www.cafetinnova.org

Indexed in
Scopus Compendex and Geobase Elsevier, Chemical Abstract Services-USA, Geo-Ref Information Services-USA, List B of Scientific Journals, Poland, Directory of Research Journals

ISSN 0974-5904, Volume 08, No. 02

International Journal of Earth Sciences and Engineering

April 2015, P.P.477-484

Service Life Modeling of Reinforced Concrete Structures-Computational Methods

RANJITH A[1], K BALAJI RAO[2] AND K MANJUNATH[1]

[1]*Department of Civil Engineering, Malnad College of Engineering, Visvesvaraya Technological University, Belagavi- 590018*

[2]*CSIR-Structural Engineering Research Centre, Taramani, Chennai – 600113*

Email: *ranjith.anand70@gmail.com, balajiserc1@gmail.com, kmnrpur@gmail.com*

Abstract: Reinforced concrete is one of the widely accepted abundant construction material using all over the world. Corrosion of reinforcement is the most significant cause of premature deterioration of reinforced concrete structures. Many of the concrete structures, which have been exposed to aggressive environments, suffer from durability problems and fail to fulfill their design service life requirements. Due to the deterioration of reinforced structural components, it is very difficult to assess the performance degradation of reinforced concrete as the age of the structure progresses. However, modeling of service life of reinforced concrete structures is a very difficult task as it includes many uncertainties in real practice. Current trends in service life modeling place emphasis on computational methods such as finite element analysis method (FEA), finite difference method (FDM), artificial neural network (ANN) etc., which are popular among researchers for modeling the service life of reinforced concrete structures subjected to deterioration. This article presents review of some of the recent service life models for existing as well as repaired concrete structures, developed through these computational tools.

Keywords: *Concrete, Chloride induced corrosion, Diffusion, Service life, modeling*

1. Introduction

Reinforced concrete is one of the most common construction and repair material used all over the world. Due to the wide range of applications, reinforced concrete structures are subjected to different aggressive exposure conditions and mechanical load at the same time.

Chloride induced corrosion is considered to be one of the major deterioration mechanism in reducing the service life of reinforced concrete structure which is subjected to aggressive or marine environment. So, the performance assessment of structures over a period of time is mandatory with routine monitoring. But, due to improper maintenance as well as monitoring, it is very difficult to assess the performance of structures over a period of time. Therefore, models are required to quantify the residual service life of structures emphasis also placed on present condition.

The concept of service life prediction for concrete structures is now becoming an area of increasing interest for engineers. In this respect, durability of concrete plays an important role. Prediction models have been developed to predict and quantify structural service life based on material resistance and environmental loads. The service life of a structure is defined as the period of time after installation until such time when costly repair becomes necessary [26]. Concrete deterioration due to chloride-induced corrosion can be represented by a simple service life model of *initiation stage* and a *propagation stage.*

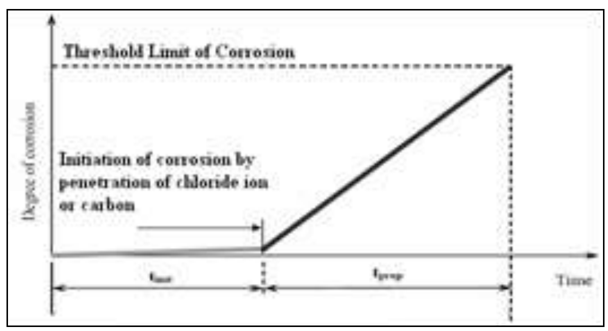

Figure 1 *Service life model suggested by Tutti (1982)*

Several methodologies and computer models were developed over the years to predict the service life of reinforced concrete structures and they have effectively been used in enhancing durability of concrete and extending the service life of RC structures.

2. Service Life Modeling

The service life of a structure is the period of time in which it is able to comply with the given requirements of safety, stability, serviceability and function, without requiring extraordinary costs of maintenance and repair.

Service life of the structural element inclusive of initiation period and the propagation period until cracking and spalling occur [6]. Service life is the period in which the structure's resistance R (t) can withstand the environmental load S (t) [9]. Service life of structure is the time from corrosion initiation to corrosion crack initiation in concrete [15]. Service life of structure is the number of years during which the structure shall perform satisfactorily without unforeseen high costs for maintenance [24].

Most of the researchers consider the total service life of a structure as sum of the corrosion initiation and corrosion propagation period. Prediction of corrosion initiation time periods based on Fick's second law of diffusion was widely accepted [18, 19]. Also, many researchers divided the service life of a structure in to three stage process i.e., the sum of corrosion initiation time, corrosion propagation time and corrosion cracking time [3, 9, &15]

2.1. Initiation Period

The initiation period, *ti*, defines the time it takes for chlorides to penetrate from the external environment through the concrete cover and accumulate at the embedded steel in sufficient quantity to break down the protective passive layer on the steel and thereby initiate an active state of corrosion. Fick's second law of diffusion is widely accepted in determining corrosion initiation time [18, 19].

2.2. Propagation Period

The propagation period, *tp*, defines the time necessary for sufficient corrosion to occur to cause an unacceptable level of damage to the structure or structural member under consideration. Bazant model and modified Bazant model can successfully been using to assess corrosion propagation time [9].

2.3. Four Governing Parameters for Initiation Stage

T_i – time to onset of corrosion

C_s – surface chloride concentration (Environmental Exposure)

Cl_{th} – chloride threshold value (Material Property, Steel)

D – chloride diffusion coefficient (Material Property, Concrete)

d_c – depth of concrete cover over the reinforcing steel (Design Parameter)

$$T_i = f(C_t, C_s, D, d_c) = \frac{d_c^2}{4D[erf^{-1}(1 - \frac{C_{th}}{C_s})]^2}$$

3. Service Life Models

In recent years, there have been numerous efforts to develop service-life models for reinforced concrete structures exposed to the corrosive effects of different environments. Various computational methods such as finite element method, finite difference method, artificial neural network in the field of civil engineering and application of fuzzy sets for remaining service life assessment was used in simulating the diffusion process.

Hodhod et al. [1] presented ANN approach to simulate the corrosion initiation time of slag concrete obtained from the Fick's second law of diffusion. The service life of RC structures was defined as two stage process; corrosion initiation stage and corrosion propagation stage. ANN model includes four neurons in the input layer, which represents the values of concrete cover depth, apparent chloride diffusion coefficient, chloride threshold value and surface chloride concentration, and one neuron in the output layer, to represent corresponding corrosion initiation time. From the study, it was found that, corrosion initiation time of slag concrete increases with increasing both concrete cover and chloride threshold value and decreases with increasing both surface chloride concentration and chloride diffusion coefficient. Also, it was evident that, there was a high correlation between corrosion initiation times obtained from Fick's second law of diffusion and ANN model.

Emilio Bastidas-Arteaga et al. [2] presented probabilistic approach for evaluating the repair strategies for RC structures deteriorated due to chloride contamination. The proposed methodology was illustrated by testing beams which were exposed to chlorides for about 80 years. The probabilistic assessment was taken in to account to include randomness of material properties, model and weather. The repair techniques (wet shotcrete, dry shotcrete and formed concrete) and the repair times for each technique were computed using the proposed probabilistic approach. Stochastic processes were used to model the environmental actions. Then, life cycle cost analysis was used to estimate the total cost when the costs of inspection, repair and rehabilitation activities incurred at different times.

Zenonas Kamaitis [3] proposed a general framework for service life prediction and reliability evaluation of anti-corrosion protective system. The effect of recoating and repair of corrosion protective system (CPS) in aggressive environments was also considered in the study. The service life of CPS was considered as 3 stage process: service life of protective barrier (tb), concrete cover (tc), and the last phase during which an unacceptable loss of reinforcement section has occurred (ts). The suitability of the proposed methodology was illustrated by considering the application of CPS on probabilistic analysis of a rectangular water tank to store inorganic acid. So, the proposed methodology is well suited for new or existing structures in order to predict the time to first repair/rehabilitation of reinforced concrete structures and to develop reliability-based corrosion protection systems as it provides more realistic service-life predictions and adequate basis for anticorrosion protection design.

Ha-Won Song et al. [4] predicted the service life of RC structures through micromechanics based corrosion model. In the study deterioration process was divided in to four parts; corrosion initiation time (ti), corrosion propagation time (tp), corrosion acceleration time (ta) and deterioration time (td). The study consists of three models namely, chloride penetration model, electric corrosion cell model and oxygen diffusion model to evaluate the rate of corrosion and accumulated corrosion products. Corrosion cracking model was then combined with the above models to evaluate the critical amount of corrosion product required for initiation cracking in cover concrete. To predict the service life of RC structures, all these models were implemented in finite element program and the results were compared with test results. The effect of crack width on corrosion and service life was also studied by the author. From the study, it was found that the service life of RC structures decreases with increasing crack width, increasing water-cement ratio, and decreasing pH of pore water.

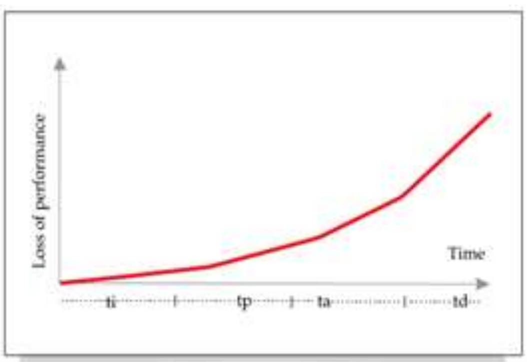

Figure 2 *Different phases of service life by Ha-Won Song et al. (2007)*

Bhaskar Sangoju et al. [5] estimated the service lives of OPC and PPC concretes reinforced with thermo mechanically treated reinforcement exposed to chloride environment. The study considered service life in to two parts: corrosion initiation period (ti), stable corrosion propagation period (tsp). The study was based on Fick's second law of diffusion, for determining chloride diffusion process. From the study it was found that, the service life of PPC based concrete was found to be nearly twice that of corresponding OPC based concrete.

Li Ying et al. [6] developed a realistic approach for service life prediction of concrete bridge element deteriorating due to chloride-initiated corrosion when spatial variation on deterioration and optimizing the repair strategy for concrete structures was included. The study was based on commonly used corrosion models and probabilistic-based reliability methods by taking into account the spatial variability of concrete properties that has a significant impact on design and maintenance decisions for structures. The end of service life was defined in two ways: (1) when 5% of the area shows concrete spalling; and (2) when 30% of the area shows concrete cracking. The service life was modeled as two stage process; initiation stage and propagation stage. Three repair strategies were discussed to extend the service life of the structure. The repair strategies were based on criterion of 5% visible area with spalling. Strategy 1: only failed (spalling) elements repaired; Strategy 2: failed elements and its horizontal adjacent elements repaired; Strategy 3: Besides failed elements, all its surrounding elements repaired. From the study it was found that, expected repair costs were relatively high from year 30 to 40, where, the strategy 3 was found to have minimum total cost.

Schiessl [7] developed a new service life design concept for the design against reinforcement corrosion in uncracked concrete regions for various new structures as well as the redesign and estimation of remaining service life of existing structures. The study considered a probability based service life design of concrete cover of the tube of the western Scheldt tunnel which was designed for expected deterioration mechanism, in which the internal walls of the tunnel were subjected to the influence of carbonation and chloride (induced corrosion) contaminated salt fog and splash environment. Reliability analyses were performed using STRUREL program. Initiation period for chloride induced reinforcement corrosion was predicted from deterioration model that describes the time-dependent diffusion-controlled penetration of chlorides.

Lu et al. [8] proposed a mathematical model to predict the service life. They considered the service life of a structure as the total time from corrosion initiation to cover corrosion cracking. The corrosion process was formulated using Faraday's law and concrete cracking was simulated using a smeared cracking approach. In the present model, the concrete around the reinforcement bar was modeled as a thick walled cylinder with a wall thickness equal to the thinnest concrete cover. Developed model can be considered as reliable as it was validated through experimental results in predicting corrosion induced cracking time and service life of RC structure.

Ming-Te Liang et al. [9] predicted the service lives of piers for two existing RC bridges exposed chloride environment using several mathematical models. The service life model consists of three stages: initiation (diffusion) time, depassivation time, and corrosion (propagation) time. The total service life of pier for the existing RC bridge can be expressed as *t = tc + tp + tcorr*. Many mathematical models were applied to predicting each value of the *tc*, *tp*, and *tcorr*. The Fick's second law, the average of Bazant and Proposed methods, and the modified Bazant method were suggested to estimate the values of *tc*, *tp*, *tcorr*, respectively. The results of these mathematical models may provide a basis for repair, strengthening, and demolition of existing RC bridges.

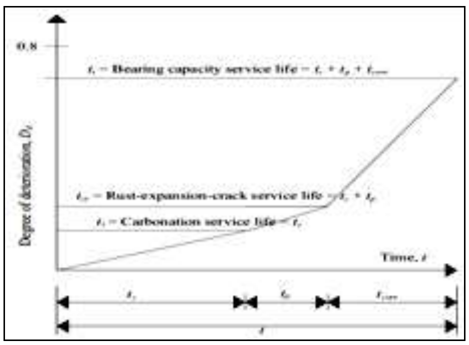

Figure 3 *Different phases of service life by Ming-Te Liang et al. (2009)*

Gert van der Wegen et al. [10] presented the application of Duracrete approach for service life design of concrete structures in marine and de-icing salts environments. Service life was defined as the period in which the structure's resistance R(t) can with stand the environmental load S (t). The study considered a probability based predictive model which was a modification of Fick's second law of diffusion to assess the chloride ion transport. Author presented a probability and performance based design procedure for determining combinations of cover depth and 28 days chloride migration coefficients that were required to achieve a specified service life. From the study it was found that, an increase of cover depth by 20mm will reduce the probability of corrosion initiation from 50% to about 10% for the typical range of cover depths for bridges and marine structures.

Huai-liang Wang et al. [11] presented a reliability model for the service life estimation of concrete structure under freeze-thaw action. Author used three-stage sequential freeze thaw cycle method to predict the residual life of concrete structure by considering three-parameter Weibull distribution. The study was based on a principle that the mechanical degradation of concrete structures under the action of freeze-thaw cycles can be equivalent to the damage due to alternate action of positive and negative peak temperature. Author derived a simple formula for calculating the residual life of concrete structure subjected to a certain degree of freeze-thaw damage and it can be easily applied to structural reliability analysis. This reliability analysis model can also be applied to concrete structures under other environmental actions (chlorine ion corrosion, fatigue load, etc.). This model can serve as a reference for the maintenance, design and the life prediction of coastal and offshore structures in cold regions.

KAT Vu et al. [12] proposed a stochastic model to quantify the service life of RC structures exposed to aggressive environments by knowing probability of cracking and spalling of concrete cover. RC slabs were tested for accelerated corrosion to predict the corrosion cracking time. To do so, rectangular slab specimens of dimension 700mm x 1000mm with 250mm thickness with water cement ratio 0.5 for 25mm and 50mm cover thicknesses were immersed in a 5% Nacl solution , then current was supplied to anode (bar) and cathode was a stainless steel plate submerged in Nacl solution. Chloride concentration was estimated by using Fick's second law of diffusion. To model the spatial variability of concrete, the structure is descretised into n rectangular elements, and then Monte Carlo simulation was used to randomly generate parameter values for each of the descretised elements. The suitability of the methodology was illustrated by the stochastic modeling of the bridge structure exposed to deicing salts. From the results it was indicated that, concrete quality is a controlling parameter in controlling the service life of RC structures exposed to aggressive environments.

Amir Rahimi et al. [13] illustrated the general procedure for condition assessment in assessing the residual service life of reinforced concrete structures located in marine environment before a repair measure. For structures which have undergone repair measure, a simplified mathematical model of chloride diffusion in a two layer system was presented to assess the residual service life. Service life was considered as the initiation period since the deterioration period was comparatively short. The chloride diffusion process was based on the error function solution of Fick's second law of diffusion. STRUREL program was used to perform the reliability analysis. The redistribution of the residual chloride ions in the remaining layer of the concrete and in the repair layer was investigated numerically using FEM (COMSOL multi physics software) software. Form the study, the results indicated that, the residual chloride content at the surface of the reinforcement played important role in quantifying the residual service life of the structural element. Also the author concluded that, the extent to which degrading the gradient of the residual chlorides and their distribution affects the results has not yet investigated.

Edna Possan et al. [14] presented application of Markov Chains associated with reliability analysis of experimental results of the degradation of concrete by chlorides. Experimental results were obtained for chloride penetration from non-accelerated tests in concrete in which the water/binder ratio was variable (0.4, 0.5, 0.6) was produced with ppc that was exposed for six months to the action of Nacl. Using simulation process, the failure and safety probabilities were calculated by reliability and using Markov Chains, a service life was estimated. For natural penetration of chlorides, concrete beams of dimension 100x200x500mm were manufactured. After 7 days humid curing and 21 days in a lab environment, the beams were submerged in a Nacl solution with a concentartion of 5%.

Thoft-Christensen [15] proposed a new service life definition based on the evolution of the corrosion crack width by taking Stochastic modeling of the deterioration of reinforced concrete structures in to account. Service life is defined as sum of the initiation time for corrosion T_{corr} of the reinforcement and the time Δt_{crack} from corrosion initiation to corrosion crack initiation and the time from initial cracking to a critical crack in the concrete.

$$T_{service} = T_{crack} + \Delta T_{cr} = T_{corr} + \Delta t_{crack} + \Delta T_{cr}$$

For determining chloride diffusion process, Fick's second law of diffusion and simple Monte Carlo simulation was used and then, to approximate the distribution of the simulated data, a Weibull distribution was used. Service life of the structure was estimated using the Monte Carlo simulation for any value of the serviceability crack width.

Lin et al. [16] developed a finite element based numerical model to predict the service life of RC structures exposed to chloride environments considering-environmental humidity, temperature fluctuations, chloride binding & diffusion and decay of structural performance. The heat transfer, moisture transport and chloride ion transport were described in space and time domains and solved numerically through finite element analysis. The numerical model was demonstrated by predicting the service life RC slabs exposed to chloride. From the study, it was found that 55mm of concrete cover was required to assure the corrosion initiation time beyond50 years. Also, by improving the binding capacity of concrete exposed to chloride, the service life of concrete structures can be prolonged significantly.

Mohammad Shekarchi et al. [17] presented a service life design model to predict the corrosion initiation for RC structures in the south of Iran. The study introduced DuraPGulf a semi empirical model which was based on Fick's second law of diffusion, for determining the chloride diffusion process. This model was developed using the finite element technique and also for the practical engineering applications, user friendly software was developed. This model serve as a practical tool for engineers of south Iran region to evaluate the service life of a RC structure as it consider effect of various parameters such as mixture proportion, curing regime, exposure condition, temperature, and humidity on the service life of RC structures.

Anoop et al. [18] proposed a general methodology to assess the remaining service life of Reinforced Concrete Bridge girders deteriorated due to chloride induced corrosion. The uncertainties in environmental variables such as temperature, relative humidity and degree of wetting and drying, and the variables which affect time to corrosion initiation and rate of corrosion were treated as fuzzy variables. Time to corrosion initiation was determined based on Fick's second law of diffusion using extension principle. The usefulness of the proposed methodology was demonstrated by considering the rocky point via duct at a coastal site 25m east of Pacific Ocean. The results showed that, predicted values were in good agreement with the reported values.

Anoop et al. [19] proposed a methodology to assess the service life of reinforced concrete flexural members under service loads. The study considers the safety and serviceability criteria for reinforced concrete structural member subjected to chloride induced corrosion. The uncertainties which arise in considering the exposure condition and quality of construction and the variables which affect time to corrosion initiation and rate of corrosion were treated as fuzzy variables. The time to corrosion initiation was determined based on Fick's second law of diffusion in modeling the diffusion of chlorides through cover concrete. The effectiveness of the proposed methodology was demonstrated by considering two case study examples i.e., by considering the rocky point via duct at a coastal site 25m east of Pacific Ocean and by designing the typical RC bridge girder. From the results it was found that, predicted results for time to corrosion initiation and time to cover cracking were in good agreement with the reported values.

Sobhani et al. [20] proposed a new methodology known as α level optimization to predict the service life of RC structures in chloride laden environments under uncertainties. The proposed method considered the uncertainties both in random and fuzzy characteristics to predict chloride initiation period. The proposed service life model divide the service life of RC structures in to three stages; corrosion initiation period Ti, corrosion induced cracking period Tcr, and failure time period which defines the ultimate service life of RC structures. Corrosion induced cracking time was formulated by using deterministic mathematical relationship which was based on thick cylinder model assumed that the pressure application over the surrounding concrete was uniform. The proposed methodology was implemented in Mat lab R.2006b environment and all computations were carried out. The suitability of the proposed model to predict the service life was illustrated by considering corrosion affected RC structure example.

Woubishet Zewdu et al. [21] reviewed the performance of repaired concrete structures and the current status in the development of service life prediction model for repaired concrete structures. Author defines the service life as the sum of the corrosion initiation stage and corrosion propagation stage. From the study it was evident that, in recent years, very few service life prediction models were developed for repaired concrete structures. The models were based on numerical methods that simulate the corrosion processes of reinforcement steel in concrete which was induced y ingress of chloride ions. From the case histories, it was found that, 50% of the repaired concrete structures were failed in which, 25% were deteriorated in first 5 years, 75% deteriorated within 10 years and 95% deteriorated within 25 years.

Leonid Chernin et al. [22] presented a new analytical model for predicting cover cracking due to corrosion of reinforcing steel. The model was based on a thick-walled cylinder approach, in which the concrete surrounding a corroding reinforcing bar is considered as a thick walled hollow cylinder with the wall thickness equal to that of the concrete cover. The corrosion-induced load, which arises due to a larger volume of the corrosion products compared to that of the consumed steel, was represented by a uniform pressure applied to the inner surface of the cylinder. The pressure leads to formation of radial cracks near the inner surface of the cylinder. Cracks in the inner cylinder are taken into account by gradually reducing its tangential stiffness along the radial direction. The model was calibrated using available experimental data and then employed to estimate the amount of corrosion products penetrated into concrete pores.

Maheswaran et al. [23] presented a probability based deterioration model to assess the chloride ingress in reinforced concrete structural elements. In the study service life of the structure modeled as initiation and deterioration stages. The deterioration due to the chloride-induced corrosion was estimated using corrosion initiation, and crack initiation and propagation models suggested by Rodriguez, Bamforth, Liu and Weyers. Then Life-365 model was used to calculate the percentage chloride concentration at various depths and also used for predicting the service life and life-cycle costs of reinforced concrete exposed to chlorides. The application of the proposed methodology was illustrated using chloride profiles for a bridge deck component along coastal regions of Victoria. The results were compared with the actual inspection data of the bridge components. Also, the study reveals that, the future condition states of the bridge components can be estimated using the chloride diffusion model presented.

Song et al. [25] proposed a numerical finite difference method to predict the service life of repaired concrete structures exposed to chloride environment. The chloride ion diffusion process was mathematically described using partial differential equations based on Fick's second law of diffusion. Numerical finite difference method was formulated to accommodate concrete cover repair and the time dependent variation of surface chloride ion concentration and diffusion coefficient. Chloride ion concentration profiles were obtained and service life of repaired concrete structures under chloride environment was predicted using finite difference method. Numerical examples were presented by considering time dependent surface chloride concentration and with constant surface chloride concentration to predict the chloride ion-time profile with different repair materials. From the study, the following conclusions were drawn:

1) If the quality of the repair material is higher, service life of concrete structures prolonged.
2) If the quality of repair material is higher, lesser will be the number of application of repair.
3) If the depth of repair is higher, the service life was found to be higher.
4) In the design of new concrete structures, it was found that, original concrete with high quality was more beneficial in prolonging the time period for first repair.

4. Commercially Available Models

Life-365 (Thomas and Bentz, 2000)

Life-365 version 2.2.1 is a computer-based model that was developed for the American Concrete Institute (ACI). The models mainly used for service life estimation and Life Cycle Cost Analysis for a wide range of applications. Life-365 estimates the service life for a reinforced concrete structure using a four-step approach**.** The four steps are: 1. predicting the time for onset of corrosion i.e. ., initiation period, ti; 2.predicting the time for corrosion to reach an unacceptable level, i.e., propagation time, tp; 3. determining the repair schedule after first repair; 4. Estimating life-cycle costs based on the initial concrete costs and future repair costs.

Life-365 defines service life as the period between construction and the time to the first repair.

STADIUM

STADIUM is a computer-based .numerical model used to predict the projected service life of new structures or the residual service life of existing ones by providing different repair scenarios in order to extend the service life of existing structures. . Model predicts chloride penetration and estimates time to initiate corrosion for steel reinforced bridge structures, marine structures, parking structures, and related concrete components. The model incorporates the effects of ionic diffusion based on a multiionic approach that considers eight ionic species, moisture transport, chemical reactions, and chemical damage also it allows to select various parameters such as chloride loading rate, cementitious materials, and type of steel reinforcement, concrete cover, local temperature and relative humidity.

5. Summary

In recent years, substantial efforts were made by the researchers in developing various service life prediction models due to the advancement in computer knowledge and material science. Researchers have used various methods like ANN, FEA, FDM, fuzzy approach and Probabilistic approach. However, expertise is needed in developing computational model.

In recent years, substantial efforts were made by the researchers in developing various service life prediction models due to the advancement in computer knowledge and material science. Researchers have used various methods like ANN, FEA, FDM, fuzzy approach and Probabilistic approach. However, expertise is needed in developing computational model. FEA method in assessing the performance of deterioration mechanisms is very popular among researchers since, this methodology enable faster simulation and best possible outcomes compared to conventional methods. However, most of the constitutive relations and boundary conditions are not yet known for the interface between original concrete and repair material, hence it is very difficult to assess the efficiency of repair strategy and hence the structural performance.

If corrosion is extensive or minimum fuzzy approach is better in handling uncertainties arising due to the use of linguistic terms to describe exposure and quality of construction. Probabilistic approach is better and reliable as it considers uncertainties in the parameters responsible for deterioration by identifying the variables to be included in simulation with respect to different responses based on sensitivity study.

Markov chain models are useful when very few inspection data is available. Bayesian belief networks are simple to use when to update probability. Neural network tools are efficient in assessing degradation performance of structure when there may be many variable parameters affecting the degradation of concrete.

6. Acknowledgements

This paper is being published with the kind permission of the Head, Malnad College of Engineering, Hassan-Research Centre, Visvesvaraya Technological University, Belagavi.

References

[1] O.A. Hodhod and H.I. Ahmed, "Modeling the corrosion initiation time of slag concrete using the artificial neural network", *HBRC Journal*, 10, 231-234., 2010.

[2] Emilio Bastidas-Arteaga and Franck Schoefs "Probabilistic evaluation of the sustainability of maintenance strategies of RC structures exposed to chloride ingress", *International Journal of Engineering under Uncertainty: Hazards, Assessment and Mitigation*, **2**(1-2), 61-74., 2010.

[3] Zenonas Kamaitis "Modelling of corrosion protection for reinforced concrete structures with surface coatings", *Journal of Civil Engineering and Management*, 14(4): 241–249., 2008.

[4] Ha-Won Song, Ho-Jin Kim ,Velu Saraswathy and Tae-Hwan Kim, " a micro-mechanics based corrosion model for predicting the service life of reinforced concrete structures", *International journal of electro chemical science*, 2, 341 – 354, 2007.

[5] Bhaskar Sangoju, Radhakrishna G. Pillai, Ravindra Gettu, B.H. Bharatkumar, and Nagesh R. Iyer, "influence of Portland pozzolona cement on the service life of reinforced concrete under chloride attack". *Third international conference on sustainable construction materials and technologies Kyoto, Japan, August 2013.*

[6] Li Ying and Ton Vrouwenvelder (2007), "service life prediction and repair of concrete structures with spatial variability", HERON Vol. 52 (2007) No. 4, 251-268.

[7] P. Schiessl (2005), "new approach to service life design of concrete structure", ASIAN Journal

of Civil Engineering (Building and Housing) Vol. 6, No. 5 (2005) Pages 393-407.

[8] C.H. Lu & R.G. Liu, W.L. Jin (2010), "a model for predicting time to corrosion-induced cover cracking in reinforced concrete structures", *Fracture Mechanics of* Concrete and Concrete Structures - Assessment, Durability, Monitoring and Retrofitting of Concrete Structures, ISBN 978-89-5708-181-5.

[9] Ming-Te Liang, Ran Huang, Shen-An Feng, and Chi-Jang Yeh, "service life prediction for pier for the existing reinforced concrete bridges in chloride-laden environment", *Journal of Marine Science and Technology*, Vol. 17, No. 4, pp. 312-319.,2009.

[10] Gert van der Wegen , Rob B. Polder , and Klaas van Breugel, "guideline for service life design of structural concrete-a performance based approach with regard to chloride induced corrosion", *HERON* Vol. 57, No. 3, 153-168.,2012.

[11] Huai-liang Wang, and Yu-pu Song, "Reliability Models and Service Life Estimation of Concrete Structure under Freeze-thaw Action", *Proceedings of the Twentieth International Offshore and Polar Engineering Conference Beijing, China*, June 20-25, 2010, pp.51-54.

[12] KAT Vu and MG Stewart, "Service Life Prediction of Reinforced Concrete Structures Exposed to Aggressive Environments", *9DBMC-2002* Paper 119, pp.1-10., 2002.

[13] Amir Rahimi, Christoph Gehlen, Thorsten Reschke, and Andreas Westendarp, "Approaches for Modelling the Residual Service Life of Marine Concrete Structures", *International Journal of Corrosion*, Volume 2014, pp. 1-11.

[14] Edna Possan, Jairo José de Oliveira Andrade, " Markov Chains and reliability analysis for reinforced concrete structure service life", *materials research*, vol.17, no.3.pp.593-602.,2014

[15] P. Thoft-Christensen, " Modelling Of The Deterioration Of Reinforced Concrete Structures",*Proceedings IFIP WG 7.5 Conference on "Reliability and Optimization of Structural Systems*", Ann Arbor, USA, September 25-27, pp. 15-26.,2010.

[16] Lin, G., Liu, Y. and Xiang, Z., "Numerical modeling for predicting service life of reinforced concrete structures exposed to chloride environments", *Cement and Concrete Composites*., 32, pp.571-579.,2010.

[17] Shekarchi, M., Ghods, P., Alizadeh, R., Chini, M. and Hoseini, M., "Durapgulf a local service model for the durability of concrete structures in the south of Iran", *The Arabian Journal for Science and Engineering*, 3(1B), pp.77-88., 2008.

[18] M.B Anoop, and K. Balaji Rao, "Application of fuzzy sets for remaining life assessment of corrosion affected reinforced concrete bridge girders". *Journal of performance of constructed facilities-ASCE*, vol.21, No.2, pp.166-171., 2007.

[19] M.B Anoop, K. Balaji Rao, and T.V.S.R. Appa Rao, "a methodology for durability-based service life design of reinforced concrete flexural members", *Magazine of concrete research*, 55, No.3, pp.-289-303., 2003.

[20] J. Sobhani and A. A. Ramezaninpour, "Modeling the corrosion of reinforced concrete structures based on fuzzy systems," in *Proceedings of the 3rd International Conference on Concrete and Development*, pp. 729–741, Tehran, Iran, April 2009.

[21] Woubishet Zewdu, Taffesea, and Esko Sistonen, "Service Life Prediction of Repaired Structures Using Concrete Recasting Method: State-Of-The-Art", *11th International Conference on Modern Building Materials, Structures and Techniques, MBMST 2013*, *Procedia Engineering* 57, pp.-1138 – 1144., 2013

[22] Leonid Chernin , Dimitri V. Val , and Konstantin Y. Volokh, "Analytical modelling of concrete cover cracking caused by corrosion of reinforcement", *Materials and Structures* 43:543–556.,2010.

[23] T. Maheswaran and Sanjayan. "Probability based chloride diffusion model to predict the condition states of RC bridge elements", Department of Civil Engineering, Monash University, Vic 3800, Australia.

[24] S. Rostam, "service life design of concrete structures: a challenge to designers as well as owners", *Asian journal of civil engineering*, vol. 6, no. 5, pp. 423–445, 2005.

[25] Song HW, Shim HB, Petcherdchoo A and Park SK, "Service life prediction of repaired concrete structures under chloride environment using finite difference method". *Cement and Concrete Composites* 31(2): 120–127., 2009.

[26] Life-365 Service life prediction model and computer program for predicting the service life and life-cycle cost of reinforced concrete exposed to chlorides, Version 2.0.1, Life-365 Consortium II, 2010.