Computers and Concrete, *Vol. 19, No. 3 (2017) 305-313*
DOI: https://doi.org/10.12989/cac.2017.19.3.305

Probabilistic time-dependent sensitivity analysis of HPC bridge deck exposed to chlorides

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(Received November 26, 2015 Revised November 8, 2016, Accepted December 29, 2016)

Abstract. A robust finite element based reinforced concrete bridge deck corrosion initiation model is applied for time-dependent probabilistic sensitivity analysis. The model is focused on uncertainties in the governing parameters that include variation of high performance concrete (HPC) diffusion coefficients, concrete cover depth, surface chloride concentration, holidays in reinforcements, coatings and critical chloride threshold level in several steel reinforcements. The corrosion initiation risk is expressed in the form of probability over intended life span of the bridge deck. Conducted study shows the time-dependent sensitivity analysis to evaluate the significance of governing parameters on chloride ingress rate, various steel reinforcement protection and the corrosion initiation likelihood. Results from this probabilistic analysis provide better insight into the effect of input parameters variation on the estimate of the corrosion initiation risk for the design of concrete structures in harsh chloride environments.

Keywords: corrosion initiation; probabilistic model; sensitivity analysis; SBRA; Monte-Carlo simulation; durability; performance assessment

1. Introduction

Chloride induced corrosion of reinforcing steel in concrete bridge decks and other concrete structures are one of the major problems in the USA for premature deterioration. As a result, safety, serviceability and durability of concrete structures are reduced with increase of life cycle cost. The possible solution to minimize the impact of corrosion is the reduction of chloride ingress and implementation of different corrosion resistant steel reinforcement to optimize life cycle cost. Though models for chloride ingress and corrosion development have been studied (Weyers *et al.* 1998, Boddy *et al.* 1999, Alisa *et al.* 1998, Papadakis 2000, Bentz *et al.* 2001, Lounis 2001), there are still major issues that need be addressed to provide useful engineering tools, especially with regards to randomness of pertinent input variables. Tikalsky *et al.* (2005), Konečný *et al.* (2007) applied Monte Carlo technique in the corrosion initiation model to show variability on estimation of the corrosion initiation time and the required depth of concrete cover to extend the service life up to 100 years. Shin *et al.* (2011) developed a new software which facilitates probability-based durability analysis and design. This software predict the chloride diffusion using the Monte Carlo simulation method based on Fick's law.

2D probabilistic reinforced concrete bridge deck model developed by Konečný *et al.* (2007) is capable of capturing the random interaction of cracks and holidays in epoxy coated reinforcement. Most finite element and finite difference approaches need mesh approach to model for corrosion initiation that takes substantial amount of time. Yao *et al.* (2015) analyzed numerical solution of chloride transport using radial point interpolation method (RPIM) and element-free Galerkin (EFG). They are all meshless methods. RPIM utilizes radial polynomial basis, whereas EFG uses the moving least-square approximation. A good agreement was obtained among RPIM, EFG, and the experimental data which provides promise of above mentioned approaches for future modeling. Shim demonstrated that the resulting probability distribution of the corrosion initiation time is most sensitive to the chloride diffusion coefficients (Shim 2005). Recently, Lounis *et al.* presented a research approach for the probabilistic modeling of the chloride induced corrosion of carbon steel reinforcement in concrete structures considering the uncertainties of the governing parameters such as concrete diffusivity, surface chloride concentration, concrete cover depth, and threshold chloride level (Lounis *et al.* 2014).The parameters were modeled as random variables and the distribution of the corrosion initiation time and probability of corrosion rate are determined by using Monte Carlo simulation technique. Kirpatrick *et al.* (2002) established a

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http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)

probabilistic model to estimate the time required for first repair and subsequent rehabilitation of concrete bridge decks exposed to chloride salt ingress. Their model expands on existing deterministic model using two different types of resampling technique namely simple and parametric boot strap with emphasis on diffusion portion of cracking model. Provided results from two methods subsequently agreed the condition of 10 bridge decks in Virginia in terms of rehabilitation assessment (Kirpatrick *et al.* 2002).

Zhang and Lounis (2006) performed sensitivity analysis of the effect of input parameters on the time to corrosion initiation using simplified 1-d diffusion model.

Hartt *et al.* (2009) performed the comprehensive study on different corrosion resistant reinforcements (CRR) as an alternative to black bar and epoxy coated rebar embedded in concrete bridge decks exposed to chloride laden environments. They determined the corrosion initiation time and critical chloride threshold of those CRR with respect to concrete quality (Hartt *et al.* 2009).

Zhang *et al.* (2011) investigated the coupling effect of humidity and curing time on corrosion initiation and it is found that the relative humidity and curing time were the most effective factors affecting the probability of corrosion initiation before and after 10 years of exposure time.

All previously mentioned corrosion models except Konečný *et al.* (2007) lack the 2D capability to address the random interaction between cracks and holidays in epoxy coated reinforcement. Bentz *et al.* (2013) studied the effect of crack on the chloride ingress. The diffusion coefficients were specified for intact material and for the damaged area near the crack and for the crack itself.

The consideration of the diffusion mechanism of chloride ingress without the effect of chloride binding is conservative according to (Bentz *et al.* 2013).The above mentioned models do not include the distribution of performance based diffusion coefficients data of various HPC mixtures along with the performance of several corrosion resistant steel reinforcements. The effect of the significance of random input parameters considering the crack effect at different ages has not been investigated.

Hence, it is necessary to perform research to incorporate variation of diffusion coefficients of HPC materials and investigate the performance of several steel reinforcements to delay chloride induced corrosion initiation time as well as to evaluate the sensitivity to input parameters variation.

2. Research significance

This research evaluates the significance of governing parameters influencing corrosion initiation risk with respect to time dependent chloride ingress of a reinforced concrete bridge deck. The influence of various corrosion resistant reinforcements is studied using a probabilistic corrosion initiation model and applying robust Simulation-Based Reliability Assessment (SBRA) approach. This model describes the inherent random dispersion of governing parameters based on data from laboratory investigation, field and engineering judgment. The preliminary version of the probabilistic model was first introduced in (Konečný *et al.* 2007).

In this study, the model is significantly enhanced with the new description of variation of HPC diffusion coefficients, the variation of surface chloride concentration from the field data of Virginia bridge decks, and the variation of critical chloride threshold for high-performance steel reinforcements. Current application only considers the diffusion coefficient as a constant parameter over the time.

The corrosion initiation risk is expressed in the form of probability over the life span of a reinforced concrete bridge deck. In addition, the probabilistic sensitivity analysis is applied to evaluate the significance of governing parameters on the chlor1ide ingress rate and the corrosion initiation over the life span of the bridge deck.

3. Chloride induced corrosion

3.1 Service life theory

Tutti's model is one of the first attempts to develop service life model of concrete structures in corrosion process and it can be expressed by Eq. (1) (Tutti *et al.* 1982),

$$t_{service} = t_{initiation} + t_{propagation} \quad (1)$$

Where $t_{\text{initiation}}$ is the time period before the onset of corrosion and $t_{\text{propagation}}$ is the time for corrosion to reach an unacceptable damage level once it has started. The initiation time period is primarily influenced by the concrete diffusion coefficients, concrete cover depth, surface chloride concentration, temperature, level of saturation and the required chloride concentration at the level of reinforcing steel to initiate corrosion. The model adopted in this paper focuses only on the initiation period.

3.2 Chloride transportation model

The chloride salt ingress into concrete bridge deck can take place in several ways namely permeability, adsorption or diffusion (Ahmed *et al.* 2009). Among these transport phenomena, diffusion is the most detrimental process related to corrosion initiation in steel reinforcement. It is widely accepted that Fick's 2nd law of diffusion can represent the rate of chloride penetration into concrete as a function of depth and time (Hooton *et al.* 2001). The solution is referred as the Crank's Solution.

$$C_{x,t} = C_0\left[1 - erf\left(\frac{x}{\sqrt{4D_c t}}\right)\right] \quad (2)$$

Where $C_{x,t}$ is the concentration of chlorides at time t (years) and depth x (meters (ft)), C_0 is the concentration of chlorides at the surface and D_c is the apparent diffusion coefficient (m^2/year). The finite element model studied here follows Fick's second law of diffusion for chloride ingress and corrosion initiation computation.

Polynomial derivation of Eq. (2) is necessary for probabilistic model with respect to 1-D problem. However, it does not take into account for cracks. It is also difficult to modify Eq. (2) to account for time dependent changes in material property or boundary conditions. For this reason, 2D numerical finite element based model is adopted in this study.

3.3 Performance assessment

Severity of the chloride ingress is assessed by comparing the chloride threshold value C_{th} with the chloride concentration at the exposed areas of reinforcing steel. This value will depend on the type and coating of the reinforcing steel and the constituents of the concrete.

The performance function, RF_t, of a bridge deck is expressed as the time-dependent exceedance of the corrosion initiation threshold by the location dependent chloride concentration, $C_{xy,t}$. Reliability function, RF=R(Resistance)-S(Load effects) is introduced and analyzed using Monte Carlo simulation technique and random variables are described by bounded histogram as well as continuous distributions. The performance function characterizing the above described limit state is expressed as

$$RF_t = (R - S) = (C_{th} - C_{xy,t}) \tag{3}$$

The highest concentration $C_{xy,t}$ surrounding one of the epoxy-coating damaged areas was selected as the critical case where corrosion would occur first whereas the highest concentration on the reinforcement level was selected for the computation of other types of reinforcement protection. Measure of reliability or performance (reliability level) is expressed by probability of failure P_f. It needs to be noted that "failure" in this case does not represent structural failure. P_f means actual corrosion initiation likelihood. The performance of the system was estimated by the probability of chloride threshold C_{th} exceedance (corrosion initiation) at a specific age $P_{f,t}$.

$$P_{f,t} = P(C_{th} - C_{xy,t} < 0) \tag{4}$$

3.4 Time-dependent sensitivity analysis

Probabilistic sensitivity analysis was implemented to evaluate the influence of input parameters on the chloride concentration at the most exposed part of the reinforcement $C_{xy,t}$ and performance function RF_t indicates the corrosion initiation likelihood. The statistical correlation factor between the input parameters and output parameters is determined at selected ages.

Numerical value of correlation factor ranges in between -1 and 1. Value -1 means negative correlation between input and output whereas +1 means positive correlation. It indicates that as the absolute value of correlation factor decreases, dependency of input parameter on output namely corrosion initiation decreases.

3.5 2-D Finite diffusion model with crack effect

The model adopted here focuses on the chloride ingress in reinforced concrete bridge decks with cracks and on the estimation of chloride ion concentration in particular locations of the embedded reinforcing steel bars or damaged areas of epoxy-coated bars.

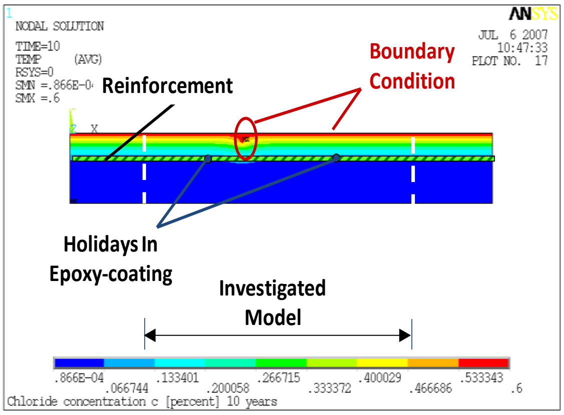


Fig. 1 Schematic 2D Finite element chloride ingress model of epoxy-coated reinforcement in bridge decks with holidays

The 2-D finite element model based on the Ficks 2nd law of diffusion focuses on the movement and accumulation of chloride ions to the level of reinforcing steel during the initiation period of corrosion. The analysis is chosen as 2-D problem to examine the interaction between the effect of crack on the chloride ion ingress and the holidays in the epoxy coating.

The crack effect is implemented by means of initial chloride concentration boundary condition on the top surface and in the crack nodes. Thus, only bulk diffusion coefficient for the intact concrete is applied and there is no difference of the diffusion coefficient between cracked and uncracked concrete. The commercial software ANSYS (2009) was used for finite element analysis. The sample mesh and chloride concentration is shown in Fig. 1.

3.6 Probabilistic evaluation

The chloride diffusion model is developed to compute chloride concentration in the most exposed epoxy-coated steel reinforcements location (holiday) throughout its life span with consideration of effect of crack due to chloride ion ingress. The probabilistic model is repeated in the Monte Carlo simulation loop.

The SBRA Module for ANSYS is a tool for managing the probabilistic Monte Carlo simulation process with random variables distributions characterized by frequency histograms according to (Marek *et al.* 1995).

The finite element task needs to be automated in order to perform probabilistic Monte Carlo simulation. It begins with the diffusion coefficient through nodes and elements assembly, followed by boundary conditions constraint application, solution and post processing part. Formulation of reliability function (Eq. (3)) is prepared next to post processing that includes comparison of worst-case scenario of chloride concentration with chloride threshold value (chloride ion concentration that allows for corrosion to proceed). Recording of reliability function with other

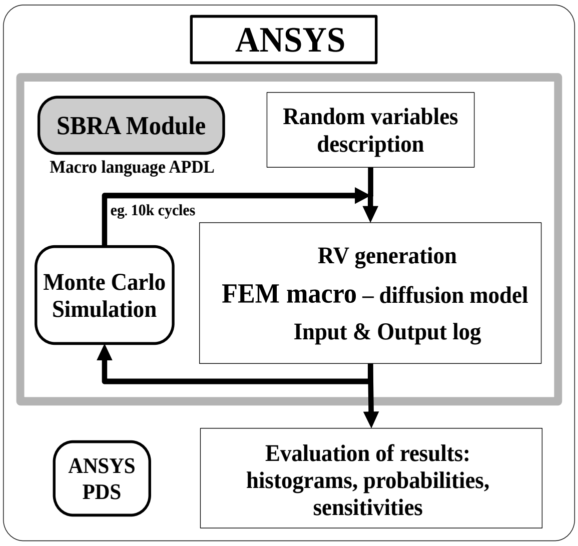


Fig. 2 Flow chart of probabilistic finite element corrosion initiation analysis via Monte Carlo simulation

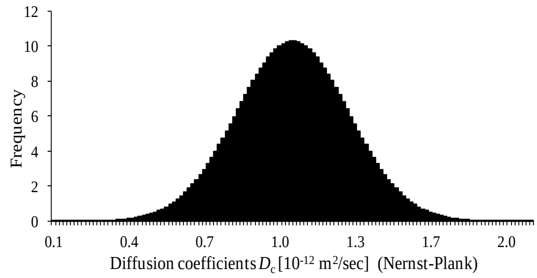


Fig. 3 Histogram for diffusion coefficients by Nernst-Plank method (Ghosh *et al.* 2011)

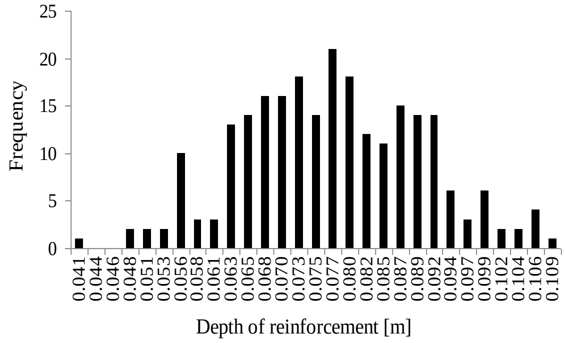


Fig. 4 Histogram for cover depth (Sohanghpurwala and Scannell 1994)

variables of interest is included in post processing. The last task is to remove all nodes, elements and variables in order to start another simulation in the next Monte Carlo simulation step. The procedure to compute the corrosion initiation time for the model is demonstrated as a flow chart in Fig. 2.

4. Governing input parameters

The input parameters in the model included both deterministic and probabilistic part as discussed below. The probabilistic distributions were prepared based on the previous literature data source of experimental investigations and finally the frequency histogram is prepared for each parameter based on available data in the corresponding references using excel spreadsheet. Deterministic parameter is chosen based on proper engineering judgment.

4.1 Diffusion coefficient

Incorporation of the variation of reliable diffusion coefficients for HPC mixtures in probabilistic model is a significant part as the diffusion coefficient plays a major role in the corrosion initiation process. Histograms for diffusion coefficients for different HPC mixtures are computed from Nernst-Plank method using fundamental electrochemistry developed in (Ghosh *et al.* 2011).

This HPC system consists of different ternary and binary based concrete mixtures combining ordinary portland cement with other pozzolans or supplementary cementitious materials (SCMs) namely different fly ashes (Class C, F and F2), silica fume, ground granulated blast furnace slag , metakaolin and volcanic tuft.

This approach computes equivalent steady state diffusion coefficients from rapid chloride ion penetration test (RCPT) data following ASTM C1202 specification with the essential adjustment factor due to the joule effect. It is to be noted that this probabilistic model assumes constant distribution of diffusion coefficients of HPC system over intended service life of bridge decks. Fig. 3 shows variation of HPC diffusion coefficients by Nernst-Plank method.

4.2 Cover depth

Cover depth is an important parameter which also affects corrosion initiation. Therefore, it is essential to incorporate variation of cover depth in the corrosion initiation model. Histogram of cover depth, presented in Fig. 4, is based on the measurement of chloride penetration and concrete cover from more than 200 samples taken from 40 bridge decks constructed under a single specification (Sohanghpurwala and Scannell 1994).

4.3 Chloride threshold for corrosion resistant steel reinforcements

Use of alternative corrosion resistant reinforcement is already in use for the last 30 years in the USA as a measure of corrosion protection strategy. The most widely used corrosion resistant steel is epoxy coated rebar for corrosion minimization. In some situations, the implementation of new corrosion-resistant steel reinforcement has been limited due to the lack of quantitative data on the corrosion threshold value of the specific reinforcement. The values of critical chloride threshold of different corrosion resistant steel have been utilized in the numerical model to predict life expectancy of reinforced concrete bridge decks. In this SBRA model, performance of epoxy coating, galvanized

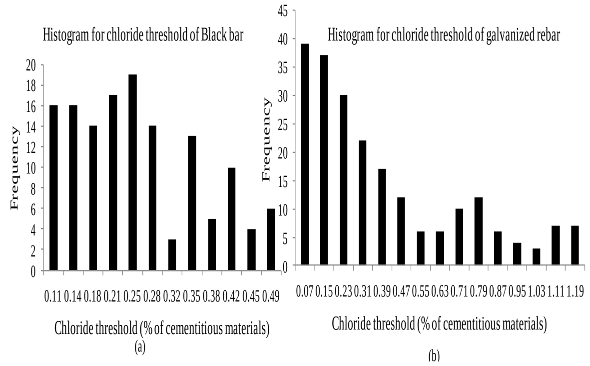


Fig. 5 Histograms for chloride threshold (a) black bar and (b) galvanized rebars (Darwin *et al.* 2009)

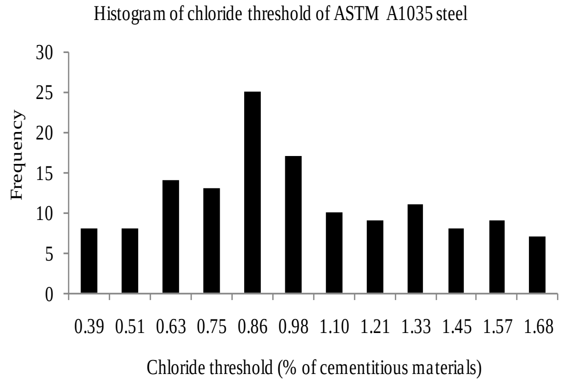


Fig. 6 Histogram for chloride threshold of ASTM 1035 Steel (Darwin *et al.* 2009)

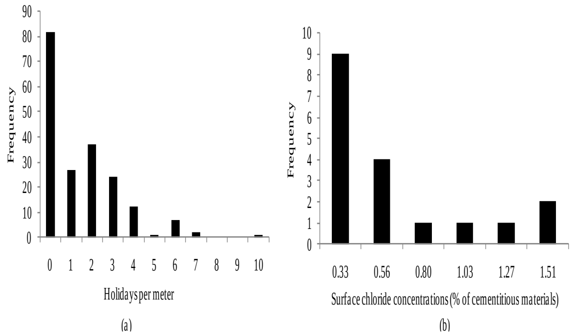


Fig. 7 Histograms for frequency (a) holidays and (b) surface chloride concentration (Pyc 1998)

Table 1 Random and deterministic input values for ANSYS model

Parameter	Range	Distribution
Diffusion coefficients D_c (10^{-12} m^2/sec) (Nernst-Plank)	0.06, 2.10	Normal distribution N(1.08;0.34) on Fig. 3
Cover depth, x(m)	0.04-0.11	Histogram on Fig. 4
Frequency of holidays, $Mash_n$ (m^{-1})	0-10	Histogram on Fig. 7(a)
Relative position of first holiday, $Mash_i$	0-1	Uniform distribution
Surface chloride concentration, C_o (%)	0.2-1.6	Histogram on Fig. 7(b)
Chloride threshold (black bar), C_{thb} (%)	0.09-0.50	Histogram on Fig. 5(a)
Chloride threshold (epoxy coated bar), C_{th} (%)	0.09-0.50	Histogram on Fig. 5(a)
Chloride threshold (Galvanized bar), C_{thg} (%)	0.04-1.23	Histogram on Fig. 5(b)
Chloride threshold (ASTM A1035 steel), C_{thm} (%)	0.34-1.74	Histogram on Fig. 6
Crack depth, $Crack_{de}$ (m)	0-Depth	Exponential
Crack spacing $Crck_s$, (m)	0.25-1.15	Normal distribution N(0.7, 1.15)
Relative crack position, $Crack_i$	0-1	Uniform distribution
Depth of slab, D_{depth}, (m)	0.23	Constant value
Life span, t (years)	100	Constant value

rebar, ASTM A1035 steel is compared on the basis of probability of failure on the corrosion initiation time with black uncoated bar as control reinforcement. The chloride threshold distribution for black bar, galvanized steel, ASTM A1035 steel (low carbon chromium) is based on the experimental data published in (Darwin *et al.* 2009). The chloride threshold distribution for epoxy-coated reinforcement is considered to be same as black bar (Fig. 5 (a)), while the performance of the epoxy coating is assessed by the evaluation of the chloride ion concentration at the nearest holiday to the crack. Fig. 6 shows the histogram of chloride threshold of ASTM A1035 type steel.

4.4 Other random variable parameters

It is beneficial to implement the variation of distribution of surface chloride concentration to obtain reliable prediction of the corrosion initiation time. To meet this requirement, the frequency of surface chloride concentration is prepared on the basis of field data from Virginia bridge decks (Pyc 1998).

Holidays in epoxy coated reinforcement also plays important role in corrosion initiation process. For this purpose, frequency distribution of holidays is prepared from the existing data of Virginia bridge decks to investigate the performance of epoxy coated rebar (Pyc 1998).

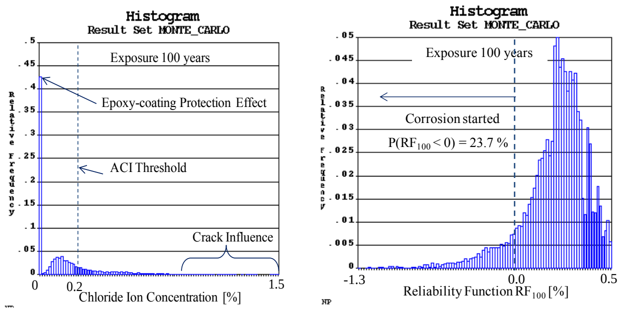
Due to the lack of available resources, distribution for crack depth is chosen on the basis of engineering estimation by exponential distribution. Minimal value is chosen as zero depth and maximal value is the bridge deck thickness. Fig. 7 shows distribution of holidays and surface chloride concentration.

Crack spacing distribution is assumed to be correlated with deck thickness and width of slab is equal to the random variable crack spacing. For this study, the worst case scenario is used with frequent cracks throughout all bridges. Spacing of the cracks is also estimated as a normal distribution with the mean value 0.7 m that is circa 3 times the thickness of the slab. Standard deviation is 0.15. The distribution is truncated within boundaries <0.25, 1.15> m. Table 1 summarizes deterministic and random input variables for investigated stochastic analysis.

Since the holiday frequency and crack spacing are random input parameters thus random interaction between cracks and holidays is taken into account.

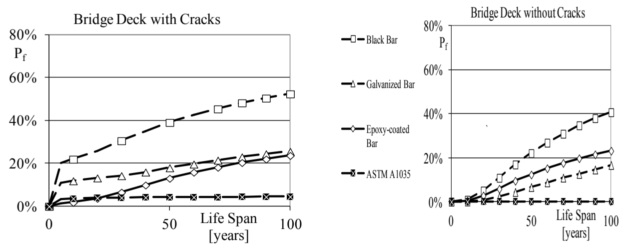
4.5 Precision of monte carlo simulation

The SBRA module governs the probabilistic analysis with 10,000 Monte Carlo simulation steps. The error of resulting probabilities obtained by the Monte Carlo simulation can be estimated using Eq. (5) as the precision



(a) Chloride ion concentration C_{xy}, (b) Performance function RF_t

Fig. 8 Histograms of performance parameters for epoxy coated reinforcement in 100 years



(a) Bridge deck with cracks (b) Bridge deck without cracks

Fig. 9 Performance of different types of steel reinforcements in a bridge deck

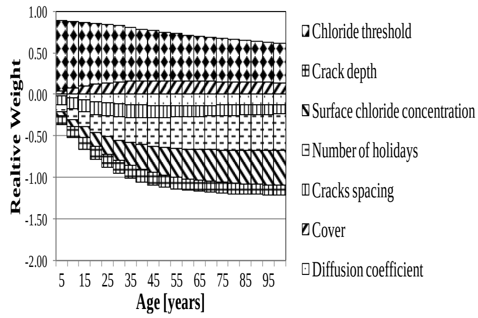


Fig. 10 Sensitivity analysis of corrosion initiation at the holiday in epoxy-coating rebar

depends on the number of simulations.

$$[-\varepsilon;\varepsilon]=[-t\sigma;t\sigma]=\left[-t\sqrt{\frac{P_f(1-P_f)}{N}};t\sqrt{\frac{P_f(1-P_f)}{N}}\right] \quad (5)$$

Where ε is confidence region, N is the number of simulations, P_f is the desired precision and t represents the confidence level. If the probability of corrosion initiation is P_f=1/100, total simulation steps will be N=10,000. For 90% confidence level (t=1.6449), the resulting probabilities will be P_f=0.01±0.0017. This precision is reasonable with respect to performed study considering the probabilities of corrosion initiation higher than 1/100.

5. Results

5.1 Chlorides build up and performance of epoxy coated rebar

The sample output of performance of epoxy-coated reinforcement is indicated in Fig. 8 with the diffusion coefficient derived from the Nernst-Plank method. The chloride ion concentration at the rebar level of exposed steel areas and performance function distributions are shown within 100 years of service. The ACI critical chloride threshold limit, C_{th}=0.2% is shown in the Fig. 8(a) for illustration purpose.

The performance function, in the Fig. 8(b), consists of random variable chloride concentration and random variable threshold based on the particular distribution. Probability of corrosion initiation of the epoxy-coated reinforcement is obtained as $P_{f,100}$=23.7% within 100 years of service life and it is shown in Fig. 8(b).

5.2 Comparison of various steel reinforcements

The performance of four different types of reinforcement namely black bar, galvanized bar, epoxy-coated bar and ASTM A1035 type rebar embedded in the concrete bridge deck is investigated. The resulting probabilities of corrosion initiation for various steel reinforcements throughout the service life (from 5 to 100 years) are shown in Fig. 9. It is evident that epoxy-coated reinforcement has shown superior performance in first 15 years, whereas the ASTM A1035 steel provides better results after initial 15 years. ASTM 1035 steel's corrosion initiation risk is always uniformly low throughout the lifespan and ranges only in between 3% to 5%. The galvanized steel starts with corrosion initiation risk of 11.4% and ends up with 28.8%. The acceptable performance of serviceability is recognized as 70.6 years. Performance of epoxy-coating and galvanized steel appears similar after 50 years of service. On the other hand, the black bar corrosion initiation risk is two times greater (20.7-56.1%) than galvanized steel while the acceptable lifespan (12.6 years) is 5.6 times lower than galvanized steel. It needs to be remembered that the resulting performance prediction and probability is strongly dependent on the critical chloride threshold level of selected steel reinforcement. The threshold distribution is based on comprehensive laboratory investigation performed by Darwin *et al.* 2009. Additionally, influence of crack is considered on all steel reinforcements. Fig. 9(a) and (b) shows the comparison of performance assessment of all steel reinforcements with inclusion and exclusion of cracks.

The most significant effect of the reduction of corrosion initiation likelihood in case of ideal bridge deck without cracks can be seen in black and galvanized reinforcement cases. Significance is more visible especially in first decade. The corrosion initiation likelihood is caused by the presence of crack all the way down to reinforcement level.

On the other hand, the epoxy coating protection effect, especially the random interaction of the distance between the holiday and closest crack, showed no dramatic decrease of corrosion initiation likelihood comparing to case with cracks.

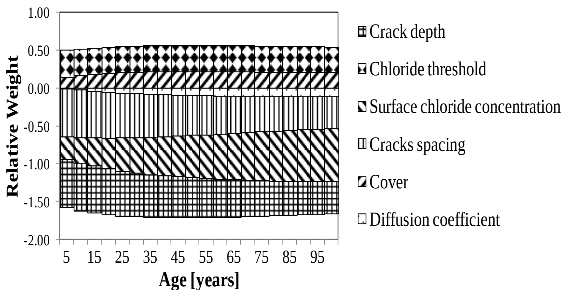


Fig. 11 Sensitivity analysis of unprotected steel reinforcement corrosion initiation in a reinforced concrete bridge deck with crack

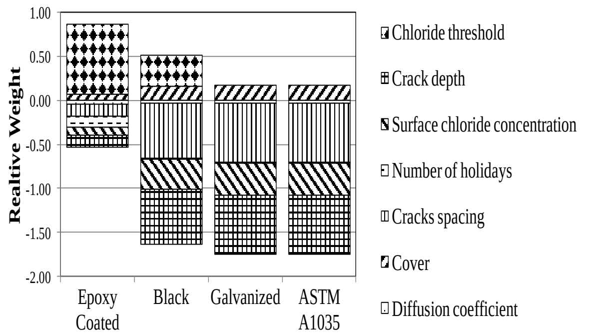


Fig. 12 Sensitivity analysis of the corrosion initiation in a reinforced concrete bridge deck with crack and with respect to different steel reinforcements

5.3 Time dependent sensitivity analysis

The influence of each individual input parameter on the corrosion initiation is studied for the reinforced concrete bridge deck including holidays in epoxy coated reinforcement and the cracks. This interaction is shown in Fig. 10.

The sensitivity of output parameter is evaluated using linear rank correlation approach between the input and output variables. At early ages (5-20 years), critical chloride threshold appears as most significant parameter influencing the corrosion initiation. Other significant parameters at early ages are number of holidays in epoxy coating, crack depth and crack spacing. At early stage, concrete cover protects the reinforcement and the chlorides can penetrate closer to the holiday in epoxy coating through the crack in concrete cover.

Hence, the probability of corrosion initiation is quite low at early ages. While the chlorides penetrate through the concrete over the years, the diffusion coefficient, surface chloride concentration, and reinforcement depth start to play major role after 15-25 years. After 60 years of service, the corrosion initiation likelihood for epoxy coated reinforcement with crack exceeds 20% and the influence of individual governing parameter is mostly balanced. Dominant parameters at this stage are the critical chloride threshold, number of holidays in epoxy coating, and the surface chloride concentration.

The sensitivity to chloride ion build up at the reinforcement level of the ordinary black steel is shown in Fig. 11. For unprotected black steel reinforcement, crack depth and spacing have significant influence from initial period as crack is an easy pathway for chloride ion ingress within a short period of time to reach the reinforcement level.

The critical chloride threshold, surface concentration and concrete cover are equally significant at early stages. It appears that the surface chloride concentration is most significant at later ages. The behavior of the Galvanized bar and ASTM A1035 is similar to black bar except the threshold value. The threshold value is not shown as significant in the analysis.

6. Discussion

The numerical simulation of bridge deck with crack indicates that the ASTM A1035 type steel reinforcement provides better protection against the corrosion initiation risk compared to epoxy-coated and galvanized steel. It needs to be noted that this result is based on the numerical simulation, laboratory data for critical chloride threshold and under laid assumptions being made. Further laboratory and field investigation are necessary to verify the exceptional effectiveness of ASTM A1035 reinforcement. The epoxy-coated reinforcement performs better compared to the black bar and the galvanized steel especially within first 50 years. The advantage of epoxy-coated reinforcement is related to its ability to handle holiday crack interaction effect. It is to be remembered that early initiation of corrosion in epoxy coated bridge decks is possibly due to close proximity of the cracks to the holidays. Thus, critical chloride threshold appears very important in this case and it is included in sensitivity analysis in Fig. 12.

Reduced frequency of holidays along with increased crack can lead to better performance of epoxy-coating in first five decades. From Fig. 10, it can be observed that cracking has severe impact on uncoated (black bar) reinforcement.

The significance of the diffusion coefficient indicated in Fig. 10 is lower than significance of the chloride threshold, surface chloride concentration and number of holidays. The relative lower diffusion coefficient importance is assumed to be related to the consideration of crack effect comparing to the Shim's 1D model (Shim 2005) that indicated high importance of the diffusion coefficient in corrosion initiation process.

The other parameter that may overestimate the crack effect is numerical consideration of the crack influence. The chloride concentration is estimated by application of deicing agents directly on the surface nodes of the bridge deck model. Here, crack is modeled as a chloride concentration parameter at the nodes closest to the crack. The concentration at the crack is the same as the surface chloride concentration from early life span of the bridge deck. Further, the chloride binding effect is not considered. Thus, this model described here is conservative modeling of the crack effect compared to the 2D model developed by Bentz *et al.* (2013). Dependence on the diffusion coefficient could be higher, if the ordinary Portland cement (OPC) and other permeable concrete mixtures would be chosen for probabilistic modeling. The reason is similar in case of critical chloride threshold value importance on the corrosion initiation for ASTM A 1035 steel. The threshold value of ASTM 1035 steel is significantly higher compared to the black bar threshold. Thus, the risk of corrosion initiation is remarkably reduced. The corrosion initiation appears to be more independent of the chloride threshold than other parameter namely as surface chloride concentration.

7. Conclusions

• This research demonstrates the application of the probabilistic corrosion initiation model with inclusion of variation of HPC diffusion coefficients and several corrosion resistant steel reinforcements. The significant advantage of this comprehensive probabilistic model is that user can incorporate their input random parameters distribution from their experimental investigation in this model and compute the corrosion initiation time within the intended service life of bridge decks.

• Application of corrosion resistant reinforcements can extend the acceptable performance of severely cracked bridges significantly according to the performed numerical simulation. Galvanized rebar extend the service life 5.6 times, epoxy-coating 7 times, and ASTM A1035 more than 8 times compared to the black bar.

• The numerical analysis showed that significance of input parameters is changing over the life span. It also depends on the types of steel reinforcement protection. The critical chloride threshold significance remains at the same level over the life span in case of corrosion resistant reinforcement protection. Another major outcome of this study is the influence of cracks at early ages. Additionally, the concrete cover protects the concrete while its importance is reduced after sufficient amount of chlorides penetrates to the reinforcement level.

• Consideration of the crack influence reduces the relative significance of the diffusion coefficient in the model. Cracks act as easy pathway for rapid chloride penetration to reach the reinforcement level.

• The low significance of some parameters on the corrosion initiation risk does not indicate that the parameter is not important. It implies that the variation of the parameter in the provided range does not affect corrosion initiation significantly. Since the corrosion initiation model studied here already includes impermeable HPC materials diffusion coefficients, its influence on corrosion initiation has been remarkably reduced. The same logic can be applied to the chloride threshold influence in case of ASTM A1035 steel.

• Corrosion initiation of HPC concrete bridge deck with crack effect is most sensitive to the surface chloride concentration. The chloride threshold variation is important in case of epoxy coated and black bar reinforcement. Moreover, epoxy coated reinforcement is sensitive to frequency of holidays while the other corrosion resistant reinforcements are sensitive to variation in crack depth and spacing.

• In addition to designing low diffusion concrete, the quality of rebar coatings and shrinkage crack frequency can be designed to prolong life span of bridge decks.

• This numerical model does not take into account time dependent diffusion coefficient effect, active corrosion in epoxy coating or propagation stage of galvanized rebar. In future, proper maintenance, installation and alternative corrosion protection strategy according to environmental condition should be implemented along with the use of corrosion resistant steel in HPC bridge decks.

Acknowledgments

The preparation of the paper was financially supported by the Ministry of Education, Youth and Sports of the Czech Republic through the Operational Program: OP for Education for Competitiveness (ECOP) under VSB-TUO, Project No. EE2.3.00/20.0013, and through the Institutional support for conceptual development of science, research and innovations for the year 2015.

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