TECHBRIEF

Linking NDE Data and Bridge Deck Performance

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INTRODUCTION

Bridge deterioration is currently studied almost exclusively by either direct observation of the operating bridge performance using visual inspection (VI), nondestructive evaluation (NDE), and structural monitoring (SM), among others, or conducting material-level tests of small-scale specimens. Unfortunately, neither of these approaches has generated the type of objective, quantitative, reliable, and, more importantly, timely information on long-term bridge performance needed to implement modern data-driven asset management systems.

Accelerated full-scale testing of bridge systems provides a key solution to overcome existing limitations and rapidly achieve a comprehensive understanding of bridge performance. Accelerated testing is perceived by the industry as a complement to both field observations and material-level tests, thereby filling a crucial gap in the current understanding of bridge performance and deterioration.

In 2021, the Federal Highway Administration (FHWA) completed accelerated testing of an untreated bridge deck specimen at the Bridge Evaluation and Accelerated Structural Testing (BEAST®) facility (figure 1), at Rutgers University in Piscataway, NJ. FHWA funded this project through the Long-Term Bridge Performance Program. The research aimed to study the performance of full-scale bridge decks under accelerated aging and loading conditions. The research team at Rutgers University collected a comprehensive set of NDE data, visual observations, and material data from the test specimen, which served as the foundation for this study.

Figure 1. Photos. BEAST facility at Rutgers University, Piscataway, NJ.

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Research Synopsis

The research team of the present study thoroughly studied accelerated testing data to demonstrate how NDE data are analyzed and interpreted to enhance understanding of bridge deck performance. The study included a reliability analysis of the NDE data collected, integration of NDE data with conventional condition assessment data, and an examination of the use of NDE data in various data-driven deterioration and service life models.

FHWA also hosted a nationwide webinar showcasing the research results for NDE technology and application developers, State departments of transportation, contractors, consultants, and other practitioners (Azari, Nejad, and Washer 2024).

Research Objectives

The primary goal of this study was to investigate appropriate use of NDE data to enhance the understanding of bridge deck performance. The research objectives included the following:

- The assessment of the quality and reliability of NDE data collected during accelerated aging of an untreated, bare concrete bridge deck.
- The development of a methodology to integrate NDE data with other condition data, such as component-level condition rating (CR) and element-level condition state (CS) data.
- The development of data-driven deterioration models and mechanistic service life models.

RELIABILITY ASSESSMENT OF NDE DATA

The team analyzed the NDE data collected at 14 intervals during the accelerated testing. The cumulative live-load cycles, brine solution application levels, and freeze–thaw cycles that occurred over each interval were also recorded. The NDE methods used to assess bridge deck conditions included the following:

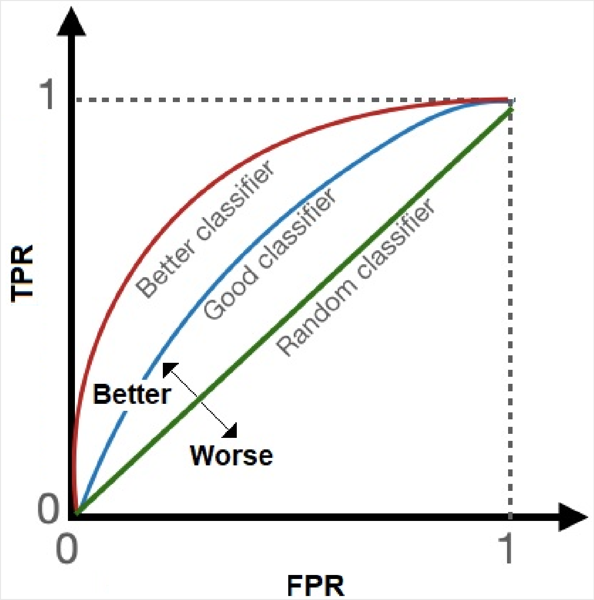
- Impact echo (IE).
- Half-cell potential (HCP).
- Ground penetrating radar (GPR).
- Electrical resistivity (ER).
- Ultrasonic surface wave (USW).
- Infrared thermal imaging (IRT).

NDE methods were categorized as predictive NDE (PNDE), which included ER, GPR, and HCP, and defect NDE (DNDE), which included IE, USW, GPR cover, and IRT. High-definition images of the deck surface were also captured at each interval. The reliability analysis of NDE data incorporated time-lapsed analyses, chronological comparison studies of NDE methods, detailed evaluations of each technology’s effectiveness through NDE condition indexing, and receiver-operator characteristic (ROC) analysis, which is briefly discussed in the following subsection.

ROC

ROC analysis provides significant insights into the reliability of different NDE methods (Metz 1978; Sultan 2017; Sultan and Washer 2018). ROC is a tool for analyzing the reliability of diagnostic methods such as NDE by comparing NDE results to the actual condition (i.e., ground truth) of the area assessed. ROC results are analyzed by assessing the true positive rate (TPR) when the diagnostic tool correctly classifies a damaged area, and the false positive rate (FPR) when the tool incorrectly classifies an undamaged area as damaged. These data are plotted for all possible threshold values that could be used to classify a particular result or measurement as indicating damage. Figure 2 shows a plot of ROC results with the TPR plotted on the ordinate and the FPR plotted on the *x*- and *y*-axes. As shown in the figure, results that extend from the origin to the top right corner of the plot represent a random classifier, meaning the probability of any result being correct or incorrect is 50–50. Results tend toward the top left corner of the plot as the ability to correctly classify damage increases and the TPR exceeds the FPR. The area under the curve can be used to compare results from one technology to another quantitively.

Figure 2. Graph. Typical conventional ROC curve.



Source: FHWA.

The team used ROC analysis to assess the effectiveness of each NDE method compared with an assumed ground truth because attaining actual ground truth data without physical sampling that would damage the deck was not possible. The assumed ground truth was obtained from a secondary NDE method. In other words, as an example, the team analyzed the results from GPR separately using each of the other NDE methods as the ground truth. Six different scenarios linked to the six NDE methods assessed the effectiveness and comparative reliability of these methods. Consistency among PNDE technologies suggested comparable reliability between the different methods. For DNDE methods, results showed that IE provided the most accurate and reliable results. Previous research corroborates the high reliability of IE and sounding technologies observed in this study (Sultan 2017; Sultan and Washer 2018).

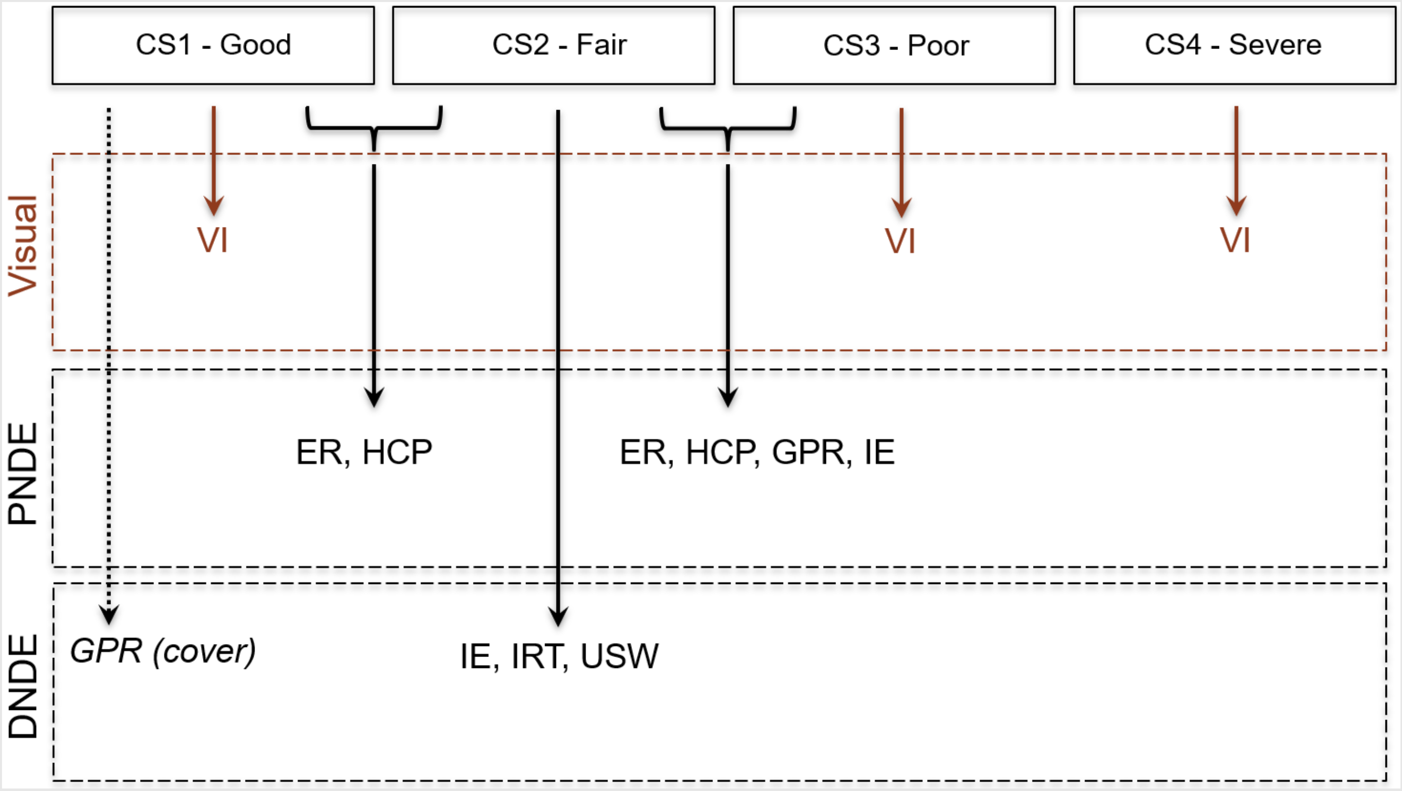
INTEGRATION OF NDE WITH CONVENTIONAL CONDITION DATA

One of the primary objectives of this study was to assess the collected NDE data alongside other conventional performance indicators such as CRs and CSs. The researchers investigated the correlation between NDE data and the reported component-level CR and element-level CS using both qualitative and quantitative assessments.

Component-level CRs typically cannot be correlated meaningfully with the outputs generated by most NDE methods. Component-level CRs serve as both a condition and a safety indicator because the impact of damage on the safety and serviceability of bridge components, based on visual assessments, is considered when assigning a CR. Conversely, NDE methods only assess the damage and do not analyze the impact of the damage on safety or serviceability. NDE results commonly require expert interpretation or are proprietary and provide information specific to the condition of a discrete area of an element rather than the entire structure or component. NDE results require interpretation and extrapolation to infer the impact of damage detected on safety or serviceability.

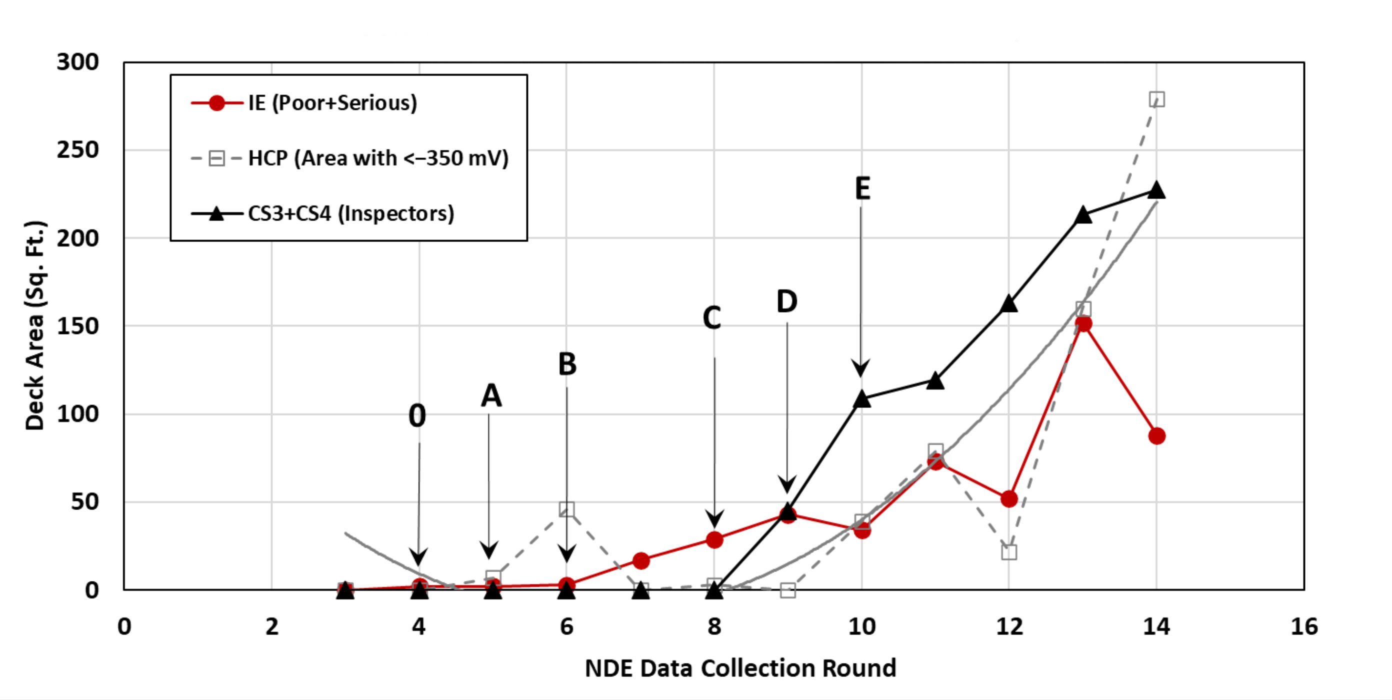
Although element-level CSs are more granular and quantifiable than component-level CRs, they still rely on visual evidence. Through the results analysis from the accelerated testing, the team demonstrated that NDE can be partially correlated with element-level CS data. Figure 3 illustrates the conceptual correlation between NDE and element-level CS, showing that PNDE methodologies such as ER and HCP can be effective for predicting the likelihood of a deck transitioning from CS1 to CS2 or CS2 to CS3. DNDE methods detect subsurface damage normally characterized as CS2, which is not available for VI, resulting in a more accurate assessment of the quantity of CS2 present in the deck.

Figure 3. Graph. Proposed integration of NDE techniques and element-level CS.



Source: FHWA.

Figure 4. Graph. Quantitative results from accelerated testing.



Source: FHWA.

0 = typical surface scaling picked by inspector; A = HCP first inflection; B = IE first inflection; C = first physical damage picked by inspector; D = HCP second inflection; E = IE second inflection.

Figure 4 plots the quantitative results from a suite of NDE and CS surveys collected from the accelerated testing. The figure shows the VI results indicating a poor or severe condition assessed in terms of the area (square feet) of the deck at each of the 14 data collection intervals. The figure illustrates that the PNDE results from HCP increase (A) and DNDE results from the IE increase (B) before the detection of damage by VI (C). Figure 4 provides a finer assessment of bridge deck conditions, enabling the early detection of issues that are not visible through traditional inspections.

The team used the results of this analysis to demonstrate how DNDE data from the accelerated testing can be used within the broader context of performance reporting, particularly for element-level CS. The PNDE and DNDE methods also provided insight into subsurface and material deteriorations that offered predictive indicators of surface damage detectable by VI that occurred later during the accelerated testing. This capability is crucial for preemptive interventions that can extend the lifespan of bridge structures and offer cost-effective solutions for maintenance and safety.

DEVELOPMENT OF DATA-DRIVEN PERFORMANCE MODELS

Two different approaches are commonly used by the bridge community to forecast bridge deck performance. The first approach involves modeling damage accumulation over time detected from VI using statistical methods to identify deterioration trends. This method relies on historical data from bridges with similar characteristics and exposure conditions to provide a macrolevel understanding of bridge performance, commonly referred to as deterioration modeling (DM). This modeling includes deterministic, probabilistic/stochastic, or artificial intelligence/machine-learning (AI/ML) techniques, which are exceptionally useful for asset management and offer valuable insights for long-term planning.

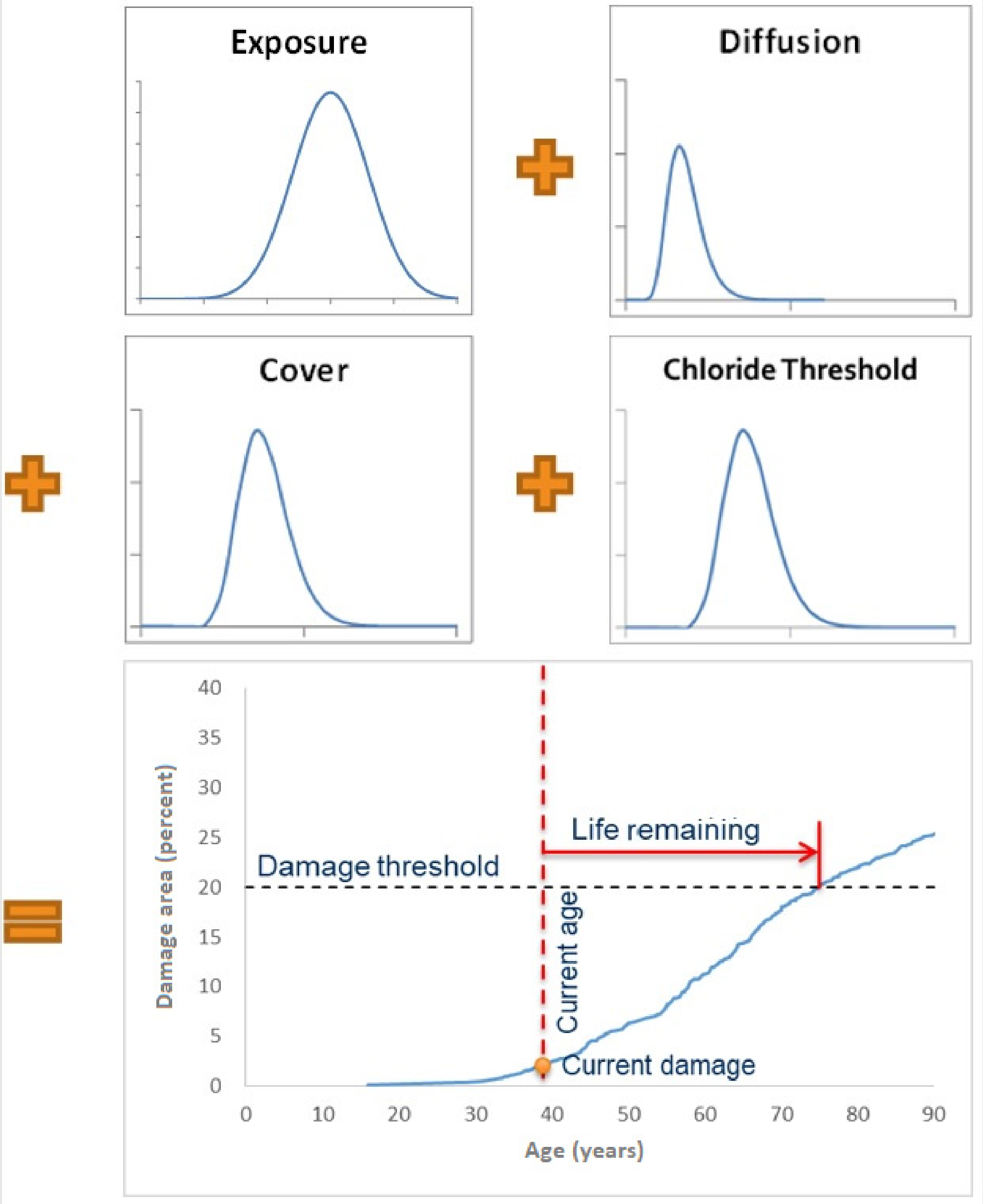
Conversely, the progression of physical and chemical deterioration mechanisms is studied using mechanistic models. These models predict the initiation of reinforcement corrosion and the rate of surface damage development and are referred to as service life models (SLMs). They focus on microlevel processes that describe local material behavior in response to environmental inputs.

SLM

The research team used a mechanistic SLM to characterize the condition of the bridge deck throughout the accelerated testing, from original construction to corrosion initiation to visible damage detection. SLM follows a two-phase process of corrosion-related damage in concrete: the initiation time and the propagation time. The initiation time marks the period required for chlorides to infiltrate and reach the rebar level, thus initiating corrosion. Propagation time begins when corrosion is underway, leading to the accumulation of corrosion products until corrosion reaches a critical volume that causes noticeable concrete damage, such as cracking or spalling.

CASLE™ (Corrosion Assessment and Service Life Estimation), the research team's proprietary in-house service life modeling software (WJE 2024), simulates chloride-induced corrosion of reinforcing steel. As shown in figure 5, CASLE incorporates various inputs, determined using NDE, SM, or material sampling. Cover depth, as an example input, is compiled from field measurements into a histogram with probabilistic distribution and integrated into the model. Using a Monte Carlo simulation, the model generates a probabilistic SLM, depicted in a plot mapping damage progression against deck age.

Figure 5. Graph. Schematic SLM methodology applied by CASLE.



Source: FHWA.

Figure 6 presents two distinct SLMs developed based on the results from accelerated testing. The first model (green solid line) represents corrosion initiation, whereas the second (blue dotted line) reflects damage progression. The outcomes of these models are cross validated with their respective NDE data (HCP and IE), showing strong correlation and reinforcing the models' accuracy.

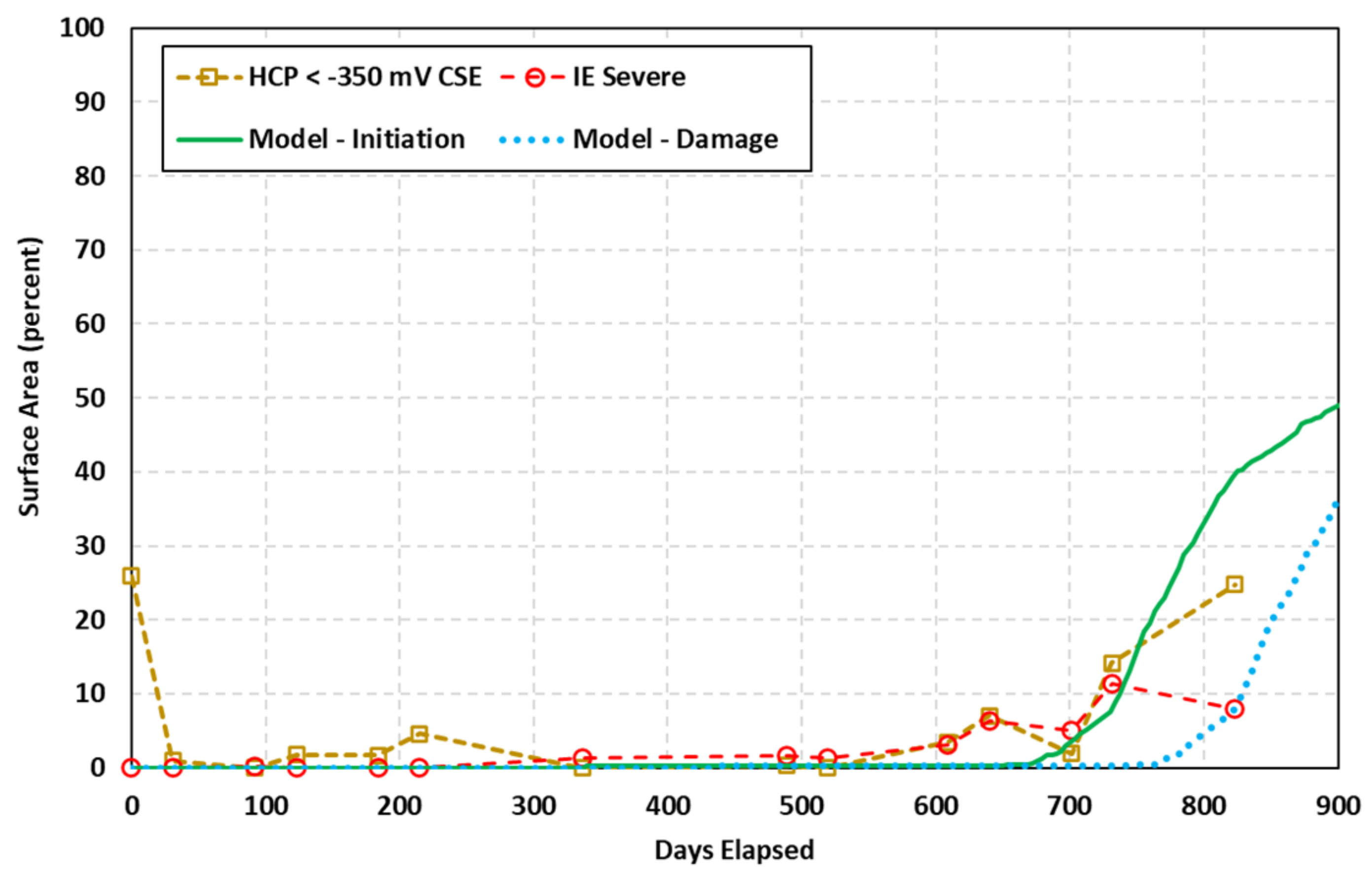
The researchers investigated two in-service bridges in Iowa to explore integrating NDE data with SLM, leveraging evaluations and models developed for these structures to examine potential correlations between NDE data and condition data. These studies validated the proposed modeling approach against observed conditions, demonstrating the application of NDE data in real-world scenarios for precise identification of deterioration stages and enabling timely, targeted maintenance interventions.

DM

A DM is a data-driven approach that determines bridge deck performance based on historical data across a network of bridges. Deck performance is gauged by either a deck CR, which is on a scale from 0 to 9, or an element-level CS, which is on a four-level scale ranging from good (CS1) to severe (CS4) in quantities ranging from 0 to 100 percent.

The study leveraged a variety of analytical deterioration methods, including deterministic and probabilistic models, alongside advanced AI/ML techniques. The study highlights how NDE data integration refines model predictions and provides a nuanced understanding of bridge deck health, supporting more informed maintenance and rehabilitation decisions. As shown in table 1, this study characterized the correlations between NDE condition indexes, defect indexes, and deck CRs, acknowledging that these conversions are derived from data collected from a single accelerated test specimen and therefore rely on a limited dataset. Furthermore, these correlation studies serve as an initial framework for the application of NDE data to a wider variety of bridge types encompassing varying deck types, geometries, and environmental conditions.

Figure 6. Graph. Comparison of model projections to NDE data obtained from IE and HCP measurements.



Source: FHWA.

CSE = cooper-copper sulfate electrode.

Table 1. Qualitatively established NDE condition and defect index thresholds versus deck CR using data from accelerated testing.

National Bridge Inventory Deck Rating (FHWA 1995)	NDE Condition Index (percent)			NDE Defect Index (percent)		
	IE	USW	HCP	IE	USW	HCP
≥7	>90	>90	>96	<5	<1	<5
6	>80	>80	>90	<10	<2	<10
5			>75		<3	
≤4	<80	<80	<75	>10	>3	>10

Note: The thresholds are derived based on limited data from the deck specimen subject to accelerated testing. NDE Condition Index and Defect Index have descending and ascending trends as bridge deteriorates, respectively.

KEY RESEARCH FINDINGS

The FHWA study on linking NDE data and bridge deck performance has yielded several key insights, as follows:

- Integration of NDE technologies within accelerated testing was successfully explored, demonstrating methods for using NDE data with conventional condition data and performance indicators to predict current and future conditions.
- HCP (as a PNDE) and IE (as a DNDE) showed the highest reliability among the methods evaluated during the accelerated testing.
- NDE was successfully integrated with a mechanistic SLM and validated against the accelerated testing specimen and two similar in-service bridges.
- NDE was successfully integrated with advanced data-driven DMs—encompassing deterministic, probabilistic, and AI/ML approaches—and quantified using condition and defect indexes.

Future research directions and recommendations for further studies include the following:

- Expanding the use of SLM to enhance understanding of actual and expected performance. Suggested actions include the following:
    - Conducting PNDE testing (e.g., HCP, ER, GPR) to quantify active corrosion in decks.
    - Performing material sampling to determine concrete properties.
    - Undertaking periodic crack mapping and DNDE assessments (e.g., IE, IRT, sounding).
- Assessing the impact of environmental conditions and material properties on the effectiveness of NDE methods.
- Linking PNDE methods with data-driven methods for deck preservation (CR5–7) and DNDE with rehabilitation strategies (CR4 or lower), including adjustments of component-level CR or element-level CS based on NDE.

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