VŠB – TECHNICAL UNIVERSITY OF OSTRAVA
FACULTY OF CIVIL ENGINEERING

DOCTORAL DISSERTATION

RELIABILITY OF REINFORCED CONCRETE BRIDGE DECKS WITH RESPECT TO INGRESS OF CHLORIDES

POSUZOVANÍ SPOLEHLIVOSTI ŽELEZOBETONOVÉ MOSTOVKY
S OHLEDEM K PŮSOBENÍ CHLORIDŮ

by

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Annotation

The aim of the submitted work is to make a probabilistic durability assessment of concrete bridges affected by deicing agents applied to melt snow. The potential of the application simulation tools, see SBRA (Based Reliability Assessment method), is studied with respect to chloride ingress induced corrosion of bridge decks with epoxy-coated steel reinforcement. Representative slabs of this type are e.g. bridge decks in some parts of the U.S.

The durability of the investigated decks is severely threatened by the risk of corrosion because the concrete surface is directly exposed to deicing salts. It is necessary to study the effect of cracks in the reinforced bridge deck which are the most likely gate for chloride ions to enter flaws in epoxy-coating.

The stochastic approach is applied in the evaluation of the corrosion process in order to respect the inherent randomness of pertinent random input variables. The Monte Carlo simulation tool is applied with random variables described by bounded distributions.

Response to the considered "loading" by chlorides is computed using Fick's second Law of diffusion. It is expressed by the concentration of chlorides in the most exposed location of the reinforcement (especially in the epoxy-coating defect). This concentration is compared in the assessment with the chloride threshold (amount of chlorides sufficient to start corrosion). The likelihood of corrosion initiation is statistically evaluated and compared with the target probability.

The stochastic model based on the SBRA method utilizes FEM as a transformation model and can significantly facilitate the study of the significance of input variables with respect to corrosion initiation. The results indicate that the variation in input parameters substantially affect durability of bridge deck. The most important variable is diffusion constant. The effect of epoxy-coated reinforcement improves durability under proper handling and construction practices.

Anotace

Předložena práce je zaměřena na pravděpodobnostní posudek trvanlivosti železobetonových mostů vystavených působení chloridů. Jsou hledány možnosti využití simulačních nástrojů viz. SBRA (Simulation-Based Reliability Assessment) při rozboru trvanlivosti z hlediska vzniku koroze u mostovky s výztuží chráněnou epoxidovým povlakem. Typickým příkladem takových desek jsou mostovky realizované v některých oblastech U.S.A.

Trvanlivost sledovaných mostovek je vážně ohrožena rizikem koroze ocelové výztuže vzhledem k vystavení povrchu betonu přímému působení posypových solí. Je nutné sledovat efekt trhliny v železobetonové mostovce usnadňující průnik chloridů k výztuži poškozenou epoxidovou ochranou ocelové výztuže.

Při rozboru korozního procesu je uplatněno stochastické modelování zohledňující vstupní nahodile proměnné veličiny. Je užita simulační metoda Monte Carlo a náhodně proměnné jsou vyjádřeny useknutými rozděleními.

Jako transformační model k určení odezvy na uvažované „zatížení“ chloridy slouží druhý Fickův zákon difuze. Odezva je vyjádřena koncentrací chloridů v nejexponovanějších místech výztuže (zejména v místech poruchy epoxidového povlaku), která je v posudku porovnána s tzv. chloridovým prahem“, což je koncentrace nutná pro započetí koroze. Statisticky je vyhodnocena pravděpodobnost vzniku koroze, která je porovnána s návrhovou pravděpodobností.

Stochastický model na bázi metody SBRA využívající jako transformační model MKP může významně posloužit ke studiu vlivu jednotlivých vstupních proměnných na trvanlivost z hlediska rizika vzniku koroze. Z výsledků práce vyplývá, že rozptyl vstupních parametrů významně ovlivňuje trvanlivost mostovky. Nejzávažnější uvažovanou veličinou je difuzní součinitel. Dále se ukazuje, že kvalitně provedená epoxidová ochrana výztuže pozitivně ovlivňuje trvanlivost železobetnové desky.

Acknowledgments

I would like to take this opportunity to express my gratitude to the many people whose support, guidance, and assistance made the completion of this thesis possible. First, I owe my greatest gratitude to my wife Nika, my mother and my family for their continuous support and patience during my graduate studies.

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Professor Tikalsky, who hosted my research visit at Penn State, inspired me to write a thesis on the topic of stochastic bridge deck performance assessment. Professor Tikalsky originated the idea of Simulation-Based Reliability Assessment of reinforced concrete structures with respect to cracks and their interaction with epoxy-coated reinforcement. He gave me helpful advice throughout interesting consultations. It was also at PSU where I assisted Dave Tepke, Dr. Tikalsky's grad student. He also helped a great deal with my introduction to the field of durability of concrete with respect to corrosion through long lasting discussions.

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Content

Notation

C_0	effective concentration of soluble chloride ions [% by mass of total cementitious materials] at the surface directly inside the concrete
C_b	background chloride concentration [%]
cd	multiplicator for crack depth […]
$Crack_i$	relative crack position […]
$Crck_{de}$	crack depth [m]
$Crck_s$	crack spacing [m]
cs	multiplicator for crack spacing […]
C_{th}	chloride threshold [%]
$C_{x,t}$	concentration of chlorides [percent by mass of total cementitious materials] at depth x [m] after t [years] of exposure
$C_{xy,t}$	concentration of chlorides in the most exposed location of the reinforcement (especially in the defect of epoxy-coating) after t [years] of exposure
D	apparent diffusion coefficient [m^2/s]
dc	multiplicator for apparent diffusion coefficient of chlorides […]
D_c	apparent diffusion coefficient of chloride ions in concrete [$10^{-12} m^2/s$]
$Depth$	depth of slab [m]
m	multiplicator for holiday frequence […]
$Mash_i$	holiday position [m]
$Mash_{i,rel}$	relative holiday position […]
$Mash_n$	holiday frequence [m^{-1}]
$Mash_s$	holiday spacing [m]
N	number of terms in power series
$N_{Failure}$	number of Monte Carlo realization with detected failure (not meeting desired performance)
N_{sim}	necessary number of Monte Carlo simulations
N_{Total}	total number of Monte Carlo simulation steps
P_d	target probability [%]
P_{dt}	derived target probability [%] for lifespan t [years]
P_{dT}	target probability P_{dT} [%] for reference time T [years]
P_f	probability of corrosion initiation [%] or generally probability of failure
$P_{f,t}$	probability of corrosion initiation [%] in time t [years]
P_{target}	target precision of P_f [%]
Q	mass transport rate [kg/m^2s; mol/m^2s]
R	resistance, carrying capacity
R_{ebd}	rebar depth (cover) [m]
RF	reliability function

RF_t	reliability function in time t [years]
S	load effect combination
T	time, age of structure or time of exposure to chlorides [years], reference time [years], temperature [K, °C]
$t_{\mathrm{initiation}}$	period before the onset of corrosion [years]
$t_{\mathrm{propagation}}$	time for corrosion to reach an unacceptable damage level once it begun [years]
$t_{service}$	service life [years]
w/c	ratio between water and cementitious material
$width$	total width of FEM model [m]
$width_{\mathrm{e}}$	extension of the FEM model that mitigates the negative effect of the crack at the edge of the model [m]
$width_{\mathrm{u}}$	width of FEM model [m] that is studied
x	depth [m] (from the exposed surface)

Greek Symbols

β	index of reliability
λ	thermal conductivity
μ	average value
ρ	mass density
σ	standart deviation

Other Symbols

$x!$	factorial of x
$\frac{\partial()}{\partial t}$	partial derivative with respect to time t
$\frac{\partial()}{\partial x}$	partial derivative with respect to x
$\frac{\partial C}{\partial x}$	concentration gradient of the chloride ions
$\mathrm{P}(A)$	probability of event A

Model Variations

Cxyt	bridge deck with the effects of crack and epoxy-coating protection of reinforcement
Blackbar	bridge deck with the effects of crack and without protection of steel bar
Reference	bridge deck without cracks and without epoxy-coating
Analytic	bridge deck without cracks and without epoxy-coating computed using /9/

Note: Notation of symbols in Annexes are explained where the symbols are used.
Model type serves also as a subscript.

1. Introduction

The reliability of reinforced concrete bridge decks is in many cases governed by durability. Many structures require premature rehabilitation or replacement resulting from environmental deterioration. The balance between initial costs and the life-cycle costs plays important role. Reduced service life leads to increased life-cycle costs, thereby increasing the burden of funding on taxpayers. For the civil infrastructure of society, long-lasting structures are essential to optimize the public costs, maintenance requirements, functional interruptions, natural resources, and environmental sustainability. By accurately predicting deterioration, engineers can better design concrete mixtures and structural systems to resist degradation from long-term environmental and structural loads. The technology to predict the long-term durability of reinforced concrete bridge decks is, however, still developing.

While it seems obvious that structures should be constructed for long-life, the engineering methods needed to accomplish this goal are still under development. Designing durability into the civil infrastructure or industrial structures requires advanced knowledge of deterioration mechanisms, material science, properties and methods of production of construction materials, structural design, quality control, and construction methods.

Unfortunately currently implemented and recommended structural codes in Europe and the U.S. are generally prescriptive in nature, (MAREK et al., 1995, TEPLÝ, 2005a, GALAMBOS, 2006) even though there are attempts to formulate performance oriented codes (EN 206 (2000), ACI Committee 201 (2001) and ACI Committee 222 (2001)). These codes formulate rather suitable material and structural properties but do not explicitely state the level of reliability in the context of durability (TEPLÝ, 2005a, TIKALSKY, 2003). Design for specific service life and/or specific level of reliability necessarily requires the utilization of stochastic approaches, mathematical models and also simulation techniques (TEPLÝ, 2005a).

There is a demand for a function-oriented design approach that would take into account the target performance quality, e.g. required level of reliability, structural service life, optimization of life cycle costs, environmental consequences etc. Attention is turning to a relatively new trend in structural design called Performance-Based Design (see eg. TEPLÝ, et. al., 2002, HÁJEK, et. al., 2002). Performance-Based Design is, along with Life Cycle Assessment, Risk Engineering, Monitoring a part of so called “Integrated design” (see eg. www.cideas.cz).

Advance in Performance-Based Design may be illustrated in concrete industry by the preparation of performance related codes and specifications and innovative decision support tools such as specialized softwares Life 365 (see BENTZ&THOMAS, 2001), RC life span (see TEPLÝ et al., 2002), Eucon (see PAPADAKIS et al., 2006), FREET-D (www.freet.cz, MATESOVÁ, et. al., 2006).

Need for development in the performance-based, oriented structural design is appraised even by the U.S. Congress. The Congress addresses the chalenges of durability concerning bridges by creating the second Strategic Highway Research Program (SHRP 2 Request for Proposal, 2007). The proposal for the program, titled *Bridges for Service Life beyond 100 Years,* calls for consistent structural assessment that can address inherent randomness of variables involved in the design. These variables affect the performance (durability) of a structural element or system because the problems that must be evaluated are not deterministic in nature.

1.1 Bridge Decks from Reinforced Concrete

The durability of concrete bridge decks may be affected by acids, bases, freeze-thaw and wet-dry cycles, thermal cycles or gradients, carbonation, moisture (or lack thereof), UV light, sulfates, fatigue, and many other factors including cracking. Among the above-mentioned, corrosion is the most significant type of distress in many bridge decks. The corrosion of reinforced steel due to the ingress of chloride salts applied to melt snow and ice is a severe problem. Since the reinforced concrete is a composite material, mild steel is used to provide needed tensile properties and to control surface cracking. When reinforcement corrodes, the formation of rust leads to a loss of bonds between the steel and concrete and subsequent spalling and delamination. It impairs not only the appearance of the bridge deck, but also its strength and safety, due to the reduction in the cross-sectional area of the reinforcement, to the deterioration of bond with the surrounding concrete. Corrosion process promotes reduced reliability, thus leads to increased life-cycle costs.

Chlorides from the deicers will diffuse through concrete to the level of the steel reinforcement. They actually do not participate in any direct reaction with the steel, but rather promote localized corrosion (pitting) with a relatively high concentration (MODAK&GUPTA, 1999). Steel corrosion may also be induced by a process called carbonation of concrete. The carbonation is not covered in the text though.

Experience has shown that the uncoated mild reinforcment steel, also called black bar, needs more protection than concrete cover in order to avoid early corrosion. The solution was to separate the reinforcement from the aggressive environment.

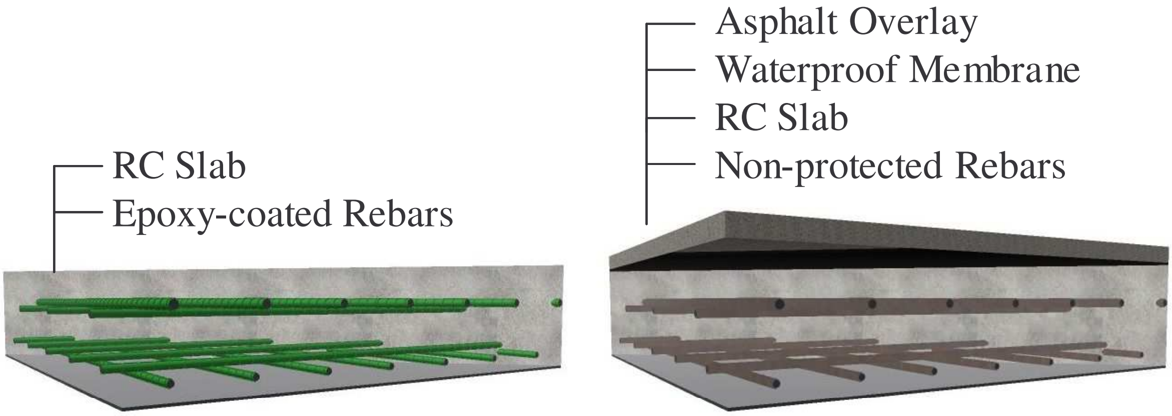

Figure 1: Scheme of Bridge Deck with Epoxy-coated Reinforcement in U.S. (left) and Deck with Asphalt Overlay on Top of Waterproof Barrier in Europe (right).

North America adopted the protective coating of reinforcement in wide scale, while the separation of concrete from the aggressive deicing agents by a water-proof membrane with asphalt overlay is the norm in Central Europe (see. Illustrative Figure 1). Both types of bridge decks in some parts of the U.S. as well as Central Europe allow for postponement of the onset of corrosion of steel reinforcement but suffers heavily from early deterioration caused by corrosion. Water proof membrane is intended to prevent the chloride ingress but the bridges still suffer from corrosion problems (DUBROVSKÝ, 2003). Reinforced concrete bridge decks in the U.S.A. do not use such systems to avoid creating half cell currents. Saturated concrete layers during freeze thaw conditions and reinforcement also corrode. Both systems have their respective advantages and drawbacks.

The investigation of the model for the prediction of bridge deck performance with respect to chloride ingress induced corrosion initiation is of particular interest herein because the understanding of the potential degradation mechanisms, life expectancy and the statistical potential that one variable will exceed the other is the key to prolong its durability. Durability of barriers and joist is not studied herein. The average bridge deck considered here would be reinforced concrete slab placed above presressed concrete girders, where composite action is being considered. The concrete of the slab is poured onto steel pans. The bridge deck is exposed directly to deicing agents and the reinforcement is protected by epoxy-coating. Such slabs can be found on bridges in some parts of the U.S.A. especially in the Northeast.

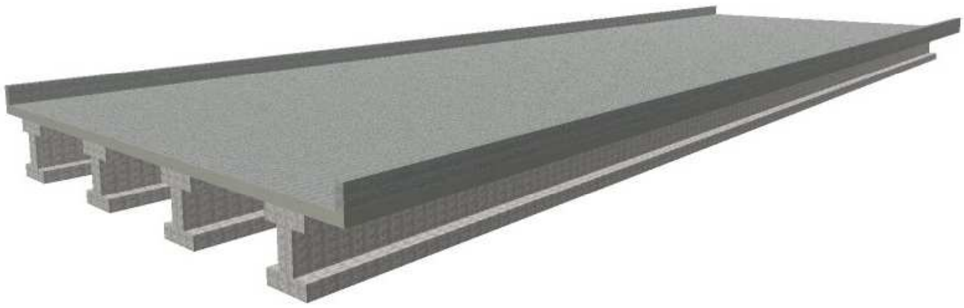

Figure 2: Reinforced Concrete Composite Bridge Deck with Pre-stressed Girders (Illustrative Scheme).

1.2 Effect of Cracks and Epoxy-Coating

The early degradation is caused in vast cases by the chloride induced corrosion. Since the bridge deck here has both roles, a structural one as well as of pavement, it is directly exposed to deicing agents. Thus the detrimental effect of cracking needs to be considered because the crack is likely to be a gate for deicing agent to enter to the rebar level much sooner.

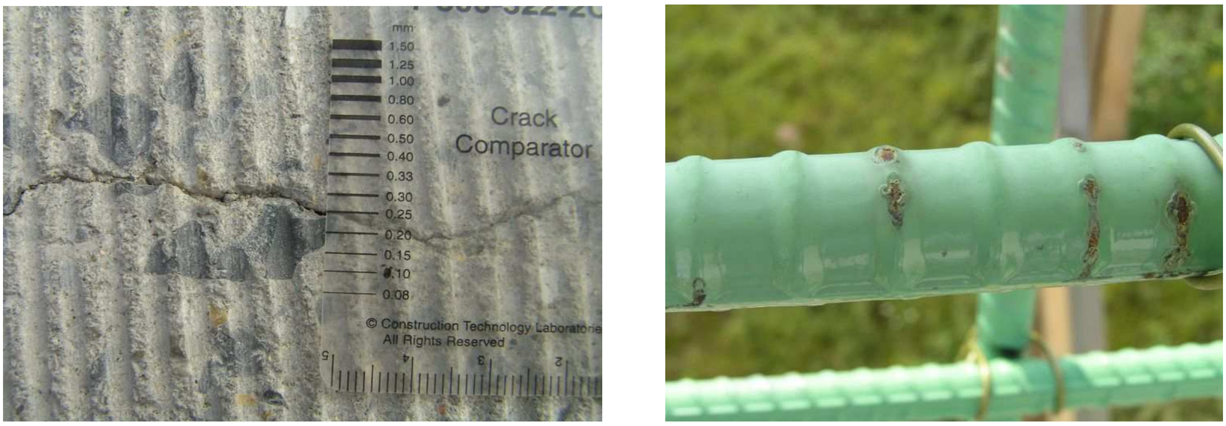

Figure 3: Crack on the Grinded Bridge Deck (left) and Scratched Epoxy-coating (right).

The initiation of corrosion depends on time and, among other properties, on the quality of epoxy-coating that is designed to seal the surface of the bar from any moisture, oxygen or corrosive elements. Epoxy-coated bar is simply normal "black bar" from mild steel, cleaned and painted with an epoxy coating. The protective effect of epoxy-coating may be damaged by mashed area, bare area, blister, and holiday (pinhole), and is widely discussed (BENJAMIN, et. al., 1990, SAGUES, et. al., 1990, AARSTEIN, et. al., 1998, BENTZ&THOMAS, 2001, WEYERS, et. al., 2002). The flaws in epoxy-coating are generally referred as holidays in the following text.

The idea of chloride ion entering through concrete and crack to the reinforcement level is showed next. If the epoxy-coating has holidays, these spots are the most prone to corrosion pitting.

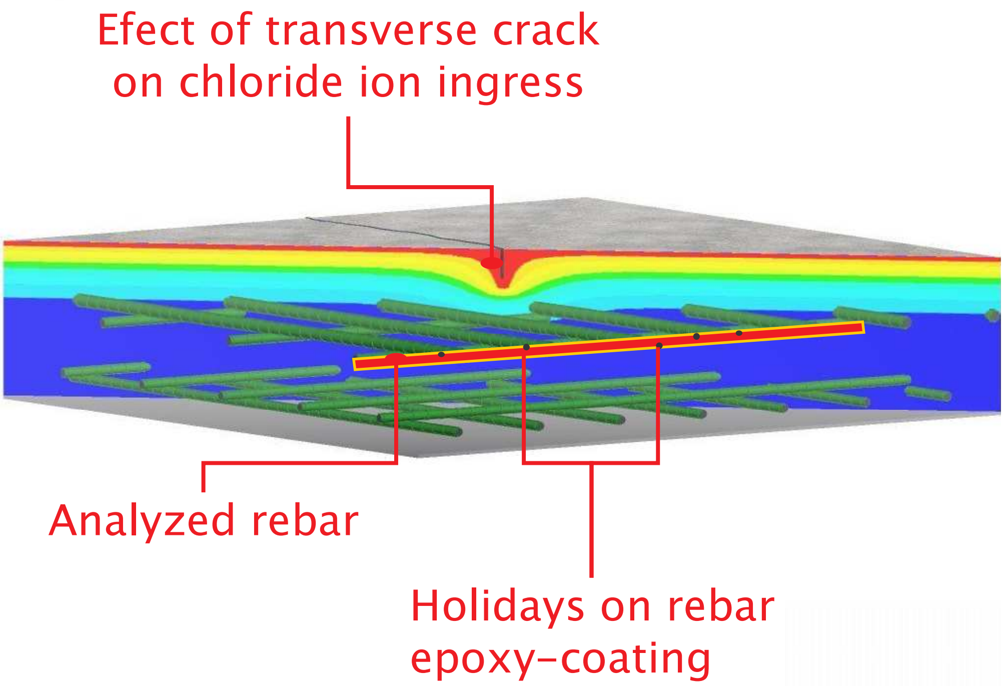

Figure 4: Chloride Ingress into Bridge Deck - Interaction of Crack Effect and the Position of Holiday (damage) in Epoxy-coated Reinforcing Bar.

The interesting question here is: "How does the crack position interact with the position of holiday in epoxy-coating throughout the time? Does the randomness influence the possibility of chlorides to get through crack into the holiday? Does random combination of crack and holiday position reduces the likelihood for corrosion initiation?"

1.3 Reliability Assessment of Bridge Deck

In order to answer the previous questions, the time-dependent stochastic reliability assessment needs to be applied. The safety, serviceability and durability of the bridge deck rely on many interrelated factors. The level of reliability changes with progress of corrosion – accumulation of damage.

Since the structural reliability criteria should be met from the very beginning, the problem of the corrosion of the reinforcement on the bridge deck and subsequent degradation is one of the most severe. Regarding the structural behaviour of the bridge, it is worth noting that the deck bears the compression, and the girder the tension, except of the negative moment regions (e.g. above middle pier in longitudinal direction with a two-span bridge). The steel reinforcement plays mainly the restraint role to control the cracking. It is protected from the exposure to aggressive agents by epoxy coating.

When considering the degradation of reinforced concrete bridge deck, the corrosion of reinforcement is the dominating effect in accumulation of damage. It is caused by the penetration of chlorides to the level of steel. The chlorides are applied as a deicing agents to melt snow. Life cycle of such structures $t_{service}$ can be quantified with regards to concrete corrosion into two phases, initiation and propagation (TUUTTI, 1982) as

$$t_{service} = t_{initiation} + t_{propagation} \qquad /1/$$

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, in case of chloride ingress, primarily influenced by the concrete diffusion characteristics, concrete cover, surface chloride concentration, temperature, level of saturation and the required concentration at the level of steel reinforcements to initiate corrosion.

The propagation period begins once a sufficient concentration of chlorides has reached the steel reinforcements to dissolve the passivation layer and initiate corrosion, and extends until the time when the structure needs repair, due to structural inability, material deterioration, or possibly even aesthetic concerns. A number of preconditions (MODAK&GUPTA, 1999) must exist for corrosion of steel embedded in concrete to occur:

- The provision of anode-cathode couple with at least part of the steel acting as an anode,
- The maintenance of an electrical circuit (difference in potential between the two sites),
- The presence of moisture,
- The presence of oxygen.

Rusting is described according to e.g. (MINDESS&YOUNG, 1981) as an electrochemical process that requires a flow of electrical current for the chemical corrosion reactions to proceed.

In the context of corrosion the following reference levels can be recognized (TEPLÝ, 2005a):

a) Depassivation of reinforcement due to chloride ion penetration,
b) Cracking,
c) Spalling of concrete cover,
d) Reduction of the effective reinforcement area (leading to excessive stres, deformation and finally to collapse).

Teplý in (2005a) sorts the above mentioned processes to appropriate reference level. Type a) and b) refers to serviceability. Type c) might fall in both categories, safety and serviceability, depending on the location and grade of degradation, and type d) is in safety (carrying capacity), and serviceability (deformations).

Depassivation of reinforcement (onset of corrosion) is a widely used reference value (KERŠNER, et. al., 1996, TIKALSKY, 2003, TEPLÝ et. al., 2005a, DAIGLE, 2005) even though it is rather conservative limit state. The reliability with respect to corrosion initiation is assessed using comparison of soluble chloride ions at the most exposed location of the rebar $C_{xy,t}$ and chloride threshold C_{th} over the considered life.

$$RF_t = C_{th} - C_{xy,t} \qquad /2/$$

1.3.1 Definition of Reliability

The definition of basic terms related to reliability and durability follows. Reliability is an ability of the structure to maintain desired function and properties over its lifespan. The structural reliability is characterized by an ability to perform without accidents, by durability, repairability, and maintainability. Safety, serviceability, and durability are parts of reliability. The reliability can be quantified by probability of failure. The "lack of reliability" represents certain probability that the failure can occur (TEPLÝ&NOVÁK, 1999).

Durability may be expressed as an ability of material, member, component and structural system to perform according to project throughout its designated lifespan under specified operational and environmental conditions with ordinary or assumed servicing.

The performance is another phenomenon along with safety and serviceability. The definition of Performance-Based Design (PBD) can be found e.g. in (AISC, 2005) It states that PBD is "An engineering approach to structural design that is based upon agreed-upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against those design goals and objectives using accepted engineering tools, methodologies and performance criteria." as is cited by GALAMBOS (2006). TEPLÝ in (2004) provides more comprehensive explanation and connects the idea of Performance-Based Design with:

- Declaration, maintaining, and evaluation of target performance as well as reliability of structures and its materials throughout their lifespan,
- Regards to inherent stochastic randomness of materials, loading (including environmental exposure), and effect of technology,
- Innovative approach that is not concentrated on the design stage, but also to construction

and service management.

The text focuses on one particular aspect of reliability. It focuses on the durability with respect to depassivation of reinforcement. Initiation period is over when depassivation occurs. It is considered here as an undesirable performance of a bridge deck. The reliability is considered as a maintained when no corrosion occurs although the probabilistic approach allows to study the level of reliability using the likelihood of corrosion initiation as a measure. The probability of corrosion is compared with target probability in order to assess the structure.

1.3.2 Degradation Model

There are a variety of degradation models in the world. Some require detailed materials data and some are more simplistic. The reliability of the models depends on the exposure, sensitivity to different variables and the predictability of variations in the material properties.

It is widely accepted that Fick's law of diffusion can represent the rate of chloride penetration into concrete to the level of steel reinforcements to initiate corrosion in bridge deck (e.g. HOOTON et. al., 2001), since the effects of hydraulic pressure and capillary absorption are minor in comparison in most cases and are neglected herein.

Diffusion occurs when a fluid containing chloride ions that are not homogeneously divided throughout the solution migrate from the place of higher concentration to the place of lower concentration until equilibrium is achieved (BAKKER, 1985). Under steady-state conditions, the rate of diffusion is expressed by Fick's first law as:

$$Q = -D\frac{\partial C}{\partial x} \qquad /3/$$

Where:

Q Mass transport rate [kg/m^2s; mol/m^2s],

D Diffusion coefficient [m^2/s],

$\frac{\partial C}{\partial x}$ Concentration gradient of the chloride ions [kg/m^4; or mol/m^4].

Since steady-state conditions on the bridge deck can be generally achieved only after uniform distribution of chloride ions throughout the deck, the diffusion coefficient for non-steady conditions (i.e., when concentration gradients are changing) is determined by Fick's second law, see Equation /4/.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad /4/$$

Where are

C	Ionic concentration [%, kg/m^3, mol/m^3],
t	Time [years],
D	Diffusion coefficient [m^2/s] ,
x	Depth [m] (from the exposed surface).

It is possible to solve this problem using analytical or numerical models. Both have its advantages and setbacks. The analytical solution, which is referred to as the Crank Solution, of the governing differential equation /4/ is given as Equation /5/, considering following boundary conditions:

$C_{(x = 0,\, t > 0)} = C_0$	(Constant surface concentration at C_0),
$C_{(x > 0,\, t = 0)} = 0$	(Initial concentration in concrete is 0),
$C_{(x = \infty,\, t > 0)} = 0$	(Concentration is 0 at a point far enough away from the surface),

It was applied to diffusion of chloride through concrete by COLLEPARDI et al., (1972).

$$C_{x,t} = C_0\left\{1 - erf\left(\frac{x}{\sqrt{4\mathrm{D}_c t}}\right)\right\} \qquad /5/$$

where

$C_{x,t}$	Concentration of chlorides [percent by mass of total cementitious materials] at time t [years] and depth x [meters],
C_0	Concentration of chlorides [% by mass of total cementitious materials] at the surface directly inside the concrete,
D_c	Apparent diffusion coefficient of chloride ions in concrete [m^2/year].

The main weaknesses of the models based on plain diffusion represented by crank solution /5/ is, according to (ČERNÝ et. al., 2004), the assumption of the constant diffusion coefficient and the fact that it neglects the influence of water transport on the transport of chemical compounds. As a consequence, a single value of the diffusion coefficient can never be obtained from the measured concentration profiles, particularly if the measurements are performed over longer time periods. The diffusion coefficient then appears as a function of time. (ROVNANÍKOVÁ, et al.,2002 and

ČERNÝ et. al., 2004) suggest to consider coupled water and chloride transport in cement-based materials in order to avoid the above mentioned drawback of the models similar to Equation /5/.

Some authors consider surface diffusion constant and chloride concentration to be time dependent. (COSTA&APPLETON, 1999) considers time for chloride concentration buildup from zero to C_0 by linear function. (BENTZ&THOMAS, 2001) characterizes the chloride diffusion coefficient D_c as function of both time $D_{(t)}$ and temperature $D_{(T)}$.

Nevertheless, Fick's second law /4/ proved to be useful in many practical applications because the calculated diffusion coefficients have at least a relative value, i.e. it is possible to compare diffusion coefficients in different types of concrete and different environments. It is also promising with respect to probability-based approaches.

Though models for chloride ingress, carbonation and corrosion development have been studied (see e.g. COLLEPARDI et al., 1972, PAPADAKIS et al., 1992, PAPADAKIS et al., 1996, BODDY et al., 1999, COSTA&APPLETON, 1999, ALISA et al., 1999, ŠMERDA et al., 1999, PAPADAKIS, 2000, BENTZ&THOMAS, 2001, PAPADAKIS&EFSTATHIOU, 2006 including those from the probabilistic standpoint (KERŠNER et. al., 1996, ZEMAJTIS, 1998, TEPLÝ et al., 1999, TEPLÝ&NOVÁK, 1999, KIRKPATRICK, 2001, TIKALSKY, 2003, DAIGLE et al., 2004, TIKALSKY, et. al., 2005, THOFT-CHRISTENSEN, 2005, MATESOVÁ et. al., 2005, TEPLÝ et al., 2005a, MATESOVÁ&TEPLÝ, 2006), 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.

1.3.3 Simulation-Based Reliability Assessment

SBRA (Simulation-Based Reliability Assessment) method developed in the late eighties by Pavel MAREK and Milan GUŠTAR (1988) is a modern simulation tool (MAREK et. al., 1995, 2001, 2003) that can be used to predict the behavior of a structural element in a deleterious environment, as documented in (BRADÁČ & MAREK, 1999, KOROUŠ & MAREK, 2002, TIKALSKY, 2003) and thus evaluates performance-based criteria.

It is based on the limit states philosophy evaluating random interaction of load effects *S* and resistance *R*. The chloride concentration at the level of reinforcement C_{xy} represents the load effect *S* while the chloride threshold C_{th} represents the resistance *R*. Reliability function can be written then as:

$$RF = R - S = C_{th} - C_{xy} \qquad /6/.$$

Reliability function *RF=R-S* is analyzed using Monte Carlo techniques and random variables can be described by bounded histogram as well as continuous distributions. Measure of reliability (reliability level) is expressed by probability of failure P_f .

$$P_f = P(R - S < 0) = P(RF < 0) \qquad /7/$$

Probabilities of failure are suitable input values for Performance-Based Design as well as other branches of the Integrated Design of structures especially for Life Cycle Assessment or Risk Engineering (HÁJEK, et. al., 2002, TEPLÝ, 2005c).

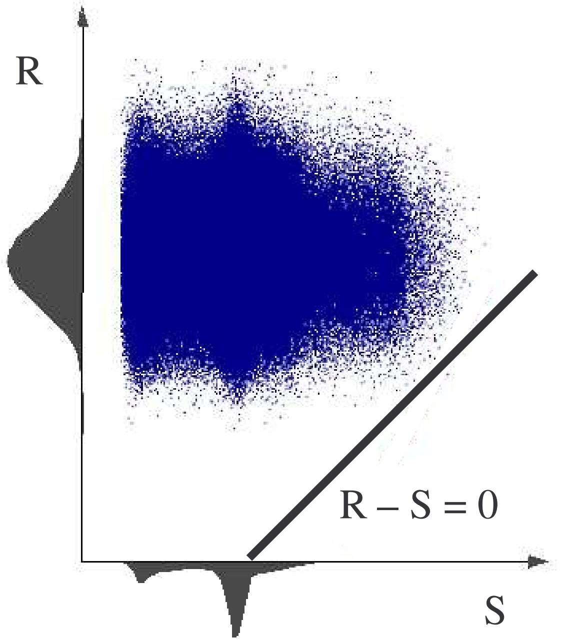

Figure 5: "Relationship" of the Load Effect S and Resistance R

The basic fundament can be explained using Figure 5 that presents results of Monte Carlo simulation. There is interaction of resistance *R* (vertical axis) and load effect combination *S* (horizontal axis) in the 2-D graph, called "anthill". Dots represent reasonably sufficient number of resistance *R* and load effect *S* combinations. Each dot in anthill, which is divided by line *R-S=0* into a safe and an unsafe domain, is one random realization (one simulation step). The ratio between the number of unreliable realization and total number of realizations is probability of failure P_f.

$$P_f = \frac{N_{Failure}}{N_{Total}} < P_d \qquad /8/$$

The reliability assessment consists of comparison of probability of failure P_f with target probability P_d. The acceptance of the performance (target probability of failure P_d) may depend on multiple criteria over the life of the structure. Performance criteria may be based on the prescription in codes as well as based on the negotiation between client, designer and specialist in the field. The performance requirements should be set at a level that is clear to the client and realistic to the contractor.

TIKALSKY (2003) discusses the target probabilities and states the probability that the structure will perform for 50 years at 3:4 (respective P_d would be 25 %) and the probability that the structure will perform for 100 years is 1:2. TEPLÝ (2005a) discusses the P_d for the corrosion imitation according to EN1990 and recommended value of the target probability for serviceability (irreversible state) as $P_d = 7\%$. It is relevant to a 50 year life span. The value of target probability P_d can be derived for particular desired lifespan from basic figures according to e.g. KMEŤ (2005).

The question of the suitable target value for the corrosion initiation depends also on the severness of the corrosion process. If the corrosion process is fast and the structure deteriorates quickly then strict target value shall be applied while if the corrosion process is slower than the target P_d may be more liberal. The other possibility is to adopt P_d for particular performance and project according to results of the life cycle assessment.

The SBRA applies available simulation tools such us Monte Carlo simulation in order to perform probabilistic analysis of clearly defined reference values. The reliability of bridge deck with respect to corrosion is expressed as a time-dependent probability of corrosion initiation $P_{f,t}$ that has to be compared to desired performance P_d.

Analysis of chloride induced reinforcement corrosion represents an analogy between loading and exposure to chemicals or environmental conditions, along with an analogy of resistance and ability to withstand a time-dependent chemical attack in the example of a bridge deck, as discussed in (TIKALSKY, 2002). Deicing salts present load-causing chlorides which penetrate concrete starting corrosion when sufficient amount of chlorides accumulates at the level of reinforcement where moisture and oxygen are present.

Time-dependent stochastic performance analysis can be thought of as a comparison of the joining extrema of the random variable load effect expressed as chloride concentration C_{xt} and chloride threshold C_{th} in case of the bridge deck. Once the probability that the load effect (chloride concentration at the steel reinforcements level) exceeds the resistance (threshold) by a user-defined amount, the desired performance is no longer met (corrosion is assumed to begin). Figure 6 displays this concept.

Time-dependent reliability of bridge deck with respect to corrosion initiation and inherent randomness of input variables is a field for the Simulation-Based Reliability Assessment (SBRA, see TIKALSKY, 2003). The assessment of corrosion initiation in case of bridge deck with crack and holidays in epoxy-coating requires more comprehensive transformation model, preferably a 2-D finite element analysis for diffusion model.

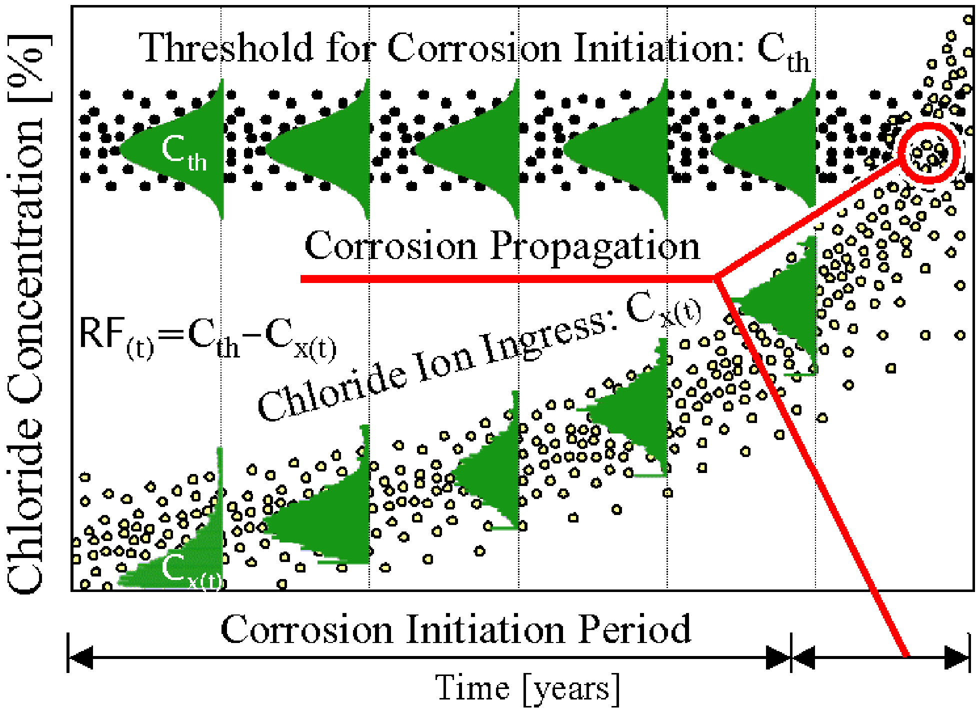

Figure 6: Time-Dependent Probabilistic Reliability Analysis Idea, Chloride Ion Concentration vs. Chloride Threshold.

The utilization of the Finite Element Model (FEM) in the Simulation-Based Reliability Assessment (MAREK et al., 1995, 2003) is a rather complicated task and represents a challenge itself. There were three promising ways considered to integrated available FEM system in the SBRA framework. The first way uses an external program to generate the file containing all random numbers realization. The pre-generated samples are pulled by the FEM system that reads the particular variable set for each finite element analysis. This procedure was used in (KRÁLIK&VARGA, 2004, 2005).

The second alternative is seamless integration of the Monte Carlo simulation tool and FEM system. Such approach represents eg. Matlab-based integration of the PRAKS's simulation tool in combination with freeware FEM package CALFEM (http://www.byggmek.lth.se/calfem/) applied e.g. in (PRAKS, 2006), or SBRA Module programmed as a plug-in to ANSYS (KONEČNÝ&MAREK, 2006).

The other possibilities are creation of a stand-alone program for the probabilistic analysis and FEM solution (e.g. KALA, 2003, KŘIVÝ et. al., 2006), or programming of the simulation-based reliability assessment software that can perform Monte Carlo as well as incorporate the FEM transformation model in the form of an executable external library (e.g. DLL under MS Windows operating system). Similar approaches represent e.g. FREET (NOVÁK, et al., 2003) and more recently the program MONTE (see MATERNA et. al., 2006).

2. Objectives of Thesis

The thesis indicates the road map to formulation of the probabilistic corrosion initiation model of a typical reinforced concrete bridge deck with steel reinforcement protected by epoxy-coating using SBRA method with respect to chloride ingress, and random interaction of crack position and holiday in epoxy-coating.

Since the topic of concrete durability assessment is of a complex nature, the emphasis of this thesis is also put on the advancement in the Simulation-Based Reliability Assessment method (SBRA) approach for durability assessment of concrete structures. Research is aimed especially on:

- Evaluating the possibility of performance assessment of the reliability of the reinforced concrete bridge deck using SBRA method. The performance of the bridge deck is rated based on the initiation of corrosion estimation.
- Time-dependent evaluation of the random interaction of input variables involved in the durability of the bridge decks with epoxy-coated reinforcement typical for northeastern U.S., especially crack spacing and reinforcement protection damage.
- Performing the sensitive analysis of variables that most influence the corrosion initiation process in order to postpone it.
- Development of the 2-D diffusion model that can address the crack effect.
- Development of the software tool for the seamless combination of the commercially available FEM software and the SBRA method.

2.1 Scope of Thesis

The basics of probabilistic simulation are introduced on the example of 1-D problem of chloride induced corrosion problem. The example is addressing reliability of reinforced concrete bridge deck with respect to chloride exposure as a chemical loading and corrosion initiation as the reference value. It is in the section 3 *Road Map to Performance-Based Design of Concrete Bridge Decks*.

The main chapter 4 *SBRA Model of Bridge Deck with Crack and Epoxy-coated Reinforcement* discusses and evaluates the performance of the structure based on the probability of corrosion initiation on the bridge deck with crack and epoxy-coating protection of the reinforcement. The discussed model also allows us to compare the performance of epoxy-coating with the behaviour of the black bar. The main emphasis is put on the stochastic evaluation of the epoxy-coated reinforcement of the bridge deck with respect to chloride ingress induced corrosion. The study is based on the field data from approximately 240 cores taken from 77 bridge spans in the northeastern U.S.A, as well as on the engineering judgment where sufficient data were not available. Subsection 4.1 provides an overview of input parameters. In part 4.2 a short introduction to transformation model is made. It describes interconnection of SBRA and applied FEM system ANSYS with respect to histogram-based random variables. Part 4.2 also contains the introduction 2-D FEM model. Monte Carlo simulation is discussed in the part 4.3. Comprehensive results of the SBRA analysis are shown in the subsection 4.4 with the plot of time-dependent probability of corrosion initiation, followed by short summary 4.5.

Section 5 *Parametric Study* discuses the influence of diffusion constant, holiday frequency, crack spacing and crack depth on the durability of reinforced concrete bridge deck in more depth. The findings are discussed at the end of the Section 5. The summary of the thesis along with conclusions, recommendations for future research, and references closes the main part of the thesis. The references are divided to three parts. It consists of the part Codes and Specifications, Literature and references of author that are related to the discussed topic.

The Annex A contains the description of FEM macro for 2-D diffusion of chloride in the bridge deck with crack and epoxy-coating flaws considered. Subsection A.3 *Deterministic Solution* presents deterministic evaluation of 2-D chloride ingress model followed by the results of analysis with alternate inputs. The description of the SBRA Module follows in the Annex B. The record files of the considered deterministic as well as stochastic performance analysis are included in the enclosed DVD-ROM along with respective input files for stochastic analysis performed in ANSYS environment.

3. Road Map to Performance-Based Design of Concrete Bridge Decks

This chapter pays attention to the procedure of the performance assessment of reinforced concrete bridge deck with respect to chloride ion ingress. 1-D performance analysis of corrosion initiation likelihood on the ideal bridge deck without crack and with unprotected steel is performed here according to TIKALSKY (2003). It is presented here for better understanding of Performance-Based Assessment using SBRA and as introduction to the 2-D problem of epoxy-coating holidays and crack interaction assessment.

3.1 Random Input Variables

Using SBRA method requires that information be compiled and statistically analyzed to understand the variations and effects of different variables. SBRA techniques use the probabilistic distributions of the properties to characterize the statistical variation of involved variables. Description of input variables is a first step in performance assessment. Variable input values that characterize loading, geometry, material properties or exposure could be represented according to the SBRA method either by variable bounded histogram (i.e. non-parametric distributions) or parametric continuous distributions.

Random variables consist of one component (e.g. onset of yielding of steel), or may be multi-component (e.g. wind rosette that consists of wind direction distribution and wind speed distributions for twelve directions, (NĚMEC&MAREK, 2000, and for application see KONEČNÝ, 2001). Variables can be uncorrelated (material density and live load action), has a certain degree of correlation (compression and tensile strength of concrete), or may correlate (material density and dead load).

Background for input variable modeling could be based on the statistical analysis of experimental data from the field or laboratory measurements, on the literature review, on the codes or on the engineering estimation.

3.1.1 Surface Chloride Concentration

Loading may be expressed in terms of forces, moments as well as environmental exposure (e.g. deicing agents in case of bridge deck) serving as input for the combination of load effects. Each individual load is usually characterized by so called Load Duration Curve (LDC) introduced in SBRA method, and described in (MAREK et al., 1995). The load duration curve LDC (and respective histogram) is a suitable way to describe loading action. Unaccustomed loading representation, and respective load-effects representation open the way to a more balanced load effect combination evaluation both for one single and multi-component loadings (see e.g. MAREK et. al., 1999), as compared to current codified approach.

The chemical effects of the environment that surround the structure generally provide time-dependent degradation of material properties or loss of desired structural performance may be recognized as a loading. Thus chloride ion concentration at the surface of the concrete bridge deck can be considered loading. Initial top surface chloride concentration, the diffusion driver, C_0 is considered a constant with value 0.6 percent (by mass of total cementitious materials) of soluble chloride ions here.

3.1.2 Diffusion Coefficient

One of the most important variables in the studied area is diffusion constant that represents the rate for chloride ion penetration through concrete. Figure 7 shows a typical histogram of the diffusion constant for concrete designed, produced and placed under a single concrete specification by many different contractors, according to (SOHANGHPURWALA et al., 1998).

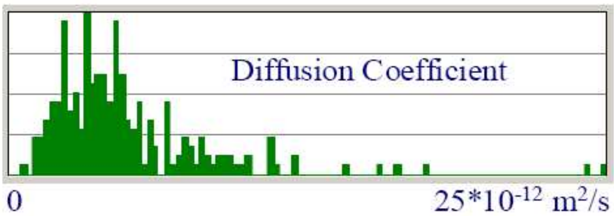

Figure 7: Histogram of Diffusion Coefficient (SOHANGHPURWALA et al., 1998).

3.1.3 Concrete Cover

The depth of concrete cover over the reinforcement plays an important role in the process of corrosion initiation. Figure 8 is a histogram of the depth of cover, according to (SOHANGHPURWALA et al., 1998).

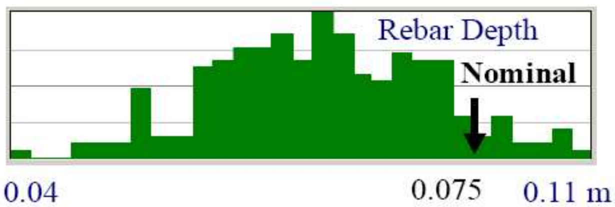

Figure 8: Histogram of Concrete Cover (SOHANGHPURWALA et al., 1998).

3.1.4 Chloride Threshold

The concentration of chlorides at the reinforcement level sufficient to start corrosion is represented as chloride threshold C_{th}. This is a more random variable, as compared to (TIKALSKY, 2003). The adopted distribution is normal $N(\mu,\sigma)=N(0.3,{}^{1}/_{3})$ that lies within range <0.2;0.4> percent.

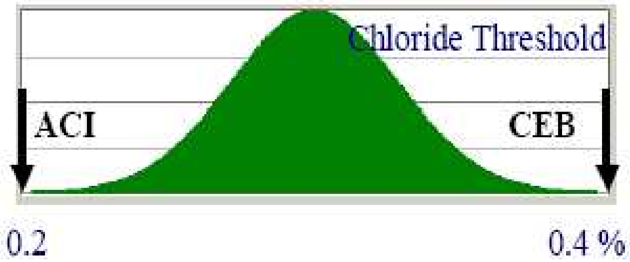

Figure 9: Histogram of Chloride Threshold Distribution C_{th} [%].

3.2 Transformation Model

Transformation models serve as an approximation of real structural behavior with precision sufficient for evaluation of structural response to the loading. Selection of transformation model should reflect uniqueness of the design situation and thus depend on the character of loading acting on the material properties, on the geometry, on the reliability criterion, and on the importance of the structure.

Transformation models serve for the calculation of the response of the structure to the loading that is a primary dominant factor governing reliability assessment. Load effect *S* is usually expressed in structural design as a stress, forces etc. It can be expressed, though, as a concentration of chlorides C_x at the level of steel reinforcements. It is a time-dependent response to the chemical loading in the example of bridge deck performance assessment computed using next formula. It is derived from the error function in the Crank solution /5/ that can be expressed using the power series. It yields in the following formula

$$C_{x,t} = C_0 \left\{ 1 - \frac{2}{\sqrt{\pi}} \sum_{n=0}^{14} \frac{(-1)^n \left(\dfrac{x}{\sqrt{4D_c t}} \right)^{2n+1}}{n!\,(2n+1)} \right\} \qquad /9/,$$

That, according to TIKALSKY in (2003), gives an error less then 0.001 for values of *x* between 0 and 1 meter, diffusion coefficient D_c between $1x10^{-8}$ and $1x10^{-14}$ m^2/s and life span ranging from 0 to 100 years with 14 terms in the series.

Equation /9/ is widely used for chloride ingress models. It is feasible for probabilistic approach that utilize Monte Carlo simulation tool but since it is a 1D model it does not account for cracks, and must be also modified to account for time dependent changes in material property or boundary conditions.

3.3 SBRA Analysis

The probabilistic SBRA analysis is performed using the *Matlab* (www.matlab.com) based Monte Carlo simulation tool. The core of the tool is programmed by PRAKS (2006). One hundred thousand simulation steps are applied here. The Monte Carlo analysis selects random values according to specified probabilistic distributions in each of the simulation cycles and performes chloride concentration analysis.

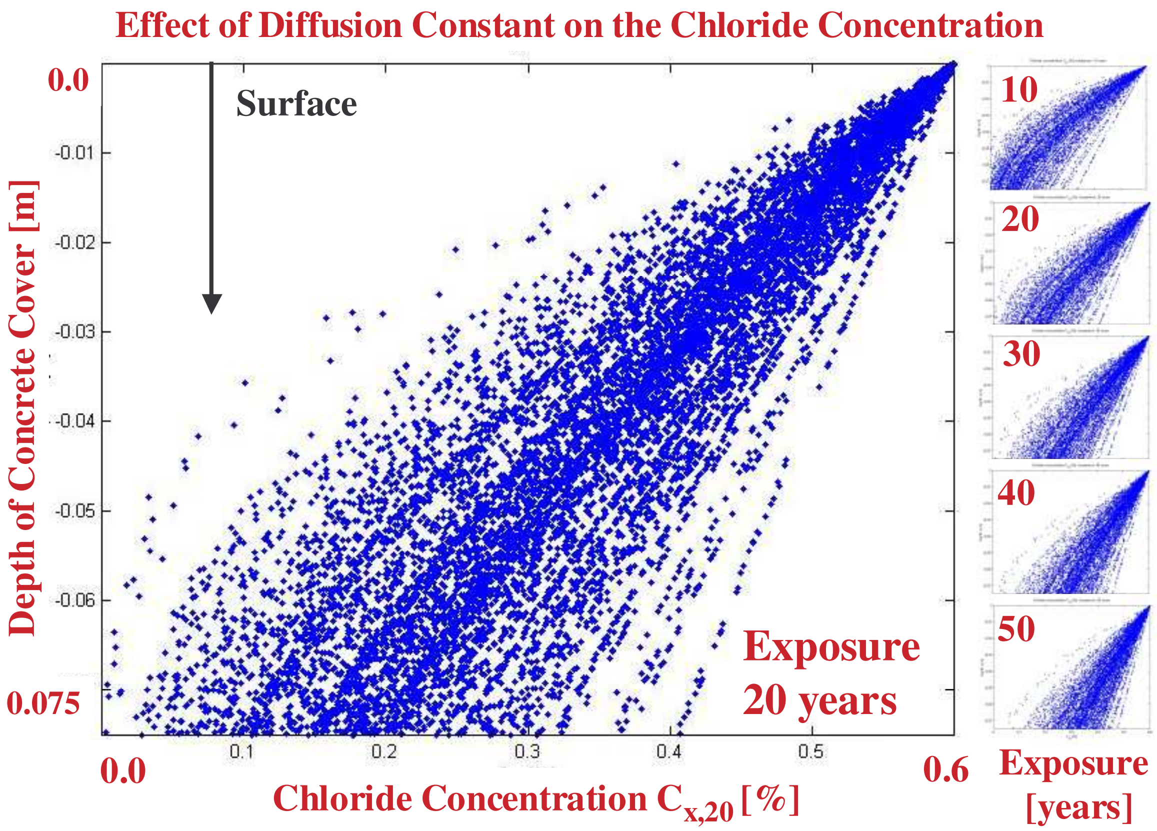

Figure 10: Effect of Variation of Diffusion Constant on Chloride Penetration (exposure 20 years – left, exposure 10, 20, …, 50 years - thumbnails)

The effect of the variation in diffusion constant on the ingress of chlorides is shown in Figure 10. The concentration of chloride is a function of time and depth using random values of the histogram shown in the Figure 7. Computing Equation /9/ thousand times using Monte Carlo simulation technique leads to statistically distributed solution. Each dot on the figure refers to an individual solution to the problem for a given depth and time.

3.3.1 Chloride Concentration at the Level of Reinforcement

The chloride concentration at the level of reinforcement represents load effects. The histograms for the chloride ion concentration at the reinforcement level $C_{x,t}$ are shown on the next Figure 11. The chloride concentration is computed for the exposure 10, 20, 30, 40, and 50 years.

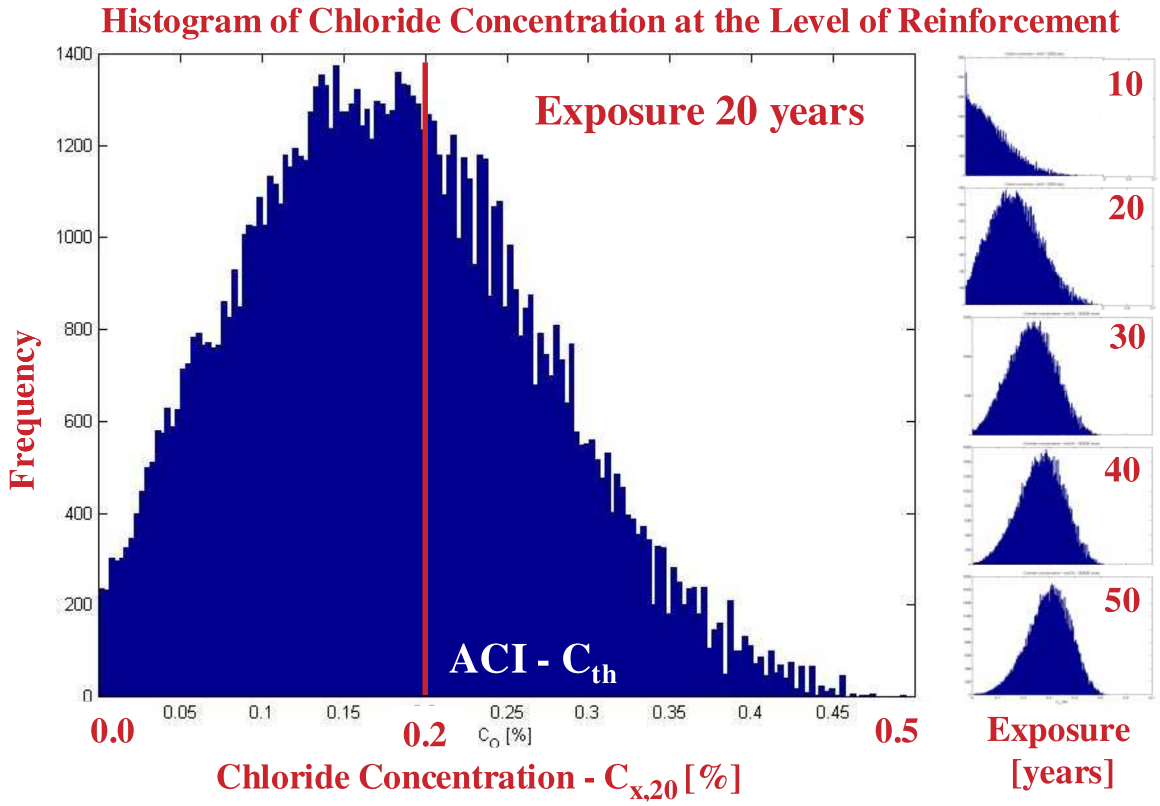

Figure 11: Histograms of Chloride Concentration $C_{x,t}$ [percent] at Rebar Level (exposure 20 years – left, exposure 10, 20, …, 50 years - thumbnails)

3.3.2 Definition of Reference Function

Reference function (value) R represents the second important factor in the reliability assessment as well as in the performance check. It serves for the definition of resistance against load effects. It can be the carrying capacity of the respective material or chloride ion threshold C_{th}. It is based on the available statistical data, experiments, estimations, calibration, and agreement between designer, responsible authority, and contractor.

Reference function, also referred to as limit state, is defined as a depassivation of the steel reinforcements (corrosion initiation). Frequently the depassivation of steel reinforcements due to chloride ingress is considered conservatively as a limiting condition. This condition is considered that “the time to depassivation = initiation period → undesirable performance”. In other words, at this stage the reinforcement is no longer secure against corrosion. Under the condition of the presence of a certain level of moisture and oxygen in concrete, corrosion starts.

Previously, Figure 11 showed the reference as constant to give an idea of corrosion likelihood estimation, although next a truncated normal distribution as reference function for the chloride threshold is applied (see Figure 9).

The visual demonstration of the time-dependent chloride ingress is shown in Figure 12 where each dot represents one combination of random variables in particular time. Blue dots represent chloride concentration at the rebar level for selected time while red dots represent a chloride threshold realization. Blue dots above the stream of red dots generally symbolize simulation where corrosion started.

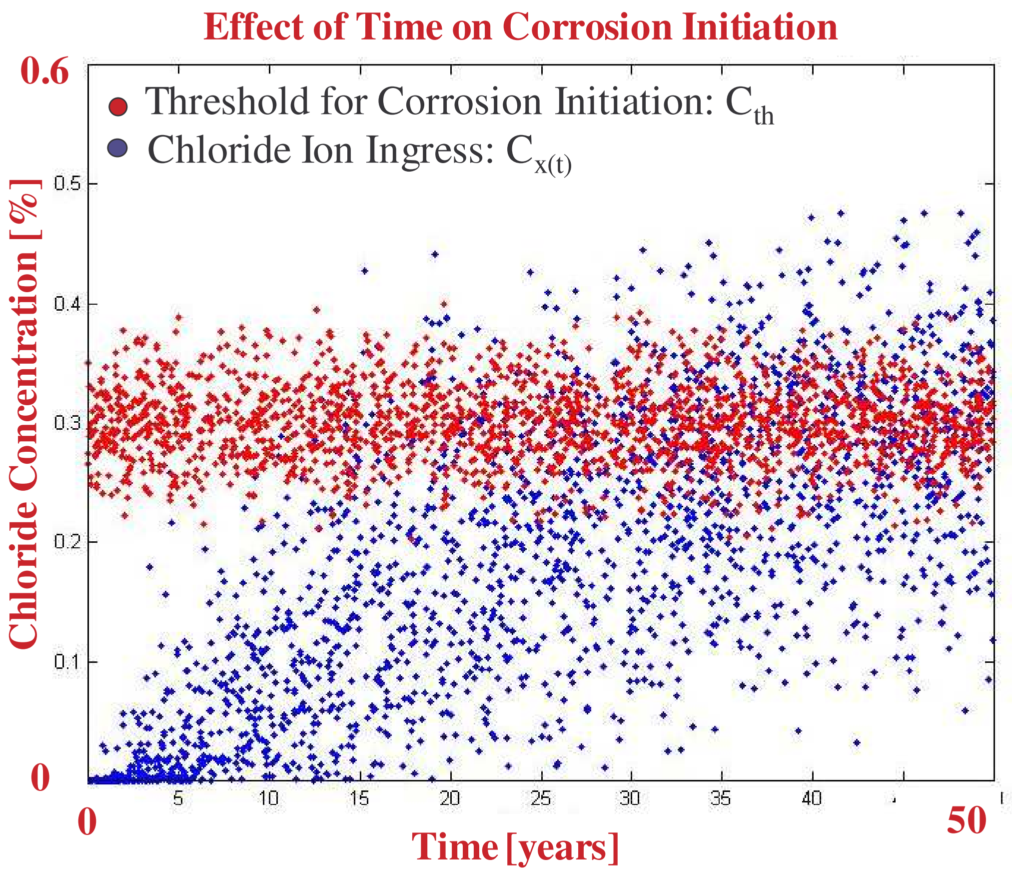

Figure 12: Effect of Time on the Scatter of Chloride Concentrations $C_{x,t}$ (blue dots) vs. Chloride Threshold C_{th} (red dots), Exposure Time up to 50 years (variable $D_{c,}$, cover, C_{th})

3.4 Reliability Assessment

The reliability function $RF = C_{th} - C_{x,t}$ where C_{th} is the resistance described by chloride threshold and $C_{x,t}$ concentration of chlorides at the reinforcing level in age t. Probability of corrosion is computed next as a probability of chlorides exceeding the threshold. The result for the 20 years exposure is indicated next:

$$P_f = P(RF < 0) = P(C_{th} - C_{x,t} < 0) = 10.7\ \% \qquad /10/$$

Statistical evaluations of reliability assessment computed for the exposure 10, 20, 30, 40, and 50 years with respective histograms and probabilities of corrosion initiation are shown in Figure 13. Histograms are divided into two domains where boundary equals to zero. Left part of histograms represents the cases where corrosion started while the right part represents the case without corrosion.

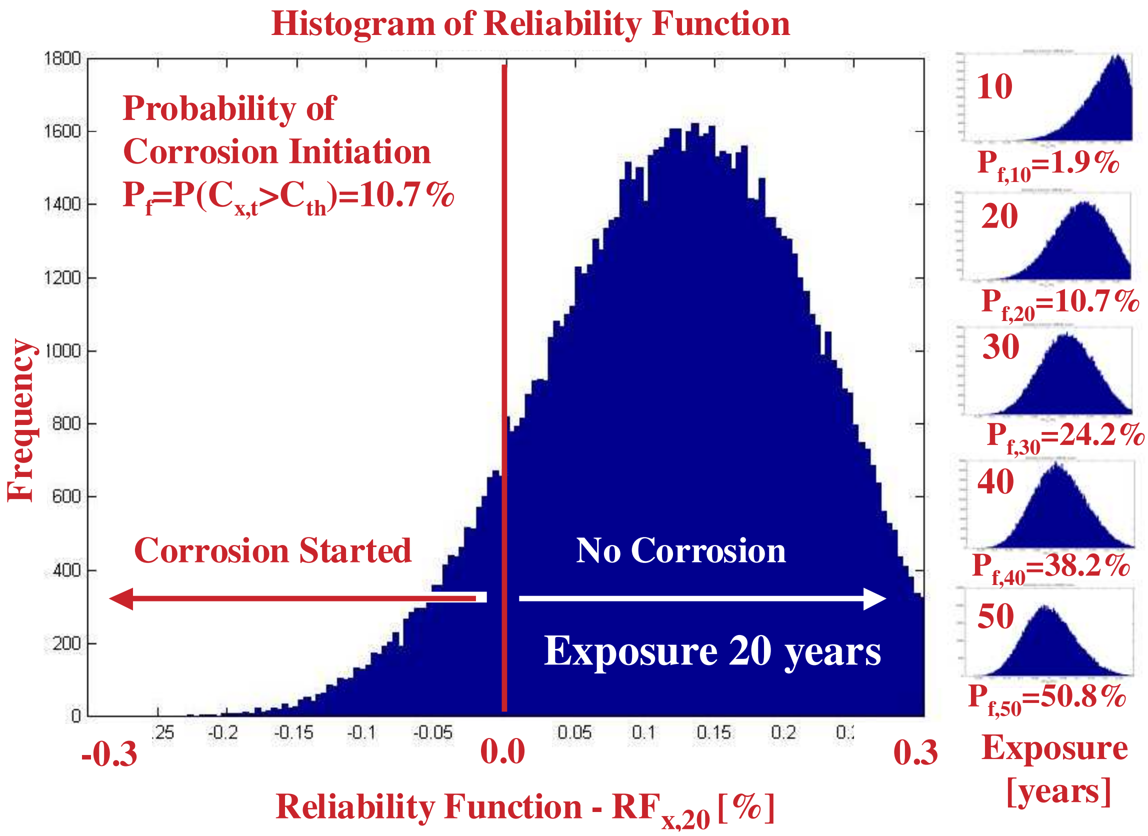

Figure 13: Histograms of Reliaility Function RF_t [percent]
(exposure 20 years – left, exposure 10, 20, …, 50 years - thumbnails)

The reliability is evaluated by comparison of probability of failure P_f with target probability P_d given in codes, or resulted from risk engineering procedures (see e.g. VAŇURA, et. al., 2003).

Desired performance or reliability level is met if following criterion is met:

$$P_f = P(RF < 0) \leq P_d \qquad /11/.$$

3.4.1 Target Probability

The level of the target probabilities for the specific performance may be much higher than in case of the ultimate limit state. It can be, according to (TIKALSKY, 2003) in order of tens of percents if considering corrosion initiation. The target probability for 50 years of service would be $P_{d,50} = 25\%$ or $P_{d,100} = 50\%$ for 100 years (TIKALSKY, 2003). (TEPLÝ et. al., 2005a) discusses a more conservative value if referring to corrosion initiation likelihood that is based on the serviceability criterion EN1990 for the corrosion initiation. It is $P_{d,50} = 7\%$ for the 50 years of service. The target value of P_d in case of corrosion initiation should reflect the speed of corrosion progress. The faster corrosion is, more strict the target probability of failure should be.

The design values of probability of failure of index of reliability, though codified e.g. in EN1990, are still a matter of scientific discussions. These values can be also requested by client or can be obtained from the assessment of life cycle costs etc..

Considering the value of target probability P_{dt} as a time-dependent value. It can be described according to Equation /12/ (KMEŤ, 2005):

$$P_{dt} = 1 - (1 - P_{dT})^{\frac{t}{T_d}} \quad \text{for} \quad t < T \qquad /12/.$$

Where target probability P_{dt} for lifespan t depends on the target probability P_{dT} in given time T.

3.5 Durability Assessment

The key issue in durability assessment is a comparison of computed likelihood of corrosion initiation $P_{f,t}$ with target probability P_d as indicated next. The probability of corrosion initiation is computed in consecutive time intervals as can be seen in Figure 13. The resulting probabilities of failure are summarized also in Table 1.

$$P_{f,t} \leq P_d \qquad /13/$$

Designed reliability and performance levels should be maintained throughout the intended service life. The reliability check is performed in consecutive time intervals, with time-dependent probabilities of corrosion initiation $P_{f,t}$ as well as with target one $P_{d,t} = 25\ \%$ according to (TIKALSKY, 2003) for 50-year life-span.

3.6 Results

The results are summarized in the following table along with information when corrosion started.

Table 1: Probabilities of Corrosion Initiation with Variable Cover and Diffusion Constant.

Exposure [years]	*10*	*20*	*30*	*40*	*50*
P_f [%]	1.9	10.7	24.2	38.2	50.8
P_d [%]			25		
Corrosion Initiated	NO	NO	NO	YES	YES

The desired performance of the bridge deck would be satisfied for slightly more than 30 years service. The corrosion did not start in more than 25 percent Monte Carlo simulations during the first 30 years. It can be also seen in the next figure. Both table and figure compare the probability of corrosion initiation with target probability.

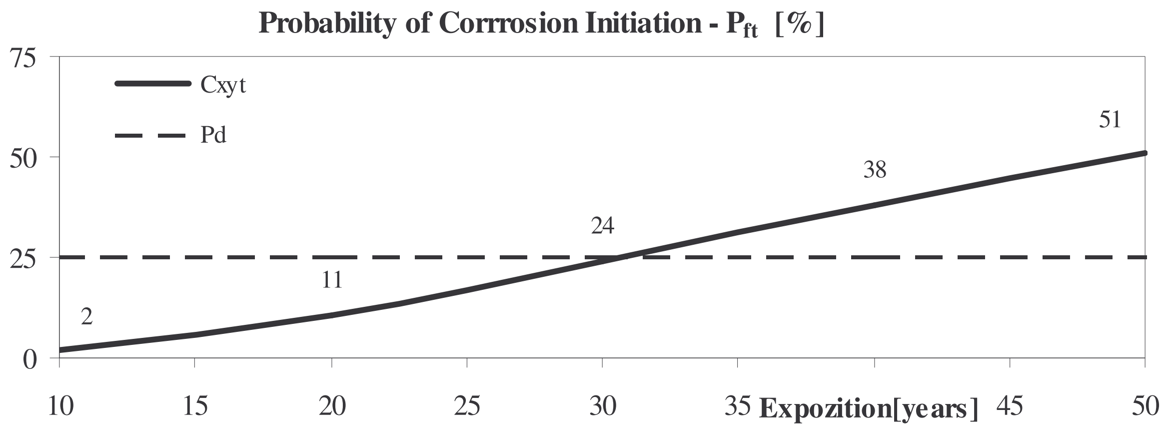

Figure 14: Probability of Corrosion Initiation $P_{f,t}$ vs. Target Probabilities P_d.

3.7 Summary

The simulation tool is used in the presented example to estimate the probability of corrosion initiation and to check the durability. The structural safety of the bridge deck remain unanswered however the example can give an idea of the performance ot bridge deck. Time to serious safety problems is a matter of a speed of corrosion process.

4. SBRA Model of Bridge Deck with Crack and Epoxy-coated Reinforcement

The performance of the reinforced concrete bridge deck is studied in this section, particularly with regard to the random interaction of holiday in epoxy-coating and crack effect, with respect to chloride ion induced corrosion initiation using SBRA method.

The Simulation-Based Reliability Assessment is used here in order to perform stochastic analysis of the bridge deck with crack. The procedure being applied is based on the probabilistic model introduced by TIKALSKY (2003) that was discussed in section 3 *Road Map to Performance-Based Design of Concrete Bridge Decks*. The crack and epoxy-coating properties are added to this model. The model allows for the study of the bridge deck with the effects of crack and epoxy-coating as well as a bridge deck without cracks, and without protection of reinforcement.

The description of involved random variables is discussed first, followed by the FEM transformation model, connection between the SBRA and FEM, and an example of bridge deck performance assessment closes this section.

4.1 Input Parameters of the Model

This section briefly discusses the evaluated parameters along with adopted probabilistic distributions. Applied distributions are also summarized at the end of this subsection. More comprehensive discussion of the involved parameters and their effect on durability can be found, e.g. in (MINDESS & YOUNG, 1981, AITCIN, 2005, SMITH, et. al., 2003 and KURGAN, 2003). Some of the input data for the chloride ingress model are obtained from the Report for Pennsylvania Department of Transportation (PennDOT) by (SOHANGHPURWALA&SCANELL, 1998) "*Verification of Effectiveness of Epoxy Coated Rebars Final Report*". The study evaluated performance of 80 bridge spans (77 bridge decks) in Pennsylvania and New York, U.S. with an average age of 10 years (from 3 to 19 winter in service) and bridge decks in good condition. The bridges were exposed from 20 to less than 9 tons of deicer per lane-mile per year. Three cores were extracted from each of the spans (total 240 cores). Since not all cores had two epoxy-coated rebars, properties-evaluation was conducted on 473 rebars. Engineering judgment is used where sufficient data were not available during research.

4.1.1 Effect of Chlorides

The amount of chloride required to initiate corrosion depends on many factors including the pH of solution in contact with the steel. Comparatively small quantities of chloride ions are needed to offset the basicity of Portland cement. Chlorides may enter into concrete from three major sources: from $CaCl_2$ added as an accelerating admixture, from deicing salts used on pavements and bridge decks and from seawater or salt spray. The corrosion of steel reinforcements in bridge decks that are regularly treated with deicing salts are generally mixtures of NaCl and $CaCl_2$, and much of the salt will penetrate into the pores of concrete and slowly diffuse down to the reinforcement. Little chloride is lost once it enters the concrete, so that there is steady buildup of chloride ion until critical concentrations (chloride threshold C_{th}) are reached at the rebar level.

One difficulty in choosing a chloride driver concentration and a threshold level comes when attempting to distinguish between the different characteristics of chlorides present in concrete. TUUTTI describes three different types of these chlorides; chemically bound, physically absorbed, and free chloride ions (TUUTTI, 1982). Other experts characterize them simply as chemically bound and free chlorides (BENTUR, et. al., 1997, GLASS&BUENFELD, 1997, THOMAS&MATTHEWS, 1996). Studies have suggested, but not sufficiently proven, that chloride binding should be categorized separately from free chlorides; bound chlorides, though different, still may present some corrosion risk (SMITH, et al, 2003, GLASS&BUENFELD, 1997). Another discrepancy among experts is the value of different chloride measuring units. Some researches believe that corrosion risk is not solely measured by the chlorides alone, but a composite parameter of a Cl^- / OH^- ratio (TALIB et. al., 2000). This concept takes into account the pH level of the concrete. As the mechanisms described above, the pH has a heavy influence on the passive layer. The hydroxyl ions play a large role in the pH level. Other studies have found that these principles are already included and not necessary for an accurate corrosion initiation determination. They believe that chloride threshold levels are represented best as a total chloride content, as a percentage of chlorides to weight of cement (GLASS&BUENFELD, 1997).

4.1.1.1 Chloride Threshold

The chloride ion concentrations that are considered critical for initiation of corrosion as well as the form of the chloride content expression vary among authors worldwide and are still matter of discussion (GLASS&BUENFELD, 1997). Researchers have developed different chloride threshold values according to percentage of chlorides per weight of cement, percentage of chlorides per weight of concrete, or ratio of chloride to hydroxyl ions. Some studies have shown that this threshold level is influenced by many factors, which further complicates quantification. Some of these factors are related to the type and amounts of supplementary cementitious materials (BENTZ&THOMAS, 2001) and corrosion inhibitors (BENTUR, et. al., 1997), the types of reinforcement (KRAUSS& NMAI, 1996), and the temperature and humidity.

The concentration of chloride ions that is sufficient to initiate corrosion is referred to as chloride threshold C_{th}. It has been commonly documented in a range of approximately 0.17 to 1.55 percent of soluble chlorides per mass of total cementitious material (1.0 to 9.2 pcy) (GLASS&BUENFELD, 1997). The histogram presented by DAIGLE (2004) shows available distribution of chloride concentration to initiate corrosion that is based on (GLASS & BUENFELD, 1997). See Figure 15.

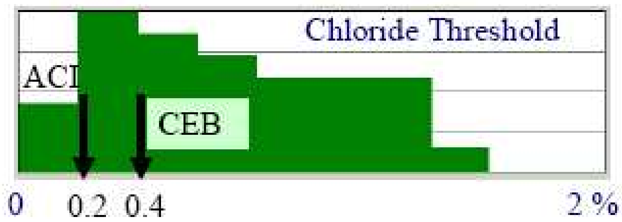

Figure 15: Histogram of Chloride Threshold Distribution C_{th} [%] according to (DAIGLE et al., 2004).

One needs to take into account the effect of moisture content of the concrete and thus the degree of pore saturation of the concrete (LOPEZ& GONZALEZ, 1993). FOOKES and WEST both reported a similar diagram in their respective reports on the effect of relative humidity on critical chloride content: (FOOKES, 1997, WEST, 1999).

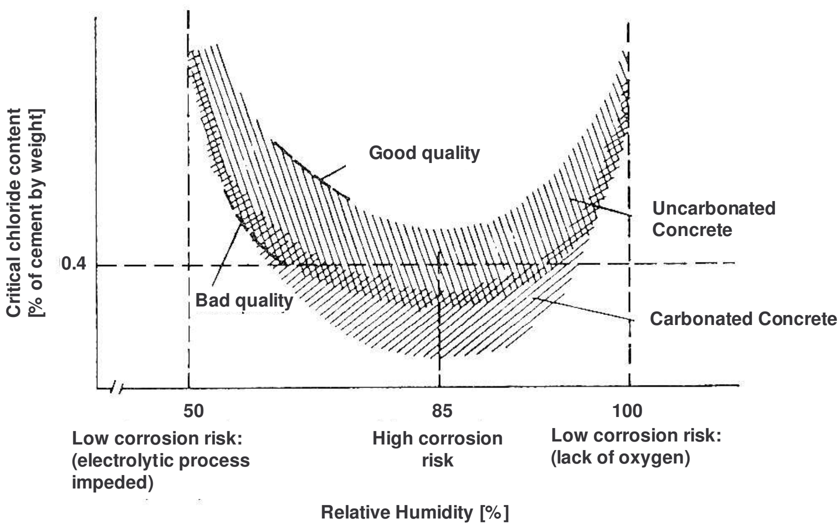

Figure 16: Variation of Critical Chloride Content with Environment (FOOKES, 1997).

As shown at the Figure 16, however, a high moisture-content is generally the worst situation for corrosion, unless too much moisture saturates the pores. At the highest moisture levels, the oxygen diffusion rate is greatly decreased, depriving corrosion of its essential element (FOOKES, 1997, KOBAYASHI, et. al., 1991).

Since the exposure of a bridge deck is severe with high moisture content, the concentration to initiate corrosion shall be in a proportion to that. Threshold selected here reflects recommendations of ACI and CEB, and refers to the high risk of corrosion area on Figure 16. Adopted distribution is normal $N(\mu,\sigma)=N(0.3,{}^{1}/_{3})$ that lies within range <0.2;0.4> percent. Threshold C_{th}= 0.2 % is recommended by ACI Committee 222 (2001) and (TIKALSKY, 2003) C_{th}= 0.4 % is a threshold according to CEB (2004).

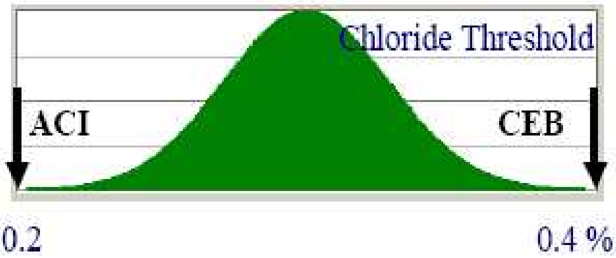

Figure 17: Applied Histogram of Chloride Threshold Distribution C_{th} [%].

4.1.1.2 Effective Surface Chloride Concentration

The surface concentration is a question of units and especially the denominator as was mentioned above. The chloride concentration is computed as a ratio of soluble chlorides per mass of cementitious material in cubic meter considering (355 kg of cement per cubic meter of concrete). SOHANGHPURWALA&SCANELL (1998) assumes that the value of surface chloride concentration C_0 for New York and Pennsylvania are 1.67 percent (5.93 kg/m^3 or 10 pcy) and 1.34 percent (4.75 kg/m^3 or 8 pcy) respectively. WEYERS, et al. (1993) considers low severity at the surface 0.48% (1.78kg/m^3 or 2.9 pcy); moderate 0.97% or 3.56 kg/m^3 (5.8 pcy); High 1.45% or 5.34 kg/m^3 (8.7 pcy); and severe 2.0% or 7.36 kg/m^3 (12 pcy). These values are generally based on the amount of deicers application. It can yield a similar exposure duration curve as is depicted next.

(TIKALSKY, 2003 and KURGAN, 2003) on the other hand states that the surplus on the surface does not drive diffusion. The diffusion driver is rather the stable saturated concentration just below the surface that is reported by KURGAN (2003). He found in laboratory tests on an accelerated specimen that was not drained, and exposed to wet and dry cycling with saturated Cl solutions for 4 months, that driver concentration C_0 for chloride ion penetration would be closer to 0.6% (The slabs were supersaturated at the top and stable below several millimeters). Surface chloride concentration C_0 = 0.6 is used as a diffusion driver (TIKALSKY, 2003, KURGAN, 2003).

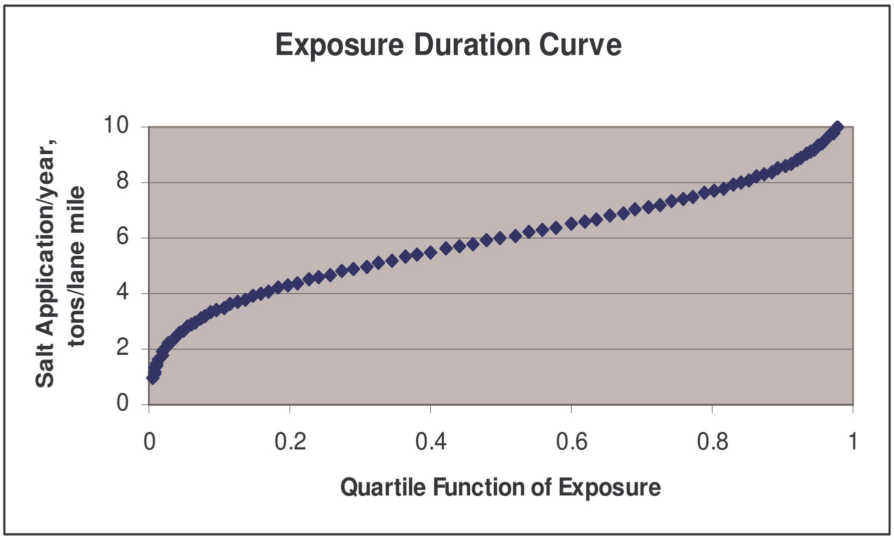

Figure 18: Salt Application Exposure Duration Curve (TIKALSKY, 2003).

4.1.1.3 Chloride Background Concentration

2-D model can handle chloride background concentration, although it is not applied in the discussed case. Assumptions are that the Chloride background concentration C_b is zero and no ingredients of concrete contain chlorides.

4.1.2 Diffusion Coefficient

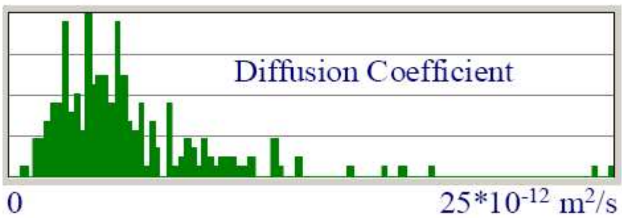

Figure 19: Histogram of Diffusion Coefficient (SOHANGHPURWALA et al., 1998).

Water cement ratio (*w/c*) is the parameter that has the largest single influence on durability of concrete with respect to chloride ion ingress. As the *w/c* ratio is decreased, the porosity of the paste is decreased and the concrete becomes more impermeable. The permeability of concrete plays an important role in durability, as it controls the rate of entry of moisture that may contain chloride ions and the movement of water during heating or freezing. Concrete with low w/c ratios can be produced by reducing the water content and by using supplementary cementitious materials such as slag, fly ash and silica fume. Lower *w/c* ratio increases the strength of concrete and hence improves its resistance to cracking from internal stresses possibly generated by adverse reactions. Concrete of adequate quality should have a w/c ratio low enough (0.4-0.5) to slow down penetration of chloride ions and the development of carbonation.

When finishing concrete, a disproportionate ratio of water to cementitious materials becomes present at the surface of the concrete. This leads to higher porosity and diffusion coefficients (HOOTON, et. al., 2001). Therefore, diffusion and permeability often vary with depth through the concrete. The quality of concrete with respect to chloride diffusion is described by the diffusion constant. It covers w/cm ratio, cementitious materials content and type, and the compaction and curing parameters. However, these implicit considerations do not provide control to the property, but rather a range of likely values for the material.

The use of high-quality, impermeable concrete with a low *w/c* ratio and adequate concrete cover can do much to alleviate the problem of corrosion. Although chloride ions will eventually fully penetrate concrete regularly exposed to deicing salts or seawater, the rate of penetration can be considerably reduced. The rate of diffusion of oxygen will also be reduced and its availability may limit the rate of corrosion even when the critical chloride ion concentration has been reached.

The variation of diffusion coefficient is described by the probabilistic distribution but is assumed to be constant over the depth in the model considered herein. No spatial correlation is considered herein. The relationship between depth and diffusion constant nor spatial variation of diffusion constant within cross-section are not considered. The measured diffusion of in-situ concrete placed under the same specification provides a view of the variation that is experienced in a typical structure in the Pennsylvania, U.S. (120 cores). Figure 19 shows a typical histogram of the diffusion constant for concrete designed, produced and placed under a single concrete specification by many different contractors (SOHANGHPURWALA et. al., 1998).

4.1.3 Concrete Cover

The depth of cover over the steel reinforcements plays a significant role in the process of corrosion initiation. Increasing the concrete cover will increase the time until the corrosive elements reach the reinforcement bar (BABAE&FOULADGAR, 2002, CLEAR, 1976, HOOTON, et. al., 2001, JONES, et. al., 1993, KRAUSS&NMAI, 1996, BENTZ&THOMAS, 2001) due to spatial separation between the steel reinforcements and the externally supplied chlorides.

Increasing the distance to the reinforcement bar will increase the time until initiation for concrete made with any type of cementitious materials, assuming good constructability and durability. In cracked specimens, a larger cover is beneficial because not all cracks penetrate to the reinforcement bar, which still leaves concrete available for the corrosive elements to permeate (BEEBY, 1983, PETTERSSON, 1998, SCHIESSL&RAUPACH, 1997, SUZUKI, et. al., 1990, ASTM C1202-97, 2000).

Proper cover determination allows for the safe transmission of bond forces, allows for the protection of steel against corrosion. It has also negative influence on cracking. When the cover is thicker cracks are wider but less frequent.

ACI Committee 318 (2002) recommends a minimum of 51 mm (2 inches) of cover for protection of slabs, while EN1992 requires minimal cover for a structure with a lifespan of 50 years and exposure to deicing agents with cyclic rewetting 55 mm (Exposure class XD3 and Structural class 4). The depth of steel is not constant, it varies substantially in the field. Figure 20 is a histogram of the depth of cover according to (SOHANGHPURWALA et al., 1998).

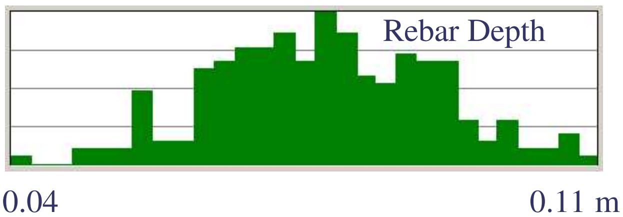

Figure 20: Histogram of Concrete Cover (SOHANGHPURWALA et al., 1998).

4.1.4 Deck Depth

The depth is considered as a deterministic value of 0.23 m. It is a common value in case of studied bridge decks. It needs to be noted that using a finite depth of the slab has the effect of a slight increase in chloride concentration over time at the level of reinforcement compared to analytical solution /5/ that uses an infinite depth.

4.1.5 Crack Properties

Cracking due to drying shrinkage and thermal expansion is caused by tensile stresses which are created by differential strains that occur under non-uniform drying, temperature rise, or uneven restraint. Effects of shrinkage and thermal cracking resemble flexural cracking and can be controlled by suitable location of reinforcement, which will reduce the amount of cracking and will cause several fine cracks rather than a single large crack. The finer the crack, the less likely it is that it will contribute to durability problems. Crack widths of less than 0.1 mm are according to (Mindess & Young, 1981) desirable in cases where sever exposure is anticipated. The ACI Committee 224 (2001) recommends the crack width less than 0.18 mm in when deicers are applied.

The amount of cracking can be controlled by suitable construction and design practices, (TIKALSKY, et. al., 2003a and SMITH et. al., 2003) creating conditions for concrete of low permeability, proper placement, consolidation and finishing, and adequate curing. Proper placement should also include a plan for a casting sequence for multi span bridges with regards to reduction, of tensile stresses induced in bridge decks by the placement of concrete (in both negative and positive moments region).

Concrete with a low *w/c* ratio has better resistance to cracking and spalling because of its higher strength. Cracking may also be controlled if the magnitude or rate of environmental changes can be reduced (temporary protection by moist curing, thermal insulation etc.). In this way tensile stresses will be lower and be further reduced by tensile creep and, in the early ages of structure, by increase in tensile strength.

4.1.5.1 Crack Depth

Distribution for crack depth is based on the engineering estimation by exponential distribution. Minimal value is zero depth and maximal value is depth all the way through the deck thickness (see Figure 21).

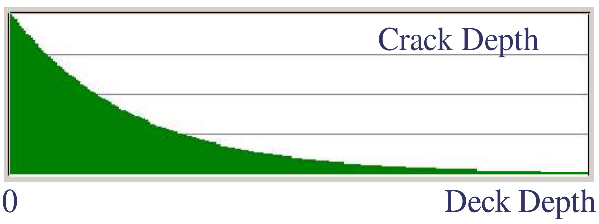

Figure 21: Histogram of the Crack Depth (estimation).

4.1.5.2 Crack Spacing

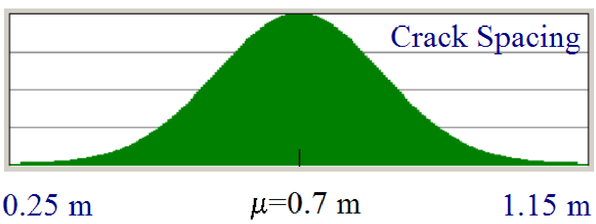

Figure 22: Histogram of Crack Spacing (estimation).

Spacing of the cracks C_{rcks} is also estimated as a normal distribution with the mean value 0.7 m that is 3 times the thickness of the slab. Standard deviation is 0.15. The distribution is truncated within boundaries <0.25,1.15> m as you can see on the next Figure.

4.1.5.3 Initial Crack Position

The initial crack position $Crck_i$ defines the position within the crack spacing $Crck_s$ because the spacing could be higher than the width of the model. If the initial crack position $Crck_i$ is less or equal to the model width then evaluated system has a crack, while if initial crack is higher than spacing no crack is studied on the model. For the details regarding the crack position, please refer to section 4.2.4 of the *Model*. In order to assess the effect of cracking, the probability of corrosion likelihood is computed per width of the model – per meter. It is then a relative measure. The initial crack $Crck_{i,rel}$ is computed as multiplication of uniform distribution with ranges <0,1> and crack spacing variable.

$$Crcki_i = Crck_{i,rel} \times Crck_s \qquad /14/$$

4.1.6 Properties of Epoxy-Coating of the Reinforcement

The easier ingress of chlorides to the level of reinforcement due to cracks could cause early corrosion. To protect the steel reinforcements steel, the epoxy-coating was introduced in North America in the late seventies of the last century. It should prevent the chlorides to reach the steel and to start corrosion. Experience and scientific studies shows however that the epoxy-coating is not total protection. The protection layer could be damaged forming islands prone to corrosion on the reinforcement called holidays herein as mentioned before.

Epoxy coated bar is simply normal "black bar", cleaned and painted with an epoxy coating that is designed to seal the surface of the bar from any moisture, oxygen or corrosive elements. Even though some laboratory studies have shown very positive results (AARSTEIN, et. al., 1998), other experts are more concerned with damaged epoxy coated bar in the field (SAGUES, et. al., 1990). Due to time constraints it has been difficult to estimate how long the epoxy coating will extend the life of the bar. One source suggests a life of approximately 20 years (BENTZ&THOMAS, 2001, BENJAMIN,et. al., 1990). There has been debate and concern towards using epoxy coated bar. Poor handling and construction practices can lead to nicks, slashes, and holes in the coating. This may cause the epoxy to de-bond from the black bar in the presence of moisture. Even if this does not happen, the small site is usually enough to begin a pitting process (at the anodic site, SAGUES, et. al., 1990). Since the rest of the bar is coated with epoxy, corrosion readings are also difficult to interpret (BROOMFIELD, 1997). These factors can not only lead to corrosion, but also to the engineers not fully understanding the corrosion and/or the locations. This leads some experts to totally discard the use of an epoxy-coated reinforcement bar (WEYERS, et. al., 2002).

Other experiments have been performed on damaged bar, showing that the epoxy still provides better protection from the elements, than "black bar" (AARSTEIN,et. al., 1998, LORENTZ&FRENCH, 1995, MCDONALD, et. al., 1998 , MIURA, et. al., 1997). MIURA and some colleagues recently ran a full study on the allowable damage on epoxy bar before being rendered inconsequential (MIURA, et. al., 1997) and still found epoxy very effective. The cost of an epoxy coated reinforcing bar is typically 1.4 to 1.6 times greater than standard black bar (www.mmfxsteel.com).

4.1.6.1 Number of Holidays

If there is epoxy coating on the steel reinforcements the chloride concentration near holidays is an additional consideration. The steel reinforcements is believed to be exposed to the effects of chlorides where holidays or other lapses in the epoxy-coating exist. It is therefore necessary to assess chloride concentration at such holidays with respect to crack proximity, considering the frequency and the potential for chloride concentrations to reach levels sufficient to initiate oxidation.

Holidays represent here all the problems related to the undesirable performance of the epoxy-coating such as mashed areas, blisters, bare areas and holidays etc. Each of these can affect the chloride ion penetration at the steel surface of the reinforcement and may allow a reaction to start. In the data set provided by the (SOHANGHPURWALA et al., 1998) a number of defects can be in each bar in a core. The distribution of epoxy-coating defects is shown on the Figure 23. It was derived as a sum of an epoxy-coating problem (holidays, mashed area, blisters etc.) per extracted length of the bar and then normalized per meter.

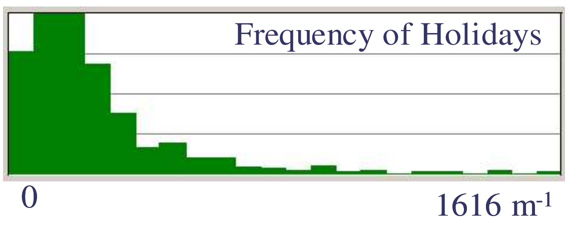

Figure 23: Histogram of Holidays According to (SOHANGHPURWALA et al., 1998).

One can see that there are a very large number of problems per meter of coating, though the coating is not very old. The question is whether the performance of such a bar is not more like an uncoated one than one which is epoxy coated. Although we have the real data, the distribution selected for simulation is uniform within the range <0;100> per meter because the number of holidays, according to Figure 23, would yield almost the same results. Details will be discussed later.

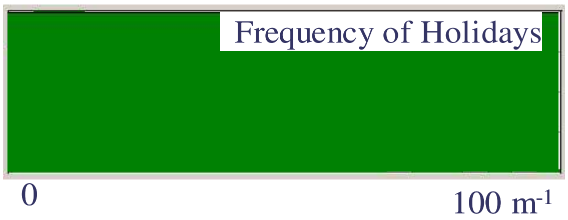

Figure 24: Histogram of Holidays – Uniform Distribution (simplification).

4.1.6.2 Initial Holiday Position

The horizontal position of the first holiday $Mash_i$ is also randomly selected within the distance of the holidays $Mash_s$ assuming that the spacing is uniform. Spacing is computed depending on the number of holidays per meter $Mash_n$ and width of the model slab. Variable $Mash_{i,rel}$, described by a uniform distribution with range <0,1>, selects a position of first holiday within the holiday spacing.

$$Mash_i = Mash_{i,rel} \times Mash_s = Mash_{i,rel} \frac{width}{Mash_n} \qquad /15/$$

Position of the next holiday is computed only by adding holiday spacing to position previous one.

4.1.7 Chloride Exposure

The chloride ingress is evaluated for the period of 100 years with the assessment every 5 years. The results are interpolated between assessed years.

4.1.8 Summary of Input Parameters

The above-discussed variables that are used in probabilistic assessment are summarized in next table.

Table 2: Random and Deterministic Input Values.

Parameters	*Range*	*Distribution*
Diffusion Coefficient D_c [$10^{-12}m^2/s$]	0-25	Histogram
Rebar Depth (Cover) R_{ebd} [m]	0.04-0.11	Histogram
Holiday Frequence $Mash_n$ [m^{-1}]	0-100	Uniform Distribution
Crack Spacing $Crck_s$ [m]	0.25-1.15	Normal Distribution N(0.75,0.15)**
Crack Depth $Crck_{de}$ [m]	0-Depth	Exponential*
Relative Crack Position $Crack_i$	0-1	Uniform Distribution
Relative Holiday Position $Mash_{i,rel}$	0-1	Uniform Distribution
Surface Soluble Chloride Concentration C_0 [%]	0.6	Constant
Chloride Threshold C_{th} [%]	0.2-0.4	Normal Distribution N(0.3,1/3)**
Background Chloride Concentration C_b [%]	0.0	Constant
Depth of Slab *Depth* [m]	0.23	Constant
Chloride Exposure *t* [years]	100	Constant

* Crack depth distribution is represented by exponential distribution that is characterized by mean value of 1, standard deviation of 1 and range <0;5>. Multiplication by 0.2×*Depth* yields it's boundary between<0-*Depth* >.
** Crack spacing and chloride threshold represents truncated Normal distribution within range of mean value ± 3 times standard deviation

4.2 Transformation Model

Differential equation /4/ may also be solved numerically. Numerical solution (such us finite differences or finite element method - FEM) allows for complex boundary condition implementation while increasing the computer-time demand. Although a probabilistic utilization is more complicated than in the Crank Solution case (eq. /5/), it gives the opportunity to solve more complex problems.

Since this work is focused on the chloride transportation in the reinforced concrete bridge decks with cracks, and on the estimation of chloride ion concentration in particular locations on the embedded steel reinforcements bars or damaged area of epoxy-coated rebars, a 2D Finite Element Method (FEM) is selected to meet the analysis requirement for the solution of Second Fick's Law /4/.

4.2.1 Thermal – Diffusion Analogy

Since diffusion process is governed by the same differential equation as heat transfer (compare please, Equation /16/ with Eq. /4/), the transient thermal analysis is used for solution of the mass diffusion problem (see e.g. LOGAN, 2002, ANSYS, 2005). Differential equation of heat transfer is listed next:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho} \frac{\partial^2 T}{\partial x^2} \qquad /16/,$$

where:

T	Temperature that is equivalent of *c* ionic concentration for diffusion problem,
λ	Thermal conductivity that is equivalent of *D* diffusion coefficient,
ρ	Mass density is set to 1 for diffusion problem,
x	Depth [m],
t	Time [years].

It can be seen that one can directly use diffusion coefficient *D* instead of thermal conductivity λ, chloride concentration *c* instead of temperature *T,* and set mass density ρ as 1 for diffusion problem solution using FEM.

4.2.2 FEM Implementation Factors

The FEM implementation process raises questions connected with selection of the suitable technique that needs to be considered:

- Universality and robustness,
- Interfacing with existing simulation software,
- Programming demand,
- Effectiveness (computer time demand),
- Target probabilities.

4.2.2.1 ANSYS FEM System Selection

Considering above-mentioned list of criteria the commercial software ANSYS (2005) is selected for 2-D probabilistic chloride diffusion process analysis. This alternative is selected because it is universal due to robust Finite Element System with a Probabilistic Design System (ANSYS PDS), which may be customized using APDL macro language for histogram based definition of random input variables. ANSYS System has a potential to solve many other structural or physical problems that may arise in the future development of SBRA method. The drawback of higher computational power demand is not a limiting value here because the target probabilities for studied performance assessment are in order of percent, thus reducing significantly the number of Monte Carlo simulation steps to thousands (refer to section 4.3 for details).

The SBRA Module plug-in had to be written because PDS does not yet have the capability to describe random input variables by the bounded histograms. It is the APDL macro language application that interconnects FEM task, PDS, and allows for histograms utilization. Running FEM program using a macro, which are essentially scripts from the programmers point of view, is rather inefficient because the computer must translate the macro commands into executable code first and than perform the desired action. It was not selected though to program single-purpose programs or to read input vector of random variables generated by other programs.

Since the target probabilities for specified problem are in percent magnitudes and thousands of simulations give satisfactory results, it was acceptable to use macro-based implementation of commercial FEM software.

It was decided also to generate histogram-characterized random variables directly within ANSYS environment. Direct generation of random variables slows down the simulation process on one hand but not significantly in comparison with the FEM analysis demand on the other hand, reducing the need for external program.

4.2.3 SBRA Module

The SBRA Module for ANSYS (KONEČNÝ&MAREK, 2006) is a tool for random variables distributions characterization by frequency histograms according to (MAREK et al., 1995) that are generated within the ANSYS governed probabilistic Monte Carlo simulation process. The SBRA Module programmed by author using ANSYS APDL (ANSYS, 2005) environment runs the FEM Macro containing the diffusion process description discussed in section A.2. 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). ANSYS PDS is used also for Monte Carlo data post processing. For the details of the SBRA Module refer to Annex B *Probabilistic SBRA Module for* ANSYS.

4.2.3.1 Note:

Monte Carlo simulation can be performed directly in ANSYS as programmed herein, or simulation input data set could be imported from other programs such as Anthill (www.sbra-anthill.com) as mentioned above (KRÁLIK&VARGA, 2004, MICKA, 2005, KONEČNÝ, 2005). Simulation results can be analyzed directly in ANSYS or exported for post processing elsewhere. This alternative is also under development (ŠEDIVÝ&BROŽOVSKÝ, 2006, GUŠTAR&MAREK, 2006).

4.2.4 FEM Model Details and Parameters

The 4-noded thermal solid element PLANE55 (ANSYS, 2005) is used for the chloride diffusion analysis. The deck is vertically divided into elements that are 10 mm by 10 mm in size. This resolution provided sufficient accuracy. The initial time step for transient analysis is depends on the diffusion constant and the element size /32/ and the load step is managed automatically by Ansys. The model scheme is presented in the Figure 25. The detailed description of the FEM macro is in Annex A.2 Model Overview.

4.2.4.1 Crack Influence Modeling

The chlorides move due to concentration differential. They move from surface towards the reinforcement in vertical direction. If there is a crack chlorides can move in horizontal direction as well because ions can penetrate through cracks much faster than through undamaged concrete creating another concentrational diferential as can be seen in Figure 25.

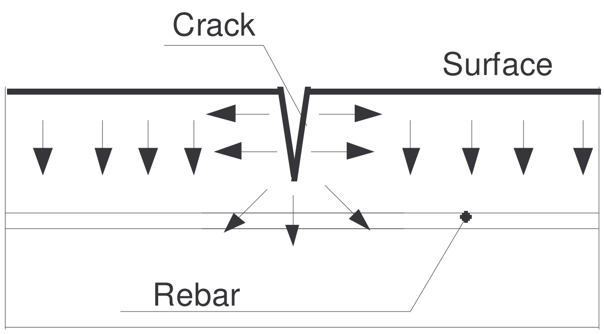

Figure 25: Scheme of Chloride Ingress in a Slab with Crack

The crack that is modeled is actually virtual because it is modeled via constraints on the respective model nodes. The model remains rectangular and chloride concentration constraint is applied on the nodes that reflect the crack position creating necessary gradient. The sample mesh with applied constraints is shown next.

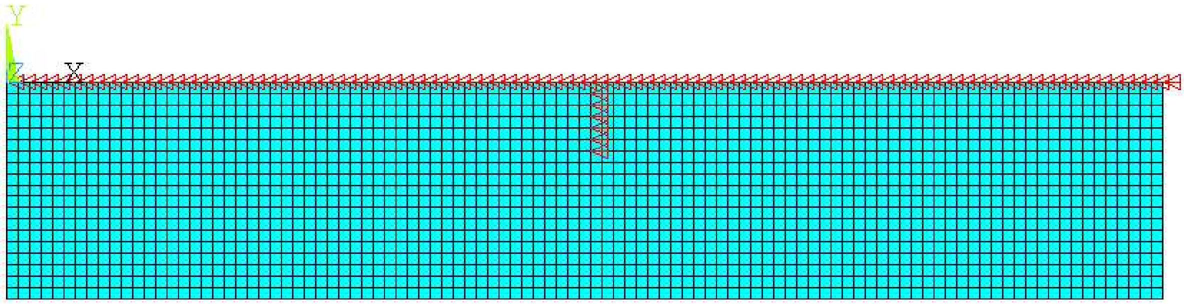

Figure 26: Scheme of FEM Mesh with Constraints (triangles).

The width of the model of interest is $width_u$ the extension $width_e$ is there to mitigate the negative effect of the crack at the edge of the model. The model can handle more than one crack.

If the position of the crack is $crack_i$ more than $width_u$ than only a 1-D problem is solved because there is no crack effect actually in the model. Reduction of the problem to 1-D speeds it up significantly.

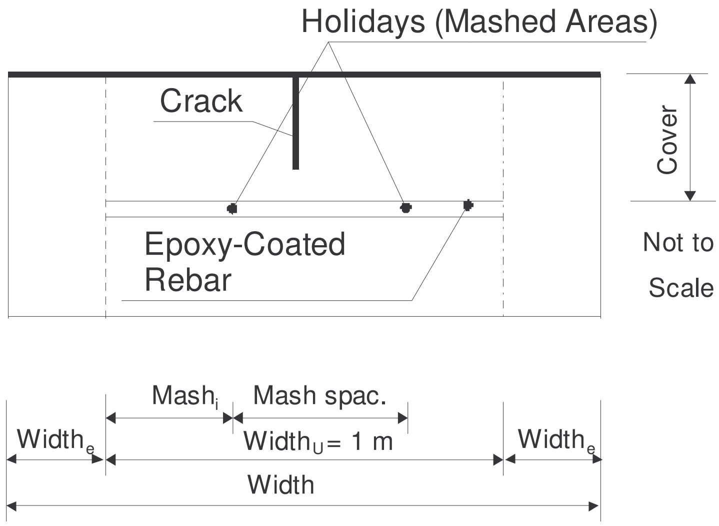

Figure 27: Scheme of Slab with Crack and Holidays on the Bar.

4.2.4.2 Epoxy-Coating Holiday Modeling

In order to estimate the corrosion of reinforcement protected by epoxy-coating, the concentration of chloride ions is investigated in the location of holidays and compared with chloride threshold. The model can handle from zero to one thousand holidays. The protection may also deteriorate over the decades of service, but this is not covered in the model yet.

4.2.4.3 Model Assumptions

The assumptions and simplifications for the model being applied follows:

- Ionic diffusion is a sole mechanism of the chloride transport,
- The concrete deck is homogeneous and is fully saturated with consistent pore fluids throughout the cross-section,
- Later-age apparent diffusion coefficients are used and are assumed constant with respect to time and 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,
- Crack influence (chloride penetration) is modeled as a boundary condition (chloride ion concentration) applied on the FEM model nodes that reflect crack position. FEM model itself remain rectangular (continuous throughout the considered crack),
- Cracks are formed perpendicular to the steel reinforcements, maximum depth of crack is considered to be slab thickness,
- Cracks which thickness is less than 0.18 mm are considered as negligible with respect to chloride ingress enhancement (ACI Comitte 224, 2001),
- Width of investigated cross-section is one meter (the FEM model has extension on both sides in order to mitigate the effect of possible cracks at the edges of investigated model),
- Crack is not created in the model if the combination of the initial crack position and the crack spacing is higher than width of the investigated cross-section (the $Crack_i$ parameter is higher then $width_u$ and crack would be out of the considered model and then the problem is reduced to 1-D).
- The resulting performance is normalized per meter of a reinforcement.
- The deck has 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. /5/), adiabatic boundary conditions is also on the bottom),

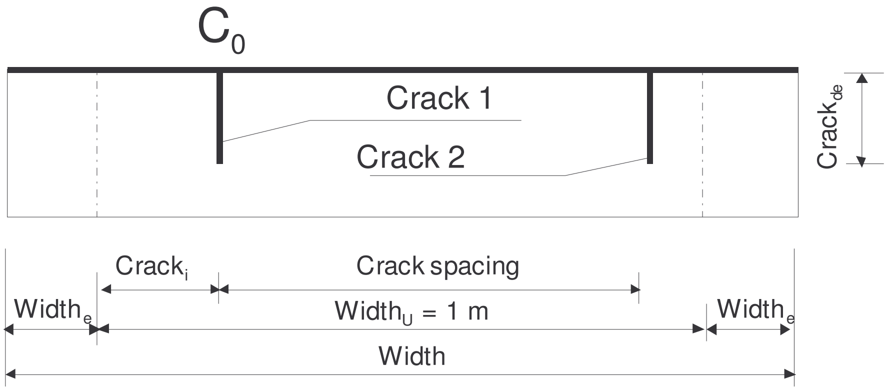

Figure 28: Crack Position and Spacing (not to scale)

- 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 chloride concentration is investigated at the top level of top matt directly under the crack,
- Chloride background concentration in concrete is C_b=0 % (it can be changed though),
- The concentration of chloride ions around the epoxy-coated steel reinforcements bar is considered to be the same as it is at the top of the rebar,
- Epoxy-coating fully protects a reinforcement against the chloride penetration if undamaged by holidays throughout the life span,
- The holidays are spaced evenly.

4.2.4.4 Evaluated Results

The model discussed here allows consideration of the crack effect on the epoxy-coated reinforcement with holidays as well as other results. The results of a particular solution will be referred to according to the name given in the respective proceeding bracket. The most interesting result of the crack and holiday interaction is referred to as C_{xyt}, the other outcomes are effect of crack on the black bar without protection (*Black Bar*), FEM result for the 1-D model without crack effect (*Reference*), and the analytical 1-D solution computed according to Equation /5/ (*Analytical*).

4.2.4.5 APDL Macro

The 2-D chloride ingress model is automated in a form of APDL macro in order to perform stochastic analysis. The FEM model for 2-D bridge deck assessment model written as a macro has capabilities to be automatically repeated with randomly selected input variables for each Monte Carlo simulation step. Each simulation step involves the construction of the nodes and elements, selection of the boundary condition, computation of the transient diffusion analysis, evaluation of the time-dependent chloride concentration, and reliability function analysis for all considered cases in selected exposure times. For the details of the macro refer to Annex A

4.2.4.6 Deterministic Solution

The deterministic solutions of the studied problem can be found in Annex A.3 and DVD-ROM only because the topic of the research is stochastic assessment. It is interesting to see the pure FEM model results though. Figure 29 shows the chloride ion concentration profile in a sample example of 2D diffusion with crack effect considered. The effect of crack allows chloride ions to move in vertical as well as horizontal direction and reach the reinforcement sooner.

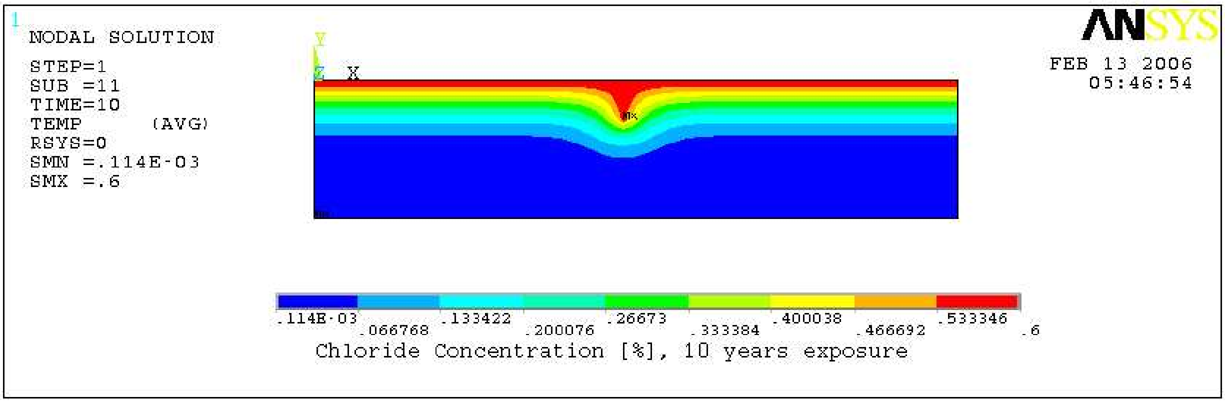

Figure 29 Chloride Ion Concentration in Concrete Slab with Crack.
Note: Only Two Decimal Places are Significant.

4.3 Monte Carlo Simulation

The Monte Carlo Simulation with 10,000 simulation steps is applied here. It is performed using FEM macro, ANSYS PDS, and SBRA Module with above-mentioned random input parameters. The numerical solution is repeated in ANSYS PDS system. The Monte Carlo simulation selects the random variables according to specified continuous distributions and histograms.

4.3.1 Simulation Steps

The number of simulations is related to target precision P_{target} that could be one percent in case of performance assessment with target probability P_{d} in order of ten percent. The necessary number of simulations can be backed up by rule of thumb saying that the desired target precision should be inverted and multiplied by one hundred in order to get the needed number of simulations:

$$N_{sim} = \frac{100}{P_{target}} = \frac{100}{0.01} = 10{,}000 \qquad /17/.$$

It can be also demonstrated on the following figure. It describes the probability of corrosion initiation as a function of simulation steps. One can see that after the initial 5000 simulation steps, the the resulting probability is almost unchanged.

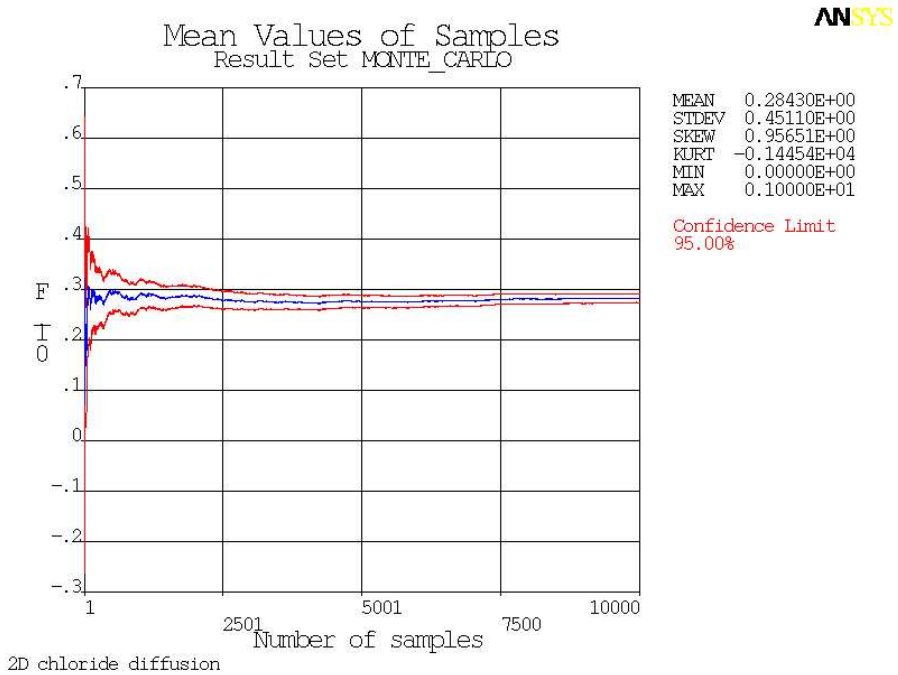

Figure 30: Iteration of The Sample Probability of Corrosion Likelihood

The simulation took about 60 hours at one dual core processor of SUN workstation, 12 GB memory and 2.4 Ghz frequency for the 100 years of chloride exposure with performance analysis in interval of 5 years. If 50 years with 10 year intervals are studied, then the analysis takes about 24 hours. The computer has a Linux operating system.

4.4 SBRA Analysis

Response to considered "loading" by chlorides is computed using Fick's second Law of diffusion with the stochastic model based on the SBRA method that utilizes FEM as a transformation model.

Response is expressed by the concentration of chlorides in the most exposed location of the reinforcement (the defect of epoxy-coating closest to the crack). This concentration is compared in the assessment with chloride threshold that is amount of chlorides sufficient to start corrosion. The likelihood of corrosion initiation is statistically evaluated and compared with target probability. The level of reliability is assessed in 10 consecutive intervals. The chloride exposure ranges from 10 to 100 years.

4.4.1.1 Crack Position

The crack position $Crck_i$ is computed from the crack spacing $Crck_s$ and initial crack position $Crck_{i,rel}$. If the position of the crack is more than 1 meter then only 1-D solution is considered and the crack has no influence on the reinforcement in studied area. The 2-D model is utilized in discussed example here in almost all cases since majority of the histogram of the crack position on the Figure 31 lies below one meter. The left side of the histogram is influenced by the uniform distribution of the relative position of the crack $Crck_{i,rel}$ while the right part has more of the bell shaped crack spacing.

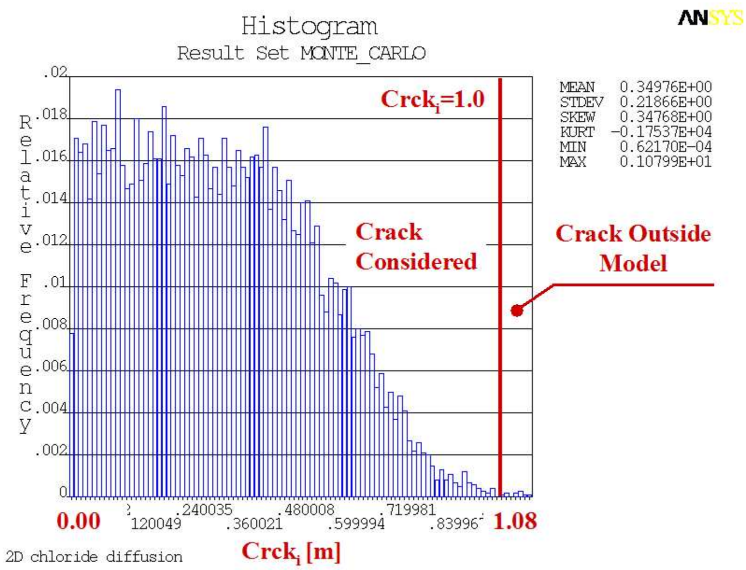

Figure 31: Histogram of the Initial Crack Position $Crck_i$

4.4.2 Evaluation of 10 Years of Chloride Exposure

The performance assessment of the bridge deck is shown on the chloride exposure lasting ten years.

4.4.2.1 Load Effect Combination (Concentration of Chlorides)

The resulting histogram of the chloride concentration at the holiday nearest to the crack tip after exposure of ten years is shown in Figure 32. The concentrations $C_{xy,10}$ range from 0 to 0.6 percent, which is actually the concentration at the surface and in the crack. Left part of the histogram represents the cases with crack far from holiday while the right part of the histogram is governed by crack tip very close to holiday. It can be seen that in cca. half of the cases corrosion would not start given the ACI reported chloride threshold.

The process of chloride ingress may be studied using the small histograms for selected ages on the right side of the Figure 32 (10, 20, 30, 50, and 100 years). It can be seen that the chloride penetration progress over time because the peak of histograms shifts to the right side. The average chloride concentration increases over time.

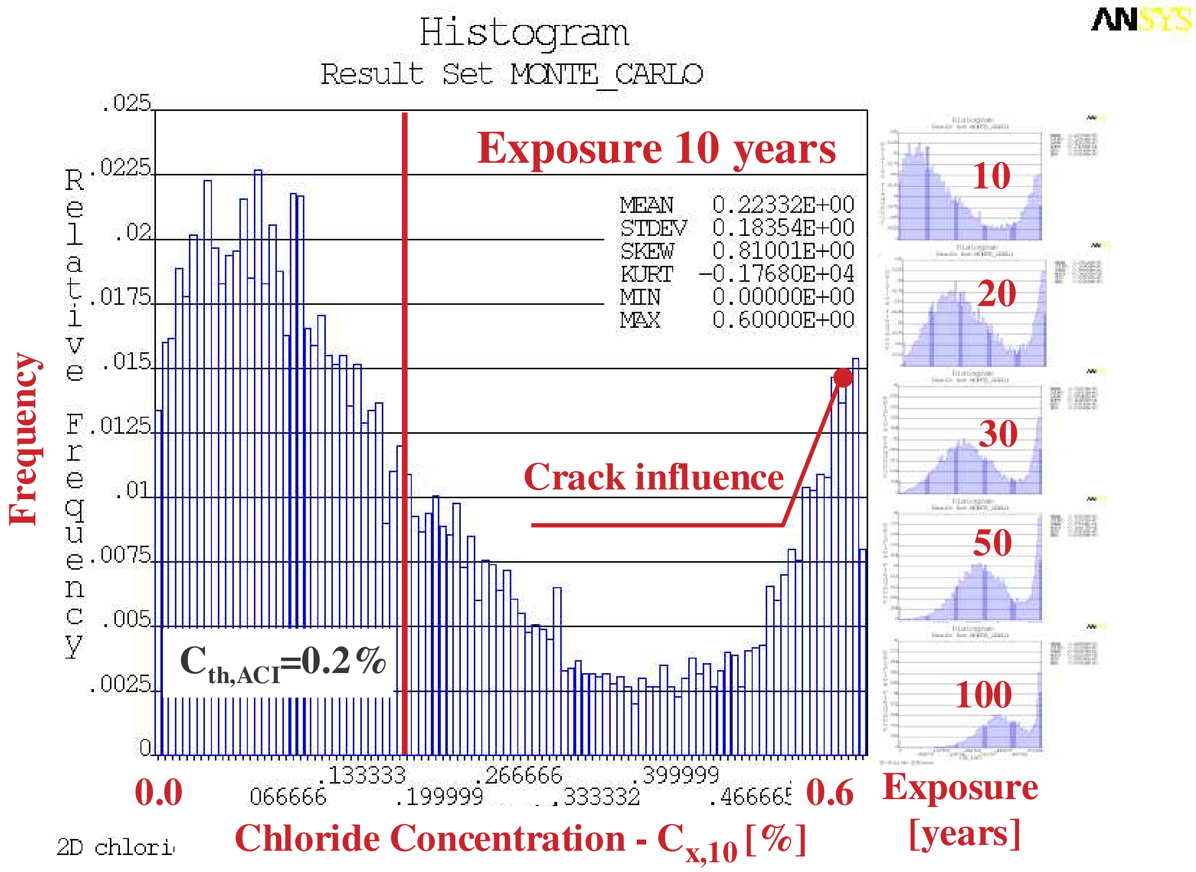

Figure 32: Histogram of Chloride Concentration C_{xy} [percent] at Rebar Level (10 years exposure - left, thumbnails for 20, 30, 50, and 100 years exposure - right)

4.4.2.2 Reference Function (Chloride Threshold)

The "resistance" of the epoxy-coated reinforcement against corrosion initiation is given by chloride concentration necessary for corrosion to start referred to as chloride threshold. The distribution generated directly according to specified input parameters are shown next.

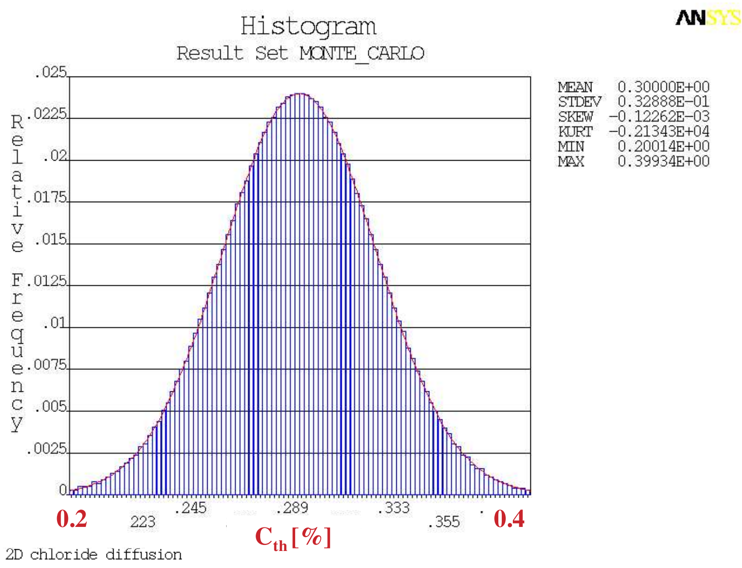

Figure 33: Histogram of Chloride Threshold C_{th} *[percent]*

4.4.3 Reliability Assessment for Exposure 10 Years

The reliability of the steel reinforcements 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 with regards to effects of crack and flaws in epoxy-coating on the performance of reinforcement with respect to corrosion initiation. The epoxy-coating damaged area with the highest concentration is selected as the critical case where corrosion would occur first. The probability of chloride threshold exceedance is the probability of corrosion initiation. The corrosion initiation likelihood is:

$$P_f = P(RF_t < 0) = P(C_{th} - C_{x,t} < 0) = 28.2\ \% \qquad /18/$$

The histogram of reliability function is depicted next along with thumbnails for age 20, 20, 30, 50, and 100 years. The development of performance can be seen from the thumbnails. The average vaule of this histogram shifts to the left (to negative values) – the reliability decreases while chlorides penetrate to the level of reinforcement over time.

It is interesting that the histogram has two peaks in early ages. First peak represents the effect of crack on the penetration of chlorides while the second one stands for crack too far from holidays. The difference becomes less visible over time. It is caused by penetration of chlorides from the surface. Chlorides have enough time to ingress in similar concentration at the reinforcement level as in case of the crack effect.

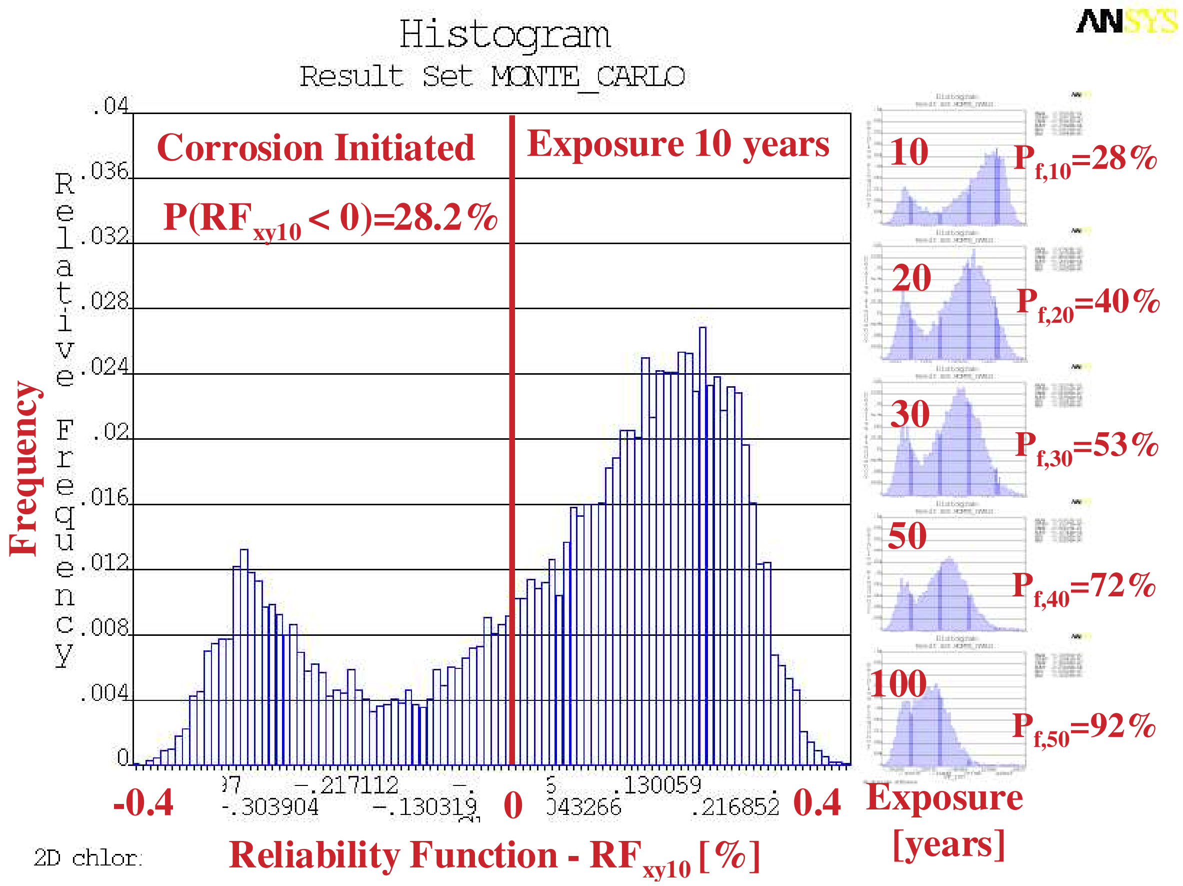

Figure 34: Histogram of Reliability Function RF_{xy} [percent] at Rebar Level (10 years exposure)

The desired performance would be met because the corrosion initiation probability P_f = 28.2 % per meter for the exposure ten years meets the acceptable performance P_d = 50% (TIKALSKY, 2003) considering lifespan of 100 years.

It needs to be noted that this probability of corrosion initiation refers to one meter of model bridge deck due to the way the influence of crack spacing and position is assessed.

4.4.3.1 Sensitivity Analysis

The significance of input variables on the chloride concentration at the most exposed holiday can be evaluated using sensitivity analysis of the output variable on the input ones. The studied parameter here is the reliability function for already discussed exposure 10 years.

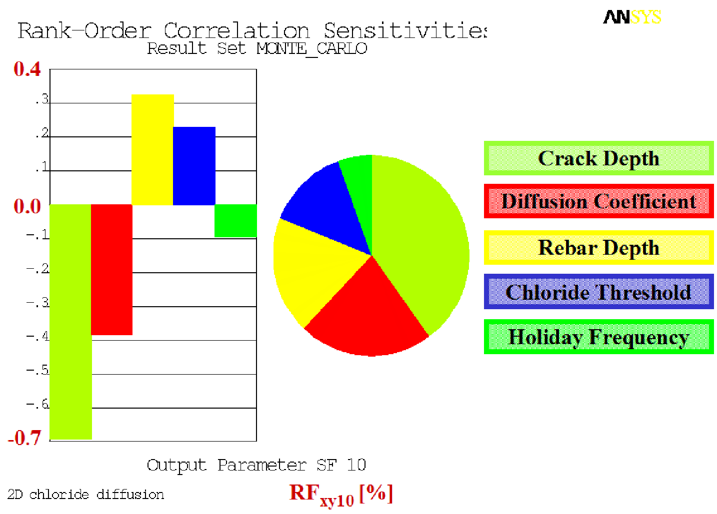

Figure 35: Significance Analysis of the Reliability Function RF_{xy10} (10 years Exposure).

The performance is influenced the most by the crack depth $Crack_{de}$, diffusion constant D_c, depth of reinforcement *x,* chloride threshold C_{th}, and frequency of holidays in epoxy-coating $Mash_n$. The crack spacing $Crack_s$ is insignificant here. It should be noted that the sensitivity analysis is somewhat a function of a probabilistic distribution that characterizes the respective variable because the sensitivity is only studied within the range of applied distribution.

4.4.3.2 2-D Scatter Plots (Anthills)

The random interaction of input variables and reliability function *RF* can be plotted. This scatter plot is called anthill in SBRA. The principles of the anthill are explained on the scatter-plot of crack depth $Crack_{\mathrm{DE}}$ (Figure 36). It is divided into two domains. The first domain represents the combination where corrosion started and the reliability function $RF<0$. The other domains represent combination without corrosion. The reliability function is on horizontal axis while crack depth is on vertical one.

This particular anthill is furnished with indicators of average reinforcement depth and the deck depth. It can be seen that if the crack depth is higher than cover then corrosion starts almost immediately.

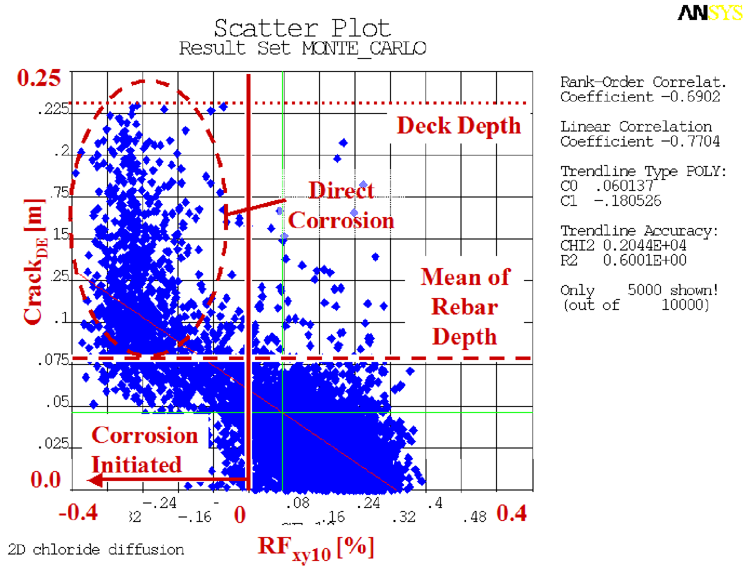

Figure 36: Anthill of Reliability Function RF_{xy10} vs. Crack Depth $Crack_{DE}$ [m].

Diffusion constant (Figure 37) and cover depth (Figure 38) are clearly important values as can be seen from the anthill that follow pattern of correlation between respective variable and reliability function. The highest reserve of reliability belongs to lowest diffusion coefficient and highest cover respectively as can be seen from following figures.

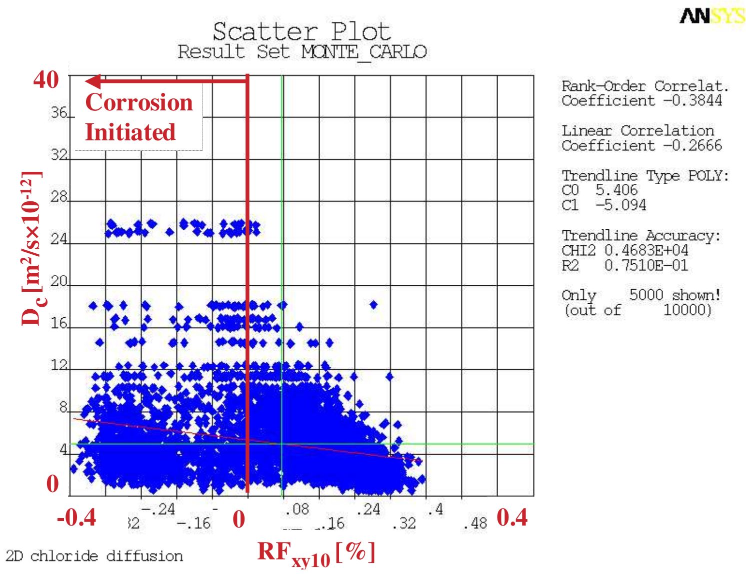

Figure 37: Anthill of Reliability Function RF_{xy10} vs. Diffusion Coefficient D_c [$m^2/s \times 10^{-12}$].

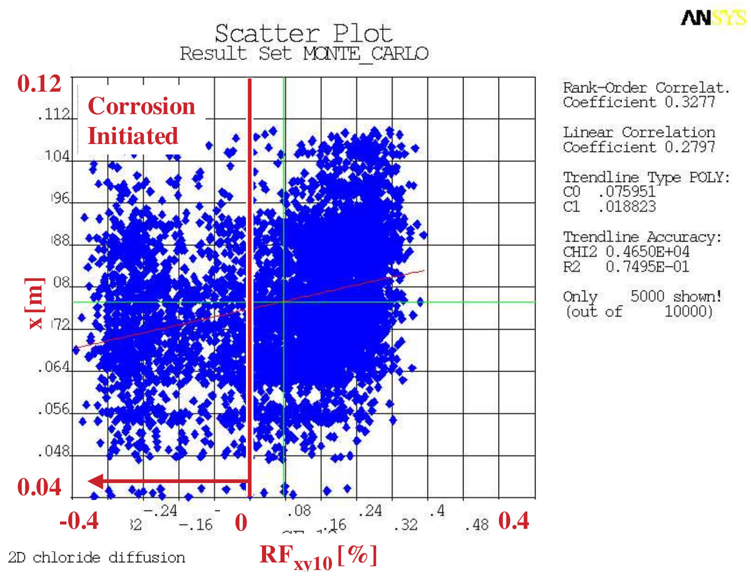

Figure 38: Anthill of Reliability Function RF_{xy10} vs. Rebar Depth (cover) x [m].

Threshold is also significant because it is one of the most important values in order to initiate corrosion. The linear correlation is clear from next figure.

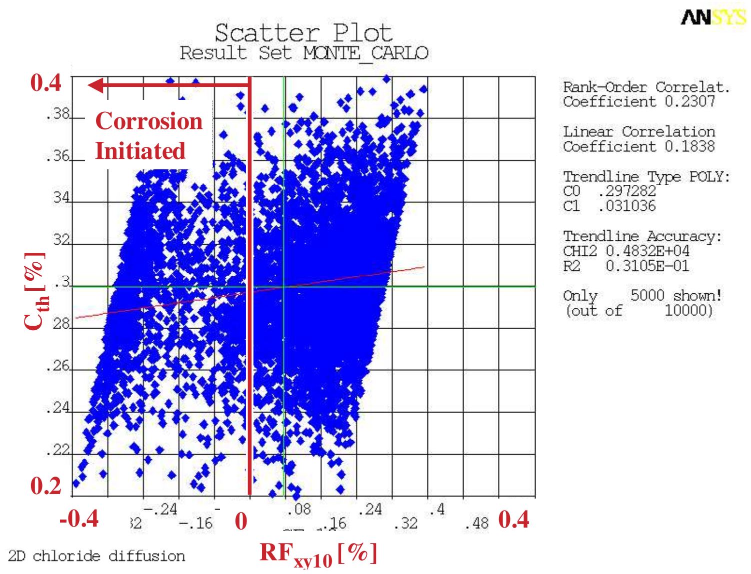

Figure 39: Anthill of Reliability Function RF_{xy10} vs. Chloride Threshold C_{th} [%].

The role of epoxy-coating could be significant if the number of holidays is reduced bellow 10 per meter but since it is mainly more frequent than 10 per meter according to adopted distribution here it plays minor role. When the holidays are more frequent, then the significance of epoxy-coating is almost none because the behaviour is similar to black bar and thus yielding almost the same result if the $Mash_n$ is 10, 20 or 100 per meter. The behaviour is visible at the next figure. Interesting is especially bottom area of scatter plot with significance of coating.

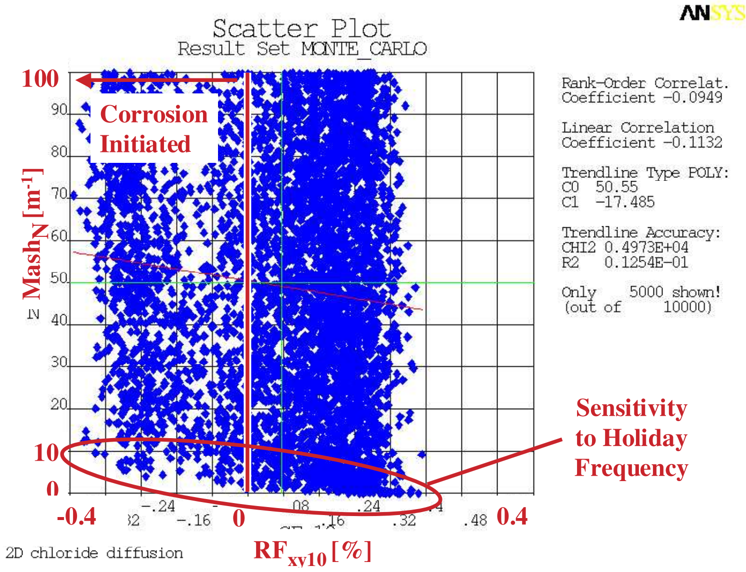

Figure 40: Anthill of Reliability Function RF_{xy10} vs. Holidays Epoxy-coating $Mash_N$ [m^{-1}].

Crack spacing and position is not as significant here because the crack position is in vast cases within 2-D model boundary here as discussed earlier. The level of reliability is not influenced too much by the differences between the 2-D and plain 1-D solution. It can be seen also from the following anthill figure.

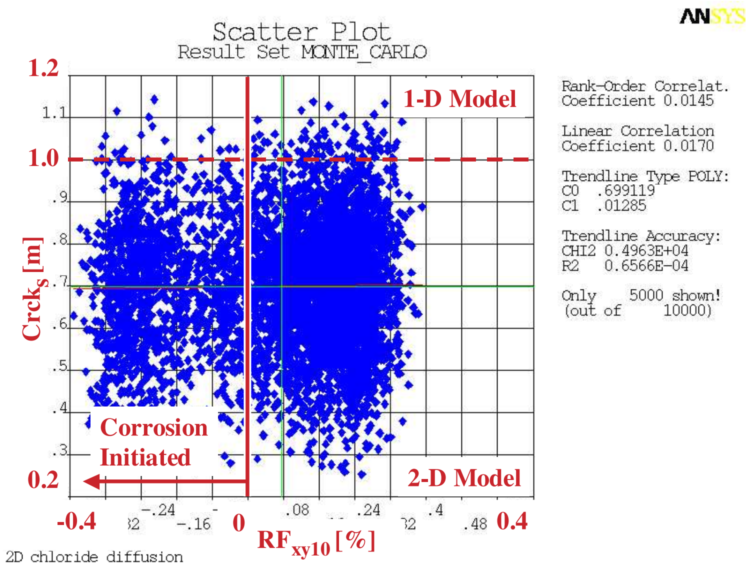

Figure 41: Anthill of Reliability Function RF_{xy10} vs. Crack Spacing $Crck_s$ [m].

4.4.3.3 Comparison with Black Bar and Analytical Solution

The same results as discussed for the simulation for exposure 10 years are obtained for other decades up to 100 years as well. The results for 100 year exposure on the bridge deck with crack and epoxy-coating as well as black bar are shown next.

Differences in chloride concentration at the rebar level between the cases with cracks and epoxy-coating protection (C_{xy}), and with analytical solution (ideal bridge deck without cracks) are indicated next. The main differences in histograms presented in the Figure 42 are two spikes at the edges of the left histogram. The first small spike represents a case with no holidays on a model yielding zero chloride concentration at the reinforcement due to proper coating. The second big spike represents crack effect close to holiday. The crack had either reached or crossed the steel bar. The chloride concentration is the maximum possible in this case.

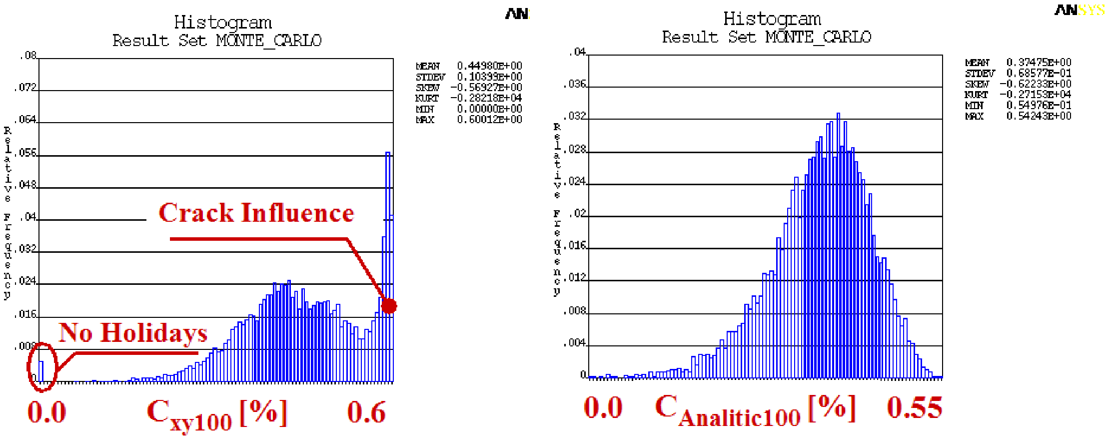

Figure 42: Histograms of Chloride Concentrations C_{xy} [percent] at Rebar Level
Epoxy-coating and Crack Effect (left), Analytical Solution (right),
(100 Years of Exposure)

The Anthill created from above-mentioned histograms creates interesting plot (Figure 43). There are visible cases of crack influence or proper coating behaviour of the epoxy-coating (no holidays).

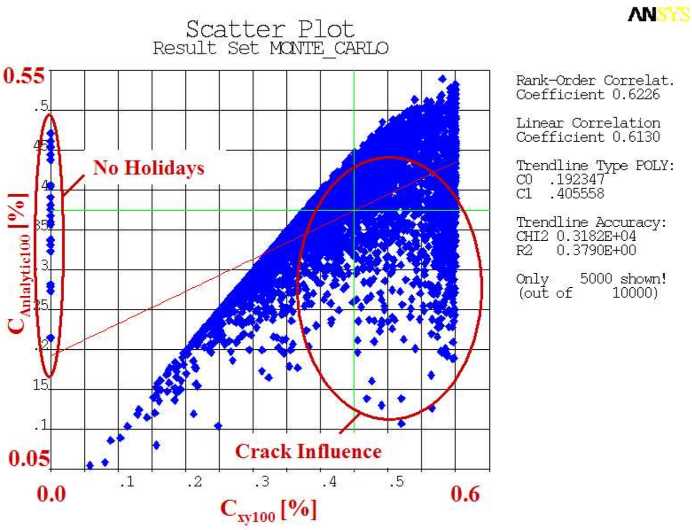

Figure 43: Anthill of Chloride Concentrations C_{xy} [percent] at Rebar Level
Epoxy-coating and Crack Effect (horizontal axis), Analytical solution (vertical axis).

The Reliability Functions for the considered cases are shown at the Figure 44 in the following order: Epoxy-coated Reinforcement, Black bar, Analytic solution. The probability of corrosion initiation is almost the same in the case of epoxy-coating and black bar (cca. 92 percent), while an analytic solution yields corrosion initiation lower. It is about 84 percent. The influence of crack and no holidays are also visible.

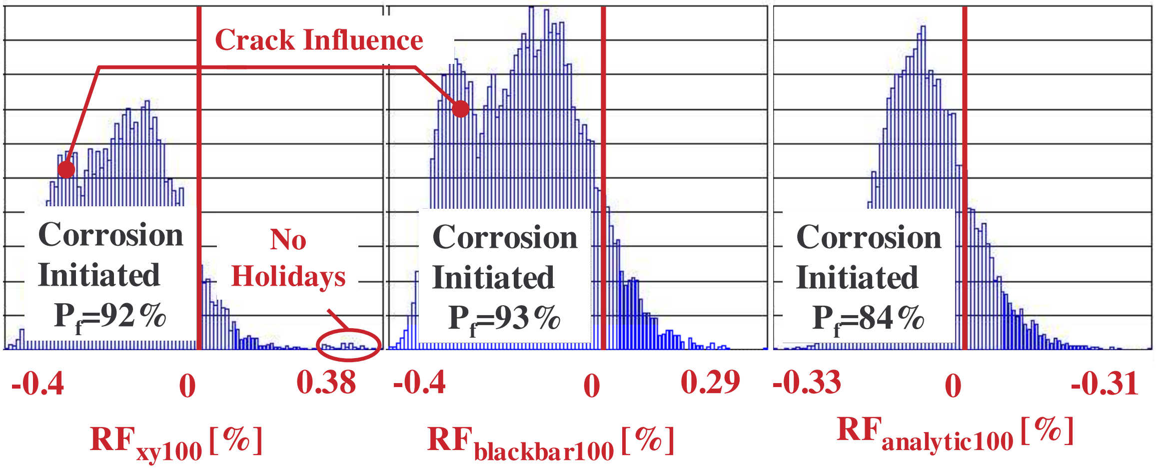

Figure 44: Histograms of Reliability Function RF_{xy} [percent] at Rebar Level Epoxy-coating and Crack Effect (left), Black Bar (middle), and Analytical solution (right), (100 Years of Exposure).

The reason for similar performance of the epoxy-coating and black bar is caused by the high number of holidays.

4.4.4 Durability Assessment

The stochastic durability assessment allows to check the performance of a bridge deck with respect to random input variables. Resulting reliability functions for selected ages are statistically evaluated in order to obtain probability of exceeding critical chloride content at the most exposed location in the reinforcement. The reliability assessment compares computed P_f that is time-dependent with target value P_d.

The chloride concentration at the level of reinforcement is increasing with the aging of the structure. The reliability of the bridge deck is decreasing with the increase of the chloride concentration. It is similar effect as the accumulation of damage. The results for all of the considered ages and cases are displayed on the table below. It presents the probabilities of corrosion initiation computed in selected age of the structure for three considered cases. The probabilities of corrosion initiation for cases with crack effect do not follow acceptable performance from the end of third decade while the ideal bridge deck cases are performing well for almost five decades.

Results for the ideal bridge deck are consistent with the findings in section 3.3.2.

Table 3: Probabilities of Failure [per meter].

Year	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
$P_{f,Cxyt}$	28	40	**53**	**63**	**72**	**78**	**83**	**87**	**90**	**92**
$P_{f,blackbar}$	31	42	**54**	**65**	**73**	**79**	**84**	**88**	**90**	**93**
$P_{f,reference}$	2	11	25	39	**51**	**62**	**70**	**76**	**82**	**85**
$P_{d,t\ Tikalsky\ (100\ years)}$					50					

Note: Probabilities of corrosion initiation written in bold exceed the target probability.

It seems that a uniform distribution for holiday with the maximum value of 100 per meter leads to the result similar to black the bar solution, as can be next seen from the probability of corrosion initiation summaries. The difference between the results of the black bar and epoxy coated bar are almost negligible here, as could also be seen from plot results.

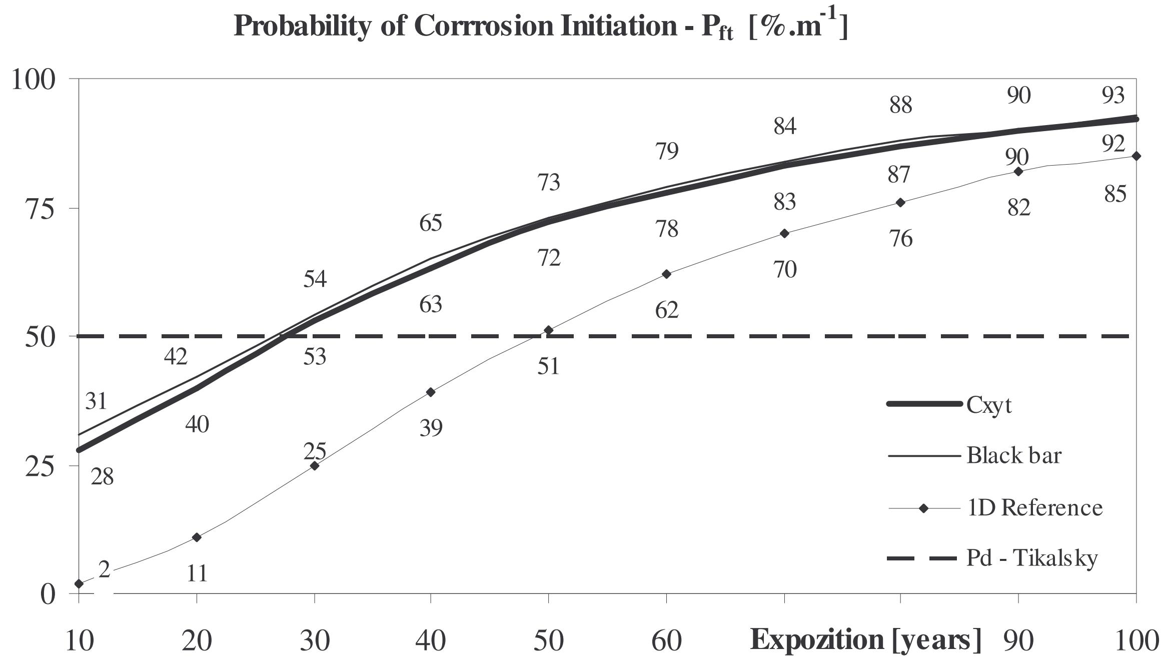

Figure 45: Time-dependent Probability of Corrosion Initiation P_f [m^{-1}]for Epoxy-coating and Crack Effect (C_{xyt}), Black Bar, and 1-D FEM (Reference) and Analytical solution.

4.5 Summary

The example of probability of corrosion initiation assessment with respect to pertinent random variables, and effect of crack and epoxy-coating properties interaction is shown using SBRA method and FEM model based on the 2.ND Fick's Law of Diffusion. The applied method allow to study the level of reliability as function of time.

The stochastic model utilizes ANSYS FEM System for finite analysis as well as probabilistic analysis that has SBRA Module plug-in that allows for characterization of random variables using bounded histograms. The variable nature of diffusion coefficients, concrete cover, chloride threshold to initiate corrosion, steel reinforcements holidays and relative proximity to cracks was modeled using histograms as well as continuous distributions based either on field data or engineering judgment.

The corrosion initiation is influenced by the crack depth, diffusion constant, cover, and chloride threshold. The epoxy-coating has a slight effect on the protection against corrosion due to the high number of holidays considered (uniform distribution $<0;100>$ [m^{-1}]). The epoxy-coating seems to have effect only in cases where it is less than 10 holidays per meter. The crack spacing was insignificant here due to low crack spacing (normal distribution N(0.7;0.15) [m]). One needs to take into account that the resulted outcome is strongly influenced by considered random variables, simplifications and assumptions.

Details of the records from the analysis are available at the Annex D in the text as well as at the enclosed DVD-ROM.

5. Parametric Study

The influence of significant variables is studied in this section in order to analyze suitable input parameters with respect to enhancement in durability of reinforced concrete bridge decks. There are two studies evaluated. The first evaluates the effect of diffusion constant and holidays in epoxy-coating. The second one goes into more depth and compares the performance of the epoxy-coating with performance of the black bar. It also provides results for the 1-D solution.

This parametric analysis aims to address suitable boundaries for the evaluated parameters, particularly crack spacing and holiday frequency in order to prolong durability of bridge decks. The probabilistic assessment is evaluated for different inputs in order to see the influence of each of the parameters.

5.1 Input Parameters

Table 4: Random and Deterministic Input Values.

Parameters	*Range*	*Distribution*
Diffusion Coefficient D_c [$10^{-12}m^2/s$]	0-25	Histogram (Figure 19)
Rebar Depth (Cover) R_{ebd} [m]	0.04-0.11	Histogram (Figure 20)
Holiday Frequence $Mash_n$ [m^{-1}]	0-1	Uniform Distribution (Figure 24)
Crack Spacing $Crck_s$ [m]	0.1-1.9	Normal Distribution N(1,0.3)*
Crack Depth $Crck_{de}$ [m]	0-Depth	Exponential
Relative Crack Position $Crack_i$	0-1	Uniform Distribution
Relative Holiday Position $Mash_{i,rel}$	0-1	Uniform Distribution
Surface Soluble Chloride Concentration C_0 [%]	0.6	Constant
Chloride Threshold C_{th} [%]	0.2-0.4	Normal Distribution N(0.3,1/3)*
Background Chloride Concentration C_b [%]	0.0	Constant
Depth of Slab *Depth* [m]	0.23	Constant
Chloride Exposure *t* [years]	100	Constant

* Crack spacing and chloride threshold represent truncated Normal distribution within range of mean value ± 3 times standard deviation.

The baseline for input parameters is displayed on the table below. It is based on the example discussed in section 4.1.8 of *SBRA Model of Bridge Deck with Crack and Epoxy-coated Reinforcement.* There are, however, some differences. The range of the distribution for holiday frequency is reduced from <0;100> to <0;1> per meter of reinforcement. Crack spacing is increased, with the mean changed from 0.7 to 1 meter and standard deviation form 0.15 to 0.3 meter (coefficient of variation is 0.3).

5.2 Alternatives

There are four parameters considered for alternating: diffusion coefficient, crack depth, number of holidays and crack spacing. The possible values are showed in next table and creates 48 combinations of probabilistic solutions.

Table 5: Multiplicators for the Parametric Study.

Parameter	*Symbol*	*Baseline*	*Multiplicator***			
Diffusion Coefficient D_c [$10^{-12}m^2/s$]	dc	25	1	0.1		
Crack Depth $Crck_{de}$ [m]	cd	5×Depth*	0.15	0.2		
Holiday Frequence M_{ashn} [m^{-1}]	m	1	1	10	100	1000
Crack Spacing $Crck_s$ [m]	cs	1	1	5	10	

*Crack depth distribution is represented by exponential distribution that is characterized by mean value of 1, standard deviation of 1 and range <0;5>. Multiplication by 0.15 or 0.2 yield it's boundary between <0-1> or <0-0.75> respectively that is multiplied again by depth of the bridge deck.
**NOTE: Multiplicators are important part of respective distributions that are modified accordingly. These are not single values applied in the simulation.

A shorthand notation has been created for the respective symbols in order to make comments as brief as possible. This short hand notation called here refers to a baseline and is explained on the first alternative next.

5.3 SBRA Analysis

There is performed stochastic analysis involving 1000 simulation steps with each of considered 48 alternatives. The number of simulation steps guarantees the precision cca. ± 2 percents that is enough here to see the influence of particular factors.

The plots that are discussed next are based on the selected interesting alternatives where 10 thousands simulation steps are applied. Records for each performed analysis are available on the Annex D.2 of the DVD-ROM.

5.4 Holiday Frequency

First referred to as *dc1-cd0.2-m100-cs1* according to applied multiplicators for baseline value, diffusion constant parameter *dc* has a value 1 that is to be multiplied with 25 yielding maximum value of respective distribution equal to 25 [$10^{-12}m^2/s$]. Crack depth parameter *cd* has 0.2 that yields the crack depth going all the way down the deck. Holiday frequency *m* is 1, meaning that maximum number of considered holidays would be one and crack spacing *cs* has also value 1 representing mean value of crack spacing.

The Figure 46 illustrates the influence of holiday frequency. One can see the plot for bridge deck with epoxy-coating (C_{xyt}). There is also a plot addressing uncoated reinforcement on the bridge deck with crack (Black bar). The magenta line is for the case of 1-D chloride ingress on the ideal bridge deck without crack and uncoated steel (Reference).

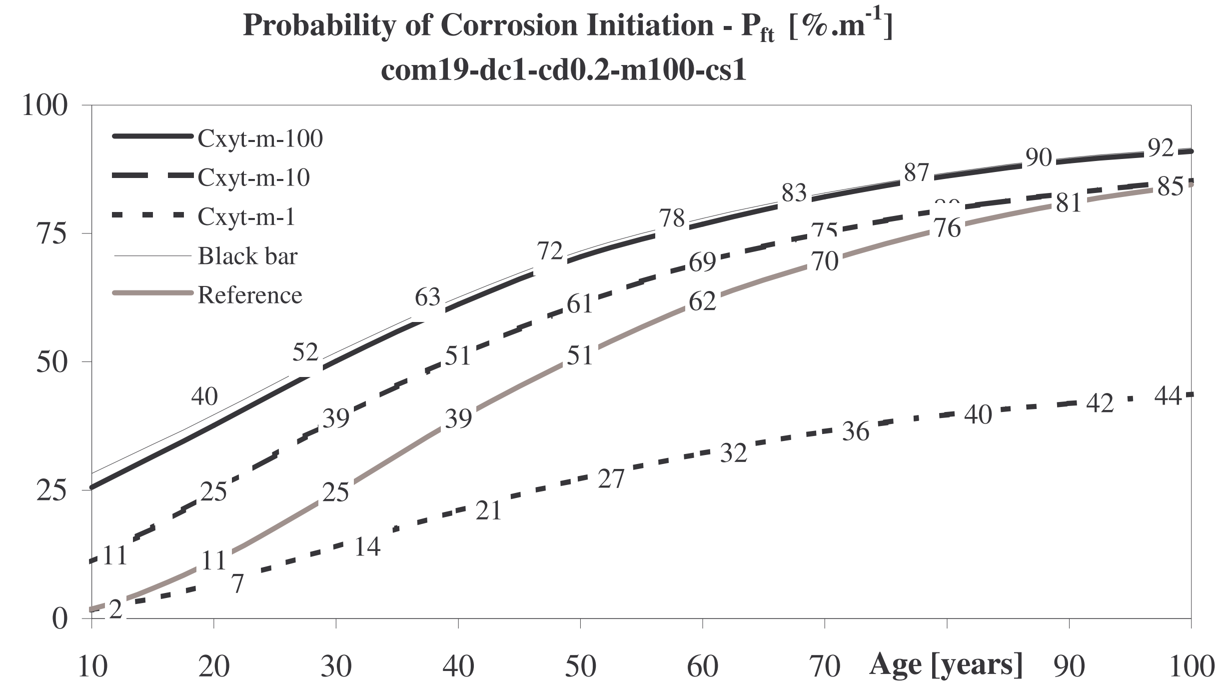

Figure 46: Effect of Holiday Frequency on the Probability of Corrosion Initiation P_f, Maximum Values of Boundary of Holiday Distribution m are 1, 10 or 100 [per meter].

It can be seen that if there are 100 holidays per meter of reinforcement, then corrosion is likely to happen with almost the same probability as in the case of black bar. If the number of holidays is reduced ten times, then the corrosion risks for coated reinforcement decrease within a range of 16 percent to 8 percent. The difference is more significant for the first decades. Further reduction of holidays to maximum of 1 holiday per meter gives good reduction of corrosion probability. The decrease goes from 28 in the exposure ten years to almost 50 percent at 100 years of exposure. The performance is far better than that of the Reference plot (1-D chloride ingress into ideal bridge deck).

5.5 Crack Spacing

The effect of crack spacing is studied on the epoxy-coated rebar as well as on the black bar. The thin continuous line of the black bar represents the same case as in previous Figure. The grey continuous line for epoxy-coating represents the same case as $m = 10$ in previous Figure (the distribution for holidays is uniform within range <0;10> [per meter]. The normal distribution of spacing is changed from average 1 meter through 5 to 10 meters (case *cs* 1, 5, and 10). The increase of the spacing (reduction of crack effect within model) is more significant in the first 50 years and in the black bar case. If the spacing average value would be even more reduced then the corrosion likelihood would probably rise significantly. It can be in e.g. the case of negative moment region above piers supporting a continuous bridge.

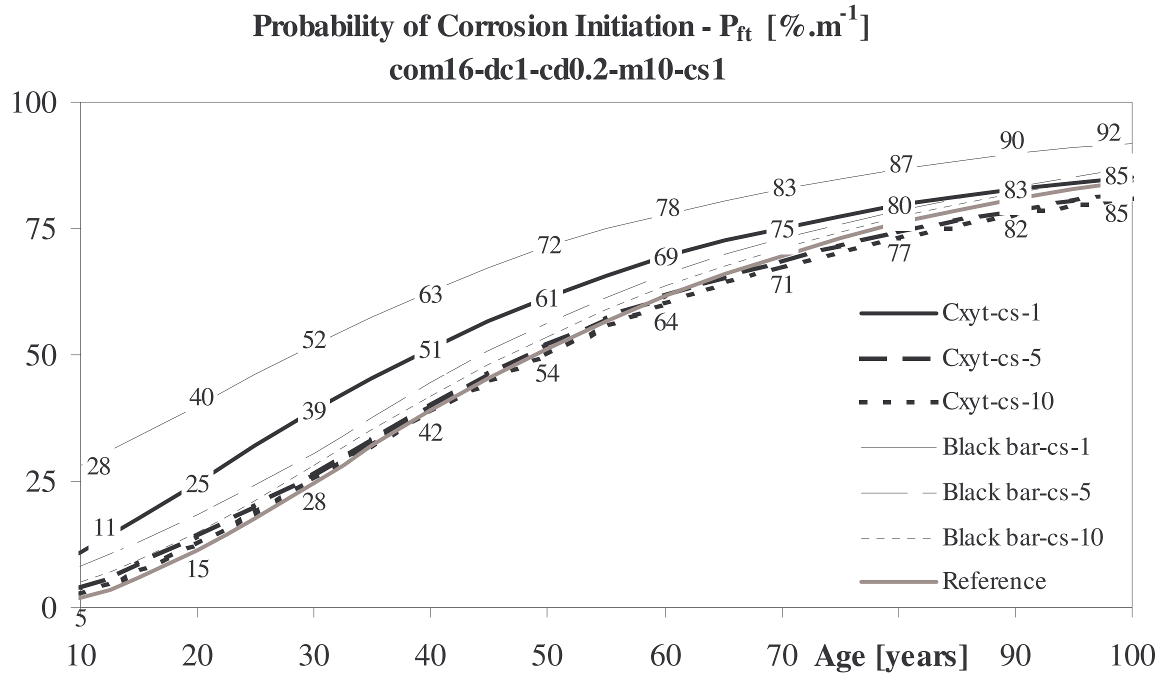

Figure 47: Effect of Crack Spacing on the Probability of Corrosion Initiation P_f, Mean Values of Crack Spacing cs are 1, 5 or 10 [m].

5.6 Crack Depth

Illustration of the effect of change in the maximum of the crack depth distribution can be seen on the next figure. The baseline is again similar as in previous case. The changed parameter is crack depth *cd*. Maximum crack depth goes either all the way through deck (*cd* = 0.2) or three quarters of the deck depth (*cd = 0.15*). The resulting corrosion likelihood differences are again more significant in the case of the black bar.

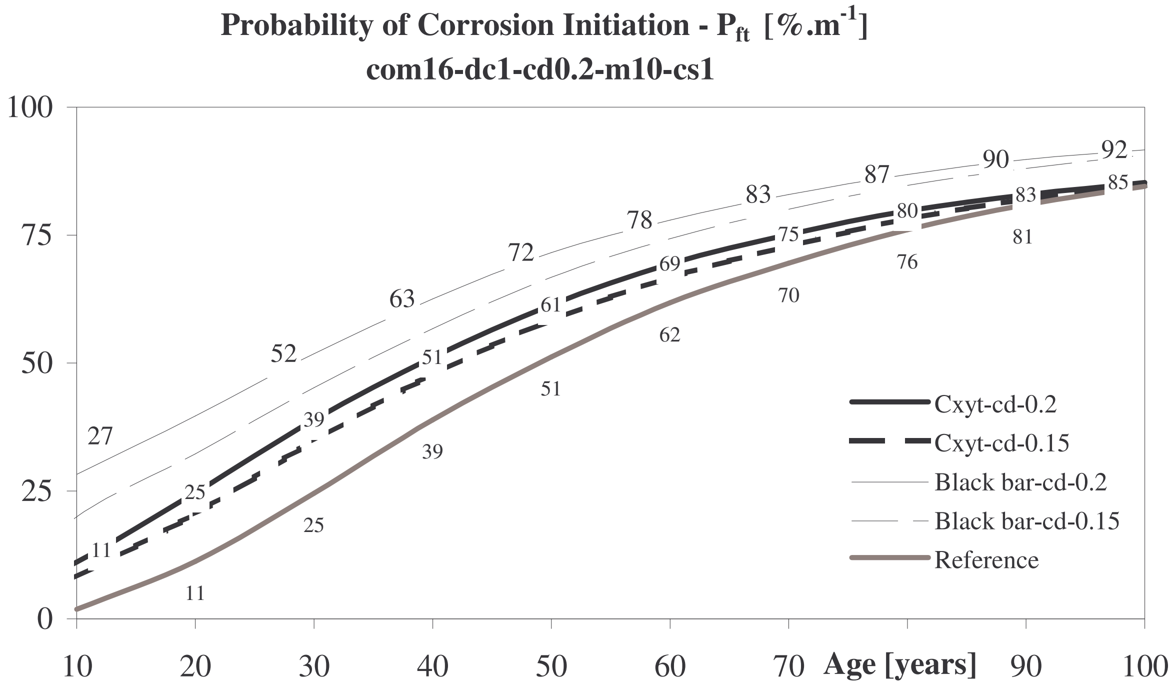

Figure 48: Effect of Crack Depth on the Probability of Corrosion Initiation P_f, Maximum Values of Crack Depth cd are 0.15 and 0.2 that mean ¾ of Deck Depth or Deck Depth Respectively.

5.7 Diffusion Coefficient

The most important parameter is undoubtedly diffusion coefficient that represents the material characteristics of concrete. The alternative, that is based on the study performed on the bridge decks from Pennsylvania (SOHANGHPURWALA et al., 1998), can be thought of as mixing with ordinary Portland cement. It is represented by *dc* = 1 multiplier. There can be also studied effect of binary and ternary blends of fly ash, and silica fume with Portland cement on the chloride ingress into bridge decks (see also TIKALSKY & KONEČNÝ, 2007). The addition of binary and ternary cementitious systems to the concrete decreases the diffusion constant by an order of magnitude. In data, collected of 15 high performance concrete bridge decks the values ranged from $0.1\text{x}10^{-12}$ to 2.4×10^{-12} (BLESZYNSKI et. al., 2002). Since this is not a large enough sample to form a histogram, the distribution from normal Portland cement construction operations can be used with these as limits. The alternative dc = 0.1 allows for quantitative performance analysis of HPC concrete mixes as is presented on the Figure 49.

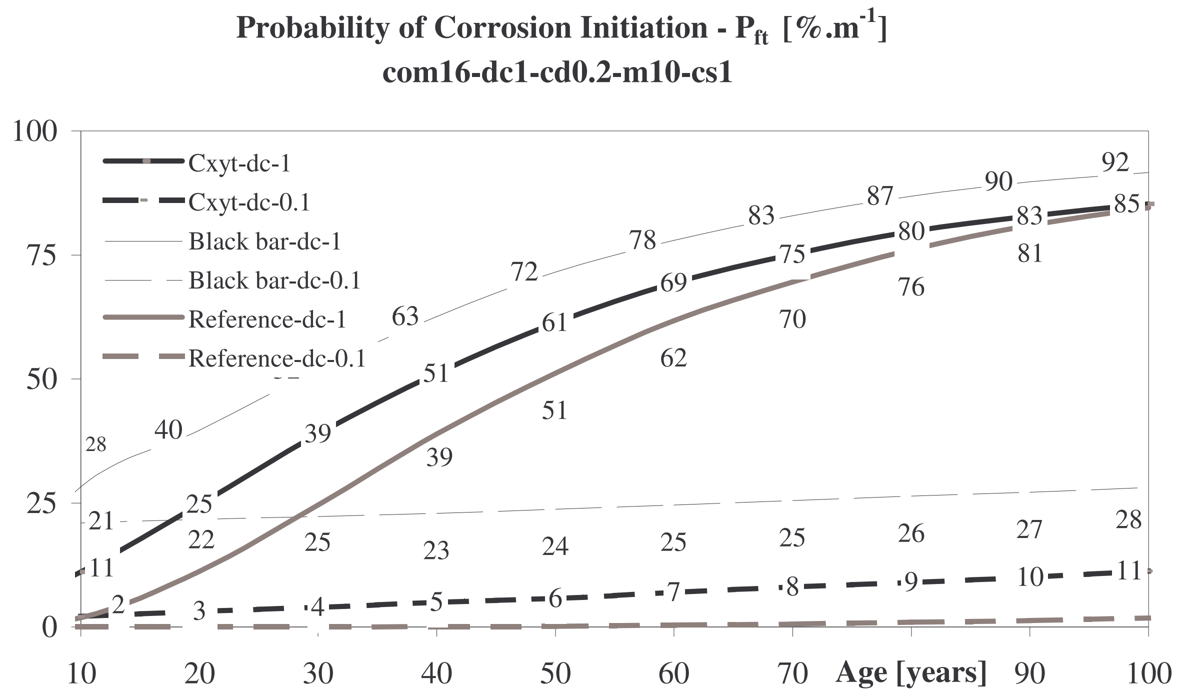

Figure 49: Effect of Diffusion Constant on the Probability of Corrosion Initiation P_f, Diffusion Constant Multipliers dc are 1 and 0.1 that means 24 and 2.4 [$10^{-12} m^2/s$] Respectively.

Plot is based on the epoxy-coating alternative with uniform distribution of holidays within range <0;10> [per meter]. It shows also behaviour of black bar under crack and without crack. The reduction of corrosion initiation likelihood is dramatic. Uncoated bar would not exceed the corrosion initiation probability of 25 percent even with crack effect consideration within first 70 years of service. The corrosion initiation likelihood for epoxy-coated reinforcement is below 12 percent throughout monitored lifespan. If the number of holidays would be reduced to maximum of one per meter than the probability of corrosion is bellow two percent and coincides with 1-D reference solution as indicates Figure 50. A similar result is achieved if the Crack spacing mean value is increased to 10 meters for the holiday frequencies distribution <0;10> [per meter] as indicates Figure 51. Increase in spacing also reduces the corrosion likelihood of black bar under a crack up to 5 percent for the 100 year life span.

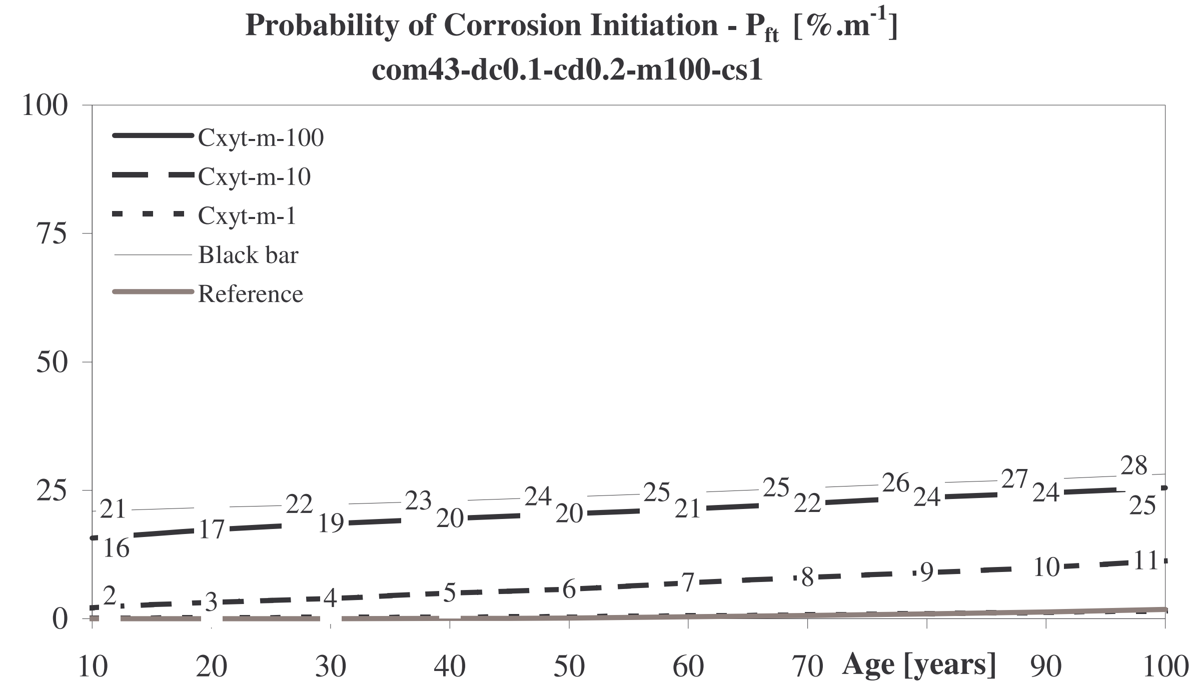

Figure 50: Effect of Holiday Distribution on the Probability of Corrosion Initiation P_f for Reduced Diffusion Constant, Maximum Values of Boundary of Holiday Distribution m are 1, 10 or 100 [m^{-1}].

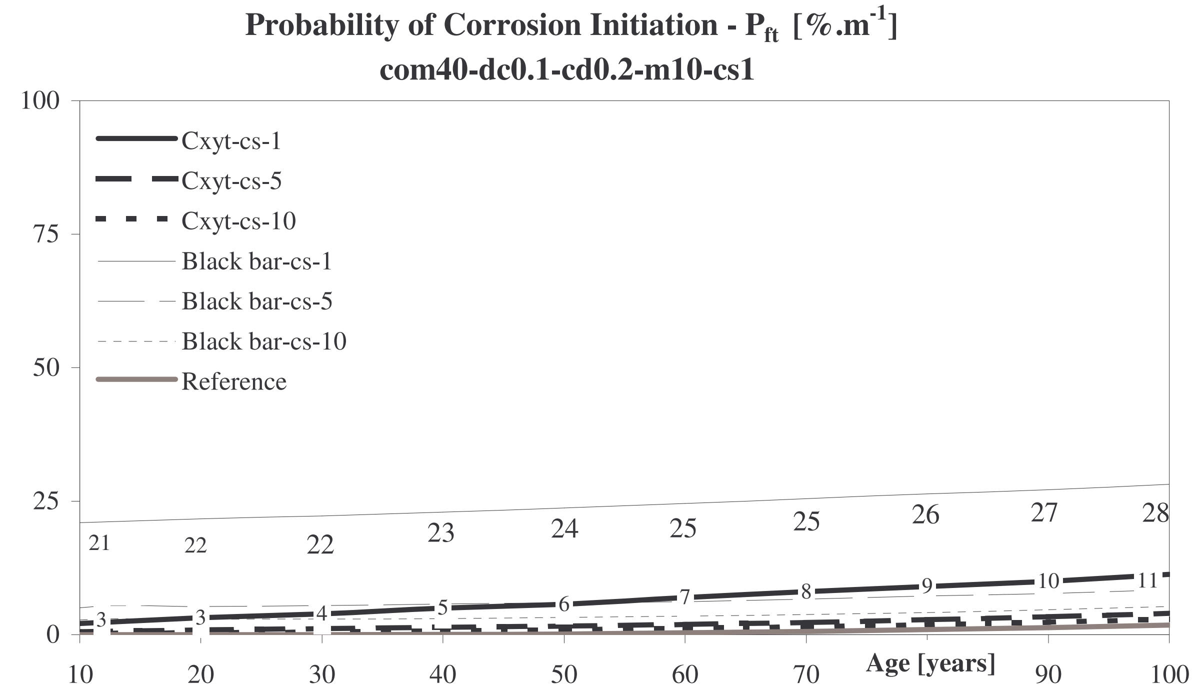

Figure 51: Effect of Crack Spacing on the Probability of Corrosion Initiation P_f for Reduced Diffusion Constant, Mean Values of Crack Spacing cs are 1, 5 or 10 [m].

5.8 Findings and Discussion

The finding of the stochastic performance behaviour of bridge deck made of reinforced concrete with cracks not only show the value gained from epoxy coated bars, holiday inspection and the reduced diffusion of binary and ternary cementitious materials. It also compares the epoxy-coating behaviour to black bar performance.

As a baseline, normal concrete with only Portland cement was analyzed. The frequency of holidays on epoxy-coating was high up to 100 per meter of reinforcement as revealed (SOHANGHPURWALA et al., 1998). Crack spacing is, given normal distribution, an average value of 1 meter.

The probabilities of exceeding the chloride threshold, and the subsequent initiation of corrosion, ranges from 25% in 10 years of service to 93% in 100 year of service for normal concrete with epoxy coated bars.

If the number of holidays in epoxy-coating of steel reinforcements bar can be reduced from amount presented in the Figure 23 revealed by SOHANGHPURWALA et al., (1998) ten times e.g. due to better control of production and placement measures, the likelihood of corrosion initiation is reduced by more than 8 percent. The other reduction to almost no holidays (up to one per meter of steel bar) reduces the probability of corrosion up to 50 percent in considered exposure of 100 years. The corrosion initiation probability ranges from 2% in 10 years of service to 44% in 100 years of service, as is shown on Figure 46.

The addition of binary and ternary cementitious systems to the concrete decreases the diffusion constant by an order of magnitude and thus decrease the probability of corrosion initiation, ranging from 2% in 10 years of service to 12% in 100 years of service for steel with epoxy-coated bars. If the crack spacing is increased to a normal distribution with mean value of 10 meters, then the corrosion likelihood for epoxy-coated bar stays below 1.5%, and also remains less than 5 percent (see Figure 51 for details) for the black bars.

6. Summary and Discussion

The thesis is focused on the research in the field of performance assessment of a real engineering problem using the Simulation-Based Reliability Assessment method introduced by (MAREK et. al., 1995). It presents improvement of the stochastic 1-D model introduced by TIKALSKY (2003) for typical bridge deck made from reinforced concrete in northeastern U.S. Bridge deck performance is assessed with respect to chloride ion ingress based on the Fick's Second Law of Diffusion. The model is analyzed using Simulation-Based Reliability Assessment (SBRA, MAREK, et. al., 1995, 2001). Bridge deck model is furnished herein with consideration for random interaction of crack effect and epoxy-coating flaws. Since there is a crack effect considered, 2-D analysis is adopted.

The FEM in conjunction with the SBRA method is used to estimate the probability of corrosion initiation from chloride ingress of epoxy-coated steel reinforcements bars throughout the life of a typical bridge deck. The effect of cracking is considered. The variable nature of diffusion coefficients, concrete cover, chloride threshold to initiate corrosion, steel reinforcements holidays and its relative proximity to crack is modeled using histograms based either on field data or engineering judgment.

Discussed model is aimed on the evaluation of the corrosion initiation. It needs to be point out that structural safety of the bridge deck remain unanswered however the studied examples can give an idea of the the corrosion related performance ot bridge decks. Time to serious safety problems is a matter of a speed of corrosion process.

6.1 Significance of Random Input Parameters

The performance study incorporates the data sets from a bridge performance study made on the 80 spans of real life structures in the northeastern U.S. (SOHANGHPURWALA et al., 1998), and shows the significance of the variables involved in the problem. The diffusion constant is undoubtedly the most important parameter. It is desirable to use high-performance concrete in order to reduce penetrability with respect to chloride ingress. The target performance for concrete is not high strength but rather in this case for the reduction of chloride penetrability.

Study also revealed that epoxy-coating of the reinforcement helps to protect the steel in a presence of a crack if the number of holidays (flaws in coating) lies in the interval 0 to 10 per meter of reinforcement. Higher amount (up to hundreds per meter of reinforcement) of holidays revealed according to (SOHANGHPURWALA et al., 1998) almost provides no protection against corrosion compared to black bar.

The model suggests that increasing the crack spacing to more than one meter increases the protection of uncoated steel bar better than properly epoxy-coated steel bar with controlled amount of holidays. This finding is influenced by the assumption herein that if one spot at the reinforcement corrodes, then the reference value (chloride threshold) is exceeded, and corrosion is assumed to start. If black bar and epoxy-coated bar are compared, then it is more likely that the corrosion on the bridge deck without crack would start more uniformly on the black uncoated bar than on the epoxy-coated bar where only certain locations would be prone to corrosion pitting. The other parts of the coated bar nevertheless remain much better protected than in case of the black bar.

Depth of concrete cover has also its significance. If one thinks only about the distance chloride ions need to travel through concrete to the reinforcement, then obviously higher cover means longer durability. But the reinforcement has its restraint role in the control of cracking also.

6.2 SBRA Module

The SBRA module is created in order to combine existing FEM system with the possibilities of histograms for description of inherent random variables. The stochastic analysis is performed within ANSYS framework in conjunction with SBRA module plug-in in order to allow for finite element analysis of 2-D chloride diffusion process using Monte Carlo simulation process with random variables characterized by histograms.

It may help to broaden the application possibilities for the SBRA in the area of engineering reliability from the very first steps (MAREK, P. et al. 1995), through extensive examples of applications (MAREK, P. et al. 2003), up to current stochastic FEM applications in the SBRA framework and Performance-Based Assessment. The development of the FEM and SBRA interaction is also based on the following works (KRÁLIK a VARGA, 2004, 2005, KALA, 2005, MICKA, 2005, PRAKS, 2006, KONEČNÝ, 2005).

The proposed approach allows for the seamless integration of the SBRA method and the universal FEM solver. It allows for random variables preprocessing, Monte Carlo simulation, and post processing including sensitivity analysis and graphical outputs. Utilization of the APDL scripting language under universal FEM leads to higher demand for computing time compared to specialized FEM software.

The SBRA Module is successfully tested on the 2-D problem of chloride diffusion. It is the task with degrees of freedom in the thousands, where are the investigated probabilities in order of percents. In this type of analysis, it is sufficient to apply thousands of simulation steps in contrast to safety limit state where millions of simulations are to be applied. In case of the safety assessment one would need to apply more sophisticated simulation tool such as Importance Sampling or Latin Hypercube Sampling in order to maintain reasonable computing time using ANSYS.

6.3 Reinforced Concrete vs. Steel Structure Behaviour Comparison

If one compares the behaviour of the reinforced concrete and the steel with respect to corrosion induced resistance degradation, there are significant differences in corrosion progress. In case of steel, the corrosion starts in a shorter time than concrete. On the other hand the corrosion rate during the propagation phase would be lower than in the case of reinforced concrete. Once a sufficient amount of aggressive agents reach the reinforcement level then the corrosion starts to propagate, reducing the cross-section as well as creating additional stresses in the concrete cover. The rust formation is also followed by the debonding of reinforcement reducing a composite action of steel and concrete with eventual cracking, cover spalling and delamination. Cracking and spalling directly expose the reinforcement to an aggressive environment, speeding up the process significantly.

The idea of comparison of corrosion processes in steel and concrete can be seen on the Figure 52, where each dot represents resistance in time that is dependent on particular set of random input variables.

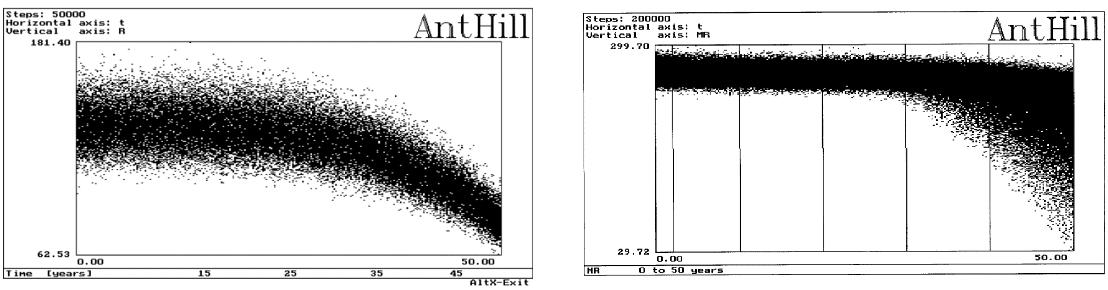

Figure 52: Idea of Resistance Development Due to Corrosion Progression in Time: Steel Structure (left-MAREK&KOROUŠ, 2002), Concrete Structure (right-BRADÁČ, 2000).

7. Conclusions and Recommendations for Future Research

Chloride induced corrosion is an important issue that reduces the service life of bridge decks. Its stochastic nature caused by variability in concrete quality, manufacturing precision and environmental properties is remarkable and should be taken into account. Simulation-Based Reliability Assessment seems to be a suitable tool for a stochastic durability analysis evaluation giving the engineer an idea of risk of corrosion initiation development over time. It can also serve as a bridge between theories of reliability and so called Integrated design serving as a tool for computation of probabilities of exceeding of specific performance criterion.

The thesis can serve as a tool for better prediction of deterioration of concrete from reinforced concrete with regards to chloride ion ingress, addressing the growing demand for desire to design long lasting structures in order to optimize the public costs, maintenance requirements, functional interruptions, natural resources, and environmental sustainability. The indicated road map to performance assessment of the bridge deck with respect to chloride ingress induced degradation process shows the value of improving the models with a modern reliability approach. It indicates the possibilities of simulation technique to address the durability issues with respect to randomness of input parameters. The bridge deck performance assessment with respect to chloride induced corrosion and thus durability is conducted using probabilistic approach addressing that way also one of goals of the *SHRP 2 Request for Proposals* (2007) for bridges with service life beyond 100 years on the example of conrete bridge deck with steel reinforcement protected by epoxy-coating. It is a typical structure e.g. in the northeastern United States.

The work gives an idea of stochastic reliability assessment of a bridge deck using SBRA method. The results show that penetrability of chlorides through concrete is one of the most significant variables governing durability of bridge deck with respect to ingress of chlorides. The study indicates the value of epoxy-coated reinforcement but calls for the improvement of handling and construction practices in order to reduce the number of holidays comparing to state indicated by (SOHANGHPURWALA et al., 1998).

The research brings the 2-D FEM chloride diffusion tool that tries to consider the interaction of the crack effect on the corrosion of reinforcement with holiday in epoxy-coating. It also allows comparison of obtained results to the situation with a crack above the black bar and to assessment of black bar without crack influence.

The Combination of SBRA Module and a commercial FEM package are allowed to repeat the 2-D diffusion problem within Monte Carlo simulation, with characterization of selected random variables by bounded histograms. The computational demand for this task is quite high. It takes days for 10 000 simulation steps. That is acceptable for the probabilities in order of percent, but not for demanding safety assessments. The application of combination of SBRA Module and ANSYS and direct Monte Carlo simulation in case of safety assessment without modifications is worth considering.

The performance assessments allow for quantifying the level of reliability for a particular age, but care must be taken when using the probability quantitatively. It should be noted that the resulting probability does not reflects ”real life” likelihood that certain performance is not met. In the discussed case of corrosion initiation, the vast amount of assumptions and simplifications made, and lack of overall scientific understanding of many complex and inter-related governing phenomena could not address the exact corrosion initiation likelihood. Quantitative application would require extensive model calibration. It, however, can be used quite effectively in the qualitative sense to compare possible structural and materials-related scenarios as shown in section 5 *Parametric Study*.

The discussed bridge deck model would be enhanced considerably by the incorporation of the early age stage (thermal effects, shrinkage, creep) especially with the modeling of the crack spacing and the depth. It would be able to help in addressing contradictory role of the concrete cover. Comparison of the reliability of the bridge deck from the Northeastern U.S.A. with bridge deck from the Central Europe would be also very helpful. The discussed topic needs more attention in the future as well due to its importance and complex nature.

Since the model is limited to the estimation of the corrosion initiation risk assessment only, it would be valuable to enhance the model capabilities by including the propagation phase of corrosion in order to evaluate also effect on the reduction of the carrying capacity due to the corrosion progress. Modeling of the propagation phase would add to a model new level especially the possibility of the safety assessment with respect to the reduced resistance due to a corrosion bringing the structural loading back to game. This stage would bring along new challenges.

Better characterization of random input variables is of particular interest, especially holiday frequency, crack depth, crack spacing. Ongoing research projects such as “High Performance Concrete” PennDOT project at Pennsylvania Transportation Institute at Pennsylvania State

University can be used to furnish valuable statistical distributions from data collected during the construction process of the full scale bridges built on the freeway I99 close to State College, PA. The bridge deck performance based on the data from (SOHANGHPURWALA et al., 1998) would be comparable with state-of-the-art one. Comparison with behaviour of the typical Central European bridge deck model would be also very interesting.

Since there is available model that can evaluate the random interaction of parameters affecting the bridge deck durability with respect to corrosion initiation, the future research should be also aimed in formation of nomograms for practicing engineers that would inform about the estimated lifespan for specified input parameters and acceptable probability of corrosion initiation.

The other possibility to bring a model closer to the field is to implement stand-alone program that would perform statistic analysis as well as FEM solution yielding information about bridge deck performance with respect to corrosion initiation.

The research in the area of reliability of RC bridge deck is valuable and deserves further attention especially due to the importance of long-lasting structures that can help to optimize the public costs, maintenance requirements, functional interruptions, natural resources, and environmental sustainability.

Závěry a doporučení pro další výzkum

Koroze vyvolaná chloridy je důležitý problém železobetonových mostovek, který zasluhuje pozornost. Nahodilost studovaného problému zejména s ohledem na kvalitu betonu, přesnost výroby a vlivy prostředí je výrazná. Je třeba ji vzít na vědomí. Simulation-Based Reliability Assessment je vhodná metoda pro stochastickou analýzu trvanlivosti. SBRA rovněž může sloužit jak nástroj pro odhad pravděpodobnosti poruchy v případě tzv. Integrovaných návrhů konstrukcí s ohledem na definovaná kriteria.

Práce má posloužit k prohloubení možnosti předpovědi degradačních procesů železobetonových mostovek s ohledem na působení chloridů. Je reakcí na rostoucí potřebu navrhovat trvanlivé konstrukce, tak aby bylo možno redukovat náklady veřejných rozpočtů, náklady na údržbu, provozní výluky, zátěž životního prostředí. Diskutovaný posudek užitnosti mostovky s ohledem na korozi vyvolanou působením chloridů naznačuje možnosti získané využíváním sofistikovaných spolehlivostních přístupů. Výzkum vyzvedává možnosti simulačních nástrojů v oblasti posudku trvanlivosti s ohledem na nahodilost vstupních parametrů. Pravděpodobnostní posudek užitnosti typické železobetonové mostovky severovýchodu Spojených Států s ohledem na korozi způsobenou vnikáním chloridů rovněž míří do jednoho z cílů projektu *SHRP 2* (2007), jehož cílem je návrh mostů na stoletou životnost.

Práce umožňuje získat představu stochastického posudku spolehlivosti železobetonové mostovky s využitím metody SBRA. Výsledky ukazují že propustnost chloridů betonem je jednou z nejvýraznějších proměnných ovlivňujících trvanlivost mostovky s ohledem na korozi vyvolanou chloridy. Ukazují rovněž na hodnotu epoxidovéhé ochrany výztuže, přičemž je nutno podotknout, že je nutno zlepšit vlastnosti povlaku tak aby byla proti (SOHANGHPURWALA et al., 1998) snížena frekvence poškození povlaku.

Součástí práce je vytvoření 2D model difuze chloridů, který se snaží zohlednit vliv trhlin na korozi výztuže s epoxidovou ochranou výztuže. Model také umožňuje porovnat získané výsledky se situací kdy se vliv trhliny projeví na nechráněné výztuži, nebo se situací bez vlivu trhliny.

Kombinace metody SBRA a komerčního MKP systému umožňuje opakovat 2D problém v rámci simulace Monte Carlo při charakterizaci vybraných náhodně proměnných za pomoci histogramů. Je nutno připustit, že výpočetní náročnost zvoleného řešení je značná, a že řešení 10000 simulačních kroků trvá dny. Toto je akceptovatelné v případě cílových pravděpodobností v řádu procent, ale neuspokojivé pro náročné posudky bezpečnosti. Aplikaci zvoleného přístupu kombinace SBRA Modulu a ANSYSu pro takové případy je nutno zvážit.

Je třeba zdůraznit, že u vyhodnocení vypočtených pravděpodobnostní poruchy je na místě opatrnost. Vypočtené pravděpodobnosti představují míru spolehlivosti, ne však skutečnou pravděpodobnost výskytu sledovaného jevu. V diskutovaném příkladě vede velký počet předpokladů a zjednodušení v důsledku komplexnosti studovaného problému a mnoha vzájemně provázaným vztahům k tomu, že vypočtená pravděpodobnost vzniku koroze není pravděpodobnostní skutečnou. Tato hodnota ovšem velmi dobře poslouží při porovnání alternativních materiálových a konstrukční řešení jak je ukázáno v kapitole 8 disertační práce nazvané *Parametrická studie*.

Model mostovky by mohl být výrazně vylepšen zakomponováním chování mladého betonu (tepelná roztažnost, smršťování a dotvarování) s ohledem na vznik trhlin, jejich frekvenci a hloubku, což může pomoci ve zhodnocení protichůdné role krytí.

Rovněž období vývoje koroze by bylo cenným obohacením modelu, vzhledem k omezení modelu na období iniciace, čímž by bylo možno zhodnotit pokles únosnosti s ohledem na úbytek průřezové plochy výztuže. Modelování fáze rozvoje koroze přidá modelu nový rozměr, a to zejména s ohledem na možnost vrátit fyzické zatížení zpět do hry posudku spolehlivosti.

Vylepšení popisu náhodně proměnných je rovněž podstatné pro další rozvoj, zejména s ohledem na frekvenci poškození epoxidového povlaku výztuže, hloubku trhlin a jejich frekvenci. Jako podklad pro popis náhodně proměnných může sloužit probíhající výzkumný projekt na Pennsylvania State University, kde jsou sbírána data z konstrukce dálnice I99. Porovnáním těchto dat s daty ze (SOHANGHPURWALA et al., 1998) lze porovnat chování moderních mostovek s mostovkami budovanými před 15, 20 lety.

Diskutovaný model rovněž může sloužit v kombinaci s doplněnými statistickými podklady jako podklad k nomogramů pro praktické inženýry, usnadňujícím odhady životnosti mostovek s ohledem na pravděpodobnost vzniku koroze ve vztahu ke zvoleným parametrům a úrovni spolehlivosti.

Pro náročné posudky bezpečnosti je vhodné se poohlédnout vzhledem k velké časové náročnosti zvoleného řešení po sofistikovanějším simulačním nástroji s ohledem na vysokou výpočetní a tedy časovou náročnost těchto úloh danou kombinací MKP systému ANSYS a přímé Monte Carlo simulaci. Efektivní by mohlo být rovněž naprogramování zvolené MKP úlohy ve formě knihovny, kterou je možno napojit na spolehlivostní programový balík typu Monte (MATERNA, et. al., 2006) či Freet (NOVÁK, et. al., 2003, www.freet.cz).

Výzkum v oblasti trvanlivosti železobetonových mostovek je cenný a zasluhuje další pozonost zejmána s ohledem na důležitost dobré predikce degradačních procesů, které umožní inženýrům lépe navrhovat betonové konstrukce a systémy s ohledem na dlouhodobé působení prostředí a zatížení.

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ANNEXES

A. Macro for 2-D Diffusion in ANSYS

A.1 Introduction

A.1.1 Analysis Control Overview

Finite element analysis may run in ANSYS (ANSYS, 2005) in an interactive mode using Graphical User Interface (GUI), in a batch mode using available ANSYS commands in command line or using macros that consists of commands and also program flow controlling elements. Using GUI mean that one access commands by the help of the interface that actually invokes them.

Utilization of GUI is much easier than controlling analysis using commands written with macros but GUI controlled analysis does not provide much assistance in terms of task analysis atomization. Using macros provide a user with a powerful tool for management of tasks that are frequently repeated.

For example if one needs to do multiple analysis of the 2-D chloride diffusion problem with different input then it would mean plenty of mouse clicking using GUI (Model creating) or invoking one command in command line using properly prepared macro to solve this problem. Preparing problem in the form of macro is also necessary for probabilistic analysis in ANSYS using ANSYS *Probabilistic Design System*.

A.1.2 Macros

ANSYS program allows writing the sequence of its commands into a macro file to automate common tasks. This macro file is a plain text file with extension *mac* placed, for example, into working directory. The task is invoked by typing the name of the macro into command line.

ANSYS provides a simple and robust tool to help create simple macros. It is the *Log* function that records invoked commands from the command line as well as from the GUI. These commands are recorded to file that may be accessed from the *Menu – List – Files - Log file.*

Since it is almost impossible to know all ANSYS commands, it is usually convenient to run the analysis using GUI and then extract the selected instructions from the *Log File* as a new macro. The created macro may include whole job (definition of analysis type, utilized elements, defined material properties and real constants, generated nodes and elements, selected boundary conditions, analysis solution and even post processing).

A job that is managed by a macro created from the *Log File* repeast exactly the task performed using GUI. If one needs to perform more sophisticated analysis than *ANSYS Parametric Design Language* (APDL) macro language is available.

A.1.3 APDL Macro Language

A scripting language is used for automation of common tasks or even building a model in terms of variables (called in ANSYS parameters). It encompasses a wide range of command repeating, *if-then-else* branching, *do*-loops, scalar, vector and matrix operations and text files input-output management procedures.

APDL scripting language is an essential tool for probabilistic analysis governed by the Monte Carlo simulation because FEM transformation model needs to be repeated thousands and thousand times, which would be almost impossible manually using GUI.

A.2 Model Overview

A.2.1 Principle

Chloride diffusion model is meant to compute chloride concentration in the most exposed epoxy-coated steel reinforcements location (holiday) throughout its life span with consideration of effect of crack on the chloride ion penetration. Example of such a model was presented in the previous text.

This task needs to be automated in order to perform probabilistic Monte Carlo simulation beginning with diffusion coefficient, through nodes and elements assembly, followed by boundary conditions constraint application, solution and post processing. Next to post processing is formulation of reliability function that includes comparison of worst-case chloride concentration with chloride threshold value (chloride ion concentration that allow for corrosion to proceed). Recording of reliability function with other interesting variables is included in post processing. The last procedure is task clearing (removing all elements, nodes and variables) in order to start another simulation in the next Monte Carlo simulation step.

The *2-D Diffusion Macro* may be invoked in ANSYS using command `di_2d_d` with proper arguments that specifies diffusion coefficient, depth of slab, meshing precision, life span of structure etc. Sample of script for running diffusion macro is in Annex F on the DVD-ROM.

A.2.2 Structure of the Diffusion Macro

The first part of the macro, *VARIABLES,* overviews variables. Following the part *INPUT*

VARIABLES describes the default input values while section *DEPENDENT VARIABLES* defines variables that are needed next. It declares arrays that stores coordinates of the crack tip, coordinates of all holidays, and selected times to be investigated. It also prepares the array for concentration at worst hit holiday and reliability function time-dependent information storage.

In the *PREPROCESSOR* part is selected element PLANE55 that is used for thermal analysis as explained in the part 0. There is specified diffusion constant in the place of thermal conductivity and other parameters density and specific heat are set to 1.

There are created nodes and elements in the subsection Modeling. They are created by direct generation because there is a need to have control over the exact position of each node and element for automated post processing. This procedure was selected instead of solid modeling that creates elements and nodes by meshing from complete geometrical shapes. Commands `N` and `E` are used for geometry building.

Boundary conditions are applied once geometry is created. Chloride background concentration is applied vie `TUNIF` command. Surface chloride concentration is applied using `D,NODE#,TEMP` command on the surface layer of nodes. Crack is created virtually by application of chloride concentration on the closest nodes to the crack. Position of the crack tip is refined by the change of crack last node position using `NMODIF`.

Details of the transient analysis along with task may be defined now in the *SOLUTION* section followed by `SOLVE` command. There is initial time step defined as well as duration of simulation (that reflects analyzed time period) set there.

When the finite element analysis is done, post processing is coming. Nodal solution (chloride concentration) for all nodes and time steps is copied to `TABLE ARRAY` for further processing. This special feature allow for convenient interpolation of results between nodes.

Concentration at worst exposed holiday of the epoxy-coated rebar is extracted from the chloride concentration array for time steps being analyzed and compared with chloride threshold level yielding into reliability function.

And the last part consists of clearing process. There are deleted all elements, nodes and arrays in order to begin next simulation step from the scratch. This part may be skipped if preformed in a deterministic way.

Analytical 1-D analytical model is also performed for the controlling purposes at the very end of the diffusion macro.

A.2.3 Description of the Diffusion Macro (di_2d_d)

The model is introduced in section 4.2.4. The details are explained here. The computation starts with the effective diffusion coefficient D_c conversion to m^2/year followed by the other dependent variables computation. The model *width* is computed next from unit width $width_u$ and width extension $width_e$.= 0.3 m. Unit width is part of the bridge deck that is of interest. The width extension of model serves to avoid problems with cracks modeled near the model edge.

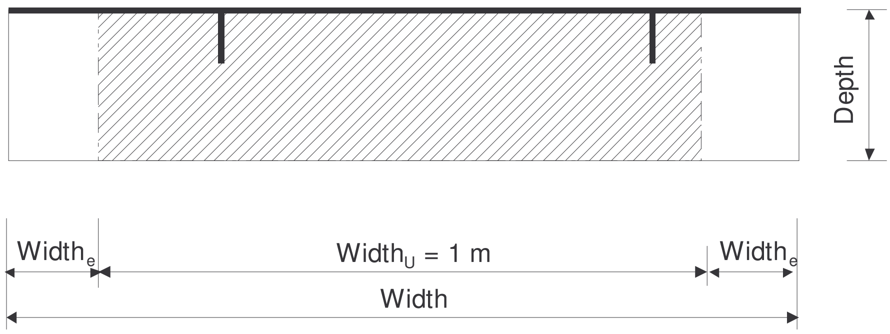


Figure *53: Model Dimensions.*

$$width = width_u + 2\ width_e \qquad /19/$$

A.2.3.1 FEM Mesh Parameters

The FEM mesh consists of elements and nodes. The computation of nodes numbers and distances in horizontal as well as vertical direction follows. The number of elements in vertical direction $vert_{elem}$ is computed next from the deck *depth* and relative number of nodes $vert_{elem,r}$. Sufficient precision is satisfied with $vert_{elem,r}$ = 100 per meter.

$$vert_{elem} = \mathtt{nint}(vert_{elem,r} \times depth) \qquad /20/$$

There are also determined the horizontal and vertical distance of the nodes (element sizes). $\Delta node_x$ is horizontal distance and $\Delta node_y$ vertical distance.

$$\Delta node_x = width / (\ vert_{elem} \times width / depth) \qquad /21/$$

$$\Delta node_y = depth / vert_{elem} \qquad /22/$$

The model consists of n_{nx} horizontal and n_{ny} vertical nodes:

$$n_{nx} = \mathtt{nint}(width / \Delta node_x + 1) \qquad /23/$$

$$n_{ny} = vert_{elem} + 1 \qquad /24/.$$

A.2.3.2 Crack

The `nint()` is function for rounding to whole integer and is used also in the next equation in order to compute number of cracks $crck_n$ per modeled slab *width* derived from spacing $crck_s$.

$$crck_n = \texttt{nint}((width_u - crck_i) / crck_s) \qquad /25/$$

The initial crack position $crck_n$ depends on the crack spacing $crck_s$ and relative crack position $crck_{i,rel.}$

$$crck_i = crck_{i,rel} \times crck_s \qquad /26/$$

If the Equation /25/ yields the number of cracks equal to zero (the crack spacing is greater than the model width) then the crack modeling depends on the initial crack position $crck_i$. Crack is modeled if the $crck_i \leq width_u$. In the other case there is no need to model crack and the task is reduced to a 1-D problem and the number of cracks considered $crck_n$ equals zero, and there are only two nodes in the horizontal direction ($n_{nx} = 2$, see Figure 63).

Coordinates of the crack tips are stored in the array *crack* that is 2 by $crck_n$ and stores both x as well as y coordinate of the respective crack tip. Horizontal position of the other cracks is computed using the crack spacing $crck_s$ and the horizontal coordinate of the first crack $crck_i$.with $width_e$ added. The cracks are dispersed evenly based on the spacing and their respective number i_{crck} (ranging from 1 to $crck_n$). The depth of all cracks is assumed the same. The depth is equal to crack depth parameter $crack_{de}$.

$$crack_i = \begin{bmatrix} horizontal\ position \\ vertical\ position \end{bmatrix} = \begin{bmatrix} crck_i + width_e + (i_{crck} - 1) crcks_s \\ - crack_{de} \end{bmatrix} \qquad /27/$$

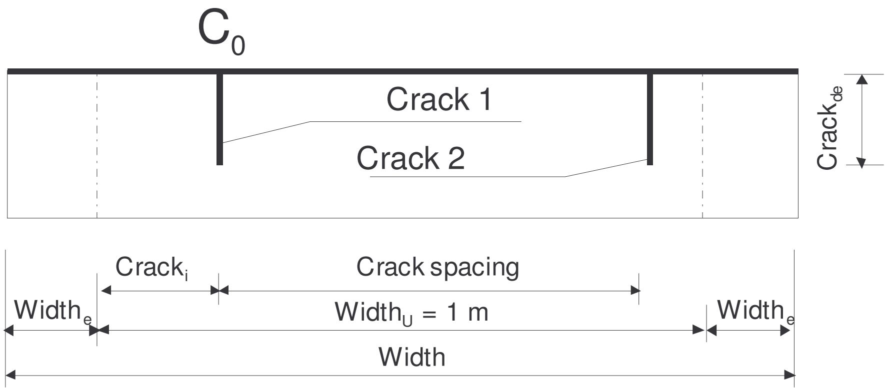


Figure 54: Distribution of cracks

If there is no crack in the model, Equation /25/ yields that $crck_n$ equals zero, than crack depth $crack_{de}$ is considered to be zero and horizontal crack position $crck_i$ is only formally considered as half of the *width*.

A.2.3.3 Holidays

The positions of the holidays, mashed areas, scratches and other flaws that allow chlorides to penetrate through the epoxy-coating are described by the array *Mashed* that is 2 by $mash_n$.(number of holidays per *width* / meter).

$$mash_i = \begin{bmatrix} horizontal\ position \\ vertical\ position \end{bmatrix} = \begin{bmatrix} (mash_i + i_{mash} - 1)mash_s + width_e \\ -reb_d \end{bmatrix} \qquad /28/$$

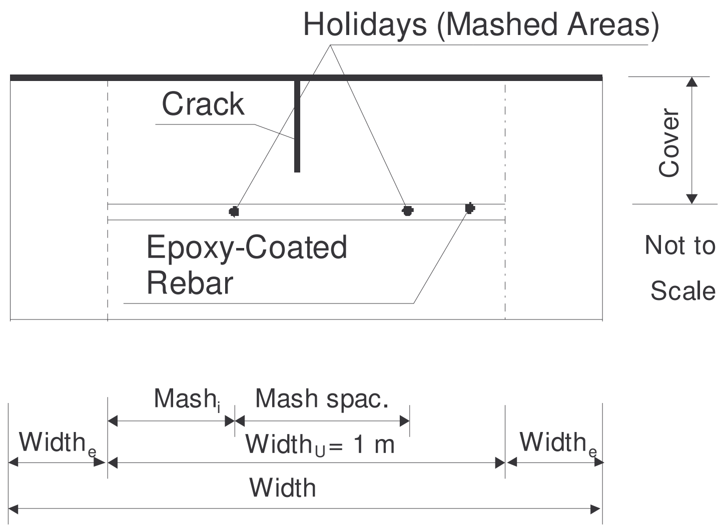


Figure 55: Distribution of Holidays and Mashed Areas.

Where depth of the holiday is considered the depth of the top of the steel reinforcements reb_d, rank of the holiday is i_{mash}, and $mash_i$ is a relative position of the first holiday within holiday spacing $mash_s$ that is

$$mash_s = 1 / mash_n \qquad /29/.$$

Holiday distribution is also assumed uniform based on their frequency per meter of steel reinforcements $mash_n$. If the holiday number is zero then the position of the holiday is set to be half of the first's crack position $crck_i$.

If there is no crack in the model $crck_i \leq width_u$ than all the results (2-D with crack and holidays, 2-D with crack above black bar, and reference are taken from the left edge of the reduced 1-D model.

A.2.3.4 Variables for Time Stepped Results

The arrays needed for the time dependent results analysis are initialised in this section. Array $time_{tab}$ stores the exposure times for chloride penetration evaluation. If the number of results to be evaluated ($n_{time,res}$ is 5 and the exposure time t is 50 years than $time_{tab}$ = [10 20 30 40 50].

The resulting concentration of chlorides is stored in table-form array called $time_{\text{concentration}}$. `Table` array allow for easy interpolation of results in order to find results between the FEM mesh nodes. Each position in the array represents a particular node in the FEM mesh.

Array $time_{\text{SF}}$ is intended for performance function *RF* storage while estimated lifespan of acceptable performance (until corrosion initiation) is stored in the $life_{\text{span,tab}}$. Both arrays are of length $n_{\text{time,res}}$+1, and width 4. They store the results for 2-D FEM solution, 1-D reference FEM solution 1-D analytic solution, and 2-D FEM with black bar solution

The estimated lifespan $life_{\text{span,tab}}$ is computed from $life_{\text{span,sf}}$, $life_{\text{span,sf,r}}$, $life_{\text{span,sf,a}}$, $life_{\text{span,sf,b}}$ that are based on the 2-D FEM solution, 1-D reference FEM solution, 1-D analytic solution, and 2-D FEM with black bar solution respectively.

The Reliability function for the zero exposure is equal to plain subtraction of chloride threshold C_{th} and chloride background C_{b}.

A.2.3.5 Element Selection and Properties

The FEM model starts here by selecting element type PLANE55 that allows to solve transient thermal problems. The diffusion is solved using thermal - diffusion analogy. Thermal conductivity is set to be diffusion coefficient D_{c} while thermal capacity and density are set to 1.

A.2.3.6 Nodes and Elements

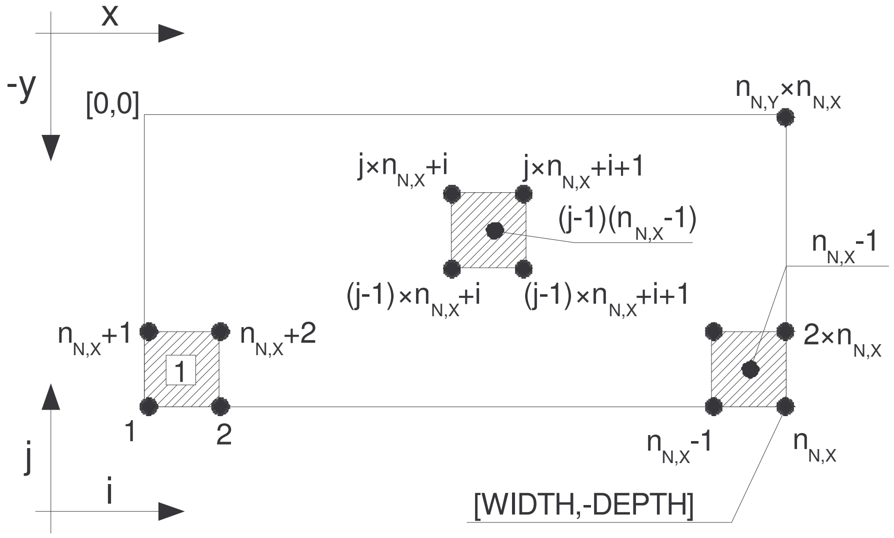


Figure 56: Nodes and Elements Numbering
(n_{nx} and n_{ny} is number of nodes in horizontal and vertical direction respectively)

The nodes are created right-wise from left bottom corner. The first row is built using the command

N and the other rows are copied from that pattern by NGEN. The elements follow the same system as nodes. The first element is built in the left bottom corner using E command. The others are copied from that pattern. See Figure 56 for details.

A.2.3.7 Boundary Conditions

Boundary condition is the chloride concentration at the surface and in the crack. Surface concentration C_0 is applied on the top layer of nodes. Crack effect is modeled by application of the chloride concentration at the respective nodes. The command D is used.

There is a loop for creating as much cracks, as $crck_s$. The ranks of the node near the crack tip are determined both in horizontal n_{cx} as well as in vertical n_{cy} direction. The i_{crck} represents the loop variable for particular crack.

$$n_{cx} = \mathrm{nint}(\ crack[1,i_{crck}]/\ \Delta nod_x)+1 \qquad /30/$$

$$n_{cy} = n_{ny} + \mathrm{nint}(\ crack[2,i_{crck}]/\ \Delta nod_y) \qquad /31/$$

The vertical position of the node that represents crack tip is modified in order to obtain the results of sufficient precision using the command NMODIF.

A.2.3.8 Solution

The transient thermal analysis is solved with automatic time stepping and initial time step $time_{inc}$ that depends on the diffusion constant as well as the size of the element as discussed in e.g. in Verification manual example VM164 of ANSYS (2005).

$$time_{inc} = \Delta nod_y^2\ /\ 4Dc \qquad /32/$$

In case that the $time_{inc}$ is greater than the first time for result evaluation described in $time_{tab}$ the latter value is applied. Solution time stepping is applied by command DELTIM and is not related to evaluation of results for particular exposure time defined by $time_{tab}$. The results for the specified time frame are stored using OUTRESS command.

A.2.3.9 Postprocessor

The results of the chloride concentration analysis are stored in the table form array *concentration* that is n_{nx} by n_{ny} by $n_{time,res}$. It means that the concentration is acquired by invoking GET command for each node in selected time according to $time_{tab}$.

The concentration for the diffusion analysis with respect to crack effect and holiday position is searched in each of the holiday locations defined by the *mashed* array and the greatest concentration is considered to be the most exposed one. The results are stored in the temporary variables that are named cx_{year}, where *year* represents the timeframe of the respective result.

The reference concentration $cx_{\text{r,year}}$, is computed at the right edge of the entire model including extension in order to address the 1D behavior of the numerical solution.

There is also analytical solution computed $c_{\text{anal,year}}$ according to Equations /5/ and /9/ The resulting reliability functions $sf_{\text{,year}}$, $sf_{\text{r,year}}$, $sf_{\text{anal,year}}$, and $sf_{\text{b,year}}$ are computed using chloride threshold C_{th} according to Equation /33 /.

The results are also prepared for the graphical plot in the arrays $time_{\text{concentration}}$ and $time_{\text{sf}}$. Life span of a bridge deck with acceptable performance is also computed at the end of the macro for all considered alternatives.

A.3 Deterministic Solution

Deterministic run of the 2-D bridge deck chloride diffusion performed in this section. The task is to compute concentration of chlorides at the most exposed location of epoxy-coated steel reinforcements with crack influence considered and also assess if the corrosion initiated.

A.3.1 Nominal Input

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 and concrete chloride background concentration is not taken into account. Top clear concrete cover over the top layer of steel reinforcements is 0.075 m. Diffusion coefficient, D_c is 1.55×10^{-5} m^2/year (4.91×10^{-12} m^2/s), chloride threshold C_{th} is 0.2 percent. Width of the investigated slab is 1 m. The deck depth is 0.23 m. Crack spacing C_{rcks} is 0.7 m. Initial position of the crack $Crck_{\text{i}}$ is 0.35 m, and crack depth C_{rck_de} is 0.027 m.

The number of holidays $Mash_n$ considered is 2 per meter of the steel rod, and the initial crack $Mash_i$ is 0.25 m from the right edge of the slab. It is the half of the spaces between epoxy flaws $Mash_s$. The frequency of holidays here as 2 per meter of the reinforcement is selected in order to show the possibilities of the model.

A.3.2 Transformation Model

The FEM model can be seen on the Figure 57. One can see that the crack depth is a relatively small comparing to the deck depth even though crack tip is half the cover thickness. The surface chloride concentration is on the top nodes and on the nodes that represents the crack. It is represented by red triangles on the Figure 57. There are also schematically drawn holidays on the reinforcement and investigated width of the FEM model.

A.3.3 Load Effect Combination – Chloride Concentration

The resulting chloride concentration distribution on the slab after the 10 years exposure can be seen on the Figure 58. One can noticed the crack influence in the upper right corner.

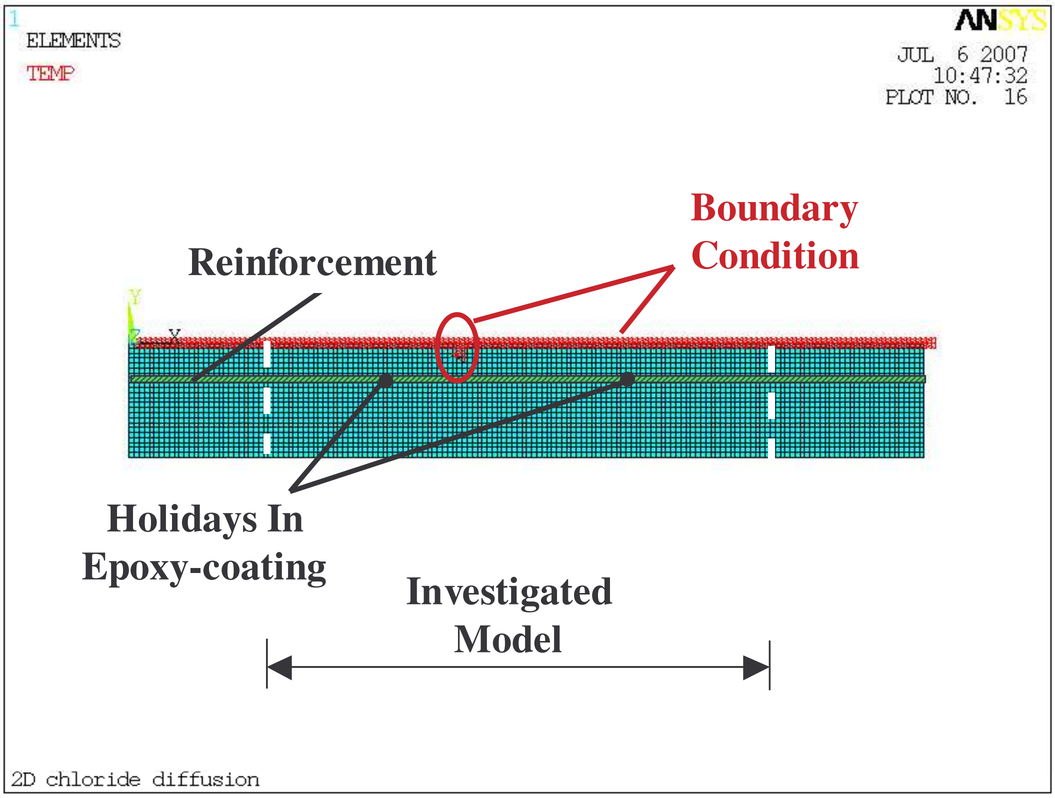


Figure 57: Slab with Crack Considered - FEM Model

Chloride concentration C_{xy} at the most exposed holiday at the reinforcement for 10 years of exposure is 0.11 %. Concentration on the uncoated bar under the crack for 10 years exposure C_{xy} is 0.14 percent. The concentration without crack effect considered was 0.11 percent. It coincide with analytical solution as computed using Equation /9/.

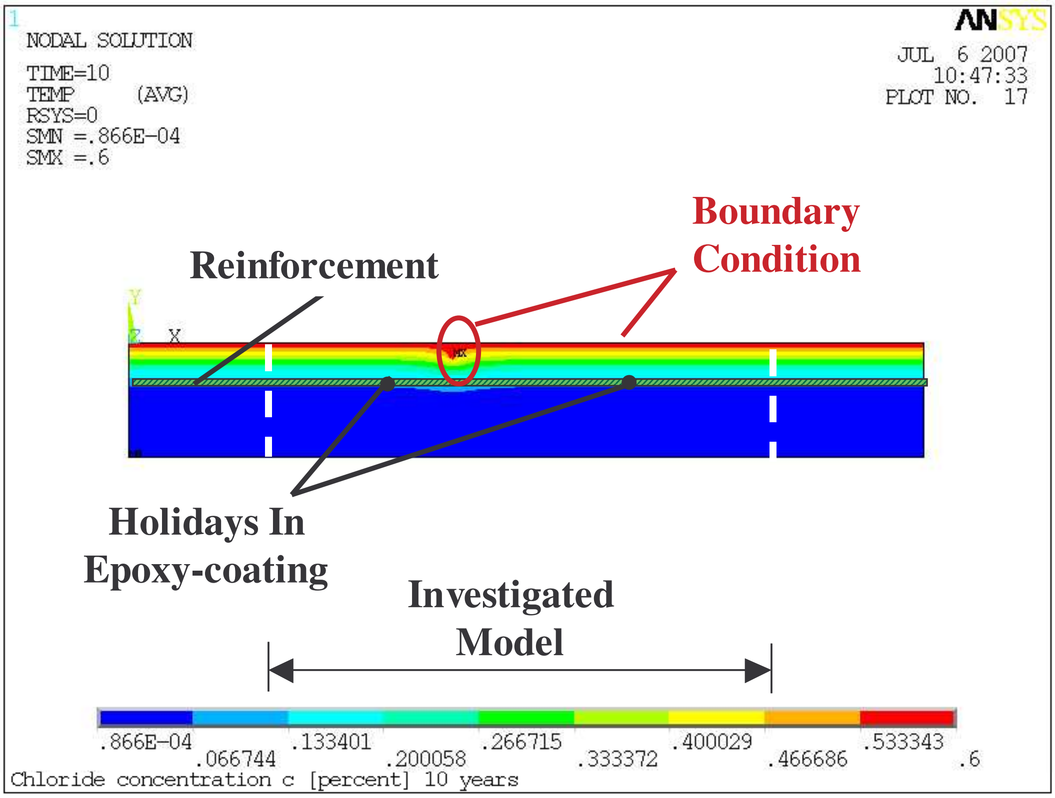


Figure 58: Chloride Concentration on the Slab with Crack (10 years exposure)

A.3.4 Performance Check

The corrosion is assumed to initiate when the chloride ion concentration exceeds chloride threshold at the rebar level. The reliability condition is satisfied if $RF > 0$.

$$RF = C_{th} - C_x > 0 \qquad /33/$$

Considering chloride threshold C_{th} = 0.2 percent according to ACI, then reinforcement would not start to corrode under specified circumstances.

The performance check for ten-years' exposure reveals that corrosion has not started. Chloride threshold C_{th} is higher than chloride concentration C_x.

A.3.4.1 Time Effect

Considering the nominal model parameters as discussed above then the chloride concentration during the 50 years exposure can be computed along with performance check that is modified for the analysis of the time effect.

$$RF_t = C_{th} - C_{x,t} > 0 \qquad /34/$$

The corresponding concentration is computed during 50 years of service. Comparison of chloride distribution for 10 and 50 years can be seen on the following figures.

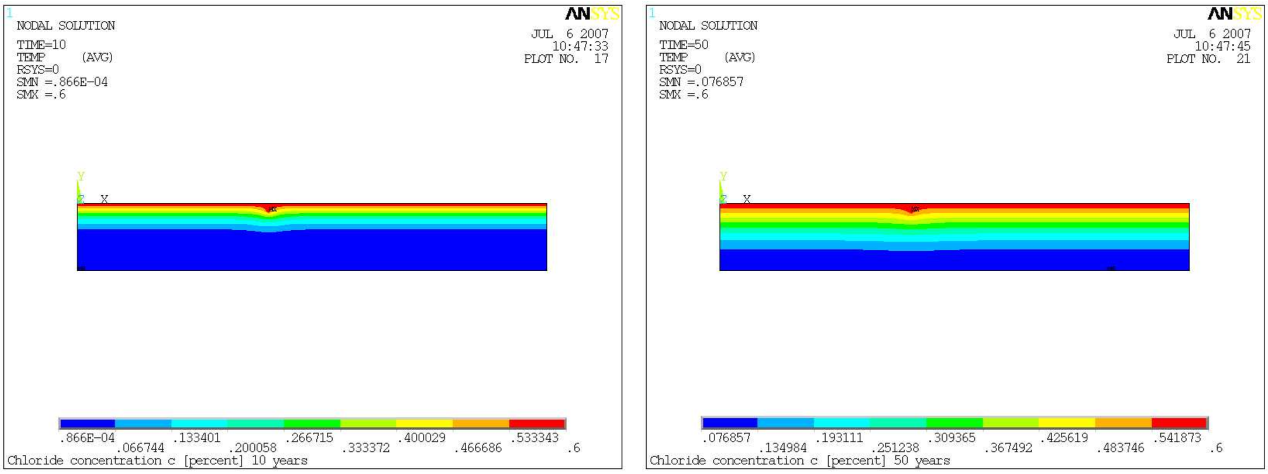


Figure 59: Chloride Concentration on the Slab with Crack (left 10 and right 50 years exposure)

Corresponding time-dependent concentrations under the crack(C_{xyt}) are shown in Table 6 and depicted on the Figure 60. The influence of the crack seems to be the same throughout the considered 50 years.

Table 6: Effect of Time on the Chloride Concentration $C_{xy,t}$ with Crack Considered.

Years		*0*	*10*	*20*	*30*	*40*	*50*
C_{xyt}	Crack	0.00	0.11	0.21	0.27	0.31	0.34
$C_{black\ bar}$		0.00	0.14	0.24	0.29	0.33	0.35
$C_{reference}$	No Crack	0.00	0.11	0.20	0.26	0.30	0.32
$C_{1D\text{-}analytic}$		0.00	0.11	0.20	0.26	0.30	0.32

The results are also plotted in the next figure. The reference value - chloride threshold C_{th} is considered as 0.2 %. It can be seen that the bridge deck with epoxy-coating and crack considered would perform without corrosion for 19 years, while a black bar 16 years only. If the ideal bridge deck without cracks were considered, it would not corrode for slightly more then 19 years of exposure.

A.3.5 Summary

The 2-D FEM analysis with deterministic nominal input shows the possibilities of the model to consider the interaction of the crack effect on the corrosion of reinforcement with holiday in epoxy-coating (C_{xyt}). The model also compares the results to situation with crack above black bar (*Black bar*). The 1-D numerical solution that represents situation without the crack and coating considered (*Reference*) coincide with analytic solution (*Analytic*) that yields the same results here).

The plot shows that the epoxy-coating in the presented case helps to protect the reinforcement considered above-mentioned assumptions. For detailed inputs and results refer to Annex D on DVD-ROM

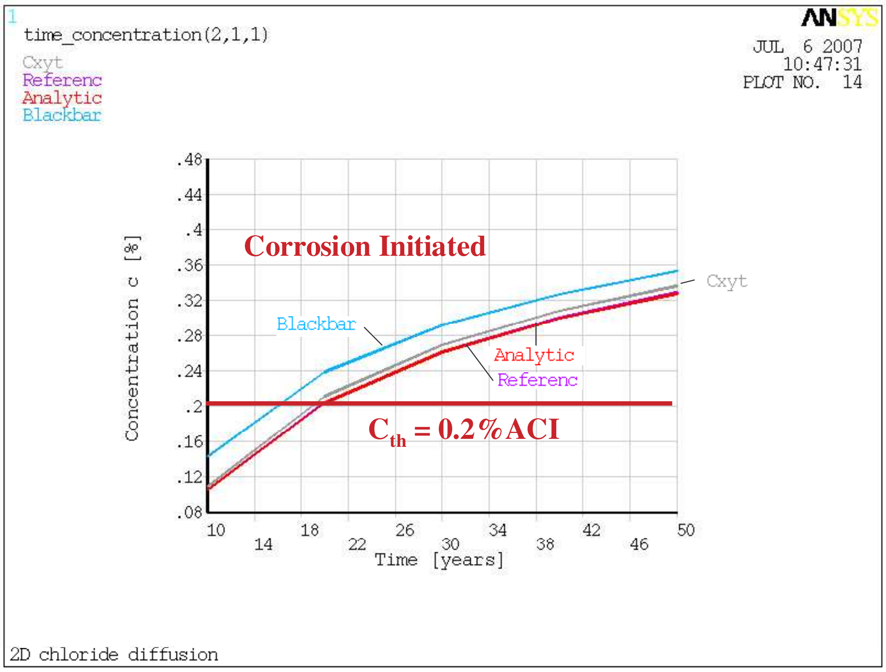


Figure 60: Chloride Concentration C [%] on the Slab with Crack and Epoxy-coating Considered (C_{xyt}) the Reinforcement is without Protection (Black bar), without Crack Influence (Reference), 1-D Analytical Solution (Analytic).

A.3.6 Alternative Input Parameters

The bridge deck model with input, as discussed in section A.3.1, is evaluated with changes in parameters such as frequency of holidays, crack spacing or crack depth. The results of 1-D solutions (Reference and Analytic) do not change though. The complete input parameters and results are to be found in Anex C *Deterministic Results*.

A.3.6.1 Holiday Frequency

If the number of holidays per rebar meter is increased from 2 to 10 then the behavior of epoxy-coated reinforcement is similar to the black bar. The chloride concentration plot is showed next. For details refer to Annex C.2 on DVD-ROM.

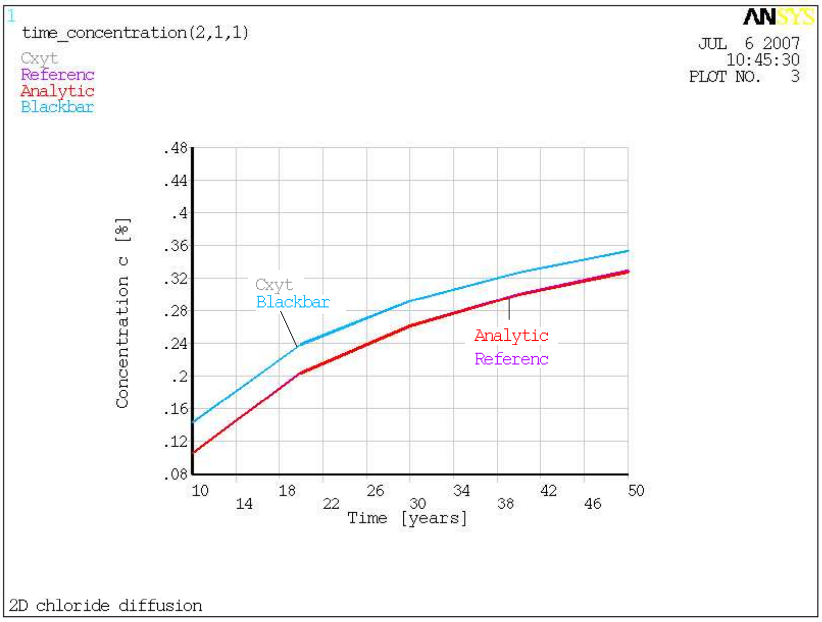


Figure 61: Chloride Concentration C [%] on the Slab with Crack and 10 Holidays[m^{-1}] on Epoxy-coating (C_{xyt}) behave as the Black bar, without Crack Influence (Reference), 1-D Analytical Solution (Analytic).

A.3.6.2 No Holidays

If there are no holidays present then the concentration at the reinforcement is assumed to be zero. The Chloride concentration C_{xy} is in the bottom of next chart. For details refer to Annex C.3 on the attached DVD-ROM.

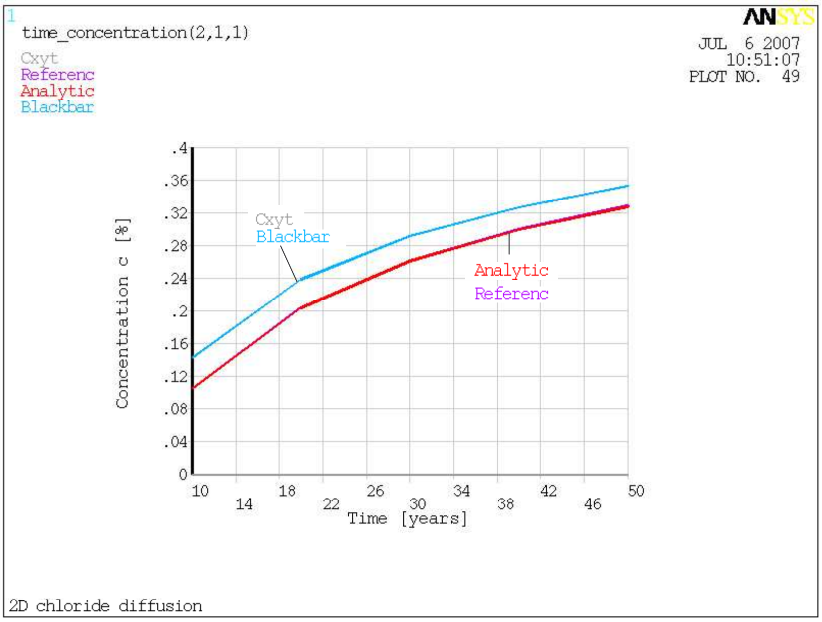


Figure 62: Chloride Concentration C [%] on the Slab with Crack and No Holidays in Epoxy-coating (C_{xyt}), Black Bar, without Crack Influence (Reference),1-D Analytical Solution (Analytic).

A.3.6.3 Crack Spacing

If the crack spacing, and especially initial crack position, is higher then width, than the 1-D problem is solved only. The crack would be positioned outside of the model. Cracks spacing is changed from 0.7 to e.g. 30 meters. The model elements are showed next.

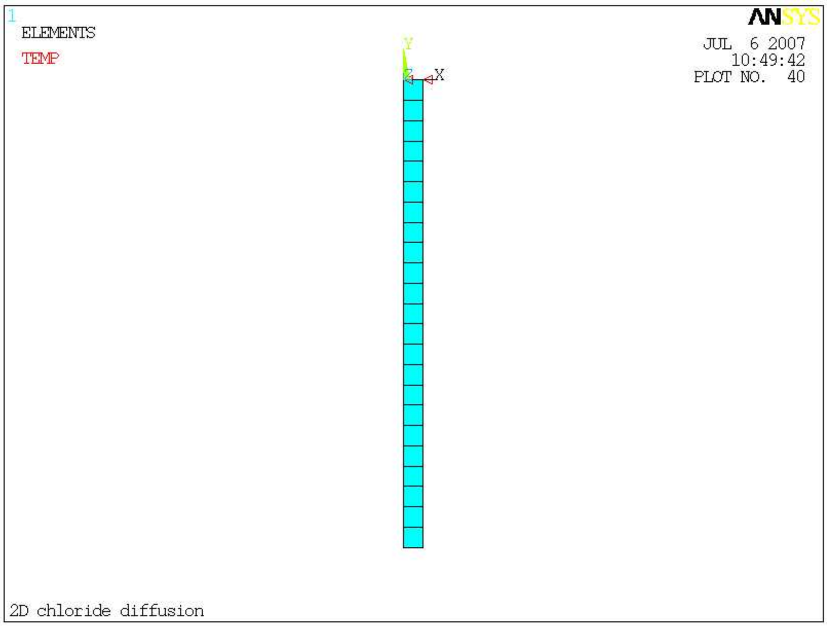


Figure 63: FEM Model Elements, Crack Position is Outside of the Model
1-D Solution is considered Only.

The resulting chloride concentrations for all considered cases (Epoxy-coating, Black bar, 1-D solution) follow the same pattern, as does the plot on the next Figure. For details refer to Annex C.4 on the attached DVD-ROM.

A.3.6.4 Deeper Crack

If the crack is deeper than the initial 0.027 to e.g. 0.038, then the difference between the Black bar and 1-D solution is stronger. The reinforcement is in depth of 0.075 mm. The difference can be illustrated at the concentration at the 50th year of lifespan, for instance. The chloride concentration at the most exposed holiday remains 34 percent while concentration at the uncoated reinforcement increased from 35 to 37 percent. For details refer to Annex C.5 on enclosed DVD-ROM

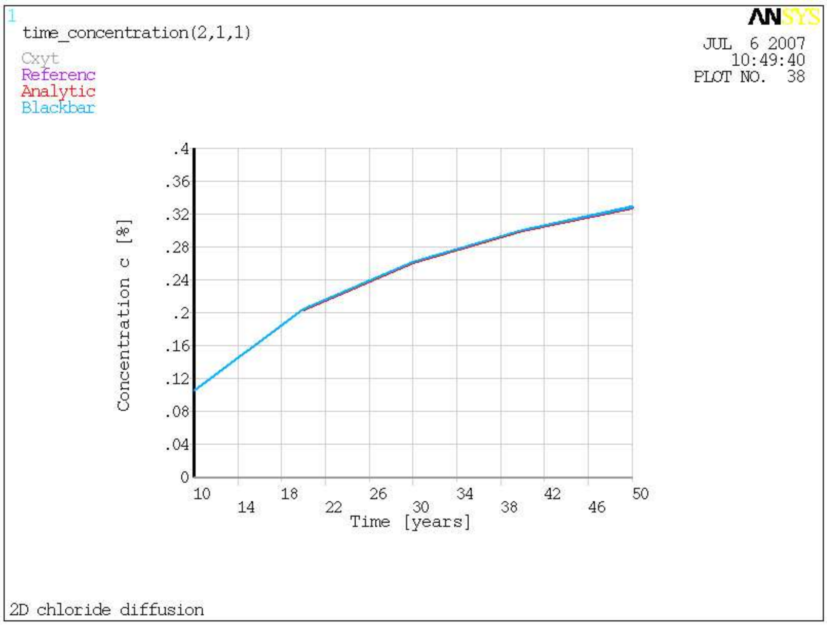


Figure 64: Chloride Concentration C [%] on the Slab with Crack Position Outside the Model, All Cases Follow the Same Pattern.

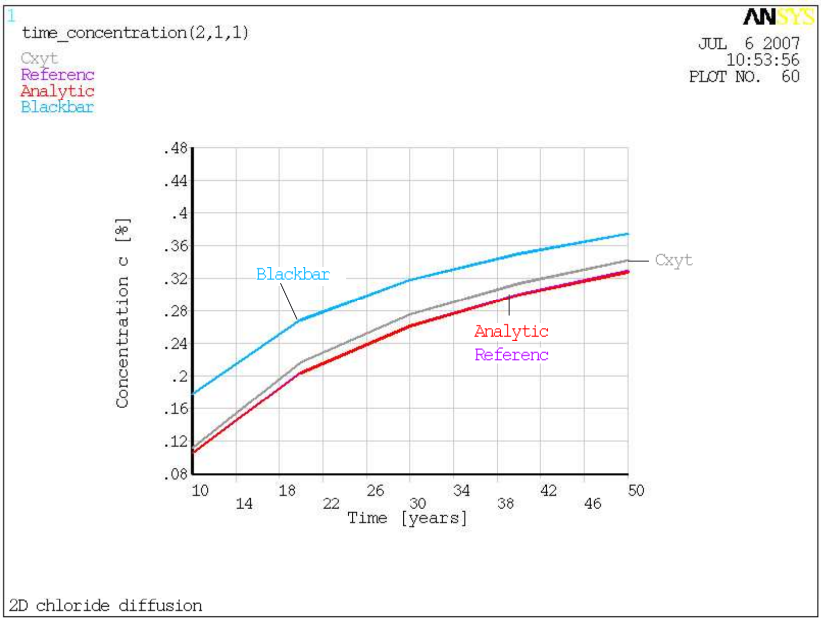


Figure 65: Chloride Concentration C [%] on the Slab with Deeper Crack Considered Epoxy-coating (C_{xyt}), Black Bar, without Crack Influence (Reference),1-D Analytical Solution (Analytic).

A.3.7 Finding and Discussion

If the number of holidays exceeds 10 than the epoxy-coated system behaves in a similar manner as a black bar. The concentration at the most exposed holiday is similar to that of uncoated reinforcement. If the crack spacing is larger than the width of the model than all the model cases (epoxy-coating, black bar and 1-D reference) behave the same. Corrosion pitting would start on the real structure at the isolated locations of the holidays only while the uncoated reinforcement would corrode more uniformly. The deeper crack made differences between coated and non-protected case more significant.

It needed to be highlighted, though, that the model says that corrosion on that particular meter of the bridge deck has started. It does not compare the corrosion severity. It is relative measure of the performance only that is related to the assumption made.

B. Probabilistic SBRA Module for ANSYS

B.1 Introduction

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 author 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 e.g. 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.

B.2 Structure of the SBRA Module

SBRA Module is interface between ANSYS Probabilistic Design System PDS and user defined FEM macro (see Figure 66). ANSYS program allows for the performance assessment of the stochastic analysis involving finite elements. Random variables are described in the ANSYS PDS by parametric distributions such as normal, beta, etc. PDS also allows for the Monte Carlo simulation, including post processing.

Since the uniform distribution can be generated by the PDS one can use it as a primary generator for the SBRA module that can generate random variables characterized by the bounded histograms. The input file is attached in Annex F on DVD-ROM The input histograms do have the same format that is applicable also for Anthill for Windows (see www.sbra-anthill.com). The algorithm of the SBRA module is based on the work of (PRAKS, 2002, 2006).

B.3 FEM Analysis using the SBRA Module

B.3.1 Building the FEM Macro

The formation of the FEM macro with respect to assessed task is the first step (see section A.1 for details). The macro may be created e.g. using the Graphic User Interface (GUI) with latter utilization of commands logged into Log file (see next). The commands are to be written into the macro file using APDL scripting language.

The model consists especially from:

- Element and its properties definition,
- Geometry,
- Model building (direct node and elements generation is recommended),
- Constraints and boundary conditions application (supports, loading),
- Analysis type selection (structural, thermal etc.),
- Solution,
- Reliability function evaluating (selection of the results onto suitable parameters and performance of the reliability assessment).

If the commands for the task evaluation are known, it is time for the macro building. This macro automates the FEM analysis for future probabilistic analysis in the ANSYS framework. The macro may be written even without GUI usage because its plain text file with the extension **.mac*. It can be called e.g. `fem.mac`

Another condition that needs to be met is replacement of the deterministic numbers in the macro by the variables called parameters in ANSYS.

B.3.2 SBRA Module Adjustments

There is governing macro (see Annex F on DVD-ROM) for the histogram-based variables characterization and for the FEM analysis invoking called eg. `fem_hisg.mac` where *fem* stands for the name of the FEM task. This macro along with the command library `pdshisg.mlib` represents the SBRA module.

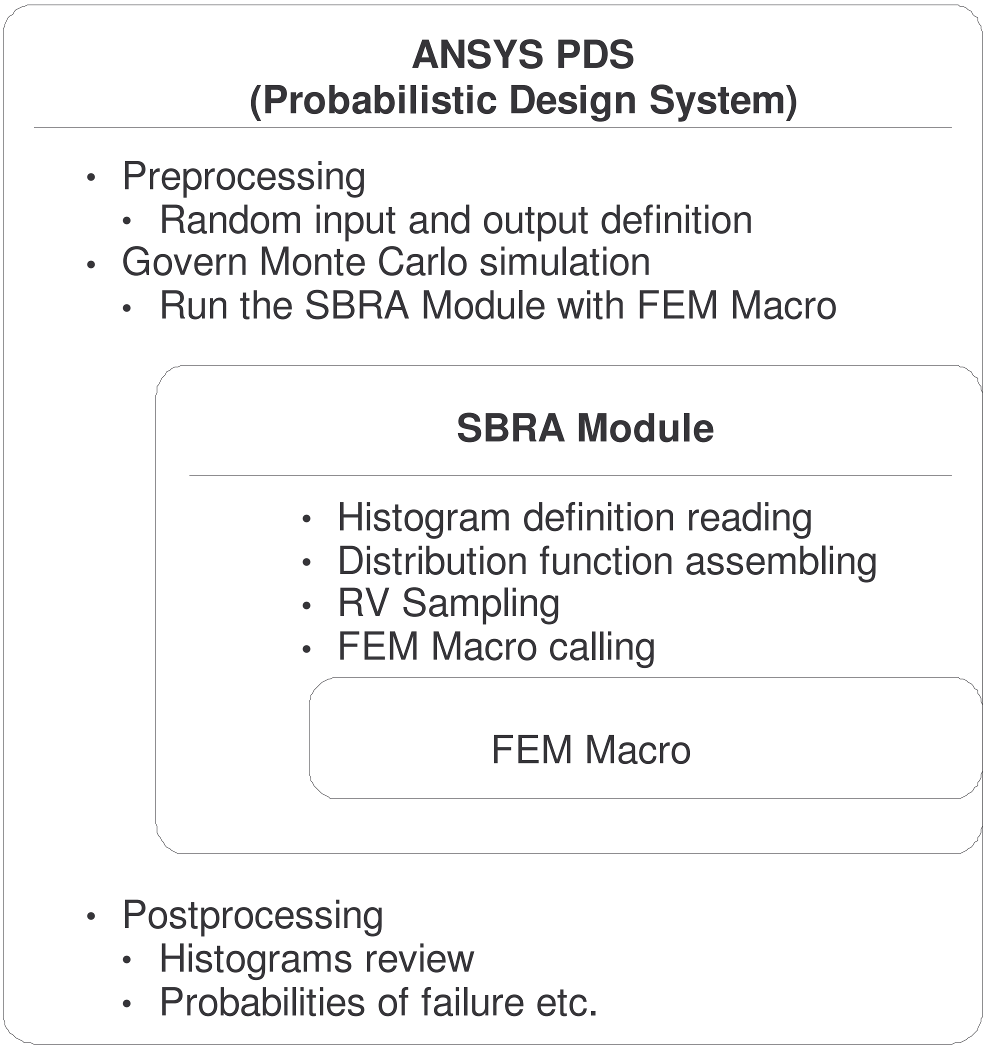


Figure 66: SBRA module in the ANSYS Probabilistic Design System.

The random variable is in the `fem_hisg.mac` described as follows:

```
input='variable_name,multiplier,histogram,file.DIS' $ *use,inputvar
```

where is:

- *input* temporarily parameter for the histogram description,
- *variable_name* name of the random variable,
- *multiplier* represents nominal value of the variable if the histogram is relative otherwise is to be set to one,
- *histogram* identification of the variable type (only histogram is being currently allowed),
- *file.DIS* utilized histogram name,
- `$ *use,inputvar` this command stores the inputvar parameters to memory.

String input should be less or equal to 32 characters and evaluation of the `*use,inputvar` command must follow.

The distribution function is created using the `CREAHIS` function after the input parameters parsing:

```
*use,creahis,'variable_name'
```

The `CREASAM` function then generates the random realization of variable according to the distribution function using the uniform primary random generator.

```
*use,creasam,'variable_name'
```

The SBRA module contain the command for the FEM macro invoking:

```
fem_hisg,1,arg1,arg2,...,ar17
```

There may be called up to17 arguments in the APDL (*arg1 - ar17*).

B.3.3 Stochastic Module ANSYS PDS Application

A model prepared in the above-mentioned way may be used in the ANSYS PDS that can be operated using GUI as well as another macro. The incorporated variables are to be assigned suitable probabilistic distribution. The output variables that are desirable for post processing are selected. Monte Carlo simulation is performed.

The probabilistic assessment is performed itself by the following sequence of steps. The Prob Design is activated by the `/PDS` command followed by the invoking the `fem_hisg` command that solves the problem deterministically in the first run. This will prepare considered variables for the PDS processing. The random inputs needs to be defined here. The random inputs will be uniform distributions in the case of histogram-based variables. The uniform distribution that needs to be assigned to the parameter called *variable_name_RND* can be selected from the *Menu - Probabilistic definitions – Random Input* as well as by command:

```
PDVAR,variable_name_RND,UNIF,0,1,0,0
```

The output variable setting follows with most important reliability function *RF*. It is done in the *Menu - Probabilistic definitions – Random Output* or by command:

```
PDVAR,RF,RESP
```

It is advised to select the SBRA module variables as an output ones for the post processing. The variables characterized by histogram.

```
PDVAR, variable_name,RESP
```

The correlation among the histogram-based variables may be induced using the procedures described in (PHOON et. al., 2004) by correlating the respective primary generators. The PDS allows for the correlation of the uniform distributions *variable_name* (*Menu - Probabilistic definitions – Correlation*).

Once are the input files (`fem.mac` and `fem_hisg.mac`) prepared and the random variables are characterized the Monte Carlo simulation takes place. There is a *Latin Hypercube Sampling* option in the *Menu - Prob Method – Monte Carlo Sims* available only. *The Direct Monte Carlo* is not available in the ANSYS 10.0 version yet although the simulation behaves like the crude Monte Carlo in case of variables characterized by histograms because the PDS is used for uniform distribution generation.

The number of the simulation steps is considered next:

```
PDMETH,simulation_name,LHS
PDLHS,n_sim_,1,RAND, ,'ALL ', , , ,CONT
```

where the `simulation_name` represents the name of the Monte Carlo simulation log database that stores random realizations for all of the simulation steps. `n_sim` is number of applied simulations. Task may be invoked from the *Menu - Run – Exec serial – Run serial* or by command:

```
PDEXE,simulation_name,SER,0.
```

The post processing follows the Monte Carlo simulation. The *Menu - Probabilistic Results – Statistics* is for the evaluation of the histograms, distribution functions (load duration curve), probabilities and quantiles. Two-dimensional scatter plot called also anthill in the SBRA method may be analyzed from the *Menu - Probabilistic Results – Trends.* There is also possibility to evaluate correlation matrix among random parameters.

C. Deterministic Results – DVD-ROM

The records for the example from the Annex A.3 Deterministic Solution are shown here. It contains the results that are recorded for each performed analysis. These results can be reviewed on the DVD-ROM.

C.1 Analysis from Section A.3

The record file has following parts.

C.1.1 Outline

- Input parameters
- Life span
- Chloride concentration table
- Input and result files (on DVD-ROM only)
- Graphs
- Figures

C.1.2 Input Parameters

Variable	*Symbol*	*Units*	*Value*
Diffusion coeff.	dc	[m2/s*10^{-12}]	4.91
Deck depth	depth	[m]	0.23
Chloride concentration	c_0	[%]	0.6
Width (crack spacing)	crcks	[m]	0.7
Crack depth	crack_de	[m]	0.027
Chloride threshold	thresh	[%]	0.2
Rebar depth	reb_d	[m]	0.075
Number of holidays	meshn	[m^{-1}]	2
Chloride background concentration	c_b	[%]	0
Initial crack	cracki	[fraction]	0.5
Initial holiday	meshi	[fraction]	0.5
Life span	t	[years]	50
Initial time increment	time_inc	[years]	0.25
Relative number of vertical elements	vert_elem_r	[m^{-1}]	100

C.1.3 Life Span [years]

Comparison of numerical and analytical solution

	[years]
C_{xyt}	18.8
$C_{2D\text{-black bar}}$	15.9
$C_{reference}$	19.5
$C_{1D\text{-analytic}}$	19.6

C.1.4 Chloride Concentration [%] as a Function of Time [years]

Comparison of numerical and analytical solution for service life 50 years

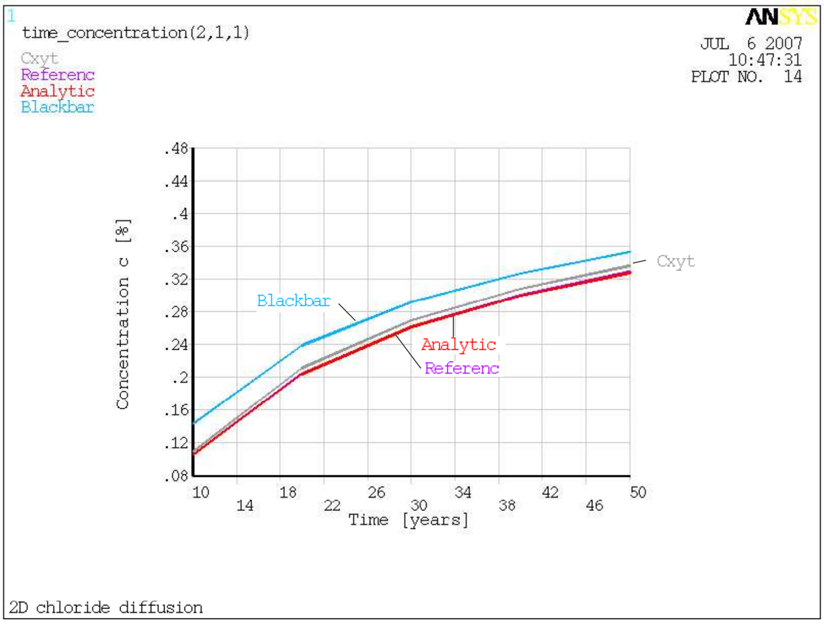
Year	*0*	*10*	*20*	*30*	*40*	*50*
C_{xyt}	0.00	0.11	0.21	0.27	0.31	0.34
$C_{black\ bar}$	0.00	0.14	0.24	0.29	0.33	0.35
$C_{reference}$	0.00	0.11	0.20	0.26	0.30	0.33
$C_{1D\text{-analytic}}$	0.00	0.11	0.20	0.26	0.30	0.33

C.1.5 Input and Result Files

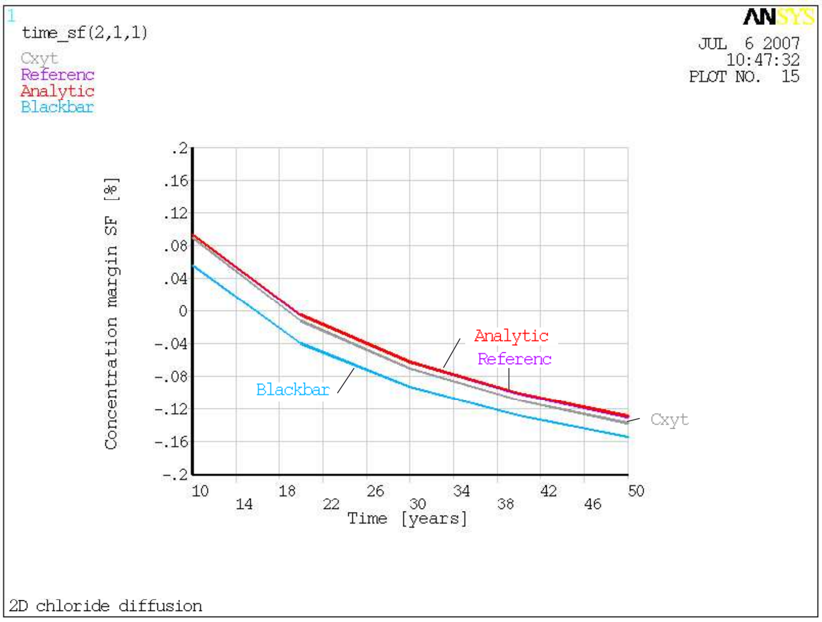
There are also link to input files written in APDL macro language that were needed to run a macro. The results in text file in ASCII form are also accessible (e.g. life span, chloride concentration, chloride margin).

C.1.6 Graphs

C.1.6.1 Chloride Concentration C [%]

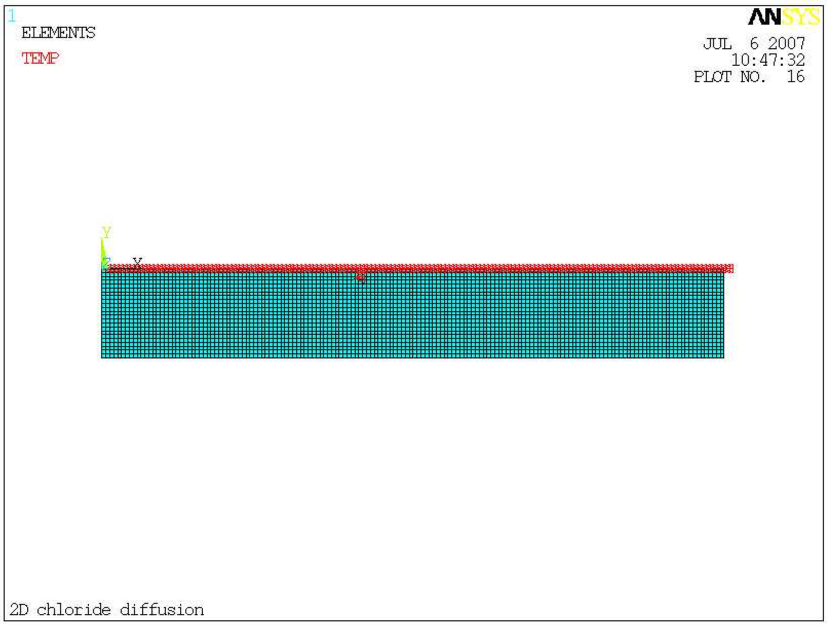


C.1.6.2 Concentration Margin SF [%]

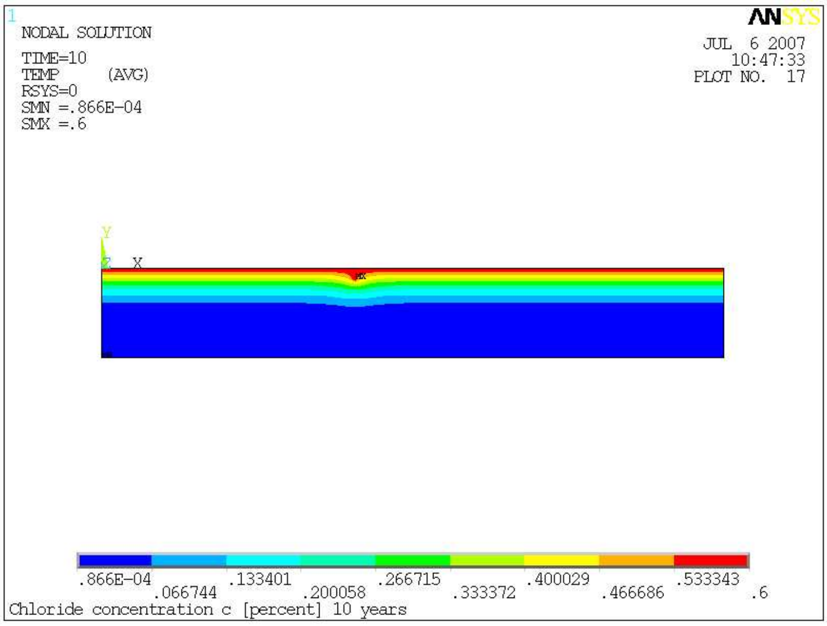


C.1.7 Figures

C.1.7.1 Meshing



C.1.7.2 Chloride Profile in 10 [years]



Chloride profiles for other ages are in the DVD.

D. Probabilistic Results – DVD-ROM

The records for the example from the Chapter 4 *SBRA Model of Bridge Deck with Crack and Epoxy-coated Reinforcement* are shown here. It contains the results that are recorded for each performed stochastic analysis. These results can be reviewed on the DVD-ROM.

D.1 Probabilistic Analysis from Section 4

The record file has following parts.

D.1.1 Outline

- Input parameters
- Probabilities of failure
- Input and result files (on DVD-ROM only)
- Graphs
- Figures (on DVD-ROM only)

D.1.2 Input Parameters

Variable	*Symbol*	*Nominal Value*	*Units*	*Distribution*	*Minimal Value*	*Maximal Value*
Diffusion coefficient	dc	1	[m2/s*10^{-12}]	DiffPA.dis	0	26
Rebar depth	reb_d	1	[m]	XDEPTH3.dis	0.04	0.11
Rel. crack depth	crdvr	0.2	[fraction]	EXPON1.dis	0	5
Number of holidays	meshn	1	[...]	UNIF	0	100
Crack spacing	crcks	1	[m]	TGAUS<0.7,0.15>	0.25	1.15
Initial holiday	meshi	0.5	[...]	UNIF	0	1
Initial crack	cracki	0.5	[...]	UNIF	0	1
Chloride threshold	thresh	1	[%]	TGAUS(0.3,$0.0\bar{3}$)	0.2	0.4
Deck depth	depth	0.23	[m]	constant	0.23	0.23
Chloride concentration	c_0	0.6	[%]	constant	0.6	0.6
Chl. background concentration	c_b	0	[%]	constant	0	0
Life span	t	100	[years]	constant	100	100
Initial time increment	time_inc	0.25	[years]	constant	0.25	0.25
Rel. number of vert. elem.	vert_elem_r	100	[...]	constant	100	100

D.1.3 Results

D.1.3.1 Probability of Failure as a Function of Time [years]

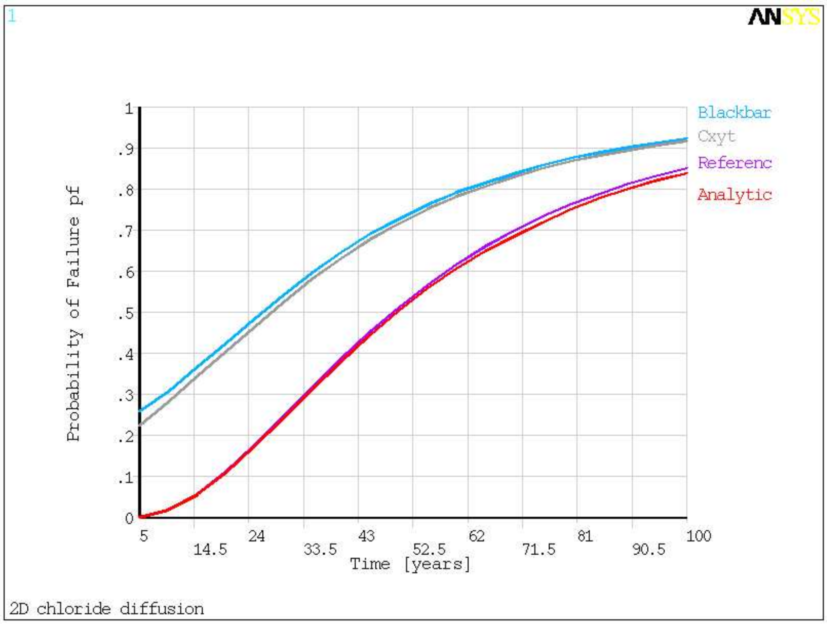
Comparison of numerical and analytical solution for service life 100 years

Year	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
pf_{xyt}	0.0	28.2	4.04	52.6	63.3	71.7	78.3	83.1	87.0	89.7	91.9
$pf_{blackbar}$	0.0	30.8	4.24	54.4	64.7	72.9	79.3	83.9	87.8	90.4	92.5
$pf_{reference}$	0.0	1.8	1.12	24.7	38.7	51.3	61.7	70.0	76.4	81.5	85.3
$pf_{1D\text{-}analytic}$	0.0	1.9	1.11	24.3	38.1	50.5	60.7	68.6	75.3	80.3	84.1

D.1.4 Input and Result Files

There are also link to input files written in APDL macro language that were needed to run a macro as well as result in text file (e.g. probability of failure, LOG file with results of all the simulation steps, report file generated by ANSYS - PDS Report file).

D.1.5 Graph



D.1.6 Figures

There is link at the end of the html page to file with figures of the input histograms, sensitivity analysis, and 2D Anthills.

D.2 Parametric Study – DVD–ROM

The results of the 48 stochastic alternative solutions given by the Table 5 are in this Annex. There can be found especially probability plots as indicated next next as well as the record file indicated in previous section.

Table 7: Available Alternatives for Parametric Study.

No.	Short Hand Notation	Applied Simulation Steps	
1	com1-dc1-r1-cd0.15-m1-cs1	1000	-
2	com2-dc1-r1-cd0.15-m1-cs5	1000	-
3	com3-dc1-r1-cd0.15-m1-cs10	1000	-
4	com4-dc1-r1-cd0.15-m10-cs1	1000	10000
5	com5-dc1-r1-cd0.15-m10-cs5	1000	-
6	com6-dc1-r1-cd0.15-m10-cs10	1000	-
7	com7-dc1-r1-cd0.15-m100-cs1	1000	-
8	com8-dc1-r1-cd0.15-m100-cs5	1000	-
9	com9-dc1-r1-cd0.15-m100-cs10	1000	-
10	com10-dc1-r1-cd0.15-m1000-cs1	1000	-
11	com11-dc1-r1-cd0.15-m1000-cs5	1000	-
12	com12-dc1-r1-cd0.15-m1000-cs10	1000	-
13	com13-dc1-r1-cd0.2-m1-cs1	1000	10000
14	com14-dc1-r1-cd0.2-m1-cs5	1000	-
15	com15-dc1-r1-cd0.2-m1-cs10	1000	-
16	com16-dc1-r1-cd0.2-m10-cs1	1000	10000
17	com17-dc1-r1-cd0.2-m10-cs5	1000	10000
18	com18-dc1-r1-cd0.2-m10-cs10	1000	10000
19	com19-dc1-r1-cd0.2-m100-cs1	1000	10000
20	com20-dc1-r1-cd0.2-m100-cs5	1000	-
21	com21-dc1-r1-cd0.2-m100-cs10	1000	-
22	com22-dc1-r1-cd0.2-m1000-cs1	1000	-
23	com23-dc1-r1-cd0.2-m1000-cs5	1000	-
24	com24-dc1-r1-cd0.2-m1000-cs10	1000	-
25	com25-dc0.1-r1-cd0.15-m1-cs1	1000	-
26	com26-dc0.1-r1-cd0.15-m1-cs5	1000	-
27	com27-dc0.1-r1-cd0.15-m1-cs10	1000	-
28	com28-dc0.1-r1-cd0.15-m10-cs1	1000	10000
29	com29-dc0.1-r1-cd0.15-m10-cs5	1000	-
30	com30-dc0.1-r1-cd0.15-m10-cs10	1000	-
31	com31-dc0.1-r1-cd0.15-m100-cs1	1000	-
32	com32-dc0.1-r1-cd0.15-m100-cs5	1000	-
33	com33-dc0.1-r1-cd0.15-m100-cs10	1000	-
34	com34-dc0.1-r1-cd0.15-m1000-cs1	1000	-
35	com35-dc0.1-r1-cd0.15-m1000-cs5	1000	-
36	com36-dc0.1-r1-cd0.15-m1000-cs10	1000	-
37	com37-dc0.1-r1-cd0.2-m1-cs1	1000	10000
38	com38-dc0.1-r1-cd0.2-m1-cs5	1000	-
39	com39-dc0.1-r1-cd0.2-m1-cs10	1000	-
40	com40-dc0.1-r1-cd0.2-m10-cs1	1000	10000
41	com41-dc0.1-r1-cd0.2-m10-cs5	1000	10000
42	com42-dc0.1-r1-cd0.2-m10-cs10	1000	10000
43	com43-dc0.1-r1-cd0.2-m100-cs1	1000	10000
44	com44-dc0.1-r1-cd0.2-m100-cs5	1000	-
45	com45-dc0.1-r1-cd0.2-m100-cs10	1000	-
46	com46-dc0.1-r1-cd0.2-m1000-cs1	1000	-
47	com47-dc0.1-r1-cd0.2-m1000-cs5	1000	-
48	com48-dc0.1-r1-cd0.2-m1000-cs10	1000	-
49	com49-dc0.1-r1-cd0.2-m10-cs0.5	-	10000
50	com50-dc1-r1-cd0.2-m10-cs0.5	-	10000

E. Input Files – DVD-ROM

The input files for deterministic solution (2-D Diffusion Macro – di_2d_d.mac) as well as probabilistic solution including SBRA Module are on the attached DVD-ROM. They are prepared for evaluation in ANSYS environment in case of interest.