Effect of cracking and randomness of inputs on corrosion initiation of reinforced concrete bridge decks exposed to chlorides

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ABSTRACT. The paper is aimed at the indicative evaluation of the effect of random scatter of input parameters in case of durability of reinforced concrete bridge deck. The time to onset of corrosion of steel reinforcement of concrete bridge deck exposed to chloride is evaluated. The effect of cracking in concrete onto chloride ingress is considered. The selected steel reinforcement protection strategies are: unprotected steel reinforcement, epoxy-coated steel reinforcement and water-proof barrier bellow asphalt overlay. The preliminary model for damage effect on chloride ion ingress through water proof membrane under penetrable asphalt overlay is used. 2-D finite element chloride ingress model is combined with Monte Carlo simulation technique. The innovative crack effect modeling via highly penetrable elements is applied. Deterministic and probabilistic calculations are compared.

KEYWORDS. Concrete; Crack; Steel reinforcement; Bridge deck; Corrosion initiation; Probability.

OPEN ACCESS

Citation: Konecny, P., Lehner, P., Effect of cracking and randomness of inputs on corrosion initiation of reinforced concrete bridge decks exposed to chlorides, Frattura ed Integrità Strutturale, 39 (2017) 29-37.

Received: 15.07.2016
Accepted: 21.09.2016
Published: 01.01.2017

INTRODUCTION

The random scatter of input parameters is important feature of many engineering tasks. Thus considering randomness in the numerical modeling via distribution functions of significant parameters is suitable approach in probabilistic reliability assessment even in case of public infrastructure.

Typical example of the civil engineering structure of interest is reinforced concrete (RC) bridge structure. The durability of such structure is, in many cases, predetermined by durability of steel reinforcement as proven by many structures requiring premature repairs or replacement. Need for repairs results from defects caused by e.g. the effect of environment or the long term actions of loads including chemical actions. Shortened lifespan leads to increased life cycle costs of the structure thus contributing indirectly to higher burden on public budgets.

The production of more durable construction systems and higher quality concrete mixes can help to reduce the overall costs of the structure (see e.g. [1] and [2]). It is assumed that higher durability can be achieved with increased knowledge of the progress of the degradation process caused by the long term actions of environmental and structural loading. (see e.g. [3-10]). However, models that aims to investigate durability of bridge deck with cracks or even waterproof membrane both from deterministic, not mentioning probabilistic, standpoint are still under intensive development. Moreover, information about the scatter or uncertainty of model parameters are of particular interest. For example, one of probabilistic 1d models of ideal bridge deck without cracks [4] applied description of variability of diffusion coefficient, surface chloride concentration, reinforcement depth in the form of frequency histogram. Histogram were based on measurements from real bridges in the Northwestern United States [11]. There are also other studies dealing with input parameters for chloride affected bridge deck steel reinforcement corrosion. The effect of steel protection reinforcement is presented in [12]. Surface chloride concentration and is part of the study dealing with epoxy-coating protection effect [13]. This study also provides data for the epoxy-coating defects. There are also attempts to codify the model and description of probability density function. fib Model Code [5] contains description of the 1d chloride ingress model with aging effect including recommendation for probability density functions of input parameters. Joint Committee for Structural Safety has prepared draft of the chapter 2.19 *Environmental Attack*. However, this chapter is not publicly available [14].

Since the concrete is brittle material where cracking occurrence is accepted thus crack effect on the chloride ion penetration shall be considered. There were attempts to reflect the need for the crack effect modeling. The Finite Element Analysis (FEA) of chloride ingress into concrete with crack was considered in [6] and [15]. Both models were based on the second Fick's Law of Diffusion. The aggressive chloride exposure was applied as boundary conditions of a concentration of chlorides applied directly in nodes relevant to surface as well as to crack position. In contrast, the authors in [16] model the effect of cracks in the form of changes in the material parameters in the area of the crack. Moreover the crack width effect important for the chloride ion penetration into concrete is discussed in [17].

Presented work aims on the indicative evaluation of the effect of randomness of input parameters on two examples: directly exposed bridge decks and bridge decks protected by waterproof insulation (see Fig. 1). The possibilities of innovative crack effect modeling, presented briefly also in [18], are discussed more in depth here in. The results of deterministic and probabilistic assessment of the selected bridge decks are compared.

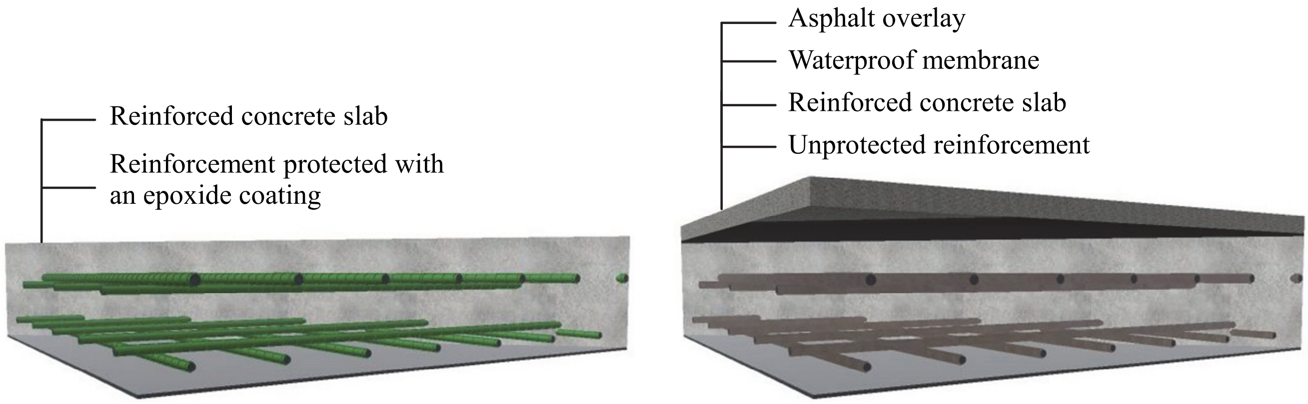

Figure 1: The RC bridge deck scheme with epoxide protection of reinforcement typical for the North East part of the USA (left) and waterproof insulation typical for Central Europe (right).

2D FEA DIFFUSION MODEL TAKING INTO ACCOUNT THE EFFECTS OF CRACKS

The FEA model [18] applied herein focusses on the transport of chloride ions through a RC bridge deck with a transverse crack and on an estimation of the concentration of chlorides at the reinforcement level or in places with damage to the epoxide coating of the reinforcement. Besides the capability of the modeling the cracking effect feature, the model also allows for simplified description of the damage to the waterproof insulation under the asphalt coating.

The durability evaluation of selected bridge deck protection strategies is based on the work [4] and [6]. It is enriched by introducing the effects of the aging of concrete via time varied diffusion coefficients [19]. Model allows for chloride ingress modeling and corrosion initiation analysis. The available model is supplemented with a special description of the effect of cracks in the directly exposed bridge deck.

The crack is applied in the form of introducing a highly permeable area [16-18]. The crack area is formed as narrow elements with width of crack. This approach allows for rather fast computation even though the irregularity of element

shape is of concern. Focus on the model precision is another part of ongoing research. The crack effect is modelled via change of diffusion coefficient in the respective area of the crack.
The calculation of the diffusion coefficient in the elements representing the crack is computed based on the work [17] as:

$$D_{c,cr} = (D_{c,cr,max} - D_{c,28})/50\times(C_{rckw} - 30) + D_{c,28}, \quad (1)$$

where $D_{c,28}$ is diffusion coefficient for an undisturbed sample [m²/s]. $D_{c,cr,max}$ is the coefficient of the media in the crack, $D_{c,cr,max} = 14\times10^{-10}$ [m²/s]. $D_{c,cr}$ is the diffusion coefficient in the crack [m²/s] and C_{rckw} is width of the crack in the range of $30 < C_{rckw} < 80$ [μm]. If the crack width is too low than the diffusion coefficient in crack $D_{c,cr}$ has the same value as for the intact material $D_{c,28}$. If the crack width is higher than the limiting value then the diffusion coefficient in respective elements has value similar to the one of porous media $D_{c,cr,max}$.

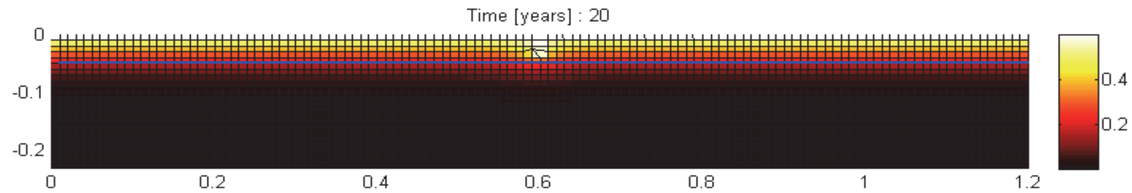

Figure 2: The sample contour plot of concentration of chloride ions in a concrete bridge deck with a crack. Deterministic solution for an exposure period t = 20 years shows the FEA meshed elements and concentration in the form of contours.

Deterministic application and the brief description of crack modeling approach were discussed in [18]. Illustrative probabilistic example of the model of a RC bridge deck from ordinary concrete with steel reinforcement protected by waterproof insulation under an asphalt cover is discussed in [20]. The finite element model with resulting concentration is shown in Fig. 2 and Fig. 3.

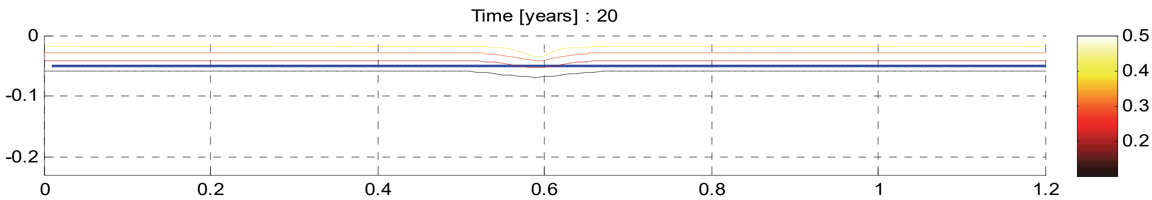

Figure 3: The sample isolines plot of concentration of chloride ions in a concrete bridge deck with a crack.

Assessment of durability

The main inputs to the durability assessment are the response of the structure to loading E_t and resistance R. The expression respecting the durability of bridge deck compares chloride concentration at most exposed spot of steel reinforcement $C_{xz,t}$ with chloride threshold C_{th} when corrosion is initiated. Their mutual interaction can be analyzed by using typical reliability function:

$$RF_t = \mathrm{R} - E_t = C_{\mathrm{th}} - C_{xz,t} \quad (2)$$

The inherent variability of studied problem is suitable for the application of probabilistic assessments. The probabilistic methods allow us to capture the random interaction between mutually contradictory parameters (see for example [21], [22] or [14]). In case of the RC bridge decks, the random interaction between cracks in concrete, defects in epoxide coatings and damage to waterproofing under an asphalt surface is of the interest. The level of reliability is expressed as the probability of given limit state exceedance:

$$\mathrm{P}_{f,t} < \mathrm{P}(\mathrm{R} - E_t < 0) = \mathrm{P}(RF_t < 0) \quad (3)$$

The reliability of the structure is generally analyzed by comparison with the probability of failure $P_{f,t}$ at particular age of the structure t and the design probability of failure P_d. In the case of parametric studies, it is also advantageous to compare the reliability of individual alternatives with the aid of computed failure probability P_f without a direct reliability assessment.

Available probabilistic approaches

When considering probabilistic methods for the reliability assessment, it is possible to select from tools analytic, simulation-based or numerical. An overview of available tools and methods can be found e.g. in [22] or [23].

Direct Monte Carlo simulation [24] is robust but the computation costs may be rather high in case of low probability events. Thus variation reduction techniques may be used in order to reduce the simulation time. These tools include for instance: Importance Sampling [25, 26]. Stratified sampling and Latin Hypercube Sampling [27, 28].

These approaches can lead to a reduction of computational burden which is necessary for large highly nonlinear tasks even nowadays. Another approach for the optimization of computation costs is so called "Directly optimized probabilistic calculation" (DOProC, [29, 30]). This method is on the boundary between combinatory and numerical integration.

SBRA probabilistic method

The Simulation-based Reliability Assessment method (SBRA, see [21]) is implemented. This method is based on the limit state design principle and on the application of a Monte Carlo simulation [24] for the calculation of probability of failure $P_{f,t}$ in time. This method applies bounded histograms for description of probability density functions.

Since the direct Monte Carlo method is applied, the question of precision arises. A very large number of steps is necessary particularly in case of tasks related to the limit state of carrying capacity with the expected probabilities of failure in order of one in one hundred thousand. In case of an analysis of corrosion initiation, the expected accuracy is in the range of single percentage. With the selection of thousand simulation steps, the Monte Carlo method induced error can be estimated with the aid of the common statistics. The estimation of probability in order of one percent falls with 90% certainty, into the interval $P_f = 0.01 \pm 0.0052$ [20]. This precision is reasonable for given task.

It is worth mentioning that the precision of the resulting probabilities estimates comparing with approaches that use continues mathematical models instead is a matter of discussion. Moreover, the opinion of the authors is that if is the resulting probability treated as measure of reliability useful for comparison of different scenarios then the difference in probability evaluation with procedures such as JCSS [14] does not play significant role.

APPLICATION OF DURABILITY ASSESSMENT

Durability assessment is computed without the variation of input parameters as well as with consideration of their randomness. An estimation of the period to the initiation of corrosion for the selected alternatives of RC bridge decks for the deterministic as well as for the probabilistic analysis uses the 2D finite element model.

The probabilistic framework extends the work [26] and calls a FEA macro with a description of a specific type of an RC bridge deck. There are two main steel reinforcement protection strategies considered as discussed in the following two sections.

The period to the onset of corrosion as well as respective probabilities are evaluated using a model prepared in an environment compatible with Octave or Matlab. The probabilistic solution of this macro is carried out repeatedly as part of a Monte Carlo simulation and always with randomly generated input variables according to the assigned histogram. The resulting probabilities are referenced to a 1x1 m square and the area of the damaged bridge structure can then be later calculated by a simple multiplication of the probability obtained by the area of the bridge deck.

The change of the diffusion coefficient due to the concrete aging is respected. The respective equation was introduced in [32] and reformulated to shape (4) in [31]. The approach for generating random values of the diffusion coefficient in time is given in (5). Thus the first step is a calculation of the nominal value of the diffusion coefficient over time t:

$$D_{c,\mathrm{nom},t} = D_{c,28} \cdot \left(\frac{t_{28}}{t} \right)^{m} \tag{4}$$

where is $D_{c,\mathrm{nom},t}$ nominal diffusion coefficient for a selected age [m²/s]. Concrete age is t [years] while t_{28} [years] is reference period of measurement for an age of 28 days. Aging factor is m [-]. The scatter of diffusion coefficient in time is possible to generate while respecting the dispersion change in time with:

$$D_{c,t} = D_{c,nom,t} + D_{c,var} \times D_{c,nom,t} \qquad (5)$$

where $D_{c,nom,t}$ is diffusion coefficient [m²/s] for the selected age t [years]. $D_{c,var}$ is respective distribution [m²/s].

Reinforced concrete bridge deck with a crack

The durability is expressed in the form of the period to the onset of corrosion. The analysis of a directly exposed RC bridge deck with unprotected steel reinforcement and consideration of crack effect is denoted as P1B. The model also contains a module for the reinforcement with an epoxide coating protection. This protection strategy is denoted as P1E. The input parameters are similar to black bar computation (P1B) with the special description of the spot on the epoxy coated steel reinforcement, called holidays, where the chloride concentration is evaluated. A summary of the parameters applied in alternative P1B and P1E is given in Tab. 1. The summary considers both random variables as well as the deterministic ones. The selection of distribution function is based on the available research studies as well as engineering judgment. If the distribution were available than the reference to literature source is given otherwise the engineering judgment is applied.

It needs to be noted that there is a minor difference between deterministic and probabilistic calculation in case of aging coefficient t. It is assumed that the difference has very low impact on the resulting time to corrosion initiation.

Parameter name	Deterministic solution	Probabilistic solution	
		Range/Value	Probability density function
Diffusion coefficient (OPC) $D_{c,28.}$ [10^{-12}m²/s]	5.59×10^{-12}	5.59×10^{-12}	Constant [2]
Aging coefficient m [-]	0.26	0.284	Constant [2]
Variation of the diffusion coefficient $D_{c,var}$ [-]	-	-0.116-0.482	Gumbel distribution (μ=0, s=1)×0.043 [33]
Depth of reinforcement (cover) R_{ebd} [m]	0.05	0.04-0.11	Histogram [11]
Chloride threshold for corrosion initiation C_{th} [%]	0.2	0.09-0.51	Histogram [12]
Depth of cracks C_{rckdpt} [m]	0.025	0.0-Depth	Histogram EXPON1.dis
Crack spacing C_{rcks} [m]	-	2.4-3.6	Bounded normal distribution. N(3,0.1)
Crack width C_{rckw} [mm]	0.3	0.035-0.565	Bounded normal distribution, N(0.3,0.05)
Relative spacing of the first cracks $C_{rcks,i}$	0.5	0-1	Uniform distribution
Frequency of defects in the reinforcement coating M_{ashn} [m^{-1}]	5	0-10	Histogram [13] (**P1E**)
Relative spacing of the first defect in the reinforcement coating M_{ashi}	0.05	0-1	Uniform distribution (**P1E**)
Concentration of chlorides at the surface C_0 [%]	0.6	0.21-1.63	Histogram [13]
Initial concentration of chlorides in concrete C_b %]	0	0	Constant
Monitored life span t [years]	100	100	Constant
Depth of RC slab *Depth* [m]	0.23	0.23	Constant

Table 1: The random variables and deterministic input parameters for ordinary concrete and a directly exposed reinforced concrete bridge deck with a crack (P1B - unprotected steel reinforcement, P1E - steel reinforcement protected by an epoxide coating). The parameters that belong exclusively to P1E are marked in the table.

Analysis with a defect in the waterproof insulation and a crack in a reinforced concrete bridge deck

By adding waterproof membrane under the penetrable asphalt overlay on the surface of alternative P1B, the corner stone of the model for a typical bridge deck in the Czech Republic (Alternative P2B) is introduced. However, the parameters of the waterproof membrane damage are based on the initial engineering judgment.

In the case of reinforcement protected by epoxide, the alternative marked as P1E becomes with the addition of waterproof insulation under the asphalt overlay alternative P2E. Deterministic as well as random variable parameters for waterproof insulation alternative are given in Tab. 2.
The asphalt is considered as totally permeable for simplification of the problem herein. The waterproof insulation is assumed to contain defects that allow chlorides to penetrate through. The area of defects in the modeled water proof barrier is assumed to grow linearly every year.

Parameter name	Deterministic solution	Probabilistic solution	
		Range/Value	Probability density function
Crack spacing in waterproof insulation C_{rckHIs} [m]	-	(0.46-1.53)	Bounded normal distribution N(1,0.1)
Width of the cracks growth in the waterproof membrane C_{rckHIw} [mm/year]	10	(1.15-18.85)	Bounded normal distribution N(10,1.65)
First defect in waterproof insulation $C_{rcksHI,i}$ [m]	0.4	0-1	Uniform distribution

Table 2: The modification of random input variables and deterministic input parameters for ordinary concrete and a reinforced concrete bridge deck with a crack under damaged waterproof insulation (P2B - unprotected steel reinforcement, P2E - steel reinforcement protected by an epoxide coating). Other parameters of the model are given in Tab. 1.

RESULTS

The prepared models allow for indicative comparison of the behavior of the steel reinforcement protection strategies (black bar vs. epoxy-coated reinforcement). At the same time, variants are studied from the point of view of the use of a waterproof membrane. The results of the growth of the probability initiation of corrosion during a simulated period of 100 years are shown on Fig. 4 including results from deterministic analysis [18]. Probabilities corresponding to time to deterministic onset of corrosion are indicated in graph as well. The resulting times to the initiation of corrosion for deterministic solution [18] and selected probability levels [20] are given in Tab. 3 on the next page.

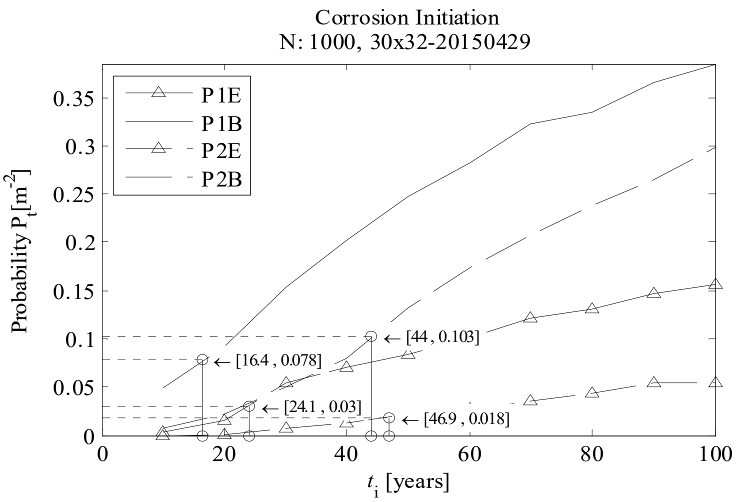

Figure 4: Probability of corrosion initiation t_i for the variants considered by type of reinforcement protection. B - unprotected reinforcement, E - epoxy-coated steel reinforcement; and the bridge deck type. 1 - directly exposed bridge deck with a crack, 2 - ordinary concrete and a bridge deck with a crack protected by waterproof insulation under an penetrable asphalt overlay.

Fig. 4 shows that unprotected steel reinforcement marked P1B has the value of computed deterministic time to onset of corrosion t_i =16.4 years that correspond to 7.8 percent of corrosion initiation likelihood in probabilistic solution. If the epoxy coating was used than the onset of corrosion started almost two times later (t_i =24.1 years) and it was related to probability of corrosion initiation P_f =3.0 percent.

The computation with initial attempt to model waterproofing with progressively widening insulating membrane defect (case P2B) showed that the risk of corrosion at the beginning of structural lifespan is almost mitigated. However due to the progressive growth of cracks the modelled effect of waterproof insulation is lost with time and this alternative follows the variant without concrete protection. The delay between cases P1B and P2B is ranging from 20 to 30 years for deterministic results. The onset of corrosion of unprotected steel reinforcement embedded in concrete under the water proof membrane is t_i =44.0 years that corresponds to probability of corrosion initiation P_f =10.3 percent. If epoxy-coated reinforcement is combined with waterproof insulation P2E then a highest durability is obtained herein (t_i =46.9 years, P_f = 1.8 percent). Addition of water proof membrane on top of the epoxy-coating protection has less significant effect comparing to unprotect steel reinforcement because it is second protection strategy in such case.

FEA mesh: 30×32	Time to corrosion initiation t_i [years]			
	Deterministic solution	Probability of corrosion initiation P_f [%]		
		5	10	25
P1B	16.4.	10.5	21.2	50.6
P1E	24.1	28.6	59.3	100.0
P2B	44.0	29.8	43.1	83.9
P2E	46.9	87.9	100.0	100.0

Table 3: Period to the initiation of corrosion t_i [years] for a selected probability of the initiation of corrosion for selected variants according to type of reinforcement protection: B - unprotected steel reinforcement, E - reinforcement covered with epoxide; the bridge deck construction: 1 - ordinary concrete and a directly exposed bridge deck with a crack, 2 - ordinary concrete and a bridge deck with a crack protected by waterproof insulation under an penetrable asphalt overlay.

Comparison of deterministic and probabilistic results

Deterministic analysis of steel reinforcement protected by epoxy-coating yields lower time to corrosion initiation comparing to probabilistic analysis in both cases: directly exposed bridge deck surface (P1E), as well as bridge deck with waterproof membrane under the penetrable asphalt overlay (P2E). If the uncoated reinforcement in directly exposed bridge deck is evaluated (P1B, t_i =16.4 years) than the deterministic results compared with the fifth percentile yielded lower time to corrosion initiation ($t_{i,05}$ = 10.5 years) while the tenth percentile yielded higher time ($t_{i,10}$ = 21.2 years). If the bridge deck is covered by waterproof membrane (P2B, t_i =44.0 years) than fifth percentile yielded lower time to corrosion initiation ($t_{i,05}$ = 29.8 years) while the tenth percentile yield similar time ($t_{i,10}$ = 43.1 years).

CONCLUSIONS AND DISCUSSION

The indicative durability assessment of reinforced concrete bridge deck exposed to chloride ingress is applied considering 2d finite element model of chloride ion ingress with crack and simplified ability to describe the waterproof membrane effect. Moreover, the implementation of a continuous model of crack effect is discussed and applied. The Monte Carlo simulation is utilized for probabilistic evaluation. The description of the basic input parameters is based on the available research data. However, the description of the crack frequency and depth in reinforced concrete bridge deck as well as description of waterproof membrane damage are based on the preliminary engineering judgment.

From the conducted analysis it is shown, that the worst protected is, as expected, the steel reinforcement without an epoxy-coating in the directly exposed bridge deck with a crack. When an epoxide coating was used on steel reinforcement then the model calculations significantly reduced the risk of the occurrence of corrosion.

The comparison of deterministic and probabilistic assessment of chloride ingress related durability of selected bridge decks with enhanced crack effect consideration is conducted. The effect of two protection strategies with respect to durability of reinforced concrete bridge deck is discussed, namely waterproof membrane under penetrable asphalt overlay and epoxy coating steel reinforcement protection.

It was observed that the application of random input parameters variation increased time to onset of corrosion on probability levels of 10 and 25 percentiles comparing to deterministic solution. It is assumed that it was caused by lower likelihood of simultaneous encountering of following phenomena: crack in bridge deck, problem in waterproof membrane and/or defect in epoxy-coating. This observation is more significant in cases with epoxy-coating where more random variables are involved.

The presented models describe the initial attempt to encounter for the effect of the water proof membrane and cracking. However, it needs to be noted that the selection of model parameters as well as probability distribution significantly affects the time to onset of corrosion, so the results reflect considered simplifications and assumptions. Thus further research is necessary in order to improve the input parameters description and model assumptions. Moreover, addressing the input parameters with respect to proposed codified approaches shall be of special interest as well.

ACKNOWLEDGEMENTS

Financial support from VŠB-Technical University of Ostrava by means of the Czech Ministry of Education, Youth and Sports through the Institutional support for conceptual development of science, research and innovations for the year 2016 is gratefully acknowledged.

REFERENCES

[1] Tikalsky, P.J., Scheetz, B.E., Tepke, D.G., Task 6 Final Report Statewide High Performance Concrete Initiative, Penndot Research, State College, PA, USA, Pennsylvania State University, (2007).
[2] Ghosh, P., Tran, Q., Correlation between Bulk and Surface Resistivity of Concrete, International Journal of Concrete Structures and Materials, 9(1) (2014) 119-132. DOI 10.1007/s40069-014-0094-z.
[3] Keršner, Z., Novák, D., Teplý, B., Bohdanecký, V., Concrete Carbonation, Reinforcing Steel Corrosion and Cooling Tower Durability, Sanace, 4 (1996) 21-23.
[4] Tikalsky, P.J., Pustka, D., Marek, P. Statistical variations in chloride diffusion in concrete bridges, ACI Struct. J., 102 (2005) 481-486.
[5] fib Bulletin 34: Model Code for Service Life design, (2006).
[6] Konečný, P., Tikalsky, P.J., Tepke, D.G., Performance Evaluation of Concrete Bridge Deck Affected by Chloride Ingress: Simulation-Based Reliability Assessment and Finite Element Modeling, Transportation Research Record, 2028 (2007) 3-8. DOI: 10.3141/2028-01.
[7] Novák, D., Vořechovský, M., Teplý, B., FReeT: Software for the statistical and reliability analysis of engineering problems and FReET-D: Degradation module, Adv. Eng. Softw., 72 (2014) 179-192. DOI:10.1016/j.advengsoft.2013.06.011.
[8] Konečný, P., Brožovský, J., Ghosh, P. Evaluation of Chloride Influence on the Cracking in Reinforced Concrete Using Korozeeneck Software. In: Transactions of the VŠB – Technical University of Ostrava, Civil Engineering Series, 11(1) (2011) 1–7. DOI: 10.2478/v10160-011-0006-y.
[9] Teplý, B., Vořechovská, D., Reinforcement Corrosion: Limit States, Reliability and Modelling, J. Adv. Conc. Technol., 10 (2012) 353-362. DOI: 10.3151/jact.10.353.
[10] Sýkora, M., Holický M., Marková, J., Verification of Existing Reinforced Concrete Bridges Using the Semi-Probabilistic Approach. Eng. Struct., 56 (2013) 1419-1426. DOI: 10.1016/j.engstruct.2013.07.015.
[11] Sohanghpurwala, A.A., Scannell. W.T.,Verification of Effectiveness of Epoxy-Coated Rebars. Final Report to Pennsylvania Department of Transportation, Project No. 94-05. Ashburn, VA [USA]: ConCorr, (1998).
[12] Darwin, D., Browning, J., O'Reilly, M., Xing, L., Ji, J., Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars, ACI Mat. J., 106 (2009) 176-183. DOI: 10.14359/56465.
[13] Weyers, R.E., Pyc, W., Springel, M.M., Estimating the service life of epoxy-coated reinforcing steel, ACI Mat. J., 95 (1998) 546-557.
[14] JCSS Probabilistic Model Code, http://www.jcss.byg.dtu.dk/Publications/Probabilistic_Model_Code.aspx, (2016).
[15] Marsavina, L., Audenaert, K., De Schutter, G., Faur, N., Marsavina, D., Experimental and numerical determination of the chloride penetration in cracked concrete. In: Constr. Build. Mater., 23 (2009) 264-274. DOI: 10.1016/j.conbuildmat.2007.12.015.
[16] Bentz, D.P., Garboczi, E.J., Lu, Y., Martys, N., Sakulich, A.R., Weiss, J.W, Modeling of the influence of transverse cracking on chloride penetration into concrete, Cement Concrete Comp., 38 (2013) 65-74. DOI: 10.1016/j.cemconcomp.2013.03.003.
[17] Djerbi, A., Bonnet, S., Khelidj, A., Baroghel-Bouny., V., Influence of traversing crack on chloride diffusion into concrete, Cement Concrete Res., 38 (2008) 877-883. DOI: 10.1016/j.cemconres.2007.10.007.

[18] Konečný, P., Lehner, P., Durability assessment of concrete bridge deck considering waterproof membrane and epoxy-coated reinforcement. Perspectives in Science, 7 (2016) 222-227. DOI:10.1016/j.pisc.2015.11.036.

[19] Lehner, P., Konečný, P., Ghosh, P., Tran, Q., Numerical Analysis of Chloride Diffusion Considering Time-dependent Diffusion Coefficient, International Journal of Mathematics and Computers in Simulation, 8 (2014) 103-106.

[20] Konečný, P., Lehner, P., Probabilistic evaluation of concrete bridge performance considering waterproof membrane and epoxy-coated reinforcement, In: proceedings of The 13th International Probabilistic Workshop, (2015). http://rpsonline.com.sg/rps2prod/ipw2015/pdf/089.pdf.

[21] Marek, P., Guštar, M., Anagnos, T., Simulation-Based Reliability Assessment fo Structural Engineers, Boca Raton, FL, USA, CRC Press, (1995).

[22] Melchers, R., Structural Reliability Analysis and Prediction (Civil Engineering) West Sussex, England, Wiley, (1999).

[23] Haldar, A., Mahadevan, S., Probability, reliability, and statistical methods in engineering design, New York, USA, John Wiley, (2000).

[24] Metropolis, N., Ulam, S.,The Monte Carlo method. Journal of American Statistical Association, 44(247) (1949) 335-341.

[25] Schueller, G.I., Pradlwarter, H.J., Bucher, C.G. Efficient computational procedures for reliability estimates of MDOF systems. Int. J. Nonlin. Mech., 26 (1991) 961-974.

[26] Praks, P., Numerical aspects of Simulation Based Reliability Assessment of Systems, International Colloquium Euro-SiBRAM'2002, Prague, ITAM CAS Czech Republic, II (2002).

[27] Iman, R.L., Conover, W.J., A distribution-free approach to inducing rank correlation among input variables, Commun. Stat. Simulat., 11 (1982) 311-334. DOI: 10.1080/03610918208812265.

[28] Vořechovský, M., Novák, D., Correlation control in small-sample Monte Carlo type simulations, In: A simulated annealing approach. Prob. Eng. Mech., 24 (2009) 452-462. DOI:10.1016/j.probengmech.2009.01.004.

[29] Janas, P., Krejsa M., Krejsa, V., Using the Direct Determined Fully Probabilistic Method (DDFPM) for Determination of failure, Briš, R., C.G. Soares a S. Martonell. Reliability, risk and safety: theory and applications, In: proceedings of the European Safety and Reliability Conference, ESREL 2009, Prague, Czech Republic, 7-10 September CRC Press, (2009) 1467-1474.

[30] Krejsa, M., Janas, P., Yilmaz, I., Marschalko, M., Bouchal, T., The Use of the Direct Optimized Probabilistic Calculation Method in Design of Bolt Reinforcement for Underground and Mining Workings, Scientific World Journal, 2013 (2013) 267593. DOI: 10.1155/2013/267593.

[31] Thomas, M.D.A., Bamforth, P.B., Modelling chloride diffusion in concrete effect of fly ash and slag, Cement Concrete Res., 29 (1999) 487–495. DOI: 10.1016/S0008-8846(98)00192-6.

[32] Mangat, P., Molloy, B., Prediction of long term chloride concentration in concrete. Mater. Struct. 27 (1994) 338–346. DOI: 10.1007/BF02473426.

[33] Konečný, P., Vyhodnocení trvanlivosti železobetonových mostovek s ohledem na vliv chloridů a na rozptyl vstupních parametrů (Evaluation of the durability of reinforced concrete bridge decks with respect to the actions of chlorides and scatter of input parameters). Habilitation thesis, VŠB-Technical University of Ostrava (2015).