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Probabilistic model for the chloride-induced corrosion service life of bridge decks

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Abstract

A statistical model to determine the time to first repair and subsequent rehabilitation of concrete bridge decks exposed to chloride deicer salts that incorporates the statistical nature of factors affecting the corrosion process is developed. The model expands on an existing deterministic model using statistical resampling techniques. Emphasis was placed on the diffusion portion of the diffusion-cracking model. Data collected for the time for corrosion deterioration after corrosion initiation can be readily incorporated into the model. Data for the surface chloride concentration, apparent diffusion coefficient and clear cover depth were collected from 10 bridge decks built in Virginia. Several ranges of the chloride corrosion initiation concentration, as determined from the available literature, were investigated. The resampling techniques known as the simple and parametric bootstrap were used to predict time to first repair and rehabilitation based on the observed field data. The two methods provide results that substantially agree for all decks investigated.

Keywords: Corrosion; Diffusion; Chloride; Reinforcement; Monte Carlo

1. Introduction

According to the Federal Highway Administration, approximately 30% of the nation's bridges are either structurally deficient or functionally obsolete. It is estimated that approximately US$90 billion will be required to rehabilitate or replace these bridges [1]. For many bridges, the concrete decks will need to be rehabilitated before other components of the bridge. Chloride-induced corrosion of the reinforcing steel is known to be a major cause of premature rehabilitation of bridge decks.

Several methods have been used to protect the reinforcing steel from chloride corrosion attack in concrete bridge decks. The methods include low permeable concrete to slow the ingress of chlorides, polymer overlays and deck sealers, increased concrete cover depth, cathodic protection, and alternative reinforcement The use of epoxy-coated reinforcement (ECR) is particularly prevalent in the United States [2]. Previous work has demonstrated that the epoxy coating on ECR will begin to debond from the steel reinforcement in bridge decks in Virginia in as little as 4 years and most likely by 12–15 years [3].

A better service life model would assist planners in two ways. First, the time to first repair and subsequent rehabilitation could be estimated with greater accuracy for a given bridge or set of bridges. Second, the effectiveness of the various protection methods could be compared and evaluated.

One common service life model for the chloride induced corrosion of reinforcing steel in concrete involves two time periods. The first is the time for chloride diffusion until a sufficient concentration of chlorides is available at the reinforcing bar depth to initiate corrosion. The second is the time for corrosion damage (from initiation to cracking and spalling of the cover concrete) to the end of functional service life [4]. The end of functional service life for the

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deicing salt region of the United States is deemed to have been reached when 12% of the worst span lane of a bridge deck has deteriorated [5]. The time to first repair is reached when 2.5% of the worst span lane of a bridge deck has deteriorated [4].

An apparent diffusion process, based on Fick's second law, can be used to model the time for chloride to reach and initiate corrosion at first repair and rehabilitation reinforcing steel depths. When solved for the condition of constant surface chloride and a one-dimensional infinite depth, Fick's second law takes the following form [6]:

$$C_{(x,t)} = C_{\mathrm{o}}\left(1 - \mathrm{erf}\frac{x}{2\sqrt{D_{\mathrm{c}}t}}\right) \tag{1}$$

Where: $C_{(x,t)}$ = chloride concentration at depth and time, C_{o} = surface chloride concentration, D_{c} = apparent diffusion coefficient, t = time for diffusion, x = concrete cover depth and erf = statistical error function.

When $C_{(x,t)}$ is set equal to the chloride corrosion initiation concentration and Eq. (1) is solved for t, the time for the diffusing chloride ions to initiate corrosion. However, for a given bridge deck, the values of $C_{(x,t)}$, C_{o}, D_{c} and x are random variables, each with their own statistical distributions, means and variances. A solution to Eq. (1) for the time for diffusion should include the probabilistic nature of the input variables.

It should be noted that it is best to measure the chloride content directly over the reinforcing steel to partially or wholly account for the presence of the reinforcing steel. Eq. (1) is the solution for a one-dimensional analysis for infinite depth, whereas the presence of the reinforcing steel has been shown to significantly influence the rate of chloride increase at bar locations [7].

The time for corrosion damage to the end of functional service life is also a random variable and depends on the corrosion rate, concrete cover depth, reinforcing steel bar spacing, and size [8]. However, little is known about the exact value or distribution of the time for corrosion damage at this time.

A statistical based model which accounts for the variability of input variables would more accurately predict the time to first repair and subsequent rate of deterioration. A model using statistical distributions has been developed for marine bridge substructures [9]. Statistical distributions are used for the surface chloride ion concentration, clear concrete cover depth and chloride ion coefficient. A discrete value is used for the chloride corrosion threshold concentration. Uncertainty of the influence of the chloride corrosion initiation concentration is addressed by solving the model using a number of discrete initiation values. The cover depth, surface chloride content and chloride diffusion coefficient are considered to be normally distributed.

The concept of probabilistic service life design was used in the Dura Crete project, a consortium of 12 European Union member states [10]. Reinforcement corrosion is modeled as two separate periods, initiation and degradation. A diffusion function is used to model the chloride penetration [11]. The chloride corrosion initiation concentration and diffusion coefficient are considered to be normally distributed and cover depth and chloride binder functions are lognormal distributions [10]. A diffusion coefficient geographic location parameter is considered to be a γ distribution and a time diffusion coefficient reduction factor is considered to be a β distribution [10]. Output is a probabilistic prediction of corrosion initiation as a function of cover depth.

One common modern statistical technique is called Monte Carlo simulation. Monte Carlo is a general class of repeated sampling methods where a desired response is determined by repeatedly solving a mathematical model using values randomly sampled from probability distributions (often assumed) of the input variables [12]. Within the category of Monte Carlo methods, a resampling method called bootstrapping uses the same repetitive sampling procedure but uses data to define the parameters for the distributions or samples directly from the existing data [13]. The two types of the bootstrapping, the parametric and simple bootstrap, were used in this research.

Data collected from 10 bridge decks in Virginia were used to model the cover depth, surface chloride concentration and apparent diffusion coefficient. A probable range of the chloride initiation concentration and a value for the time to cracking were determined from the available literature.

The primary objective of this study is to incorporate the statistical nature of chloride induced corrosion of reinforcing steel into existing models to predict the time to first repair and rehabilitation of concrete bridge decks relative to chloride induced corrosion.

2. Methods and materials

This study utilizes data from bridge decks in Virginia to incorporate probabilistic considerations into a service life model. The data to be used in this research project was collected from 10 geographically diverse bridge decks in Virginia , see Table 1.

The bridge decks chosen in the study ranged in age from 4 to 18 years (at the time of data collection). Eight of the 10 bridge decks were constructed with ECR, while two were constructed with bare reinforcement. The decks were all constructed under the same specification. The specified water/cement ratio for the decks is a maximum of 0.45 and the specified clear cover depth is 63.5–76.2 mm (2.5–3.0 in.). The specification requires a 28-day compressive strength of 27.6 MPa (4000 psi).

2.1. Data

The field data includes clear cover depth measurements and chloride content analysis on powdered samples removed from the deck. The data estimated from the literature includes the chloride initiation concentration and time for corrosion damage.

2.1.1. Clear cover depth

Approximately 40 cover depth measurements were taken on each span of the bridge decks using a Profometer 3 cover depth meter. Typically, the bridge decks consisted of three spans. One hundred and twenty measurements were taken from each bridge [14]. Because of restrictions in traffic control, safety considerations and field observations that the right traffic lane deteriorates first, all of the measurements were taken from the right traffic lane.

Bridge deck rehabilitation projects are often decided on the condition of the worst span lane. Because reinforcing that is closer to the surface of the concrete will be the first to suffer chloride-induced corrosion, the worst span lane coincides with the span lane with the lowest clear cover depth. Since cover depths in concrete bridge decks have natural variability, the span lane with the lowest cover depth cannot be decided by the mean value alone. The standard deviation of the cover depth distribution must also be taken into account. Thus, the span with the lowest 12 percentile value of the clear cover depth was used in the service life prediction model. Therefore, approximately 40 clear cover depth measurements are available for each of the 10 bridge decks. Clear cover depth measurements have been shown to be normally distributed [14,15].

2.1.2. Chloride content analysis

Powdered samples to be used for chloride content analysis were extracted from three locations on each of the bridge decks. The samples were extracted adjacent to a reinforcing bar and in 12.7-mm (0.5 in.) increments to a depth of approximately 76.2 mm (3 in.). Powder removed

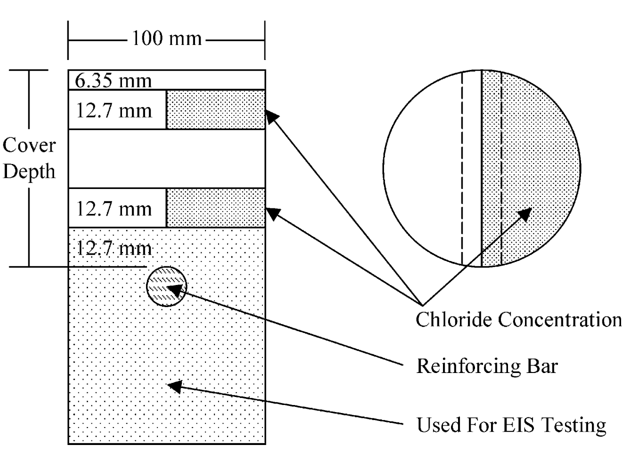
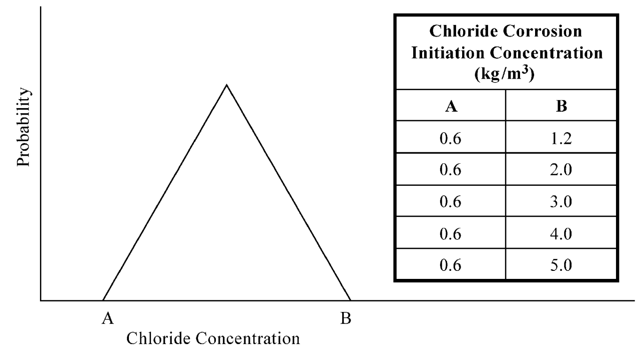


Fig. 1. Location of chloride samples from field cores.



Chloride Corrosion Initiation Concentration (kg/m^3)	
A	**B**
0.6	1.2
0.6	2.0
0.6	3.0
0.6	4.0
0.6	5.0

Fig. 2. Probability distribution of chloride corrosion initiation concentration.

from the upper 6.4 mm (0.25 in.) of the deck was discarded. A hollow core drill bit with a diameter 1.5 times the maximum aggregate size and a vacuum collection device was used to collect the powder at each incremental depth.

In addition to powdered samples, approximately 12 cores were removed from each deck. Although the primary use of

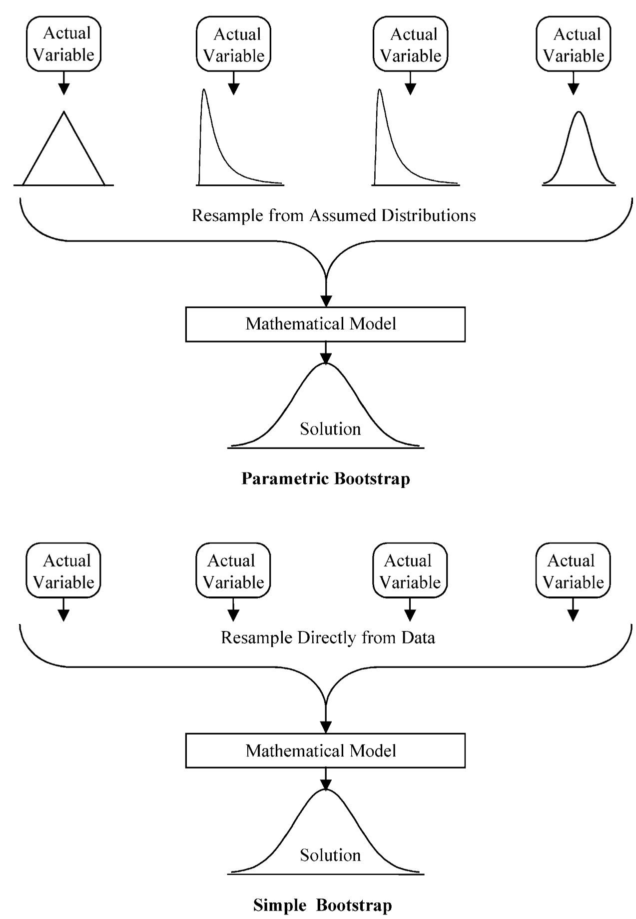


Fig. 3. Parametric and simple bootstrap.

the field cores was for a concurrent study, powdered samples were removed from two locations on each core. The powdered samples were directly above the reinforcing bar and were located 12.7 mm (0.5 in.) below the top surface of the core and 19 mm (0.75 in.) above the top reinforcing steel. The samples were 12.7-mm (0.5 in.) thick. Fig. 1 presents the field core chloride content sampling method. The cores were dry cut to prevent leaching out of the chlorides due to wet cutting and the partial cores were crushed to a powder suitable for use in chloride content testing.

The powdered concrete samples were then analyzed for the acid soluble chloride concentration using the silver nitrate titration method [16]. The diffused chloride concentrations were adjusted by subtracting the background chloride content.

2.1.3. Surface chloride concentration

For bridge decks, the surface chloride concentration, C_o, is commonly defined as the concentration of chlorides located 12.7 mm (0.5 in.) below the deck surface because the chloride concentration at this depth is relatively constant with time [4]. Above 12.7 mm (0.5 in.), the chloride content decreases with spring, summer and fall rains and increases within the winter deicing salt period [4]. For the field drilled powdered and core samples, the first sample removed from the deck was centered at 12.7 mm (0.5 in.) below the surface and represents C_o. Therefore, three C_o values were available from the field drilled powdered samples, and between 4 and 12 C_o values were available from the cores for each bridge deck. The surface chloride concentration is thought to be best described by a γ distribution [17].

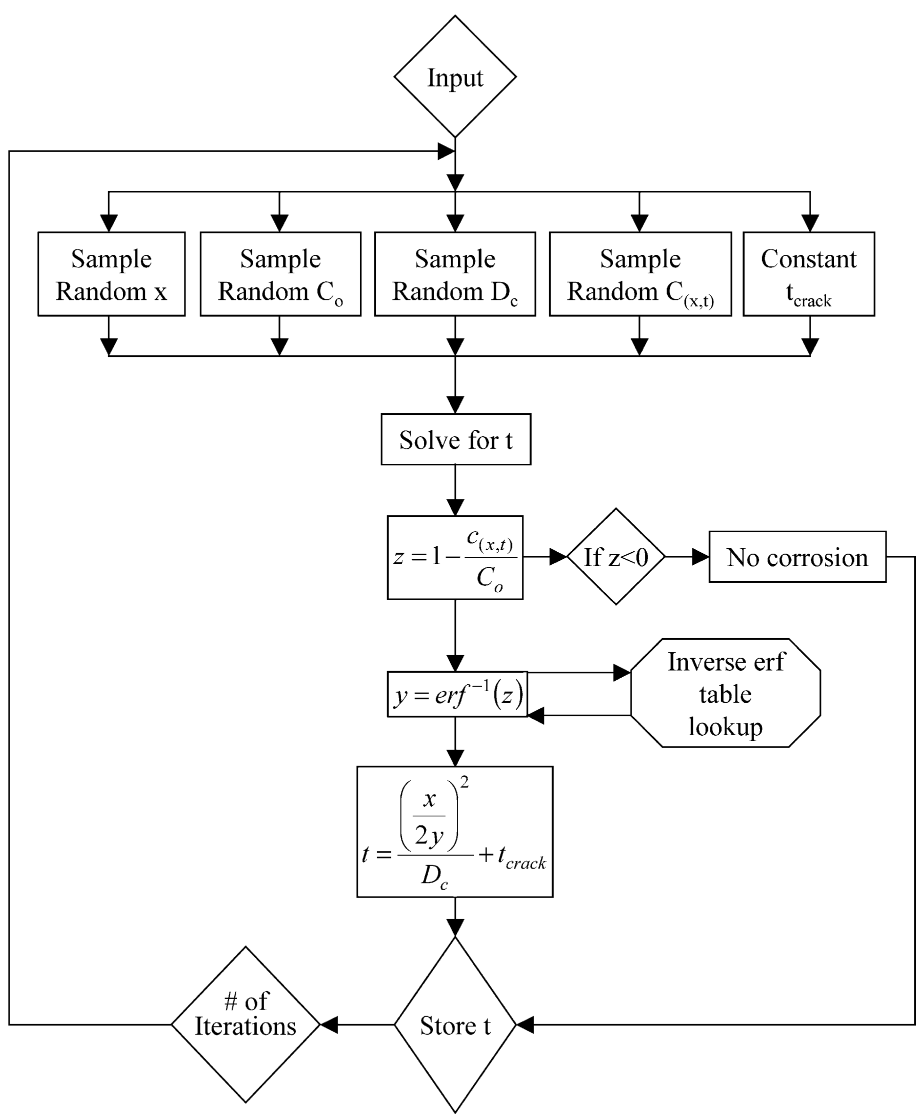


Fig. 4. Schematic of simulation routine.

Table 1
Summary of bridge decks

District	Structure number	Year built	Age at sampling (years)	Reinforcement type
7—Culpeper	1001	1992	7	ECR
6—Fredericksburg	1004	1993	6	ECR
3—Lynchburg	1004	1983	16	ECR
2—Salem	1015	1987	12	ECR
7—Culpeper	1019	1990	9	ECR
1—Bristol	1136	1995	4	ECR
5—Suffolk	2021	1981	18	ECR
9—Northern Virginia	2262	1985	14	ECR
1—Bristol	6037	1983	16	Bare steel
2—Salem	6128	1981	18	Bare steel

2.1.4. Apparent diffusion coefficient

The apparent diffusion coefficient, D_c, was back calculated from each set of chloride concentration measurements obtained from the bridge decks. A computer program [17] using the minimum sum of square error procedure was used to back calculate D_c from the measured chloride profiles. The computer program was validated with β versions of two programs currently in development at other institutions. After correcting for discrepancies in the boundary condition assumptions, all three programs provided similar results.

For the core samples, only two chloride concentration measurements were available to back calculate an apparent diffusion coefficient. In this case, back calculating D_c from Eq. (1) represents an exact fit of the two measured chloride values and the best fit given the limited chloride data available. However, the calculated D_c may not produce the minimum sum of square errors and may not represent the true apparent diffusion process of the bridge deck. Therefore, D_c values for a given bridge, calculated from two chloride concentration measurements, were carefully compared to D_c values calculated using the minimum sum of square errors procedure and a full chloride profile. D_c

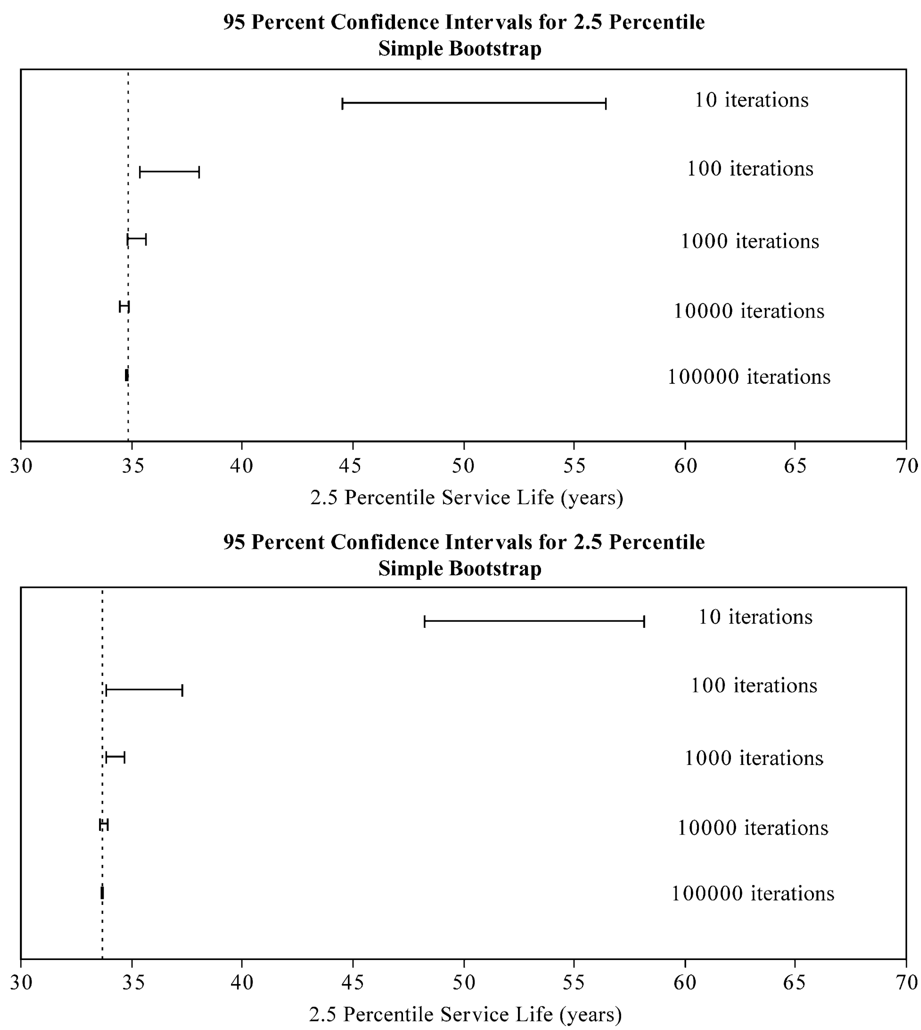


Fig. 5. Number of iteration plots for 2.5 percentile.

values calculated using two chloride measurements that were significantly out of the range of D_c values calculated using a full chloride profile were discarded.

The same number of D_c and C_o values is available for each bridge deck. Current literature suggests that the apparent diffusion coefficient is best described by a γ distribution [17].

2.1.5. Chloride corrosion initiation concentration

The exact concentration of chlorides necessary to initiate corrosion of the reinforcing steel is a variable that depends on several factors. The range typically reported in the literature for field structures is from 0.6 to 5.5 kg/m^3 (1.0–9.2 lb/cy) [18–20]. No indication is given as to the shape of the distribution of the chloride initiation concentration. Experience indicates that the shape may be weighted toward the center of a range of values. For this reason, a distribution with a symmetric triangular shape was used for this study. Because there is question about the range of values of initiation, the time for diffusion was determined using several ranges of initiation. The lower limit of all ranges is 0.6 kg/m^3 (1.0 lb/cy). The upper limits were set at 1.2, 2.0, 3.0, 4.0 and 5.0 kg/m^3 (2.0, 3.3, 5.0, 6.7 and 8.3 lb/cy). Fig. 2 presents the distribution of the chloride corrosion initiation concentration used in this study.

2.1.6. Time to corrosion damage

The time for corrosion deterioration after initiation is currently under debate among researchers. Although the time for corrosion damage for bare bar is generally accepted to be approximately 4–6 years, less is known about the time for corrosion damage for ECR [21,22]. Field studies have estimated 1–7 additional years for the time to corrosion damage for ECR [23–25]. The focus of this study is not on the time to corrosion damage, rather it is on incorporating probabilistic considerations into the service life model, with particular emphasis on the time for diffusion. Therefore, a single point estimate for the time

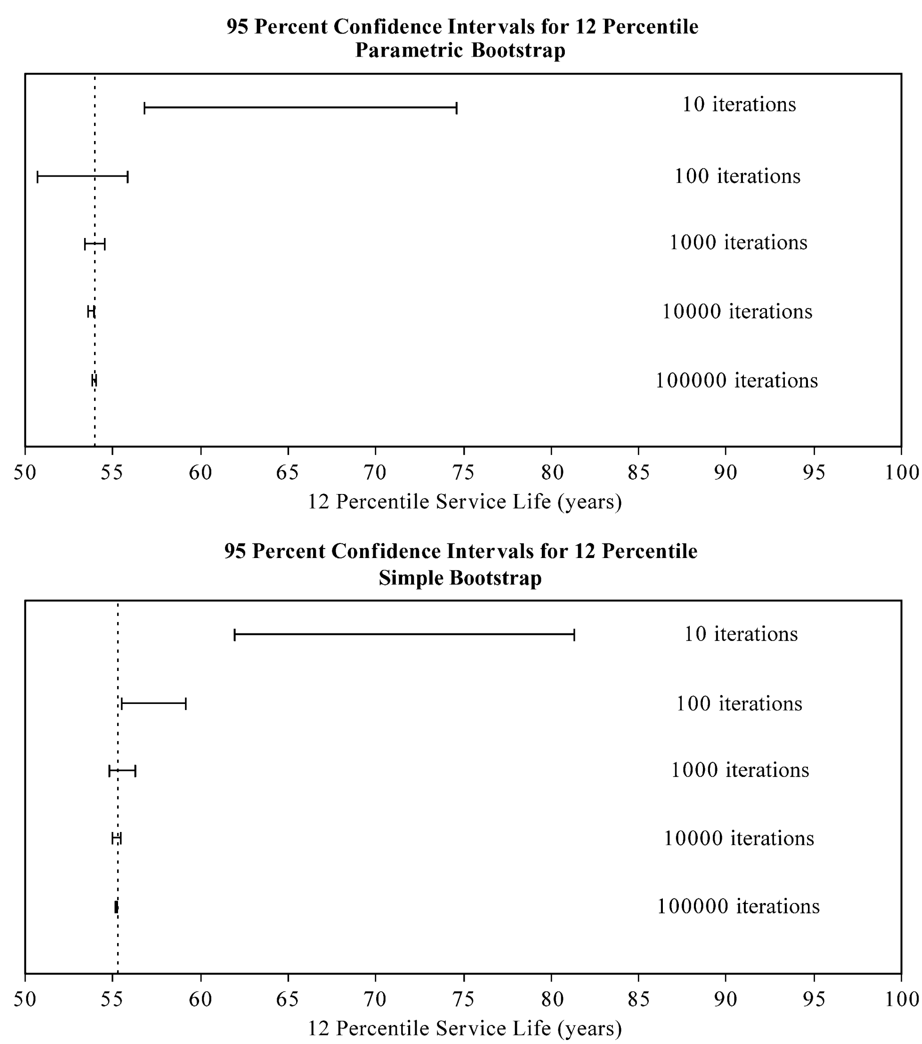


Fig. 6. Number of iteration plots for 12 percentile.

for corrosion of 4 years was used for both bare bars and ECR. As the time for corrosion damage is better determined, the results can be easily incorporated into the service life model.

2.2. Simulation

The data described above is used in a statistical simulation that will provide a stochastic solution for the time to first repair and rehabilitation [26]. To provide confidence in our simulation, the solution will be obtained using two resampling techniques. The first is the parametric bootstrap, and the second is the simple bootstrap. Both techniques are part of a larger class of statistical resampling techniques generally known as Monte Carlo techniques. The parametric bootstrap uses the sample data to determine parameters for assumed distributions. The distributions are chosen to best fit the total populations of the input variables and values are randomly sampled from the distributions. The simple bootstrap assumes that the shape of the population distribution can be entirely represented by the sample distribution shape. The values of the data collected from the field are sampled directly for each input variable and the population is not assumed to fit a known distribution. Fig. 3 presents the process for the parametric and simple bootstrap.

The use of resampling techniques has been made tractable by modern computing power, since a large number of iterations must be performed to obtain sufficiently descriptive results. Several computer packages capable of performing these simulations are available today. The statistical package S-Plus 2000, developed by MathSoft, was selected for this study because of its flexibility, power and speed.

2.2.1. S-Plus

S-Plus is a user programmable software package with many powerful built in functions that are geared toward data exploration and statistical simulations. The program runs on either a UNIX or PC platform. On the PC platform, a graphical user interface is provided. Functions created by the user are stored and can be accessed along with built-in routines. S-Plus is unique because it combines the power of built in statistical resampling techniques with basic mathematical manipulation. Therefore, the time for diffusion and service life determined from Eq. (1) can be solved directly from within S-Plus. S-Plus 2000, Professional Release 3 for the PC platform, was used in this study.

2.2.2. Simulation routine

The simulation routine created for this project runs and reports the results for both the parametric and simple bootstrap. The numerical results reported by the routine can be used to generate descriptive graphs and summary statistics.

For a given bridge or set of bridges, the input parameters for the simulation routine include field data for x, C_o and D_c;

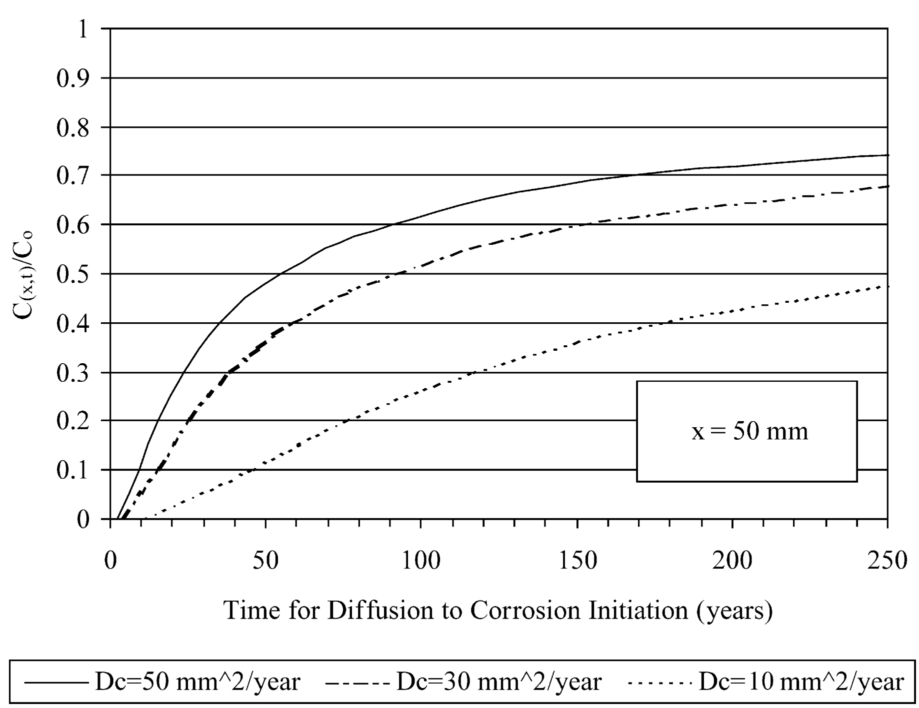


Fig. 7. Ratio of $C_{(x,t)}/C_o$ vs. time for diffusion to corrosion initiation.

Table 2
Time to first repair and rehabilitation (in years)

$C_{(x,t)}$ from 0.6 to 1.2 kg/m^3						
Structure no.	Parametric bootstrap			Simple bootstrap		
	% Corroded	2.5%	12%	% Corroded	2.5%	12%
1015	100	10	13	100	11	13
1004.3	100	23	31	100	23	30
1136	100	33	46	100	33	47
1001	100	28	48	100	28	49
1019	99	30	47	100	33	45
2262	96	31	56	91	34	52
2021	27	–	–	27	–	–
1004.6	19	–	–	18	–	–
6037	7	–	–	8	–	–
6128	0	–	–	0	–	–

the time to corrosion deterioration after initiation; the range of the expected chloride initiation concentration; and the number of iterations. An outline of the basic routine is presented in Fig. 4 and is identical for both the parametric and simple bootstrap, except that parameters are estimated from the data for the population distributions in the parametric bootstrap. The basic outline of the parametric bootstrap is described first, and then differences in the simple bootstrap are highlighted. It should be noted that the model described here is a general procedure that can be adapted to any computing platform with varying degrees of programming effort and is not limited to the statistical program S-Plus.

2.2.2.1. Parametric bootstrap. For the parametric bootstrap, the field data for x, C_o and D_c must be used to determine the appropriate parameters for the distribution assumed to represent the population. The distribution of the cover depth has been shown to be normal. The parameters required to define the shape of a normal distribution are the mean and standard deviation. Therefore, the mean and standard deviation of the cover depth are calculated and used to define the appropriate normal distribution that matches the field data for a particular bridge or set of bridges.

The surface chloride concentration and apparent diffusion coefficient are best described by a gamma distribution. Two parameters describe the gamma distribution, the shape and the rate [27]. The definitions of the shape and rate differ slightly depending on the source and mathematical formulation of the γ distribution. However, in S-Plus, the rate is equal to the mean divided by the variance and the shape is equal to the product of the mean and rate [28]. The appropriate gamma distribution is defined for both the surface chloride concentration and apparent diffusion coefficient. The observed data were found to be consistent with these distributions.

Once the parameters estimates for the distributions of x, C_o and D_c have been determined based on the field data, the routine uses a random number generator to sample from each of the distributions of x, C_o, D_c and the chloride initiation concentration (already defined as triangular in shape). The number of values sampled from each distribution is equal to the number of iterations specified by the user.

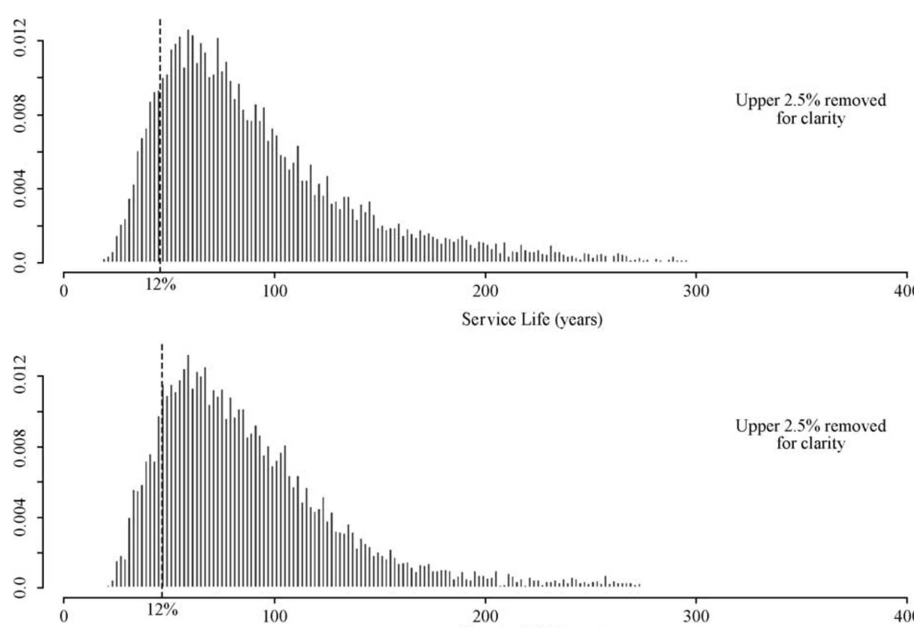


Fig. 8. Histogram for parametric and simple bootstrap for bridge 1136.

The next step in the routine is to solve for the time for diffusion in Eq. (1). Eq. (1) can be rearranged such that the time for diffusion is expressed as a combination of x, C_o, D_c and $C_{(x,t)}$. Then, a time for diffusion is calculated for each successive set of input variables. For example, the fifth randomly sampled x, C_o, D_c and $C_{(x,t)}$ are used to solve for the fifth estimate of time for diffusion. Hence, the total number of estimated diffusion times is the equal to the total number of iterations.

The process up to this point is relatively straightforward. However, the solution of Eq. (1) for the diffusion time requires the inverse of the error function (erf). Tables for the error function are readily available, but no simple mathematical expression is available [6]. Although table lookups

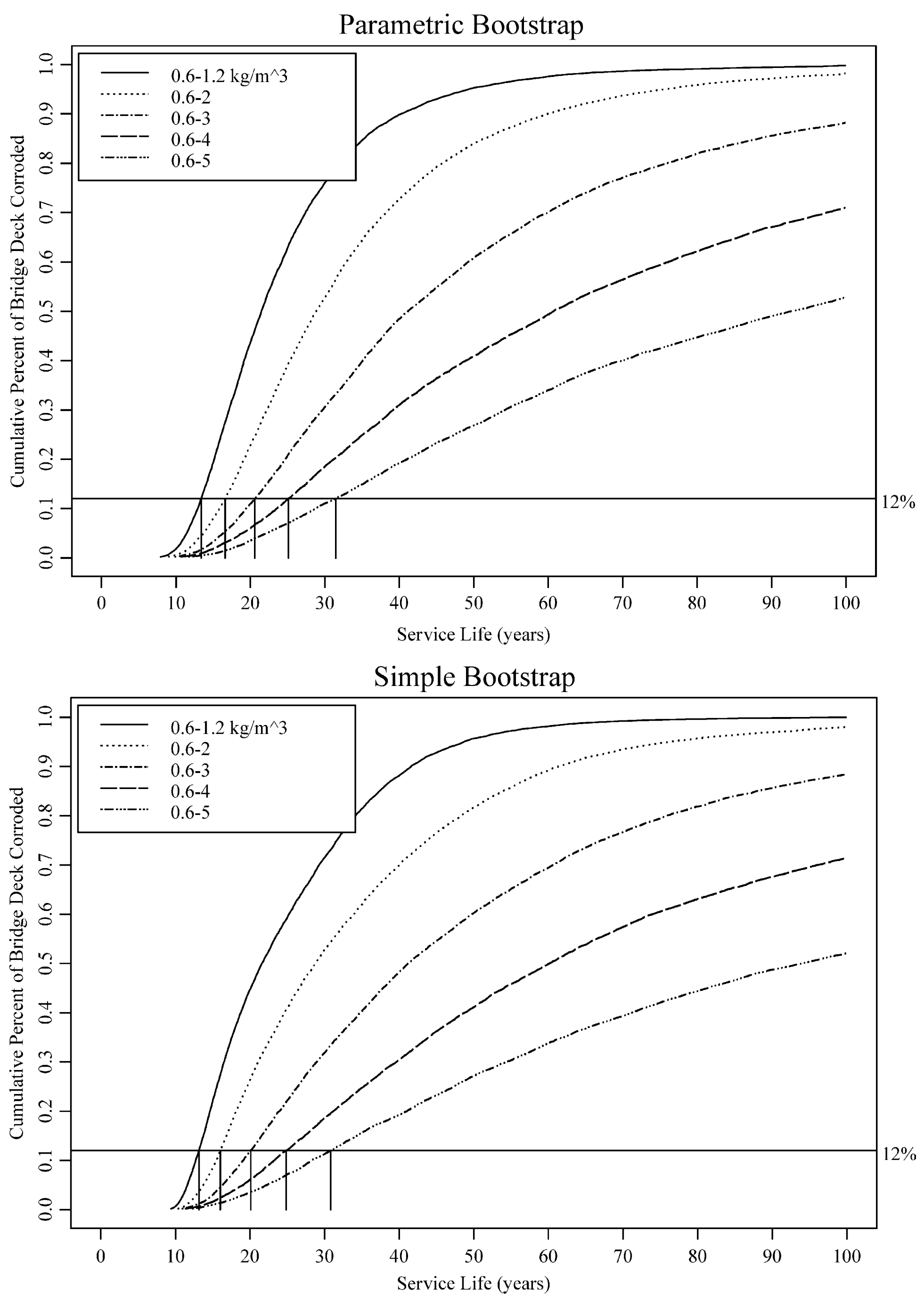


Fig. 9. Service life estimates for bridge 1015.

are generally inefficient in computer programs, the vector based programming nature of S-Plus makes table lookups relatively efficient. Therefore, a table lookup with linear interpolation between table values was utilized to solve the inverse of the error function.

When the surface chloride concentration is lower than the chloride initiation concentration, the resulting time for diffusion is undefined. In other words, chlorides will never be present at the bar depth in a sufficient concentration to initiate corrosion. Mathematically, the condition is represented by attempting to take the inverse of the error function for a negative number, which is undefined. Therefore, no time for diffusion was calculated for iterations of the routine that produce a surface chloride concentration less than the initiation concentration (no corrosion predicted). Instead, the number of iterations that predicted no corrosion were counted and reported as a percentage of the number of iterations.

The routine has randomly sampled each input variable and solved for the time for diffusion for a specified number of iterations. For each iteration, the time for corrosion (also specified in the routine's input) is added to the time for diffusion to determine the service life for each iteration. The

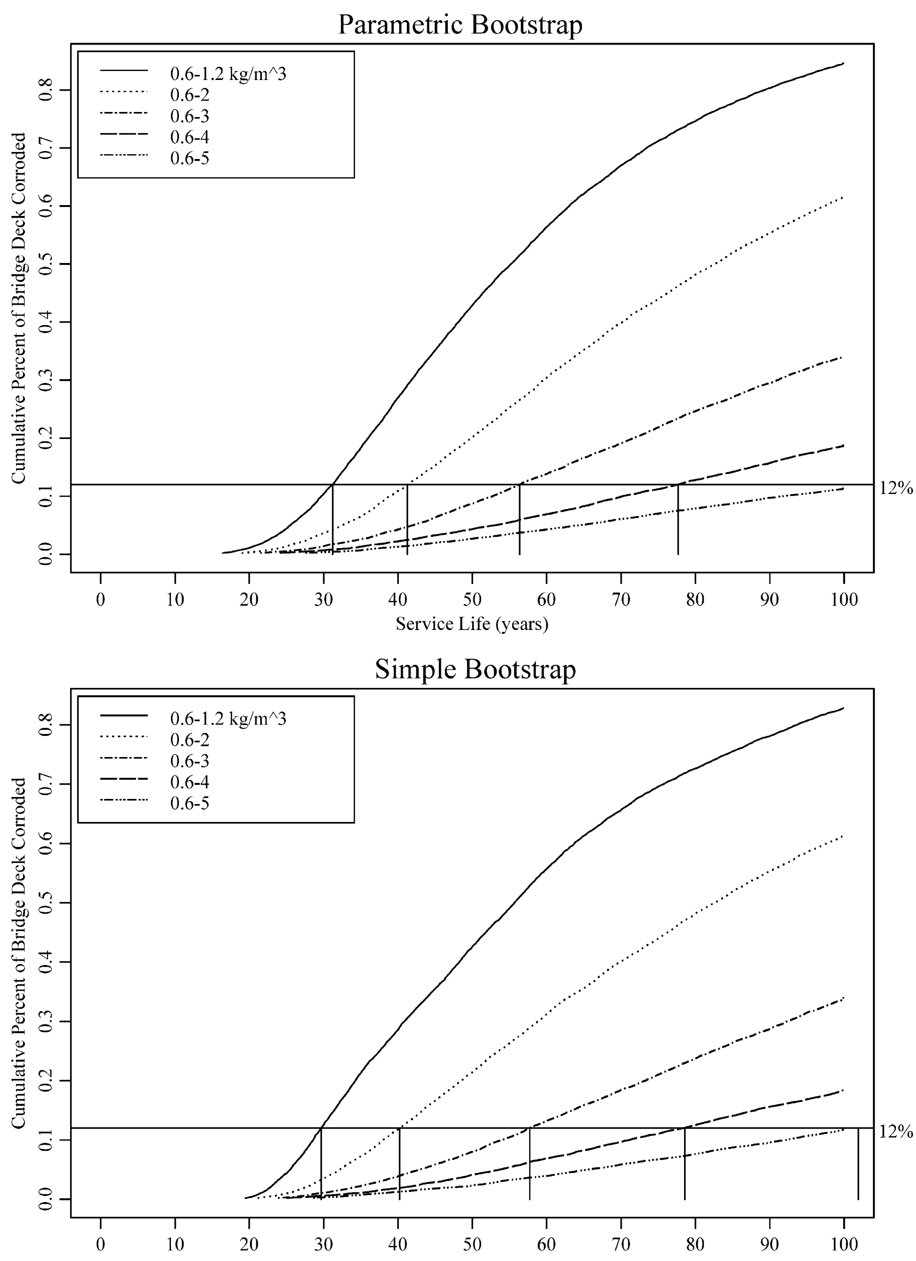


Fig. 10. Service life estimates for bridge 1004.3.

result is a distribution of the service life for the bridge or set of bridges.

A bridge deck is estimated to be at the time to first repair and rehabilitation when 2.5% and 12% of the worst span lane has deteriorated, respectively. These conditions are represented in the probabilistic service life model as the 2.5 and 12 percentile values of the distribution of the service life, respectively.

The routine returns a value for the percent of the iterations that predict corrosion and values for the 2.5 and 12 percentile of the distribution of the service life. The full list of calculated service life estimates is available for creating other summary statistics or descriptive graphs. The results of several intermediate steps are also available for diagnostic testing.

2.2.2.2. Simple bootstrap. The procedure for the simple bootstrap is identical to that of the parametric bootstrap except that no distributions are fitted to the field data. Instead, the routine samples values directly from the field data for each of the input variables x, C_o and D_c, a number of times equal to the specified number of iterations. The distribution of the chloride initiation concentration is still assumed to be triangular in shape.

The routine runs both the simple and parametric bootstraps from the same set of input parameters and returns the

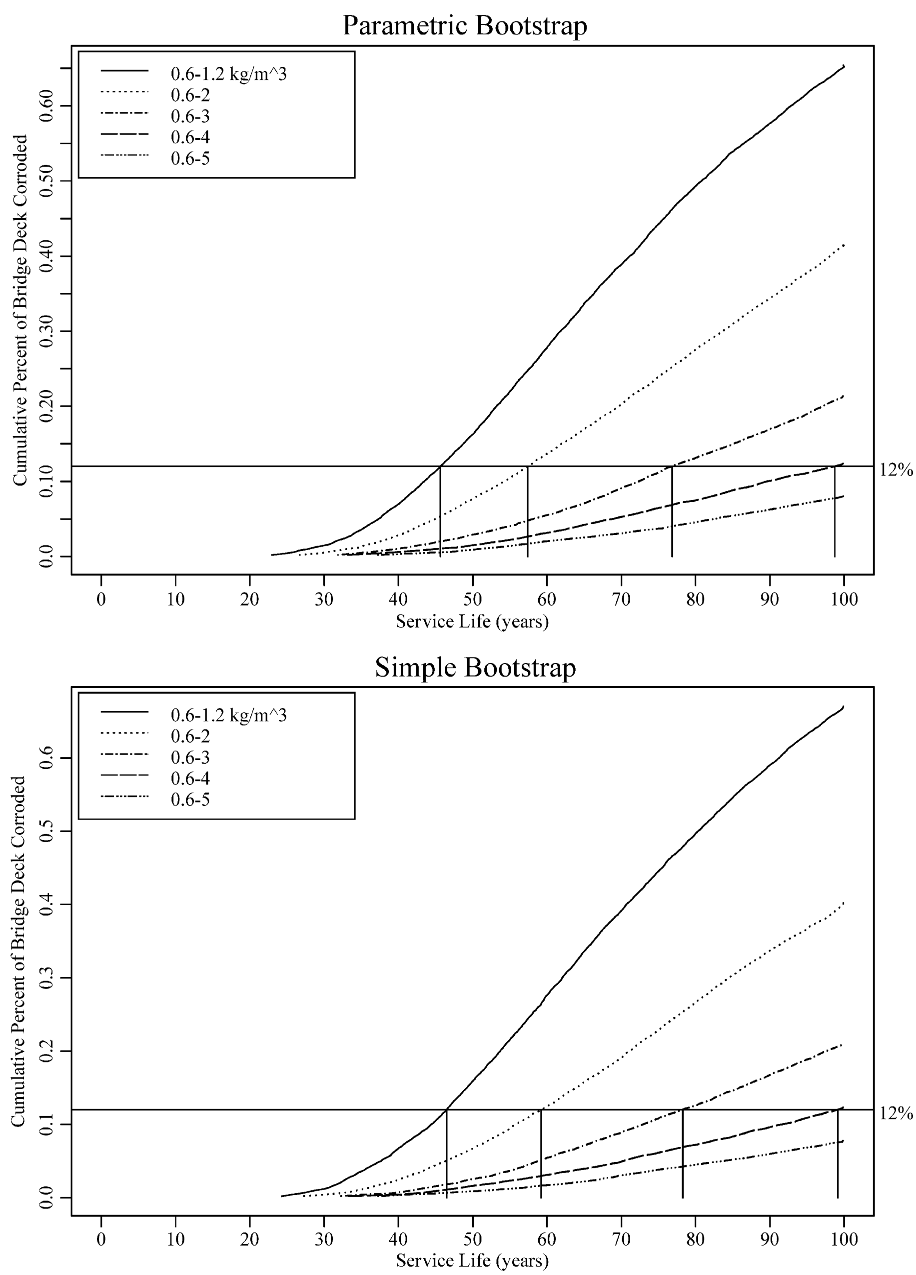


Fig. 11. Service life estimates for bridge 1136.

results of both the simple and parametric bootstrap simultaneously.

3. Results

In Section 2, a method that incorporates the probabilistic nature of bridge decks was developed to predict the time to first repair and subsequent rehabilitation of concrete bridge decks subjected to chloride induced corrosion of the reinforcing steel. In this section, the results of further development of the model in predicting the service life of 10 Virginia bridge decks are presented (Table 1).

3.1. Number of iterations

Before the model could be used to predict the service life of real structures, the appropriate number of iterations required for the model to provide precise results had to be determined. In this case, the precision of the results represents the range of predicted service life estimates expected for successive runs of the model with the same input

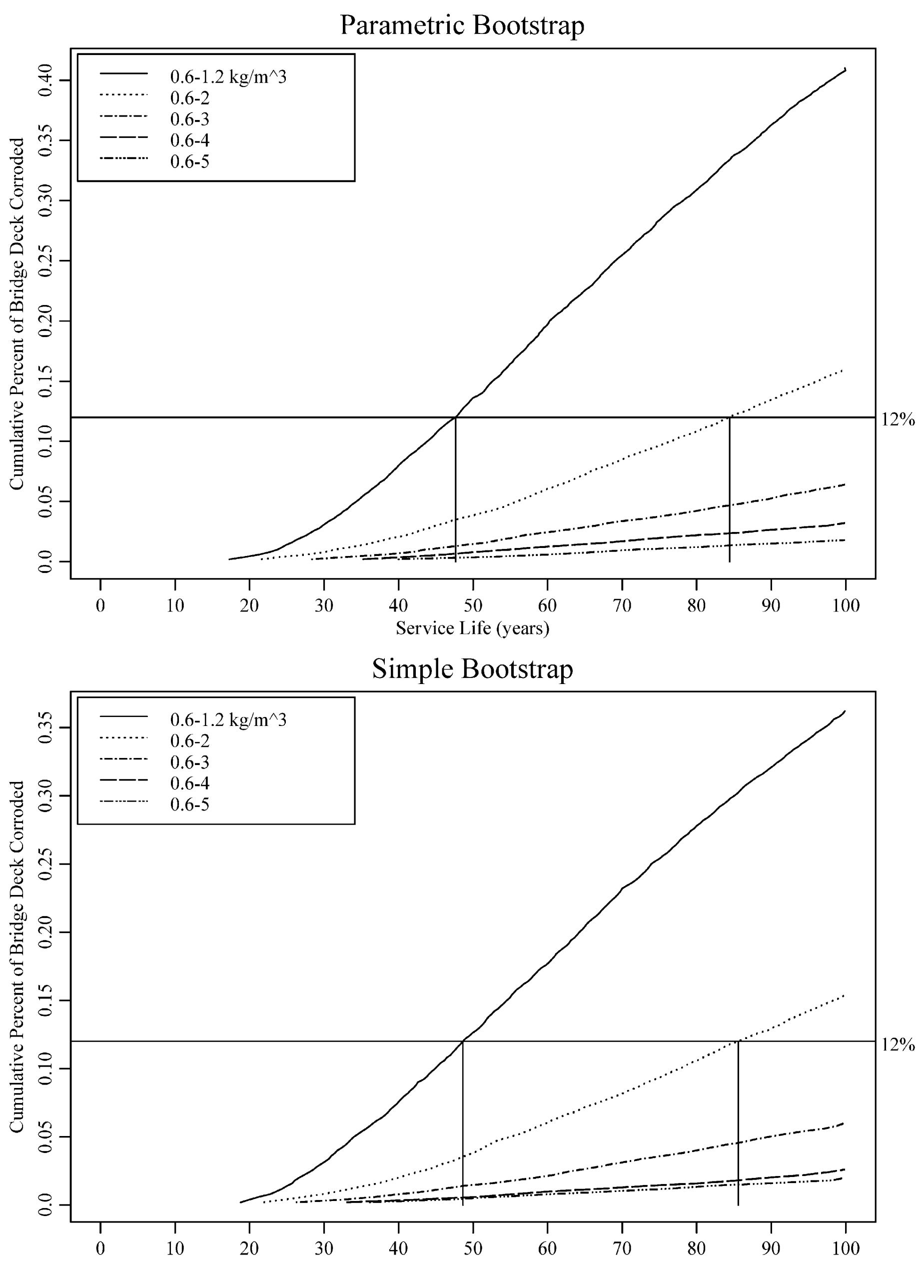


Fig. 12. Service life estimates for bridge 1001.

variables. The appropriate number of iterations is a compromise between the time required to run the simulation and the precision of the results. As the number of iterations increases, the range of predicted service life estimates decreases for a given set of input values.

To determine the appropriate number of iterations for this simulation, the service life was estimated 20 times each for numbers of iterations ranging from 10 to 100,000. The resulting service life estimates were used to generate the 95% confidence intervals for the predicted time to repair and rehabilitation for each number of iterations. The data from Bridge 1001 was used for the calculations. Figs. 5 and 6 show the converging behavior and tighter confidence intervals for increasing numbers of iterations.

Based on the results of these trials, 10,000 iterations were chosen for this simulation because of the good balance between the precision of the estimate and the time to run the simulation. The same number of iterations was chosen for a similar project involving bridge decks in Pennsylvania [29].

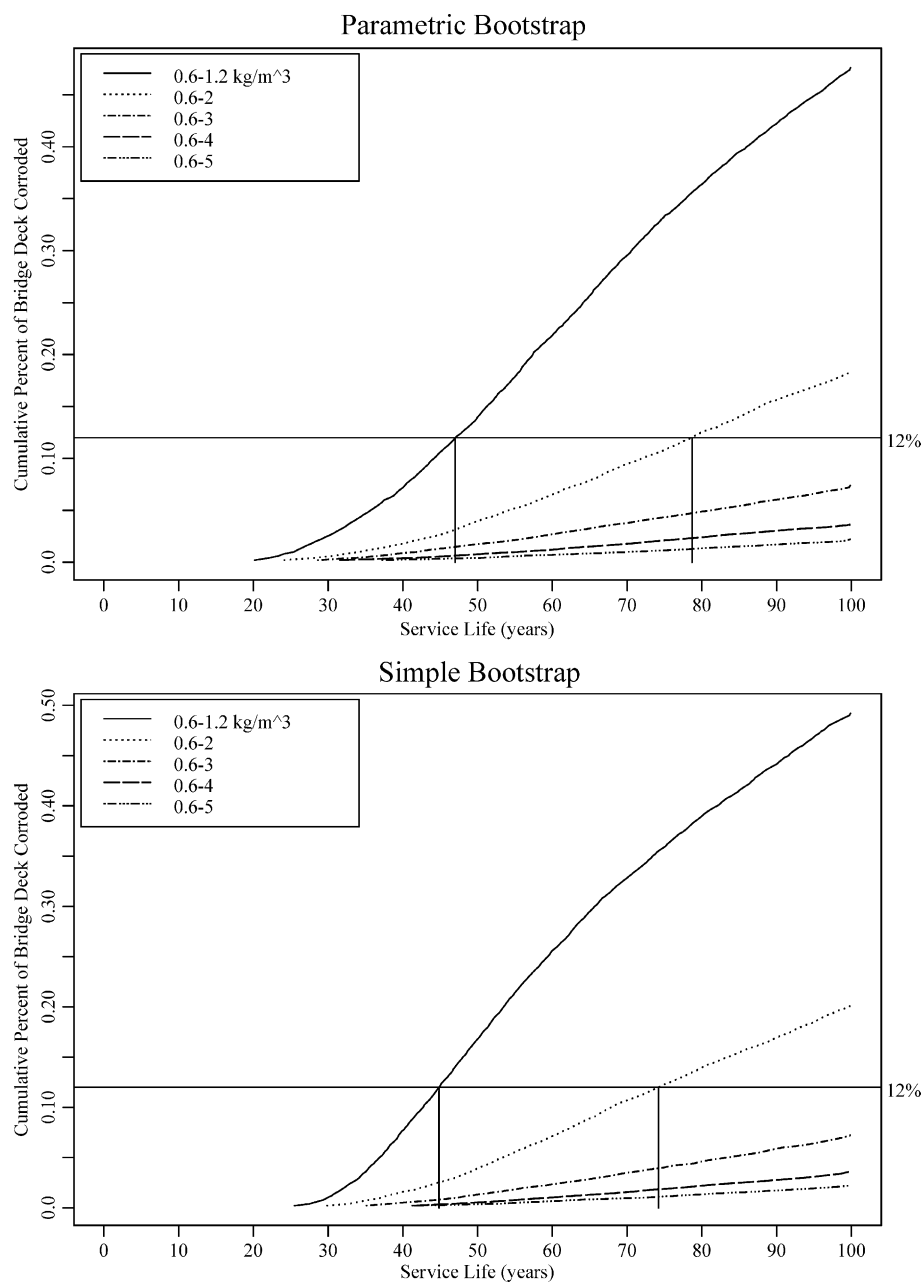


Fig. 13. Service life estimates for bridge 1019.

3.2. Sensitivity of the model

To interpret the results of the simulation, it is useful to understand the sensitivity of the various input parameters on the predicted time to first repair and rehabilitation. The sensitivity of a variable indicates the expected change in the predicted time to first repair and rehabilitation associated with a change in the input variable. Because probabilistic considerations are not currently included in the time for corrosion deterioration portion of this model, the sensitivity of the input parameters was only investigated for the time for diffusion to corrosion initiation.

Fig. 7 presents the relationship between the ratio of $C_{(x,t)}/C_o$ and the time for diffusion to corrosion initiation. The value of the cover depth was held at 50 mm (2.0 in.). Separate curves were generated for values of D_c equal to 10, 30 and 50 mm^2/year (0.016, 0.047 and 0.078 in.^{2}/year).

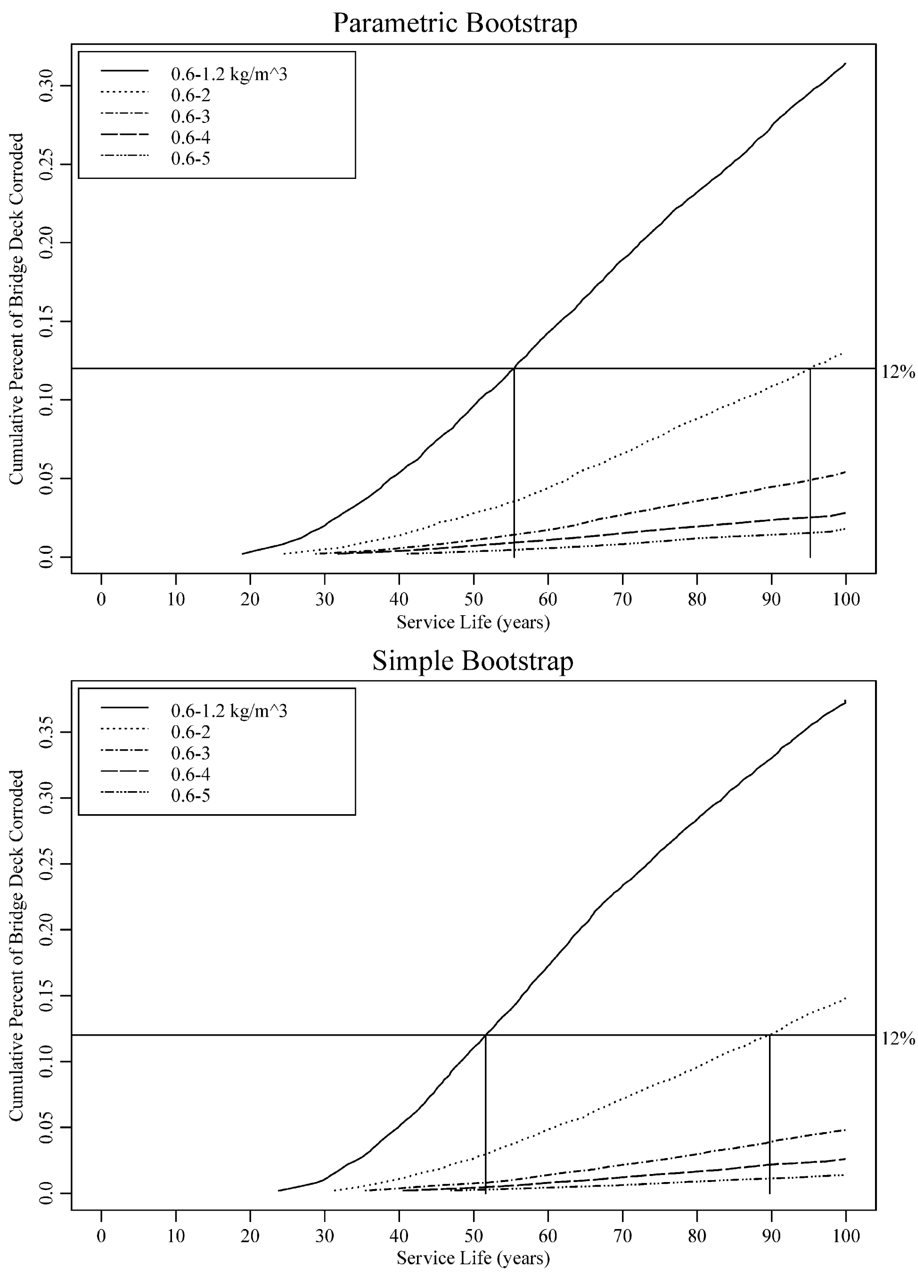


Fig. 14. Service life estimates for bridge 2262.

3.3. Results of the simulation

Once the number of iterations and the sensitivity of the model were determined, the time to first repair and rehabilitation were determined for the 10 bridge decks included in this study.

3.3.1. Parametric vs. simple bootstrap

Both the parametric and simple bootstraps were used for each bridge. Table 2 shows the estimated percent corroded and 2.5 and 12 percentile service life estimates for each bridge for both the parametric and simple bootstrap for the range of chloride initiation from 0.6 to 1.2 kg/m^3 (1.0–2.0 lb/cy). These values include an estimated time for corrosion damage (cracking and spalling) after initiation of 4 years. The percent corroded corresponds to the number of model iterations in the simulation that predict corrosion damage in a bridge deck (C_o is larger than $C_{(c,t)}$). The 2.5 and 12 percentile values correspond to the time to first repair and time to rehabilitation, respectively. Predicted times to first repair and rehabilitation longer than 100 years were deemed to be unrealistic and were not reported.

Fig. 8 presents a histogram of the results of the simulation for the parametric and simple bootstrap for bridge 1136 and for the range of chloride initiation from 0.6 to 1.2 kg/m^3 (1.0–2.0 lb/cy). For clarity, extreme values in the right tail were not shown. Histograms plotted for the other bridges in the study were similar. The values for the 2.5 and 12 percentile of the distributions are most important because they represent the time to first repair and rehabilitation, respectively. Comparing the shape of the distributions for the parametric and simple bootstrap is also useful.

3.3.2. Effect of the chloride initiation concentration

Figs. 9–14 are cumulative distribution plots for the distributions of service life determined from the model. The 12 percentile line is shown on the graph and represents the estimated time to rehabilitation. A fixed time for corrosion damage of 4 years is included in the values. No graphs were generated for bridges 2021, 1004.6, 6037 or 6128 because corrosion was not predicted to occur on these structures within 100 years at any of the ranges of the chloride initiation concentration.

4. Discussion

In this section, topics related to the prediction of the time to first repair and rehabilitation and the effects of the individual parameters of the model on the predicted service life are discussed.

4.1. Number of iterations

The results used to determine the number of iterations required for the model to provide precise results is presented in Figs. 5 and 6. For both the parametric and simple bootstrap, the range of times to first repair and rehabilitation tend to shorten and converge to a single value for increasing numbers of iterations. For very small numbers of iterations, the range predicted by several successive runs of the simulation is quite large, approximately 15 years for the time to first repair and 20 years for the time to rehabilitation. In addition, the predicted time at the center of the range for smaller numbers of iterations is higher than the predicted time at the center of the range for larger numbers of iterations. It is clear from the figures that at 10,000 iterations, the results have both converged and shifted to a near constant value.

The shifting behavior is of particular interest. It is expected that the range of predicted values will be larger for smaller numbers of iterations, but one might not expect the center of the range to be different for large and small numbers of iterations. If the behavior is not understood, the model may lead to inaccurate predictions of the time to first repair and rehabilitation. For smaller numbers of iterations, the shape of the input variable distribution is not well defined, especially in the tails. For larger numbers of iterations, the distributions are better modeled and more values are randomly sampled from the tails. The better defined input variables in turn lead to a better defined distribution of the predicted time to first repair and rehabilitation, especially in the tails. Therefore, for larger numbers of iterations, the model will tend to produce results that are more consistent and converge to a single value.

It is also important to distinguish between the precision of the model and the accuracy of the predicted time to first repair and rehabilitation. At 10,000 iterations, the model can be expected to predict times to first repair and rehabilitation that agree to within approximately 1 year for a given set of input variables. This does not imply that the prediction is accurate to 1 year, but that the error associated with the model has been limited to 1 year. The true accuracy of the prediction depends on the accuracy of the input variables, the sensitivity of the input parameters on the model and how closely the true deterioration mechanism matches the diffusion-cracking model employed here. The sensitivity of the input parameters is discussed in Section 4.2.

4.2. Sensitivity of the input variables

Knowing the sensitivity of the input variables on the predicted time to first repair and rehabilitation is useful to understand possible sources of error in the model and to evaluate the likely affect of altering one of the input variables. The results of the sensitivity analysis are presented in Fig. 7.

4.2.1. Surface chloride concentration and corrosion initiation concentration

The relationship between $C_{(x,t)}/C_o$ and the time to corrosion initiation is positively correlated and asymptotic for

$C_{(x,t)}/C_o$ approaching one. In other words, for values of C_o that are very close to the initiation concentration, a long time is required for the chlorides to diffuse through the cover concrete to the depth of reinforcing steel in quantities sufficient to initiate corrosion of the reinforcing steel. For low values of D_c, the slope of the curve changes gradually and becomes asymptotic for very large times for diffusion to corrosion initiation. For higher values of D_c, the curve becomes asymptotic for much smaller values of times for diffusion to corrosion initiation.

For a corrosion initiation concentration of 0.9 kg/m^3 (1.5 lb/cy), C_o values in the mild exposure category have $C_{(x,t)}/C_o$ values that are relatively close to 1.0 and cause the predicted time for diffusion to corrosion initiation to be very large. C_o values in the moderate and severe exposure categories have $C_{(x,t)}/C_o$ values that are much less than 1.0 and cause the predicted time to corrosion initiation to be shorter. The predicted time for diffusion to corrosion initiation when D_c is equal to 10 mm^2/year (0.016 in.^{2}/year) is much longer than the predicted time for diffusion to corrosion initiation when D_c is equal to 30 or 50 mm^2/year (0.047 or 0.078 in.^{2}/year) for the entire range of $C_{(x,t)}/C_o$.

Generally speaking, bridges that are in the mild exposure category (typically rural routes with little traffic) are of much less concern than bridges that are located in moderate or high exposure zones (typically Interstate or highway routes). It can be inferred that corrosion deterioration is much less likely to occur on bridge decks that receive only small salt applications than on bridge decks that receive higher salt applications.

4.2.2. Apparent diffusion coefficient

The time for diffusion to corrosion initiation when D_c is equal to 30 mm^2/year (0.047 in.^{2}/year) is only slightly longer than the time for diffusion to corrosion initiation when D_c is equal to 50 mm^2/year (0.078 in.^{2}/year). The time for diffusion to corrosion initiation when D_c is equal to 10 mm^2/year (0.016 in.^{2}/year) is much longer than the time for diffusion to corrosion initiation when D_c is equal to either 30 or 50 mm^2/year (0.047 or 0.078 in.^{2}/year). D_c values below approximately 10 mm^2/year (0.016 in.^{2}/year) can be expected to produce times for diffusion corrosion initiation that are very large. A large change in D_c above approximately 30 mm^2/year (0.047 in.^{2}/year) can be expected to change the time for diffusion to corrosion initiation by a smaller amount.

The results of the sensitivity analysis indicate that the time to corrosion initiation is highly sensitive to D_c because the apparent diffusion coefficient is within the square root function in the denominator of the statistical error function. Thus, further reductions in D_c below 10 mm^2/year will have a large impact on the time to initiate corrosion. This realization is troublesome because D_c is more difficult to obtain and is less well defined than the other input variables. It is clear that care must be exercised when calculating D_c from a chloride profile or when comparing D_c's from field data to those obtained experimentally from laboratory studies.

4.2.3. Clear cover depth

The relationship between the clear cover depth and the time for diffusion to corrosion initiation was found to be positively correlated with a decreasing slope for increasing cover depths. For clear cover depths greater than approximately 38 mm (1.5 in.), the relationship is approximately linear with a slope that depends on the values of the other variables.

It is reasonable to conclude that increasing the clear cover depth will increase the time for chlorides to diffuse through the concrete to the reinforcing steel, and that the predicted time to corrosion initiation is not highly sensitive to the clear cover depth.

4.3. Results of the simulation

Topics relative to the results of the simulation for the 10 bridge decks included in this study are discussed in the following sections.

4.3.1. Parametric vs. simple bootstrap

The parametric bootstrap makes the assumption that the populations of the input variables match known distributions and that the observed sample populations define the distributions. This assumption must be evaluated along with the results of the simulation. The simple bootstrap makes the least amount of assumptions regarding the input data because the observed sample populations are assumed to represent the entire population for each variable. Comparing the results of the two methods provides confidence in the model.

The results of the simulation for the parametric and simple bootstrap are presented in Table 2. The times to first repair and rehabilitation generated by the two methods agree well. Generally, the two methods are in closer agreement for times to repair and rehabilitation that are shorter, but the trend is not pronounced. The results of the two methods never differ by more than approximately 8%.

Along with the 2.5 and 12 percentiles, it is also helpful to compare the histograms of the predicted times calculated by the simulation. If the two methods provide results that are substantially the same, the shape of the histograms should be comparable. A representative histogram (from Bridge 1136) is presented in Fig. 8. The shape of the distribution calculated by the two methods is similar and has a positive skew and long right tail. The parametric bootstrap typically has a few values in the extreme right tail that are larger than those predicted by the simple bootstrap (for clarity, extreme values in the right tail were not shown on the histograms). The distributions used for the input variables by the parametric bootstrap are expected to have longer tails than the observed sample population, and it is expected that the occasional extreme input value will produce an extreme prediction of the service life. Extreme values in the right tail do not affect the lower 2.5 and 12 percentiles, which represent the time to first repair and rehabilitation.

The fact that the two methods provide results that match well for each bridge deck suggests one of two conclusions. First, the shape of the distribution of the input variables does not seriously affect the shape of the predicted time to first repair and rehabilitation. Second, the distributions used to model the input variables in the parametric bootstrap closely match the true shape of the population. It has been shown in the literature that clear cover depths on bridge decks follow a Normal distribution and that surface chloride concentrations and diffusion coefficients follow a gamma distribution [14,15,17]. Quantile–quantile, or probability plots of the input data, reviewed for this project essentially confirm these observations, suggesting that the distributions used in the simulation accurately match the true population. However, it was also noted that the surface chloride concentrations and diffusion coefficients might be equally well described by normal distributions, suggesting that slight variations in the shape of the input distributions does not seriously affect the shape of the time to first repair and rehabilitation [26]. The specific ideal distribution for the input variables cannot be precisely confirmed based on the results of this study, and in any case is not the focus of the study. It is enough to recognize that the two methods provide results for each bridge that are comparable, providing confidence in our predicted times to first repair and rehabilitation.

4.3.2. Effect of chloride initiation concentration

Because the true range of the chloride initiation concentration is not presently known, the time to first repair and rehabilitation was determined for several ranges of $C_{(x,t)}$. The results of the increasing range of $C_{(x,t)}$ are shown graphically in Fig. 9 through Fig. 14. The figures include an estimated 4 years for the time for corrosion damage of the reinforcing steel. As expected, increasing the range of $C_{(x,t)}$ increases the time to first repair and rehabilitation.

For bridge 1015, the time to rehabilitation was 13 years for the lowest range of $C_{(x,t)}$ and 32 years for the highest range of $C_{(x,t)}$. Even at the highest range, the predicted time to rehabilitation is less than the design life of 50 years. Four of the bridges included in the study (1136, 1001, 1019 and 2262) have predicted times to rehabilitation of approximately 50 years at the range of $C_{(x,t)}$ from 0.6 to 1.2 kg/m^3 (1.0–2.0 lb/cy). Predictions of the time to rehabilitation using the higher ranges of $C_{(c,t)}$ are clearly longer, but for these bridges, the design life is nearly exceeded even at the most conservative estimate of $C_{(x,t)}$ used in this study, and the bridges would not be of concern at this time. Bridge 1004.3 has a time to rehabilitation that is less than 50 years at the lowest range of $C_{(c,t)}$ and longer than 50 years at an intermediate range of $C_{(x,t)}$. The remaining four bridges in the study have times to rehabilitation longer than 100 years at all levels of $C_{(x,t)}$.

The observations of the data suggest that increasing the range of the chloride initiation concentration may increase the predicted time to rehabilitation by a factor of two or more. However, if a bridge deck is of concern at the lowest range of chloride initiation, then it will likely be of concern at the higher ranges of chloride initiation. If the bridge deck is not of concern at the lowest ranges, then it will not be of concern at the highest ranges. There will be bridge decks somewhere in between these extremes, and for these bridge decks, estimating the correct chloride initiation concentration is particularly important.

5. Conclusions

The following conclusions are based on the parametric sensitivity analysis of the diffusion model and the Monte Carlo probability simulations of chloride corrosion degradation of bridge decks.

5.1. Sensitivity analysis

- The time to corrosion initiation is highly sensitive to diffusion coefficient values. At and below 10 mm^2/year (0.016 in.^{2}/year), the times to initiate corrosion are much larger than above 30 mm^2/year (0.047 in.^{2}/year). This underscores the necessity of establishing accurate values from field data or in comparing diffusion coefficients from field data to experimental laboratory results.
- The time to corrosion initiation is not as highly sensitive to cover depth as it is to the diffusion coefficient. For clear cover depths greater than 38 mm (1.5 in.), the relationship of time for corrosion initiation with increasing clear cover depth is approximately a linear relationship with a slope that depends on the values of the other variables.
- Ratios of chloride corrosion initiation concentration to surface chloride concentration relatively close to 1.0 cause vary large predicted times for diffusion corrosion initiation. Bridge decks in mild exposure zones (low chloride exposure zones as rural bridges) are of much lesser concern than bridges in moderate or high exposure zones (Interstate and US routes).

5.2. Simulations

- As the number of iterations increase, the range of predicted times to corrosion initiation decreases and the center of the range decreases. If the behavior is not understood, the model may lead to inaccurate predictions of the times to first repair and rehabilitation. At 10,000 iterations, the results converge and shift to a near constant value.
- The parametric and simple bootstrapping provide similar estimates of the time to first repair and rehabilitation. Thus, the shape of the distributions of the input variables does not seriously affect the shape of the

predicted time to first repair and rehabilitation. Also, the distributions used (normal for cover depth, gamma for surface chlorides and diffusion coefficient, and triangular for chloride corrosion initiation) closely match the true shape of the populations. This suggests that a normal distribution shape may be used for all four of the input parameters without seriously affecting the time estimates.

- Increasing the range of chloride corrosion initiation from 0.6 to 1.2 kg/m^3 (1.0–2.0 lb/cy) to 0.6 to 5.0 kg/m^3 (1.0–8.3 lb/cy) may increase the predicted time to rehabilitation by a factor of two or more. However, if a bridge deck is of concern (time to rehabilitation of less than 50 years) at the lowest range, it will likely be a concern at the higher ranges of chloride initiation.

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