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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
Reinforced concrete buildings and components have a limited service life due to degradation processes that impact structural materials. These include chloride ion intrusion, concrete carbonation, and the corrosion of reinforcement. Finding out how a building is doing now and making educated guesses about how it will perform in the future is the goal of structural condition assessments. In order to evaluate buildings and their components over time, more sophisticated approaches and models of predicting degradation are required. Models for simulating chloride ion intrusion into concrete and the carbonation process of concrete that are part of the fib Model Code 2010 are the main topic of this study. Beginning with a basic quantification based on code and literature guidelines, we go on to more complex levels of evaluation that include design documentation, visual inspection data, extra on-site measurements, and/or laboratory testing.

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

1 | INTRODUCTION

The business Degradation processes happen on structural materials, affecting their life and durability, especially in reinforced concrete buildings and structural parts. The three most prevalent forms of degradation in concrete are carbonation, chloride ion intrusion, and reinforcing corrosion thatfollows.With an eye on reducing total expenditure, the most prevalent kind of The structural evaluation is a kind of informal assessment that relies on visual inspections to determine a structure's condition. Finding out how a structure is doing now and making educated guesses about how it will perform in the future with little effort and maximum precision is the goal of structural condition assessments. The primary purpose of data collected during visual inspections is to identify the most critical issues and provide a plan to further investigate them by monitoring, more on-site measurements, and/or laboratory testing.A growing trend in durability design is the use of models grounded on mathematical principles and measurable material attributes to guarantee the occurrence of desired durability results. The 20101 Fib Model Code includes include a performance-based strategy in the design of this kind. Here, some methods for checking limit states related to structures' durability are as follows: (a) the completely probabilistic format; (b) the partial safety factor format; (c) the deemed-to-satisfy technique; and (d) the avoidance-of-deterioration strategy. The use of characteristic values and partial safety factors in conjunction with limit state principles is the standard procedure for structural evaluation. But if more accurate procedures are required, the completely probabilistic technique is the only one that gives quantitative data on the safety level.The aim of this paper is to describe the levels of assess- ment of input parameter values for the prediction of deteri- oration due to chloride ion ingress into concrete and concrete carbonation process for existing structures. Due to

inherent uncertainties in material, technological, and envi- ronmental characteristics, stochastic models, dealing with probabilistic approaches and presenting the performance-related design of structures for durability, are rec- ommended 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 incor- porated 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 degrada- tion models and its input parameters. Nevertheless, the proposed categorization developed for existing structures can already be transferred to the models for the verifica- tion of the quality of new concrete structures, which will be in a next step treated in the corresponding *fib* commis- sions, 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:

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

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 concen- tration 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 car- bonation 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

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

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

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

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

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

For meaning of the individual model input parame- ters, see Table 1.

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

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

The constant A is quantified through the evaluation of carbonation depths measured on real concrete struc- tures. 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* Bul- letin No. 34,[6] the carbonation depth $x_c(t)$ (mm) at a cer- tain point of time is defined a

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.

$$x(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R^{-1}_{NAC} + \varepsilon_t\right) \cdot C_S} \cdot W(t) \cdot \sqrt{t} \quad (6)$$

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

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

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

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

$$W(t) = \left(\frac{t_0}{t}\right)^{\frac{w}{2}} = \left(\frac{t_0}{t}\right)^{\frac{(p_{SR} \cdot ToW)^{b_w}}{2}} \quad (9)$$

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	$R^{-1}_{ACC,0}$	$\frac{mm^2/years}{kg/m^3}$	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

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

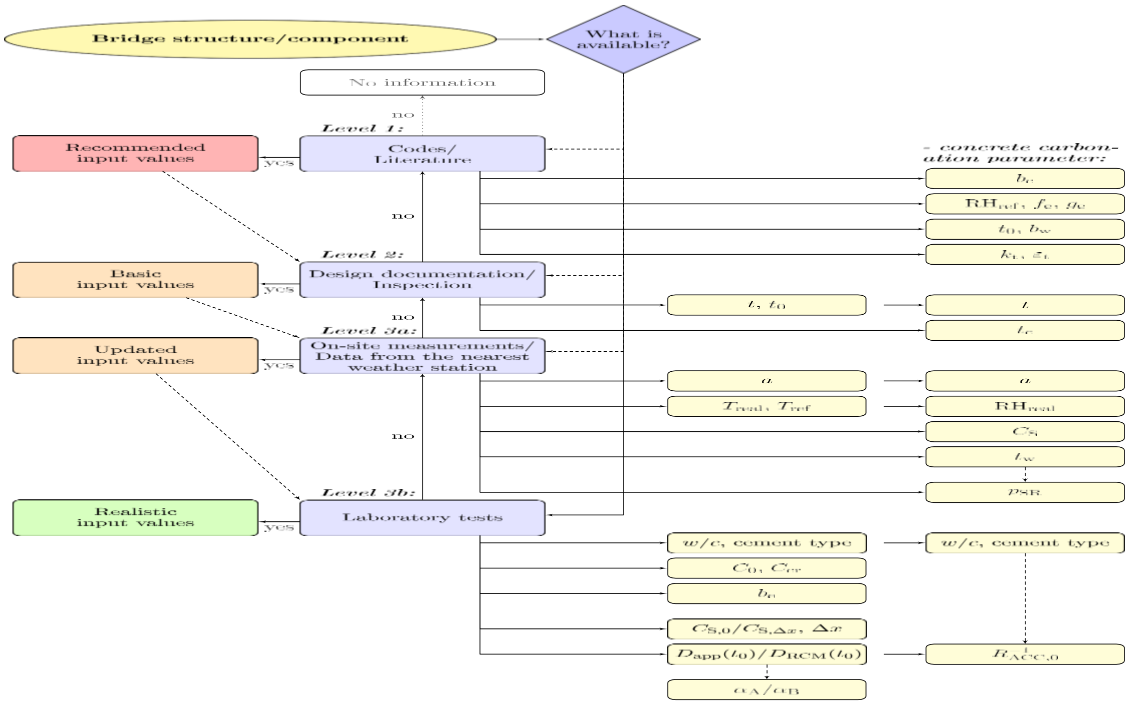
Furthermore, function k_a [−] describes the effect of CO_2 concentration in the ambient air.

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 uncer- tainties. 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*



FIGU RE 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

(ii) input parameter definitions utilising suitable statistical features, such as the probability density function, mean value, coefficient of variation, and limitations if necessary, may be found in the specifications ("Source" column in Tables 1, 2). These are derived from prior assessments and/or practical knowledge. It is possible that input value definitions based only on codes and other literature sources are not always entirely correct. Using additional levels of evaluation in conjunction with the probabilistic technique allows for a more concise analysis.

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

(iv) It is possible to get concise information on material characteristics when the structure's design documentation is accessible and the structure is well-documented. To accurately quantify the input variables for the modelling of the degradation processes over time, it is essential to have data on parameters such as cement type, water to cement/binder ratio, chloride diffusion properties, carbonation resistance properties, curing period, and depth of concrete cover. Much too often, documentation of even the most fundamental input criteria, such the structure's age and/or concrete cover, is lacking. A visual assessment is necessary if the necessary data cannot be gathered from the design documentation. We may estimate the remaining service life from the findings of a single visual examination. Then, we can use that information to choose when to do future inspections and maintenance depending on the current degree of risk. We can also use it to see whether more tests are needed in various areas.
part four)Third Level—Measurements taken on-site (Level 3a) and/or further laboratory testing (Level 3b) provide up-to-date or realistic input values.
It is recommended to do extra on-site measurements and/or laboratory testing in the absence of trustworthy data provided by design documentation or visual examination. It is possible to conduct tests on test specimens created in the lab or extracted from the structure, or on the structure itself (in-situ testing). At various points during the structure's lifetime, nondestructive testing and sample analysis procedures may be used. Data from the closest weather station may also be used for environmental metrics. When these are not accessible, it is possible to use on-site measurements of environmental variables including temperature, humidity, and precipitation. Additionally, calibration procedures may provide certain values with enough precision. The specific procedures for measuring each parameter are detailed in the "Method" column of Tables 1, 2; for further information, refer to Šomodíková et al.20.

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

All three levels indicated above are generally applicable to the probabilistic approaches.
At the first level, mathematical-numerical treatment is usually possible since the problems are modelled (e.g., see Equations (2)-(9)). In these models, every variable is assigned a single value, often a fractile value. The outcome is therefore represented by a single integer. When dealing with issues involving dimensions and assessment, this is the standard engineering technique to use. To ensure that the findings are not affected by any changes, it is advised to employ a range of numerical values in the models mentioned before.
Level 1 should therefore include the introduction of the variables whose reliability theory-influenced evaluation issue is under consideration, together with the statistical parameters (mean, standard deviation, etc.) and probability density functions (PDFs) that govern their distributions. By following clear statistical relationships and considering standard background documentation like the Joint Committee on Structural Safety's Probabilistic Model Code21, we can transform the influencing variables—typically defined as fractile values in standards—into distribution forms and their associated statistical parameters.

Common on-site testing at a structure is level 2. At this stage, data on the structure's mechanical and environmental conditions is being updated. In most cases, this process involves specialised expert bodies. Instead, it makes more sense and uses less money to utilise the insights from Level 1 to establish a focused and appropriate inspection program and figure out what needs to be checked.

In bridge engineering, it is common practice to evaluate the condition of concrete structures using Level 2/Level 3a tests. Information update is the process phase that is often carried out by specialised departments. Incorporating the supplementary data acquired from these tests into the evaluation helps to prove enough dependability and put to rest any remaining uncertainties from Level 1. Typically, these techniques will make use of the typical probabilistic models that were provided before, together with the updated data. The aforementioned probability density functions and the statistical parameters linked to them may be further characterised with the use of Bayesian or comparable approaches in this setting. The values for the enhanced probability density function are derived by adding additional information that takes into consideration a posteriori predictor, based on "a priori proba-bilities" (such as those from the Level 1 surveys).

We recommend a structural performance at Level 3 process if the dependability that has been attained is deemed inadequate and if the general test-specific criteria reveal an excessively complicated assessment. Probabilistic models are mainly used for evaluation in the Level 3 phase. Consequently, Level 3's probabilistic expert evaluations take the place of the standards, ensuring a balanced degree of safety throughout the structural design process. Experts should be the ones who decide whether to accept higher risks or less safety.

4 | DISCUSSION ON THE RELEVANCE OF THE CORROSION PROPAGATION TIME

It is important to consider the pace and kind of corrosion propagation while monitoring the length of service life. It is anticipated that corrosion would propagate at a relatively sluggish pace in a carbonation environment once it has begun. So, even when the first fractures show up, the material and mechanical changes to the concrete member in question would be minimal. Nevertheless, carbonation-induced corrosion stands in stark contrast to chloride-induced corrosion characterised by pitting. Very little corrosion products are generated throughout the process, and cracking may be minimal or nonexistent, depending on the exposure environment. Pitting corrosion may also quickly reduce the area of rebar, which in turn reduces the member's bearing capacity. Pitting corrosion alters bond and anchorage strengths, decreases material properties like yield strain and elongation at failure, and has ancillary effects like reducing the confinement of the main reinforcement as a result of corrosion damage to the stirrup reinforcement.

There is a risk of hydrogen embrittlement of the steel when a propagation allowance is included, hence it is not suitable for prestressing wires or tendons that are susceptible to carbonation or chloride-induced corrosion. Additionally, in cases of fatigue or fretting, both prestressed and reinforced concrete components must be considered in the same way.

There is a clear requirement to specify how to include corrosion propagation development into service life design (SLD) while monitoring the evolution of regulations and norms in the future. Various design scenarios including potential actions and environmental repercussions must be identified and fully considered. singularly, or perhaps in conjunction. In summary, all accompanying circumstances of the corrosion propaga- tion 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

This study provided a concise overview of the input parameter values used to simulate chloride ion entry into concrete and the concrete carbonation process. It focused on the models that were included in the fib simulate Code 2010.1 and were considered broadly acceptable. There are three tiers that may be identified according on the accuracy of the input values and the associated uncertainty. It is possible to quantify the input parameters for the initial estimate in deterioration modelling using suitable statistical features, such as the probability density function, mean value, coefficient of variation, and limitations if necessary, in accordance with the codes and/or other literature sources. The usage of these values for many of the input parameters could result in very unpredictable (and sometimes dangerous) modelling outcomes since they aren't necessarily correct or realistic. As a result, it is advised to conduct more extensive assessments with more measured on-site and/or laboratory testing.

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