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PERFORMANCE ASSESSMENT OF CONCRETE BRIDGE DECK APPLYING SBRA APPROACH AND FEM MODEL WITH REGARD TO CHLORIDE INGRESS

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Summary: *The effect of cracks on the chloride ingress into bridge decks with epoxy-coated reinforcing steel is studied. A finite element diffusion model in conjunction with a probabilistic method called Simulation-Based Reliability Assessment (SBRA) is used to address the inherited randomness of input variables. Data used for diffusion coefficients and concrete cover depths are based on a study performed on North Eastern the bridges in the U.S.A. and reported in (SOHANGHPURWALA & SCANNELL, 1994).*

1. Introduction

The reliability of reinforced concrete structures is in many cases governed by durability. Many structures require premature rehabilitation or replacement resulting from environmental deterioration. Reduced service life leads to increased life-cycle costs and increases the burden of funding on taxpayers. The technology to accurately predict the long-term durability of reinforced concrete bridge decks is still developing. By accurately predicting deterioration, engineers can better design concrete mixtures and structural systems to resist degradation from long-term environmental and structural loads.

One of the most significant types of distress in many bridge decks in the North Eastern United States is the corrosion of reinforcing steel from the ingress of chloride salts applied to melt snow and ice. This can lead to loss of structural capacity and promote reduced serviceability, thus leading to increased life-cycle costs. Though models for chloride ingress, carbonation and corrosion development have been studied (see e.g. COLLEPARDI et al., 1972, BODDY et al., 1999, BENTZ et al., 2001, ALISA et al., 1999, PAPADAKIS et al., 1992, 2000, ŠMERDA et al., 1992) including those from the probabilistic standpoint (KERŠNER et al., 1996, TEPLÝ et al., 1999, DAIGLE et al., 2004, THOFT-CHRISTENSEN, 2005), there are still many issues that must be addressed for them to become useful engineering tools, especially with regards to randomness of pertinent input variables.

This paper is focused on a reinforcesd concrete bridge deck 2-D chloride ingress model that

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accounts for the scatter of input random variables and surface cracks by combining a finite element model and SBRA introduced in (MAREK et al., 1995, 2003). SBRA approach for durability assessment with regards to chloride ingress model was proposed by (TIKALSKY, 2003), and (TIKALSKY et al., 2005).

2. Chloride Ingress Induced Deterioration

2.1 Service Life

If one considers the corrosion process driven by chloride ingress as the governing durability issue then service life $t_{service}$ can be written according to (TUUTTI, 2003) as

$$t_{service} = t_{initiation} + t_{propagation}$$

where $t_{initiation}$ is the period before the onset of corrosion and $t_{propagation}$ is the time for corrosion to reach an unacceptable damage level once it has begun. The initiation period is primarily influenced by the concrete diffusion characteristics, concrete cover, surface chloride concentration, temperature, level of saturation and the required concentration at the level of reinforcing steel to initiate corrosion.

2.2 Reinforcement Protection Measures

If there is epoxy coating on the reinforcing steel, as is common in the U.S.A., one must consider the concentration near holidays, if any are present. The reinforcing steel is in fact exposed to corrosion due to the holidays and other problems in the epoxy-coating. It is necessary to assess chloride concentration near such holidays.

The model presented in this paper focuses on this initiation period. The propagation period begins once a sufficient concentration of chlorides has reached the reinforcing steel to dissolve the passivation layer and initiate corrosion.

It is useful to note that while bridge decks in the ČR do have usually waterproof barrier under the asphalt layer to protect reinforced concrete, reinforced concrete on the bridge deck in the U.S.A. does not have such protection. Structural bridge deck is exposed directly to deicing salts there (see. illustrative Fig. 1). Epoxy-coating is answer to need for rebar protection from chloride attack.

One can understand chloride ingress as an exceptional loading in our country because reinforced concrete (RC) may be exposed to chloride ingress and subsequent rebar corrosion after the failure of waterproof insulation.

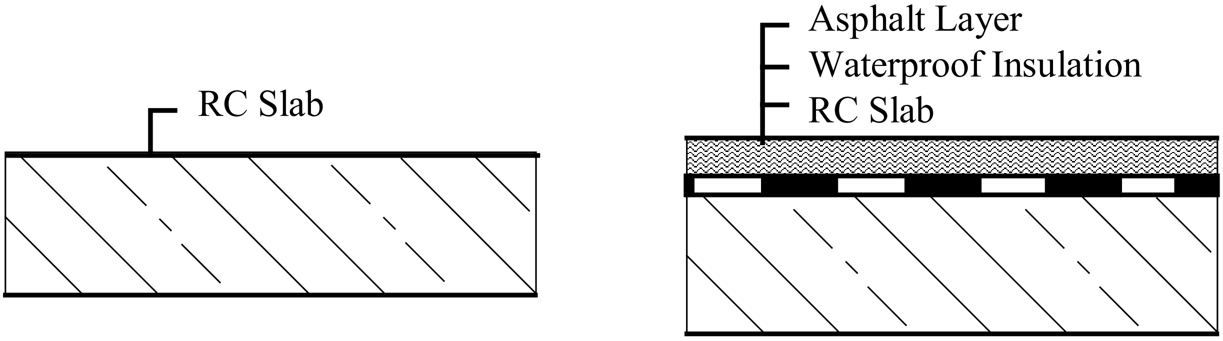

Fig. 1 Scheme of bridge deck in U.S. (left) and in ČR (right)

2.3 Mechanism of Chloride Ingress and Transportation Model

Diffusion is the primary mean by which chlorides penetrate to the level of reinforcing steel to initiate corrosion. The effects of hydraulic pressure and capillary absorption are minor in comparison in most cases and are neglected herein. 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, see e.g. (HOOTON, 2001). The solution (referred to as the Crank Solution) of the governing differential equation is given as Equation 2 (COLLEPARDI et al., 1972)

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

where $C_{x,t}$ is the concentration of chlorides (percent by mass of total cementitious materials) at time t (years) and depth x (meters), C_0 is the concentration of chlorides (% by mass of total cementitious materials) at the surface directly inside the concrete and D_c is the apparent diffusion coefficient (m^2/year) Equation (2) is widely used for chloride ingress models but does not account for cracks and must be modified to account for time dependent changes in material property or boundary conditions.

2.4 Reliability Assessment

Severity of the chloride ingress can be 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 preparation of the reinforcing steel and the constituents of the concrete as well as other factors. Typical values are 0.2 percent chlorides by mass of total cementitious materials according to ACI 207R-01 and 0.4 percent for CEB [20].

The reliability, RF_t, of a bridge deck is expressed as the time-dependent exceedance of the corrosion threshold by the location dependent chloride concentration, $C_{xy,t}$ The reliability function characterizing the above described limit state is expressed as:

$$RF_t = C_{th} - C_{xy,t} \tag{3}$$

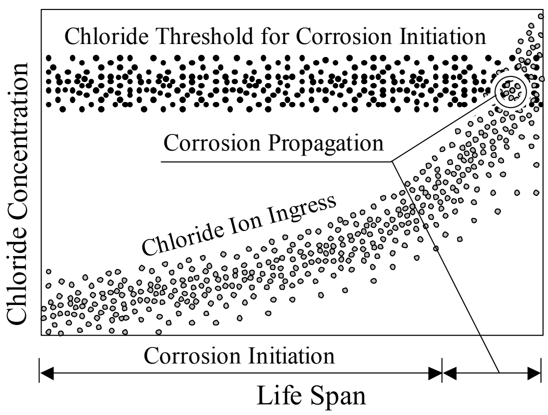

Fig. 2 Time-Dependent Probabilistic Reliability Analysis Idea, Chloride Ion Concentration vs. Chloride Threshold

Probabilistic time-dependent analysis can be thought of as a comparison of the joining extrema of the chloride concentration C_t and threshold C_{th} random realizations. Once the probability that the chloride concentration at the reinforcing steel level exceeds the threshold by a user-defined amount (dependent on structure importance), corrosion is assumed to begin and the structure is designated as unreliable in terms of further delaying the onset of corrosion. Figure 2 displays this concept.

2.5 2-D FEM Diffusion Model with Crack Effect Considered

This proposed model focuses on the chloride transportation in reinforced concrete bridge decks with cracks and on the estimation of chloride ion concentration in particular locations on the embedded reinforcing steel bars or damaged areas of epoxy-coated bars. Although transverse reinforcing steel bars are susceptible to corrosion, the presented model is focused on longitudinal steel. To meet the analysis requirements, a 2-D Finite Element Method was chosen for the solution of Second Fick's Law (eq. 2). The commercial software ANSYS was used (ANSYS, 2005).

2.5.1 Assumptions

The assumptions for this model are as follows:

- ionic diffusion is a sole mechanism of the chloride transport,
- the concrete deck is homogenous and is fully saturated with consistent pore fluids thoughout the cross-section,
- later-age apparent diffusion coefficients are used and are assumed constant with respect to temperature,
- the maximum soluble chloride ion concentration on the surface and in the crack is 0.6 percent, surface and crack chloride concentration is uniform over time,
- cracks are formed perpendicular to the longitudinal reinforcing steel, maximum depth of crack is considered to be ¾ of slab thickness,
- a width of cross-section that is modeled is equal to crack spacing,
- crack is placed in the middle of investigated cross-section,
- the deck has infinite length (adiabatic boundary conditions on the edges),
- deck depth of the model is equal to the depth of the respective bridge deck (depth is not infinite as in the Crank solution (eq. 2), adiabatic boundary conditions on the bottom),
- maximum soluble concentration is applied on the relevant model nodes on the top surface and on the nodes relevant to the effective crack depth,
- the vertical position of the nearest node to the effective depth at a crack is changed so it matches the effective crack depth exactly,
- the concentration of chloride ions around the epoxy-coated reinforcing steel bar is considered to be the same as it is at the top of the rebar,
- chloride background concentration in concrete C_b=0 %.

2.5.2 Input data

Initial top surface and effective crack depth concentrations (boundary conditions on the respective nodes) C_0 are 0.6 percent (by mass of total cementitious materials) of soluble chloride ions. Top clear concrete cover over the top layer of reinforcing steel is 0.075 m. Diffusion coefficient, D_c is 1.55×10^{-5} m^2/year. Width of the investigated slab is equal to crack spacing and is 1 m. Crack depth is 0.06 m. The distribution of epoxy-coating defects (holidays) is characterized by a distance of 0.5 m from the right edge and a spacing of 1 m (one deficiency under crack). The concentrations are computed for t equals 10 years.

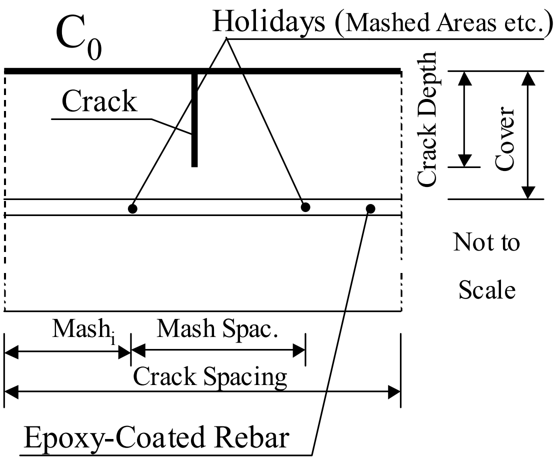

Fig. 3 Scheme of Slab with Crack

2.5.3 ANSYS model (FEM Diffusion Macro)

The 4-noded thermal solid element PLANE55 was used for the chloride diffusion analysis because of the similarities between the mechanisms of thermal flow and ion diffusion. The 0.25 m thick deck was vertically divided into 25 elements that are 10 mm by 10 mm in size. This resolution provided sufficient accuracy. The model scheme is presented as Figure 3.

The transient analysis time stepping was controlled automatically with initial time step set at 0.25 years.

Sample graphical output from the analysis for t =10 years is shown as Figure 4. One can observe the effects of a crack that allow the chloride ions to move in both directions and reach the rebar level more rapidly than if no crack was present.

2.5.4 Chloride Concentration & Reliability Assessment

The concentration (percent mass by total cementitious materials) after 10 years at the level of the longitudinal reinforcing steel under a crack is 0.3189 percent. According to the ACI threshold, corrosion would occur in this situation. The reference value computed at the same depth but without the crack influence 0.1064 percent, which would not be sufficient to start the reaction. The concentration computed using the Crank solution to Fick's 2ND Law (eq. 2) is 0.1066 percent. The concentration where no crack is present is much lower than where one exists, and is comparable with the analytical (Crank Solution) value.

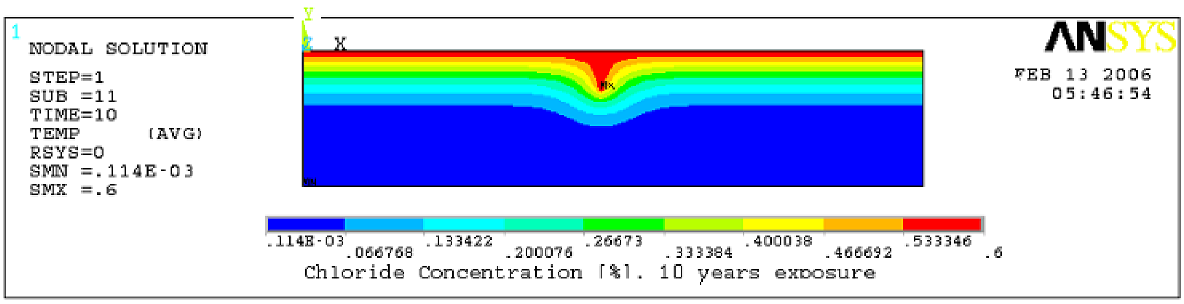

Fig. 4 Chloride Ion Concentration in Concrete Slab with Crack, t = 10 years

3. SBRA Application

3.1 Probabilistic Approach

A probabilistic approach was adopted to address the inherent variability of important input parameters used to describe the onset of corrosion. Diffusion coefficients, reinforcing steel depths, and chloride threshold histograms were developed based on field data presented in (SOHANGHPURWALA & SCANNELL, 1994). Epoxy coating holidays on steel reinforcing rods and crack frequency distributions were estimated based on anticipated behavior. The onset of corrosion depends on the chloride level and this is significantly affected by the random proximity of the cracks to exposed steel from holidays. Probabilistic analysis can be used to adequately approximate this relationship.

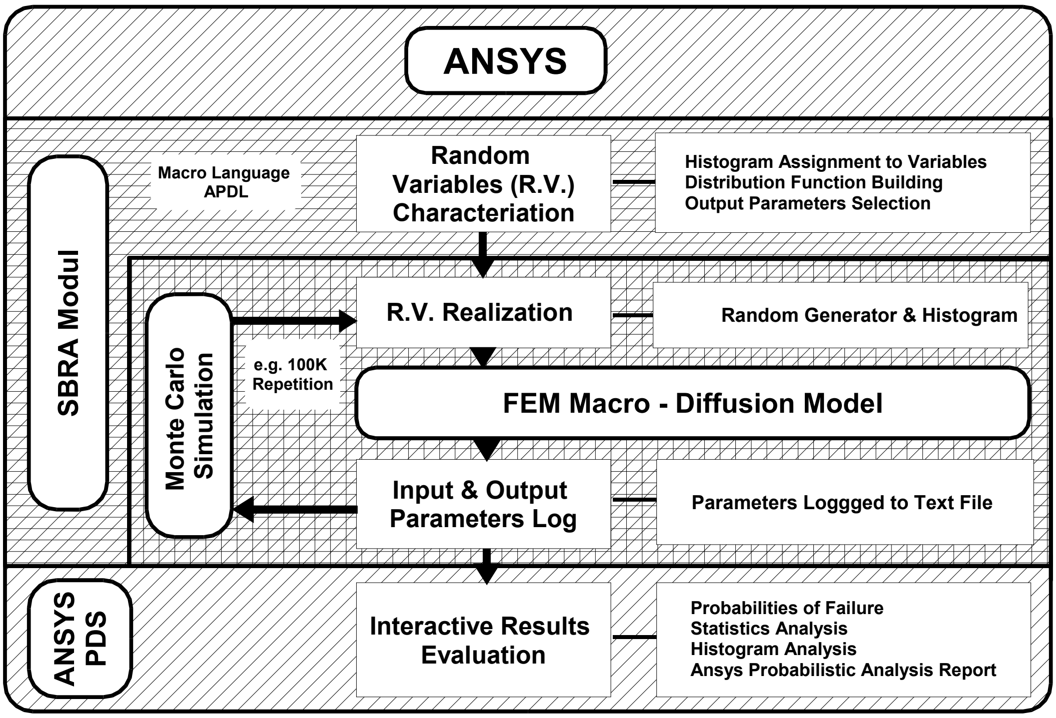

Fig. 5 SBRA Module for ANSYS Flow Chart

The stochastic nature of the 2-D chloride diffusion problem is addressed using the SBRA method used to describe 1-D behaviour in (TIKALSKY, 2003).

The reliability function, RF_t, is computed in consecutive time intervals. Probability of "failure" $P_{f,t}$ is obtained by reliability function analysis. It is not actually the failure probability, but the probability of specified limit state exceedance and is expressed as:

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

The structure is believed to be safe if $P_{f,t}<P_d$ criterion is met, where P_d is the target or design probability of failure. It has different values according to (MAREK et al., 2003) for different safety and serviceability limit states. Target probability for common structures for safety and serviceability limit states is P_d=7e^{-5} and P_d=7e^{-2}, respectively.

3.2 SBRA Module for ANSYS

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 SBRA Module programmed by authors in ANSYS APDL (ANSYS, 2005) environment runs the FEM Macro containing the diffusion process description. Random variable parameters in the FEM macro were automatically replaced by randomly generated variables throughout the Monte Carlo simulations.

SBRA module was developed for easier characterization of random variables by histograms in ANSYS program Probabilistic Design System (PDS) (ANSYS, 2005). Though widely used option to generate random variables in external program (see eg. Králik & Varga, 2004, 2005, Micka, 2005, Konečný, 2005) such as Anthill for Windows and solve the FEM in ANSYS was not adopted here. ANSYS PDS was used for Monte Carlo data post processing.

4. Probabilistic 2-D Diffusion Analysis Example

4.1 Input and Random Variables

Table 1 summarizes possible deterministic and random input variables for specified analyses. Histograms of diffusion coefficient and reinforcing steel depth, presented in Figures 6a & 6b, are based on the measurement of chloride penetration and concrete cover from more than 200 samples taken from 40 bridge decks (SOHANGHPURWALA & SCANNELL, 1994). The chloride threshold distribution obtained from (DAIGLE et al., 2004) is based on (GLASS & BUENFELD, 1995). Crack depth variation is estimated using beta distribution assuming that maximum crack depth is ¾ of the deck depth and that crack depth mean value is 1/5 of the deck depth. Crack spacing distribution is assumed to be correlated with deck thickness and width of model slab is equal to the random variable crack spacing.

Table 1 Random and Deterministic Input Values

	Range	***Description***
Diffusion Coefficient D_c [10^{-12}m^2/s]	0-25	Histogram
Rebar Depth (Cover) R_{ebd} [m]	0.04-0.11	Histogram
Chloride Threshold C_{th} [%]	0-2	Histogram
Crack Depth C_{rckdpt} [m]	0.0-¾depth	Beta Distribution, Beta(0.0,¾depth, 2,4) *
Crack Spacing C_{rckrs}	(2.7-3.3) × depth	(Normal Distribution N(3,0.1)) × depth **
Damaged Area Frequence M_{ashn} [m^{-1}]	0-100	Uniform Distribution.
Relative Damage Area Position M_{ashi}	0-1	Uniform Distribution
Surface Soluble Chloride Concentration C_0 [%]	0.6	Constant
Background Chloride Concentration C_b [%]	0.0	Constant
Life Span t [years]	50	Constant
Depth of Slab *Depth* [m]	0.19	Constant
Size of Element *Delta* [m]	0.0075	Constant

* Crack depth distribution is represented by beta distribution that is characterized by four parameters minimal and maximal values and shape factors α and β.

** Bounded histogram for Crack Spacing represents Normal distribution with mean value equal to 3 and standard deviation equal to 0.1.

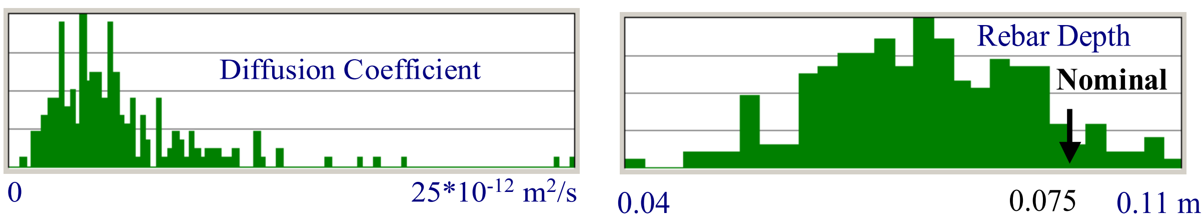

Fig. 6a Histograms of Diffusion Coefficient (left), Reinforcing Steel Depth (right)

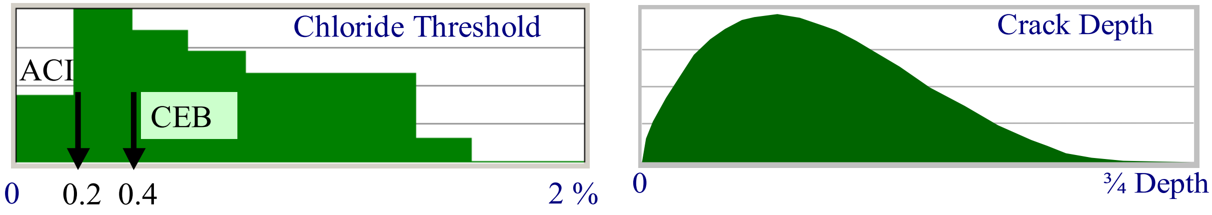

Fig. 6b Histograms Chloride Threshold (left) and Crack depth (right)

4.2 FEM Transformation Model

The FEM Macro described in 2.5 has capabilities to automatically repeat with randomly selected input variables for each Monte Carlo simulation step. The highest concentration surrounding one of the epoxy-coating damaged areas was selected as the critical case where corrosion would occur first.

4.3 Probabilistic Analysis by SBRA Method

The SBRA module governs the probabilistic analysis with 50,000 Monte Carlo simulation steps. The reliability of the reinforcing steel is computed as probability, $P_{f,t}$, that random variable chloride ion concentration $C_{xy,t}$ is higher than random variable chloride threshold C_{th} at a particular age.

The chloride ion concentration at the rebar level at the exposed reinforcing steel areas and reliability function distributions are shown in Figure 7.

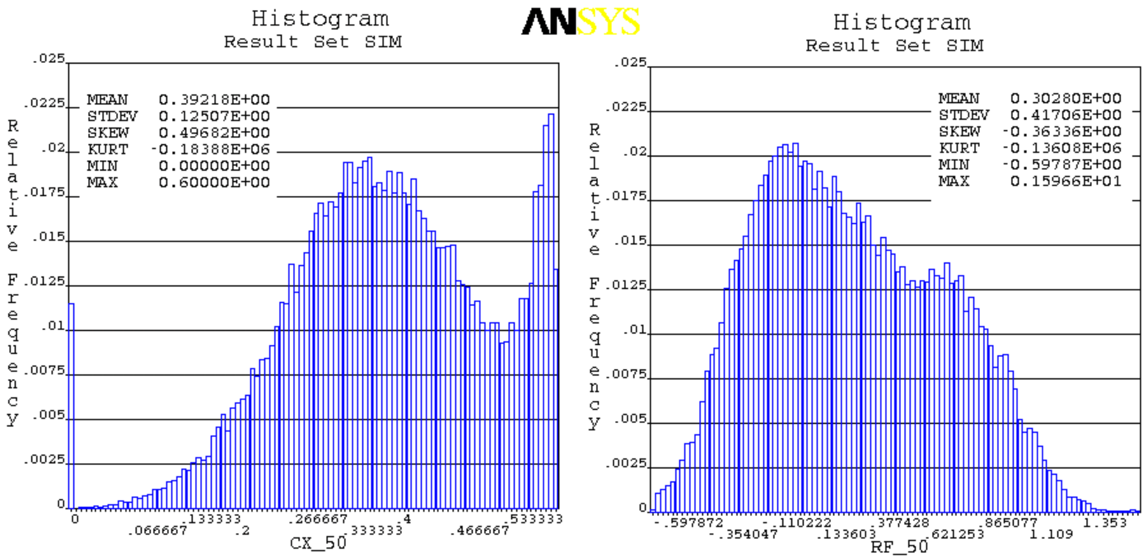

Fig. 7 Chloride Ion Concentration $C_{xy,t}$ (left) and Reliability Function RF_t (right) in 50 years [%]

4.4 Result and Comments

The probabilities of chloride threshold exceedance are shown in Figure 8 (continuous line). Probability of corrosion initiation ranges from 13.6 % in 10th year of service to 27.8 % in 50th year of service.

If one can reduce number of holidays from up to 100 per meter (see Tab. 1 - Damaged Area Frequence M_{ashn}) up to 10 per meter of reinforcing steel bar than likelihood of corrosion initiation could be reduced by 5 % (see Figure 8 dashed line).

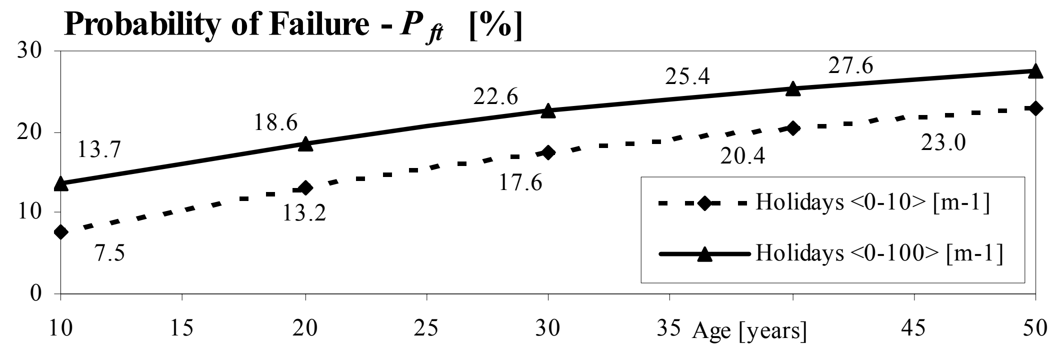

Fig 8 Probability of corrosion initiation (Probability of Failure) $P_{f,t}$

The other result from is sensitivity analysis. It is shown, as pie chart, for reliability function RF_{50} in Figure 9 indicating that most significant variable here is chloride threshold followed by crack depth and diffusion coefficient.

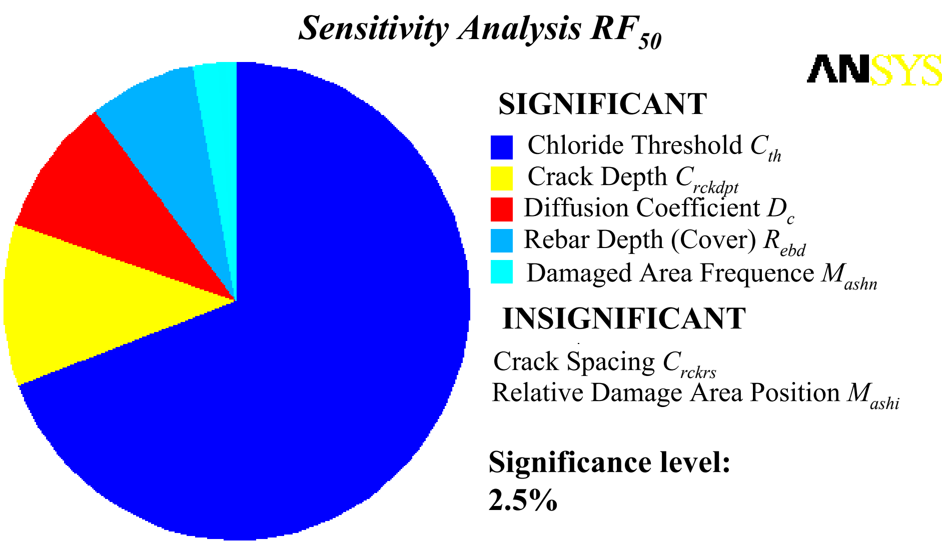

Fig 9 Sensitivity Analysis for Reliability Function RF_{50} at age t = 50 years

5. Discussion and Conclusions

The FEM in conjunction with a Simulation-Based Reliability Assessment (SBRA) method was used to estimate the probability of corrosion initiation from chloride ingress of longitudinal epoxy-coated reinforcing steel bars throughout the life of a typical bridge deck. The effect of cracking was considered. The variable nature of diffusion coefficients, concrete cover, chloride threshold to initiate corrosion, reinforcing steel holidays and relative proximity to cracks was modeled using histograms based either on field data or engineering judgement and reasonable results were obtained.

There was SBRA module used in ANSYS to allow for finite element analysis of 2-D chloride diffusion process using Monte Carlo simulation process with random variables characterized by histograms.

An appropriate target probability, P_d, for corrosion initiation could likely be higher than the probability for serviceability assessment of 7% as mentioned in (TIKALSKY, 2003), since the structure will be exposed to the propagation period prior to ultimate serviceability failure.

Acceptable value should be a matter of further discussion and specification.

Care must be taken when using the probability quantitatively. It is noted that the resulting probability does not reflect exact likelihood that corrosion initiates due to the vast amount of assumptions and simplifications made, and lack of overall scientific understanding of many complex and inter-related governing phenomena. It, however, can be used quite effectively in the qualitative sense to compare possible structural and materials-related scenarios.

Further research is aimed on the effects of epoxy-coating damage distribution and crack spacing interaction, changing salt concentrations from seasonal use, fluctuating temperature and changing diffusion coefficients from temperature and time. Additional studies will also be conducted to incorporate transverse reinforcing steel bar corrosion as part of the model.

6. Acknowledgements

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