Cement and Concrete Composites 93 (2018) 140–154

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Carbonation depth predictions in concrete bridges under changing climate conditions and increasing traffic loads

Chao Jiang[a,b], Xianglin Gu[a,b,*], Qinghua Huang[a,b], Weiping Zhang[a,b]

[a] Key Laboratory of Performance Evolution and Control for Engineering Structures, Ministry of Education, Tongji University, 1239 Siping Rd., Shanghai 200092, PR China
[b] Department of Structural Engineering, College of Civil Engineering, Tongji University, 1239 Siping Rd., Shanghai 200092, PR China

ARTICLE INFO

Keywords:
Concrete
Carbonation
Fatigue damage
Climate change
Traffic loads

ABSTRACT

This paper first introduced a numerical carbonation model (NCM) for fatigue-damaged concrete. Then, based on the NCM, a simplified carbonation model (SCM) for fatigue-damaged concrete was established, comprised of a non-damaged concrete contribution term and a fatigue damage contribution term, through Monte Carlo simulations. Both the NCM and SCM were verified by experimental results reported in the literature. Subsequently, an incremental method was proposed to consider the time-variant fatigue damage and exposure conditions. Finally, a case study was conducted, which determined that cumulating fatigue damage could have a big influence on carbonation depth evolution. Meanwhile, differences in the cumulating fatigue damage could lead to noticeable differences in carbonation depth evolution among different points in the same concrete bridge. Moreover, drastic increases of CO_2 concentration and temperature could induce relationships of carbonation depths with square roots of service times to remarkably deviate from the proportional laws widely accepted under a time-invariant environment.

1. Introduction

Reinforced concrete (RC) bridge construction has been a priority in China for many years along with the rapid development of highway or high-speed railway networks. Under an atmospheric environment, these RC bridges not only suffer carbonation-induced steel reinforcement corrosion but also undergo fatigue damage caused by running vehicles or trains. Steel reinforcement corrosion usually causes RC bridges to be functionally deficient or even obsolete due to delaminating concrete covers and decreasing reinforcement cross-sections [1–11]. Furthermore, fatigue damage often induces micro cracks in concrete to coalesce into macro ones, which accelerates the carbonation process in concrete. Therefore, the influence of fatigue damage on concrete carbonation has drawn significant attention.

Several researchers [12–17] have conducted experiments to discern the effects of fatigue damage on carbonation. These researchers consistently found that both tensile and compressive fatigue damage can increase carbonation depths. However, in most cases, these experiments were designed to explore carbonation depth evolution with respect to exposure duration in fatigue-damaged concrete under constant exposure conditions. The effects of exposure conditions, i.e., temperature (T), relative humidity (RH) and carbon dioxide (CO_2) concentration on carbonation depths in fatigue-damaged concrete were thus underrepresented. Moreover, except for Jiang et al.'s experiment [13] which involved axial fatigue-damaged prism concrete specimens, the majority of these experiments [12,14–17] utilized fatigue-damaged plain concrete beam specimens. In plain concrete beams, the stresses in the compressive zones are comparable to stresses in the tensile zones, which are usually less than or equal to the tensile concrete strength f_t'. For concrete, the tensile strength f_t' usually ranges from 1/10 to 1/8 of the corresponding compressive strength f_c'. Consequently, compressive stresses in plain concrete beams, which range from 0 to f_t' (i.e., from 0 to $0.1f_c'$ or $0.125f_c'$), are much smaller than those ranging from $0.4f_c'$ to $0.6f_c'$ which commonly exist in real-world concrete structures. To remedy these deficiencies, the authors' group conducted a systematic experimental investigation on carbonation in prism concrete specimens damaged by uniaxial and eccentric compressive fatigue loads under multiple exposure conditions [18]. In that experimental investigation, three common fatigue damage patterns were identified, which were gradient compressive damage (GCD), gradient tensile damage (GTD) and uniform compressive damage (UCD). Residual strain and residual curvature were chosen as fatigue damage indexes to evaluate fatigue damage degree and fatigue damage gradient, respectively, in GCD, GTD and UCD concrete. The effects of fatigue damage, i.e., residual strain

---

* Corresponding author. Key Laboratory of Performance Evolution and Control for Engineering Structures, Ministry of Education, Tongji University, 1239 Siping Rd., Shanghai, 200092, PR China.
E-mail addresses: cjiang@yeah.net (C. Jiang), gxl@tongji.edu.cn (X. Gu), hqh@tongji.edu.cn (Q. Huang), weiping_zh@tongji.edu.cn (W. Zhang).

https://doi.org/10.1016/j.cemconcomp.2018.07.007
Received 25 December 2017; Received in revised form 2 June 2018; Accepted 16 July 2018

and residual curvature, on carbonation of concrete were thoroughly analyzed and reported [18].

Despite the large number of experimental studies, few efforts have been made to model the carbonation process in fatigue-damaged concrete theoretically. Fatigue damage affects concrete carbonation through influencing the effective diffusion coefficient of carbon dioxide (CO_2) in fatigue-damaged concrete. The authors established and verified a numerical carbonation model (NCM) for concrete with tensile fatigue damage by incorporating a residual strain-based effective CO_2 diffusion coefficient [15]. In this paper, the NCM was extended to concrete with compressive fatigue damage by proposing a similar form of residual strain-based effective CO_2 diffusion coefficient (Section 2). The extended NCM was validated by comparing the model-predicted carbonation depths with experimental results from studies done by the authors [15,18] and other researchers [12,13,16,17] (Section 3).

Although the NCM can be used to accurately predict carbonation depths in fatigue-damaged concrete with various fatigue damage degrees and fatigue damage gradients under multiple exposure conditions, the numerical carbonation model is too complex for most civil engineers as well as prohibitive due to huge computational costs involved in solving partial differential equations. Hence, a simplified carbonation model (SCM) for fatigue-damaged concrete, which establishes an explicit relationship between the carbonation depth and the exposure duration, is needed for fast carbonation depth predictions in real-world projects. As such, this paper further developed a SCM that considered the effects of both tensile and compressive fatigue damage based on the NCM through Monte Carlo simulations (Section 4). This SCM comprised of a non-damaged concrete contribution term and a fatigue damage contribution term, which was also verified by experimental results reported in the literature. The simplified carbonation model can be used to predict the carbonation depth evolution in concrete with determined fatigue damage degrees and gradients under constant exposure conditions.

On the other hand, global climate change is altering the exposure conditions around RC bridges year by year [19] and, simultaneously, fatigue damage in RC bridges is accumulating with service time [20]. Thus, both exposure conditions and fatigue damage are time-variant. For that reason, if one wants to predict the carbonation depths in RC bridges under the context of global climate changes and traffic load increases, the simplified carbonation model alone is inadequate. Accordingly, based on the simplified carbonation model established in this paper, the authors further proposed an incremental method to consider the time-variant exposure conditions and fatigue damage (Section 5). Finally, a case study was conducted to observe carbonation depth developments with respect to service times at representative points of an RC bridge under the context of changing climate conditions and increasing traffic loads (Section 6).

2. Numerical carbonation model (NCM)

2.1. Carbonation equation

Although there are three different fatigue damage patterns, i.e., GCD, GTD and UCD (identified by the authors in Ref. [18], or see Fig. 1), modeling the carbonation process in fatigue-damaged concrete is similar to modeling that in non-damaged concrete as conducted by Papadakis et al. [21]. Fig. 1 presents the equation schematic for Eq. (1), based on the mass conservation of CO_2 in the fatigue-damaged concrete strip and Fick's diffusion laws. This made it easy to obtain the following partial differential carbonation equation for fatigue damaged concrete:

$$\frac{\partial}{\partial x}\left(D_{\mathrm{d}}\frac{\partial[\mathrm{CO_2}]}{\partial x}\right)=\frac{\partial}{\partial t}(\varphi(1-S)[\mathrm{CO_2}])+Q \tag{1}$$

where, $[CO_2]$ denotes the concentration of CO_2 in the gaseous phase of concrete pores ($\mathrm{mol/m^3}$). φ is the porosity of concrete, and S is degree of saturation of concrete pores, both of which can be determined by the methods proposed by Papadakis et al. [22]; D_{d} and Q denote the effective CO_2 diffusion coefficient ($\mathrm{m^2/s}$) and the total reaction rate of carbonation ($\mathrm{mol/m^3{\cdot}s}$) in fatigue-damaged concrete, reflecting the physical and chemical aspects of the carbonation issue, respectively.

2.2. Effective CO_2 diffusion coefficient (D_d)

In our previous work [15], we established a residual strain-based effective CO_2 diffusion coefficient for concrete with tensile fatigue damage by choosing fictitious cracks to represent tensile fatigue damage. Bazant and Hubler's work showed that while tensile fatigue damage of concrete can be characterized by propagation of Mode I cracks, compressive fatigue damage of concrete can be characterized by propagation of Mode I crushing bands [23]. Inspired by their work, by considering compressive fatigue damage as fictitious crushing bands, we could obtain a similar effective CO_2 diffusion coefficient for concrete with compressive fatigue damage as compared with that for concrete with tensile fatigue damage (see Eq. (2)). In other words, effective CO_2 diffusion coefficient for concrete with tensile or compressive fatigue damage can be rewritten into a generalized form, as shown by Eq. (2), where the total effective CO_2 diffusion coefficient is composed of a non-damaged concrete contribution term and a fatigue damage contribution term:

$$D_{\mathrm{d}}=\underbrace{k_0\cdot\varphi_{\mathrm{p}}^{k_1}\cdot(1-RH)^{k_2}\cdot(k_3\cdot T+k_4)}_{\text{Contribution by Non−damaged Concrete}}+\underbrace{|\varepsilon_{\mathrm{r}}(x)|\cdot(1-\alpha\cdot\lambda_1(x))\cdot D_{\mathrm{air}}}_{\text{Contribution by Fatigue Damage}} \tag{2}$$

where, k_0, k_1, k_2, k_3, and k_4 are fitting coefficients; $\varepsilon_{\mathrm{r}}(x)$ is the space-dependent residual strain; $\lambda_1(x)$ denotes the aggregate fraction at each concrete fiber; φ_{p} is the porosity of hardened cement paste; α is an empirical coefficient, which is taken as 0 and 0.5 for tensile and compressive damage, respectively; D_{air} is the CO_2 diffusion coefficient in air, which can be calculated by the Wille-Lee or Fuller et al.'s method (see Ref. [15] for details). The fitting coefficients k_0, k_1 and k_2 are equal to 1.64×10^{-6}, 1.8 and 2.2, respectively. These fitting coefficients apply to ordinary Portland cement-based concrete with water-cement ratios ranging from 0.5 to 0.8 [22]. For concrete mixed with ordinary Portland cement and supplementary cementing materials, in which water-bind ratios vary from 0.38 to 0.58, k_0, k_1 and k_2 are equal to 6.10×10^{-6}, 3 and 2.2, respectively [24]. The fitting coefficients k_3 and k_4 should be equal to 0.02 and 0.6, respectively [25]. The porosity of hardened cement paste, φ_{p}, varies with the degrees of both hydration and carbonation reactions, which can be calculated by the formulas proposed by Papadakis et al. [22]. Residual strain $\varepsilon_{\mathrm{r}}(x)$ can be calculated as (see Fig. 1c):

$$\varepsilon_{\mathrm{r}}(x)=\begin{cases}\varepsilon_{\mathrm{rm}} & (\mathrm{UCD})\\ \varepsilon_{\mathrm{rm}}^{\mathrm{t}}-\kappa_{\mathrm{r}}\cdot x & (\mathrm{GTD})\\ \varepsilon_{\mathrm{rm}}^{\mathrm{c}}+\kappa_{\mathrm{r}}\cdot x & (\mathrm{GCD})\end{cases} \tag{3}$$

in which, $\varepsilon_{\mathrm{rm}}$, $\varepsilon_{\mathrm{rm}}^{\mathrm{t}}$, and $\varepsilon_{\mathrm{rm}}^{\mathrm{c}}$ are residual strains at the edges of UCD, GTD and GCD concrete zones, respectively. These residual strains can be calculated by the fatigue damage prediction model proposed by the authors [26]; κ_{r} represents the residual curvature which can also be calculated by the fatigue damage prediction model [26]. Different from our previous work [15] in which λ_1 was considered as a constant, the NCM in this paper considered λ_1 as a space-dependent parameter in order to take into account the wall effect, as shown by Eq. (4):

$$\lambda_1(x)=\begin{cases}\lambda_{\mathrm{co}}\cdot x/(a_{\max}/2) & 0\le x\le a_{\max}/2\\ \lambda_{\mathrm{co}} & a_{\max}/2\le x\le L_x-a_{\max}/2\\ \lambda_{\mathrm{co}}\cdot(L_x-x)/(a_{\max}/2) & L_x-a_{\max}/2\le x\le L_x\end{cases} \tag{4}$$

where, $a_{\max}$ is the maximum size of aggregates, L_x denotes the dimension of the specimen in x direction, and λ_{co} is the aggregate fraction in the core area.