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DECISION SUPPORT TOOLS FOR LIFE PREDICTION AND REHABILITATION OF CONCRETE BRIDGE DECKS

by

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Abstract

The selection of the optimum rehabilitation method of corrosion-damaged concrete bridge structures requires an assessment of the total costs that will be incurred throughout their life cycles for all rehabilitation methods. A reliable estimate of the life cycle cost requires reliable information and data on the service life of different rehabilitation methods. The prediction of the service life of rehabilitated bridge structures presents considerable uncertainty associated with the analytical models of damage initiation and damage accumulation, variability of material properties, structural dimensions, and applied environmental and mechanical loads. Existing approaches and guidelines for service life prediction and rehabilitation of bridge structures are based on expert opinion or simple deterministic predictive models that are of limited reliability and utility. Therefore, a new approach for a reliable prediction of the service life of bridge structures with different rehabilitation treatments is necessary. The main objective of this paper is to provide an overview of a proposed research project related to the development of software-based decision support tools for service life prediction and rehabilitation of corrosion-damaged concrete bridge decks. The emphasis on bridge decks is due to the fact that they are the most stressed elements in highway bridges, and their maintenance accounts for about one-third to one-half of the bridge rehabilitation costs. The proposed tools consist of a reliability-based service life prediction model and a life cycle costing model that will assess the impact of alternative rehabilitation strategies on extending the life of the deck and their corresponding total costs.

Keywords: corrosion initiation, chloride attack, corrosion-induced damage, life cycle cost, rehabilitation options, reliability, service life, simulation.

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1. INTRODUCTION

The aging and deterioration of highway bridges in North America and the limited financial resources allocated for their maintenance are major challenges that need to be addressed in order to ensure a sustainable highway infrastructure. Concrete structures (including reinforced and prestressed concrete) constitute a large component of highway bridge networks in North America. Common deterioration mechanisms include reinforcement corrosion, sulfate attack, alkali-aggregate reaction, freeze-thaw cycling, creep and shrinkage, and temperature effects. In addition to these environmental factors, overloading, poor design, detailing and protection, and inadequate inspection and maintenance constitute the other main causes of deterioration and failure of concrete bridge structures. Chloride-induced reinforcement corrosion is recognized as the major cause of deterioration of concrete structures, and it is estimated that one-third to one-half of the projected bridge rehabilitation costs in the U.S. are related to bridge deck deterioration (Cady and Weyers, 1983). The major sources of chlorides are the deicing salts applied to roadways and bridges during winter and seawater for coastal structures. The corrosion of the reinforcement leads to delamination and spalling of the concrete surface, loss of concrete and reinforcement cross sections, loss of bond between the reinforcement and concrete, and subsequently reduction in strength and ductility. As a result, the safety and serviceability of concrete structures are reduced and their useful service lives are shortened.

Several protection and rehabilitation methods have been used to extend the service life of concrete bridge decks. These include waterproofing membranes, concrete overlay, polymer concrete overlay, patching, cathodic protection, electrochemical chloride removal, and partial or full deck replacement. These rehabilitation methods extend the service life of the deck by different amounts and result in different costs to owners and users. Simplified decision matrices for the rehabilitation of concrete bridge decks have been developed by various highway agencies (AASHTO 1976, 2000; MTO, 1988; NY DOT, 1992; FHWA, 1995). These guidelines are based on simple heuristic estimates of the service life of rehabilitation treatments rather than on field data or actual modeling of their performance, which limits their reliability.

The service life of non-rehabilitated and rehabilitated bridge decks is a function of several variables that present considerable uncertainty and variability. These variables include the initial deck condition, depth of the concrete cover, concrete permeability, chloride concentration at the surface, chloride threshold level for corrosion, rate of corrosion, concrete tensile strength, bar spacing, and rate of deterioration (cracking, delamination, and spalling). As a result, there is a considerable scatter in the times at which the various parts of the deck start deteriorating and reach different thresholds of damage. Existing heuristic or deterministic prediction models cannot consider explicitly the variability in the above variables and cannot capture the variability in the times at which different damage limit states are reached. As a result, the decision models based on such predictive models have a very limited utility and can lead to the selection of rehabilitation strategies that are not necessarily optimal.

Recognizing the limitations of the existing guidelines and the lack of reliable service life prediction methods, the development of a reliability-based service life prediction model constitutes the primary objective of the proposed research project presented in this paper. The prediction of the service life of rehabilitated and non-rehabilitated concrete bridge decks will be based on a realistic modeling of the chloride ingress into concrete and the mechanisms of corrosion initiation and damage accumulation. The uncertainty in all variables that affect the deck performance will be considered by modeling them as random variables and solving the service life prediction problem using reliability-based methods (e.g. advanced first-order reliability method or Monte Carlo simulation). The second objective of the proposed research project is to integrate the proposed service life prediction model with a life cycle costing model to develop a self-contained software for bridge deck rehabilitation. This software will provide bridge owners with a reliable and effective decision support tool for the selection of cost-effective strategies for bridge deck rehabilitation. It can be used on its own or as a component of a bridge maintenance management system at both project- and network- levels.

This paper provides an overview of the proposed research methodology and describes the proposed predictive models.

2. RESEARCH METHODOLOGY

To achieve the stated objectives of the project, the research program will consist of a literature review, collection of information and data, analytical and numerical modeling, model development for service life prediction and life cycle costing, and software development. The research project is structured into the following separate, but related five tasks.

- **Task 1- Survey of Rehabilitation Methods**

At the start of the project, information on existing guidelines used for the selection of protection, repair and rehabilitation methods for concrete bridge decks will be collected. In addition, data on the impact of rehabilitation alternatives on the deck condition, rate of chloride ingress, rate of corrosion, service life, and failure mode will be collected. This will be accomplished by searching through industrial databases, source books and trade publications. Bridge owners, consulting firms, and material manufacturers will be contacted to obtain information and collect data on the costs associated with alternative rehabilitation methods. Statistical data on the parameters that govern the service life of protective systems, corrosion initiation time and corrosion propagation time will also be collected. These data include the types of distribution and coefficients of variation of different parameters.

- **Task 2 - Modeling of Impact of Rehabilitation on Service Life**

This includes a systematic parametric analysis of the impact of the different rehabilitation methods (including protection, repair and "Do nothing") on the chloride ingress, corrosion time, and corrosion propagation time.

- **Task 3 - Modeling of Uncertainty in Service Life**

This includes the modeling of the uncertainty in all parameters and models, and formulation of the limit state functions corresponding to corrosion initiation, longitudinal cracking, delamination, and spalling.

- **Task 4- Development of Reliability-Based Service Life Prediction Model**

This model development consists in integrating advanced first order reliability methods or Monte Carlo simulation to predict the service life as formulated in the limit state functions in Task 3.

- **Task 5 - Development of a Life Cycle Costing Model**

This model evaluates all costs associated with each rehabilitation option, which can include the costs of design and construction, costs of approaches, costs of demolition and disposal, and costs to users due to detours, traffic delay, and traffic accidents.

A flowchart of the data needs and integration of the proposed decision support tools is shown in Fig.1. The details of the main tasks are given in the following sections.

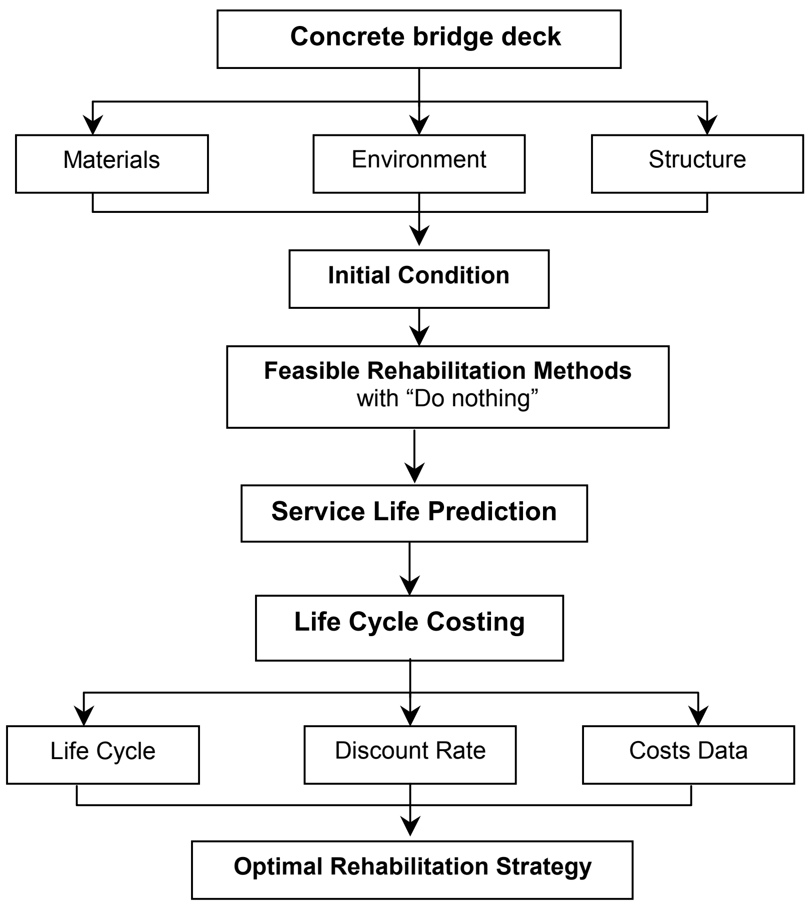

Fig. 1: Flowchart of decision support tools for bridge deck rehabilitation

3. PREDICTION OF SERVICE LIFE OF CONCRETE BRIDGE DECKS

The proposed approach for service life prediction is developed for concrete bridge decks subjected to chlorides from deicing salts. However, the approach can be applied to model the service life under other damage mechanisms. The service life of concrete structures exposed to chlorides can be described by the modified version of Tuutti's two-stage model (Tuutti 1982), as shown in Fig.2, namely:

- Corrosion initiation time, which is the time at which steel is depassivated by the chloride ions that reach the threshold concentration level.
- Propagation period, which corresponds to damage accumulation resulting from increasing loss of reinforcing steel and concrete sections until a limit state is reached.

The initiation of corrosion also defines a limit state, and thus the time to corrosion initiation can be defined as the service life of a structure, assuming the onset of corrosion as the limit state. Figure 2 illustrates the different possible values of the propagation time and service life depending on the definition of the limit state (e.g. onset of longitudinal cracking, onset of spalling, delamination, attainment of maximum acceptable damage).

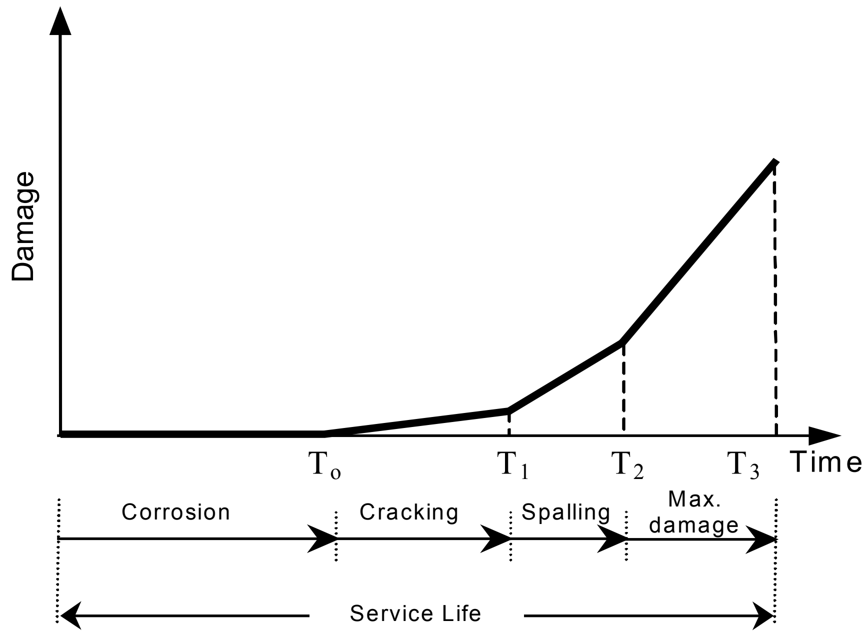

Fig. 2: Service life stages of concrete bridge decks

3.1 Prediction of Corrosion Initiation Time

The corrosion initiation period is defined as the time from initial exposure until chlorides have penetrated the concrete cover, reached the reinforcement and their concentration level is above the so-called 'threshold' needed to start corrosion. The length of the initiation period (T_o) depends on the rate of ingress of chlorides into concrete, surface chloride concentration, depth of concrete cover, and the value of the threshold chloride level. A reliable prediction model for the ingress of chlorides into concrete should consider the complex combination of several transport processes that include diffusion, capillary sorption (absorption of water containing chlorides into unsaturated concrete), and permeation (or water flow in concrete due to a pressure gradient) (Cady and Weyers, 1983; Kropp and Hilsdorf, 1995).

The time-dependent distribution of chloride concentration over the depth of the bridge deck can be obtained from the solution of Fick's second law of diffusion assuming the concrete deck as a homogeneous isotropic semi-infinite medium. For the initial condition C(x,t=0)=0 and boundary condition C(x=0,t) = C_s (constant), the chloride distribution at depth x and time t is given by (Crank, 1975):

$$C(x,t) = C_s[1\text{-erf}(x/2\sqrt{Dt}] \quad (1)$$

where C_s is the chloride concentration at the exposed surface, and D is the diffusion coefficient of chlorides into concrete (also assumed constant).

This widely used simple model has two main shortcomings. First, the diffusion coefficient is not a constant but depends on time, temperature, and depth because of the heterogeneous nature and aging of concrete(Kropp and Hilsdorf, 1995). Second, the top surface of the bridge deck is subjected to a continually changing chloride exposure (Cady and Weyers, 1983). In general, the values of the surface chloride concentration and diffusion coefficient can be estimated from Eq. (1) by determining the best fit curve through experimental data obtained from chloride profiles at different exposure times.

In this project, these shortcomings will be addressed by using a rigorous two-dimensional finite element chloride transport model that considers chloride diffusion, sorption and binding, accounts for the time-dependence of governing parameters, and couples chloride transport with heat and moisture transfer. A systematic parametric analysis of the impact of the different rehabilitation methods on the chloride penetration fronts will be carried out. The results will be used to develop adjustment factors that will be built into Crank' solution to Fick's 2^{nd} law of diffusion for predicting the chloride contamination of the deck.

The length of the corrosion initiation time is controlled by the quality of concrete (permeability, cracking intensity), presence of protective systems (membrane, epoxy coating of reinforcement), depth of the concrete cover, chloride concentration at the surface, and chloride threshold level. The corrosion process is accelerated if there are cracks of significant width (due to drying shrinkage, flexural, or thermal stresses) that allow direct ingress of chlorides, oxygen and moisture, or if the concrete is carbonated, which may also facilitate chloride-induced corrosion.

The time to the initiation of corrosion T_o, is the time when the chloride concentration at the reinforcement level reaches the specified corrosion threshold value. Using Eq. (1) and assuming the same initial and boundary conditions, the time to onset of corrosion is determined as follows:

$$T_o= d_c^2/4D\ [\text{erf}^{-1}(1-C_{th}/C_s)]^{-2} \quad (2)$$

where d_c: depth of concrete cover; D: chloride diffusion coefficient; C_{th}: threshold level of chloride concentration; and C_s: surface chloride concentration. In the literature, there is no consensus regarding the definition of a single value for the threshold chloride level (Kropp and Hilsdorf 1995).

3.2 Prediction of Corrosion Propagation Time

The propagation period is defined as the time from the onset of corrosion until a critical damage level or 'limit state' is reached. These limit states include the serviceability (excessive cracking, delamination, spalling, excessive deformation), and ultimate limit states (e.g. flexural failure, shear failure, punching shear failure). The determination of the propagation time depends on the acceptable risk of failure associated with the different damage levels, minimum performance requirements, functional obsolescence, and cost of repair. For concrete bridge decks, the end of life is generally dictated by the reaching of a threshold level of delamination and spalling of the deck (FHWA, 1995; NY DOT, 1992; MTO, 1988).

The prediction of the times to onset of cracking and spalling of the cover will be based on a combination of a hydraulic-pressure analogy and a fracture mechanics approach, where the concrete cover is treated as a thick-wall cylinder subjected to the internal pressure build-up of expansive corrosion products. The times to onset of cracking and spalling are determined from the times at which the developed stresses exceed the resistance of the cover to cracking and spalling, respectively. The length of these two times depend on the corrosion rate, fracture properties of concrete, cover-to-bar diameter ratio, bar spacing, degree of confinement provided by shear reinforcement, and the level of traffic and/or environmental load (e.g., thermal stresses).

3.3 Impact of Rehabilitation on Service Life of Bridge Decks

The different protection, repair and rehabilitation methods extend the service life of damaged bridge decks by different amounts. Depending on the state of damage of the deck, some rehabilitation methods are more effective than others in slowing down the rate of chloride ingress, increasing the corrosion initiation time, and/or corrosion propagation time, which in turn improves the initial condition of the deck and extends its service life, as shown in Fig.3.

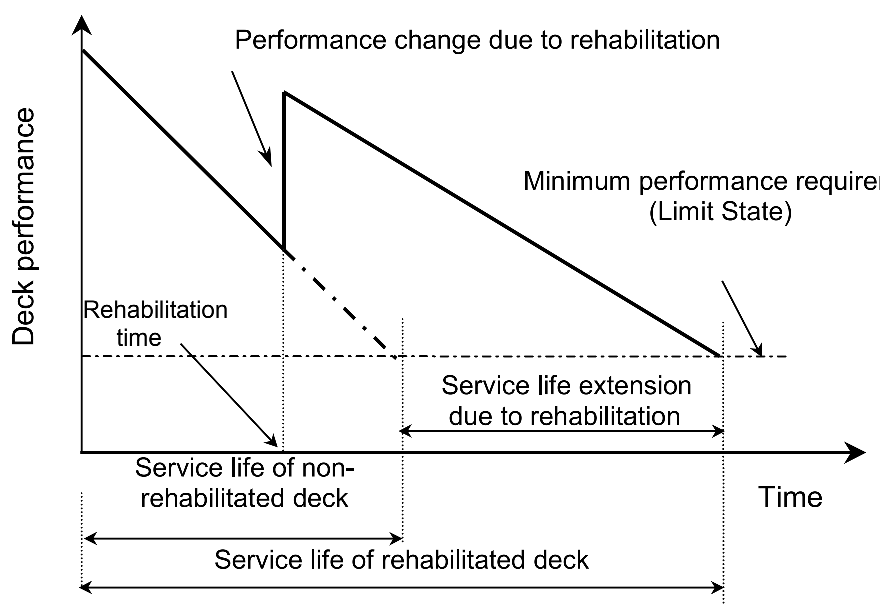

Fig.3: Illustration of the impact of rehabilitation on service life of bridge deck

The modeling of the impact of various rehabilitation methods on the corrosion initiation time will be based on a rigorous two-dimensional finite element chloride transport model. This model will consider chloride diffusion, sorption and binding, accounts for the time-dependence of governing parameters, and couples chloride transport with heat and moisture transfer (Martin-Perez et al., 2001). A systematic parametric analysis of the impact of the different rehabilitation methods on the chloride penetration fronts will be carried out. The results will be used to develop adjustment factors that will be built into Crank' solution to Fick's 2^{nd} law of diffusion for predicting the chloride contamination of the deck.

4. Modeling Uncertainty and Development of Reliability-Based Service Life Model

A considerable level of uncertainty is associated with the assessment of the service life of bridge decks. This uncertainty may be divided into physical uncertainty, statistical uncertainty, model uncertainty, and decision uncertainty. The physical or inherent uncertainty is that identified with the inherent random nature of a basic variable such as: (i) variability of the concrete cover thickness; (ii) variability of the surface chloride concentration and chloride diffusion coefficient; and (iii) variability of the loading from traffic and deck's own weight. The statistical uncertainty arises from adopting a probability density function or estimating statistical parameters from a limited sample size. The model uncertainty results from the use of a simplified physical model or relationship between the basic variables to represent the actual phenomena, such as: (i) use of a simplified form of Fick's diffusion law to model the chloride transport mechanism; (ii) use of simplified chloride threshold level to define the corrosion resistance of concrete structures; and (iii) use of a simplified resistance degradation model in the propagation stage to assess the safety and serviceability of the structure. The decision uncertainty is that associated with the definition of a limit state and acceptable probability of failure, which depends on the risk of loss of life and injury, costs of repair and replacement, redundancy of the structure, and failure mode.

All uncertain parameters in the corrosion initiation time and corrosion propagation time will be modeled as random variables, which will be defined by their statistical distributions and their first two statistical moments. If appropriate data are not available for a bridge deck, default values of the coefficients of variation and statistical distribution models will be provided from the data and information collected in Task 1. From the results of Task 2, the limit states functions corresponding to the times at which specified percentages of the deck area have corroded reinforcement, longitudinal cracking, delamination, and spalling will be formulated. The solution of the problem will be obtained by using advanced first-order reliability methods or Monte Carlo simulation that will be incorporated into the prediction software.

The uncertainties associated with the surface chloride concentration and diffusion coefficient will be considered by modeling them as random variables with probability density functions that are obtained from field measurements of chloride profiles or from the survey analysis. The chloride diffusion coefficient will be determined by fitting the solution of Fick's second law of diffusion to measured chloride profiles expressed in terms of total chloride concentrations (including both free and bound chlorides). Since only the chlorides dissolved in the pore solution (free chlorides) are responsible for the initiation of the corrosion process (Tuutti, 1982; Kropp and Hilsdorf, 1995), this procedure yields only the value of the apparent diffusion coefficient because chloride binding is not taken into account. The probabilistic distribution of chloride concentration at a given depth and exposure time can be generated using Monte Carlo simulation as shown in Fig. 4.

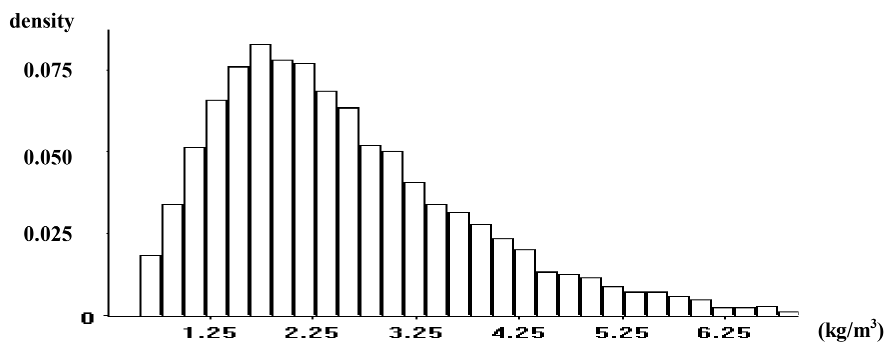

Fig.4 : Example of simulated chloride concentration at steel level (Lounis & Mirza, 2001)

If failure is defined as the onset of corrosion, then the failure probability at time t, is given by:

$$P_f(t) = P[T_o \leq t] = \int_0^t f_{To}(x)dx \quad (3)$$

where $f_{To}(x)$ is the probability density function of time to corrosion initiation, which is generated by Monte Carlo simulation using the probability density functions of D, d_c, and C_s generated from field measurements, or assumed data (including C_{th}) as shown in Fig. 5.

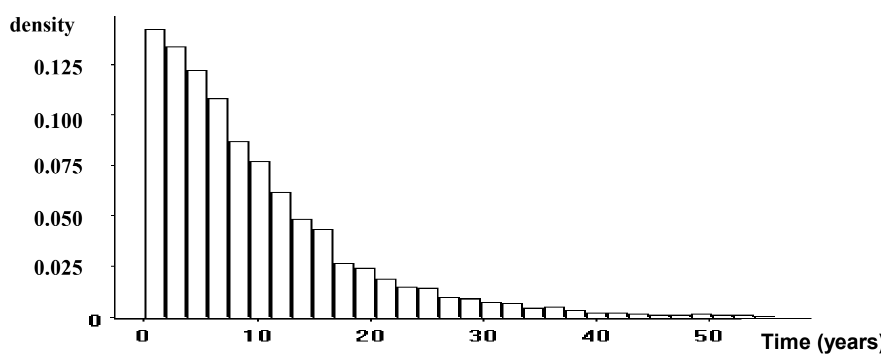

Fig.5: Reliability-based modeling of corrosion initiation time (Lounis & Mirza, 2001)

The proposed software will enable the user to generate the density functions and cumulative distributions of the chloride profiles at different depths, time to corrosion initiation, time to cracking, time to delamination, and time to spalling. The cumulative distributions will provide the times at which different percentages of the deck area have reached the different limit states, including corrosion of reinforcement, longitudinal cracking, delamination, and spalling. Depending on the user's requirements, these times are then used to determine the service life of the bridge deck.

An illustration of the software output is shown in Fig.6, which shows the time-variation of the cumulative distribution of damage for different rehabilitation options. The damage limit state can represent the corrosion of reinforcement, cracking, delamination, spalling, or total damage.

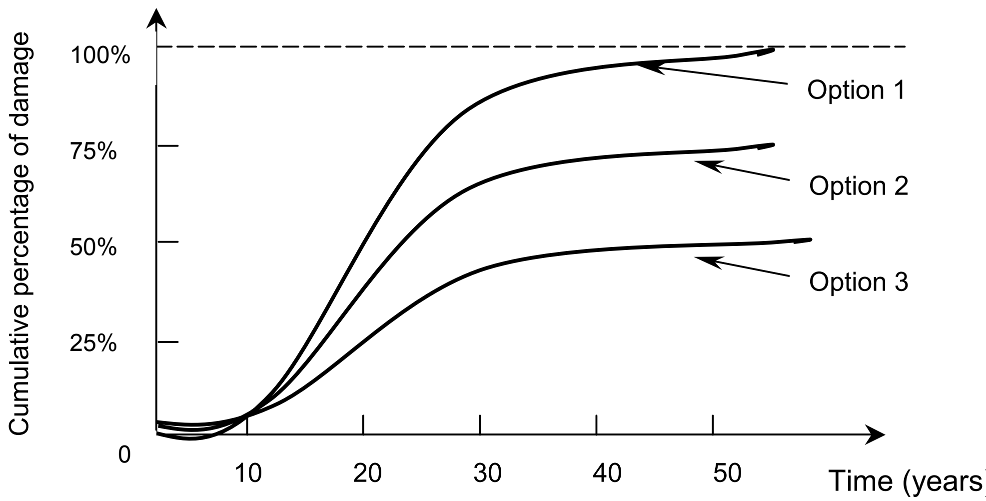

Fig.6: Cumulative damage distribution for different rehabilitation options

5. LIFE CYCLE COSTING MODEL FOR BRIDGE DECKS

The proposed life cycle costing (LCC) model will consider all costs associated with each rehabilitation strategy that can include the costs of design and construction, costs of approaches, costs of demolition and disposal, and costs to users due to detours, traffic delay, and traffic accidents. The proposed software will also enable the user to undertake a probabilistic life cycle cost analysis if there is a high level of uncertainty in the cost data.

The LCC model will use the output of the service life prediction software as one of its main inputs. For the selected rehabilitation strategies, the LCC software will determine the present values of their total life cycle costs by using a user-provided discount rate. To account for the difference in residual life of different rehabilitation methods at the end of the life cycle, the software will consider the residual value in the present life cycle cost. The software will then provide a ranking of the rehabilitation strategies in terms of their present value of their life cycle costs.

6. CONCLUSIONS

This paper presented an overview of a proposed project to develop decision support tools for the rehabilitation of aging concrete bridge decks. The proposed tools consist of a reliability-based approach for modeling the service life of concrete structures. The approach will take into account the uncertainties in the physical modeling, and variability of the material and structural parameters affecting the corrosion process, in addition to the statistical and decision uncertainties. The proposed reliability-based service life prediction model will overcome the shortcomings of existing deterministic life prediction models. The implementation of such tools will provide better predictions of the impact of different rehabilitation strategies (including the "do nothing" option) on the condition and service life of the bridge decks and their life cycle costs. This in turn will result in an effective allocation of maintenance funds. The proposed tools will enable bridge owners and decision-makers to select cost-effective rehabilitation strategies that will extend the life of highway bridges and will reduce the life cycle costs.

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