Defence of DOCTORAL DISSERTATION

Ostrava, December 12, 2007

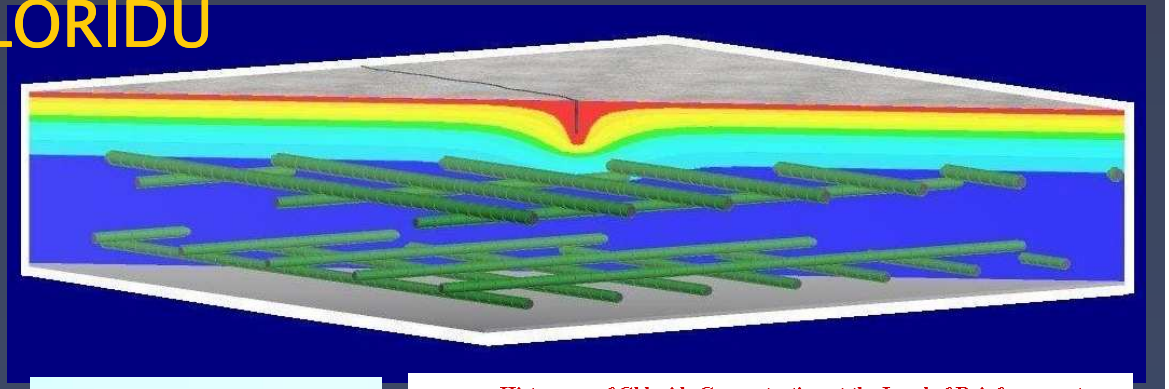
RELIABILITY OF REINFORCED CONCRETE BRIDGE DECKS WITH RESPECT TO INGRESS OF CHLORIDES

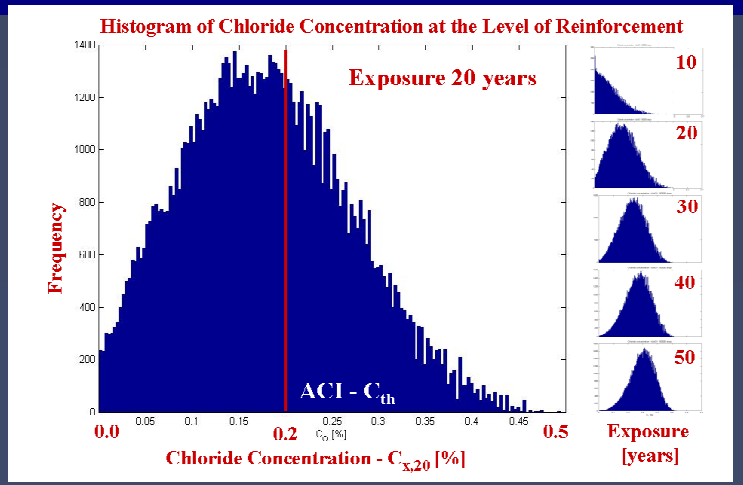
POSUZOVÁNÍ SPOLEHLIVOSTI ŽELEZOBETONOVÉ MOSTOVKY S OHLEDEM K PŮSOBENÍ CHLORIDŮ

Ing. Petr Konečný

Supervisor:
Prof. Ing. Pavel MAREK, DrSc.

Faculty of Civil Engineering
VŠB-Technical University of Ostrava
Czech Republic.





Outline

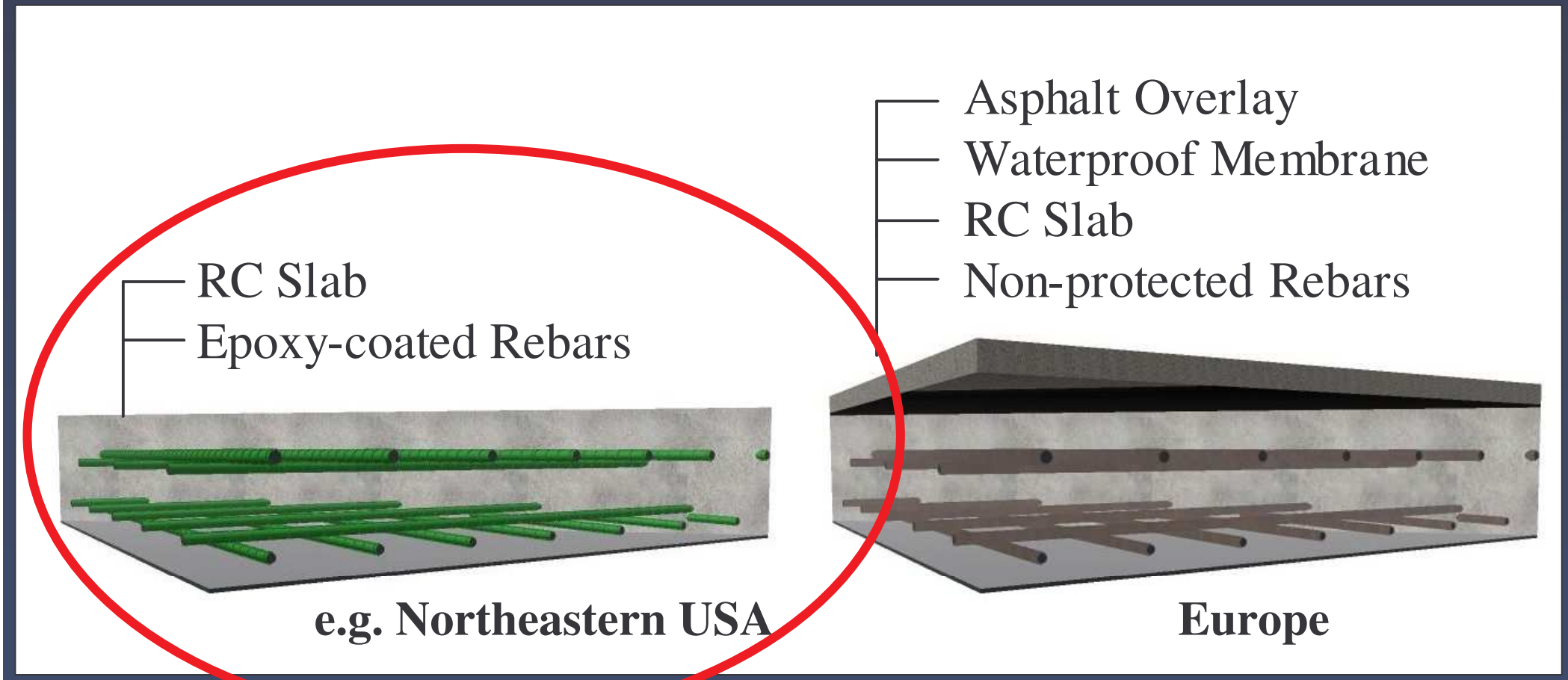
- Introduction
- Objectives of the thesis
- Chloride diffusion – 2D FEM model
- SBRA in ANSYS FEM system
- Example
- Results of parametric study
- Brief summary and conclusions

Introduction

- A lot of bridges from reinforced concrete needs early reconstructions due to early degradation.
- Durability of RC bridge decks are reduced especially due to corrosion of reinforcement followed by cover degradation and loss of carrying capacity.
- Deterioration models can help in the identification of significant parameters in order to build more durable structures.
- Nature of deterioration problems involves stochastic parameters. It is a field for application of probabilistic method such as Simulated-Based Reliability Assessment (SBRA)

Introduction – Protection against Deicers

- Selected bridge deck has reinforcement protected by cover and epoxy-coating
- Typical protection in Northeastern USA

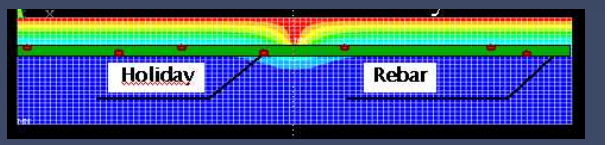


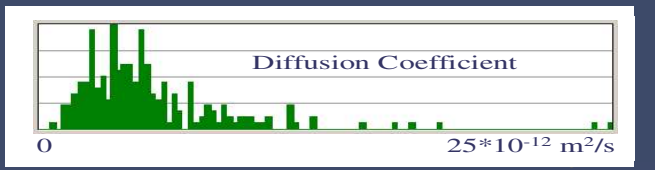
Introduction – Crack vs. Holidays

- Reinforcing steel corrosion initiation is accelerated by interaction of:
  - Cracks in RC bridge deck
  - Flaws in epoxi-coating of reinforcing steel (mashed and bare areas, holidays)

Objectives of the thesis

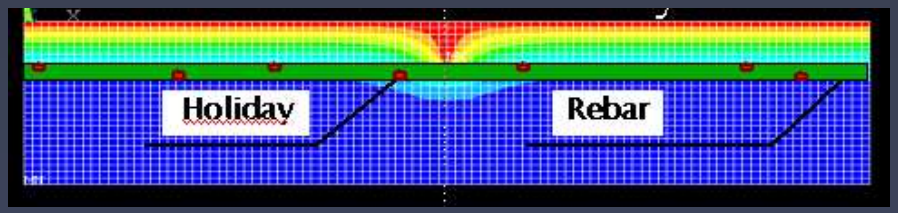
- Probabilistic durability assessment of concrete bridges affected by deicing agents applied to melt snow.
- Study of the potential of SBRA method with respect to chloride ingress induced corrosion of bridge decks that have steel reinforcement protected with epoxy-coating.
- Development of the:
  - 2-D FEM diffusion model that can address the crack effect.
  - Software tool for integration of the SBRA method and commercial FEM package.

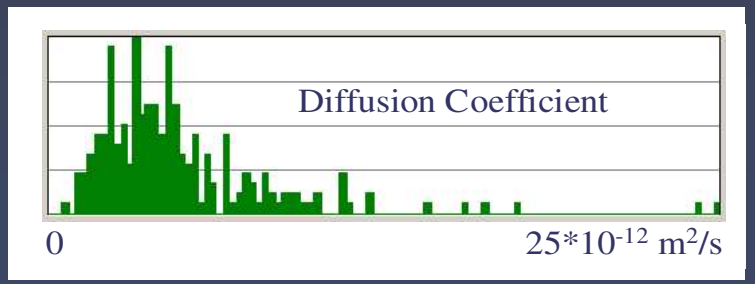


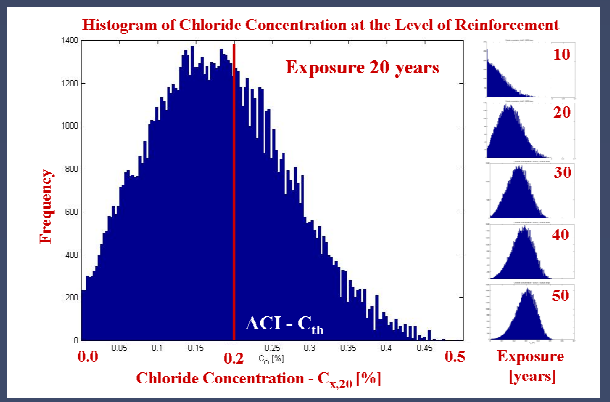


Estimation of Corrosion Initiation Likelihood

- 2D – FEM chloride ingress model
- SBRA module for ANSYS PDS environment
- Example

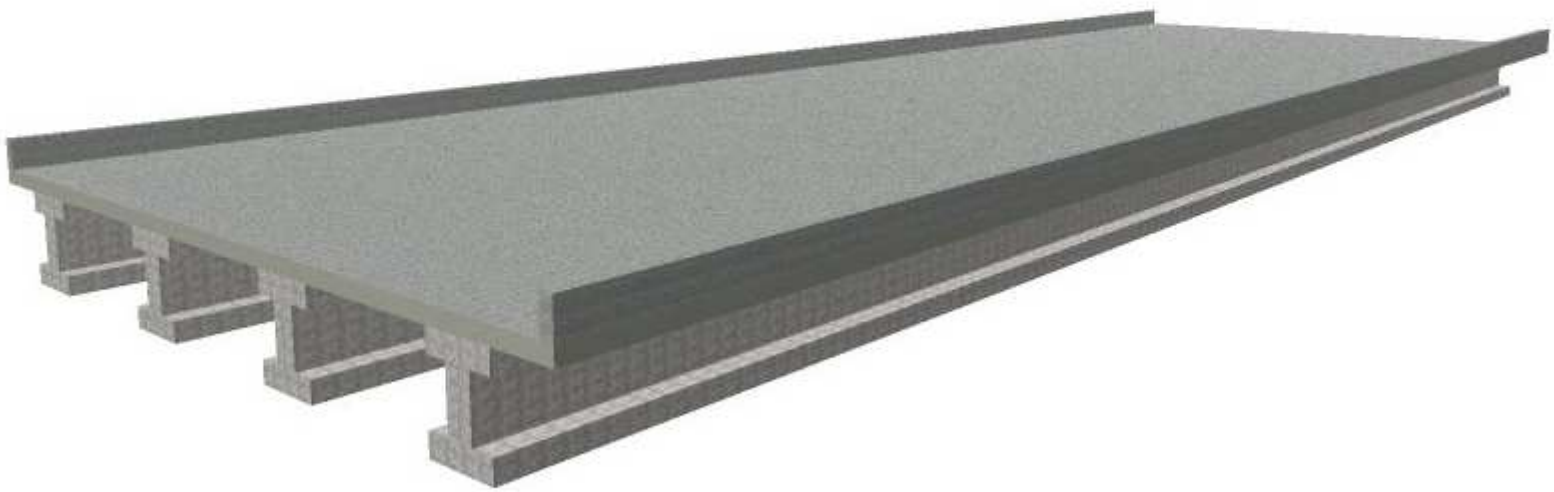






Introduction – Bridge Deck

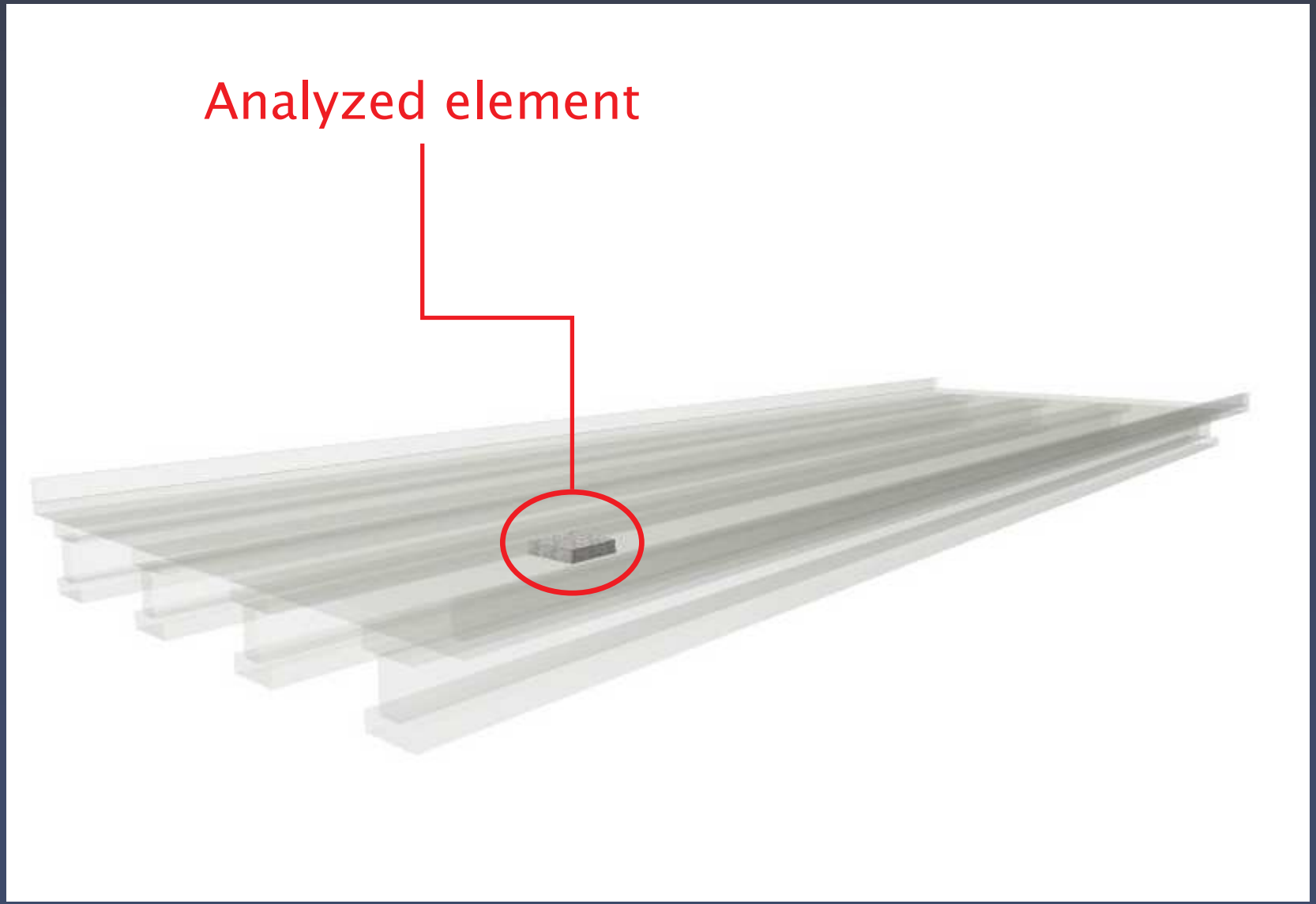
Bridge Structure



Introduction – Bridge Deck

Transverse cross-section

Introduction – Bridge Deck



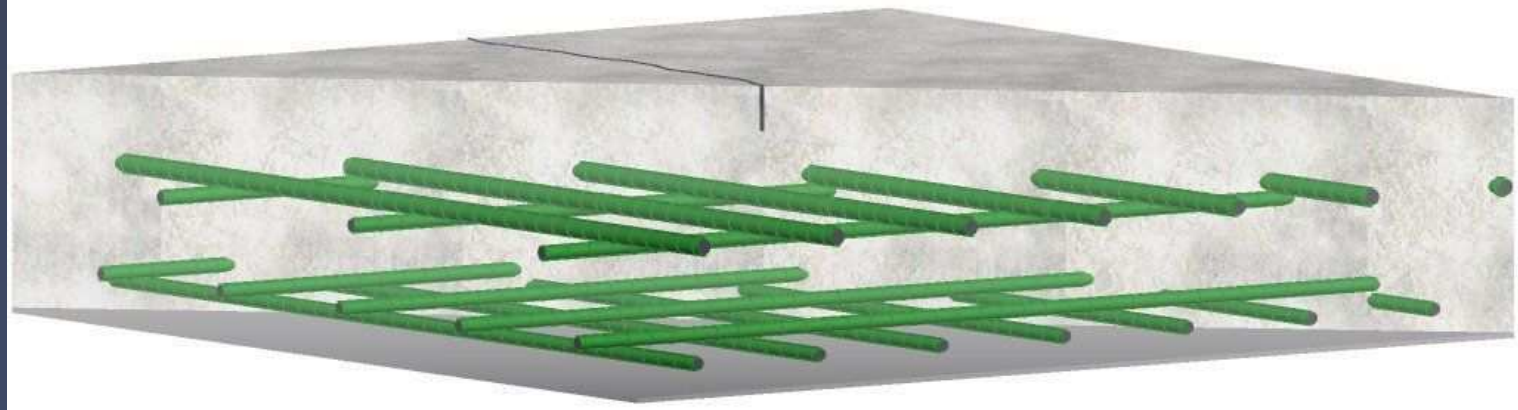
Introduction – Bridge Deck

Analyzed element

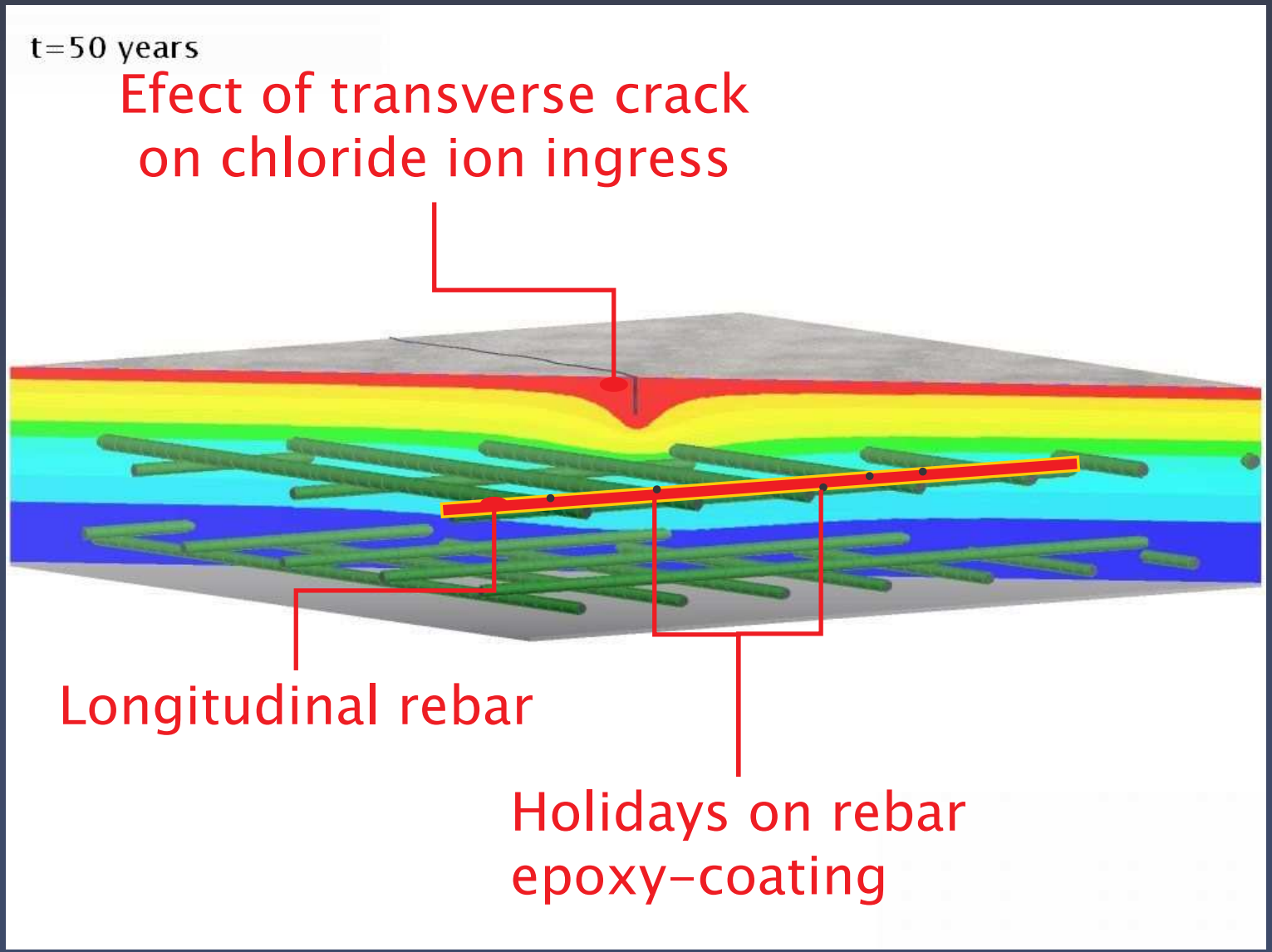
Introduction – Bridge Deck

Introduction – Bridge Deck

Element cross-section



Introduction – Bridge Deck

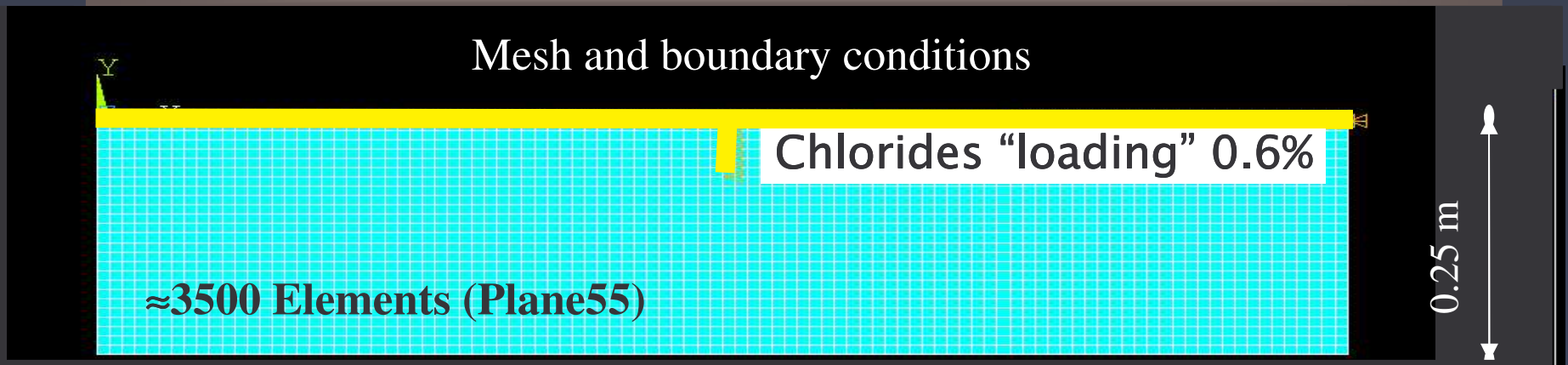


2D – FEM chloride ingress model

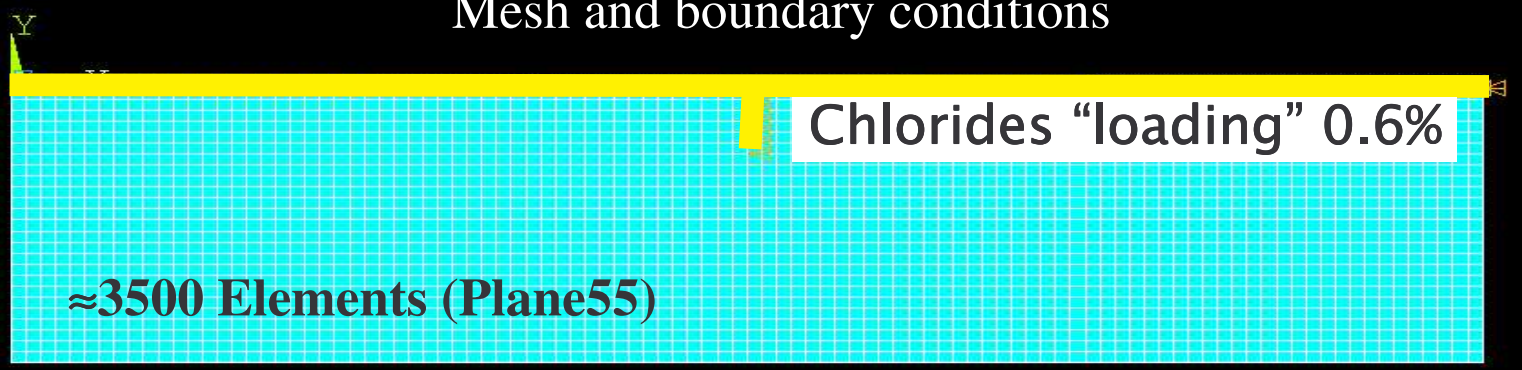
- Chloride ingress is modelled by diffusion using 2.ND Ficks law
- 2D – Numerical solution with FEM utilization
  - Acceptable for chloride ingress modelling with regards to bridge deck crack vs. damaged epoxy-coated rebar system interaction.
  - ANSYS Program system
    - Heat transfer / diffusion process analogy
    - Transient analysis
- Stochastic parameters
  - Apparent diffusion coefficient,
  - Rebar depth,
  - Crack depth,
  - Epoxy-coated rebar damage, etc.

$$\frac{\delta C}{\delta t} = D_c \left\{ \frac{\delta^2 C}{\delta x^2} \right\}$$

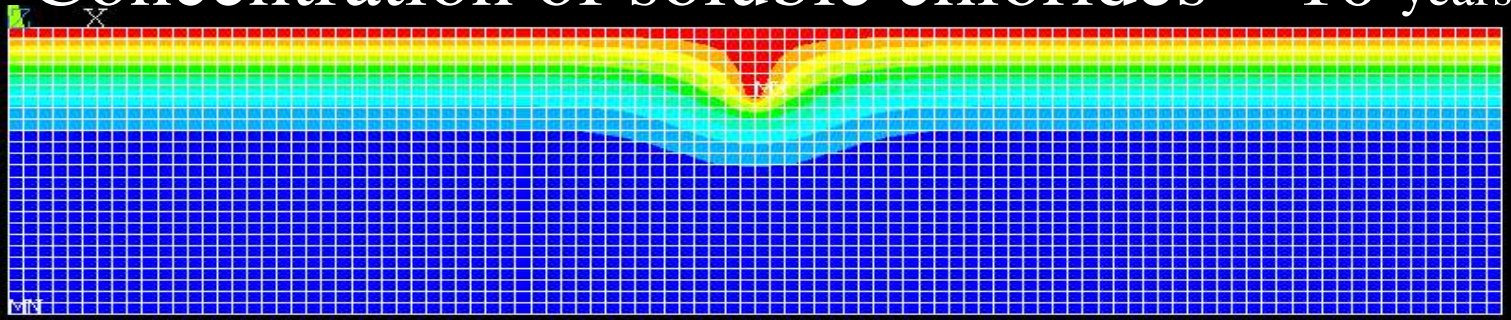
2D – FEM chloride ingress model



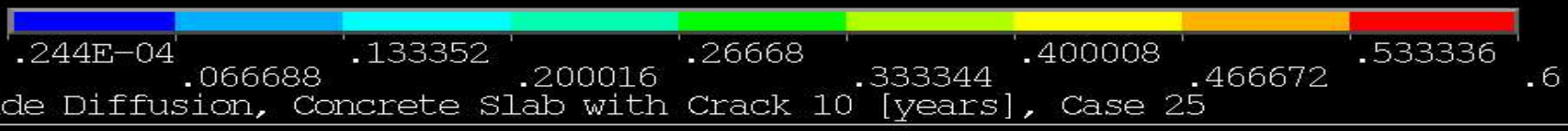
2D – FEM chloride ingress model



Concentration of soluble chlorides – 10 years



Model of bridge deck in ANSYS



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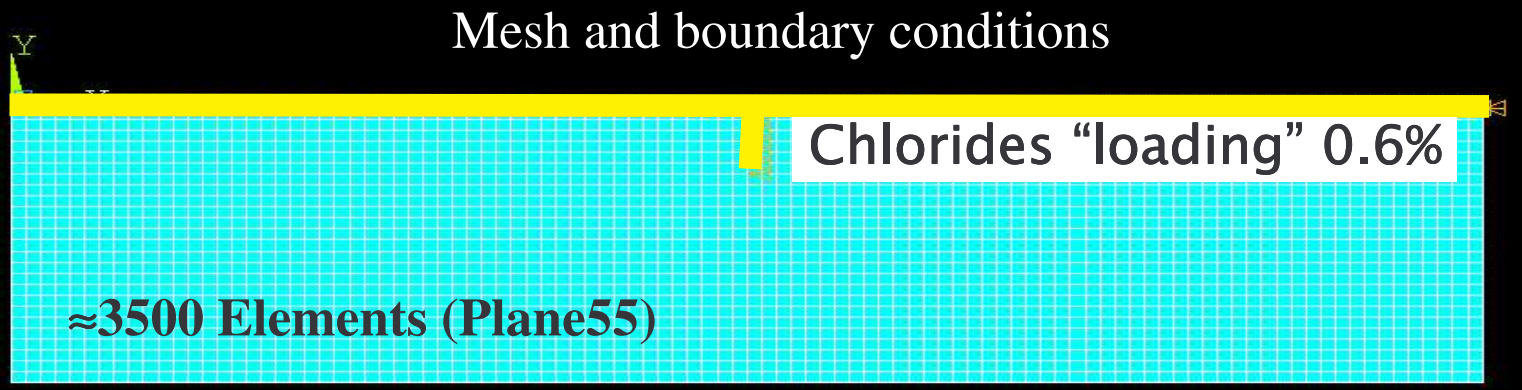

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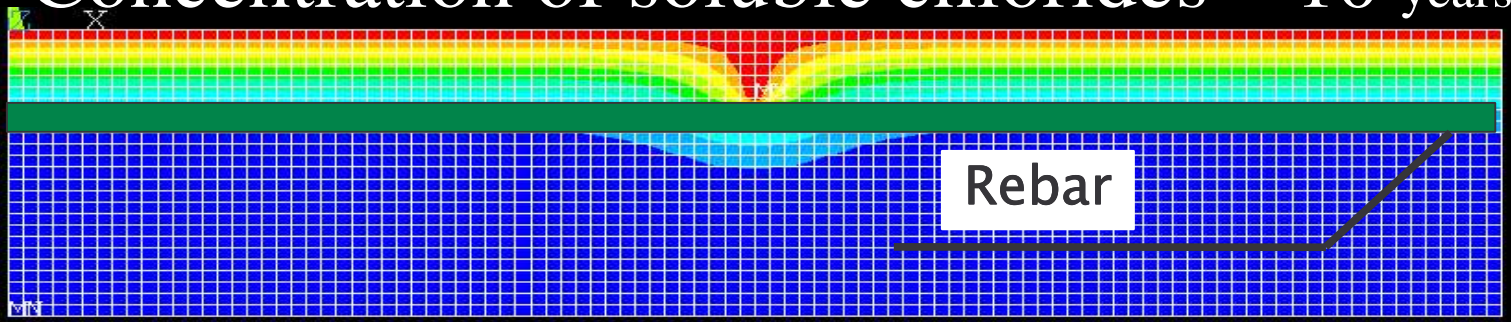

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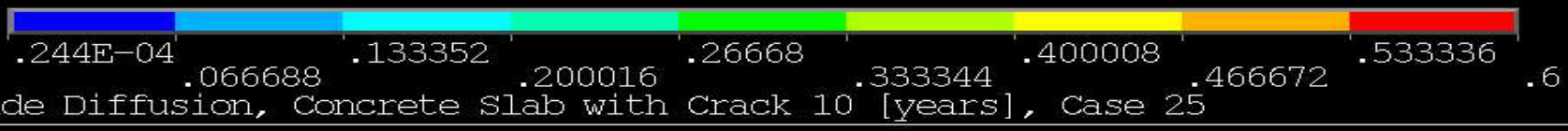
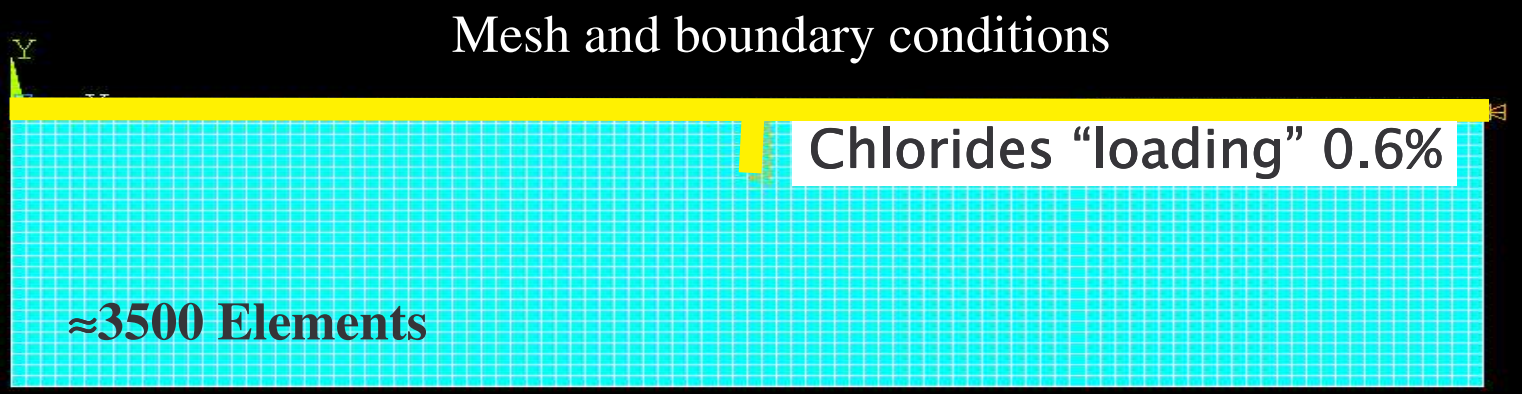


2D – FEM chloride ingress model



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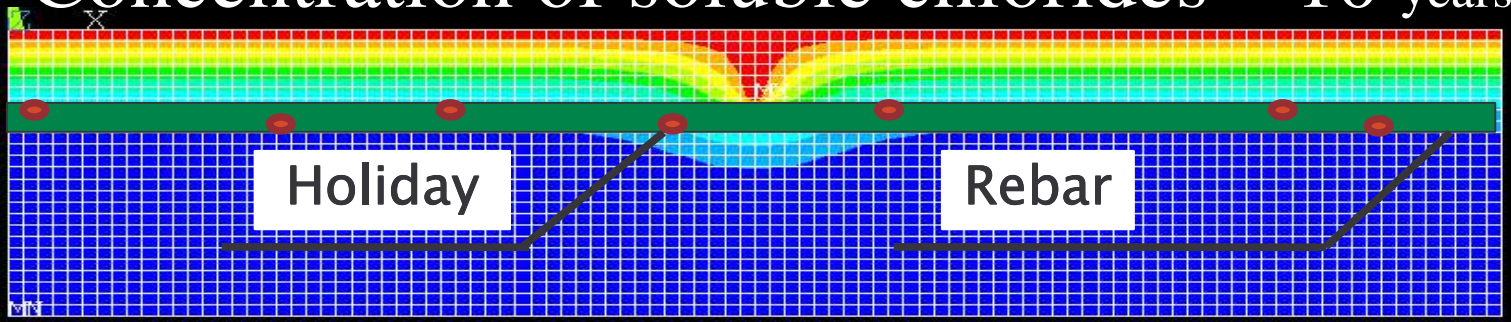
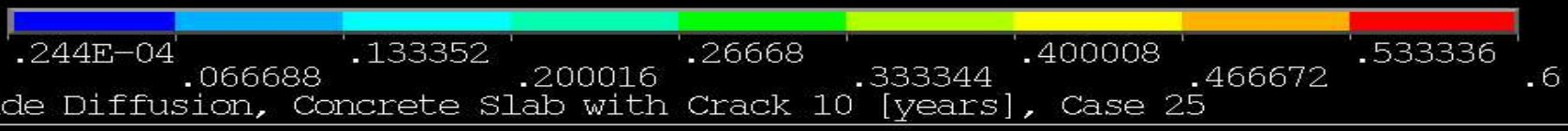


Model of bridge deck in ANSYS



2D – FEM chloride ingress model

FEM macro scheme

Input

↓

2-D FEM model (time-dependant chloride ion concentration computation)

↓

Reliability Analysis (corrosion initialisation)

di_2d_d.mac - Notepad

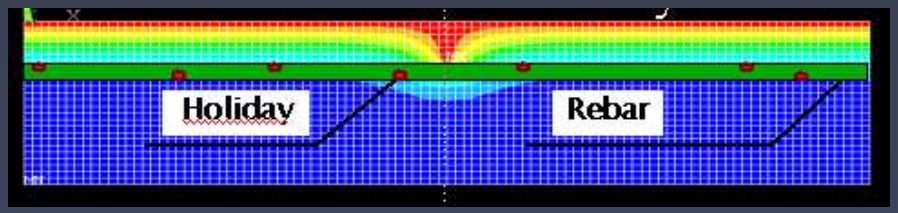
File Edit Format View Help

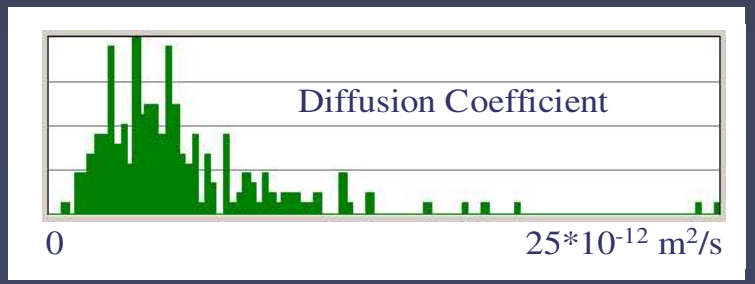
```
!-----------------------------------------------------------------
! FEM MODEL
!-----------------------------------------------------------------
!PREPROCESSOR
!-----------------------------------------------------------------
!Element type
!-----------------------------------------------------------------
/PREP7
ET,1,PLANE55
R,1,1                    ! ARBITRARY AREA
!*
!-----------------------------------------------------------------
!Material properties
!-----------------------------------------------------------------
!*
MP,KXX,1,Diff    ! DIFFUSION COEFFICIENT D [m^2 / sec]
MP,DENS,1,1              ! ARBITRARY DENSITY AND CAPACITANCE
MP,C,1,1
!*
!-----------------------------------------------------------------
!Screen Redirection
!-----------------------------------------------------------------
!/SHOW,PNG,,0 !Redirect screen to file
!/SHOW,TERM !Redirect screen to screen
PNGR,COMP,1,-1
PNGR,ORIENT,HORIZ
PNGR,COLOR,2
PNGR,TMOD,1
/GFILE,800,
!-----------------------------------------------------------------
!*
!-----------------------------------------------------------------
!Modelling
!-----------------------------------------------------------------
!Nodes
!-----
N,1,0,-depth     ! FIRST NODE
*IF,crckn,GT,0,THEN  N,N_N_X_,(width),-depth                    ! Horizontal end
 FILL                        ! Create nodes between N1 and last horizontal N
 NGEN,N_N_Y_,N_N_X_,1,N_N_X_,,,delta_nod_y ! Copy nodes vertically
*ELSE !*MSG,WARN,'no crack',crcks !%s %E  N,N_N_X_,DELTA_NOD_X,-depth ! In case
! Copy nodes vertically
*ENDIF  /AUTO,1 /REPLOT !*
!Elements
!------
E,1,2,N_N_X_+2,N_N_X_+1                 ! Number of node assigned to first nodal
*IF,crckn,GT,0,THEN  egen,N_N_X_-1,1,1                ! Generates first row of
*ENDIF egen,N_N_Y_-1,N_N_X_,1,N_N_X_-1 ! Generates all others elements
!-----------------------------------------------------------------
!* DOF CONSTRAINTS - Chloride concentration
!-----------------------------------------------------------------
TUNIF,c_b                ! INITIAL MOISTURE CONCENTRATION (THAT OF CONCRETE) [%]
!*
! Surface concentration (Question wheather to model it on the 20 mm layer
!----------------------
```

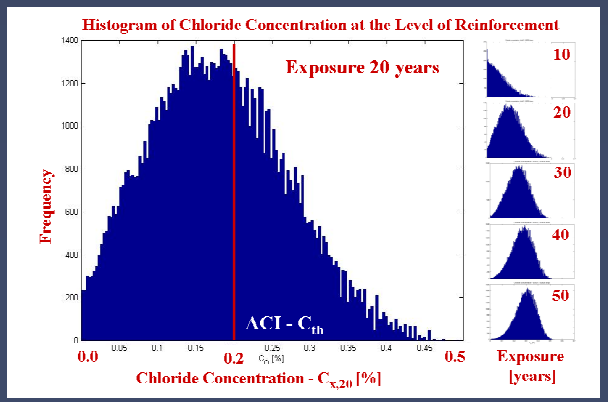
ANSYS APDL macro language.

Estimation of Corrosion Initiation Likelihood

- 2D – FEM chloride ingress model
- SBRA module for ANSYS PDS environment
- Example



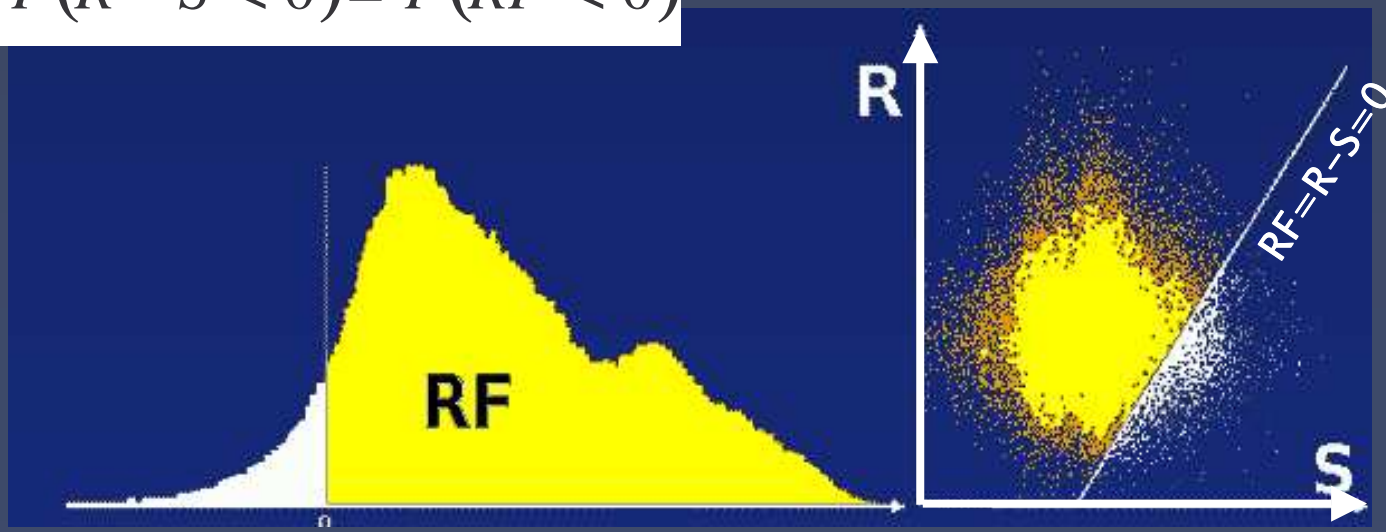




Introduction – Reliability Assessment

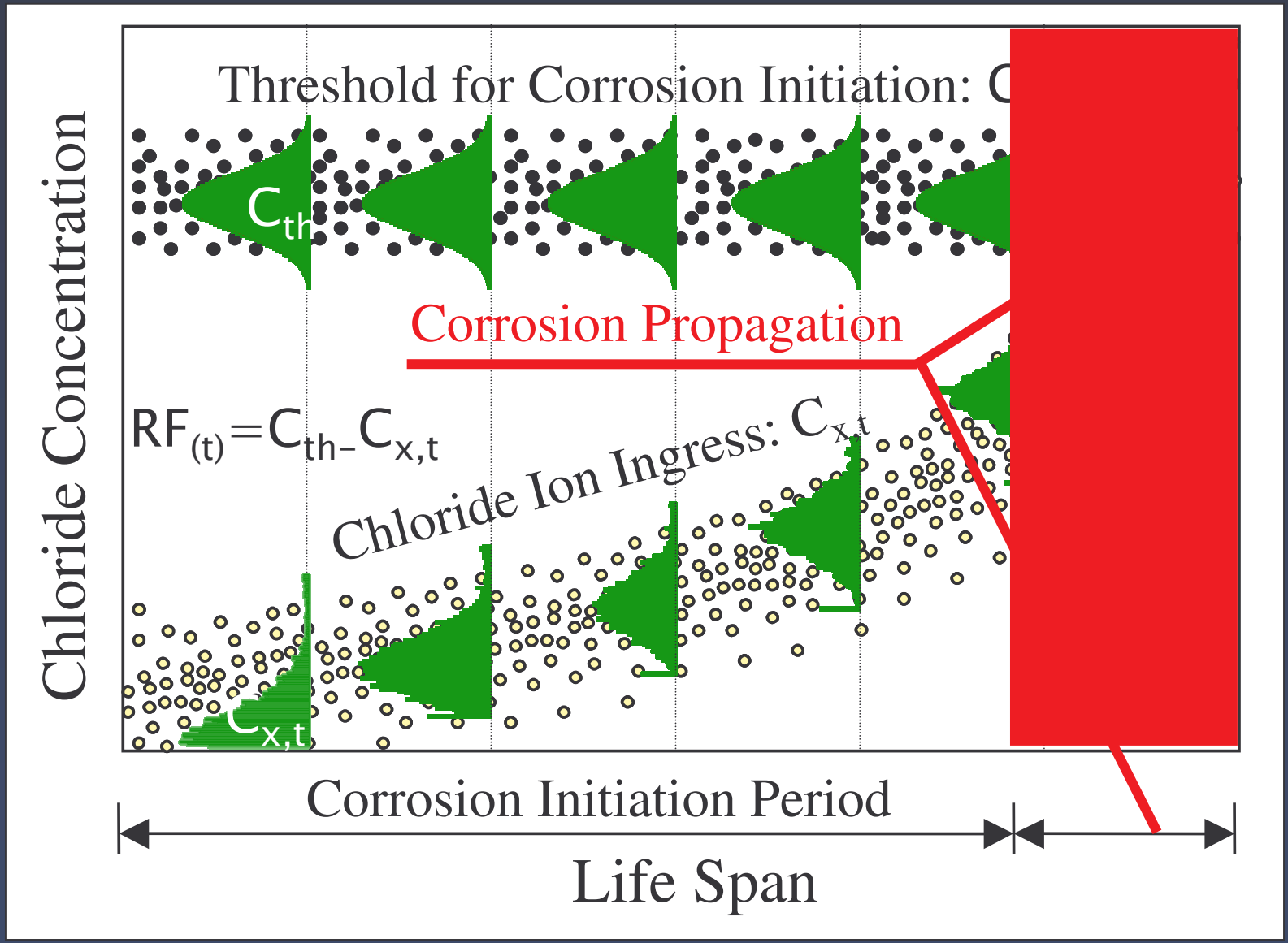
- Simulation-Based Reliability Assessment SBRA
  - Safety, Serviceability
  - Performance-Based Design
    - Durability, Corrosion, Fatigue, Degradation of Materials
  - Reliability is expressed by probability of corrosion initiation P_f

$$P_f = P(R - S < 0) = P(RF < 0)$$



Stochastic Idea of Deterioration Problem

Durability with Regards to Chloride Ion Ingress



$$P_{f,t} = P\left(C_{th} - C_{x,t} < 0\right) = P\left(RF_t < 0\right)$$

SBRA in ANSYS FEM system

- Probabilistic reliability analysis using SBRA module for ANSYS:
  - Probabilistic analysis of systems using universal FEM software.
  - Variables described by both nonparametric distributions (histograms) and parametric.
  - Direct Monte Carlo simulation.

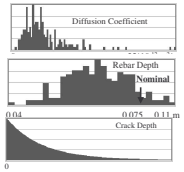
SBRA module for ANSYS

ANSYS

SBRA Module

Macro language APDL

Random variable (RV) description



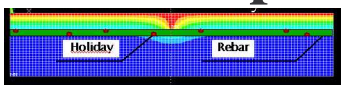
eg. 10k cycles

Monte Carlo Simulation

RV generation

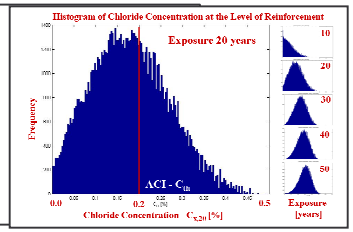
FEM macro – diffusion model

Input & Output log



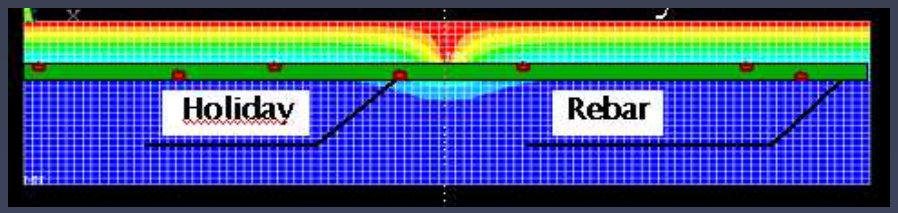
ANSYS PDS

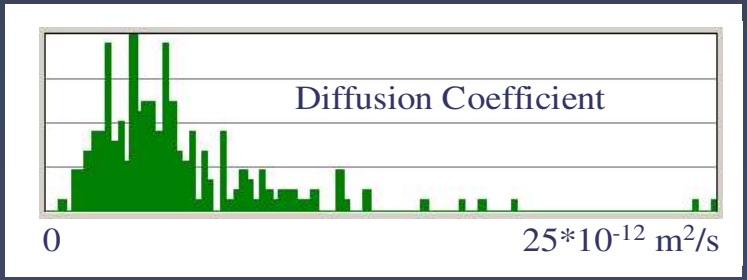
Interactive evaluation of results

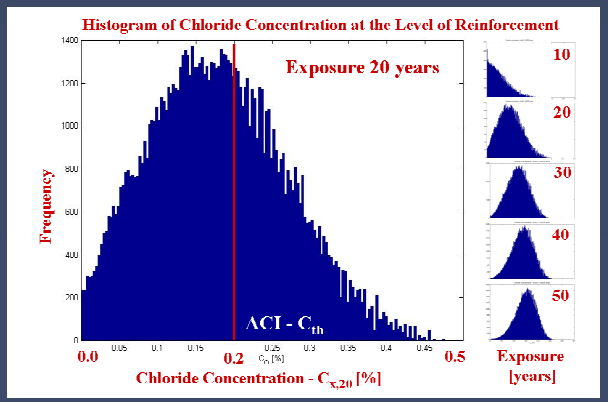


Estimation of Corrosion Initiation Likelihood

- 2D – FEM chloride ingress model
- SBRA module for ANSYS PDS environment
- Example





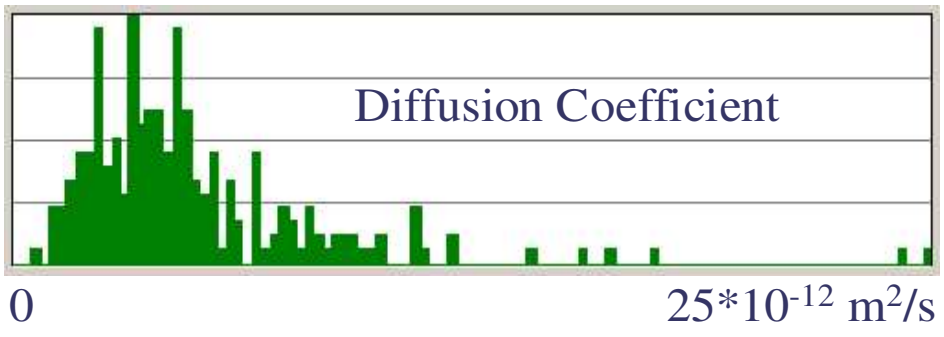


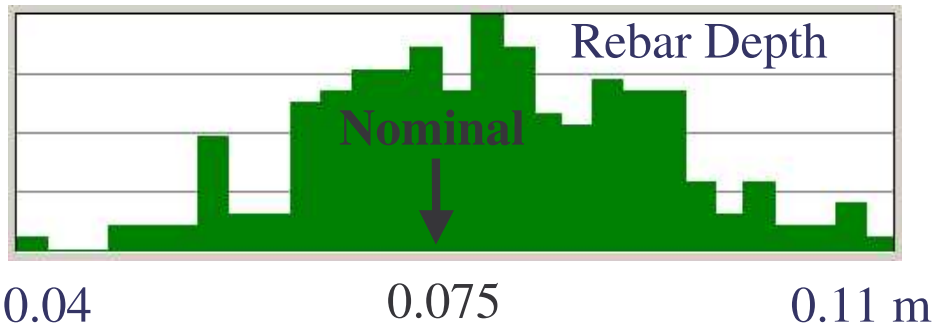
Example

- Response to the considered “loading” by chlorides is computed using Fick’s second Law of diffusion.
- Reliability is expressed using probability of corosion initiation, that is time-dependent.
  - $P_{f,t} = P(RF_t \leq 0)$ [m^{-2}]
- Reliability function: $RF = C_{th} - C_{x,y,t}$
  - $C_{x,y,t}$ – chloride ion concentration in the most exposed loaction of the reinforcement
  - C_{th} – chloride threshold
    [% by mass of total cementitious materials]

Example – Input Parameters

- Random variables are described based on field date and engineering judgement using histograms and parametric distributions.
- Histograms – field date



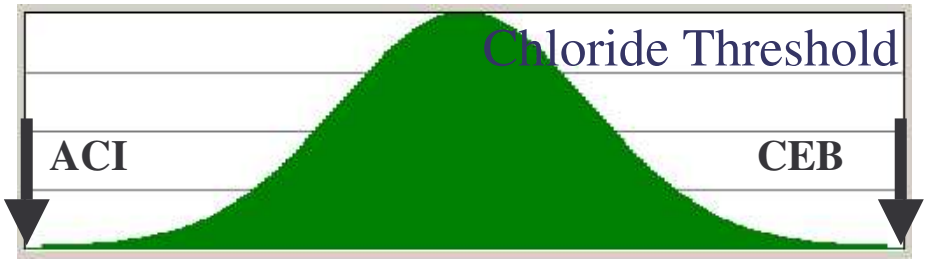


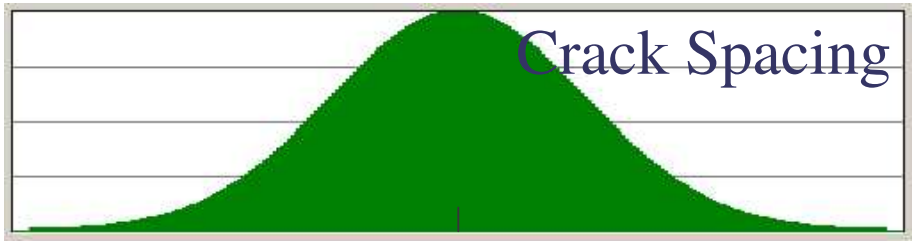
- Apparent coefficient of diffusion
- Depth of reinforcement

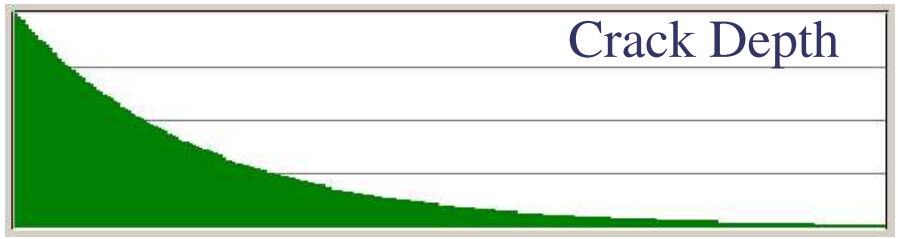
240 cores taken from 77 bridge spans: **(SOHANGHPURWALA et al., 1998)**

Example – Input Parameters

- Parametric distributions – Aproximation



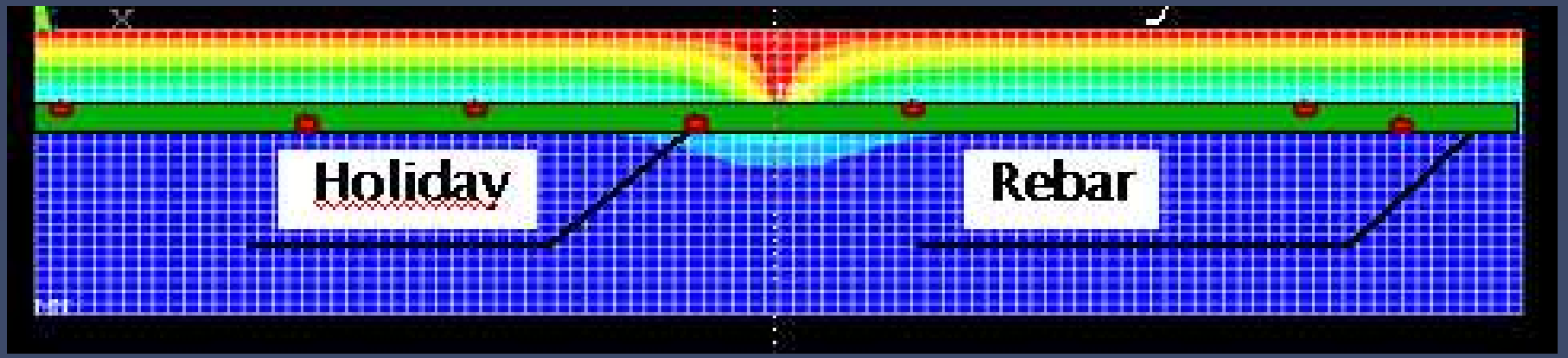




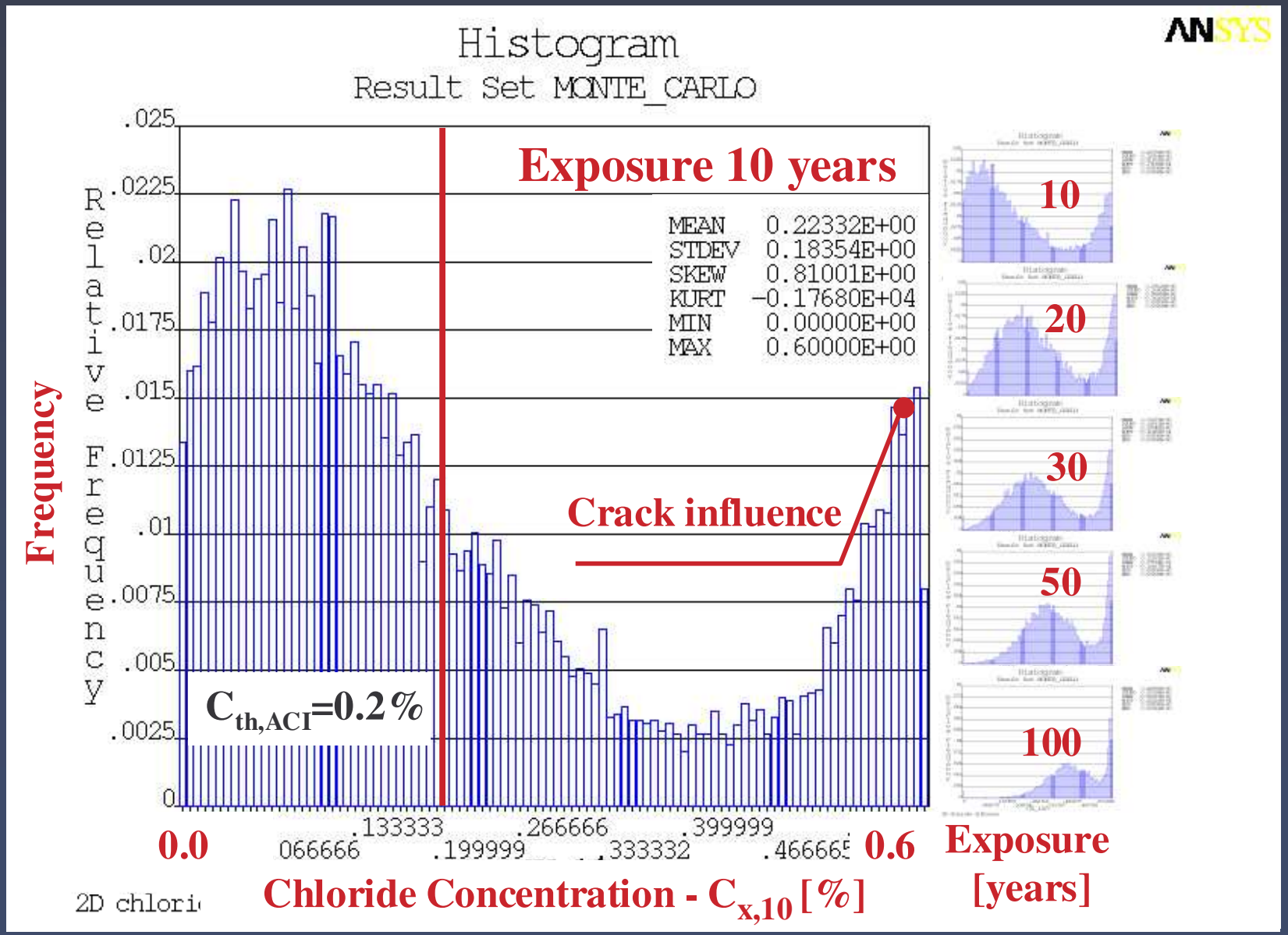
  - Relative position of first holiday – Uniform <0,1>
  - Relative position of first crack – Uniform <0,1>
- Deterministic parameters
  - Surface Soluble Chloride Concentration – 0.6 [%]
  - Depth of Slab – 0.23 [m]

Example – FEM Macro

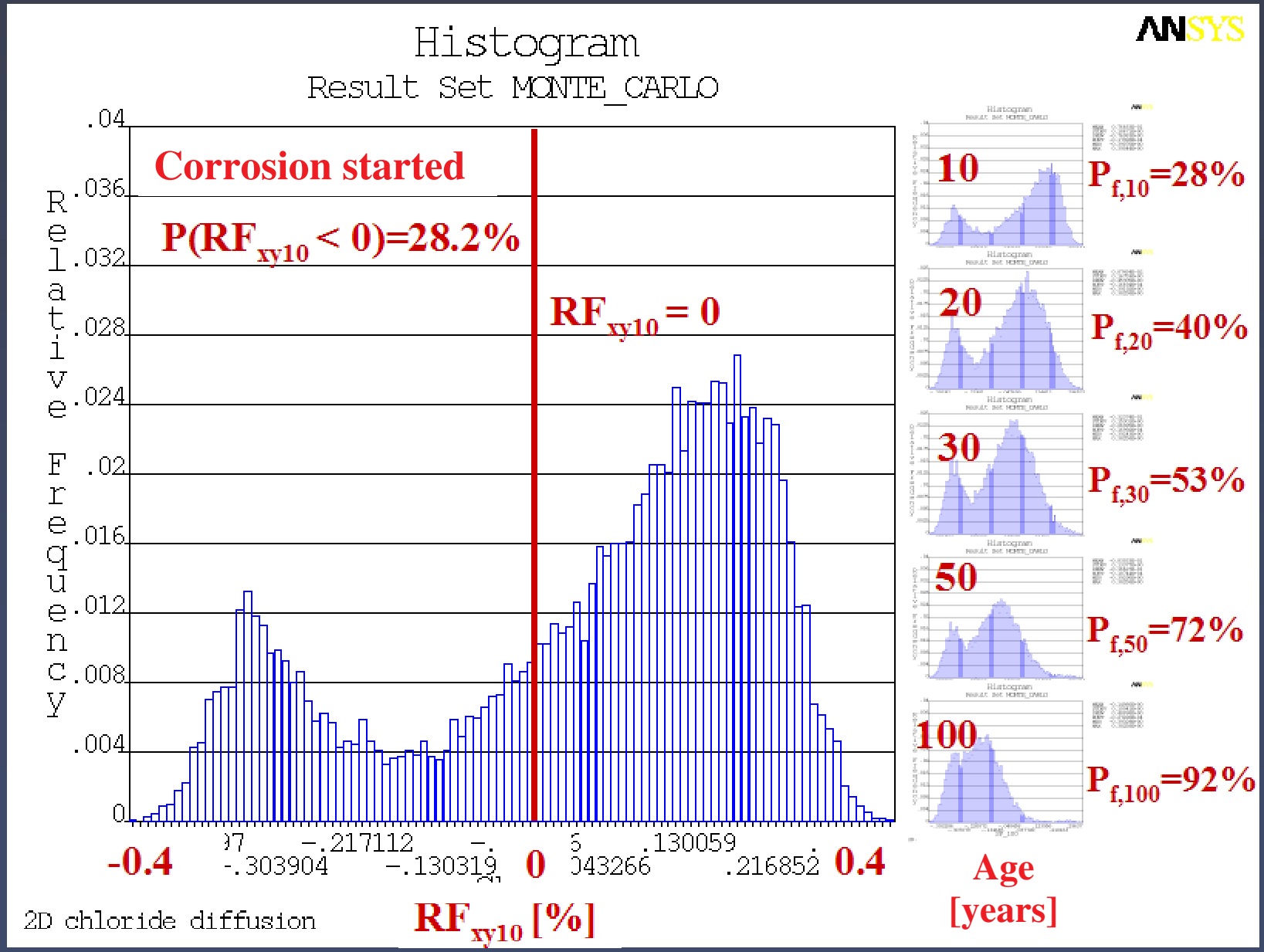
- FEM model is used with Monte Carlo simulation within the SBRA module framework in ANSYS environment.
- FEM model is repeated 10 000 times with variable input parameters.



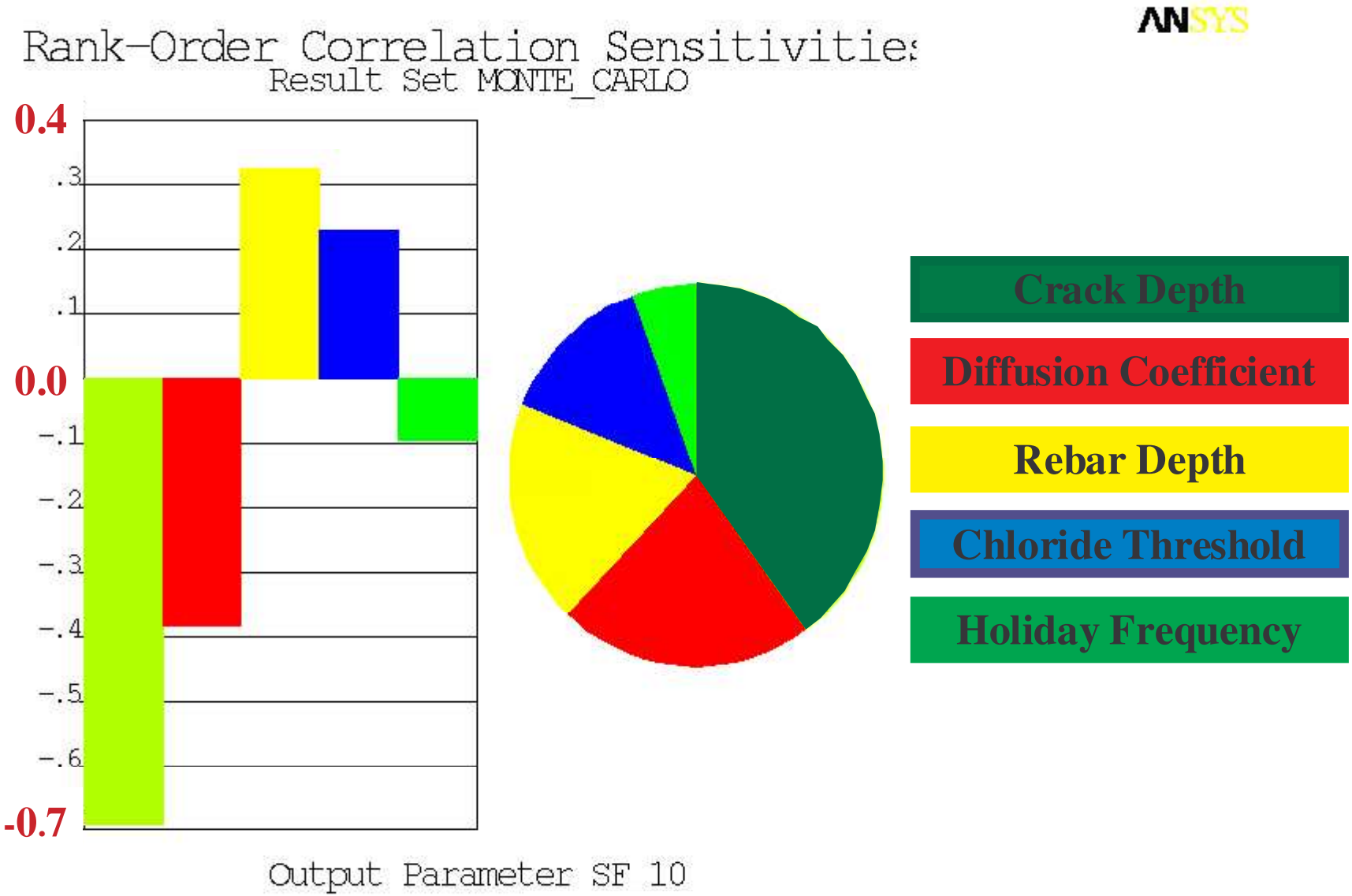
Example - Chloride Concentration



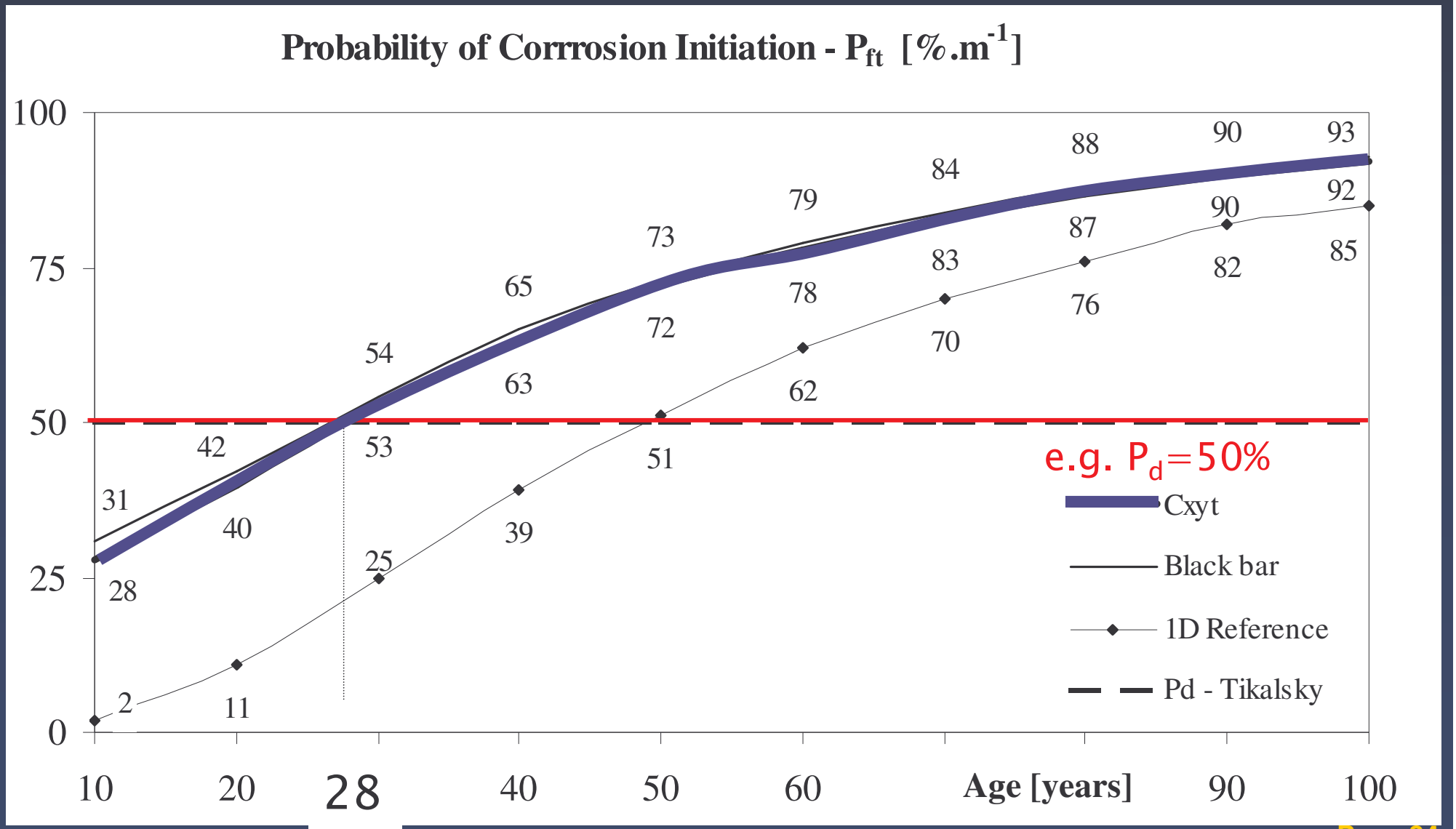
Example – Corrosion Initiation



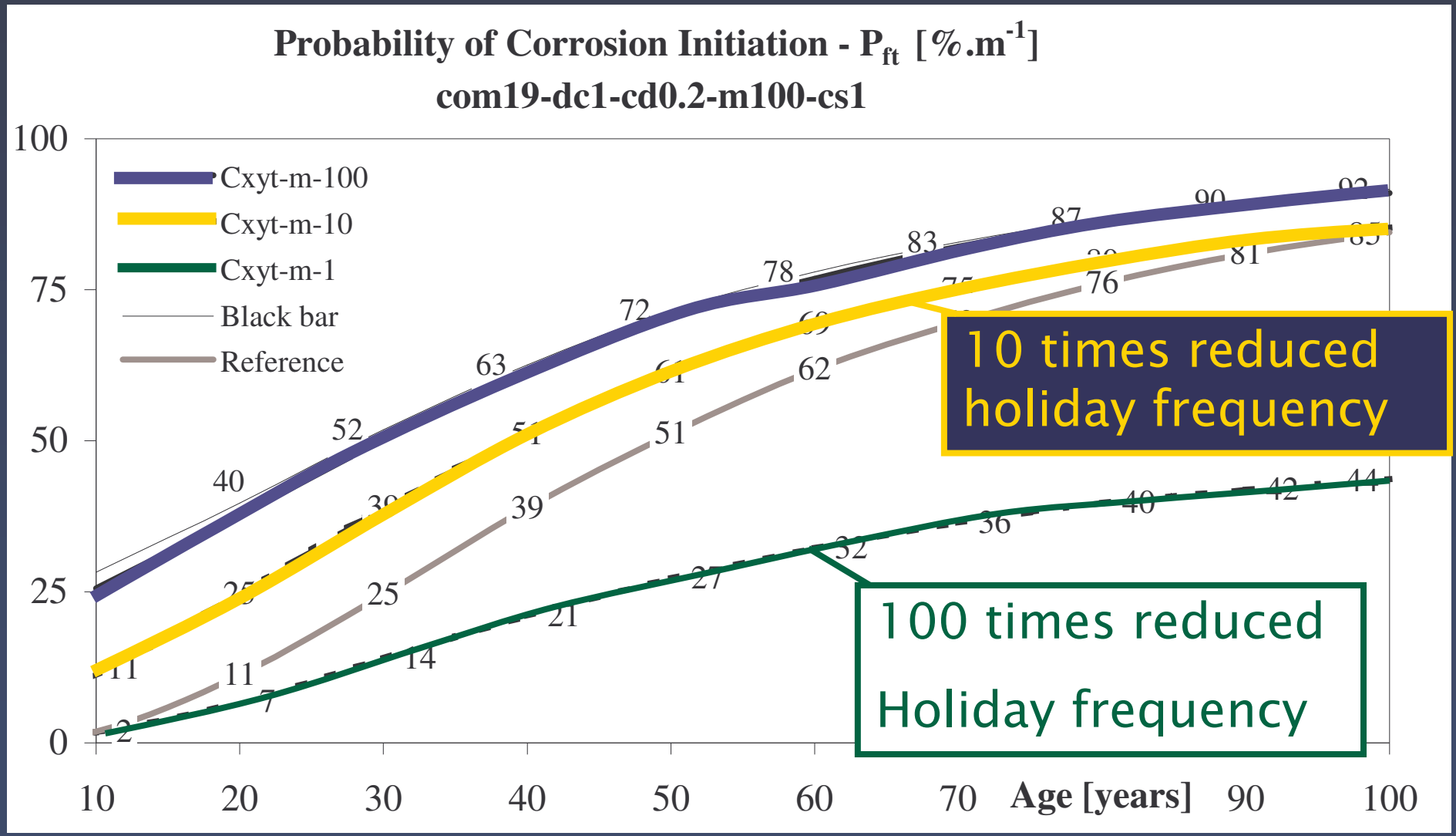
Example - Sensitivity Analysis



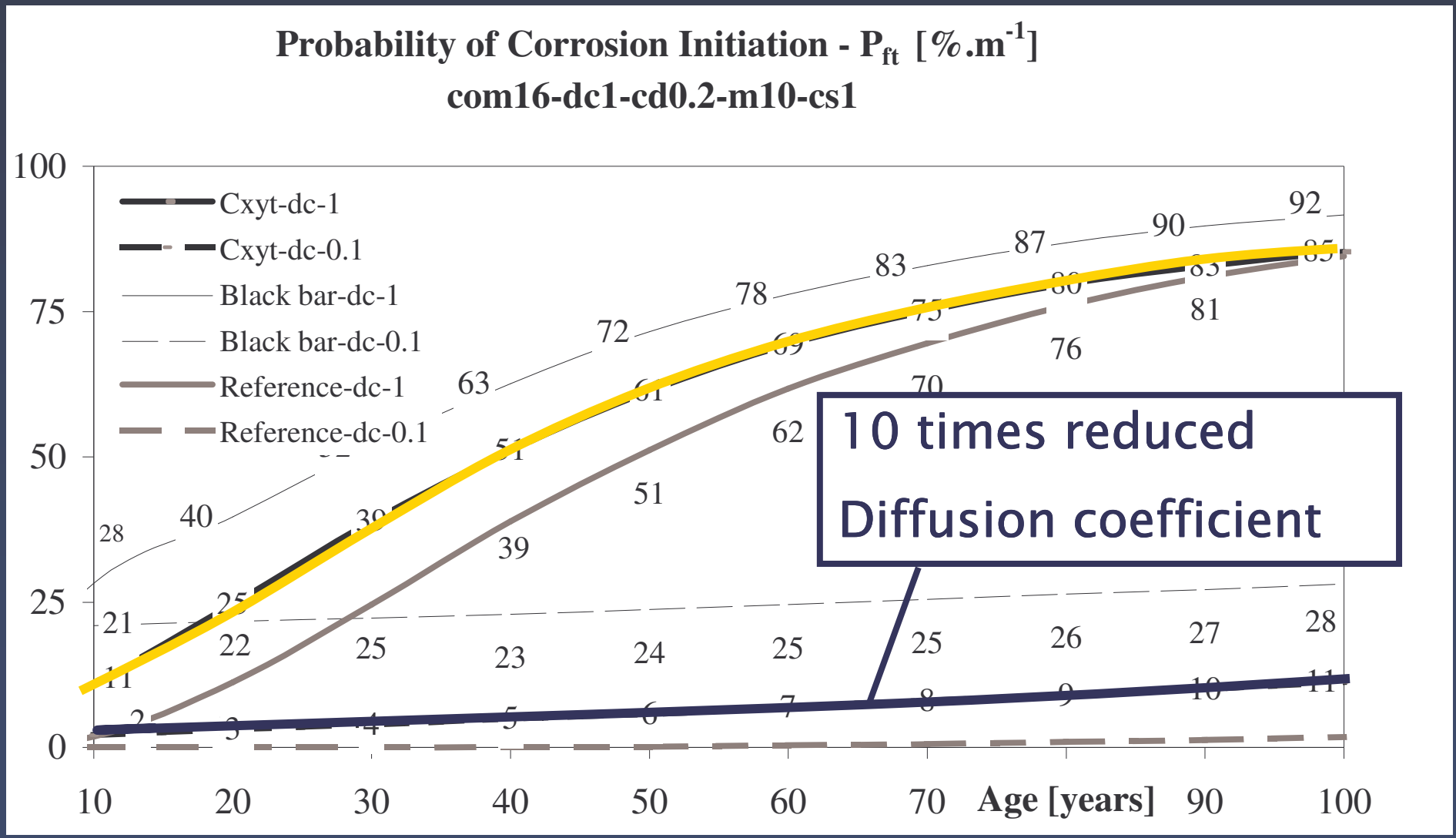
Example - Probability of Corrosion Initiation



Parametric Study – Effect of Holidays



Parametric Study – Effect of Diffusion Coefficient



Summary

- Probabilistic approach for estimation of the corrosion initiation of bridge deck reinforcing steel with by method SBRA using 2-D FEM model in ANSYS is presented.
- SBRA module for ANSYS is used for application of random variables described by bounded histograms in Monte Carlo.
- Chloride ingress is modelled by 2.ND Fick's Law for diffusion using 2D FEM application with regards to stochastic interaction of bridge deck crack vs. damaged epoxy-coated rebar system.
- The probability of corrosion initiation is used in order to qualitatively compare various scenarios with respect to durability.

Conclusions

- Probabilistic approach can be used to study effect of crack and holiday interaction with regards to bridge deck durability.
- The most important variable is diffusion coefficient (mix design).
- The effect of epoxy-coated reinforcement improves durability under proper handling and construction practices.
- The research in the area of reliability of RC bridge deck is valuable and deserves further attention.

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

by

Ing. Petr Konečný

Thank you