Data-Driven Approaches for Optimizing Concrete Bridge Deck Preservation

by Stephen Garrett, Marwa Abdelrahman, and Mohamed ElBatanouny

Fig. 1: Bridge Engineers performing in-depth assessment of a reinforced concrete bridge deck (photograph by WJE)

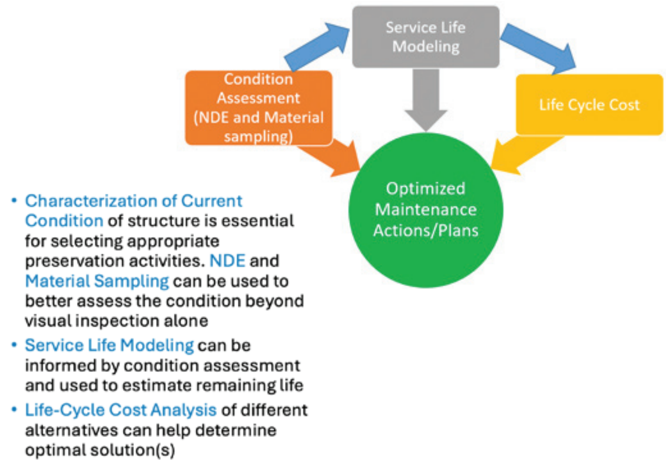

Fig. 2: Conceptual framework for use of condition assessment data, combined with service life and life cycle cost analyses to select optimized maintenance actions or plans

INTRODUCTION

Service disruptions associated with maintaining and upgrading aging infrastructure systems are costly to transportation agencies and burdensome to the public. Engineers and asset managers responsible for maintaining bridge performance are tasked with determining inspection needs and selecting strategies to provide optimal value to the end users of these critical systems. To this end, implementing data-driven inspections and condition assessment practices can increase the knowledge base for decision-making, reducing decision risks and life-cycle costs (Figure 1).

Recent trends in advanced assessment techniques have endeavored to minimize traffic disruptions by performing inspections using rolling lane closures with rapid assessment tools. Certainly, there is value added by performing routine assessments without significant operational disturbances; however, a more accurate understanding of the structure's condition gained through hands-on, advanced assessment techniques can then inform service life modeling, which combined with engineering judgment can offer insight into alternative repair strategies and ultimately the optimal course of action for a given structure (Figure 2).

CURRENT STATE OF PRACTICE FOR REQUIRED INSPECTIONS

In the United States, highway bridge inspections have been standardized with the National Bridge Inspection Standards (NBIS) framework. The NBIS framework guides inspectors and agencies in performing and interpreting bridge conditions from a holistic and elemental level (Figure 3).

Through the routine NBIS inspection framework, bridge deck assessment techniques typically include visual assessments to identify cracking, delaminations, spalls, and other deterioration mechanisms. Quantification of these conditions factors into the overall condition rating for a structure. Inspections also provide a normalized basis for asset-level decision-making. The Federal Highway Administration (FHWA) states that the NBIS inspection data *"is necessary for bridge owners to make informed investment decisions as part of an asset management program."*[1] The inspection results include both the general condition ratings of the component and the element-level inspection data.

Fig. 3: Bridge Inspection Engineer performing routine inspection of a bridge deck

Beyond the conventional NBIS framework, there are a variety of advanced assessment techniques and data analysis tools available. This article introduces some of these methods.

ADVANCED NDE AND MATERIAL TESTING

Concrete bridge decks are susceptible to several deterioration mechanisms including cracking, corrosion of reinforcing steel, overlay debonding, and abrasion. The goal of advanced bridge deck assessments is to gather pertinent information to formulate a service life model and predict the future performance of the structure with and without maintenance or rehabilitation intervention. Beyond visual inspection, various non-destructive evaluation (NDE) inspection methods can yield useful condition data. These NDE methods are not explicitly mandated by the federal government as implementation and interpretation of data can be a burden to owners. Nonetheless, many agencies elect to collect data beyond visual inspections, utilizing techniques like sounding (Figure 4), cover surveys, and material testing.

Fig. 4: Example of a bridge deck with previous repairs, cracks, and delaminations identified from visual inspection and conventional chain-drag sounding techniques

Emerging NDE technologies are being adopted to assess bridge deck conditions and include rapid, cart- or vehicle-mounted scanning systems equipped with high-resolution cameras, infrared cameras, radar equipment, and even acoustic-sounding technologies. Rapid scanning techniques reduce traffic disruptions, but their accuracy can be limited without calibration through destructive or semi-destructive means. Ultimately, some level of hands-on inspection utilizing lane closures is prudent for an accurate in-depth assessment.

Chloride-induced corrosion is a common deterioration mechanism and the service life of concrete bridge decks located where deicing salts are used or in marine or brackish environments is typically controlled by chloride-induced corrosion, resulting in cracking and delamination of the concrete cover in bridge decks. A variety of corrosion evaluation techniques can be utilized including half-cell potential testing (Figure 5), electrical surface resistivity (Figure 6), and corrosion rate measurements. Corrosion surveys are especially effective when a baseline condition assessment

Fig. 5: Half-cell potential survey of a bridge deck

Fig. 6: Surface resistivity survey of a bridge deck

has been performed through conventional assessment techniques, followed by an evaluation of corrosion risk which adds further context to these findings. The nature of the corrosion reaction is such that active corrosion can occur in regions that have not yet propagated damage, and thus corrosion potential maps offer a future view of damage progression. Half-cell potential maps of a bridge deck, for example, can indicate areas of corrosion risk beyond what can be identified through sounding (Figure 7).

Another important aspect of advanced bridge deck surveys is combining material sampling and laboratory testing with field findings. Core drilling not only offers a means of creating inspection openings to calibrate and verify NDE findings, but the core samples can be evaluated for chloride concentration and material degradation using laboratory techniques. As discussed below, chloride concentration profiles can be used to determine the concrete's resistance to chloride ingress as well as assess the risk for corrosion-related damage progression.

SERVICE LIFE MODELING AND LIFE CYCLE COST

Service life modeling is an essential tool for optimizing preservation and rehabilitation plans for existing reinforced concrete bridge decks. Modeling of future performance can

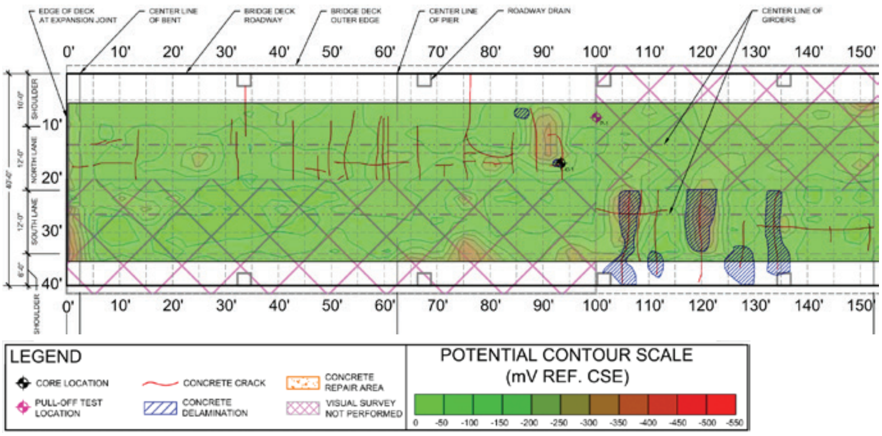

Fig. 7: Results from sounding and corrosion surveys showing observed damage and measured corrosion potentials

valuable tool to accurately quantify areas affected by corrosion activity and areas of delamination (especially with deep concrete covers), which in return enables accurate calibration of model inputs affecting the corrosion initiation and propagation times, respectively. An example of this process from a bridge investigation in Iowa is shown in Figure 8, where model predictions of the percentage of surface area affected by corrosion initiation and corrosion damage at the current age were verified against findings of half-cell potential and sounding surveys, respectively.

effectively evaluate the remaining service life, guide repair decisions, and most importantly inform the timing of those repairs.

Modeling corrosion-related damage is needed to predict the behavior of bridges exposed to deicer salts or in marine environments. This process involves predicting the development and progression of corrosion-related damage based on various influencing factors such as the exposure conditions, concrete properties, type of reinforcing steel, as-built cover, width, and frequency of cracks, and the presence and effectiveness of existing protective measures. The accuracy of predictions is significantly improved by careful evaluation of past performance data (if available) and current conditions, achieved through comprehensive field investigations with in-depth field assessment and laboratory testing of material samples to inform the service life model parameters.

Several modeling approaches are available for predicting corrosion in reinforced concrete, including deterministic and probabilistic approaches. The deterministic approach is defined by ACI Code-365-24 *Service Life Evaluation—Design Specification* as design based on characteristic input parameter values to provide a single output value, while the probabilistic modeling approach is designed based on consideration of input parameter values described by statistical distributions which is typically interpreted by evaluating the output at a certain level of reliability. Probabilistic modeling provides the advantage of incorporating the inherent variability of concrete properties and construction, by defining the input parameters with statistical distributions that best characterize the collected field data.[2] This approach is used to predict the amount of concrete surface area affected by corrosion-related damage with time and recognizes that corrosion is a local process that can develop at multiple locations on the structure. A reliable model is calibrated to accurately reflect the actual circumstances and exposure conditions of the modeled structure. Additionally, model predictions should be verified by evaluating the predicted damage at the current age relative to the currently observed distress quantified during the field investigation. NDE is a

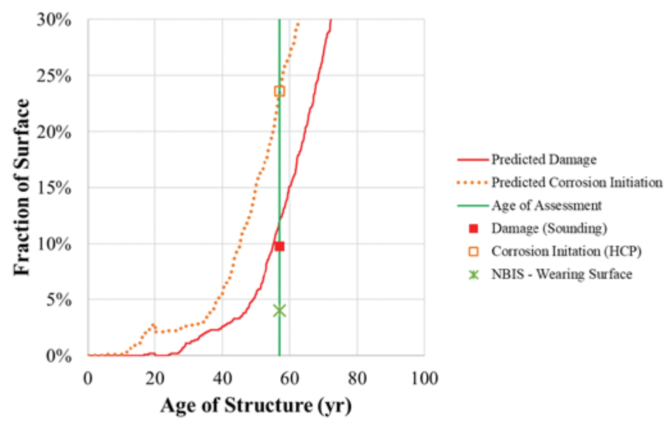

Fig. 8: Data fusion of field and service life modeling data to verify model predictions of corrosion initiation and damage propagation rates

Once the future performance has been estimated, different preservation or rehabilitation options and their respective impact on future performance can be explored (Figure 9). For example, the impact of surface and crack sealing can be compared to overlay installation/replacement. Modeling of the impacts of these options provides insight into the respective service life extensions and whether they achieve owner objectives. The cost associated with each of the preservation/rehabilitation options versus the service life extension benefits can be evaluated through a life cycle cost analysis to select the cost-optimal approach that achieves the project objectives.[3] Rehabilitation plan alternatives, each consisting of a series of preservation activities over the bridge's life span, can also be explored for long-term planning and efficient allocation of resources (Figure 10). This process of informed repair decision-making facilitates proactive and cost-effective management strategies.

APPROACHES FOR BRIDGE DECK PRESERVATION, MAINTENANCE, AND REHABILITATION

The NBIS framework is intended to ensure inspectors remain focused on the safety of traveling public on highway bridges. However, these limited data are often used by state Departments of Transportation (DOTs) and other agencies to determine required preservation activities to keep a bridge

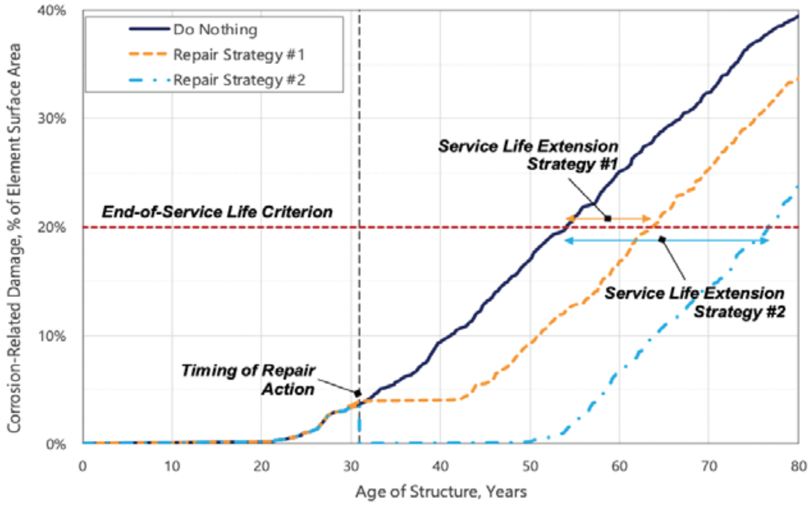

Fig. 9: Example of service life modeling projections considering different repair strategies

deck in good or fair condition. Preservation, as defined by the Federal Highway Administration (FHWA), involves actions that prevent, delay, or reduce deterioration, restore existing bridges' function, and extend their service life.

Guidance for selecting preservation activities is available. Many state DOTs implement preservation policies or preventive maintenance programs and have associated manuals, guides, or decision matrices for local engineers and bridge owners. Federal and national-level organizations have also developed several resources to help bridge owners make informed maintenance decisions, including the Guide to Bridge Preservation Actions and the Guide to Preservation of Highway Bridge Decks.[4,5] More recently, state DOTs and FHWA are funding research to develop an interactive decision-making aide that can be tailored to bridge-specific scenarios for practitioners.[6]

While the available resources aid in the selection of appropriate preservation and maintenance activities for common bridges in our transportation systems, more complete data will better inform these decisions. This is especially true for critical and signature bridges, which represent a fraction of our bridge inventory but can have a significant impact on the functionality of the transportation network. For such bridges, the risk of making less-than-optimal repair decisions based on limited data significantly outweighs the cost of obtaining additional NDE data and completing structure-specific service life modeling and life cycle cost analyses.

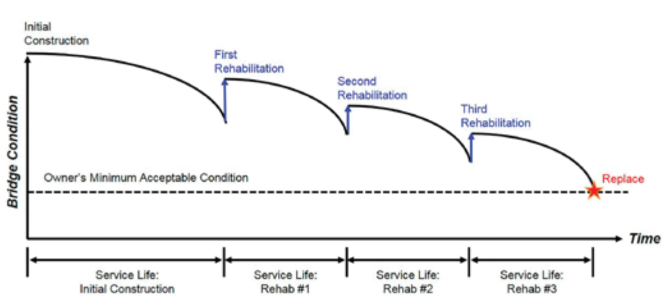

Fig. 10: The life cycle of a long-term bridge rehabilitation program[7]

CLOSING

Given the extensive transportation networks and constrained resources for preservation and maintenance efforts, transportation agencies face the challenge of finding cost-effective asset management strategies. Commonly, a "worst first" approach prioritized addressing bridge decks in the worst condition, but this sometimes allowed newer bridges to deteriorate prematurely. More effective strategies, now focus on preserving bridges in good condition, thereby extending their service life and reducing total life cycle costs. To enhance decision-making, many states developed their policies or utilize bridge management software, which stores detailed inspection reports and condition assessments.

The use of advanced NDE techniques and material sampling can provide more detailed and accurate information to assess the condition of bridge decks. Service life modeling further provides insight into the future performance of a given bridge deck. These methods can then be used to provide structure-specific data-driven comparisons between different preservation and maintenance strategies allowing bridge owners to make better informed decisions. Investing in a more complete understanding of the structure can significantly reduce the repair-selection risks and associated life-cycle costs of maintaining the bridge, especially for critical and signature bridges.

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Stephen Garrett is a Senior Associate and Professional Engineer at Wiss, Janney, Elstner Associates in Northbrook, IL. He has over 10 years of experience in condition assessment and nondestructive evaluation, corrosion evaluation and mitigation, field and laboratory testing, service life and durability evaluations, and repair/rehabilitation design, particularly for reinforced concrete structures and bridges. In addition to his professional practice, Mr. Garrett is an active voting member in ICRI 210 and 510, and currently serves as the Chair of ICRI 160. He received his BS and MS in Civil Engineer at University of Illinois at Urbana-Champaign, is a licensed Professional Engineer in multiple states, and holds a NACE CP-3 Cathodic Protection Technologist (CP3) certification.

Marwa Abdelrahman is a Senior Associate at Wiss, Janney, Elstner Associates with ten years of experience in concrete durability. She worked on various projects involving condition assessment of in-service structures, concrete durability, and service life modeling of existing and new construction. These projects included a variety of existing bridges, industrial ports, and other infrastructure. Dr. Abdelrahman contributed to several research projects involving remediations for bridge deck cracking, preservation and maintenance planning, and concrete durability for many notable organizations, such as Federal Highway Administration (FHWA) and several Departments of Transportation. She received her MS and PhD in civil engineering at the University of South Carolina. She currently serves as the secretary of ACI 365 Service Life Prediction and an active voting member of ACI 222 Corrosion of Metals in Concrete and holds a NACE Cathodic Protection Technician (CP2) certification.

Mohamed ElBatanouny is a Senior Associate and Unit Manager at Wiss, Janney, Elstner Associates with over 15 years of experience in evaluation of in-service structures, repair and rehabilitation design, nondestructive evaluation and instrumentation, and bridge engineering. He is the Committee Research Coordinator (CRC) for TRB Committee AKT60 "Standing Committee on Bridge Preservation" and holds leadership roles in several ACI committees related to structural evaluation, repair, and load testing. Dr. ElBatanouny has managed and served on numerous sponsored research projects funded by the Iowa Highway Research Board (IHRB) and FHWA funded research. He has authored over 60 publications including four book chapters and has presented numerous lectures on bridge preservation/maintenance and asset management, concrete material degradation, structural evaluation, load testing and nondestructive evaluation. Dr. ElBatanouny received his MS and PhD in civil engineering at the University of South Carolina and is a licensed Structural/Professional Engineer in multiple states.