Methodology of Taking Local Climate Data into the Concrete Carbonation Depth Prediction. Proposition of a Model Predicting the Temporal and Spatial Variation of the Carbonation Depth on Cooling Towers.

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Abstract

EDF operates a large fleet of cooling towers for its thermal and nuclear plants. The ageing of their atmospheric cooling tower shells is periodically monitored. Generalized corrosion due to the carbonation of the concrete cover is considered as an important ageing risk for the tower shell. That's why predicting its evolution with respect to time is necessary in order to optimize the towers' maintenance program. Our monitoring data showed that the carbonation depth varies in different zones on the same cooling tower shell. According to our observation, this variation is related to the direction and the frequency of winds arriving to the cooling tower. Unfortunately, carbonation prediction models available in the literature are unable to predict this phenomenon.

Based on the monitoring data of the local climate around the cooling towers and the experimental data of their material properties and carbonation depth, EDF R&D has developed an analytical model allowing the prediction of the carbonation depth spatial variation and its evolution with respect to time. In this model, the impact of wind is taken into account by a parameter called effective carbonation time. The impact of the orientation of the concrete surface is taken into account by adapting a specific parameter of Duracrete model developed in the literature to the model of this study. Furthermore, we integrate the advantages of some other models existing in the literature in order to make the model reliable and complete. The model has been validated by comparing the prediction with the values measured on four cooling towers of EDF.

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I. INTRODUCTION

EDF operates a large fleet of cooling towers for its thermal and nuclear plants. The ageing of their atmospheric cooling tower shells is periodically monitored. Generalized corrosion due to the carbonation of the concrete cover of structures is considered as an important ageing risk for the tower shells. That's why predicting its evolution with respect to time is important to optimize maintenance program of the towers.

The monitoring data acquired by EDF showed that the measured carbonation depth varies from one zone to another on the same cooling tower shell [Fig. 1.]. This variation seems to be related to the orientation of concrete surfaces which are exposed to the wind, the water vapor plume, the rain and the environment humidity. Unfortunately, carbonation prediction models available in the literature are unable to predict this phenomenon.

The objective of this study is to build a new model able to predict the temporal and spatial evolution of the carbonation depth on the cooling tower. This model need to be useful for EDF's engineering services when assessing the cooling towers' aging.

Our important experimental data source includes the local climate data (of EDF DTG) measured on the nuclear power plant sites and the data related to the carbonation depth & material properties (measured by EDF CEIDRE & EDF CNEPE). Thanks to these data, a correlation between the environment-exposed orientation of concrete surface and the spatial variation of the carbonation depth has been found. An analytical formulation of this correlation has been developed to model this phenomenon. After, based on the above formulation and the advantages of other models of the literature [1, 2, 3], a new model able to predict the temporal and spatial evolution of the carbonation depth at all positions on the cooling towers has been developed. The model has been validated by comparing the prediction results to the monitoring data acquired on some cooling towers of EDF. In this study, the cooling towers are renamed due to the confidentiality of their data.

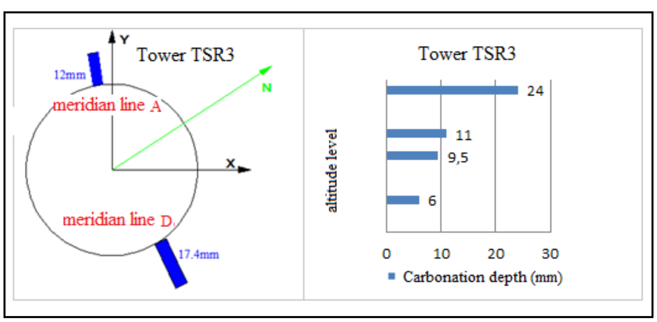

Fig. 1. Illustration of the spatial variation depth in azimuthal and vertical directions observed on the tower TSR3 (in the right: mean value by meridian line, in the left: mean value by zone on the meridian line A).

II. METHODOLOGY OF PREDICTING THE SPATIAL VARIATION OF THE CARBONATION DEPTH

A. How to explain the spatial variation of the carbonation depth

As mentioned above, the wind has a direct impact on the direction of the water vapor plume of the cooling towers. The water vapor plume could belong to the analyzed tower or come from its next towers. That's why on the zone which is exposed to the water vapor plume [Fig. 2.], the environment relative humidity (RH) is higher than on the opposite zone. So, the carbonation propagation is slower in the vapor plume exposed zone. On the other hand, due to the wind and to the orientation of concrete surface, the RH is higher in the bottom than in the top of tower. This could explain why we observe a carbonation depth lower in the bottom than in the higher zones of the cooling tower.

B. Method of processing the monitored climate data

An illustration of the climate data measured at each cooling tower site is presented on the table [Table 1.].

The data are measured at the climate station of the cooling tower site. The temperature, the pressure and the relative humidity are monitored in a position sheltered from the rain and located at one meter from the ground. The wind is monitored at the top of a ten meters high pole.

The wind frequency is the appearance frequency. Each month, there are around "n" (between 4300-4500) records of the wind appearance. The record is done every ten minutes. If the wind in a certain direction is recorded b times, the frequency of the wind in that direction is equal to the ratio b/n. A wind is called "prevailing wind" if there are the most records in its direction.

For most of the time, the cooling towers are in operation and their concrete shell is subjected to the water vapor plume. So, the impact of rain is very small compared to the vapor plume. In this study, the rain data are not taken into account.

Back to the wind data, because the number of records per

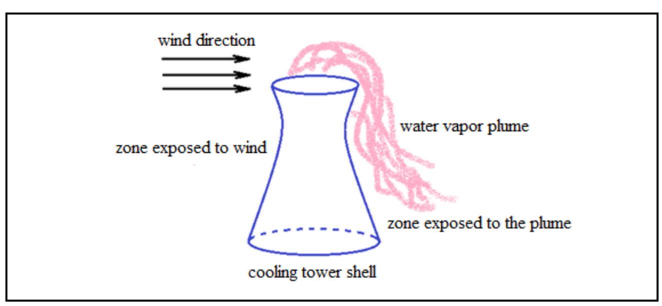

Fig. 2. How the wind makes impact on the cooling tower

Table 1. Format of a climate monitoring record. (the most important data is in the red box)

	WIND				Hygro	Rain	Temperature
Month	Prevailing direction compared to the geographical North (in degrees)	Frequency of prevailing wind %	Average speed of the prevailing wind m/s	Average speed of all directions of wind m/s	Average relative humidity %	Precipitations 1/10 mm	Temperatures °C
janv-90	180	33,9	3,0	2,5	95	64	3,0
févr-90	180	20,6	2,9	5,2	84	1015	
mars-90	360	12,6	3,6	3,0	78	96	9,0
avr-90	360	10,1	3,1	3,3	75	488	8,4
mai-90	60	15,4	5,1	4,1	69	228	9,3
juin-90	240	21,8	6,1	4,5	76	658	15,7
juil-90	60	17,1	5,5	5,0	64	156	
août-90	240	18,5	5,3	4,6	64	488	20,5
sept-90	60	18,1	5,3	4,9	73	186	21,4
oct-90	160	18,9	6,0	5,3	84	728	14,8
nov-90	260	14,7	6,3	4,4	92	670	12,9
déc-90	240	10,8	6,0	4,6	90	552	6,7
janv-91	240	14,9	6,7	4,7	88	439	3,4

month "n" is very big, the appearance frequency tends to the ratio between the duration of the wind in the prevailing direction and the total time of the considered period (1 month). The sum of these values over all recorded duration (16 years) determine the total duration (in months) of the prevailing wind in the considered direction. Applying this calculation for other prevailing wind directions, we will have the total duration of every prevailing wind directions recorded by the climate monitoring station. It is calculated by the equation {1}:

$$\{1\} t_{pw}^{(i)} = \sum_{j=1}^{p} f_j^{(i)} \ (months)$$

where "f" is the appearance frequency of the prevailing wind in the direction "i" during the month "j", "p" is the number of months when the direction "i" is prevailing.

For each site, there are only several wind directions. From one period to another, there are always one direction which is prevailing. Because the monitoring duration is long enough and monitoring data volume is big enough (16 years = 16*12 months), one hypothesis is adopted in this study: the total appearance duration ratio of one wind direction to another one doesn't change whether they are prevailing or not. So, we can calculate the total duration of the wind in the direction "i" over "t" years of monitoring by the equation {2} and the total appearance frequency of this direction by the equation {3}:

$$\{2\} t_w^{(i)} \approx \frac{t_{pw}^{(i)}}{\sum_{i=1}^{m} t_{pw}^{(i)}}.12.t = \frac{\sum_{j=1}^{p} f_j^{(i)}}{\sum_{i=1}^{m}\left(\sum_{j=1}^{p} f_j^{(i)}\right)}.12.t(months)$$

$$\{3\} P_i = \frac{\sum_{j=1}^{p} f_j^{(i)}}{\sum_{i=1}^{m}\left(\sum_{j=1}^{p} f_j^{(i)}\right)}$$

where "m" is the number of the wind directions observed in-situ.

C. Results of climate data processing

For the sake of illustration, the results of processing climate data for the two towers TSR3 and TTN1 are presented in the figure [Fig. 3.]. Each tower shell is divided in eight zones (A, B, C, D, E, F, G and H) in the azimuthal

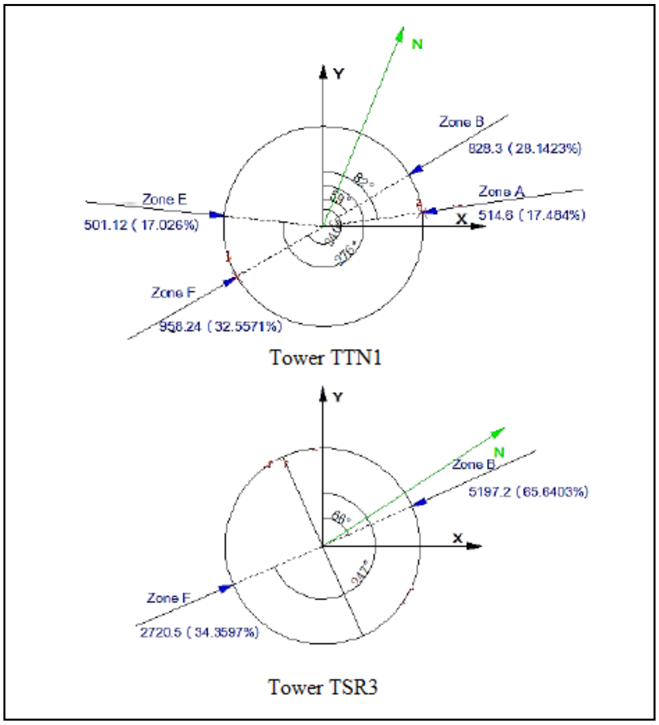

Fig. 3. Results of climate data processing for the towers TTN1 and TSR3

direction. The wind directions determined by the above processing method are projected to these zones. The tower TTN1 is subjected to four main wind directions coming to the zones A, B, E and F. The tower TSR3 is subjected to two main wind directions coming to the zones B and F. For each direction, we have the informations on the angle determining the direction and the frequency determining its appearance duration.

D. Introduction of the notion "effective time"

When a position on the cooling tower shell is exposed to the water vapor plume, the relative humidity is very high on it. So, the carbonation propagation is stopped. The propagation process continues after the wind direction changes. That is why we introduce in this study the notion "effective time" which is defined as the total time during that the studied point is not exposed to any water vapor plume. It is calculated by the below formula:

$$\{4\} t_{eff} = 12t - \sum_i^k t_w^{(i)} = 12t - 12t \sum_i^k (\varphi_i P_i) \quad (month)$$

$$\{4\} t_{eff} = t\left(1 - \sum_i^k (\varphi_i P_i)\right) (year)$$

where "$t_w^{(i)}$" and "P_i" are calculated by {2} and {3}. "k" is the number of the wind directions stopping the carbonation at the studied point. "φ_i" is a coefficient taking into account the position of the studied point.

The meaning of the coefficient "φ_i" is to reduce the impact of the wind depending on the position of the studied

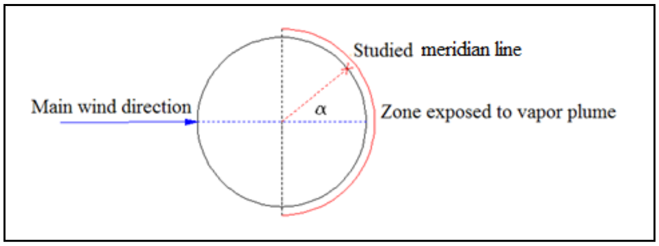

Fig. 4. Water vapor plume exposition level varies depending the angle α.

point in the zone exposed to the vapor plume. As illustrated on the figure [Fig. 4.], the position of the studied point is determined by the angle α. When α=0°, the impact of the wind is maximum. When α=90°, the impact of the wind is negligible. When α takes an intermediate value, the impact of the wind is reduced by the coefficient "φ_i" which is calculated as below:

$$\{5\}\varphi = \frac{90° - \alpha}{90°}$$

E. How to take into account the orientation of concrete the surface from the bottom to the top of the cooling tower shell

The monitoring data show that the carbonation depth is slower in the bottom and higher in the top of the same vertical meridian line of the cooling tower shell. This variation could be explained by the orientation of the concrete surface. Regarding this orientation on the cooling tower shell, we realize that, in the lower zones, the surface stagnates more easily the water vapor coming from the plume. This impact has been introduced in the model Duracrete [1] whose formula having the format as below:

$$\{6\}x_c = A\sqrt{t}\left(\frac{t_0}{t}\right)^n \ (m)$$

where "t_0" is a reference time which is equal to 1 year, "t" is the real age of the studied structure, "n" is the parameter allowing to take into account the impact of the surface orientation, "A" represent the impact of all other parameters of the model As illustrated on the figure [Fig. 5.], the value of "n" is equal to 0.1 if the surface is completely sheltered from the rain or the vapor plume and it is equal to 0.4 if the surface is highly exposed to the rain or the vapor plume. If the surface is inside, its value is equal to zero.

Adapting this formula to our study, the term $\sqrt{t}$ is replaced by $\sqrt{t_{eff}}$. The parameter "n" of the important term $\left(\frac{t_0}{t}\right)^n$ need to be determined with respect to surface orientation. In general, the cooling tower shell is vertically divided in four zones as shown on the figure [Fig. 5.]. The value of "n" has to increase from the top to the bottom. At the bottom zone, we observe that it is often wet because of the condensation of the water vapor falling from the plume or coming from the space under the base lintel. The value of "n" in this zone is set to the maximum value (0.4). Four the

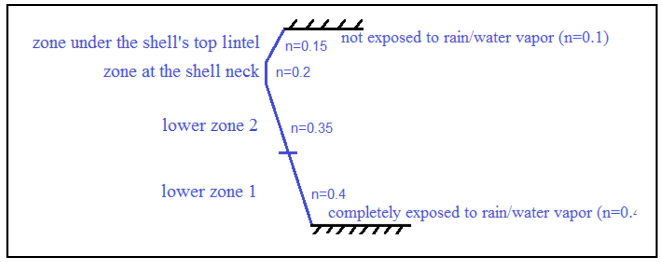

Fig. 5. Proposition of values for the parameter "n" with respect to surface orientation.

three remaining zones, we propose the intermediate values 0.35, 0.2 and 0.15 as presented in the figure [Fig. 5.].

F. Final formula and validation of the methodology predicting the spatial variation of the carbonation.

Based on the developments mentioned above, we could introduce the final formula of the methodology predicting the spatial variation of the carbonation depth:

$$\{7\}x_c = A\sqrt{t\left(1 - \sum_i^m(\varphi_i P_i)\right)}\left(\frac{t_0}{t}\right)^n$$

At this step, we focus on the spatial variation, that's why the term A is not built in this section. It will be proposed for the next section related to the development of a complete model predicting the carbonation depth.

In order to validate this formula, we have applied the model to different towers and calculated the carbonation depth ratio of one zone to another zone on the same cooling tower shell. Then, this calculated ratio is compared to the experimental ratio determined from monitoring data.

First, this validation is done for the azimuthal variation of the carbonation depth. For this purpose, the carbonation depth ratio of a vertical meridian line to another vertical meridian line is calculated using the formula {7} with the value of zero for the parameter "n". The experimental ratio is acquired by comparing the average carbonation depth measured on a vertical meridian line to the one measured on another vertical meridian line. The table [Table 2.] shows the errors for four towers (TTN1, TSR3, TMN4 and TLL1). In the field of concrete carbonation & corrosion, the prediction error is often around 20-30%. In this study, these errors are so small that the prediction could be considered very successful.

Then, the validation of the model is also carried out for

Table 2. Carbonation depth ratio of a vertical meridian line to another one - comparison between the calculated and experimental values.

	TTN1	TSR3	TMN4	TLL1
Measured ratio	0.99	1.45	0.86	0.97
Calculated ratio	0.98	1.35	0.92	0.88
Error (%)	0.71%	6.85%	7.20%	10%

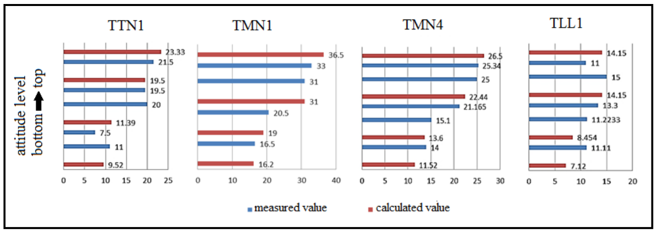

Fig. 6. Relative comparison of the carbonation depths calculated and measured on each vertical meridian line.

the vertical variation on the same meridian line. This time, the comparison is illustrated by diagram. For this purpose, using the average measure value at the shell neck zone as reference value, the absolute values of the carbonation depth at one zone on the same vertical meridian line are calculated as product of the reference value and the carbonation depth ratio between the studied zone and the reference zone. The figure [Fig. 6.] show us how the methodology allows a good prediction of the spatial variation of the carbonation depth on each vertical meridian line.

III. PROPOSITION OF A COMPLETE MODEL PREDICTING THE CARBONATION DEPTH ON IN-SITU STRUCTURES

A. Strategy adopted for developing an engineering-oriented model

In order to build a complete and strong model, the last work to do is determining a formula for the term “A” in the equation {7}. In general, this term takes into account the impact of the local environment (T & RH parameters) and material properties (cement type, f_c, W/C, chemical composition...). For the civil engineering structures in service, it is not easy to have the information about the chemical composition of concrete. Moreover, when using the chemical composition data, the prediction precision gain is smaller than the error due to the incertitude of the material properties on a real structure. So, the empirical models using the easily accessed parameters (like T, RH, cement type, f_c, W/C) are more suitable for engineering studies.

In 2013, a study inside EDF has tested different models in terms of predicting the average carbonation depth of some cooling towers of EDF. The model Leo [2] was concluded quite reliable and the most suitable for engineering studies. That’s why it will be used in this study to develop the new model. However, its’ inconvenient is no taking into account the cement type. Fortunately, the impact of the cement type is proposed in the model Hakkinen [3]. So, the strategy adopted for this study is to combine the model Leo and the model Hakkinen to build a formula of the term “A” mentioned above.

Table 3. Values of the parameters “a” and “b” for different types of cement.

	a	b
Portland cement (p.c.)	1800	-1.7
p.c.+ fly ash 28 %	360	-1.2
p.c.+ silica fume 9 %	400	-1.2
p.c.+ blast furnace slag 70 %	360	-1.2

B. Development of a new and complete model

The model Leo [2] has its original expression as in the equation {8} where the parameters “f” and “k” are given in {9} and {10}. Integrating the term “A” of this model to our study, we have the expression of the new model as in {11}.

{8} $x_c = \gamma.f.k.\sqrt{t}$ (cm)

{9} $f(RH) = -3.5833.RH^2 + 3.4833.RH + 0.2$

{10} $k(f_c) = \sqrt{365}.\left(\frac{1}{2.1.\sqrt{f_c}} - 0.06\right)$

{11} $x_c = \gamma.f.k.\sqrt{t.(1-\sum_i^m(\varphi_i P_i))}.\left(\frac{t_0}{t}\right)^n$ (cm)

The parameter “γ” of the model Leo is built to take into account the rain exposition level of the concrete surface. In our model, this is taken into account by the parameter “n”. So, the unique value of “γ” (=1.2) corresponding to the condition that the surface is sheltered is taken for the new model. Because this condition corresponds to the value 0.1 for “n”, the new model’s formula is rewritten as in the equation {12}.

{12} $x_c = 1.2.f.k.\sqrt{t.(1-\sum_i^m(\varphi_i P_i))}.\left(\frac{t_0}{t}\right)^{n-0.1}$ (cm)

Now, we have a new model allowing predicting the carbonation depth in the concrete made of Portland cement. In order to have a complete model, we need to integrate the impact of cement type into the model. This integration is inspired from the parameters “a” and “b” of the model Hakkinen [3] which has its expression as in the equation {13}. The values of “a” and “b” are determined by interpolation based on the reference values in the table 3. The parameter “f_{cm}” is the average strength of concrete. Applying these parameters to the new model, it is necessary to introduce a new parameter “C” represents the increase/decrease in the carbonation depth from the one of Portland cement. This parameter is calculated as in the equation {14}.

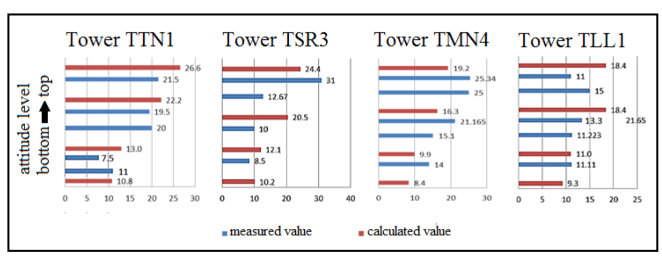

Fig.7. Carbonation depth profile (in mm) calculated by the new model and measured on scored specimens for four towers of EDF.

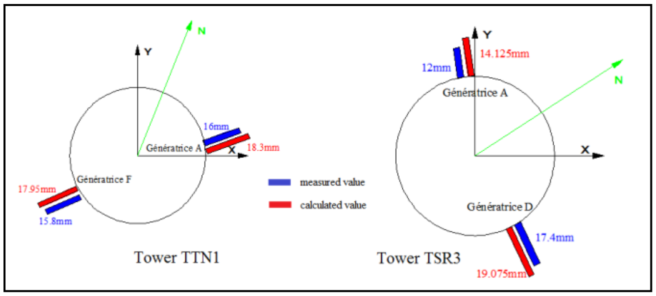

Fig.8. Carbonation depth averaged on each of vertical meridian lines of the towers TTN1 and TSR3, calculated by the new model and measured on scored specimens.

$$\{13\} x_c = c_{env}.c_{air}.a.f_{cm}^{b}.\sqrt{t}\ (\mathrm{mm})$$

$$\{14\} C = \frac{a.f_{cm}^{b}}{1800.f_{cm}^{-1.7}}$$

Integrating "C" into our study, we have the final expression of the new model in the equation {15} where the parameters "f", "k" and "C" are determined by the equations {9}, {10} and {14}.

$$\{15\} x_c = 1.2.f.k.C.\sqrt{t.(1-\sum_i^m(\varphi_i P_i))}.\left(\frac{t_0}{t}\right)^{n-0.1}\ (cm)$$

C. Validation

The new model has been applied on different towers of EDF. Without fitting any parameter, the model manages to give a good estimation of the carbonation depth at different positions on the same cooling tower shell. The figures [Fig. 7. and Fig. 8.] show some validation results. The values calculated by the model are close to the ones measured on the specimens scored from the cooling towers. In terms of average carbonation depth for each tower, the model gives a very good prediction with errors less than 10-15%. Furthermore, the model captures well the azimuthal and vertical variations of the carbonation depth. Nevertheless, at some local points, the measure-compared prediction error is bigger and gets in the range 15-30%. This is unavoidable because there is always some incertitude of material properties on an in-site structures.

IV. CONCLUSION

The work carried out in this study has shown clearly the importance of taking into account the wind direction and the concrete surface orientation in order to predict well the spatial variation of the carbonation depth with respect to time on real structures.

The climate monitoring data processing methodology and the carbonation prediction model developed in this study have shown their performance when applied to real structures. It is the first model able to predict the carbonation depth variation in both directions: azimuthal and vertical. In most of positions on the structure surface, the prediction error is less than 15%. It is a good improvement compared to other models existing in the literature that we have tested on the cooling towers of EDF. Another advantage of this model is that its parameters are easy to access and the model is easy to use for engineers.

The developed model could be useful for the cooling tower operators to predict the corrosion risk of the structure with respect to time, to determine the most risky zones and to optimize the maintenance program for these structures. A numerical tool suite built for this objective has been recently developed at EDF R&D for the engineering services of EDF [4]. The model will be integrated in this tool suite.

The approach developed in this study could be extended to other big civil engineering structures like high buildings, bridges, dams…

Due to the incertitude of material properties on big structures, there is always some error in carbonation prediction. That's why it is difficult to obtain a better precision than 10-15%. If the operators of these structures have enough data on this incertitude, the model could be used in a probabilistic study in order to have more reliable results.

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