Life-365 Service Life Prediction Model

Program helps engineers, owners, and contractors choose the right corrosion protection system

BY BRAD VIOLETTA

Fig. 1: Corrosion-induced damage in a concrete structure

Chlorides from deicing salts, groundwater, and seawater corrode steel reinforcement embedded in concrete, causing the most common form of concrete deterioration. Each year, billions of dollars are spent on infrastructure repair and replacement because of corrosion damage (Fig. 1). Much of this damage can be avoided by using corrosion protection systems such as low-permeability concrete, high-performance concrete, corrosion-inhibiting admixtures, epoxy-coated steel reinforcement, corrosion-resistant steel reinforcement, waterproofing membranes or sealants, or combinations of the previously mentioned methods and materials.

Because each of these corrosion protection systems has technical merits and costs, the best way to select the optimum strategy is to perform a life-cycle cost analysis (LCCA), which weighs the increased initial costs of a system against the potential extension of service life of the structure. In the past few years, a number of computer-operated LCCA models have been developed, each with a different approach, so the results from each model varied considerably. This caused concern and confusion within the engineering community regarding the effectiveness of the various corrosion protection systems.

COLLABORATIVE RESEARCH AND IMPLEMENTATION

In May 1998, ACI's Strategic Development Council (SDC) identified the need to develop a "standard (LCCA) model." The SDC and ACI also recommended that a workshop be held to investigate solutions to the confusion in the industry caused by lack of consistent LCCA modeling techniques. In November 1998, the National Institute of Standards and Technology (NIST), ACI, and ASTM sponsored such a workshop, entitled "Models for Predicting Service Life and Life-Cycle Cost of Steel-Reinforced Concrete." At this workshop, a decision was made to begin the development of an LCCA model based on industry consensus.

To expedite the model's development, a consortium was established under the SDC to fund the development of the computer model. Members of this consortium were Master Builders, Inc. (Brad Violetta and Matt Miltenberger), Grace Construction Products (Timothy Durning and Neal Berke), the Silica Fume Association (Terence Holland), and the University of Toronto (Michael Thomas and Evan Bentz). Contributing members of the consortium included NIST, the National Ready-Mixed Concrete Association (NRMCA), ACI, and the Concrete Corrosion Inhibitors Association (CCIA).

Life-365 is the resulting service life and LCCA computer model developed by the consortium. Prior to the release of Life-365 to the concrete industry, over 20 beta testers volunteered to evaluate the program in practice. In a true collaborative effort, the beta testers recommended to the consortium changes that would make the program more valuable to the design community.

The consortium released Version 1.0, free of charge, to the concrete construction industry in October 2000. Life-365 is the first industry-sponsored computer model that engineers can use to help design better corrosion-resistant reinforced concrete structures. Life-365 provides the owner with information on alternatives and costs regarding concrete durability and increased service life.

Collaboration of the consortium went well beyond the development of Life-365. The consortium created and implemented a comprehensive introduction plan that included awareness and program training. Seminars were conducted across the United States, Canada, Puerto Rico, and South America to ensure that design engineers understood the intricacies of Life-365.

INNOVATIVE TECHNOLOGY

Life-365 is used to predict the time to the onset of corrosion, and the time for corrosion to reach a level requiring repair. Life-365 can then estimate costs over the entire design life of a structure, including initial construction costs and predicted repair costs.

Life-365 requires the following general user inputs for each project:

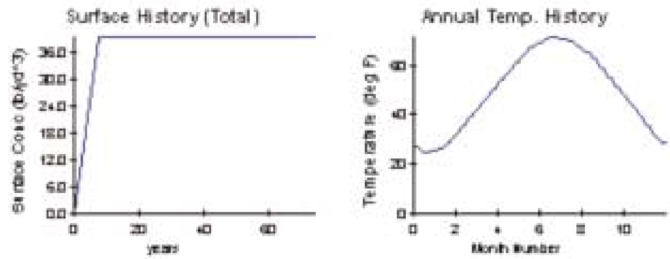

Fig. 2: Life-365 automatically determines temperature profiles (right) and surface chloride concentration profiles (left) for the geographic location of the structure. These graphs are for a structure located in Cleveland, OH

- Geographic location;
- Type of structure and nature of exposure, one-dimensional (parking or bridge deck) or two-dimensional (marine pile) model;
- Depth of clear concrete cover to the reinforcing steel; and
- Details of each corrosion protection strategy scenario such as water-cementitious material ratio (*w/cm*); type and quantity of fly ash, ground-granulated slag, silica fume, or corrosion inhibitors; type of steel, uncoated or coated; and presence of membranes or sealers.

Environmental conditions based on geographic location

Using a database compiled from meteorological data, Life-365 determines annual temperature profiles based on the geographic location of the structure. For example, if a user selects Cleveland, OH, the model would use the temperature profile for that location (Fig. 2, right).

The model determines a maximum surface chloride concentration and the time taken to reach that maximum based on the type of structure, its geographic location, and the exposure conditions. For example, if a user selects a bridge deck in an urban area of Cleveland, the model would automatically use the surface-chloride-concentration profile on record for that area (Fig. 2, left).

Time to concrete damage from corrosion

The analyses carried out within Life-365 can be split into four separate steps as follows:

1. Predicting the time to the onset of corrosion, commonly called the initiation period t_i;
2. Predicting the time for corrosion to reach an unacceptable level, commonly called the propagation period t_p. The time to first repair t_r is the sum of these two periods: $t_r = t_i + t_p$;

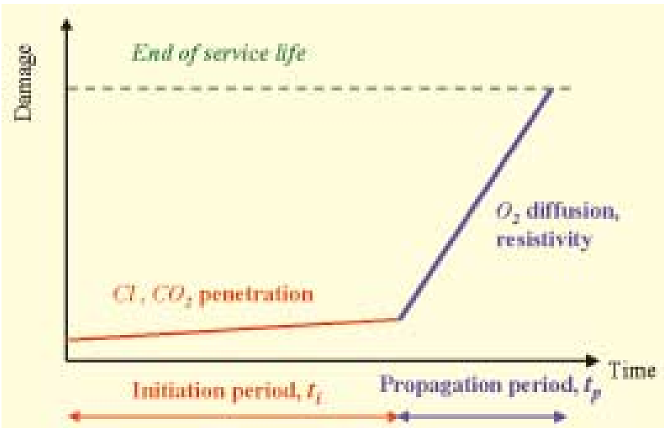

Fig. 3: Life-365 estimates the time it takes for a structure to reach the end of its service life. The initiation period t_i is the time it takes for chlorides to penetrate the concrete cover and accumulate at the reinforcement. The propagation period t_p is the time it takes for corrosion to reach an unacceptable level

3. Determining the repair schedule after the first repair throughout the design life of the structure; and
4. Estimating life-cycle costs based on the initial concrete costs, corrosion protection system costs, and future repair costs.

The initiation period t_i defines the time it takes for chlorides to penetrate the concrete cover and accumulate at the location of the embedded steel in a sufficient quantity to break down the protective passive layer on the steel, initiating an active state of corrosion (Fig. 3). The length of this period is a function of the concrete quality, depth of cover, exposure conditions (including the level of chloride at the surface and the temperature of the environment), and the threshold chloride concentration C_t required to initiate corrosion. A simple approach used to predict the initiation period is to assume that ionic diffusion is the mechanism of chloride transport and to solve Fick's second law of diffusion.

The propagation period t_p defines the time necessary for sufficient corrosion to occur to cause an unacceptable level of damage to the concrete structure or element under consideration (Fig. 3). The length of this period depends not only on the rate of the corrosion process, but also on the definition of "unacceptable damage." This level of damage will vary depending on the requirements of the owner and the nature of the structure. A large number of factors—including the nature of the embedded metal, properties of the surrounding concrete, corrosion protection systems, and environmental conditions—influence the corrosion rate.

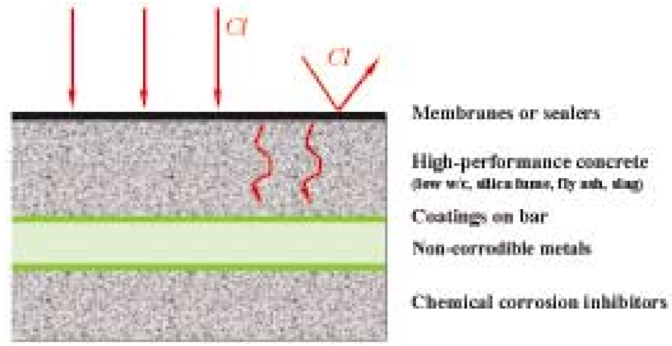

Fig. 4: There are multiple methods available to protect concrete from corrosion damage

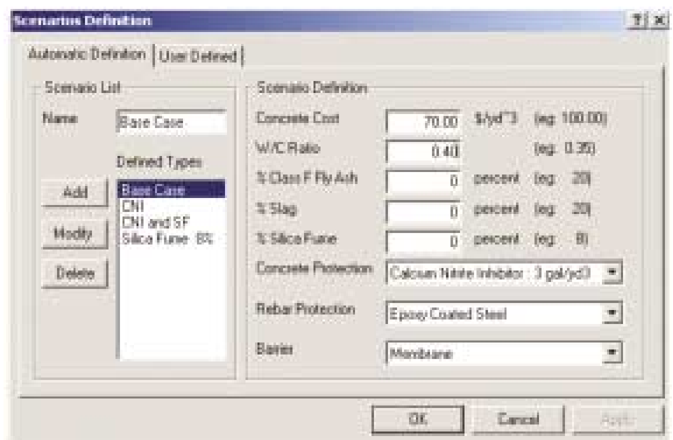

Fig. 5: Life-365 allows the user to analyze several corrosion protection methods at once

Methods of corrosion protection

A variety of methods can protect steel embedded in concrete from corrosion (Fig. 4). Membranes and sealers prevent chloride from entering the concrete. Greater concrete cover increases the distance chlorides need to travel. Low *w/cm* and admixtures such as silica fume, fly ash, and slag reduce the permeability of concrete, limiting the ability of chlorides to migrate to the steel. Epoxy coating on the reinforcing steel provides a barrier against the chlorides. Corrosion-inhibiting admixtures increase the amount of chloride needed at the reinforcing steel to induce corrosion.

Life-365 allows the designer to analyze various individual corrosion protection systems (Fig. 5). An innovative aspect of Life-365 is that it also allows the user to analyze multiple combinations of corrosion protections systems. For example, the combination of silica fume, a corrosion inhibitor, and epoxy-coated steel could be compared to a lower water-cement ratio (*w/c*), additional concrete cover, and a membrane.

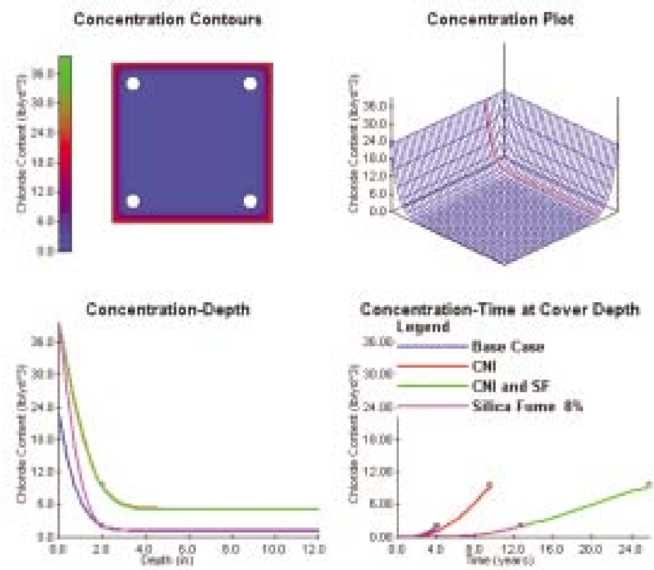

Fig. 6: Results of an analysis of a marine pile involving chloride penetration from two directions. The complete cross section through the pile (top, left); the chloride concentration in two dimensions (top, right); the chloride profile at the time of initiation of corrosion (bottom, left); and the rate of chloride accumulation at the reinforcement prior to the corrosion threshold (bottom, right)

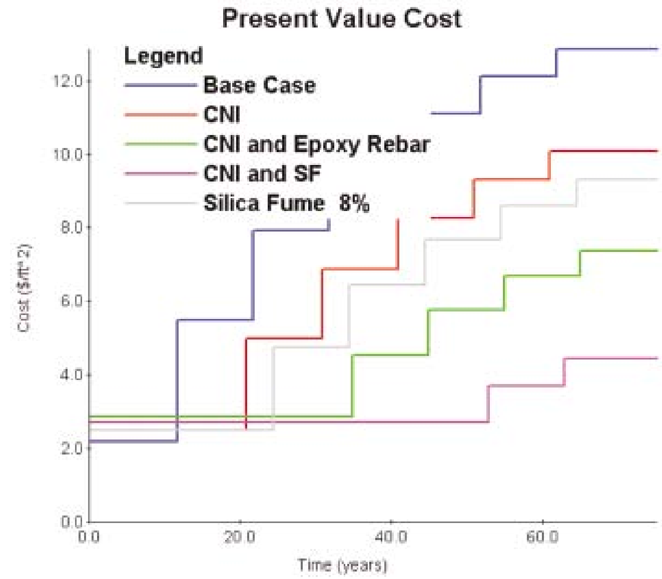

Fig. 7: Total life-cycle costs as the sum of initial construction costs and discounted future repair costs over the life of the structure for several corrosion-protection methods

Engineering analysis

Life-365 calculates chloride ingress information for the various corrosion protection scenarios. This is particularly useful when analyzing cases involving chloride penetration from two directions such as a square marine pile (Fig. 6).

The plot at the top left of Fig. 6 shows a complete cross section through the pile, the location of the reinforcing steel, and a chloride concentration plot (at the time of corrosion initiation). The example shown is a 24-in.-pile (600 mm) with 2 in. (50 mm) of clear concrete cover. The plot at the top right of Fig. 6 depicts the chloride concentration in two dimensions and demonstrates how the bar with 2 in. (50 mm) of cover is influenced by chloride ingress from the two orthogonal faces. The plot at the bottom left of Fig. 6 shows the chloride profile (pounds of chloride per yard at different depths) at the time of initiation of corrosion. The plot at the bottom right of Fig. 6 illustrates the rate of chloride accumulation at the reinforcing steel up to the point at which the corrosion threshold is reached (C_t = 0.05% for the base case and C_t = 0.12% for the concrete containing corrosion inhibitor).

Life-cycle cost analysis

The total life-cycle costs are calculated as the sum of the initial construction costs and the discounted future repair costs over the life of the structure (Fig. 7). Initial construction costs are simply the cost of the concrete (including corrosion protection systems), the cost of the reinforcing steel, and cost of any surface protection (membrane or sealer). Life-365 expresses these costs on the unit area of the structure (for example, $/ft^2). Future repair costs (as represented by the step functions in Fig. 7) are calculated on a "present worth" basis using the discount rate provided by the user. Life-365 calculates all predicted future repair costs over the entire design life of the structure in this manner and adds them to the initial construction costs to give the total life-cycle cost.

IMPACT ON CONSTRUCTION INDUSTRY PERFORMANCE

The capabilities of Life-365 have been demonstrated to thousands of engineers since its release in October 2000, and the feedback has been extremely positive. Design engineers now are using Life-365 as a tool to convince owners of a greater initial investment in corrosion protection systems that will dramatically extend service life and save the owner money over the structure's design life.

The Maryland State Highway Administration (MSHA) recently completed construction of a high-performance concrete bridge on Route 64 in Washington County, MD. A unique feature of this bridge is that MSHA designed it to provide a service life of 75 years. Using Life-365, specifiers determined that if the deck was constructed using current specifications, corrosion could be expected to initiate at age 13 years. Adding epoxy coating on the reinforcing steel would inhibit corrosion for 25 years. Use of high-performance concrete increased the time to corrosion initiation to 50 years. Combining the epoxy coating and the high-performance concrete dramatically extended the service life of the bridge, with the expected first significant repair estimated at an age of 75 years.

Using data generated from the computer program, specifiers on the Route 64 bridge insisted on epoxy coating the steel reinforcement and employing a calcium nitrite corrosion-inhibiting admixture at 2.0 gal./yd^3 (10 L/m^3) to inhibit chloride-induced corrosion. A low *w/cm* and ground-granulated blast-furnace slag were used to provide resistance to the ingress of chlorides and other deleterious substances.

Joseph Faye Co. constructed the bridge and Thomas Bennett Hunter, Westminster, MD, furnished the concrete. The ACI Maryland Chapter recognized the bridge with an award for excellence in concrete construction.

Life-365 also permits modeling of various elements in a single structure and, thus, the use of the most cost-effective protection options for the desired service life in the region of interest. In the past, a typical recommendation to combat reinforcement corrosion in piles and wharf structures in Southern California and elsewhere has been the use of 4.5 gal./yd^3 (22 L/m^3) of calcium nitrite corrosion inhibitor, regardless of the precise nature of the chloride exposure—splash zone, spray, or airborne chlorides. While this inhibitor dosage may be appropriate for piles that are subjected to significant splashing, it is often far in excess of the dosage actually needed in structural members with less-aggressive chloride loading.

In an example featuring a marine wharf located in San Diego with a design life of 40 years, two different elements were modeled: a slab with 2-1/2 in. (65 mm) of concrete cover exposed to airborne chlorides and a prestressed concrete pile with 3 in. (75 mm) of concrete cover directly exposed to chlorides in the tidal zone.

For the base case, which Life-365 assumes to be a concrete mixture containing no corrosion-inhibiting admixtures, Life-365 predicted corrosion initiation of the slab (one-dimensional chloride ingress) within 10 years and 4.5 years for the pile (two-dimensional chloride ingress). The addition of 4.5 gal./yd^3 (22 L/m^3) of a calcium nitrite inhibitor to the concrete mixture increased the times to corrosion initiation to 90 and 22 years for the slab and the pile, respectively. Here, designers could deduce that 90 years was clearly an overdesign for the slab.

A Life-365 analysis showed that 2 gal./yd^3 (10 L/m^3) of the calcium nitrite inhibitor increased the time to initiation to 34 years, resulting in a time-to-first-repair of 40 years in the slab, at a considerable cost savings to the owner.

FUTURE OF LIFE-365

Life-365 has been in use for approximately 2 years. Based on feedback from designers, the consortium made upgrades to Life-365 and released Version 1.1 in December 2001, again at no cost to the industry.

Ownership of Life-365 will eventually be transferred to ACI. During the interim, ACI Committee 365, Service Life Prediction, has begun preparations to accept responsibility for Life-365. At a recent meeting, the subcommittee unanimously recommended that ACI 365: 1) use Life-365 as example software to accompany their guide document; and 2) assume responsibility for future development of the Life-365 program.

The Silica Fume Association, Concrete Corrosion Inhibitors Association, National Ready-Mixed Concrete Association, and the Slag Cement Association have formed a second consortium to fund updates to Life-365, continue the implementation of an industry awareness and training plan, and help define standardized test procedures for the creation of input parameter data for Life-365.

Life-365 Service Life Prediction Model is a truly innovative computer software program, developed under an industry-wide consortium that brings significant value to the industry through the construction of economically durable concrete structures.

Portions of this article are from the Life-365 Users' Manual.

Selected for reader interest by the editors.

—Master Builders, Inc.
CIRCLE 61

Brad Violetta is Director of Marketing for Master Builders, Inc. He has more than 21 years of technical and marketing experience in the ready-mix concrete, precast concrete, and masonry industries. Violetta is a member of ACI Committees 212, Chemical Admixtures, and 309, Consolidation of Concrete. He serves as a member of the Board of Directors of the NRMCA–Materials Division and the CCIA.