Service Life Prediction of RC and UHPC Bridge Decks Exposed to Regional Environments

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Abstract

The work presented in this paper is an investigation of bridge deck deterioration after exposure to regional environmental conditions and traffic loading. The service life of a set of bridge decks containing UHPC and normal strength reinforced concrete were studied through a two-dimensional modeling technique that couples harmful material transport processes and structural deterioration in a time dependent manner. Regional environmental characteristics, such as periodically applying de-icing salts (chloride ions) and realistic local temperature fluctuations were considered in the simulations. Furthermore, mechanical damage induced by bridge deck traffic loading was considered in the chloride diffusion modeling approach. The simulation results show that the normal strength reinforced concrete bridge deck had cracks under traffic loading, while the reinforced UHPC bridge deck showed no observable damage at the same loading level. As such, the UHPC bridge deck had slower chloride penetration. Simulated chloride profiles confirmed that the material ingress process was influenced by the variation of temperature and de-icing material concentrations. The normal strength reinforced concrete bridge deck experienced corrosion induced cracking and delamination under the combined effects of sustained traffic loading and regional environmental conditioning. In contrast, the reinforced UHPC bridge deck was sound and intact even after a much longer exposure time.

Keywords: UHPC, Service Life, Chloride, Bridge Deck, Corrosion, Deterioration.

1. Introduction

Ultra-high performance concrete (UHPC) is a novel class of building materials, which has garnered immense attention as a durable construction material. The dense and uniform microstructure of UHPC provides it with exceptional mechanical and durability properties, exhibiting great resistance to damage and harmful material penetration (Naaman and Reinhardt; Sohail et al.). As a result, the structural deterioration of reinforced UHPC structures was slower than that of conventional reinforced concrete components (Ghafari et al.). As such, UHPC is well-suited for a wide range of applications in transportation infrastructure. In cold regions, reinforced concrete bridge decks are among the most vulnerable structural components as they are exposed to harsh environmental conditioning and vehicular loading.

Numerous studies have demonstrated that UHPC specimens exhibit greater resistance to corrosion induced by de-icing materials when compared to normal strength concrete specimens (Ghafari et al.). For example, the experimental results indicated that the corrosion rate of reinforced UHPC specimens were two orders of magnitude smaller than that of normal reinforced concrete (Roux et al.; Ghafari et al.). However, the initial cracking status, which is a crucial factor influencing the corrosion development and propagation in concrete, varies depending on the structural type and load conditions. As such, the durability performance of reinforced UHPC bridge decks that are exposed to traffic loading and environmental conditioning may be affected by cracks that develop *in situ*. Additionally, regional environmental characteristics, such as the periodic application of chloride materials and local temperature fluctuations, can affect the corrosion performance of a bridge deck (Cheung et al.). A comprehensive study of reinforced UHPC bridge decks under realistic environmental conditions is needed to better understand their superior durability characteristics and potential for use in bridge construction.

This study aims to evaluate, quantify, and compare the long-term serviceability characteristics of reinforced normal strength concrete bridge decks and reinforced UHPC bridge decks. A time-dependent multi-physics modeling framework from the authors' previous research was adopted (Fan et al.). The computational approach considers realistic regional environmental conditions, including seasonally applied de-icing materials and temperature changes throughout the service life of the bridge decks. Simulation results on damage patterns, chloride distributions, and structural deterioration after corrosion are analyzed to determine the service life performance of reinforced UHPC and reinforced normal strength concrete bridge decks.

2. Simulation Description and Modeling Parameters

A representative reinforced concrete bridge deck is shown in Figure 1. The thickness of the reinforced concrete bridge deck was 250 mm (10 in). The top and bottom concrete cover was 63 mm (2.5 in) and 25 mm (1 in.), respectively. Half of the geometry was simulated due to symmetrical geometry.

A time-dependent multi-physics modeling procedure was adopted from the author's previous work to simulate the chloride penetration, corrosion propagation, and corrosion induced structural deterioration (Fan et al.; Fan et al.). First, the initial damage status was obtained from structural analysis by introducing a traffic load which caused flexural stresses in the member. The damage condition was integrated in the study-chloride transport analysis, in which the chloride and oxygen transport properties were updated based on the cracking status. After this, the corrosion propagation was simulated, and corrosion product expansion was calculated. Then, the corrosion product expansion load was applied together with the traffic load. The duration of each time step for reinforced concrete and reinforced UHPC bridge deck were four months and five years, respectively. DIANA FEA Version 10.5 was used for the structural analysis portion, while chloride transportation and corrosion development were performed in COMSOL Multiphysics Version 5.4 (DIANA FEA; COMSOL).

The de-icing material was applied at the top surface only, while oxygen was assumed to enter from both the top and bottom sides. As shown in Figure 1, the mesh size of the concrete and UHPC materials was 12.5 mm (0.5 in.). Through redesign, the reinforced UHPC bridge deck had a smaller depth of 125 mm (5 in.), so that the load capacity of both the reinforced concrete bridge deck and reinforced UHPC bridge deck were approximately equivalent (142.3 kN (32.0 kips) and 145.1 kN (32.6 kips), respectively). The cover depth of UHPC was also reduced to 25 mm (1 in.).

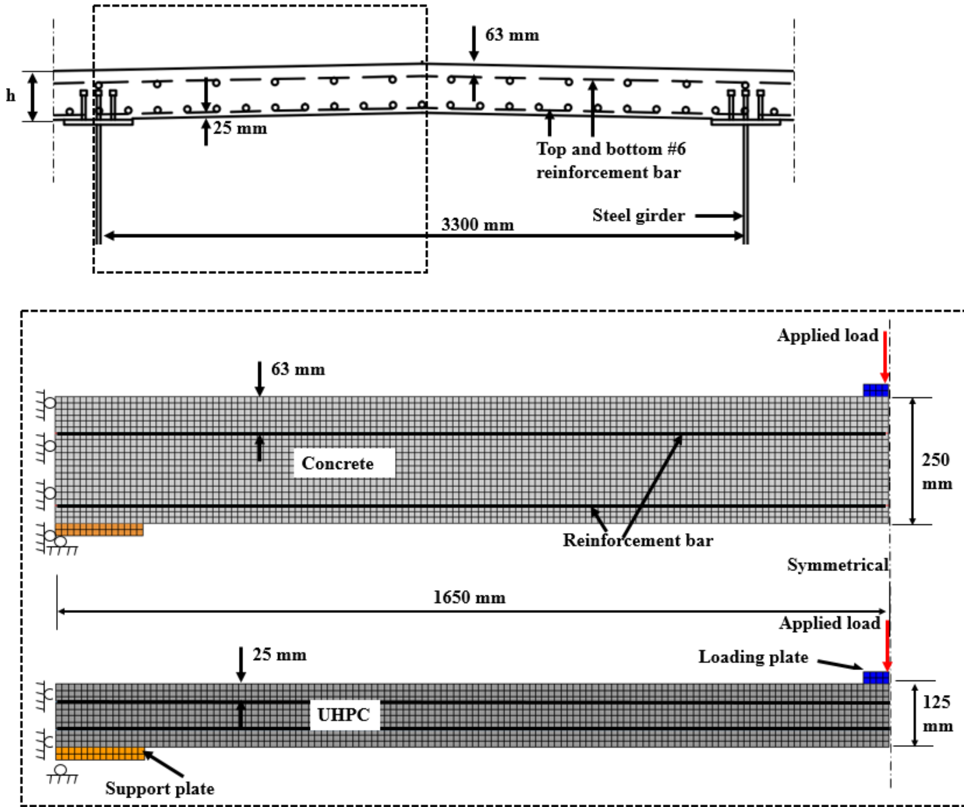

Figure 1: Cross section of a reinforced concrete bridge deck and the modeling set up. The unit can be converted as 1 inch =25.4 mm.

Chloride transport in cracked concrete and UHPC materials were considered using the following equations, respectively:

$$D_{Cl\_concrete}(m^2/s)\begin{cases} = 2\times10^{-11}w - 4\times10^{-10}, 30\mu m \le w \le 80\mu m \\ \approx 14\times10^{-10}, w > \ 80\mu m \end{cases} \quad (1)$$

$$D_{Cl\_UHPC}(m^2/s)\begin{cases} = 4\times10^{-12}w - 3\times10^{-11}, 10\mu m \le w \le 80\mu m \\ \approx 3\times10^{-10}, w > \ 80\mu m \end{cases} \quad (2)$$

where w is the crack width (μm) (Djerbi et al.; Fan et al.).

Seasonally applied surface chloride contents and the local temperature fluctuations in the studied region are shown in Figure 2. A higher chloride concentration of 0.6% of the concrete/UHPC mass was applied in the snow seasons while a lower concentration of 0.2% was assumed at the rest of the year (Cheung et al.). The influence of temperature on chloride transport was considered using Equation (3) (Saetta et al.).

$$\mathrm{f(T)} = \exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3)$$

where U is the activation energy ($44.6\,KJ/mol$), R is the gas constant ($8.3\,J/mol$), T_{ref} ($293.2\,K$) is the reference temperature of the measured diffusion coefficient, and T is the concrete/UHPC temperature (Saetta et al.).

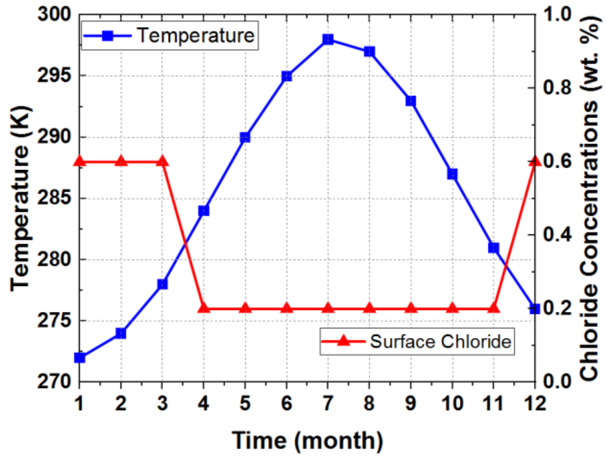

Figure 2: Source chloride concentrations and temperature.

The mechanical properties of normal strength concrete and UHPC were obtained from literature (Shao and Billington). The tensile strength of normal strength concrete was 3.1 MPa with a tensile fracture energy of 0.144 MPa-mm, while UHPC had a tensile strength of 10.5 MPa and a tensile fracture energy of 11.2 MPa-mm. The compressive strength of normal strength concrete was 41.9 MPa with a tensile fracture energy of 35.7 MPa-mm, while UHPC had a compressive strength of 180 MPa with a tensile fracture energy of 185.8 MPa-mm. The reinforcing bar had a yielding strength of 455 MPa and an ultimate strength of 675 MPa (Bandelt and Billington).

The reference chloride transport coefficients of concrete and UHPC were $D_{Cl\_c} = 1.3 \times 10^{-11} m^2/s$ and $D_{Cl\_UHPC} = 4.5 \times 10^{-13} m^2/s$), respectively (Rafiee). The concrete resistivity was reported as $159\ \Omega \cdot m$, while the electrical resistivity of UHPC at same saturation level was $23067\ \Omega \cdot m$ (Rafiee). The critical chloride content was assumed to be 0.06% of the concrete/UHPC mass (Isgor and Razaqpur). The anodic Tafel slopes ($\beta_{Fe\_c} = 65\ mV/dec$, $\beta_{Fe\_UHPC} = 61\ mV/dec$), cathodic Tafel slopes ($\beta_{O_2\_c} = -138.6\ mV/dec$, $\beta_{O_2\_UHPC} = -130.9\ mV/dec$), were also adopted from literature (Rafiee). The anodic and cathodic equilibrium potentials were $-600\ mV$ and $200\ mV$, respectively. The anodic and cathodic exchange current densities were $2.75 \times 10^{-4}\ A/m^2$ and $6 \times 10^{-6}\ A/m^2$, respectively (Rafiee). A detailed explanation of the input parameters can be found from the authors' previous work (Matthew J. Bandelt).

ACI 224 R (2001) specifies an allowable crack width of 0.18 mm (0.007 in.) for the tensile face of reinforced concrete structures that are exposed to de-icing chemicals (ACI Committee 224). Therefore, in the case of the reinforced concrete bridge deck, the initial condition was set at the load level where the crack width reached 0.18 mm (0.007 in.). The reinforced UHPC bridge deck exhibited an initial crack width of 0.017 mm (0.0007 in.) at the same loading level, which was considered as the initial damage condition.

3. Simulation Results and Discussions

3.1. Chloride Profiles

The chloride profiles of normal strength concrete and UHPC after 30 years of chloride exposure are shown in Figure 3. Due to the dense microstructure of UHPC and smaller crack widths of the reinforced UHPC bridge deck, chloride penetration was considerably slower than that of the reinforced concrete bridge deck. For example, the corroded area where chloride concentrations reached the critical chloride value of the reinforcing bar in normal strength concrete bridge deck was 100% after 30 years of de-icing material ingress. In contrast, only 13.3% area of reinforcing bar in the UHPC bridge deck was corroded after the same chloride exposure duration.

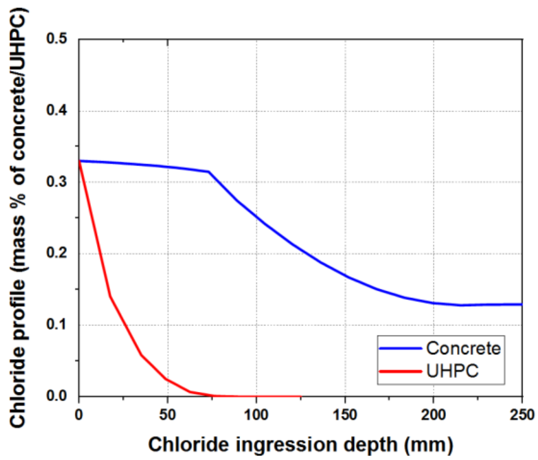

Figure 3: Chloride profile along bridge deck depth at the left.

3.2. Structural Deteriorations

3.2.1. Steel Cross Section Loss

After corrosion initiation, corrosion products accumulate, filling the pores around the steel-concrete interface (Michel). The internal stress increases as the corrosion products continue to grow, due to the higher volume of corrosion products compared to the original steel (Zhao and Jin). The corrosion-induced cracking and the initial cracking from traffic loading further accelerate chloride ingress, which in turn induces more damage to the materials.

In comparing the reinforced concrete and reinforced UHPC bridge decks, simulation results showed that after 29 years of corrosion development, the steel reinforcement bars in the reinforced concrete deck had a maximum cross-sectional loss of 12%, whereas the cross-sectional loss in the reinforced UHPC deck was only 2.6% after 55 years of corrosion. The significant difference in cross-sectional loss was due to the slower corrosion propagation rate in the reinforced UHPC bridge deck, despite the reinforcing bars in the UHPC bridge deck experiencing longer corrosion time than those in the reinforced concrete bridge deck (55 years compared to 29 years).

3.2.2. Delamination Ratings

The structural deterioration can be measured using an indicator called the delamination rating, which measures the extent of damaged area and can be calculated as follows (Szary and Roda):

$$\text{Delamination rating} = \%\,\text{area in severe}\cdot 0 + \%\,\text{area in poor}\cdot 40 + \%\,\text{area in fair}\cdot 70 + \%\,\text{area in sound}\cdot 100 \tag{3}$$

where a rating of 0 indicates worst condition, while a rating of 100 indicates best condition. The damage level of the materials was categorized using the principal strain of the finite elements (Fan et al.; Fan et al.). The simulated results show that after 30 years of chloride exposure, the reinforced concrete deck had a delamination rating of 79.1%, while the reinforced UHPC deck had a delamination rating of 93.3% after 80 years of chloride exposure. This indicates that the reinforced UHPC deck performed better than the reinforced concrete deck in terms of resistance to delamination, even after a much longer exposure to the harmful material.

3.2.3. Cracking Densities and Cracking Numbers

To further evaluate the extent of cracking in the bridge decks, the crack density was calculated as the total cracked area over a measured area. The length and width of the cracks were found to increase over time due to the combined effects of traffic loading and corrosion product expansion after exposure to chlorides. Figure 4 shows the cracking density and number of cracks of the bridge decks. The crack width selected to measure the crack density was smaller in the UHPC (0.01 mm) bridge deck than in the RC bridge deck (0.05 mm) due to the microcracking characteristics of UHPC.

As shown in Figure 4, the number of cracks at 30 years of chloride exposure were at the same level between the reinforced concrete and reinforced UHPC bridge decks. However, the cracking density of the reinforced UHPC bridge deck was 43.3% lower than the reinforced concrete bridge deck. This was attributed to the smaller crack depth in UHPC materials. The lower crack density in the UHPC bridge deck could result in a longer service life and reduced maintenance needs, making it a more cost-effective and sustainable option over time.

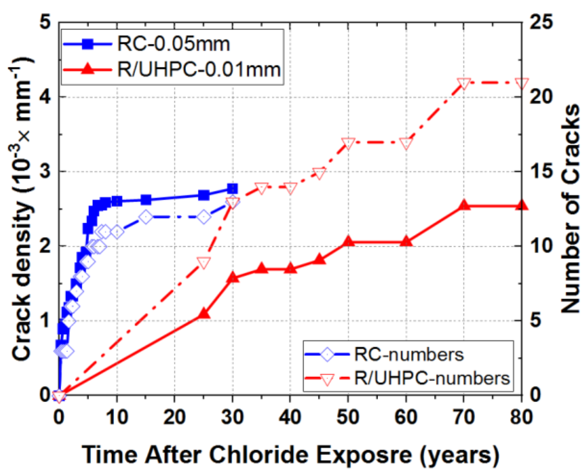

Figure 4: Crack density and crack numbers.

4. Conclusions

The study compares the performance of reinforced concrete and reinforced UHPC bridge decks under identical temperature fluctuations and de-icing materials exposure conditions. The simulation results demonstrated that the reinforced UHPC bridge deck experienced significantly slower structural deterioration, as evident by lower measures of reinforcing bar cross-section loss, delamination rating, and cracking densities.

The excellent long-term durability performance of the reinforced UHPC bridge deck demonstrates the great potential of UHPC materials in structural components. The significantly better service life performance can lead to a reduction in maintenance costs over time. Furthermore, the smaller bridge deck cross-section of the reinforced UHPC bridge deck can offset some of the higher initial construction costs. The insights provided by this study can help inform the selection of UHPC materials for potential applications in structural design and achieving a more sustainable infrastructure.

5. Acknowledgements

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