Finite Element Analysis of 2-D Chloride Diffusion Problem Considering Time-dependent Diffusion Coefficient Model

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Abstract: Effects of deicing salts are one of significant factors causing a corrosion of reinforcement of concrete bridge. This important influence on construction lifetime is desirable to research and suitable numeric models serve for that goal. The work discusses preparation of a model of transient diffusion of chloride, calculation of the chloride concentration and the example shows the functionality of the program. Second part of this project focuses on time effects on size of diffusion coefficient, as well as on the application of time-dependent concrete diffusion coefficient to existing algorithm for transient diffusion of chloride ions though concrete bridge. The graphic comparison of the changes, that shall illustrate significance of above mentioned effect.

Key-Words: Diffusion of chloride, nonstationary, FEM, concrete, corrosion, reinforcement, time-dependency.

1 Introduction

The paper is focused on the enhancement if chloride induced corrosion model of bridge decks from reinforced concrete [7], [8] with respect to the application of time-dependent diffusion coefficient [3] and simulation speed-up.

One of the most significant types of distress in many bridge decks is the corrosion of reinforcing steel from the ingress of chloride salts applied to melt snow and ice. The chloride ions penetration process is dominantly governed by diffusion in case of bridge decks.

In Central Europe, there is dominantly used water-proof membrane to protect the steel reinforcement in concrete. The epoxy-coated reinforcement is wide-spread protection in Northeastern United State spread epoxy resin directly to the steel reinforcement. Both methods postpone the corrosion initiation although the reparations or rehabilitations are necessary within 20-30 years of service [7], [8], [3], [11].

There is a need for the more focus on the development of numerical deterioration models of chloride induced corrosion of bridge decks from reinforced concrete.

2 Numerical Solution

The application of probabilistic assessment with the Monte Carlo simulation and 2-D Finite Element Analysis is used in the model of reinforced concrete bridge deck with crack and epoxy-coated reinforcement [7], [8]. The model was not able to address the effect of concrete hardening expressed as time-dependent diffusion coefficient increase. The change of diffusion coefficient over time is significant espacially in case of high performance concrete.

2.1 Nonstationary Model

However, the problem of chloride diffusion shall be addressed probabilistically thus creating a demand for large computing capacity. In this case model implemented using scripting language under commercial FEA package [4] runs rather slow. We are preparing a way to create an executable code that can speed-up the process.

There is prepared in house software uFem that is faster but it allowed model only stationary 2-D diffusion problems yet. This paper describes non-stationary model prepared under Matlab [12] as a step before the executable form preparation [5].

2.2 Effect of Transverse Crack

The cracking in structural concrete affects directly the ingress of chlorides in case bridge decks in the Northeastern U.S.A [7], [8], [2]. Figure 1 shows how chloride ions penetration to bridge deck and

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shows 2- D effect of transverse crack. This is the output of the Matlab model [9].

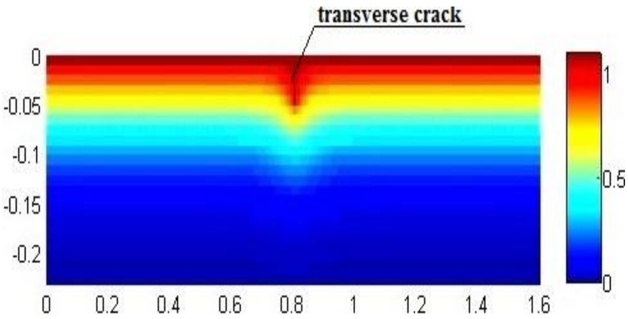

Fig. 1: Effect of transverse crack

2.3 Time-dependent Diffusion Coefficient

The other part of the paper focuses on the implementation of time-dependent diffusion coefficient based on the model [3]. The time-dependent effect allows modeling the increase of concrete resistance against the chloride ingress during concrete maturing. The prolonged maturity is significant especially with selected high performance concrete (HPC) mixtures [9].

3 Problem Solution

The current stage of the work is focused on the implementation of the non-stationary 2-D diffusion problem under MatLab [12]. The nonstationary diffusion of chloride ions is modeled using thermal diffusion analogy. While the thermal process describes the Fourier equation, the process of nonstationary chloride is determined by Fick's second law [5], see equation (1):

$$\frac{dC_{x,t}}{dt} = D_c \cdot \frac{d^2 C_{x,t}}{dx^2} \qquad (1)$$

where $C_{x,t}$ is the concentration of chlorides (percent by mass of total cementitions materials) at time t (years) and depth x (meters) and D_c is the apparent diffusion coefficient (m^2/year).

3.1 Implementation of the Algorithm

The Matlab program code [10] itself offers user interface for the computation of chloride concentration in selected point of the bridge deck cross-section and selected age including graphical and text output. Figure 2 shows one of the color charts, which is used for visual display of 2-D concentrations of chloride ions in the construction.

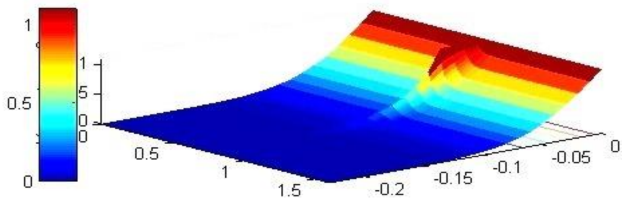

Fig. 2: Example of 3D graphical output

3.2 Numerical Example

The following example compares results obtained using our code [10] and commercial FEA package macro [7], [1].
This example represents a model of unprotected concrete deck with transverse crack epoxy-coated steel reinforcement.

Concentration of chlorides on surface of bridge deck [%]	1,1
Diffusion coefficient $D_{c,}$ [$10^{-12}m^2/s$]	4,91 [7]
Depth of the bridge deck D_{epth} [m]	0,23
Width of the bridge deck B [m]	1,60

Table 1: Parameters for example

Finally, we compare the concentration of chloride ions at three points on the structure.
In figure 3 we can see that the results of our program [10] and commercial FEA system are almost same.

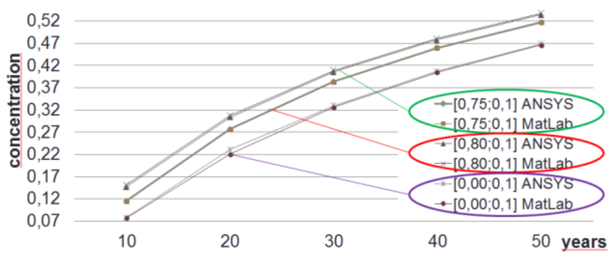

Fig. 3: Example results

3.3 Time-dependent Diffusion Coefficient

The chloride diffusion coefficient D_c is a function of both time and temperature se discussed e.g. in [3]. The relationship that is adopted in the paper uses the following relationship to account for time-dependent changes in diffusion [3], see equation (2):

$$D_c(t) = D_{c,ref} \cdot \left(\frac{t_{ref}}{t} \right)^m , \qquad (2)$$

where $D_c(t)$ is diffusion coefficient at time t, $D_{c,\mathrm{ref}}$ is diffusion coefficient at some reference time t_{ref} (e.g. 28 days), m is constant depending on mix proportions. The following equation (3) is used to modify m based on the level of fly ash (%FA) or slag (%SG) in the mix-design. Following relationship is only valid up to replacement levels of 50% fly ash or 70% slag [3]:

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70). \qquad (3)$$

The Equation (3) is current enhancement of the program [10]. In this case we tested 1-D behavior on the 2-D model. Finally, we compared the previous results with the new ones.

In first example we used values concentration of chlorides in depth 0.09 m under surface of concrete deck. The first step was to compare two diffusion coefficients in time. It is on figure 4. The blue color indicates coefficient with no slag, green color shows coefficient with %50 of slag.

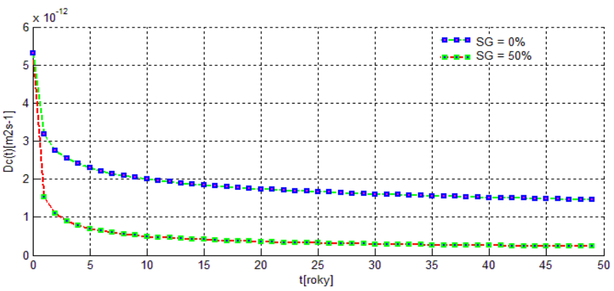

Fig. 4: No slag and %50 of slag

Than we use for example and compare results from ANSYS [1] and Matlab [10] like figure 5.

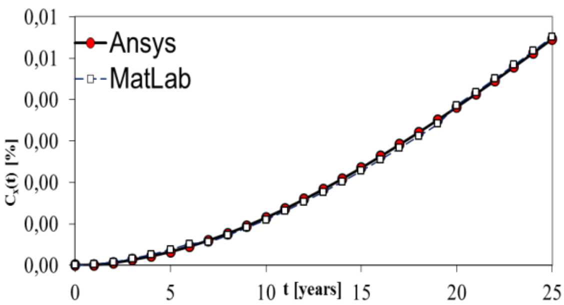

Fig. 5: Compare results – MatLab vs. Ansys

Figure 6 shows graphical display of the concentration. In this case, the bridge deck is without transverse crack and diffusion coefficient is uniform over time.

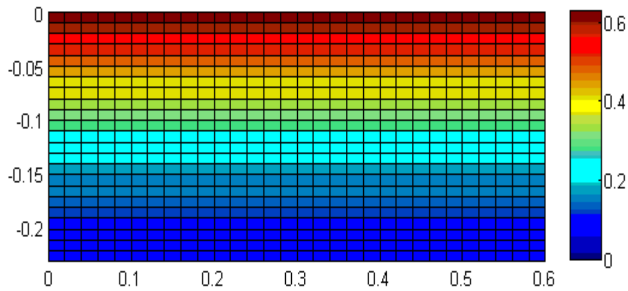

Fig. 6: Time-independent diffusion

In the case of Figure 7, it is the same model, but the diffusion coefficient is considered time-dependent.

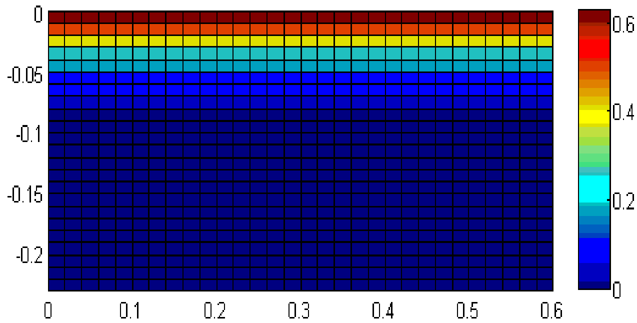

Fig. 7: Time-dependent diffusion coefficient

4 Summary and Conclusion

There is presented implementation of the 2-D diffusion problem related to chloride ion ingress into bridge deck. The special attention is paid to the application of time-dependent diffusion coefficient.

The first part of the paper describes the introductory numerical solution of 2-D chloride diffusion problem using FEA. The derived algorithm was implemented using MatLab software. The results were compared with commercial FEA package.

This software is suitable understanding of the numerical background, but the speed of calculation is unfortunately slow. The algorithm is being currently recoded under the C++ and translated to the in-house to software uFEM for better performance.

There is evaluated possibility of the application of time-dependency in case of diffusion coefficient. The results are compared with commercial FEA system as well. Adopted equations that describe the

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time-dependency are rather optimistic according to the authors.

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