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fib models for modeling of chloride ion ingress and concrete carbonation: Levels of assessment of input parameters

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Abstract

Degradation processes affecting structural materials, such as chloride ion ingress, concrete carbonation, and the subsequent corrosion of reinforcement, are limiting factors for the service life of reinforced concrete structures and/or structural elements. The objective of a structural condition assessment is to determine the current state and estimate the future performance of a structure with a maximum degree of accuracy and a minimum of effort. There is therefore a need for advanced methodologies and predictive deterioration models for the assessment of structures/structural elements over time. In the paper, the focus is on the widely accepted models for modeling of chloride ion ingress into concrete and concrete carbonation process incorporated in the *fib* Model Code 2010. Three levels of assessment of input parameters are presented, starting with simple quantification based on codes/literature recommendations and progressing to higher levels of assessment using design documentation and visual inspection data, additional on-site measurements, and/or laboratory tests.

KEYWORDS

chloride ion ingress, concrete carbonation, *fib* model code 2010, levels of assessment

1 | INTRODUCTION

The service life and durability of reinforced concrete structures and/or structural elements are affected by degradation processes which act on structural materials. Concrete carbonation, chloride ion ingress, and the subsequent corrosion of reinforcement are the most common deterioration phenomena.

Within the management of structures, due to the desire to minimize overall cost, the most common type of structural evaluation is the nonformal assessment, where the condition of a structure is evaluated on the basis of visual inspections. The objective of a structural condition assessment is to determine the current state of a structure and estimate its future performance with a maximum degree of accuracy and a minimum of effort. Data collected during visual inspections should mainly provide information about the most serious problems and suggest the most suitable scheme for the extension of the performed inspection via monitoring, additional on-site measurements, and/or laboratory tests.

In order to ensure the desired durability outcomes occur, modeling based on mathematical principles and measured material characteristics is seeing increased use in durability design. The *fib* Model Code 2010[1] has

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incorporated a performance-based approach for such design. Here, the verification of limit states associated with the durability of structures may be performed using the following approaches: (a) the fully probabilistic format; (b) the partial safety factor format; (c) the deemed-to-satisfy approach; and (d) the avoidance-of deterioration approach. In general, structural assessment is carried out using limit state principles with characteristic values and partial safety factors. However, only the fully probabilistic approach provides quantitative information about safety level and hence is increasingly supported if more refined methods are necessary.

The aim of this paper is to describe the levels of assessment of input parameter values for the prediction of deterioration due to chloride ion ingress into concrete and concrete carbonation process for existing structures. Due to inherent uncertainties in material, technological, and environmental characteristics, stochastic models, dealing with probabilistic approaches and presenting the performance-related design of structures for durability, are recommended creating an effective tool for the assessment and prediction of time-dependent degradation processes (see *fib* Model Code 2010[1] and ISO 16204:2012[2]). Hence, the focus is on the widely accepted analytical models incorporated into the *fib* Model Code 2010[1] and consequently in the *fib* Model Code 2020 for existing structures, as well as on the fully probabilistic approach, see Strauss et al.[3,4]

This paper does not primarily deal with the required adaptation of models developed for new structures to existing structures, or vice versa, which would certainly be of interest to the engineering community. It deals with the survey options on construction sites and laboratory and its applicability for processing the suggested degradation models and its input parameters. Nevertheless, the proposed categorization developed for existing structures can already be transferred to the models for the verification of the quality of new concrete structures, which will be in a next step treated in the corresponding *fib* commissions, for example, in Chapter 27.11 of ModelCode 2020.

2 | MODELING OF CHLORIDE ION INGRESS AND CONCRETE CARBONATION ACCORDING TO THE *FIB* MODEL CODE 2010

The limit state associated with the durability of structures is described by the limit condition:

$$P_f(t_D) = P\{R(t_D) - A(t_D) \le 0\} \le P_d, \qquad (1)$$

where $R(t_D)$ and $A(t_D)$ represent the resistance capacity and the cumulative degradation of the structure/structural component at the end of its design life, t_D, and P_f and P_d stand for the actual and design probability of failure. For the case of chloride ion ingress into concrete, the resistance capacity is replaced by the critical concentration of dissolved Cl^- leading to steel depassivation and degradation is represented by the concentration of Cl^- at the depth of concrete cover. Similarly, the concrete cover is compared to the carbonation depth at time when carbonation process is considered.

The widely used analytical models for modeling of chloride ion ingress into concrete are based on the error function "erf."[5] According to *fib* Bulletin No. 34,[6] the Cl^- concentration at the depth of concrete cover at time, $C(a, t)$ (wt%/c) is calculated as

$$C(a,t) = C_0 + (C_{S,\Delta x} - C_0) \cdot \left[1 - \mathrm{erf}\frac{a - \Delta x}{2\sqrt{D_{app}(t) \cdot t}}\right]. \qquad (2)$$

According to *fib* Bulletin No. 76,[7] $D_{app}(t)$ can be determined based on field data obtained via the chloride profiling method or the rapid chloride migration (RCM) test method. Subsequently, an aging exponent may be determined using the following approaches A or B:

$$D_{app}(t) = k_e \cdot D_{app}(t_0) \cdot \left(\frac{t_0}{t}\right)^{\alpha_A} \text{ or } \quad D_{app}(t) = k_e \cdot D_{RCM}(t_0) \cdot \left(\frac{t_0}{t}\right)^{\alpha_B}, \qquad (3)$$

where the environmental variable k_e [−], which takes into consideration the effect of temperature on chloride ingress into concrete, is described as

$$k_e = \exp\left[b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right]. \qquad (4)$$

For meaning of the individual model input parameters, see Table 1.

A simple approach to the calculation of carbonation depth at time, $x_c(t)$ [mm] can be defined, according to which

$$x_c(t) = A\sqrt{t}. \qquad (5)$$

The constant A is quantified through the evaluation of carbonation depths measured on real concrete structures. Using different forms of parameter A, it is possible to cover the whole range of carbonation situations.

Based on DuraCrete Project[9] and according to *fib* Bulletin No. 34,[6] the carbonation depth $x_c(t)$ (mm) at a certain point of time is defined as

TABLE 1 List of input parameters for the modeling of chloride ingress

No	Parameter	Notation	Unit	Level	Source	Method
Material parameters						
1	Cement and binder types	CEM I–V	—	(1), 2, 3b		Petrographic examination
2	Water to cement (water to binder) ratio	w/c (w/b)	—	(1), 2, 3b	EN 206:2013	Petrographic examination/chemical analysis
3	Initial Cl^- content in concrete	C_0	Wt%/c	1, 2, 3b	EN 206–1:2000, *fib* Bulletin 76	Chemical analysis
4	Cl^- migration/diffusion coefficient at time t_0	$D(t_0)$[a]	mm^2/years	1, 2, 3b	*fib* Bulletin 76 EN 12390-11:2015[8]	Chloride migration/diffusion tests; fitting of Equation (2)
5	Aging exponent	α	—	1, 3b	*fib* Bulletin 76	Chloride profiling method/Diffusion tests; fitting of Equation (3)[b]
Environmental parameters						
6	Reference temperature	T_{ref}	K	1, 3a	*fib* Bulletin 76	
7	Temperature of structural element or ambient air	T_{real}	K	1, 3a	*fib* Bulletin 76	On-site measurements/nearest weather station
8	Temperature coefficient	b_e	K	1, 3b	*fib* Bulletin 76	
9	Depth of convection zone	Δx	Mm	1, 3b	*fib* Bulletin 76	Chloride profiling method
10	Surface/substitute surface cl^- content in depth Δx	$C_{S,0}/C_{S,\Delta x}$	Wt%/c	1, 3b	*fib* Bulletin 76	Chloride profiling method; fitting of Equation (2)
Other parameters						
11	Reference point of time	t_0	Years	1, 2	*fib* Bulletin 76	
12	ime	t	Years	1, 2		
13	Concrete cover	a	Mm	1, 2, 3a	EN 1992-1-1:2004, *fib* Bulletin 76	On-site nondestructive methods (cover meters, ground penetrating radar, ultrasonic pulse echo)
14	Critical chloride content	C_{cr}	Wt%/c	1, 3b	*fib* Bulletin 76	No standardized test method is available[c]

[a]Migration coefficient based on RCM-test method $D_{RCM}(t_0)$ or the apparent coefficient of chloride diffusion based on the field data $D_{app}(t_0)$ can be used.
[b]The long-term behavior of the $D_{app}(t)$ of existing structure has to be considered by analyzing the development of chloride profiles over time; at least two different points in time for $D_{app}(t)$ or combination of the $D_{app}(t)$ obtained from the field data and the $D_{RCM}(t_0)$ of the design concrete gained from laboratory RCM tests are required in order to be able to quantify the aging exponent α.
[c]By measuring the corrosion current and electrode potential at different depths in the concrete cover, it is possible to predict when the chloride-based corrosion front will reach the reinforcement. The critical chloride content, C_{cr}, can thus be assessed.

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{NAC}^{-1} + \varepsilon_t\right) \cdot C_S \cdot W(t) \cdot \sqrt{t}} \qquad (6)$$

with the environmental function k_e [−] and execution transfer parameter k_c [−] assessed according to following formulas:

$$k_e = \left(\frac{1 - \left(\frac{RH_{real}}{100}\right)^{f_e}}{1 - \left(\frac{RH_{ref}}{100}\right)^{f_e}} \right)^{g_e}, \qquad (7)$$

$$k_c = \left(\frac{t_c}{7}\right)^{b_c}. \qquad (8)$$

Meso-climatic conditions due to the re-wetting of concrete surfaces caused by rain events are taken into account using the time-dependent weather function, which is defined as

$$W(t) = \left(\frac{t_0}{t}\right)^{\frac{w}{2}} = \left(\frac{t_0}{t}\right)^{\frac{\left(p_{SR} \frac{t_W}{365}\right)^{b_W}}{2}} \qquad (9)$$

with w [−] being the weather exponent. Meaning of all the model input parameters is summarized in Table 2.

Later, von Greve-Dierfeld and Gehlen[11–13] introduced an additional parameter—carbonation rate k_{NAC}, which

TABLE 2 List of input parameters for the modeling of concrete carbonation

No	Parameter	Notation	Unit	Level	Source	Method
Material and execution parameters:						
1	Cement and binder types	CEM I–V	—	(1), 2, 3b		Petrographic examination
2	Water to cement (water to binder) ratio	w/c (w/b)	—	(1), 2, 3b	EN 206 (2013)	Petrographic examination/ chemical analysis
3	Inverse effective carbonation resistance of concrete	$R_{ACC,0}^{-1}$	$\frac{mm^2/years}{kg/m^3}$	1, 2, 3b	DARTS (2004) EN 12390–10:2018[10]	
4	Period of curing	t_c	Days	1, 2	DARTS (2004)	
Environmental parameters:						
5	Relative humidity	RH_{real}	%	1, 3a	*fib* Bulletin 34	RH sensors or RH probes/ nearest weather station
6	CO_2 concentration of the ambient air	C_S	Kg/m^3	1, 3a	*fib* Bulletin 34	Chemical or infrared sensors
7	Probability of driving rain	p_{SR}	—	1, 3a	*fib* Bulletin 34	Wind sock or vane/nearest weather station
8	Time of wetness	t_w	Days	1, 3a	*fib* Bulletin 34	Rain gauge/nearest weather station
Test and other parameters:						
9	Exponent of regression of parameter k_c	b_c	—	1	DARTS (2004)	
10	Regression parameter (influence of the ACC-test method)	k_t	—	1	DARTS (2004)	
11	Error term of the ACC-test method	ε_t	$\frac{mm^2/years}{kg/m^3}$	1	DARTS (2004)	
12	Reference value of relative humidity	RH_{ref}	%	1	*fib* Bulletin 34	
13	Exponent	f_e	—	1	DARTS (2004)	
14	Exponent	g_e	—	1	DARTS (2004)	
15	Time of reference	t_0	Years	1	DARTS (2004)	
16	Time	t	Years	1, 2		
17	Exponent of regression of function $W(t)$	b_w	—	1	DARTS (2004)	
18	Concrete cover	a	Mm	1, 2, 3a	*fib* Bulletin 34	On-site nondestructive methods (cover meters, ground penetrating radar, ultrasonic pulse echo)

replaced the inverse carbonation resistance $R_{NAC}{}^{-1}$. Here, $x_c(t)$ is defined as

$$x_c(t) = k_{NAC} \cdot \sqrt{k_e \cdot k_c \cdot k_a \cdot} W(t) \cdot \sqrt{t}. \tag{10}$$

Furthermore, function k_a [−] describes the effect of CO_2 concentration in the ambient air.

For a detailed overview of carbonation and chloride ingress parameters, and their implementation for condition assessment in existing structures, see Zambon et al.[14,15]

3 | LEVELS OF ASSESSMENT OF THE INPUT PARAMETERS

Different levels of assessment of the input parameter values ('Level' column in Tables 1, 2) can be used based on input value precision and the accompanying uncertainties. In the case of an existing structure, three levels can be distinguished (see also Figure 1):

(i) *Level 1—No inspection of the structure and/or on-site measurements has been carried out and the only available information about materials, loading, and the*

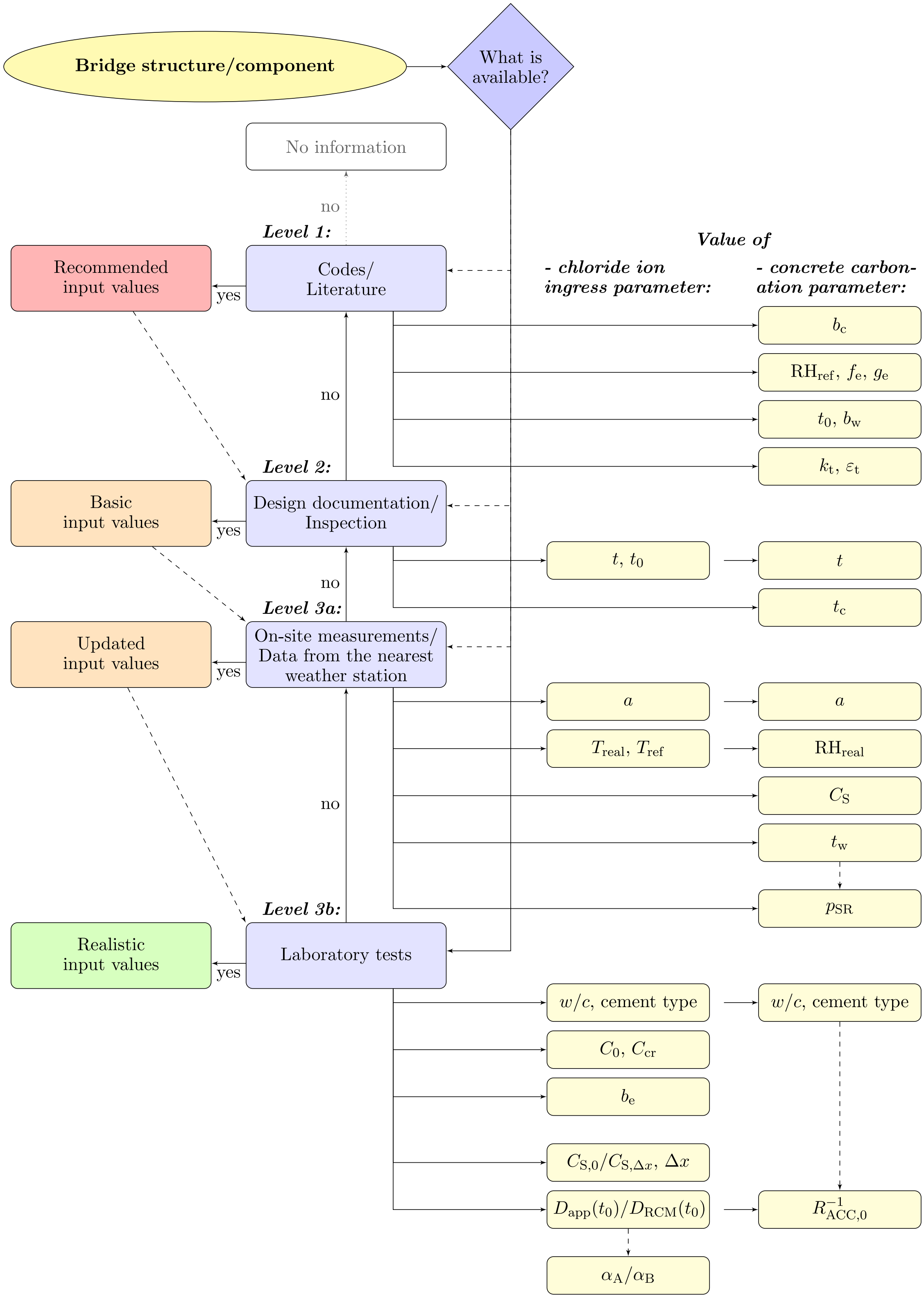

FIGURE 1 Process of the quantification of input parameters for the modeling of chloride ingress and concrete carbonation

surrounding environment is from codes and other literature sources.

Structural requirements and recommended input parameter values can be used according to the European standards (e.g., EN 1992-1-1:2004[16]; EN 206-1:2000[17]; EN 206:2013[18]) and/or other literature (e.g., DARTS[19]; *fib* Bulletin No. 34[6]; *fib* Bulletin No. 76[7]; *fib* Model Code 2010[1]). For details see code/literature specifications ("Source" column in Tables 1, 2) where definitions of input parameters using appropriate statistical characteristics such as the probability density function, mean value, the coefficient of variation and limits if needed can be found. These are based on former measurements and/or experience. The definition of input values using only codes and other literature sources may not always be completely accurate. For a more precise analysis, it is recommended that higher levels of assessment be utilized in combination with the probabilistic approach.

(ii) *Level 2—The design documentation is available, and/or a visual inspection of the structure was carried out.*

When design documentation is available for the structure, and the structure is well documented, precise information about material properties can be obtained. Especially data on parameters, such as cement type, water to cement/binder ratio, carbonation resistance properties, chloride diffusion properties, period of curing, depth of concrete cover, are crucial for the realistic quantification of input variables for the modeling of the degradation processes over time. Unfortunately, in the prevailing number of cases, only basic input parameters such as the age of the structure and/or concrete cover are documented. If the required data cannot be obtained from design documentation, a visual inspection is needed. The results from a single visual inspection may be used to estimate the remaining service life, from which the timing of future inspections/maintenance can be determined based on the current level of risk, and the need to perform other tests in different areas can be assessed.

(iii) *Level 3—Updated or realistic input values are available from on-site measurements (Level 3a) and/or supplementary laboratory tests (Level 3b).*

If reliable data are not available from design documentation or visual inspection, additional on-site measurements and/or laboratory tests should be carried out. Tests may be carried out directly on the structure itself (in-situ testing), or on test specimens made in the laboratory or taken from the structure. Nondestructive test methods and methods of sample analysis can be employed at intervals during the structure's life. Regarding the environmental parameters, data from the nearest weather station can also be utilized. If these are not available, on-site measurements of environmental characteristics such as temperature, relative humidity, or precipitation can be employed. Some parameters can also be obtained with sufficient accuracy using calibration processes. Individual test methods for quantifying the individual parameters are mentioned in "Method" column of Tables 1, 2; for details, see also Šomodíková et al.[20]

3.1 | Suitability of each level to apply a probabilistic service life analysis

In general, the probabilistic methods can be used at all three levels described above.

At *Level 1*, it is typical that the issues to be treated are represented in models (e.g., see Equations (2)–(9)), which are accessible to a mathematical-numerical treatment. For these models, always a single value (usually a fractile value) is used for each variable. The result consequently appears in a single number. This is usually an engineering procedure used for dimensioning and evaluation problems. However, it is particularly recommended to use several different numerical values in the models presented above to test the sensitivity of the results.

It is therefore already important at *Level 1* to introduce those variables with their statistical distribution forms (probability density functions, PDFs) and statistical parameters (mean, standard deviation, etc.) influencing the considered assessment problem in terms of reliability theory. The transfer of the influencing variables, which are mostly defined as fractile values in standards, into distribution forms and the associated statistical parameters can be carried out according to clear statistical relationships taking into account standard background documentation, such as the Probabilistic Model Code[21] by the Joint Committee on Structural Safety.

Level 2 tests are typical on-site tests at the structure. This level is associated with the updating of information on environmental and mechanical condition of the structure. Specialized specialist bodies are usually involved in this procedure. Rather, it is reasonable and cost-effective to use the *Level 1* gained insights to set up a targeted and suitable examination program, as well as to determine what needs to be checked.

Level 2/Level 3a tests are typical for the condition assessment of concrete structures in bridge engineering. The process step is known as information updating and is performed in general by specialized departments. The additional information obtained from these testing is included in the assessment in order to finally dispel the doubts that still exist at the end of *Level 1* and to demonstrate sufficient reliability. In general, the conventional probabilistic models proposed above and the updated values will be used for these procedures. In this context, Bayesian or similar methods can be used, in order to process the additional information in the characterization of the above mentioned probability density functions and its associated statistical parameters. Based on "a priori probabilities" (e.g., from the Level 1 surveys), by adding additional information, taking into account a posteriori predictor, values for the improved probability density function are determined.

If the reliability achieved is received as insufficient and the general test-specific criteria show a high assessment complexity, then a structural performance at *Level 3* procedure is proposed. In *Level 3* procedure, probabilistic models are predominantly used in the assessment. The probabilistic expert analyses in *Level 3* consequently substitute the standards, which guarantee a balanced level of safety in the structural design phase. The acceptance of increased risks or a reduced safety should in principle be reserved for an expert panel.

4 | DISCUSSION ON THE RELEVANCE OF THE CORROSION PROPAGATION TIME

When observing the duration of service life, a rate and type of corrosion propagation is to be taken into account. In the carbonation environment, the rate of corrosion propagation after the point of initiation is expected to be very slow. Accordingly, there would be only negligible material and mechanical changes of the concrete member concerned, even at the point in time when the first cracks appear.

However, there is an obvious contrast of carbonation caused corrosion in comparison with the situation where chloride induced corrosion involving pitting occurs. The process is followed with very limited amounts of corrosion products being produced, and possibly little of no cracking, depending upon the nature of the exposure environment. Furthermore, pitting corrosion can rapidly induce significant local loss of rebar area causing significant losses of member carrying capacity. The effects of pitting corrosion include a reduction of material properties such as yield strain and elongation at failure, changes in bond and anchorage, as well as associated effects such as the reduction in the confinement of the main reinforcement due to corrosion damage to stirrup reinforcement.

When a possible propagation allowance is observed, it is important to mention that it would not be appropriate in cases where prestressing wires or tendons could be affected by carbonation or chloride induced corrosion, as there is a likelihood that hydrogen embrittlement of the steel could arise. Furthermore, there are similar considerations for circumstances where fatigue or fretting occur, for both reinforced and prestressed concrete members.

When observing future development of codes and regulations, there is an obvious need to define how to take in account corrosion propagation development in service life design (SLD). It is necessary to recognize and differentiate a full account of different design situations where various actions and environmental effects could arise, singularly, or perhaps in conjunction. In summary, all accompanying circumstances of the corrosion propagation process have to be clarified, to define in which cases the corrosion propagation time could be implemented in SLD and within which limits, as well as under which constraints.

5 | CONCLUSIONS

In the paper, levels of assessment of input parameter values for modeling of chloride ion ingress into concrete and concrete carbonation process were briefly presented with the focus on the widely accepted models incorporated into the *fib* Model Code 2010.[1] Based on input value precision and the accompanying uncertainties, three levels can be distinguished. For the first estimation in degradation modeling, input parameters can be quantified using appropriate statistical characteristics, such as the probability density function, mean value, the coefficient of variation and limits if needed, according to codes and/or other literature sources. For many of the input parameters, these values may not be entirely accurate and realistic, and consequently their use may lead to very uncertain (and sometimes even unsafe) modeling results. Hence, higher levels of assessment using additional on-site measurements and/or laboratory tests are recommended.

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