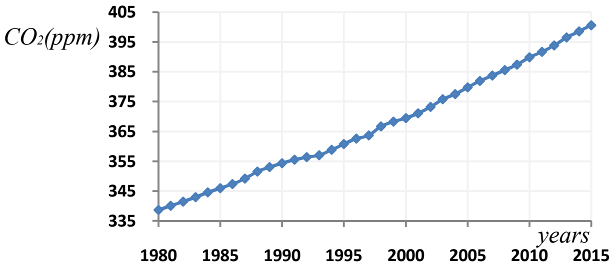

Figure 7 - CO_2 concentration in the Globe (Source:CO2Now.org, 2015).

Such level of concentration added to the concentration due to emission sources around the structure can definitely accelerate the carbonation process. Tunnels, chimneys and parking garages are sort of structures where additional CO_2 concentration must be considered. Even structures in urban environment are expected to have at least few times higher concentrations than the usual structures. For this kind of structure, the environmental impact can be calculated as sum of carbon dioxide on atmosphere ($C_{S,atm}$) and carbon dioxide due to emission source ($C_{S,emi}$):

$$C_S = C_{S,atm} + C_{S,emi} \tag{6}$$

When the structure has no additional source of carbon dioxide, the environmental impact will be represented only by the atmospheric concentration. One important aspect of $C_{S,atm}$ is its constant growth. Therefore, when predicting the carbonation depth the increase of this parameter must be considered. In such case, a grown ratio of 2 ppm/year is quite realistic.

- Weather function W

The presence of water inside concrete's pores has a very high influence on the diffusivity of carbon dioxide. When the pores are fully saturated, the carbonation process will hardly evolve, mainly, due to the reduced diffusion rate of CO_2 (Bakker,1988). This characteristic is considered by the weather function as described in the following equation:

$$W(t) = \left(\frac{t_0}{t}\right)^{\frac{(p_{SR} \cdot ToW)^{b_w}}{2}} \tag{7}$$

where:

t_0 is the time reference in years, generally adopted as 0.0767;

b_w is the exponent of regression taken as a normal distribution (μ=0.446, σ=0.163);

p_{SR} is the probability of driving rain. This variable represents the average distribution of the wind direction in rain events. Data from the nearest weather station can be considered. However, when analyzing horizontal elements this values is taken as 1. When the element is an interior structure, p_{SR} =0;

ToW is the time of wetness and is computed by:

$$ToW = \frac{\text{days with rainfall} \geq 2.5\text{mm per year}}{365} \tag{8}$$

The Model Code (FIB, 2010) recommends to take *ToW* as a constant value, but in this paper it is considered as a random variable, since data related to this are very common and well organized in Brazil. Figure 8 depicts the *W* behavior for Belém city (north of Brazil) taking into consideration different values of p_{SR}. Belém city is famous in Brazil because of the historical tradition of raining almost every day. On the other hand, Figure 9 shows the *W* behavior for Campina Grande city (northeast of Brazil),very dry and close to an outback region in Paraíba state.

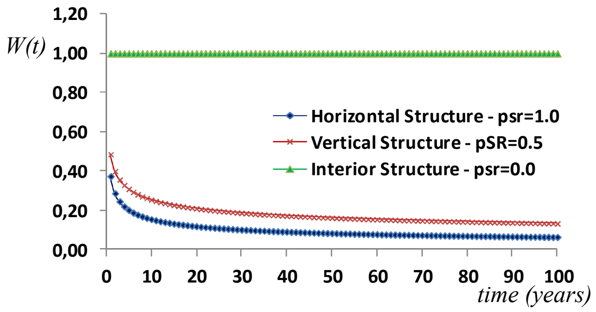

Figure 8 - W(t) for different values of p_{SR} for Belém city.

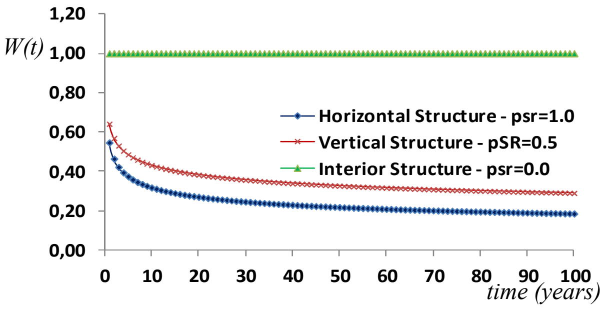

Figure 9 - W(t) for different values of p_{SR} for Campina Grande city.

With daily measurements of precipitation for the past 47 years, an average of 187 days/year have a rainfall equal to or greater than 2.5mm in Belém city, while in Campina Grande city this average is 66.62 days/year. Therefore, the *ToW* will have μ = 0.519, σ = 0.0466 and μ = 0.185, σ = 0.0410, respectively, in Belém and Campina Grande.

- Inverse carbonation resistance $R^{-1}_{ACC,0}$

When determining this parameter, an accelerated carbonation tests (ACC) is required. In such test laboratory pre-stored concrete specimens are tested under defined conditions (FIB, 2010). In general, this test takes 56 days and of course it is supposed to be done with the same concrete that will be used in the construction. It is easy to conclude that doing such test for existing concrete structures it is not an affordable process. But it is important to correctly estimate this parameter. Rozière *et al.* (2009), Khunthongkeaw (2006) and Papadakis (2000) pointed out that depending on the chosen cement mixture, this parameter can differ by an order of magnitude. Although it is suggested by Model Code that data from literature can be used, it is hard to classify the concrete of old structures. Besides, database that relates concrete type and inverse carbonation resistance is relatively small and does not cover all kinds of concrete.

In this paper a mathematical artifice is suggested to calculate the inverse effective carbonation resistance of concrete. A phenolphthalein test is performed and data from the period that the structure has been constructed is considered. In this case, the depth of carbonation front is known and since the construction date is also known using Equation (2) it is possible to determine the value of $R^{-1}_{ACC,0}$. When the mean value of $R^{-1}_{ACC,0}$ is computed, Equation (9), which relates mean and standard deviation of inverse effective carbonation resistance of concrete, can be used to compute the standard deviation of this parameter.

$$\sigma_{R^{-1}_{ACC,0}} = 0.69\mu^{0.78}_{R^{-1}_{ACC,0}} \tag{9}$$

The procedure to estimate $R^{-1}_{ACC,0}$ is as follows:

i) Compute the mean of RH_{real} and k_e with data from the bridge lifetime - Equation (4);

ii) Compute k_c , normaly t_c = 3 days - Equation(5);

iii) Compute C_s, also with data from the bridge lifetime - Equation(6)

iv) Compute *ToW*, so the *W* can be computed - Equations (8) and (7), respectively;

v) "*t*" is taken as the time from the end of construction until the test date;

vi) The maximum average value of carbonation depth found in the phenolphthalein test will be *x(t);*

vii) Compute $R^{-1}_{ACC,0}$ - Equation (2)

4 RELIABILITY ANALYSIS OF CARBONATION

A simple example is provided to begin to illustrate the concepts presented in this paper. The carbonation front will be estimated over time as described in Equation (2). Equation (3) will be used to compute the reliability index and probability of failure (actually, probability of depassivation) over time. The model is applied to a bridge over the Suaçui River, located close to the Governador Valadares city in the state of Minas Gerais (18°57'03.7"S 42°03'50.5"W).

The bridge was constructed in 1974 and it is part of an important chain of rail bridges used to transport ores. The total length of the bridge is 54.77 meters split into three spans of 18.67 meters. All the three spans are isostatic. Figure 10 and Figure 11 present a lateral view of the structure.

Figure 10 - Oblique view of Suaçui river bridge (2011).

Figure 11 - Oblique view of Suaçui river bridge (2011).

Data from Jan/1974 to Jan/2011 were used in this analysis. A total of 11000 daily measurements of relative humidity were used to construct a histogram as in Figure 12. Also, 11295 daily measurements of precipitation from the bridge's nearest weather station were considered in order to compute mean and standard deviation of *ToW*. A routine in Python was built to process these data. Following the procedure presented in the last subsection, the value of C_s can be estimated with data from the co2now.org. This organization maintains free access to concentration of carbon dioxide in our atmosphere since 1959. A time of concrete cure of 3 days was considered in this analysis.

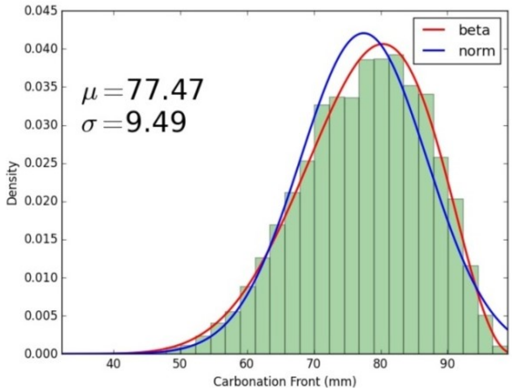

Figure 12 - Histogram of RH_{real} (1974-2011).

In order to apply Equation (2) to estimate the inverse effective carbonation resistance, it is necessary to measure the carbonation front in the bridge. Table 4 shows the results of phenolphthalein test made in 2011. The measurements were done with caliper rule of 0.01mm precision and phenolphthalein diluted in 1% of ethyl alcohol.

Table 4 - Carbonation front measures from Suaçui bridge.

Point of Measurement	Carbonation front (mm)		
	Min	Max	Mean
1	0.36	7.27	3.81
2	0.00	1.72	0.86
3	0.94	1.51	1.05
4	0.00	0.43	0.21
5	1.45	5.21	3.33
6	0.48	3.14	1.81
7	0.81	2.01	1.41
8	0.05	4.90	2.47
9	0.32	1.92	1.12
10	0.61	2.63	1.62
11	0.45	2.99	1.72
12	1.19	4.22	2.70
13	0.30	2.29	1.29
14	0.14	2.20	1.17
15	0.00	3.00	1.50
		Mean	1,74
		Std	0,93

With the mean value of the variables in Equation (2), and the results in Table 4 the mean value of $R_{ACC,0}^{-1}$ is computed as 740.6 (mm²/years)/(kg/m³). This value is considered to predict the carbonation front in the Suaçui bridges from 2011 on.

Table 5 - Statistical data used in the model.

Distribution	Parameter	Mean	Stand. Deviation	Unity
Beta	*RH_{real}*	77.47	9.49	%
Normal	*b_c*	-0.567	0.024	-
Normal	*C_s*	6.45e-4 + (3.6e-6)t	0.0001	kg/m³
Normal	*b_w*	0.446	0.163	-
Normal	*K_t*	1.25	0.35	-
Normal	error	315.5	48	(mm²/years)/kg/m³)
Normal	*ToW*	0.182	0.0249	-
Normal	*R_{ACC}^{-1}*	740.61	423.51	(mm²/years)/kg/m³)
Normal	Cover	35	10	mm

In Table 5 all statistical data are summarized. Special attention must be given to the fact that *Cs* is updated each year by a factor of 2 ppm. With the exception of relative humidity, all random variables are modeled by a Gaussian distribution as the Code requires.

A Monte Carlo simulation with 50000 samples was performed to compute the histograms from Figure 13 to Figure 16. As expected, the depth of carbonation front is increasing as time goes by. Also, it is worth noting that the beta and lognormal distribution fit very well the data over time. The beta distributions are considered in performing reliability analysis.

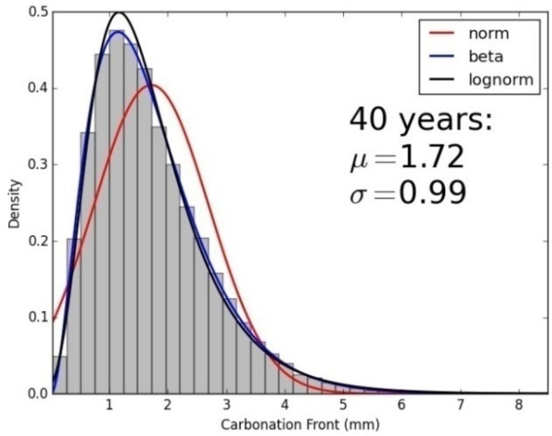

Figure 13 - Histogram of carbonation for 40 years.

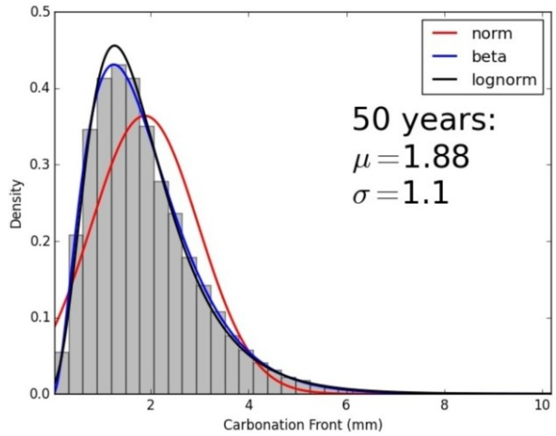

Figure 14 - Histogram of carbonation for 50 years

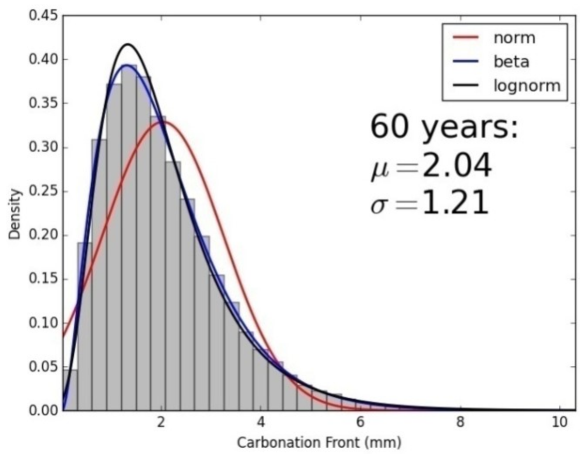

Figure 15 - Histogram of carbonation for 60 years

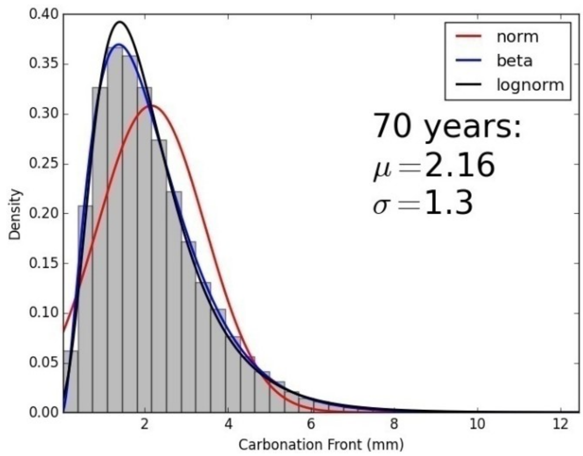

Figure 16 - Histogram of carbonation for 70 years

In order to make a time-dependent reliability analysis of Equation (3), an Importance Sampling Monte Carlo simulation and a First Order Reliability analysis were performed. A point-in-time approach will be considered to make analysis over time. This means that the time effects are sequentially taken into account at many points in time across the structure's lifetime. Each computation gives the probability of failure specific to the point in time considered. Figure 17 and Figure 18 depict the results of these analyses and Figure 19 provides the behavior of the distributions over three different time steps. The analysis stands thirty-eight years, which gives a total lifetime of seventy-five years, as the bridge is already thirty-seven years old. As expected, the reliability index decreases over time while, of course, the probability of failure increases.

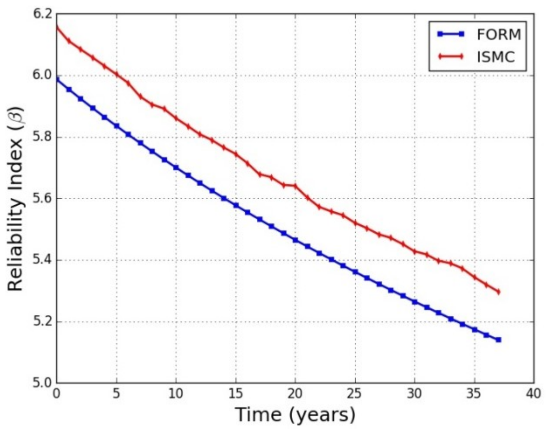

Figure 17 - Reliability Index evaluated by FORM and ISMC simulation.

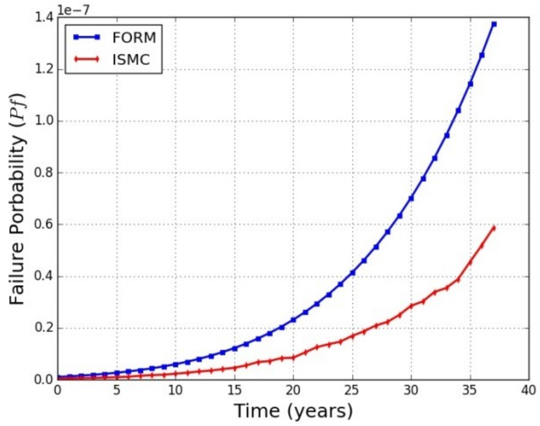

Figure 18 - Failure probability evaluated by FORM and ISMC simulation.

The initial value of reliability index is 5.99 for FORM and 6.15 for ISMC. The probabilities of failure computed by FORM are more conservative than the ones computed by ISMC, probably because the failure domain is convex. After 35 years, the reliability index reaches 5.16 and 5.32 for FORM and ISMC, respectively. The Model Code fixes the limit value of reliability index for depassivation in 1.3. Thus, it is safe to argue that, based on the finding of this example and according to Model Code limit, the bridge over the Suaçui River would not likely suffer corrosion due to carbonation of concrete.

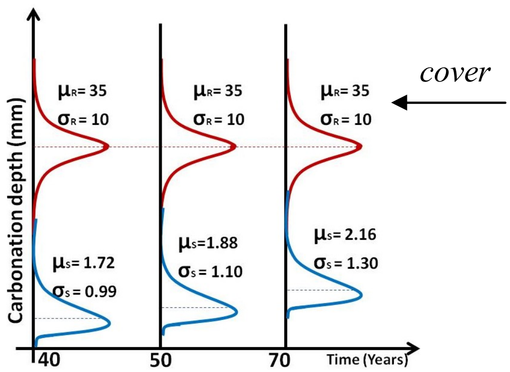

Figure 19 - Behavior of the distributions over different time steps.

5 CONCLUSION

A time-dependent point-in-time probabilistic approach to perform carbonation front depth prediction in RC structure has been presented. Even though a variety of methods are available to detect carbonation penetration, there is no consensus on which method yields the most reliable results. What is expected is that a method which considers more variables related to the process tends to be more realistic and it is believable to be more accurate. The methodology presented in this paper is a feasible way of predicting the carbonation front over time, while considering a significant number of random variables related to this problem.

In this work a mathematical artifice is used to computed the inverse effective carbonation resistance of an existing concrete bridge. Results from phenolphthalein test and data from the period that the structure has been constructed is considered. The procedure consists in determining the inverse effective carbonation resistance by Equation (2). With $R_{ACC,0}^{-1}$ value estimation can then be made.

One specific disadvantage of the procedure applied in this paper is that the region where the structure is located may not have a weather station close enough to offer representative data. Also, it could happen that the station exists, but the data is scarce or not reliable. Another drawback of this procedure is that it can only be applied to older bridges, since it must have developed an initial carbonation front, from which the inverse carbonation resistance is evaluated. It is important to mention that, when computed as described in this article, carbonation inverse resistance loses its physical meaning, since it is computed through a mathematical artifice. The procedure presented in this paper may appear to be very long, but once it is implemented, it is easy and fast to perform.

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