

Model of Reinforced-Concrete Structure Deformation Under Combined Effect Carbonation and Chloride Corrosion

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Abstract. The present paper is devoted to creating a model of deformation and destruction of reinforced-concrete bridge structures subject to combined effect of load and carbonation (caused by presence of carbon dioxide), and chloride corrosion triggered by salts used for bridge road deicing. The model is a hybrid of several models such as loading model; structural element model (pier, beam, roadway slab, span structure); impact models of two corrosive environment triggering carbonation and chloride corrosion; concrete deformation models (considering transformations caused by impact of various corrosive environments); reinforcement corrosive wear model. Concrete deformation model is created with due regard to nonlinearity of its operation and variable tension and compression resistance. Impact functions are the tool that demonstrates the influence carbonation and chloride corrosion have on the structure. Corrosive wear model is built as a piecewise function with a zero value at the incubation period, and as a power function after the end of the incubation period. Due to combined effect of carbonation and chloride corrosion, critical content of chlorides (which triggers reinforcement corrosion) drops twofold at a critical value of the carbonation process parameter, and this significantly shortens the incubation period. The paper describes the generalized model bridge pier deformation due to combined effect of load, carbonation, and chloride corrosion. The model shows the stages of how pier operates during ingress of the chloride-containing environment and carbon dioxide to the cross-section from the outside. The pier calculation methodology has three phases: loading, pier submerging into a corrosive environment (which causes chloride corrosion and carbonation), and pier deformation over time with due regard to change of mechanical qualities of concrete (caused by carbonation and chloride corrosion), and to reinforcement corrosion. When calculating pier deformation over time, time steps are used; step duration is set to ensure that changes of all step-sensitive parameters (chloride content, stress) would not exceed the preset limits. Following the methodology, a software package was developed, which enabled to calculate the values of the vertically loaded pier under combined effect of a chloride-containing environment and carbonation. As a result, it was found that under the combined effect of chlorides and carbon dioxide, the incubation period of reinforcement corrosion shortens significantly, corrosion intensity grows, and pier durability turns out to be shorter than when impacted by each factor separately.

1. Introduction

Reinforced-concrete structures of transport constructions can be destroyed by carbonation and chloride corrosion, which often act jointly. Carbonation is caused by carbon dioxide penetrating into concrete elements, while chloride corrosion is triggered by deicing salts or marine atmosphere. Until



quite recently, the evaluation of impact that these factors have on such structures had been rather qualitative than quantitative. Papers of A.I. Vasilyev [1], I.G. Ovchinnikov and his students [2] considered the problem of reinforced-concrete facility destruction caused by carbonation and chloride corrosion. Lately, active studies of how reinforced-concrete structure behave under combined effect of load, carbonation and chloride corrosion, have been carried out abroad [3-6]. However, the problem of correct modeling of reinforced-concrete structure behavior under several corrosive factors (particularly, carbonation and chloride corrosion), is not even close to any solution yet. The present paper describes the problem of modeling degradation of a reinforced-concrete structure under combined effect of the abovementioned factors, and ways of using it to forecast behavior of such a structure.

2. Main Body

According to the analysis of laboratory and field experiments, carbonation and chloride corrosion often act jointly — due to that, the degradation of reinforced-concrete structures goes significantly faster than in case of separate action of these factors. The generalized model is to describe the destruction of reinforced-concrete structures under the abovementioned conditions. The model comprises several simple models: structural element model; material model (including concrete deformation and reinforcement deformation models); corrosive environment impact model; loading model; critical structure state model. The corrosive environment impact model includes models of penetration of carbon dioxide and chlorides into concrete, carbonation model, and reinforcement corrosive wear model. To describe carbonation, a scalar chemical interaction parameter μ is introduced, which (1) is related to each point of the structure, (2) varies from 0 to 1, and (3) represents the ratio of the current $CaCO_3$ content at a given cross-section point to the max $CaCO_3$ content at the point:

$$\mu = \frac{C_{cur}^{CaCO_3}}{C_{max}^{CaCO_3}}, \quad (1)$$

The change of this parameter describes the kinetics of interaction between carbon dioxide and calcium hydroxide, resulting in the formation of calcium carbonate. The kinetic equation for μ is assumed as a logistic equation [8]:

$$\frac{d\mu}{dt} = q\mu(1 - \mu), \quad (2)$$

where q is a coefficient regarding the nature of a corrosive environment and concrete qualities. To describe the kinetics of penetration of carbon dioxide and chloride-containing environment into concrete, diffusion equations or simpler but yet correct diffuse-front penetration models are used [9]. The following model is used to describe reinforcement corrosive wear:

$$\delta = \begin{cases} 0, & t \leq t_{inc}; \\ \alpha(t - t_{inc})^\beta, & t > t_{inc} \end{cases} \quad (3)$$

where δ is corrosion depth; α , β are coefficients, t_{inc} is incubation period — a period before corrosion starts (at critical chlorides content at the reinforcement surface). Under combined effect of carbonation and chloride corrosion, the critical chlorides content decreases twofold, which leads to a significant shortening of the incubation period and earlier reinforcement corrosion. Concrete deformation model is assumed as follows:

$$\sigma = \begin{cases} A_{0p}\chi_1(\mu)\psi_1(C)\varepsilon - B_{0p}\chi_2(\mu)\psi_2(C)\varepsilon^3, & \sigma > 0; \\ A_{0c}\chi_1(\mu)\psi_1(C)\varepsilon - B_{0c}\chi_2(\mu)\psi_2(C)\varepsilon^3, & \sigma < 0, \end{cases} \quad (4)$$

where σ is stress, ε is deformation, $\chi(\mu)$ is carbonation effect function; $\psi(C)$ is chloride corrosion effect function; C is chlorides content. It is assumed that concrete is a nonlinearly deforming

material showing variable behavior at tension or compression. Reinforcement deformation model is assumed in the form of Hooke's law. The relationships above were used to calculate the reinforced-concrete beam of a rectangular cross-section (Figure 1) exposed to carbonation and chloride corrosion at the same time.

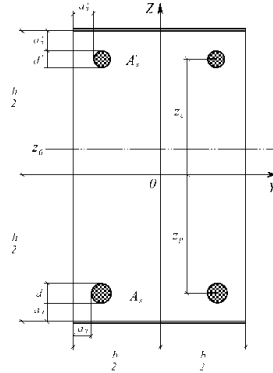


Figure 1. Beam Cross-Section Reinforcement Pattern

Resolving equations regarding beam deformation exposed to full-scale effect of chloride-containing environment and load, are as follows:

$$\begin{aligned}
 N + \int_{z(y, C_1, C_3)}^{z_0} \int_{-\frac{b}{2}}^{y_3} A_p(C_3) \phi(z_0 - z) dz dy + \int_{-\frac{h}{2}}^{z_1} \int_{y(z, C_1, C_3)}^{y(z, C_1, C_4)} A_p(C_1) \phi(z_0 - z) dz dy + \int_{z(y, C_1, C_4)}^{z_0} \int_{y_4}^{\frac{b}{2}} A_p(C_4) \phi(z_0 - z) dz dy + \\
 + \int_{z_1}^{z_0} \int_{y_3}^{y_4} A_p \phi(z_0 - z) dz dy + \int_{z_0}^{z_1} \int_{-\frac{b}{2}}^{y_3} A_c(C_3) \phi(z_0 - z) dz dy + \int_{z_2}^{\frac{h}{2}} \int_{y(z, C_3, C_2)}^{y_3} A_c(C_2) \phi(z_0 - z) dz dy + \\
 + \int_{z_0}^{z(y, C_4, C_2)} \int_{y_4}^{\frac{b}{2}} A_c(C_4) \phi(z_0 - z) dz dy + \int_{z_0}^{z_2} \int_{y_3}^{y_4} A_c \phi(z_0 - z) dz dy - \int_{z(y, C_1, C_3)}^{z_0} \int_{-\frac{b}{2}}^{y_3} B_p(C_3) \phi^3(z_0 - z)^3 dz dy - \\
 - \int_{-\frac{h}{2}}^{z_1} \int_{y(z, C_1, C_3)}^{y(z, C_1, C_4)} B_p(C_1) \phi^3(z_0 - z)^3 dz dy - \int_{z(y, C_1, C_4)}^{z_0} \int_{y_4}^{\frac{b}{2}} B_p(C_4) \phi^3(z_0 - z)^3 dz dy - \int_{z_1}^{z_0} \int_{y_3}^{y_4} B_p \phi^3(z_0 - z)^3 dz dy - \\
 - \int_{z_0}^{z(y, C_3, C_2)} \int_{-\frac{b}{2}}^{y_3} B_c(C_3) \phi^3(z_0 - z)^3 dz dy - \int_{z_2}^{\frac{h}{2}} \int_{y(z, C_3, C_2)}^{y_3} B_c(C_2) \phi^3(z_0 - z)^3 dz dy - \\
 - \int_{z_0}^{z(y, C_4, C_2)} \int_{y_4}^{\frac{b}{2}} B_c(C_4) \phi^3(z_0 - z)^3 dz dy - \\
 - \int_{z_0}^{z_2} \int_{y_3}^{y_4} B_c \phi^3(z_0 - z)^3 dz dy + a A_s [\phi(z_0 - z_p)]^m - a A_s [\phi(z_0 - z_c)]^m = 0; \quad (5)
 \end{aligned}$$

$$\begin{aligned}
 M + \int_{z(y, C_1, C_3)}^{z_0} \int_{-\frac{b}{2}}^{y_3} A_p(C_3) \phi(z_0 - z) z dz dy + \int_{-\frac{h}{2}}^{z_1} \int_{y(z, C_1, C_3)}^{y(z, C_1, C_4)} A_p(C_1) \phi(z_0 - z) z dz dy + \int_{z(y, C_1, C_4)}^{z_0} \int_{y_4}^{\frac{b}{2}} A_p(C_4) \phi(z_0 - z) z dz dy +
 \end{aligned}$$

$$\begin{aligned}
& + \int_{z_1}^{z_0} \int_{y_3}^{y_4} A_p \phi(z_0 - z) z dz dy + \int_{z_0}^{z(y, C_3, C_2)} \int_{\frac{b}{2}}^{y_3} A_c(C_3) \phi(z_0 - z) z dz dy + \int_{z_2}^{\frac{h}{2}} \int_{y(z, C_3, C_2)}^{y(z, C_4, C_2)} A_c(C_2) \phi(z_0 - z) z dz dy + \\
& + \int_{z_0}^{z(y, C_4, C_2)} \int_{y_4}^{\frac{b}{2}} A_c(C_4) \phi(z_0 - z) z dz dy + \int_{z_0}^{z_2} \int_{y_3}^{y_4} A_c \phi(z_0 - z) z dz dy - \int_{z(y, C_1, C_3)}^{z_0} \int_{\frac{b}{2}}^{y_3} B_p(C_3) \phi^3(z_0 - z)^3 z dz dy - \\
& - \int_{\frac{h}{2}}^{z_1} \int_{y(z, C_1, C_3)}^{y(z, C_1, C_4)} B_p(C_1) \phi^3(z_0 - z)^3 z dz dy - \int_{z(y, C_1, C_4)}^{z_0} \int_{\frac{b}{2}}^{y_4} B_p(C_4) \phi^3(z_0 - z)^3 z dz dy - \int_{z_1}^{z_0} \int_{y_3}^{y_4} B_p \phi^3(z_0 - z)^3 z dz dy - \\
& - \int_{z_0}^{z(y, C_3, C_2)} \int_{\frac{b}{2}}^{y_3} B_c(C_3) \phi^3(z_0 - z)^3 z dz dy - \int_{z_2}^{\frac{h}{2}} \int_{y(z, C_3, C_2)}^{y(z, C_4, C_2)} B_c(C_2) \phi^3(z_0 - z)^3 z dz dy - \int_{z_0}^{z(y, C_4, C_2)} \int_{y_4}^{\frac{b}{2}} B_c(C_4) \phi^3(z_0 - z)^3 z dz dy - \\
& - \int_{z_0}^{z_2} \int_{y_3}^{y_4} B_c \phi^3(z_0 - z)^3 z dz dy + a A_s z_p [\phi(z_0 - z_p)]^m + a A_s^{\odot} z_c [\phi(z_0 - z_c)]^m = 0.
\end{aligned}$$

N is longitudinal stress, M is bending moment, h is height, w is section width, z is a vertical coordinate, coordinate ϕ is curvature of the bending line of a beam; z_0 is a coordinate of a neutral axis.

With that, the hypothesis of plane sections is assumed valid: $\mathcal{E} = \mathcal{E}_0 - \phi z = \phi(z_0 - z)$

Beam calculation consists of three stages: loading, start of interaction with the corrosive environment, beam deformation over time following the destruction [10]. Beam cross-section was approximated by a grid of equally-spaced points where values C, μ , σ , ε belonged. During deformation, the problem was solved with time steps t . A software package was developed to calculate the reinforced-concrete beam loaded with the bending moment. Beam parameters are as follows: h = 0.25 m; b = 0.15 m; protective layer thickness $a_{pr} = 0.03$ m; diameters of reinforcement bars (upper and lower) d = 0.010 m. The beam was loaded with the bending moment M = 1,000 N·m. Calculation results are presented in Figure 2, Figure 3, and Table 1.

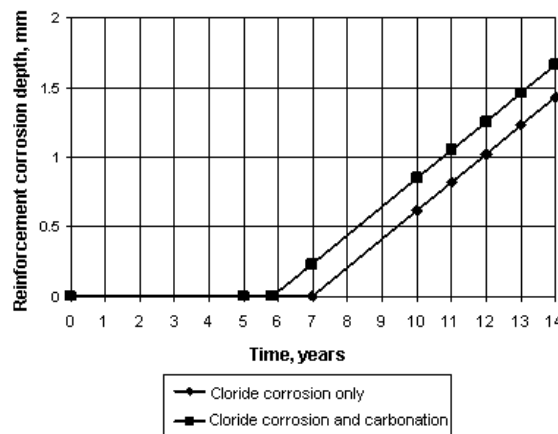


Figure 2. Reinforcement Time-Dependent Corrosion Kinetics

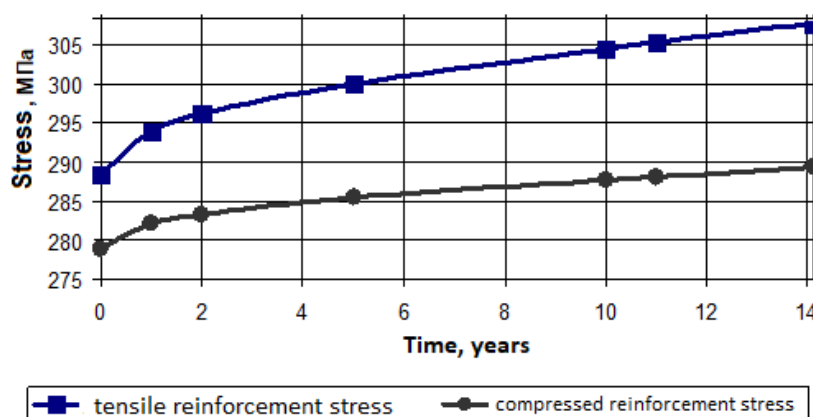


Figure 3. Time-Dependent Change in Reinforcement Stresses

Table 1. Incubation Period Duration (t_{inc}) and Critical State Time (t_{crit})

Carbonation	Critical Chlorides Content, % of cement weight	t_{inc} , days	t_{crit} , days
-	0.4	2,539	5,297
+	0.2	2,122	5,155

As is obvious, the combined effect of carbonation and chloride corrosion leads to significant shortening of the incubation period before reinforcement corrosion start, and earlier beam destruction.

Conclusion

According to the analysis, the combined effect of carbonation and chloride corrosion has a destructive impact on mechanical qualities of reinforced concrete and behavior of such structures during operation. As the durability of reinforced-concrete structures shortens as a result, it makes the accounting of the combined effect of carbonation and chloride corrosion when predicting behavior of loaded reinforced-concrete structures, totally necessary. With that, it shall be not about trivial evaluation of the combined effect but correct analysis of structure behavior by virtue of the developed models.

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