

# Service Life of Iowa Bridge Decks Reinforced with Epoxy-Coated Bars

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In an effort to minimize corrosion of the reinforcement in bridge decks, the Iowa Department of Transportation started using epoxy-coated rebars as top reinforcing mat around 1976. However, the presence of cracks in bridge decks has raised some concerns among bridge and maintenance engineers. The impact of deck cracking on the service life of a bridge deck was investigated herein. This was accomplished by collecting core samples from 80 bridges, calculating the chloride content in these cores, developing a relationship for chloride infiltration through the deck, examining the condition of several rebar samples, and developing a rebar rating-age relationship, and estimating a bridge deck service life. No signs of corrosion were observed on the rebars collected from uncracked locations. In addition, no delaminations or spalls were found on the decks where bars at cracked location exhibit some signs of corrosion. Considering a corrosion threshold for epoxy-coated rebars that range from 3.6 lb/yd<sup>3</sup> to 7.2 lb/yd<sup>3</sup>, the predicted service life for Iowa Bridge decks was over 50 years. Key words: epoxy-coated bars, bridge deck, durability, corrosion, chloride.

## INTRODUCTION

The problem of corrosion of the reinforcement in concrete bridge decks due to the intrusion of chloride ion resulting from the use of deicing salts was recognized in the mid 1970s. In a bridge deck, a corrosive reinforcement expands its volume by 3 to 6 times and eventually could cause delamination and spall of the surrounding concrete that would shorten a bridge deck service life (1). To prevent the reinforcing steel from corrosion, epoxy-coated rebars (ECR) were first used in the construction of a four-span bridge deck over Schuylkill River in Pennsylvania in 1973. Since then, ECR have been the most widely used corrosion protection method in bridge components in the United States.

Although the performance of ECR in corrosive environments is thought to be superior to typical black reinforcing bars, presence of cracks in bridge decks has caused some concern as to the condition of the ECR in these areas. This paper summarizes the results of an investigation with the objectives of determining the impact of bridge deck cracking on deck durability and approximately estimating the remaining functional service life of a bridge deck.

## CORROSION PROCESS

Corrosion of reinforcing steel in concrete can be modeled in a two-stage process. The first stage is known as initiation or incubation period in which chloride ion transport to the rebar level. In this stage, the reinforcing steel experiences negligible corrosion. The time,  $T_1$ , required for the chloride concentration to reach the threshold value at the rebar level can be determined by the diffusion process of chloride ions through concrete following Fick's second law (2). In the second stage, which is known as active and deterioration stage, corrosion of reinforcing steel occurs and propagates resulting in a noticeable change in reinforcing bar volume. This could induce cracking, delamination, and spalling of the surrounding concrete. The length of the second stage,  $T_2$ , depends on how fast the corroded reinforcing bars deteriorate resulting in an observable distress. To the authors' knowledge, no information regarding the prediction is available in the published literature. However, in this work, an approximate length of this stage is proposed.

## ESTIMATING BRIDGE DECK SERVICE LIFE

Estimation of bridge deck durability involves defining the time required for rehabilitation. For a bridge deck, the end of functional service life is reached when severe deterioration occurs. An intensive opinion survey among 60 bridge engineers to quantify the end of functional service life was conducted, and the results were documented in reference (3). The study concluded that it is likely that the end of functional service life for concrete bridge decks is reached when the percentage of the worst traffic lane surface area that is spalled, delaminated, and patched ranges from approximately 9% to 14%. In addition, reference (3) documents that based on current local practices, it is likely that the end of functional service life for concrete decks is reached when the percentage of the whole deck surface area that is spalled, delaminated, and patched ranges from 5.8% to 10.0%.

The diffusion-spalling model is among the models that are available to estimate the service life of a bridge deck (3). This method utilizes the concepts of a chloride diffusion period plus a deterioration period to determine when to rehabilitate a bridge deck. The length of the diffusion period can easily be calculated using Fick's second law (2). This can be accomplished if the surface chloride exposure, the corrosion threshold, the mean and the standard deviation of the cover depth, and the chloride diffusion constant are known. These variables can be different for bridges from state to state or even among bridges in one state.

The diffusion-spalling model is often used to assess corrosion of black reinforcing bars (2). A similar approach was used herein to

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estimate the service life of bridge decks constructed using ECR. However, a higher chloride threshold than that used for black steel bars and a longer deterioration stage need to be considered.

### CORROSION THRESHOLD

For black bars, the corrosion threshold at the reinforcing steel level was determined to be 0.2% of weight of the cement content of concrete (4,5). Cady and Weyers (6) estimated the corrosion threshold for unprotected reinforcement to be 1.2 lb/yd<sup>3</sup> (0.73 kg/m<sup>3</sup>) of concrete based on 6½ sacks of cement per cubic yard of concrete. However, it is believed that the use of ECR will delay the time required for initiating corrosion. As a result, the corrosive threshold should be higher than that for the black steel bar. A corrosive threshold for ECR of 3.6 lb/yd<sup>3</sup> (2.19 kg/m<sup>3</sup>) has been suggested (7).

### CHLORIDE IONS INGRESSION IN CONCRETE

Fick's second law (2) to determine the length of the initiation stage, i.e., time  $T_1$ , it takes chloride ions to migrate through a bridge deck to reach the top reinforcing steel in an isotropic medium can be expressed as:

$$C(x,t) = C_o \left\{ 1 - \operatorname{erf} \left[ \frac{x}{2\sqrt{(D_{ac}t)}} \right] \right\} \quad (1)$$

where:

$C(x,t)$  = the measured chloride concentration at a desired depth,  $x$ ;  $C_o$  = the surface concentration measured at 0.5 in below the deck surface, lbs/yd<sup>3</sup>;

$t$  = the time in years; and

$D_{ac}$  = the diffusion constant, in in<sup>2</sup>/yr.

The  $\operatorname{erf}(y)$  function is the integral of the Gaussian distribution function from 0 to  $y$ .

### CONCRETE COVER DEPTH

A sufficient cover depth can effectively provide corrosion protection for reinforcement. As reinforcing steel cover depth increases, the corrosion protection increases, and hence the initiating time,  $T_1$ , increases. However, to calculate a realistic time,  $T_1$ , for chloride ion to reach the reinforcing bar level, one must make use of the end of functional service life. Reference (3) recommended using an average cumulative damage of 11.5%, i.e., the average of 9% to 14%, damages in the worst traffic lane for a bridge deck as the end of functional service. In other words, one may assume that after the period of time elapsed, the chloride ions have been transported adequately to critically contaminate 11.5% of the top reinforcing steel (3). In this case, the depth,  $x$ , used in Equation 1 needs to be calculated as:

$$x = x_m + \alpha\sigma \quad (2)$$

where:

$x_m$  = the mean reinforcing steel cover depth, in.;

$\alpha$  = the a standard normal cumulative distribution of 11.5%;

$\sigma$  = the standard deviation of the cover depth.

### EPOXY-COATED REBAR CONDITION RATING

The surface condition of ECR extracted from the bridge decks can be used to provide some type of an assessment of the condition and hence the performance of the ECR. Although the time required for a rebar to deteriorate from one rating to another is not explicitly stated, one can estimate the deterioration of ECR. This can be accomplished if a large population of ECR over a wide range of time is collected and rated in accordance with the rating scales listed in Table 1.

A similar rating scale was used by the Pennsylvania Department of Transportation (7) to rate the ECR.

**TABLE 1 Reinforcing Steel Rating Description**

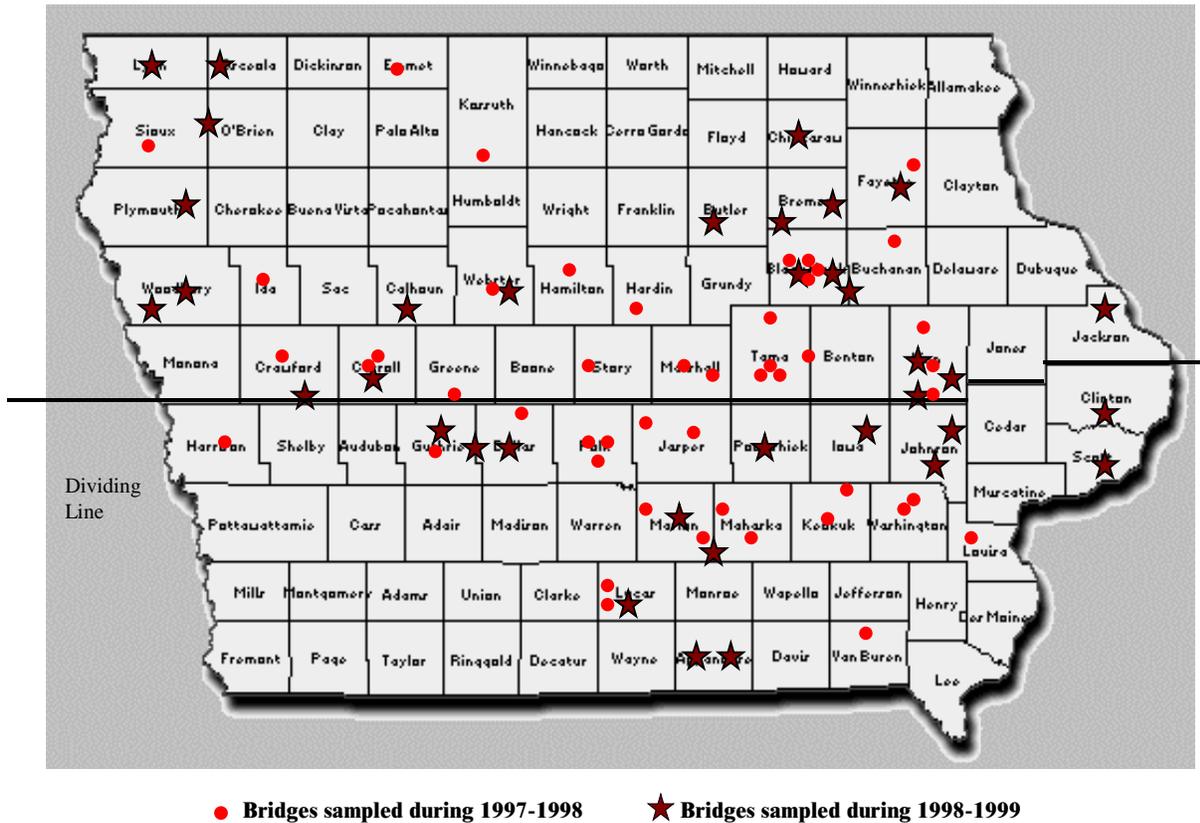
Rating	Description
5	No evidence of corrosion.
4	A number of small, countable corrosion.
3	Corrosion area less than 20% of total ECR surface area.
2	Corrosion area between 20% and 60% of total ECR surface area.
1	Corrosion area greater than 60% of total ECR surface area.

### CHLORIDE DIFFUSION IN IOWA BRIDGE DECKS

Figure 1 illustrates the locations of the eighty bridge decks that were selected to evaluate the surface chloride content,  $C_o$ , and the chloride diffusion constant,  $D_{ac}$ . This information is needed to calculate the length of the initiation stage,  $T_1$ . Factors such as geographic location, average daily traffic, bridge structure type, and number of spans were among those considered when selecting these bridges. From each deck, two core samples from cracked locations and two from uncracked locations were obtained. Concrete powder samples from different depths were gathered and analyzed. Rebar samples were also obtained and rated utilizing the scale listed in Table 1.

### CHLORIDE CONTENT ANALYSIS

Four concrete powder samples were collected from each core for chloride content analysis. The locations of these samples were at 1/2 in. below the surface, midway between the first sample and the rebar level, at the rebar level and, and at about 1/2 in. below the rebar level. Powder samples from cracked cores were drilled from the uncracked quadrant to avoid splitting the cores in half. Drilling penetrated through the crack so that the sample contained powders collected from the cracked surface. The chloride concentration was tested in the material laboratory at Iowa State University using PHILIPS PW 2404 x-ray fluorescence spectrometer (8). This is a device that could be used to determine and identify the concentration of elements contained in a solid, powdered, and liquid sample (8).



**FIGURE 1** The state of Iowa map showing locations of cored bridge decks

**SURFACE CHLORIDE AND DIFFUSION CONSTANTS**

When reviewing the collected data, it was noticed that some data appeared to be unrealistic. For instance, the chloride analysis showed that, in some cases, a higher percentage of chloride existed at deeper locations than at shallower locations. These results were filtered out, and the remaining results were utilized to determine the coefficients  $C_o$  and  $D_{ac}$  needed to calculate the time for the corrosion initiation stage,  $T_i$ . The computational process involved the utilization of Matlab software to perform the iterative solution. Approximate ranges of  $C_o$  and  $D_{ac}$  were selected, and an iterative solution was carried out for several combinations of these two variables. The solution was terminated when the minimum of the sum of squared errors between the predicted and measured values was reached. This process yielded a surface chloride content,  $C_o$ , and diffusion constants,  $D_{ac}$ , for the state of Iowa bridges of 14 lb/yd<sup>3</sup> and 0.05, respectively.

**CONDITION OF ECR VERSUS BRIDGE DECK AGE**

According to the Federal Highway Administration (9), bridges are inspected every two years. Thus, it was reasonable to subgroup the rebar samples from the bridge decks according to age in two-year intervals. All samples collected from uncracked locations appeared to have no corrosion and were given a rating value of 5 or 4 (see Table 1). In contrast, 5%, 11%, and 3% of the reinforcing bar samples

obtained from cracked locations were evaluated at rating of 3, 2, and 1 respectively, indicating some degree of corrosion of these rebar samples.

Since there is a range of possible values of reinforcing bar samples that can be rated at a specific rating condition, one would naturally be interested in some central value such as the average. However, there are different probabilities that different numbers of rebars in each time interval can be associated with different rating condition. Therefore, a weighted average, i.e., the expected value of the rating within each interval, would be more representative rather than just using a straight average value (10).

Having calculated an expected rating value,  $E(r, j)$ , where,  $r$  is the rating condition within an interval,  $j$ , the Matlab program was utilized in conjunction with the second order polynomial model given in the following equation to develop a rebar-condition-age relationship (11).

$$r(t) = \beta_o + \beta_1 t + \beta_2 t^2 + \epsilon \tag{3}$$

where:

$r(t)$  = rebar rating at specified deck age  $t$  in years,

$\beta_i$  = a constant, and

$\epsilon$  = an error term that represents the degree of uncertainty between predicted and measured values.

For a new bridge deck, i.e.,  $t = 0$ , the recorded rebar rating should always be 5, i.e.,  $\beta_o$  should equal 5. Although it is meaningful to force the intercepts to be 5, it is statistically unnecessary to force that since the raw data are empirical. For this reason, the second order polynomial regression analysis was made without forcing the intercept to be five. This regression yielded the following two relationships:

1. ECR condition-age relationship for rebars collected from cracked locations

$$r(t) = 5.18 - 0.002 t^2 - 0.026 t \quad (4)$$

2. ECR condition-age relationship for rebars collected from uncracked locations

$$r(t) = 4.88 - 0.002 t^2 + 0.0334 t \quad (5)$$

### ILLUSTRATIVE EXAMPLE TO CALCULATE SERVICE LIFE OF A BRIDGE DECK

As previously mentioned, a corrosive threshold for ECR was defined as about 1.2 to 3.6 lb/yd<sup>3</sup> (0.73 kg/m<sup>3</sup> to 2.19 kg/m<sup>3</sup>); and for black steel bar is 1.2 lb/yd<sup>3</sup> (0.73 kg/m<sup>3</sup>) (12). However, the data collected in this work revealed that an average chloride concentration of 7.5 lb/yd<sup>3</sup> (4.56 kg/m<sup>3</sup>) existed in locations where rebar samples had a rating of 3 (see Table 1). This is the condition at which corrosion becomes noticeable on ECR. Therefore, a corrosive threshold for ECR from range 3.6 lb/yd<sup>3</sup> to 7.5 lb/yd<sup>3</sup> (2.19 kg/m<sup>3</sup> to 4.56 kg/m<sup>3</sup>) was selected in this work.

Utilizing Fick's Second Law, one can then calculate the time in which the chloride concentration at the rebar level reached the corrosive threshold for black or epoxy coated rebars. Assuming an additional time needed for spalling to take place in bridge decks, one can then determine the service life of a bridge deck. However, searching the published literature did not reveal any data related to the time required for spalling to occur in bridge decks with ECR. In this work, spalling is assumed to occur when approximately 60% or more of the rebar surface was corroded, i.e., when reinforcing bars reach a condition rating of 1. Using this information in conjunction with Equations 3 or 4, a time period of approximately 15 years can be estimated for ECR to deteriorate from condition rating 3 to 1. The following example illustrates how to incorporate the above assumptions to estimate the functional service life of a bridge deck in the state of Iowa.

Example: Given an Iowa bridge deck with  $C_o = 14.0$  lb/yd<sup>3</sup>, and  $D_c = 0.05$  in<sup>2</sup>/yr. End of functional life = 11.5% which is the average of 9% to 14% damage in the worst traffic lane (2). Average concrete cover depth  $\bar{x} = 2.75$  in. associated with standard deviation  $s = 0.444$  in. The corrosive chloride threshold ranged from 3.6 lb/yd<sup>3</sup> to 7.5 lb/yd<sup>3</sup> for ECR. Assuming that 11.5% of the rebar is contaminated by the chloride ion and an  $a$  value of -1.2, the time required reaching the corrosive threshold and time to rehabilitation.

For a threshold of a 3.6 lb/yd<sup>3</sup> and a cover depth,  $x$ , of 2.75 in. (see Equation 2), one calculates a time,  $t$ , of 38 years. Similarly, for a corrosion threshold of 7.5 lb/yd<sup>3</sup>, one estimates a time of 126 years. Assuming an additional 15 years for spalling to occur, the time required for spalling to occur would range approximately from 53 to 141 years. In comparison to black steel bar where a corrosive threshold of 1.2 lb/yd<sup>3</sup> was used, one estimates a time,  $t$ , of 17 years. Assuming an average time for spalling of 3.5 (13) years, time required to rehabilitation for unprotected steel equals  $17 + 3.5 = 20.5$  years. As can be noted, this example illustrates the significant increase in the service life of a bridge constructed with ECR.

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