12th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-12
B.L.A. Pichler, Ch. Hellmich, P. Preinstorfer (Eds)

EFFICIENT MACRO-SCALE MODELS FOR REINFORCEMENT CORROSION MODELING IN REINFORCED CONCRETE STRUCTURES

JAN ČERVENKA[*], MOHAMAD AHMAD[*], JIŘÍ RYMEŠ[*], AND LIBOR JENDELE[*]

[*] Červenka Consulting s.r.o., Na Hřebenkách 55, Praha 5, Czech Republic
e-mail: jan.cervenka@cervenka.cz, www.cervenka.cz

Keywords: Reinforcement corrosion, Chloride ingress, Fracture mechanics, Nonlinear simulation

Abstract: Reinforcement corrosion due to chloride ingress or carbonation is an important deterioration mechanism, which may compromise the service life of reinforced concrete structures. This paper presents an efficient macro-scale model, aiming to capture the most important aspects of the deterioration of reinforced concrete structures due to reinforcement corrosion. A chemo-mechanical model covers the initiation and propagation of chlorides using a 1D time-dependent model. This model is combined with the nonlinear modeling of cracking, bond failure, and reinforcement yielding. These models are implemented in the ATENA software and have been previously proven to provide a reliable prediction of structural performance deterioration. An example of an application from the consultancy practice is presented in the paper.

1 INTRODUCTION

Structures operating close to their limit states, or those with complex loading and environmental histories, often present challenges that traditional linear-elastic finite element (FE) analysis cannot adequately address. These methods often fall short when dealing with the nonlinear material behavior and complex interactions present in aging or damaged infrastructure. In such cases, nonlinear FE simulation can provide additional perspective to the problem as it can realistically simulate the actual structural response. Advanced numerical tools can simultaneously account for multiple interacting phenomena in concrete, such as thermal loading, concrete creep, and shrinkage, or even the progressive degradation due to chloride ingress and subsequent reinforcement corrosion.

The application of the finite element method (FEM) for the nonlinear analysis of reinforced concrete structures was pioneered in the 1970s through groundbreaking studies by Ngo and Scordelis [1], Rashid [2], and Červenka and Gerstle [3] During the following decades, numerous material models for reinforced concrete were developed, including notable contributions by Suidan and Schnobrich [4], Lin and Scordelis [5], De Borst [6], Rots and Blaauwendraad [7] Pramono and Willam [8], Etse [9] Lee and Fenves [10], and Červenka [11],[12]. These models are typically implemented in finite element software, where a concrete material model is assigned to each integration point to evaluate internal forces. To address mesh size dependency and mitigate spurious zero energy dissipation as element sizes approach zero, the crack band method introduced by Bažant and Oh [12] is frequently employed.

This paper shows an efficient approach for simulating the impact of chloride-induced reinforcement on the mechanical performance of reinforced concrete structures. It uses chloride diffusion and reinforcement corrosion models to simulate the chloride attack. Additionally, the adopted chloride diffusion model can consider the impact of mechanical cracks on the acceleration of the chloride penetration into the concrete cover. The deterioration modeling is coupled with a nonlinear finite element (FE) solver, where the reinforcement cross-section area is automatically reduced based on the corrosion degree. In doing so, the long-term structural degradation can be predicted, including its impact on the reduction of the load-bearing capacity.

The proposed modeling method enables proactive maintenance and repair strategies, thus optimizing structural lifespan, enhancing safety, and reducing both economic and ecological burdens. An example of an application from a consultancy practice is shown. It represents a reinforced concrete bridge structure where considerable cracks formed soon after construction. The goal of the numerical simulation was to first explain the origin of crack formation and, second, to predict how they impact the load-bearing capacity in the long term.

2 MODEL DESCRIPTION

2.1 Nonlinear modeling

Nonlinear simulations require accurate material models that are capable of realistically simulating the actual material response. The fracture-plastic model of Červenka et al. [1], [12] implemented in the ATENA software [13] is used in this study. It decomposes its nonlinear behavior in tension and compression.

Once the tensile strength is exceeded, the softening is controlled by the amount of the fracture energy dissipated in the cracking process as shown in Figure 1. The smeared crack approach with a crack band is applied. Furthermore, crack spacing limiters can be defined allowing an increase in the size of the finite elements and thus the computational efficiency can be achieved even for large structures, typical in engineering practice.

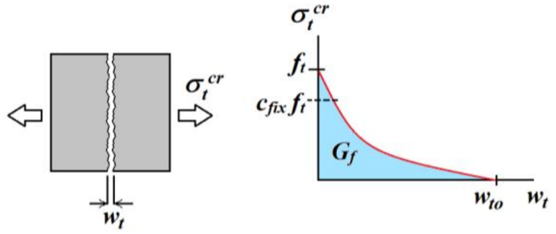

Figure 1: Crack opening law controlling the softening in the tensile branch of the material model.

The compressive response uses a plasticity approach with the Menetrey & Willam failure criterion [14] shown in Figure 2. Hardening occurs after reaching the crushing stress, followed by linear softening after the compressive strength peak, both depicted in Figure 3.

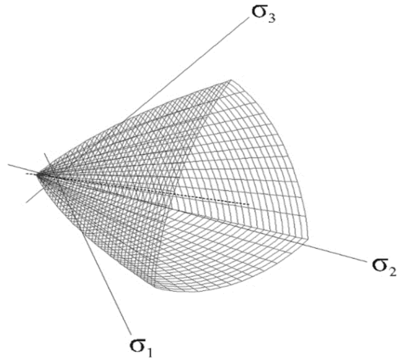

Figure 2: Menetrey & Willam failure criterion.

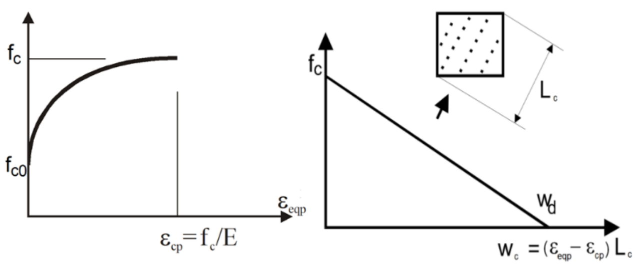

Figure 3: Pre-peak hardening and post-peak softening laws in the compression branch of the material model.

The final set of nonlinear equations is solved in an iterative manner using well-known approaches, such as the Newton-Raphson or Arc-Length methods.

2.2 Analysed structure and materials

The structure subjected to the analysis is a reinforced concrete bridge with a span of 15.3 m that supports an overpass ramp at a highway junction. The structure consists of an abutment subjected to earth pressure and a top deck supporting the highway ramp. The thickness of the abutment wall is 750 mm and the thickness of the slab varies from 910 mm at the abutment wall to 510 mm at the mid-span. The geometry of the model is shown in Figure 4.

After construction completion, considerable cracks were observed in the bridge deck. These cracks cannot be explained by the acting mechanical loads. Although the cracking seemed stabilized, it was necessary to explain their origin to rule out or estimate their further growth. Furthermore, the crack's presence necessarily affects the durability of the structure thus there was a need for a long-term performance assessment.

The estimated concrete compressive strength was 30 MPa, which was used to derive the parameters of the nonlinear material model summarized in Table 1.

For the assessment of the long-term structural performance, creep and shrinkage were calculated according to Bažant's B3 model [15] and the resulting initial strain as well as the evolution of the material parameters were applied in the numerical model. The important parameters of the B3 model are given in Table 2.

All reinforcement bars present in the structure were modeled according to their exact geometry using embedded truss elements as shown in Figure 5. The bar size varied from M15 to M35. The reinforcement material parameters are shown in Table 3.

Table 1: Parameters of the concrete material model.

compressive strength	f_c [MPa]	-30.0
Young's modulus	E [GPa]	25.6
tensile strength	f_t [MPa]	2.2
fracture energy	G_f [N/m]	70
onset of crushing	f_{c0} [MPa]	-4.4
plastic strain at the compressive strength	ε_{cp} [-]	-0.0013
maximum compressive displacement	w_d [mm]	-0.5

Table 2: Parameters of the B3 creep model.

humidity	h [-]	0.70
concrete density	ρ [kg/m^3]	2447
ACI concrete type	-	normal
water-to-cement ratio	w/c [-]	0.40
aggregate-to-cement ratio	a/c [-]	4.0
type of curing	-	air
end of curing	[day]	4.0
max. compressive displacement	w_d [mm]	-0.5

Table 3: Material parameters used for the discrete reinforcement.

Young's modulus	E [GPa]	25.6
yield strength	f_y [MPa]	360
ultimate strength	f_u [MPa]	374
ultimate strain	ε_u [-]	0.0045

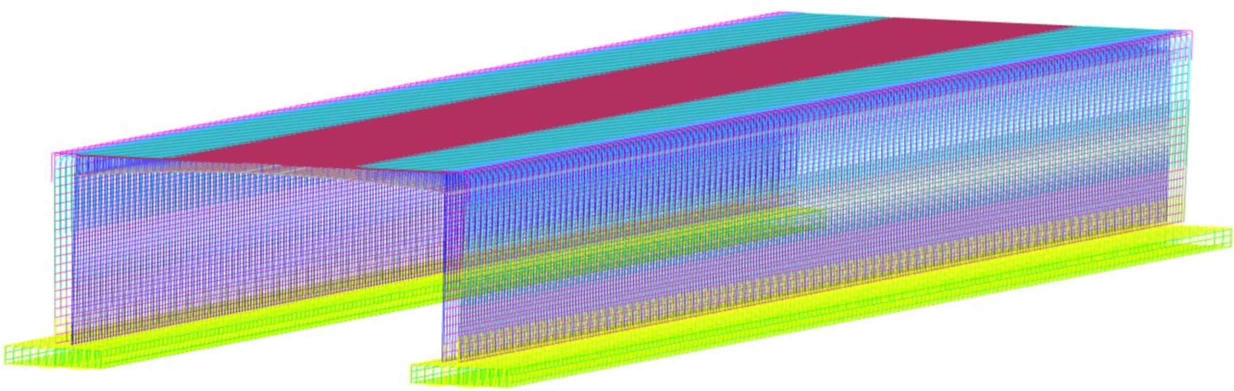

Figure 4: Layout of the discrete reinforcement bars in the model.

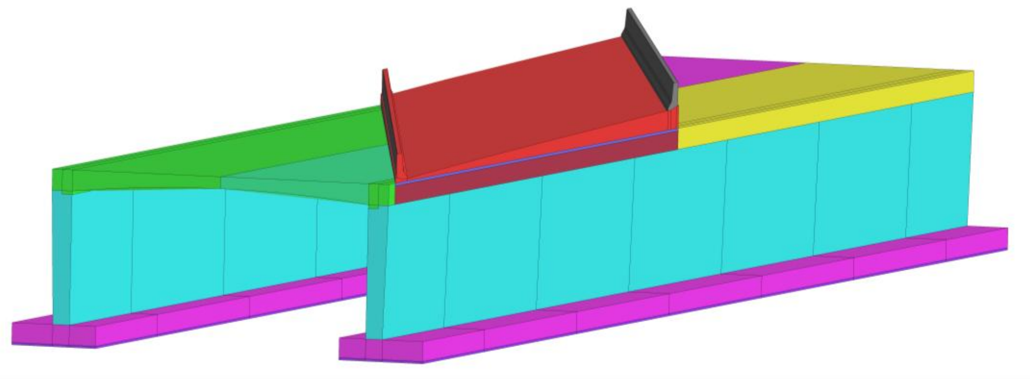

Figure 5: Geometry of the analyzed structure.

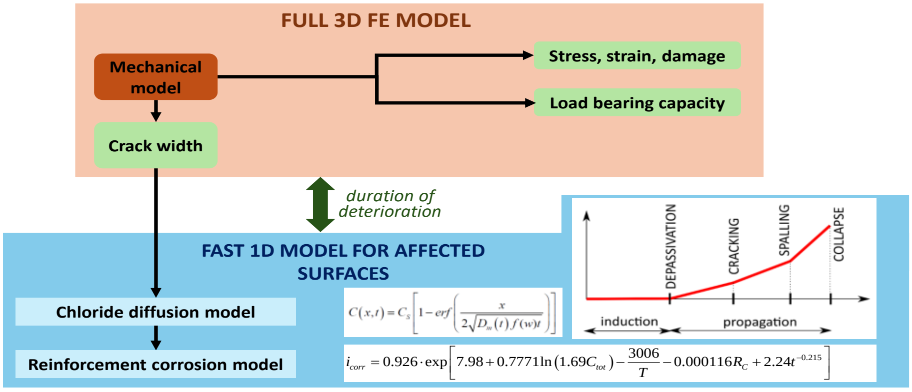

Figure 6: Schematic illustration of how the 1D chloride diffusion and corrosion models are coupled with the 3D FE solver.

maximum temperature reached during the hydration of the fresh concrete.

After the thermal loading, additional dead loads were prescribed to simulate the complete construction process. After that, creep, drying shrinkage and chloride attack were simulated with a duration of 75 years.

2.3 Loads

Multiple loading combinations were investigated for the overall assessment. In this paper, we present the results of the serviceability state check. The load cases include self-weight, live loads, earth pressure on the abutment walls, thermal loading, creep, shrinkage, and chloride attack. Unlike in a linear-elastic simulation, where a combined effect of multiple load cases can be obtained through their superpositioning, in the nonlinear analysis, these load cases are prescribed subsequently (or concurrently) according to the actual loading history.

The simulation includes the construction stage simulating the unmoulding (i.e., application of the deck's self-weight) together with thermal loading that was applied on the bridge deck to induce differential volumetric strain between the deck and the abutment walls. It was applied as an initial strain with a value corresponding to the cooling from the

2.4 Modelling of chloride attack

The cracks presented in the structure may compromise the durability of the structure as they accelerate the external deterioration mechanisms. Therefore, a durability study was conducted simulating a long-term chloride attack. This is done using a coupled mechano-chemical model, which is schematically depicted in Figure 6.

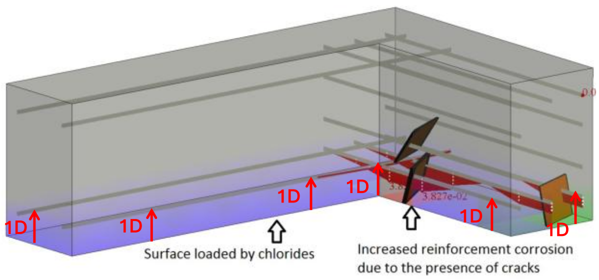

Figure 7: Schematic illustration of how mechanical crack accelerates the chloride penetration and thus the corrosion process.

The chloride-induced corrosion model involves two phases: induction and propagation. The induction phase describes chloride penetration into the concrete cover, often modeled as a diffusion process [16]. The diffusion rate is affected by the material characteristics, namely the diffusion coefficient and chloride binding ability, and the exposure conditions such as the boundary chloride content. Furthermore, the chloride diffusion is accelerated by the presence of mechanical cracks. This is shown in the schematics in Figure 7.

Once chloride concentration at the reinforcement reaches a critical level, the propagation phase begins, and the reinforcement cross-section area is automatically reduced within the solution loop. In the solution of the mechanical problem, only the uncorroded reinforcement area is assumed to carry stress.

Table 4: Parameters used for simulation of the chloride attack.

cement content [kg/m^3]	25.6
cement type [-]	CEM I
decay rate (i.e., age factor) [-]	0.37
mean diffusion coefficient	1.85×10^{-12}
reference diffusion coefficient [m^2/s]	1.16×10^{-12}
reference time for diffusion coefficient [year]	20
boundary chloride content [% in cement]	0.5
critical chloride concentration [%]	0.4
pitting factor [-]	3
corrosion rate after spalling [mm/year]	0.0375

The corrosion rate of reinforcement steel is influenced by several key factors, including the chloride concentration, temperature, duration of corrosion, and the pitting factor. In the mechanical analysis, the expansion of corrosion products and the resulting pressure within the concrete cover are not explicitly considered. Instead, the moment of concrete spalling is estimated using an empirical relationship that incorporates the tensile strength of the concrete and the initial diameter of the reinforcement. Once spalling of the concrete cover is assumed to have occurred, the corrosion rate of the reinforcement becomes dependent on the environmental and exposure conditions at the site.

It is noteworthy that the mechanical problem is addressed using the finite element (FE) method as a fully three-dimensional (3D) analysis, capturing the complexities of the structural response. In contrast, the chloride diffusion process is simplified by modeling it as a one-dimensional (1D) problem, which is applied exclusively to the surfaces exposed to chloride concentration. This simplification ensures computational efficiency without compromising the accuracy of results for practical purposes. At each time step of the solution, the chloride concentration is directly computed using a closed-form solution to the 1D diffusion equation, which makes the approach not only robust but also highly applicable to engineering practice. This methodology allows for a streamlined yet effective evaluation of the coupled processes of corrosion and structural performance in reinforced concrete systems.

Further details regarding the model, including its development and validation, can be found in reference [17]. The input data for the model were primarily derived from the DuraCrete reports [16]. This document provides extensive guidelines and recommendations, and from experimental measurements conducted by RISE [18]. A summary of these input data, along with key parameters and assumptions, is presented in Table 4 for clarity and reference. The robustness and applicability of the proposed model have been demonstrated in various scenarios, with additional examples and case studies available in the literature, specifically in references [19],[20],[21]. These studies highlight the versatility and reliability of the model in addressing a wide range of engineering challenges.

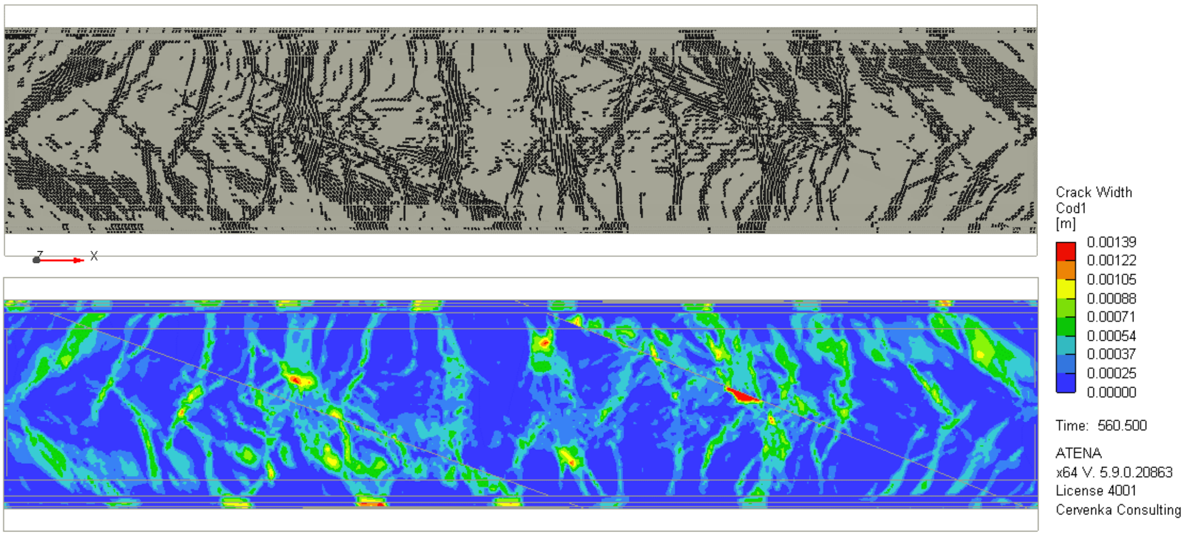

Figure 8: Numerical results at the bottom surface of the bridge deck after finishing the construction process: (top) Crack pattern, and (bottom) crack width. The crack pattern displays only cracks wider than 0.25 mm.

3 RESULTS

Figure 8 shows the crack pattern and crack width at the bottom surface of the bridge deck. These results are given at the solution step that corresponds opening of the bridge for operation. The applied loads include both characteristic dead and live loads. Furthermore, thermal strains were applied during the construction phase to simulate the cooling of the deck from the elevated temperature during the concrete hydration.

From Figure 8, it can be observed that there are multiple cracks with a width exceeding 1 mm. To predict, how these cracks will impact the chloride penetration, the chloride attack was simulated using the approach described earlier. Furthermore, together with the chloride diffusion simulation, the concrete creep and drying shrinkage were modeled using the B3 model [15]. The results after a 75-year-long chloride attack are shown in Figure 9 in terms of crack pattern and width, chloride content at the concrete cover, and reinforcement corrosion.

The results predict that the maximum chloride concentration will exceed 0.5 % and more than 40 % of the original reinforcement cross-section area will be lost due to corrosion at the most affected regions of the deck. Furthermore, due to the combined effect of creep, shrinkage, and reinforcement corrosion, further crack growth is predicted during this period at the bottom surface of the deck.

4 CONCLUSIONS

This paper presents an efficient numerical framework for simulation of the chloride-induced reinforcement corrosion on reinforcement concrete structures. The simulation approach combines the 1D chloride diffusion and corrosion models with full 3D finite element simulation. The chloride diffusion model accounts for the presence of mechanical cracks, accelerating the diffusion process. The adopted model allows a realistic estimation of the deterioration effects on the structural scale while preserving excellent computational efficiency.

An application example is then shown in the paper. It presents a reinforced concrete bridge where considerable cracks formed in the deck just after finishing the construction. The numerical simulation reproduced the cracks and further predicted the corrosion process and crack propagation during a 75-year-long chloride attack.

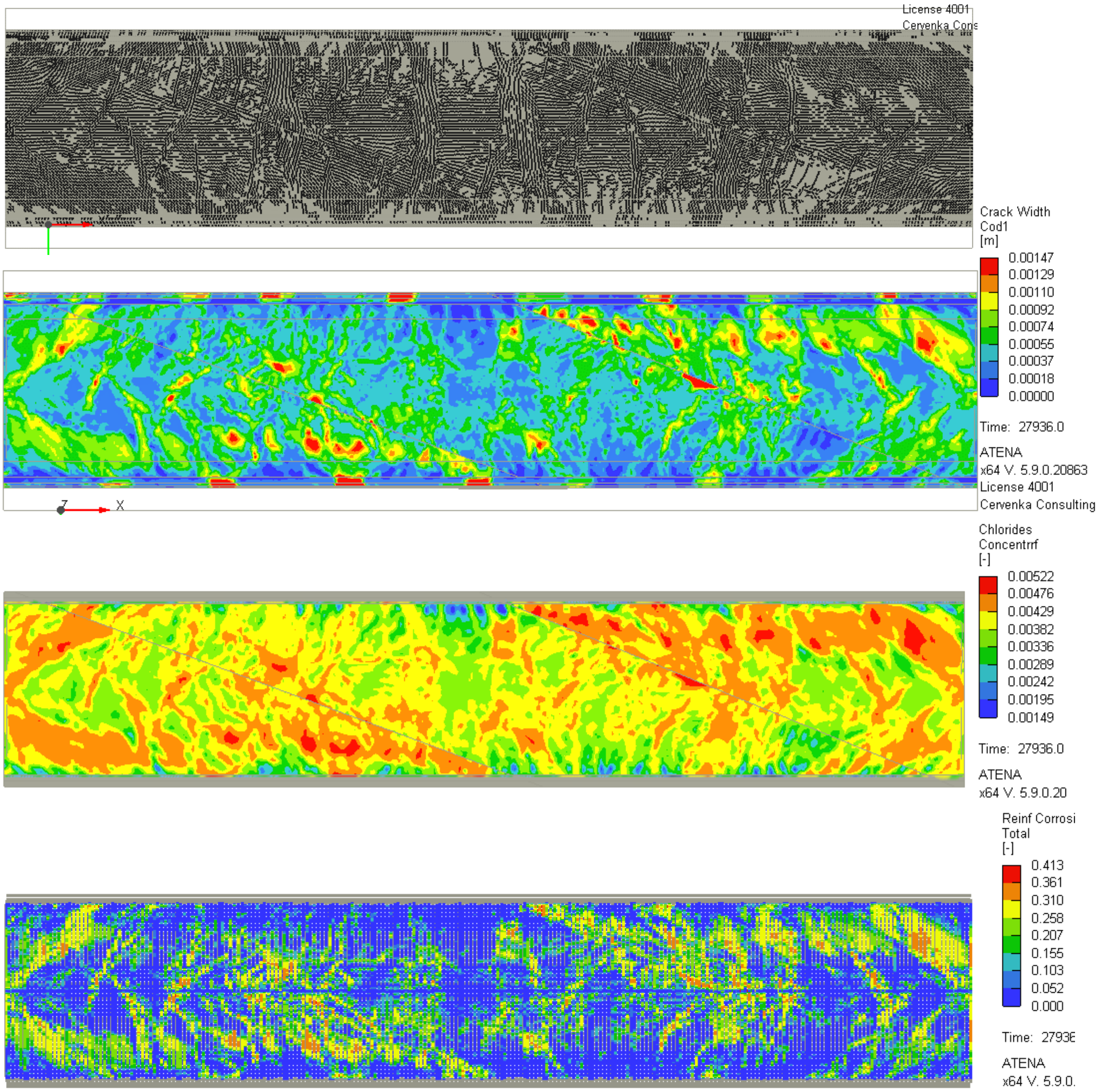

Figure 9: Numerical results at the bottom surface of the bridge deck after a 75-year-long chloride attack: (from top) Crack pattern, crack width, chloride concentration at the level of bottom reinforcement, and reinforcement corrosion degree. The crack pattern displays only cracks exceeding 0.25 mm.

ACKNOWLEDGEMENTS

This work presented here was done with the financial support of the Technology Agency of the Czech Republic under the project TM04000012 “BRIHIS - A concrete bridge health interpretation system based on mutual boost of big data and physical mechanism” within the Delta 2 Programme. The financial support is greatly acknowledged.

REFERENCES

[1] Ngo, D., Scordelis, A.C. 1967. Finite element analysis of rein-forced concrete beams, J. Amer. Concr. Inst. 64, pp. 152-163.

[2] Rashid, Y.R. 1968. Analysis of prestressed concrete pressure vessels. Nuclear Engineering and Design 7 (4), 334-344.

[3] Červenka, V., Gerstle, K., 1971. Inelastic analysis of reinforced concrete panels. Part I : Theory. Publication I.A.B.S.E. 31 (11), 32-45.

[4] Suidan, M., Schnobrich, W.C. 1973. Finite Element Analysis of Reinforced Concrete, ASCE, J. of Struct. Div., Vol. 99, No. ST10, pp. 2108-2121

[5] Lin, C.S., and Scordelis, A. 1975. Nonlinear Analysis of RC Shells of General Form, ASCE, J. of Struct. Eng., Vol. 101, No. 3, pp. 152-163.

[6] de Borst, R. 1986. Non-linear analysis of frictional materials. PhD Thesis, Delft University of Technology, The Netherlands.

[7] Rots, J.G., Blaauwendraad, J. 1989. Crack models for concrete: Discrete or smeared, Fixed, multi-directional or rotating? Heron 34 (1).

[8] Pramono, E., Willam, K.J. 1989. Fracture energy-based plasticity formulation of plain concrete. J. of Eng. Mech., ASCE 115 (6), 1183-1204.

[9] Etse, G. 1992. Theoretische und numerische untersuchung zum diffusen und lokalisierten versagen in beton. PhD Thesis, University of Karlsruhe.

[10] Lee, J., Fenves, G.L. 1998. Plastic-damage model for cyclic loading of concrete structures. J. of Eng. Mech., ASCE 124 (8), 892 - 900.

[11] Červenka J., Červenka V., and Eligehausen R., 1998, Fracture-plastic material model for concrete, application to the analysis of powder actuated anchors. In: *Proceedings FRAMCOS (3)*, pp. 1107–16.

[12] Červenka J., and Papanikolaou V.K., 2008, Three dimensional combined fracture–plastic material model for concrete. *Int J Plast*., Dec 1;24(12):2192-220.

[13] Červenka V., Jendele L., and Červenka J., 2022, *ATENA Program Documentation: Part 1 Theory*, Prague.

[14] Menetrey, P., and Willam, K.J., 1995, Triaxial Failure Criterion for Concrete and its Generalization, *ACI Struct J*. 92(3), 311-318.

[15] Bažant, Z.P., and Baweja S., 2000, Creep and shrinkage prediction model for analysis and design of concrete structures: Model B3, *ACI Special Publications*, 194:1-84.

[16] The European Union–Brite EuRam III, 2000, Probabilistic performance-based durability design of concrete structures: *Final technical report of Duracrete project.*

[17] Hájková K, Šmilauer V, Jendele L, and Červenka J., 2018, Prediction of reinforcement corrosion due to chloride ingress and its effects on serviceability. *Eng Struct*, 174:768–777.

[18] Luping T., Boubitsas D., Utgenannt P., Abbas Z., 2018, Chloride Ingress and Reinforcement Corrosion - After 20 years' field exposure in a highway environment. Borås.

[19] Rymeš J., Červenka J., and Radomír Pukl R., 2022, Advanced modelling of concrete structures for improved sustainability, Acta Polytechnica CTU Proceedings, 38: 190–195.

[20] Červenka J., and Rymeš J., 2022, Digital twin for modelling structural durability, In *RILEM International Conference on Numerical Modeling Strategies for Sustainable Concrete Structures*, Cham: Springer International Publishing, 2022.

[21] Červenka, J., Rymeš, J., Jendele, L., and Pukl, R., 2023, Digital twins for reinforced concrete structures. In *International Symposium of the International Federation for Structural Concrete* Cham: Springer Nature Switzerland, 1621-1630.