AN OPTIMIZED LIFETIME RELIABILITY-BASED INSPECTION PROGRAM FOR DETERIORATING STRUCTURES

Allen C. Estes, M. ASCE
United States Military Academy, West Point, NY 10996
ia2804@trotter.usma.edu

Dan M. Frangopol, F. ASCE
University of Colorado, Boulder, CO 80309-0428
frangopo@spot.colorado.edu

Abstract

No matter how well they are designed, all civil engineering structures will deteriorate over time and a program of lifetime inspection, maintenance and repair represents a substantial portion of the total lifetime cost of most structures. An optimized inspection program is the key to making appropriate repairs at the right time to minimize cost and maintain an appropriate level of safety in a structure. When a visual inspection will not provide the necessary level of information, some other non-destructive evaluation method is often needed. This study summarizes a methodology for optimizing the timing, the frequency, and the type of inspection over the expected useful life of deteriorating structures. A decision tree analysis is used to develop an optimum lifetime inspection plan which can be updated as inspections occur and more data is available. This methodology is illustrated using a half-cell potential test on a deteriorating concrete bridge deck. The study includes the expected life of the structure, the minimum prescribed safety level of the structure, costs of inspection and specific repairs, discount rates, the capability of the test equipment to detect a flaw, and the management approach of the owner towards making repairs. The optimum strategy can be updated after each inspection to incorporate new data.

Introduction

The lifetime maintenance of a deteriorating structure can comprise a far greater portion of the total lifetime cost than the original cost of construction. The infrastructure of the United States consists of thousands of deteriorating structures and the national cost of maintaining them is a substantial portion of the budget. Of the almost 600,000 structures in the National Bridge Inventory, roughly 80% describe bridges and 20% describe culverts. Over 35% of the bridges are structurally deficient, functionally obsolete, or both, and the estimated cost to eliminate the backlog of bridge deficiencies and maintenance repair levels is about $80 billion (ASCE, 1998). The National Dam Inventory Data Base lists 512 dams which all require lifetime maintenance. Depending on the type of dam, maintenance accounts for 79 to 96 percent of the total expenditures in the dam and reservoir budget (CERL, 1999). With such huge expenditures, any realized efficiency or optimization can result in significant savings. This paper summarizes a methodology developed by the writers (Estes and Frangopol, 1998; Frangopol and Estes, 1999) for optimizing the lifetime inspection and repair of any deteriorating structure and then illustrates the technique using a concrete bridge deck whose steel reinforcement is corroding. The results are an optimum inspection technique, the number and timing of the inspections, and the expected lifetime maintenance cost of the structure.

Optimization Methodology

The general methodology for optimizing the lifetime inspection and repair of a deteriorating structure is the one proposed by the writers (Estes and Frangopol, 1998; Frangopol and Estes, 1999). It consists of the following steps. Define the structure and the criteria which constitute failure of the structure; develop a deterioration model which predicts how the structure will change over time; specify the inspection methods available to detect this deterioration; quantify the inspection costs and capability of these methods to detect the relevant flaws or changes in the structure; define the available repair options, their effect on the structure, and their costs; quantify the probability of making a repair if a defect is detected; formulate the optimization problem based on the optimization criterion, failure constraints, expected life of the structure, and any other imposed constraints; use an event tree to account for all of the repair/no repair decision possibilities that occur after every inspection; optimize the timing of these inspections; and repeat the problem for other inspection techniques and numbers of lifetime inspections. The optimum strategy is the one which provides the best expected value of the optimization criterion.

Concrete Bridge Deck Example

The structure whose lifetime inspection and repair strategy is optimized is a 42.1 m by 12.2 m concrete bridge deck which deteriorates over time as spalls and delaminations appear in the concrete. The deterioration is caused by corroding reinforcing steel in the bridge deck. Consistent with the Colorado Department of Transportation (CDOT) repair policy, deck failure will be defined when active corrosion is underway in at least 50% of the deck (CDOT, 1994).

The concrete deteriorates as chlorides from deicing salts penetrate the concrete and reach the steel reinforcing. At a critical chloride concentration, the reinforcing corrodes which causes the concrete deck to spall. The corrosion initiation time which is the amount of time between the application of surface chloride and the onset of corrosion is expressed as (Thoft-Christensen et al., 1997):

$$\mathrm{T_I} = \frac{(\mathrm{d_I} - \mathrm{D_I}/2)^2}{4\mathrm{D_c}} \left(\mathrm{erf}^{-1}\left(\frac{\mathrm{C_{cr}} - \mathrm{C_o}}{\mathrm{C_i} - \mathrm{C_o}}\right)\right)^{-2} \qquad (1)$$

where d_I is the concrete cover and D_I is the initial diameter of the reinforcing bar, C_o is the equilibrium chloride concentration on the concrete surface, C_i is the initial chloride concentration, D_c is the chloride diffusion coefficient, and C_{cr} is the critical chloride concentration that will initiate corrosion. Using the parameters listed in Estes (1997) for all of these random variables, T_I was calculated to be normally distributed with a mean value $\mu_{T_I} = 19.6$ years and standard deviation $\sigma_{T_I} = 7.51$ years. The deterioration model can predict the percentage of corrosion in the deck at any time.

The half-cell potential test is an inexpensive, accurate, and non-destructive means of detecting active corrosion in a concrete deck. The half-cell potential survey measures the electrical potential difference between a standard portable half-cell placed on the surface of the concrete and the embedded reinforcing steel. The voltage readings are compared to empirically derived values which indicate relative probabilities of active corrosion (FHWA, 1992).

The correlation between the half-cell readings and the presence of active corrosion has been the subject of considerable research. The ASTM guideline prescribes that half-cell readings more positive than –0.20 volts indicate a greater that 90% probability of no active corrosion. Similarly, values more negative that –0.35 volts indicate 90% probability of active corrosion. Marshall (1996) studied the data from 89 bridges to determine the probability density functions of the half-cell potentials for both sound and damaged deck areas. The half-cell potentials in areas where the deck was known to be undamaged was a normal distribution with a mean of $\mu =$-0.207 volts and a standard deviation $\sigma = 0.0804$ volts and the half-cell potentials in areas where the deck was known to be damaged was a normal distribution with a mean of $\mu =$-0.354 volts and a standard deviation $\sigma = 0.0697$ volts. The regions where the curves overlap indicate half-cell readings where the predicted damage has a high degree of uncertainty.

The uncertainty associated with assessing the condition of the entire deck from a finite number of half-cell readings was considered. Three different inspection options were used where the number of readings varied from one every five feet (Option A) to one every 20 feet (Option C). The inspection costs, developed in consult with CDOT (CDOT, 1996) included fixed costs such as travel time to site, traffic control, equipment set-up, and writing the final report and variable costs such as marking the grid pattern, prewetting the test locations, taking readings, and traffic control while the test was being conducted. Although several repair options such as a concrete overlay, waterproofing membrane, and cathodic protection were considered, the only repair option used in this study was replacement of the deck at a cost of $225,600 (CDOT, 1996). The effect of the repair is to return the deck to its original condition. Local damage will be patched and repaired as necessary to keep the bridge deck serviceable.

The probability of making a repair once a defect has been detected is a function of the bridge manager’s willingness to make a repair, which could be based on past performance. Availability of funds, competing priorities, and political considerations become relevant variables. Four repair approaches as shown in Estes (1997) are used where the *delayed* approach waits the longest to make a repair (only 30% chance of making the repair when the deck is 50% damaged) and the *proactive* approach employs a preventive strategy (80% chance of repair when the deck is 50% damaged).

A discrete optimization of the bridge deck with an expected service life of 45 years was conducted for two, three, and four lifetime inspections and the objective to be minimized was the expected total cost $E(C_t)$ which equaled the actual inspection cost C_{insp} plus the expected cost of repair $E(C_{rep})$. The expected damage $E(Damage)_t$ must be below the 50% damage limit established by the replacement policy. The total expected cost and the expected amount of damage are a weighted average over all possible paths which sums the effect of a particular path multiplied by the probability of taking that path. Additional constraints ensure that inspection times are at least two years apart but not more than 20 years. The optimal inspections times are 10.05 years, 19.76 years, and 35.45 years with an expected lifetime cost $E(C_{tot})$ of $174,280. Inspection Technique A (five foot spacing of readings) was used with a *proactive* approach to repair and a 2% discount rate on money.

After every inspection, a decision is made to repair or not repair the deck. The event tree which illustrates the possible paths in the three inspection example is shown in Figure 1. Figure 2 shows the effects of each of the eight possible outcomes. The optimum solution can be seen as a weighted average of the eight branches shown in Figures 1 and 2. The timing of the inspections is optimized to meet all the constraints. The decrease in the expected damage to the deck after each inspection is based on the probability of taking a branch in which the deck is replaced after that inspection. For example, the probability of making a repair after the first inspection is only 6.7%. The expected effect of this repair is very small. The probability of making a repair after the second inspection is 75.3% and the expected effect of the repair is therefore very large. The probability of repair after the third inspection is 40.2%.

Branches 1, 2, 4, and 8 in Figures 1 and 2 have almost no chance of occurring. The most likely path is Branch 6 which would involve one repair after 19.76 years. This branch taken alone would not meet the constraints of the problem. It is the combined effect of all eight paths and their relative probabilities of occurrence that determined the optimum least-cost inspection strategy. In reality, none of these eight paths will be taken. While the optimum strategy at this time is for three lifetime inspections at 10.05, 19.76, and 35.45 years, the plan will be updated after each inspection to account for the new information that the inspection provides. After the first inspection, the first replacement decision will be made and half of the eight paths can be eliminated. With that additional information, an updated optimum inspection plan is developed.

Optimizing and Updating

The optimum inspection strategy is obtained by performing the same discrete optimization for different inspection techniques, and numbers of lifetime inspections and selecting the option which offers the minimum expected lifetime cost without violating any of the constraints. The analysis was also performed for different expected service lives of the structure, other management repair approaches, alternative repair policies, and different discount rates. After completing an inspection and deciding whether or not to make a repair, the optimum inspection strategy is updated based on the remaining paths of the tree and the information obtained from the inspection as demonstrated in Estes (1997).

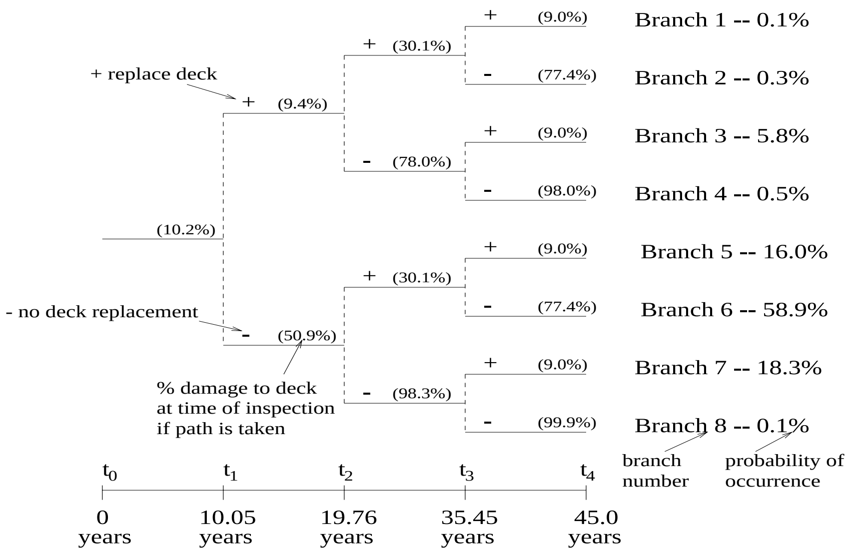

Figure 1: Event Tree for the Optimum Inspection Strategy for a 45 Year Bridge Deck Using a *Proactive* Repair Approach and Three Lifetime Inspections

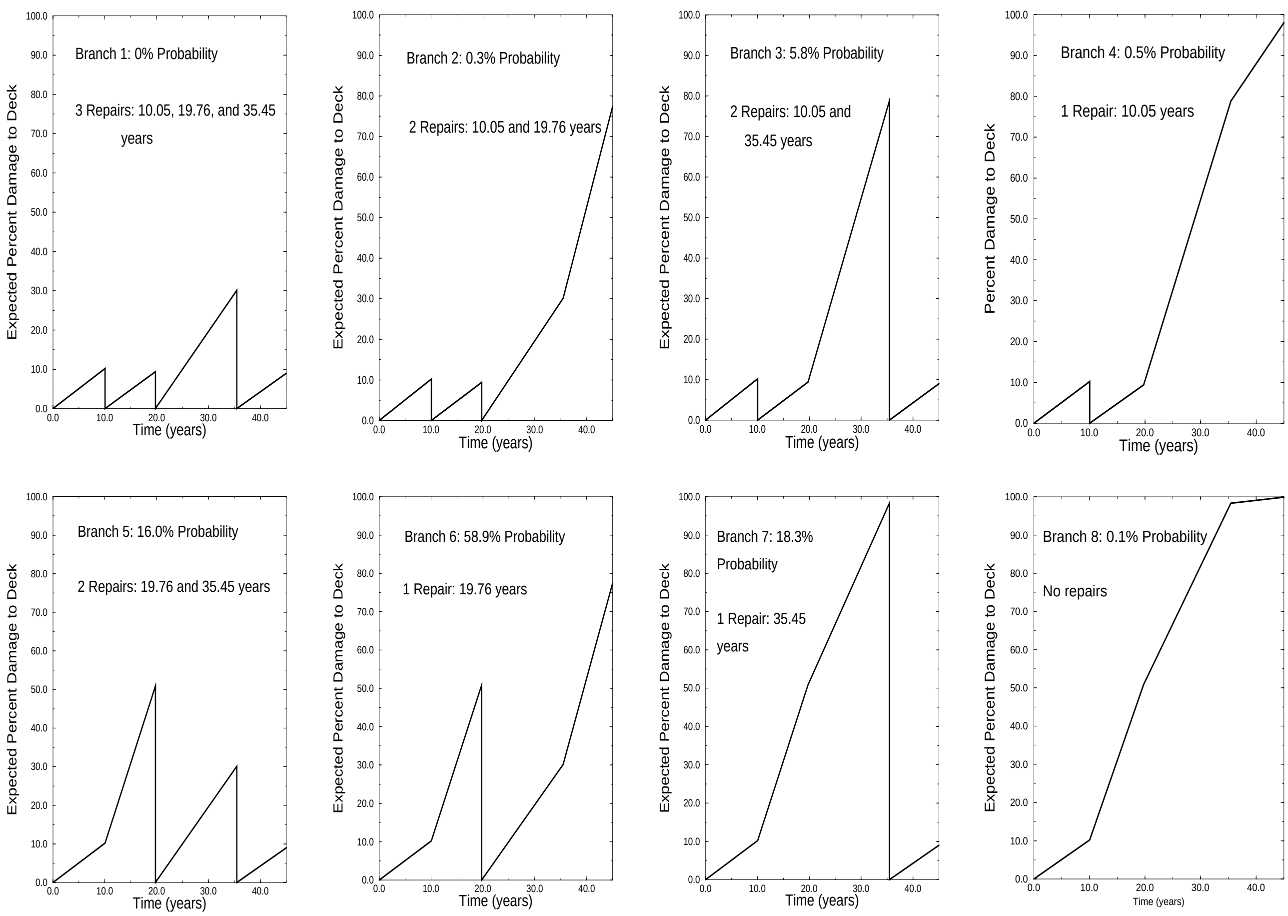

Figure 2: Branches 1 Through 8 of the Event Tree for the Optimum Inspection Strategy

Conclusions

The methodology outlined offers a rational and logical approach for optimizing the inspection/repair strategy for a deteriorating structure and could result in both improved safety and reduced cost. This method requires a great deal of input data that is not readily available and demands investment of time and research. The investment would be justified for expensive, critical structures such as dams or nuclear power plants or for a large number of similar less-critical structures where the same input data could be used repeatedly. If the number of lifetime inspections becomes more than five, the size of the event tree becomes large and extremely difficult to manage. In such cases where updating is possible, the problem should be solved over a shorter time period where fewer inspections can be considered. Additional research is needed in the areas of quantifying the probabilistic capability of NDE inspection techniques, probability of making repairs, and the modeling of deterioration. An optimization strategy that considers the results of several different inspection techniques taken in combination merits further study.

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