Report

STAR - Service life modelling of chloride induced corrosion of steel reinforced concrete structures
- Overview of models and parameters

Author: Roar Myrdal

Report number : 2024:01134

Project number: 102028198

Report EXCON

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KEYWORDS
Corrosion, concrete, chloride, steel reinforcement, service life modelling, model parameters

VERSION
1

DATE
2024-09-12

CLIENT(S)
SINTEF AS

CLIENT'S REFERENCE
Tor Arne Martius-Hammer

2
102028198

NUMBER OF PAGES AND ATTACHMENTS
22

SUMMARY
This report provides an overview of service life models and parameters linked to reinforced concrete structures suffering from chloride induced corrosion of the steel reinforcement. All deterioration phases from chloride ingress to corrosion initiation, propagation and concrete cracking/spalling are covered. A representative selection of 18 models developed over the last 50 years are discussed and sorted into 3 model groups: (1) Chloride ingress modelling, (2) Corrosion onset modelling, and (3) Corrosion rate and damage modelling.

All input parameters and output data found in the models have been summarised in separate overviews to make it easy to search for models dealing with specific parameters. Also, sensors for in-situ monitoring of parameters are covered.

The main conclusion is that there is no clear consensus among researchers and scientists what is the best way to model the service life of steel reinforced concrete structures suffering from chloride induced deterioration. Surprisingly few models provide rate of corrosion as a model output (typical <u>input</u> parameter in several models).

COMPILED BY
Roar Myrdal

CONTROLLED BY
Jan Arve Øverli

ENDORSED BY
Tor Arne Martius-Hammer

SIGNATUR

REPORT NR.	ISBN	GRADATION	GRADING THIS PAGE
2024:01134	978-82-14-07100-9	Open	Open

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1 Introduction

Corrosion of steel reinforcement is by far the primary cause of deterioration of reinforced concrete structures. The corrosion process leads to cross section loss and can cause strength reduction and stress concentration in the reinforcement steel, weakening the mechanical resistance of both individual components and the entire concrete structure.

Steel reinforcement corrosion is classified into several types, one of the most frequent being pitting corrosion caused by chloride ingress into the concrete. Further, concrete cracks have a major impact on the corrosion activity because they can provide easy access to the agents required for corrosion, such as water, oxygen, and chloride ions.

1.1 Objective

The objective of this state-of-the-art report is to give an overview of existing models used to predict the deterioration development of non-rehabilitated steel reinforced concrete structures potentially suffering from chloride induced corrosion. The input parameters used in the models, as well as the output data from the modelling, are covered.

An overview of embeddable sensors that may provide input data for the modelling, or output data for testing of models, is also presented.

The report concludes with a brief discussion on the need for model improvements/adjustments.

1.2 Scope and limitations

This report covers only chloride induced corrosion; not carbonation induced corrosion. However, the pH of the concrete is also treated as this parameter affects chloride induced corrosion.

An outline of several models published over the last 50 years is presented. The models were mainly found by undertaking English literature search at Google Scholar, ResearchGate, and ScienceDirect. Search terms used were *Concrete, Corrosion, Service life modelling, Service life design*. Models dealing only with carbonation induced corrosion were not included in this work.

The strict distinction between model types in terms of empirical, analytical, and numerical models is not followed. Instead, the distinctions are more related to mechanisms involved in the deterioration process. One might characterise this as material scale modelling, i.e. how the materials (the concrete and the steel reinforcement) are affected by chloride induced corrosion. This kind of material scale modelling can serve as an input to structural modelling – a model type which is outside the scope of this report.

Detailed descriptions of the mechanisms and assumptions incorporated in the models are not presented in this report. The overview is meant to offer help in the search for suitable models incorporating relevant input parameters and output data of interest for a given steel reinforced concrete structure. References given for the various model types will offer the details. An overview of available sensors for in-situ monitoring may also offer some help in the search for, and evaluation of, service life models, or further development of service life modelling.

1.3 Outline of the report

The below model descriptions are separated into six parts (Chapters 2-7):

Chapter 2 gives a brief and general outline of the parameters affecting the corrosion stages initiation, propagation, and structural damage linked to chloride induced corrosion of steel reinforcement.

Chapter 3 presents selected types of material scale models developed over the last 50 years, from initiation to concrete cover cracking.

Chapter 4 provides an overview of input parameters used in the service life models.

Chapter 5 provides an overview of the output data coming from the service life models.

Chapter 6 gives a brief outline of embeddable sensors for in-situ monitoring of the initiation and propagation of corrosion.

Chapter 7 summarises state-of-the-art of service life modelling of corrosion and suggests further steps to be taken.

Appendix A shows a list of "Ten Commandments" providing general guidance to research on service life prediction of building materials and components.

Appendix B offers a detailed summary of the main characteristics of the service life models.

2 Corrosion damage and limit states

Embedded steel bars in concrete are normally protected against corrosion by a protective ferric oxide layer (passive film) on the steel bar formed by oxygen and high pH moisture in the surrounding cement paste. Corrosion may occur when this protective layer is destroyed, either by lowering of the pH (as a result carbonation of the concrete), or by the presence of chloride ions.

Corrosion due to carbonation is considered to cause uniform corrosion along the steel bar, whilst chloride induced corrosion often cause localised corrosion ('pitting corrosion'). Chloride contamination leading to pitting corrosion is an extremely challenging cause of corrosion damage of steel reinforced concrete structures due different deterioration limit states compared to carbonation induced corrosion (Chapter 2.2).

2.1 Chloride induced corrosion in steel reinforced concrete structures

Chloride ions (Cl^-) may enter concrete in two ways, either as part of the materials used to make concrete, or by penetrating the hardened concrete from outside the structure after the placement. Today, there are strict rules to ensure that the ingredients in concrete recipes (e.g. concrete admixtures) are chloride-free when building a new steel reinforced concrete structure. However, old concrete structures – build in the 1980s and earlier – sometimes contained mixed-in chloride salts, either deliberately or simply by accident (contaminated components).

There are two main sources of chloride salts entering concrete from the surroundings outside the structure, either contact with sea water (marine environment) or contact with de-icing salts sprayed onto roads and other infrastructures during wintertime. The major transport mechanisms causing chloride salt ingress are:

- *Capillary absorption* (caused by capillary action)
- *Permeation* (caused by hydrostatic pressure gradients)
- *Diffusion* (caused by concentration gradients)

With very few exceptions, diffusion is the anticipated ingress mechanism in most service life models.

Chloride ions – dissolved in the pore water, not bound chloride – in contact with the steel rebar will react with the passive film (iron oxides) on the steel surface and may start a local breakdown of this film. If the amount of dissolve chloride ions in contact with the steel is above a certain limit, a localised corrosion attack may be initiated forming a cavity in the steel. This chloride-induced corrosion is termed 'pitting corrosion' (see Figure 1).

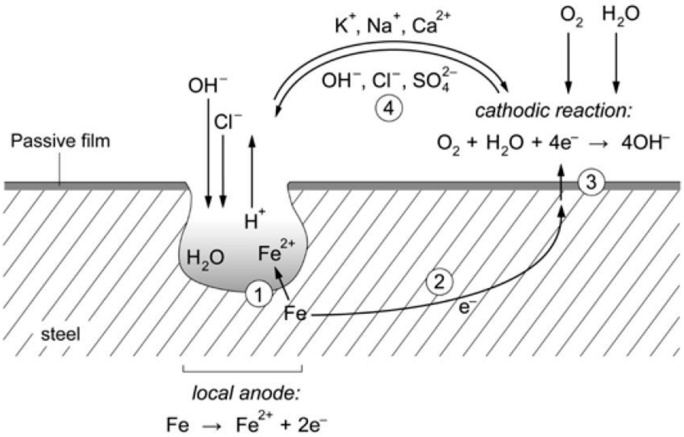

Figure 1: Schematic illustration of chloride induced pitting corrosion and reaction steps: 1. Anodic iron dissolution; 2. Flow of electrons through metal; 3. Cathodic reduction reaction; 4. Ionic current flow through the electrolyte [Angst, 2013].

For pitting corrosion to take place at a noticeable rate (≥ 0.1 µA/cm^2, corresponding to 1.16 µm/year), the amount of chloride in contact with the steel must reach a threshold value, often referred to as the *critical chloride content* (C_{crit}). This is not an absolute value, but may vary with several physical and chemical parameters, like porosity, permeability, moisture content, oxygen diffusion, concentration of OH^- (pH) in the pore solution, and other parameters linked to the steel-concrete interface (SCI). C_{crit} is a widely used parameter in service life modelling.

Chloride may exist in the concrete in a chemically bound state (e.g. Friedel's salt, $3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}\ 10H_2O$) which is not able to initiate the pitting process. Only dissolved chloride ions can cause corrosion damage in the way shown in Figure 1. However, it is common to measure the total chloride content in the concrete, not distinguishing between dissolved and bound chloride. In such cases there is an unknown relationship between chemically bound chloride and dissolved chloride, which again may lead to uncertainties/variations when deciding the C_{crit} value to be put into the service life model. Several other factors, like moisture conditions, may also have a great impact on C_{crit} [Angst et al, 2022].

2.2 Corrosion deterioration stages and limit states

More than 40 years ago Tuutti divided the corrosion induced deterioration process of concrete structures into two time periods, that is the "*Initiation period*" and the "*Propagation period*" [Tuutti, 1982]. This can be seen as a two-stage model for service life of steel reinforced concrete structures subjected to corrosion. Further elaborations on this model have been carried out by numerous research groups and professionals over the years, for example as outlined in fib bulletin 34 "*Model Code for Service Life Design*" [fib, 2006], and in a more recent publication (Figure 2).

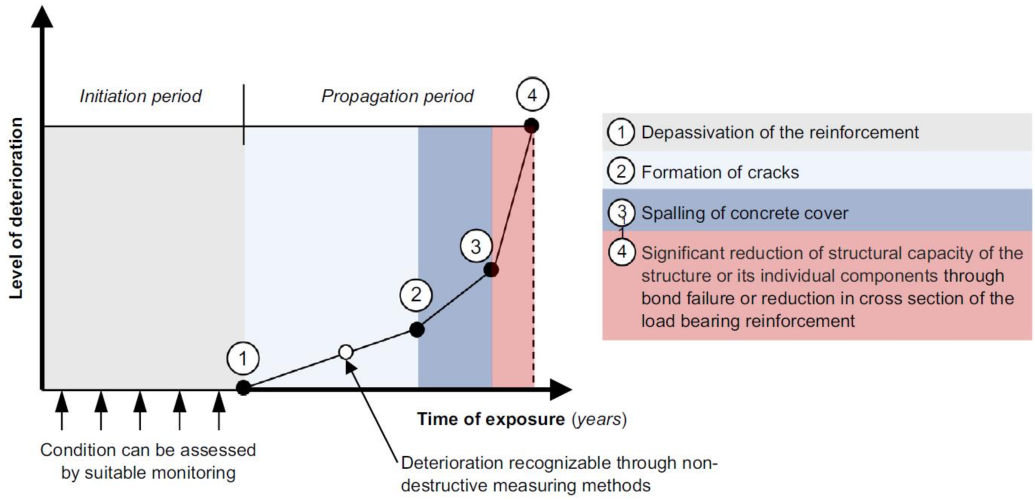

Figure 2: Two-phase model for service life of reinforced concrete structures subjected to corrosion of steel reinforcement [Alexander et al, 2019]. (Adapted from [Tuutti, 1982] and from [fib, 2006])

Figure 2 is a general schematic illustration of this traditional two-stage service life model often used to predict the operational life of a concrete structure. Be aware that the limit states 2 and 3 (formation of cracks and spalling of concrete cover) can be less noticeable for chloride induced corrosion. The damage propagation related to localised pit formation described in Figure 1 is often characterised by a 'pitting factor' affecting the loss of the steel cross-sectional area during corrosion [Gulikers, 2002; Yu et al, 2015]. The pitting factor can be used to modify uniform steel bar cross section loss to section loss due to localised pitting corrosion (more details in Chapter 3).

The remaining service life of the structure, or an element of the structure, may be predicted by knowledge of its present condition and extrapolating to when it either needs extensive repair, restoration, or must be replaced. This also involves how preventive measures will affect costs linked to the service of the structure, as illustrated in Figure 3 showing how repair alternatives can prolong service life in various ways. This implies the need to determine the number of years left for a steel reinforced concrete structure to reach a relevant limit state. However, there is no solution that can last forever. Proactive maintenance can reduce the overall cost of maintaining a structure. Once corrosion has initiated, prompt action can still be taken if the structure was monitored and maintained properly. Further discussions on costs related to repair and maintenance are outside the scope of this report.

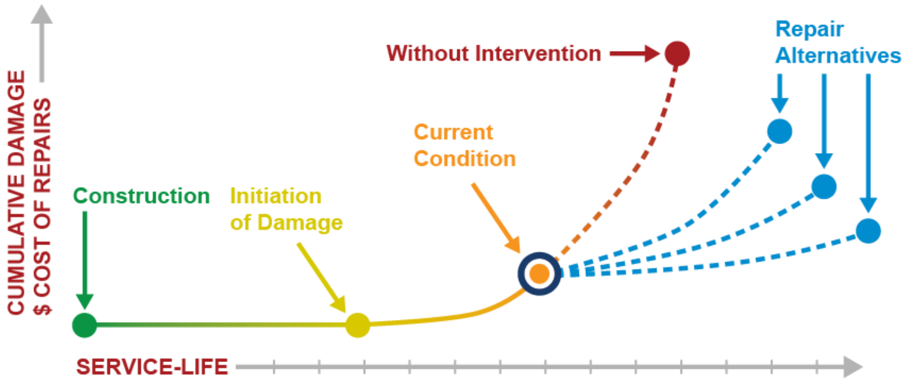

Figure 3: The effect of service life and repair on cost (www.structuraltechnologies.com/service-life/).

The American Concrete Institute (ACI) defines the service life of a building component, or a building material, as the period of time after installation (or in the case of concrete, placement) during which all the properties exceed the minimum acceptable values when routinely maintained. Three types of service life have been defined (Sommerville 1986) [ACI 365, 2000]:

- Technical service life is the time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable, or failure of elements.
- Functional service life is the time in service until the structure no longer fulfils the functional requirements or becomes obsolete due to change in functional requirements, such as the needs for increased clearance, higher axle and wheel loads, or road widening.
- Economic service life is the time in service until replacement of the structure (or part of it) is economically more advantageous than keeping it in service.

Over the years, international codes and standards have defined various limit states to be incorporated into modelling of service life of concrete structures. In 2012, the standard ISO 16204 declared that "*the design service life is defined by the relevant limit states, number of years and level of reliability for not passing each limit state during this period*" [ISO 16204, 2012]. The concept of limit state can also be divided into two main groups covering 'engineering' limit states and 'sustainability' limit states [Geiker et al, 2019].

No doubt, the importance of service life modelling of concrete structures dates back several decades. Even 'Ten Commandments' were offered in the 1980's to help researchers in their effort to develop service life models of building materials and components (see Appendix A).

2.3 Parameters affecting corrosion initiation and propagation

There are many parameters that can affect the initiation and propagation of chloride induced steel reinforcement corrosion. Some are linked to the material and structural properties of the reinforced concrete, whilst others are linked to properties outside the structure. A broad overview of the parameters can be summarised like this:

- Concrete mix design (materials and ingredients affecting transport properties)
- Steel reinforcement (type of steel, for example black steel or galvanised steel)
- Concrete geometry (concrete cover and design, for example corners)
- Concrete surface treatments (for example coatings and overlays)
- Exposure conditions (for example chlorides, pH, moisture, and temperature)
- Mass transport of substances (permeation, absorption, diffusion)

Mass transport is probably the most studied part of this, and many models include the prediction of the progress of the carbonation front and the ingress of chlorides, but they treat the concrete as a continuum, i.e., they do neither consider cracked concrete nor elemental zonation and depth-dependent changes in chloride binding [Geiker et al, 2021; Jakobsen et al, 2016].

Certainly, additional degradation mechanisms may increase the complexity of the problem and therefore play a huge role in the corrosion induced damage of concrete structures. At the end of the propagation phase – after a certain time of ongoing corrosion – local damages may occur leading to [Finozzi et al, 2018; Hanjari et al, 2013; Vorechovska et al, 2013]:

- Decrease in the cross-sectional area of the steel bar
- Loss of bond between steel bar and concrete
- Change in the ductility of the reinforcement bar
- Cracking and spalling of concrete due to volume expansion of rust products
- Loss of bearing capacity of a structural member or the whole structure
- Collapse of the member/structure

Cracking/spalling and loss of bond are mostly related to uniform corrosion caused by carbonation and are normally less severe in pitting corrosion. One might add that pitting corrosion tends to cause less visible damage, and that "*chloride attack is extremely dangerous and difficult to fully understand, due to its localized and non-uniform nature*" [Finozzi et al, 2018].

3 Service life modelling

A total of 18 models have been selected. These models do not differ in all aspects (actually, some are quite similar), but each of them is considered to add new ideas and parameters into the modelling. Obviously, this is not an exact number of all models published over the last 50 years, but a representative selection of the various types of models. These are sorted into 3 model groups:

- Chloride ingress modelling
- Corrosion onset modelling
- Corrosion rate and damage modelling

Details related to the various models within each group, like input parameters and output data, can be found in Appendix B.

3.1 Chloride ingress modelling

This model group includes service life models dealing primarily with the rate of chloride ingress. Some of these models also include the effect of chloride binding. The first model of this type was published more than 50 years ago, dealing only with diffusion of chloride ions in concrete [Collepardi et al, 1972].

The last published model version within this group is only a few years old, documenting a square root time dependency of the chloride ingress depth behind the microstructurally changed zone affected by leaching and elemental zonation [Fjendbo et al, 2021; Poulsen et al, 2018].

Table 1 gives an overview of the main characteristics of chloride ingress models. For further details, see Appendix B.

Table 1 Chloride ingress modelling (chronological order 1972 – 2018)

Year	Model *)	Chloride ingress type	Main characteristics of the model	Reference
1972	ERFC model	Diffusion	ERFC = Error Function Complement. Classic simple model based on chloride ingress rate using the error-function solution to Fick's 2nd law. Chloride binding and critical chloride content is not included.	[Collepardi et al, 1972]
1996	ClinConc model	Diffusion	Uses free chloride as the driving force (Fick's law) and takes non-linear chloride binding into account. Time-dependent chloride diffusion coefficient.	[Luping, 2008]
1998	DuraCrete model	Diffusion	Probabilistic calculation to determine the probability of corrosion initiation based on outer exposure conditions and surface chloride concentration. ERFC version with time dependent chloride diffusion.	[Lindvall, 1998]
2000	CDD model	Diffusion	Concentration-Dependent Diffusion model which considers the effect of chloride binding to better estimate chloride penetration depths and depassivation time of reinforcing steel.	[Martin-Perez et al, 2000]
2001	Stadium model	Diffusion and capillary absorption	Multi-ionic model, based on Nernst-Planck equation. Includes ionic diffusion (chloride and other ions), moisture transport, chemical reactions, and chemical damage (not only steel bar corrosion).	[Marchand, 2001]
2018	Square Root model	Diffusion	Model based on the linear relationship between the depth of a reference chloride content and the square root of exposure duration.	[Fjendbo et al, 2021]

*) These 'model names' are linked to a project name or given by the developers of the model, and not necessarily protected by intellectual property/trademark.

From this overview (Table 1) it is seen that diffusion is the main transport mechanism used in the models. Only one model (Stadium) has incorporated capillary absorption in the chloride ingress mechanism, and there is a lack of ingress caused by permeation in these models. Table 1 also shows that the role of chloride binding was considered important from around 1996.

Whereas the models up to 2018 included a time-dependent diffusion coefficient, the square root model has a constant rate factor (k_1) [Fjendbo et al, 2021]:

$$X = k_1\sqrt{t} + k_2$$

where *t* is the exposure time, X is the depth of a fixed chloride concentration, and k_1 and k_2 are constants.

From this overview it can be concluded that chloride ingress into concrete has been modelled in various ways over several decades. However, it is important to point out that these models are all dealing with crack-free concrete. Cracks in the concrete cover may change the ingress totally, as cracks may act as 'open corridors' to external water containing chloride salts.

3.2 Corrosion onset modelling

This model group takes the modelling phase a step further, including critical chloride content (C_{crit}) and the initiation of corrosion. Some of the models also include the propagation of corrosion after being initiated by the chloride. From around 20 years ago the models within this group were mainly concentrating on chloride diffusion coefficient, critical chloride content, depassivation and in some cases the corrosion propagation phase. Table 2 gives a representative overview of published models within this group (more details in Appendix B).

Table 2 Corrosion onset modelling (chronological order 2003 – 2022)

Year	**Model *)**	**Chloride ingress type**	**Main characteristics of the model**	**Reference**
2003	DuraCon model	Diffusion	A probability-based modelling of chloride penetration (Fick's law) and time to depassivation using a time dependent diffusion coefficient. The model can express the probability of failure or risk for 'Serviceability Limit State' to be reached after a certain period of time.	[Ferreira et al, 2004]
2006	fib Model code	Diffusion and capillary absorption	Probability-based mathematical calculation of time to depassivation based on an established C_{crit} value. The kinetics and rate effects related to deterioration are quantified as far as possible. (The fib Model code also covers the corrosion propagation period and provides some guidelines on the effect of concrete cracks).	[fib, 2006]
2022	Chen et al's model	Diffusion	Numerical and empirical models for structures in marine environment, incorporating the effect of w/b ratio, concrete cover, critical chloride content, and rebar diameter. The model considers the time-varying boundary of chloride concentration, critical chloride concentration, and density of corrosion current.	[Chen et al, 2022]

*) These 'model names' are linked to a project name or the name of one of the developers of the model, and not necessarily protected by intellectual property/trademark.

The models presented in Table 2 shows that chloride diffusion is still an important parameter. However, the chloride diffusion coefficient is not seen as a fixed parameter, but more as a variable dependent on time and temperature.

Even though corrosion propagation mechanisms are discussed to some extent in this model group in relation to limit states (e.g. fib Model code), modelling of the corrosion rate/propagation leading to corrosion damage is not an explicit part of these models. However, Chen et al's model includes corrosion rate as one of its output parameters. In that respect this model could also fit into the model group described below in Chapter 3.3.

3.3 Corrosion rate and damage modelling

At the same time as the 'chloride based' modelling was developed (Tables 1 and 2) – and not as a follow up of this modelling – other model developers were focusing more on the propagation phase by including modelling of rebar cross-sectional loss, rust formation and concrete cover cracking. In some of these models, the chloride ingress part is left out, and the focus is more on the effect of rust formation and expansion after the initiation of corrosion. This approach has been dealt with over several decades (see Table 3). Further details are shown in Appendix B.

It seems that the first attempt to model corrosion induced cover cracking was done in 1979. Even the rebar perimeter and the rebar spacing were included in this model [Bazant, 1979]. Then, from the late 1980's onwards detailed mechanisms related to rust formation and expansion were incorporated in the models.

Around 20 years ago the development of these models also included the ability of rust to enter open voids (pores and cracks), and thereby delaying the expansive forces and extending the time to cover cracking.

Surprisingly, only two of the models presented in this report incorporate the parameter 'corrosion rate' (i_{corr}) as <u>output</u> data from the model [Gulikers, 2002; Chen et al, 2022]. However, as many as seven of the models in Table 3 are using i_{corr} as an <u>input</u> parameter. By varying a fixed value of this input parameter in the model, the rate of rust formation can be calculated and used to predict the reduction in steel bar diameter and the movement and expansion of the rust.

<u>The importance of corrosion rate</u>

The corrosion rate plays an important role in the prediction/calculation of corrosion damage propagation. It can be used to calculate the reduction in rebar cross-sectional area and the formation rate of rust. The corrosion rate can be expressed as the corrosion current density, i_{corr} (μA/cm^2), or as the corrosion penetration rate (μm/year) using Faraday's law, which for steel results in:

1 μA/cm^2 = 1.16 μm/year

This can then be used to calculate the reduction in the cross-sectional area of the steel. Unexpectedly, only three models listed in Tables 2 and 3 (Chen et al, Gulikers, Wang et al) have this parameter among the output data.

Table 3 Corrosion rate and damage (chronological order 1979 – 2016)

Year	Model *)	Main characteristics of the model	Reference
1979	Bazant's model	Numerical model for calculating the time to corrosion induced concrete cover cracking due to rust formation and expansion. Parameters in the model are C_{crit}, apparent chloride diffusion coefficient, corrosion rate, rebar perimeter, and rebar spacing.	[Bazant, 1979]
1989	Morinaga's model	Simple geometrical model based on rust formation and expansion. The model predicts the time to concrete cracking using the parameters corrosion rate, concrete cover depth and steel bar diameter. Only geometrical properties are covered.	[Anand et al, 2016]
2000	Life-365TM model	Semi-probabilistic model based on chloride diffusion (Fick's law), Ccrit, and the corrosion propagation phase. The diffusion coefficient is both time and temperature dependent. The model estimates the time to cracking and first repair, and the lifecycle cost associated with different corrosion protection strategies.	[Life-365]
2002	Gulikers' model	The model allows calculation of the probability that a given reduction of the reinforcement cross-section has taken place at a given time. The model also discusses the combination of micro- and macrocells.	Gulikers [2002]
2007	El Maaddawy et al's model	Mathematical model that can estimate the time to corrosion initiation and cover cracking due to rust formation and expansion by considering a porous zone around a steel reinforcing bar. The model accounts for the time required for corrosion products to fill a porous zone before they start inducing expansive pressure on the concrete surrounding the steel reinforcing bar.	[El Maaddawy et al, 2007]
2011	Lu et al's model	A model for calculating the concrete cover cracking time using Faraday's law and taking existing cracks and porosity into consideration. The model accounts for rust entering existing cracks, and thereby extending the cover cracking time.	[Lu et al, 2011]
2011	Lundgren et al's model	Model including the flow of corrosion products through cracks. The volume flow of corrosion products through a crack is assumed to depend on the splitting stress and the crack width. The splitting stress is evaluated from the strain in the corrosion products, and the crack width is computed from the displacements across the crack.	[Hanjari et al, 2013]
2013	Wang et al's model	Virtual modelling of corroded bars using 3D laser scanning technology. Modelling cross-sectional area loss for corroded rebars in reinforced concrete structures. Residual cross sections can be simplified into ellipses for general corrosion; otherwise, it can be ascribed to combined pit and general corrosion.	[Wang et al, 2013]
2016	Michel et al's model	Model for estimating time to cover cracking caused by the expansive nature of solid corrosion products. The model includes the penetration of solid corrosion products into the available pore space, including deformations and cracks.	[Michel et al, 2016]

*) These 'model names' are linked to the name of one of the developers of the model, and not necessarily protected by intellectual property/trademark, except Life-365™.

An important aspect of steel bar cross section loss is the distinction between uniform corrosion and pitting corrosion. Therefore, to account for the localised nature of chloride induced corrosion, any model describing a uniform corrosion mechanism can be modified by introducing a pitting factor. One example is [Gulikers, 2002]:

$$Ø_{res} = Ø_{rebar} - \alpha \cdot \lambda \cdot i_{corr} \cdot t_p$$

where $Ø_{res}$ = residual rebar diameter [mm]
$Ø_{rebar}$ = initial rebar diameter [mm]
α = pitting factor [dimensionless number]
λ = factor to convert average i_{corr} to average penetration rate [2.3294×10^{-3} mm/(mA/m^2)]
i_{corr} = corrosion current density [mA/m^2]
t_p = the time elapsed since corrosion initiation [yr]

Further development of the modelling of cross-sectional area loss related to pitting corrosion can be found in the models developed by [Wang et al, 2013] and [Chen et al, 2022].

From this overview (Tables 1,2,3) it is seen that many of the models tend to focus on just a part of the deterioration process from chloride ingress to mechanical corrosion damage. This has been addressed recently by several researchers. Therefore, a multi-scale and multi-disciplinary approach has been proposed aiming to cover all relevant chemical, physical and mechanical aspects of chloride induced corrosion damage [Angst et al, 2022].

However, no such model has yet been developed, only proposals for further model developments. This implies an attempt to quantify the corrosion/ damage rate from the moment steel is placed in concrete until it reaches the end of the service life. One model proposal is to combine the scientific and practical contributions from several fields: Materials science, corrosion science, cement/concrete research, and structural engineering [Angst et al, 2022].

4 Model input parameters

The models described above uses several input parameters to predict/calculate the development of the deterioration process (initiation and propagation phases). Two of the parameters were discussed in Chapter 3 (chloride ingress and corrosion rate). A broader overview of input parameters can be grouped into three types, two related to the material properties of the concrete structure, and one specifying the environmental exposure:

- Concrete material properties
- Steel reinforcement (plain carbon steel, not stainless steel)
- Exposure conditions

An overview of input parameters in the models is shown in Table 4. Since these models only deals with chloride induced corrosion, the input exposure parameter ‘chloride’ is not included as this parameter is an intrinsic part of the models.

Table 4 clearly demonstrates that some input parameters dominate, whilst others are only used in a few models. Concrete cover thickness and chloride diffusion coefficient are the two main parameters mostly used, which illustrates the focus on chloride ingress.

Unexpectedly, input parameters like electrical resistivity in the concrete and exposure to wetness cycles and relative humidity are hardly used.

The model from 1979 was the first and only attempt (among the models listed in this report) to incorporate electrical resistivity in the modelling [Bazant, 1979].

Surprisingly, one potential input parameter – pH – is not used in any of these models. This parameter will affect the chemical binding of chloride as well as the chloride threshold value (C_{crit}).

Table 4 Input parameters in the service life models

Parameter related to	**Input parameter**	**Used in model** *(Full model names: See references in Tables 1,2,3)*
Concrete material properties	Binder content	Stadium, DuraCon, Life-365
	Binder type	ERFC, Square Root, DuraCon, Life-365
	w/b ratio	Stadium, DuraCon, Chen
	Concrete strength	Lu, Lundgren, Michel
	Cover thickness	Bazant, Morinaga, Life-365, Gulikers, El Maaddawy, Lu, Lundgren, Michel, Chen
	Concrete cracks	Lu, Lundgren, Michel
	Permeability/porosity	Stadium, Lu, Lundgren, Michel
	Moisture content	Stadium, Square Root, Chen
	Electrical resistivity	Bazant
	pH	*Not used*
	Chloride diffusion coefficient	ERFC, ClinConc, DuraCrete, CDD, Stadium, DuraCon, fib, Chen, Bazant, Life-365
	Chloride threshold/C_{crit}	ClinConc, DuraCret, fib, Chen, Life-365
	Chloride binding	ClinConc, CDD, fib
	Aging factor	Lundgren, Michel
Steel reinforcement	Corrosion rate	fib, Bazant, Morinaga, El Maaddawy, Lu, Lundgren, Michel
	Rebar diameter	Chen, Bazant, Morinaga, Gulikers, El Maaddawy, Lu, Lundgren, Wang, Michel
	Rust formation and expansion	Bazant, Morinaga, El Maaddawy, Lu, Lundgren, Michel
Exposure conditions	CO_2/carbonation	DuraCrete, Stadium, fib, Gulikers, Wang
	Wetness cycles	Fib, Wang
	Relative humidity	Chen
	Temperature	ClinConc, DuraCrete, Stadium, Chen, Life-365

5 Model output data

The output data from the models can be grouped into the two phases *Initiation* period and *Propagation* period. An overview is presented in Table 5.

As expected, Table 5 clearly shows that chloride profile dominates as output data from service life modelling of chloride induced corrosion deterioration. It is also seen that only two models are providing corrosion rate as output data. However, corrosion rate is included as input parameter in several models (see Table 4), either as an assumed/fixed parameter, or measured in-situ.

Even though loss of bond between steel and concrete – caused by corrosion in the propagation period – is an important deterioration parameter, it is not included as output data in any of the models.

Table 5 shows no reference to any model regarding structural collapse as this is meant to include the whole concrete structure. However, mechanical collapse of structural components caused by reinforcement corrosion is of course covered in several models.

Table 5 Output data from the service life models

Deterioration phase	**Output data**	**From model** *(Full model names: See references in Tables 1,2,3)*
Initiation period	Chloride profile	ERFC, ClinConc, DuraCrete, CDD, Stadium, DuraCon, fib, Chen, Life-365
	Chloride ingress rate	Square Root
	Free chloride	ClinConc, CDD
	Depassivation/onset of corrosion	Stadium, Chen, Life-365
Propagation period	Corrosion rate	Gulikers, Chen
	Rebar cross-sectional loss	Gulikers, Wang, Chen
	Rust formation / expansion	Bazant, Morinaga, Lu, Lundgren, Michel
	Concrete cracking	Bazant, Morinaga, Life-365, El Maaddawy, Lu, Lundgren, Michel
	Concrete spalling	Lundgren, Michel

6 Sensors for in-situ monitoring of input parameters and output data

In-situ sensors that could provide reliable and valid input data for the service life modelling of a concrete structure would be of great importance in both developing and evaluating the models. To some extent, such sensors are already developed, even tailor-made for embedment in concrete. Table 6 gives an overview of these sensors; some are already commercialised whilst others are under development.

A question often raised during planning of in-situ monitoring is where to install the sensors. The apparently obvious answer is to install the sensors in parts of the structure where deterioration is expected to occur. However, it may also be wise to install a few sensors in parts of the structure where no deterioration is expected. In this way, the long-term stability of an undisturbed sensor – meaning not triggered by the activating factor (e.g. chloride concentration) – can be monitored in an almost similar environment. In addition to stability, the accuracy of the sensor is important. Suppliers of commercial sensors should be able to state the accuracy of the measured value in terms of $\pm$ uncertainty. Also be aware that temperature will influence the measured value for some of the sensors.

Ideally, the best practice for installing most of these sensors would be to install them already when building the structure. For existing structures, the installation should preferably be carried out before the depassivation state of the steel has been reached.

Table 6 Sensors for in-situ monitoring of steel reinforcement corrosion deterioration

Parameter to be measured	**Type of sensor**	**Commercially available?**	**Reference** *(mode of operation)*
Chloride concentration	Ion-selective electrode (Ag/AgCl) + Reference electrode	Yes	[Angst et al, 2010]
pH	pH-sensitive electrode (IrO_x) + Reference electrode	Yes	[Femenias et al, 2017]
	Fibre optical sensor	Yes	[Grengg et al, 2023]
Moisture / Relative humidity	Various types: Capacitive, Resistivity, Electrolytic	Yes	[De Weerdt et al, 2016]
Moisture content	Fibre optical sensor	Partly	[Bremer et al, 2016]
Temperature	Thermocouple	Yes	[Angelucci, 2018]
	Fibre optical sensor	Yes	[López-Higuera et al, 2011]
Electrical resistivity	Wenner electrode	Partly	[Ramón, 2021]
Corrosion potential	Reference electrode (MnO_2, Ag/AgCl/KCl, …)	Yes	[Myrdal, 2006]
Corrosion rate	Linear Polarisation Resistance sensor incl. Reference electrode	Partly	[Vedalakshmi et al, 2009]
Corrosivity (macro-cell corrosion initiation)	Anode-ladder sensor	Yes	[Shevtsov et al, 2022]
	Multi-ring sensor	Yes	
	CorroWatch sensor	Yes	https://forcetechnology.com/-/media/force-technology-media/pdf-files/0-to-4000/2522-corrowatch-installation-instructions.pdf
	CorroRisk sensor	Yes	https://forcetechnology.com/-/media/force-technology-media/pdf-files/4001-to-4500/4087-corrorisk-en.pdf
Mechanical strain and cracks	Fibre optical sensor	Partly	[Clauss et al, 2021]
	Piezoelectric sensor	Partly	[Ahmadi et al, 2021]

7 Conclusion

One might conclude from this broad model overview that there is no clear consensus among researchers and scientists what is the best way to model the service life of steel reinforced concrete structures suffering from chloride induced deterioration.

Over the last 50 years the service life modelling of steel reinforced concrete structures suffering from chloride induced corrosion deterioration has focused mainly on the ingress of chlorides into the concrete, incorporating the chloride diffusion coefficient as the key input parameter. Parameters like chloride threshold value (C_{crit}) and chloride binding were gradually included. The latest inputs to the 'chloride models' were factors like the effect of type of binder, moisture, temperature, aging, and time to corrosion initiation.

Parallel to this, and increasingly more noticeable over the last years, are the attempts to incorporate the deterioration mechanisms observed after corrosion has started (the propagation phase). Factors linked to

rust formation and expansion, and concrete cover cracking have become more of a basic part of several recent models. However, surprisingly few models provide rate of corrosion as a model output (only Gulikers' model and Chen et al's model). Instead, corrosion rate is used as an input parameter in several models.
Many of these service life models have been criticised for focusing too narrowly on a limited selection of factors involved in the deterioration process, mainly the 'chloride factors', and not incorporating all relevant factors into one model, i.e. a multi-scale and multi-disciplinary model [Angst et al, 2022]. This also involves modelling the service life from when the structure was placed until the end of its service life. There seems to be a new approach heading towards a new regime in service life modelling. This approach will need to include several contributions from different professionals in a collaborative effort to develop a new and comprehensive service life model for reinforced concrete structures.

An important part of service life modelling will be to have reliable and valid input data. To achieve this, in-situ sensors can be used to monitoring various input parameters. There are many types of sensors that are commercially available, some even specially designed for use in concrete. One should investigate the possibility of utilising a set of different sensors to see if a sensor combination could give a better understanding of variables and how these interact and develop over time.

Acknowledgements

The author of this report wants to acknowledge SINTEF and its partners for establishing the EXCON project supported by the project known as Green Management of Structures for Infrastructure (Research Council Norway project number 340843).

Special thanks go to Professor Mette Geiker and Professor Jan Arve Øverli at NTNU for their helpful guidance and fruitful discussions on models and parameters related to chloride induced corrosion of steel reinforced concrete structures.

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Appendix A

The following 'Ten Commandments' are offered as a means of providing guidance to research on service life prediction of building materials and components [Masters, 1987].

Number	Commandment
1	Thou shalt define the problem explicitly before attempting to solve it.
2	Thou shalt define service life such that a) it can be measured (quantitatively), and b) it can be related to in-service performance.
3	Thou shalt be open to new approaches and methods rather than blindly accepting those of tradition.
4	Thou shalt use simple and systematic procedures having a basis in logic, common sense and materials science.
5	Thou shalt be aware that unsystematic, qualitative accelerated ageing test data can be used to make anything look good, bad, or indifferent.
6	Thou shalt recognize that a) it is impossible to simulate all possible weathering stresses in the laboratory, and b) it is not necessary to do it anyway.
7	Thou shalt ensure that degradation processes induced by accelerated tests are the same as those encountered in service.
8	Thou shalt measure the degradation factors.
9	Thou shalt be wary of the *Correlation Trap.*
10	Thou shalt recognize that, by using systematic, quantitative procedures, valid accelerated tests can be developed.

Appendix B

(Readable when zoomed in to 400 % or more)

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Chronological overview of models published over the last 50 years - divided into 3 model groups

					Deterioration stage(s) covered in the model				
					Chloride ingress			Corrosion	
Model group	Model name	Year	Reference	Model characteristics	Diffusion	Absorption	Permeation	Initiation	Propagation
Chloride ingress	ERFC model	1972	Collepardi et al, 1972	Classic model based on chloride ingress rate using the Error-function solution to Fick's 2nd law.	x				
	ClinConc model	1996	Luping, 2008	Uses free chloride as the driving force (Fick's law), and takes non-linear chloride binding into account. Time-dependent chloride diffusion coefficient.	x				
	DuraCrete model	1998	Lindvall, 1998	Probabilistic calculation to determine the probability of corrosion initiation. ERFC version with time dependent chloride diffusion.	x				
	CDD model	2000	Martin-Perez et al, 2000	Concentration-Dependent Diffusion model taking into account the effect of chloride binding	x				
	Stadium model	2001	Marchand, 2001	Multi-ionic model, based on Nernst-Planck equation. Provides chloride ingress rate.	x	x			
	Square Root model	2018	S. Fjendbo et al, 2021	Model based on the linear relationship between the depth of a reference chloride content and the square root of exposure duration.	x				
Corrosion onset	DuraCon model	2003	Ferreira et al, 2004	Modelling chloride penetration (Fick's law) and time to depassivation in combination with a time dependent diffusion coefficient.	x				
	fib Model Code	2006	http://www.fib-international.org/publications/fib-bulletins/model-code-for-service-life-design-pdf-detail.html	Probabilistic calculation of time to depassivation based on an established 'chloride threshold' value.	x	x		x	x
	Chen's model	2022	Chen et al, 2022	Numerical and empirical models for structures in marine environment, incorporating the effect of w/b ratio, concrete cover, critical chloride content, and rebar diameter.	x			x	x
Corrosion rate and damage	Bazant's model	1979	Bazant, 1979	Corrosion induced concrete cover cracking due to rust formation and expansion. Parameters in the model: Corrosion rate, rebar perimeter, and rebar spacing.	x				x
	Morinaga's model	1989	Anand et al, 2016	Simple geometrical model based on rust formation and expansion. Mechanical properties of concrete not included.					x
	Life-365 model	2000	http://www.life-365.org/images/service-life-prediction.pdf	Semi-probabilistic model based on chloride penetration (Fick's law) and providing time to corrosion initiation, and time to concrete cracking.	x			x	x
	Gulikers' model	2002	Gulikers, 2002	A probabilistic model which allows calculation of the probability that a given reduction of the reinforcement cross-section has taken place at a given time.					x
	El Maaddawy's model	2007	El Maaddawy et al, 2007	Corrosion induced concrete cover cracking due to rust formation and expansion. Using concrete E modulus and Faraday's law to calculate the concrete cover cracking time.					x
	Lu's model	2011	Lu et al, 2011	A model for calculating the concrete cover cracking time using Faraday's law and taking existing cracks and porosity into consideration.					x
	Lundgren's model	2011	Hanjari et al, 2013	Model including the flow of corrosion products through cracks. The volume flow of corrosion products through a crack is assumed to depend on the splitting stress and the crack width. The splitting stress is evaluated from the strain in the corrosion products, and the crack width is computed from the displacements across the crack.					x
	Wang's model	2013	Wang et al, 2013	Modelling of corroded bars using 3D laser scanning technology. Cross-sectional area loss for corroded rebars in reinforced concrete structures using easy-to-measure variables. Residual sections can be simplified into ellipses for general corrosion; otherwise, it can be ascribed to combined pit and general corrosion.					x
	Michel's model	2016	Michel et al, 2016	Modelling of the expansive nature of solid corrosion products and the penetration of solid corrosion products into the available pore space, including deformations and cracking.					x

	Input parameters in the model													
	Concrete material properties													
Model name	Binder content	Binder type	w/b ratio	Concrete strength	Cover thickness	Concrete cracks	Permeability porosity	Moisture content	Electrical resistivity	pH	Chloride diff. coeff.	Chloride threshold	Chloride binding	Aging factor
ERFC model		x									x			
ClinConc model											x	x	x	x
DuraCrete model											x	x		x
CDD model											x	x	x	
Stadium model	x		x				x	x			x			
Square Root model		x						x				x		x
DuraCon model	x	x	x								x	x		
fib Model Code											x	x		
Chen's model			x		x			x			x	x		
Bazant's model					x				x		x	x		
Morinaga's model					x									
Life-365 model	x	x			x						x	x		
Gulikers' model					x									
El Maaddawy's model					x									
Lu's model				x	x	x	x							
Lundgren's model				x	x	x	x							x
Wang's model														
Michel's model				x	x	x	x							x

	Steel reinforcement properties				Exposure properties				
Model name	Corrosion rate	Rebar diameter	Rust formation	Rust expansion	Chloride	Carbonation/ pH	Wetness cycles	Relative humidity	Temp
ERFC model					x				x
ClinConc model					x				x
DuraCrete model					x	x			x
CDD model					x				
Stadium model					x				x
Square Root model					x				
DuraCon model					x				
fib Model Code	x				x	x	x		x
Chen's model		x			x			x	x
Bazant's model	x	x		x	x				
Morinaga's model	x	x		x	x				
Life-365 model					x				x
Gulikers' model		x			x	x			
El Maaddawy's model	x	x		x	x				
Lu's model	x	x		x	x				
Lundgren's model	x	x	x	x					
Wang's model		x			x	x	x		
Michel's model	x	x	x	x					

	Output data from the model								In-situ sensors that could provide data for the modelling									
Model name	Chloride profile	Ingress rate	Free choride	Onset of corrosion	Corrosion rate	Cross sect. loss	Concrete cracking	Concrete spalling	Chloride	pH	Moisture / RH	Temp	Resistivity	Corrosion potential	Corrosion rate	Macrocell corrosivity	Mechanical strain	Piezoelectric
ERFC model	x								x			x						
ClinConc model	x		x						x			x						
DuraCrete model	x								x			x						
CDD model	x		x						x									
Stadium model	x			x					x			x						
Square Root model		x							x									
DuraCon model	x								x									
fib Model Code	x								x			x						
Chen's model	x			x	x	x			x		x	x	x				x	x
Bazant's model							x										x	x
Morinaga's model							x										x	x
Life-365 model	x			x			x		x			x						
Gulikers' model					x	x									x			
El Maaddawy's model							x										x	x
Lu's model							x										x	x
Lundgren's model							x	x									x	x
Wang's model						x									x			
Michel's model							x	x									x	x

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The project is funded by the Green Platform scheme, which is a collaboration between the Research Council of Norway, Innovation Norway, Siva and Enova, and the following partners: