

A Theoretical Framework for Service Life Prediction of Reinforced Concrete Structures in Chloride Environment using Load Factors

Amjad Ali Pathan

Department of Civil Engineering
Mehran University of Engineering and
Technology, Jamshoro, Pakistan
amjad.Pathan@faculty.muett.edu.pk

Ghous Bux Khaskheli

Department of Civil Engineering
Isra University
Hyderabad, Pakistan
ghous.bux@isra.edu.pk

Abdul Sami Qureshi

Department of Civil Engineering
Mehran University of Engineering and
Technology, Pakistan
sami.qureshi@faculty.muett.edu.pk

Abstract-Service life modeling of reinforced concrete structures in a chloride environment is mainly performed without considering the loading effects. Different loading effects can produce different service life results. This study presents a theoretical framework for the modeling of the service life of reinforced concrete structures in a chloride environment using loading factors, showing that, depending on the loading nature (either compression or tension), different diffusion results could be obtained. This paper also highlights various approaches to service life modeling, such as the deterministic, probabilistic, and semi-probabilistic, which consider different ways to estimate the service life of reinforced concrete structures in chloride environments. The importance of various distributions for the input parameters in the chloride ingress modeling was examined. The proposed framework includes a procedure to estimate the probability of concrete failure in chloride environments.

Keywords-concrete durability; service life design; service life framework; chloride ingress

I. INTRODUCTION

Service life modeling, in terms of durability, is performed to estimate the service life and performance of reinforced concrete structures. A structure's performance is defined as its capacity to meet the target service time for its intended performance. Service life modeling estimates the residual life and is needed to apply any repair and maintenance strategies. Several studies have been conducted for modeling the estimation of service life [1-6], presenting various frameworks. In [7], a framework for the degradation of concrete was presented, highlighting the importance of the deterministic, probabilistic, and semi-probabilistic approaches, and the importance of cover thickness, concrete strength, cement type, and water to cement ratio. A detailed study for the chloride ingress parameters was conducted in [6], providing a procedure of using input parameters for the service life modeling of chloride ion ingress. In [8], the service life of concrete was quantified by a reliability index, utilizing the probabilistic method to consider the distribution laws of input parameters. Authors in [9] reported that the initiation period starts with the exposure of structure and ends with the de-passivation of

reinforcement. In [2], a probabilistic model was presented and validated with data collected from two projects. The results showed that the chloride ingress process involved great uncertainties and randomness in material input parameters and structure's geometry. The proposed model was validated through a parametric analysis, finding the influences of diffusion co-efficient D_o , surface chloride concentration C_s , age factor m , cover depth X , and chloride threshold C_{TH} . Authors in [10] reported that the degrading state of an aging concrete structure could be updated for reliability purposes. Authors in [11] reported that the level of reliability for service life design was generally unclear, proposing that the criteria should be based on long-term experience. In [12], the factors influencing the chloride transport mechanism such as diffusion coefficient, surface chloride ion concentration, and drying and wetting regimes were analyzed, while the results showed that diffusion coefficient, drying, and wetting influenced the maximum transmission depth.

In [4], the deterministic approach to analyze service life was reported to fail due to uncertainties on input parameters, while a probabilistic model was proposed and developed. Probabilistic methods including uncertainty parameters for input parameters were presented in [3], considering the sensitivity of the corrosion probability to different parameters and a durable design concrete cover as the most important parameter. A probabilistic model including uncertainties arising from the loadbearing capacity of reinforced concrete structures was proposed in [5]. Durability extension and service life predictions were reported to be important in [1], as corrosion has many consequences such as cracking and spalling of concrete, as well as losses of bond strength in cross-sectional areas of steel. In [6], an in-depth study was presented on the use of the concrete diffusion coefficient. The durability properties of fuel ash concrete and metakaolin concrete were studied in [13] and [14] respectively.

This study aims to develop a framework for the chloride diffusion in concrete, considering the loading effect using semi-probabilistic and probabilistic analysis.

Corresponding author: Amjad Ali Pathan

II. CHLORIDE INGRESS MODELING

The estimation of chloride content in concrete requires a deep study of the input parameters for service life modeling. The following equation was used in [5] for the probabilistic analysis:

$$C(X, T) = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{DT}} \right) \right] \quad (1)$$

The chloride diffusion coefficient D for an aging factor m is given by:

$$D(t) = D_o \left(\frac{t_o}{t} \right)^m \quad (2)$$

A. Service Life Modeling

Service life modeling is essential to apply repair and maintenance strategies for existing and enhancing the durability of new structures. Service life modeling can be performed in three different ways: deterministic, probabilistic, or semi-probabilistic. Table I shows a comparison of these three approaches in terms of complexity and Table II summarizes the three approaches.

TABLE I. SERVICE LIFE MODELING APPROACHES

Approach	Obtained results	Procedures
Deterministic	Over-estimated	Simple
Probabilistic	Balanced-estimated	Complex
Semi-probabilistic	Under-estimated	Semi-complex

TABLE II. SERVICE LIFE MODELING APPROACHES SUMMARIZATION

Approach	Values	
	$C(X, T)$	C_{TH}
Deterministic	Mean (μ)	Mean (μ)
Probabilistic	Mean (μ) and standard deviation (σ)	Mean (μ) and standard deviation (σ)
Semi-probabilistic	Mean (μ) and standard deviation (σ)	Mean (μ)

B. Deterministic

In this approach, the values of variables are considered deterministic, and the approach can be conducted as a discrete or continuous overtime study. The deterministic approach considers average values, such as μ , taken as input parameters, and the calculation procedure is simple. The disadvantage of this approach consists of not considering the variation and scatter of input parameters.

C. Probabilistic

In this approach, the input parameters are defined using distributions. The selection of the distribution depends on available data, previous conducted studies, and designer's experience. This approach uses load and resistance concepts in general. The input parameters for load are taken as $C(X, T)$ as defined in (1) and (2). C_{TH} input values are obtained from the average and standard deviation of available data or previous studies. This procedure gives acceptable results, despite its complexity. The designer's experience in selecting input parameters plays an important role, as an incorrect selection could result in over or under-estimated results.

D. Semi-probabilistic

In the semi-probabilistic approach, the input parameters for $C(X, T)$ are defined using distributions, while C_{TH} values are considered as a deterministic uniform value without any variation or scatter in resistance.

III. LOADING FACTORS

Real concrete members perform differently under different loading conditions in experimental tests. Load causes strain in the members, as shown in Table III. A column under loading conditions causes negative strain increasing tortuosity, while a beam under tense causes positive strain lowering tortuosity. In general, parapet walls do not experience any loading and their tortuosity levels are normal. Table IV shows an example of various members' nature in a bridge structure. A bridge deck experiences both compressive and tensile forces, a column remains under tensile forces, a pier remains under compressive forces, and a deck beam remains under both compressive and tensile forces.

TABLE III. MEMBERS UNDER LOAD AND NATURE OF STRAINS

Concrete members	Strain levels	Example	Tortuosity level (τ)
Compression members	Negative	Columns	Higher
Tension members	Positive	Beams	Lower
Normal members	Neutral	Parapet walls	Normal

TABLE IV. EXAMPLES FOR COMPRESSION AND TENSILE MEMBERS IN A BRIDGE

Structure	Compression members	Tension members	Comments
Bridge deck	✓	✓	Varies due to the stress level along the deck
Bridge columns	✓		Loading causes compressive strain
Bridge piers	✓		Loading causes compressive strain
Bridge deck beams	✓	✓	Varies due to the stress level along the length

A. Compression Members

Service life modeling for compression members, such as the columns in a bridge, may differ from normal concrete under no loading. Members under compression generally develop shrinkage stress, increasing concrete's compactness by filling micro-pores. In such cases, a reduction in diffusion can be observed. So instead of assuming D_o as a constant value, a reduced D_o can be used. The revised values for D_o are shown in Table V.

TABLE V. LOADING FACTORS

Compression members	Tension members
Revise DO for compressive strain, so: $D_o (new) = D_o - 1.1 D_o$ for loading value 0.4 times the limit state value $D_o (new) = D_o - 1.2 D_o$ for loading value of 0.5 times the limit state value	Revise DO for tensile strain, so: $D_o (new) = D_o + 1.2 D_o$ for loading value 0.4 times the limit state value $D_o (new) = D_o + 1.4 D_o$ for loading value 0.5 times the limit state value

B. Tension Members

Tension members in a structure are subjected to stresses that cause strains, defined by:

$$\epsilon = E \cdot \sigma \quad (3)$$

where σ is stress, E is the modulus of elasticity, and ϵ is the strain. This strain is a measure of expansion in concrete members, producing micro-cracks that accelerate the diffusion process within the concrete body.

C. Normal Members

In normal members, D_o with aging factors could be considered as normal. So, a revised diffusion coefficient (D) is needed for service life modeling.

IV. DURABILITY PARAMETERS AND THEIR PROBABILITY DISTRIBUTIONS

Probabilistic and semi-probabilistic analyses require a probability distribution, which is obtained from large data. The analysis is performed after deciding on the shape of the curve to be developed from large data. This also depends on designer's experience. Table VI shows various distributions used in several studies, and in the present study.

TABLE VI. PARAMETERS AND LOAD

Parameter	Reference				
	[2]	[4]	[9]	[11]	Present study
D_o	Log normal	Log normal	Normal	Log normal	Normal
C_o	Log normal	Log normal	Deterministic	Log Normal	Normal
C_s	Log normal	----	----	----	Normal
M	Beta	----	Normal	----	Normal
A	Normal	----	----	----	Normal
X	Normal	Normal	----	Log normal	Normal
C_{TH}	Normal	----	Deterministic	Log normal	Normal
$C(X,T)$	----	Uniform	Beta	----	Normal

V. SERVICE LIFE MODELING FRAMEWORK DESIGN

Service life modeling can be performed utilizing various simple or complex approaches, as can be seen in Figure 1. Analysis can be performed based on the design level. For instance, a deterministic approach may be followed during the design of a new structure, as it produces a quick result. Later, a semi-probabilistic analysis could be performed. A probabilistic analysis could be performed when detailed information for service life and maintenance is needed, requiring large datasets and experience.

VI. UNDERSTANDING THE PROBABILITY OF FAILURE

The probability of failure is a common region between both Probability Density Functions (PDFs) of $C(X, T)$ and C_{TH} , as seen in Figure 2. This is based on the concept of load and resistance, as a failure occurs when the load value exceeds resistance. Figure 2 shows the resistance of concrete in terms of its chloride uptake capacity, which is a theoretical chloride

content C_{TH} . The load is described by chloride content on depth X over time T written as $C(X, T)$. So, a failure occurs when $C(X, T)$ overlaps the region of C_{TH} .

- Stage 01: Data Collection
 - Testing Methods
 - Data obtained from literature
- Stage 02: Deciding Distributions
- Stage 03: Selecting a Model for $C(X,T)$ and D
 - $C(X, T) = C_s \left[1 - \operatorname{erf} \left(\frac{X}{2\sqrt{DT}} \right) \right]$
 - $D(t) = D_o \left(\frac{t_o}{t} \right)^m$
- Stage 04: Deciding an approach
 - Deterministic, only μ is required
 - Semi-probabilistic, μ, σ are required
 - Probabilistic, μ and σ are required
- Stage 05: Selecting members based on loading criteria
 - Compression members, revise D
 - Tension members, revise D
 - Normal members, no revision in D is required
- Stage 06: Based on Member Type apply changes in D_o
 - For tension members $D_o \text{ new} = D_o + 1.4 D_o$ [tension causes positive strain ϵ]
 - For compression members $D_o \text{ new} = D_o - 1.2 D_o$ [compression causes negative strain ϵ]
 - For normal members $D_o = D_o$ [no loading causes no-strain ϵ]
- Stage 07: Finding Service Life Time for Limit State and Ultimate State
 - Corrosion initiation
 - Corrosion Propagation
 - Loss of steel area
 - Cracking of concrete
 - Failure of member
- Stage 07: Deciding For Repair and Maintenance
 - Finding repair and maintenance cost

Fig. 1. Flow chart of service life modeling.

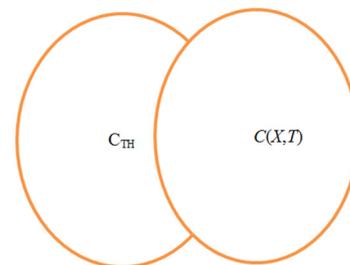


Fig. 2. Domains of failure and success.

VII. DURABILITY PERFORMANCE AND COST EFFECT

Concrete's durability performance is directly related to cost-effectiveness, as more durable concrete structures reduce service life cost. Similarly, concrete's poor performance results in earlier demolition of structures raising the overall cost. Enhanced service life can be achieved for new and existing structures by applying a repair strategy before major failures. The design framework includes all necessary parameters for service life modeling. The load effect has a major contribution to the analysis, as concrete performs differently depending on loads' nature. Based on the loads' nature (i.e. compression (columns) and tension (beams)), different results can be obtained. Table VII shows various levels of durability designs and their effect on cost. Durability performance is enhanced by the use of high strength concrete with cementitious materials having chloride binding properties and aggregates with low porosity. Sustainability involves economic considerations, as extending service reduces the total cost of construction and maintenance.

TABLE VII. ENHANCING DURABILITY PERFORMANCE

Criteria	Enhancing durability	Effect on initial cost	Service life cost
Resistance	Using conventional materials, Ordinary Portland Cement (OPC), and aggregates	Low	Low
Capacity	Cementitious additives such as fly ash, slag, silica, and metakaolin are added to the concrete	More	More
Performance	High-performance materials are used in concrete such as OPC with fly ash and silica fume	High	High
Service life-corrosion initiation	Corrosion inhibitors are used	High	High
Service life-corrosion propagation	Cathode protection measures are applied	High	High
Service life-corrosion cracking	Additional measures are applied, such as sealing of cracks and protection of anode and cathode	High	High
Sustainability	High strength concrete with low porosity aggregate is used	Very high	Very high

VIII. CONCLUSION

This study highlighted the importance of the deterministic, probabilistic, and semi-probabilistic approaches for service life modeling, which give different levels of analysis. The probabilistic analysis is more complex, as it involves a lot of computational stages. A theoretical framework for service life modeling was presented considering the loading factors, while the loading effect on chloride ingress was ignored. Theoretically, it was shown that coefficient D can be applied based on the loads' nature corrections in diffusion. Moreover, it was shown that the diffusion process in concrete is not as straightforward as using (2), but using time steps the chloride content inside the concrete volume increases raising tortuosity and reducing chloride's ingress. Previous studies proposed various distributions for the input parameters of service life modeling. Concrete's performance level can be enhanced by using various high-performance materials, such as OPC with fly ash and silica fume, for sustainable concrete with aggregates with low porosity. This study's results can be concluded as:

- Better performance of concrete structures reduces their service life costs. The service life can be estimated based on the level of analysis.
- Service life can be estimated based on deterministic, semi-probabilistic, or probabilistic modeling. Probability distributions have been proposed for various parameters.
- Chloride diffusion in concrete is a time-dependent process.
- Structural loads affect the chloride diffusion in concrete, and different loadings on structural members can produce different results. For instance, the same concrete will perform differently under different load conditions. Beams are generally assumed under both compressive and tensile

forces, while columns are assumed under compressive forces. Based on the nature of the loads, the diffusion coefficient may be revised for compression and tension members.

- Durability performance could be enhanced from resistance to sustainability. This affects the initial cost of construction and service life, as shown in Table VII.

REFERENCES

- [1] A. Tarighat, "Stochastic modeling and calibration of chloride content profile in concrete based on limited available data," *International Journal of Civil Engineering*, vol. 10, no. 4, pp. 309–316, Dec. 2012.
- [2] A. Duan, J.-G. Dai, and W.-L. Jin, "Probabilistic Approach for Durability Design of Concrete Structures in Marine Environments," *Journal of Materials in Civil Engineering*, vol. 27, no. 2, Feb. 2015, Art. no. A4014007, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001023](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001023).
- [3] B. Saassouh and Z. Lounis, "Probabilistic modeling of chloride-induced corrosion in concrete structures using first- and second-order reliability methods," *Cement and Concrete Composites*, vol. 34, no. 9, pp. 1082–1093, Oct. 2012, <https://doi.org/10.1016/j.cemconcomp.2012.05.001>.
- [4] C. G. Nogueira and E. D. Leonel, "Probabilistic models applied to safety assessment of reinforced concrete structures subjected to chloride ingress," *Engineering Failure Analysis*, vol. 31, pp. 76–89, Jul. 2013, <https://doi.org/10.1016/j.engfailanal.2013.01.023>.
- [5] D. L. Allaix, V. I. Carbone, and G. Mancini, "Modelling uncertainties for the loadbearing capacity of corroded simply supported RC beams," *Structural Concrete*, vol. 16, no. 3, pp. 333–341, 2015, <https://doi.org/10.1002/suco.201500016>.
- [6] M. Shafikhani and S. E. Chidiac, "Quantification of concrete chloride diffusion coefficient – A critical review," *Cement and Concrete Composites*, vol. 99, pp. 225–250, May 2019, <https://doi.org/10.1016/j.cemconcomp.2019.03.011>.
- [7] E. Possan, D. C. C. Dal Molin, and J. J. O. Andrade, "A conceptual framework for service life prediction of reinforced concrete structures," *Journal of Building Pathology and Rehabilitation*, vol. 3, no. 1, Jan. 2018, Art. no. 2, <https://doi.org/10.1007/s41024-018-0031-7>.
- [8] F. Deby, M. Carcasses, and A. Sellier, "Toward a probabilistic design of reinforced concrete durability: application to a marine environment," *Materials and Structures*, vol. 42, no. 10, Dec. 2008, Art. no. 1379, <https://doi.org/10.1617/s11527-008-9457-8>.
- [9] M. Beck *et al.*, "Deterioration model and input parameters for reinforcement corrosion," *Structural Concrete*, vol. 13, no. 3, pp. 145–155, 2012, <https://doi.org/10.1002/suco.201200004>.
- [10] R. Schneider *et al.*, "Assessing and updating the reliability of concrete bridges subjected to spatial deterioration – principles and software implementation," *Structural Concrete*, vol. 16, no. 3, pp. 356–365, 2015, <https://doi.org/10.1002/suco.201500014>.
- [11] S. Helland, "Design for service life: implementation of fib Model Code 2010 rules in the operational code ISO 16204," *Structural Concrete*, vol. 14, no. 1, pp. 10–18, 2013, <https://doi.org/10.1002/suco.201200021>.
- [12] X. Gang, L. Yun-pan, S. Yi-biao, and X. Ke, "Chloride ion transport mechanism in concrete due to wetting and drying cycles," *Structural Concrete*, vol. 16, no. 2, pp. 289–296, 2015, <https://doi.org/10.1002/suco.201400035>.
- [13] O. M. Ofuyatan, F. A. Olutoge, and O. A. Olowofoyeku, "Durability Properties of Palm Oil Fuel Ash Self Compacting Concrete," *Engineering, Technology & Applied Science Research*, vol. 5, no. 1, pp. 753–756, 2015.
- [14] A. Saand, M. A. Keerio, and D. K. Bangwar, "Effect of Soorh Metakaolin on Concrete Compressive Strength and Durability," *Engineering, Technology & Applied Science Research*, vol. 7, no. 6, pp. 2210–2214, Dec. 2017, <https://doi.org/10.48084/etasr.1494>.