TECHNOTE

Ultra-High Performance Concrete (UHPC) Overlays: An Example of Lifecycle Cost Analysis

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INTRODUCTION

In the United States, ultra-high performance concrete (UHPC) is a nascent solution for thin bonded overlays and highway bridge deck partial-depth replacements. In the United States, UHPC has been used for this purpose since 2016. The first adopter, Switzerland, has used UHPC in this manner since 2004.(1,2) UHPC overlays are expected to add decades of service life to existing bridge decks. The expectations for enhanced service life are based on the following key properties of UHPC-class materials: very low permeability, strong bond strength to conventional concretes, and post-cracking tensile ductility through the formation of uniformly distributed microcracks.(2–4) Additionally, an investigation into the first UHPC bridge deck overlay in Switzerland revealed that the deterioration of the bridge deck, which was visible from the soffit of the bridge deck prior to installation of UHPC overlay, had not worsened in more than decade since the installation of the overlay.

OBJECTIVE

There are two challenges to broader adoption of UHPC overlays: lack of long-term in-service performance data and high initial material cost of UHPC relative to other bridge deck overlay materials. This document provides information addressing the latter challenge. The lifecycle cost analysis (LCCA) can be used to counter arguments against the high initial material costs of UHPC overlays. This document presents a summary of an LCCA study that was performed by a signature bridge owner evaluating different overlay options for one of their bridges. The analysis compared UHPC overlays with several thicknesses with conventional concrete overlay solutions and complete deck replacement. The findings show the net present cost of the different solutions and a break-even analysis. Lastly, the study also represents an example of what bridge owners could do to create a project-specific cost comparison.

BACKGROUND

Formed by an interstate compact in 1968, the Delaware River and Bay Authority (DRBA) is a bi State government agency that provides transportation links between Delaware and New Jersey. DRBA operates two ferry ways, five regional airports, and most notably, in the context of this document, the Delaware Memorial Bridge (DMB) structures, which are shown in figure 1; this document focuses on the First Structure. The First Structure carries northbound I–295 from Newcastle, DE into New Jersey, and onto the New Jersey Turnpike. The First Structure bridge includes a 3,650-ft suspension bridge with a 2,150-ft main span, plus elevated approach structures composed of girder-supported spans and deck-truss spans at each end, for a total bridge length of 10,795 ft. The DMB structures are a key component of the I–95 corridor connecting the Washington, DC-area with New York, NY, carrying

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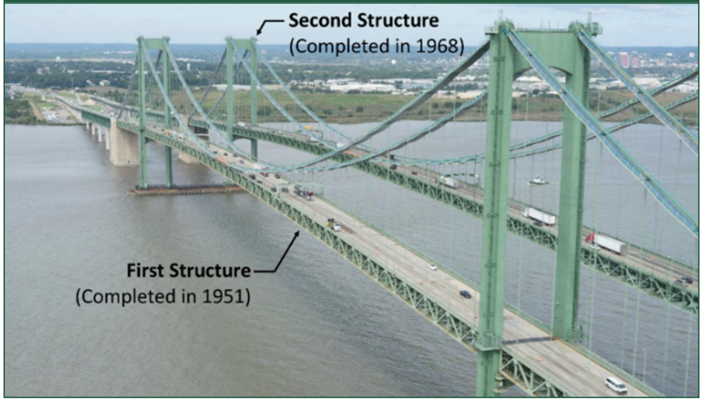
Figure 1. Photo. DMB Structures.



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truck traffic trying to avoid congestion on I–95 through Philadelphia, PA.

The First Structure opened to traffic in 1951. In 1968, DRBA constructed the second parallel bridge, referred to as the Second Structure, and replaced the deck on the First Structure to convert it from bidirectional traffic with a raised center median to full-width unidirectional traffic. The First Structure's bridge deck is 51-ft wide, with a total surface area of 550,575 ft^2; a typical section is shown in figure 2.

Over the past few decades, DRBA has been spending an ever-increasing amount of time and money installing localized patching repairs to the deck that have been lasting an average of 10 yr. In 2019, as the deck of the First Structure approached 50 yr of service life, DRBA performed a detailed deck condition evaluation. They determined that continued deck patching was unsustainable, and they would likely need to replace the entire deck within the next 5 to 15 yr. As such, DRBA and their engineering consults conducted a detailed LCCA to evaluate alternatives to complete deck replacement. Their analysis included different bridge deck overlay solutions and different deck replacement solutions.

OVERVIEW OF THE ANALYSIS PERFORMED

LCCA was performed to compare multiple deck rehabilitation strategies and multiple deck replacement options. The results of the analysis were used to determine the cost effectiveness and break-even analysis of each approach. Three different overlay materials, three different installation strategies, and the four deck replacement options were initially considered for the analysis. Notably, the DMB does not have enough reserve structural capacity to support additional dead load on the deck. As such, overlay materials could not be placed on top of the existing deck. Rather, all the overlay options included removing existing deck concrete to a depth equal to the thickness of the new materials placed. As such, each "overlay" solution is effectively a partial-depth deck replacement.

OVERLAY MATERIALS

As noted in table 1, three different overlay materials were initially considered: latex modified concrete (LMC), high early strength LMC (LMC-VE), and UHPC. DRBA selected UHPC because they were interested in investigating this emerging solution. The LMC materials were selected as comparison points. DRBA has used LMC and is most familiar with it. It should be noted that there are a number of other overlay solutions available on the U.S. market.(5)

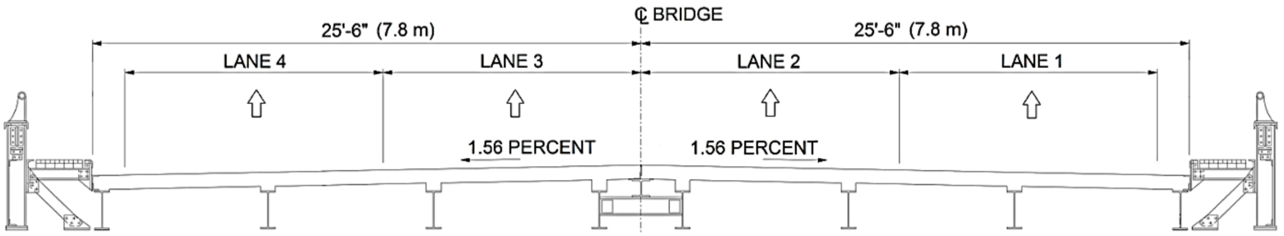
LMC

LMC has a long deployment history for bridge deck overlays in the United States. The State of Virginia has used LMC for over 50 yr.(6) The addition of latex to conventional concrete increases flexural strength and reduce permeability.(7) LMC has also demonstrated the ability to bond well with conventional concrete if the substrate is adequately prepared.(8) The main challenges for LMCs are related to installation. LMC overlays require specialized equipment and experienced contractors, while the quality of the construction is also sensitive to weather conditions.(5)

LMC-VE

LMC-VE is a variant of LMC that gains strength at a faster pace but exhibits properties similar to a conventional LMC. The primary difference between the two products is the type of cement used: LMC-VE

Figure 2. Illustration. Cross-section of DMB deck and stringers.



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employs rapid hardening hydraulic cement (ASTM C1600) in place of ordinary Type Ⅰ and Ⅱ portland cement (ASTM C150).[9,10] Virginia has successfully used this material in bridge deck overlays since 1997.[6] The primary advantage of LMC-VEs is that they allow short construction windows. Construction crews can place an overlay and open a structure to traffic in as little as 3 hr.[6] The material cost of LMC-VE is higher than that of conventional LMC, but this higher cost is offset by the reduction in traffic control costs associated with the short construction window. The primary challenge with LMC-VEs is the need for tight construction and curing controls. The high heat of hydration, and delayed curing has been known to result in plastic shrinkage cracking. Additionally, moist curing is essential.[6,11]

UHPC-Class Materials

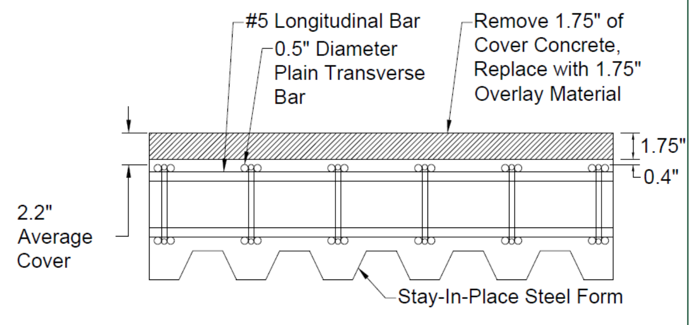
UHPC-class materials are much newer than LMCs, having only been used in bridge engineering applications in the United States since 2006. Furthermore, these materials are emerging as a bridge deck overlay solution. UHPC-class materials offer a lot of potential benefits as overlay materials. UHPCs can act as both a water-proofing layer and a wearing surface. However, UHPCs can also become part of the structural deck, increasing its structural capacity and stiffness. UHPCs have high resistance to freeze–thaw damage, extremely low permeability, and tensile ductility due to internal microfiber reinforcement. Additionally, when UHPC cracks, the cracks are typically very fine and uniformly distributed. UHPC-class materials also bond very well to existing concrete.[12,13] Lastly, UHPCs that are formulated for bridge overlay applications are typically designed to be thixotropic, which allows the material to be placed on inclined surfaces.[8] As such, vibration is required to develop an adequate bond between UHPC and the concrete substrate; this requirement is contrary to UHPCs formulated for joint fill applications.

OVERLAY INSTALLATION STRATEGIES

Three different overlays installation strategies were considered. All options involved removing a portion of the existing deck concrete to accommodate the overlay (partial-depth deck replacement) to avoid additional dead load and expansion joint modification. The deck of the DMB First Structure includes a steel stay-in-place form and welded truss bars, which link the top and bottom mats of transverse reinforcement; shown in figure 3 through figure 5. A prior deck evaluation, which was completed by the owner, determined that the deck has an average cover of 2.2 inches. Details for the three installation strategies are listed below:

Installation Strategy 1 (IS1): Remove existing cover concrete to within 0.4 inches of the top mat of the reinforcing bars (rebar). This change is equated to approximately 1.75 inches of concrete removal. Remove the concrete to replace it with overlay material. This strategy is illustrated in figure 3.

Figure 3. Illustration. IS1 using a 1.75 inch overlay.



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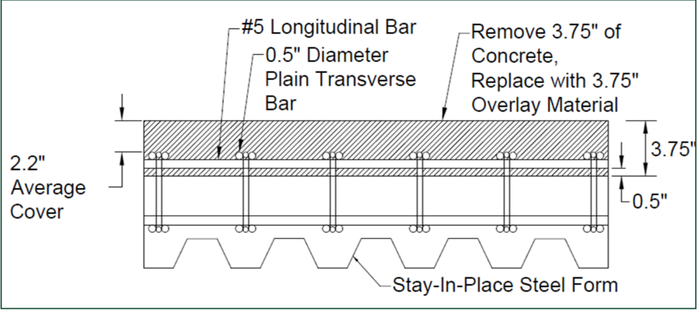
Installation Strategy 2 (IS2): Remove existing concrete to a depth of 0.5 inches below the top mat of rebar. This change is equated to approximately 3.75 inches of concrete removal. Remove the concrete to replace it with overlay material. The primary benefit of this strategy is that removing existing concrete to a greater depth would eliminate chloride-contaminated concrete around the rebar, and the overlay material would encapsulate the top mat of steel reinforcement. As such, greater protection of the reinforcing steel would be achieved along with an enhanced durability of the deck. This strategy is illustrated in figure 4.

Figure 4. Illustration. IS2 using a 3.75 inch overlay.



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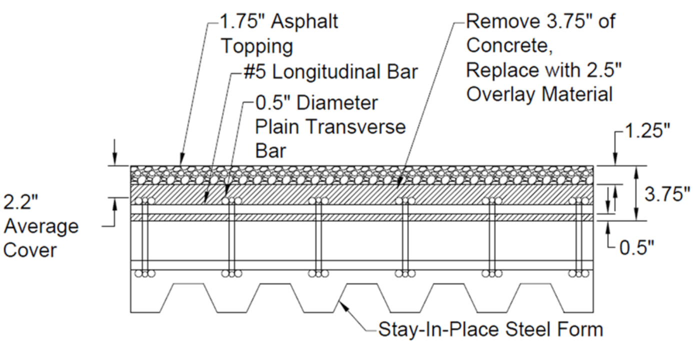
Installation Strategy 3 (IS3): Remove existing concrete to a depth of 0.5 inches below the top mat of rebar. This change is equated to approximately 3.75 inches of concrete removal. Remove the concrete and replace it with 2.5 inches overlay material and a 1.25-inch asphalt topping. This strategy has the same advantages of IS2, but at a lower cost due to the use of asphalt as a topping layer. This strategy is illustrated in figure 5.

Figure 5. Illustration. IS3 using a 2.5 inch overlay with 1.25 inch asphalt.



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OVERLAY CONSTRUCTION COSTS

A key component of the LCCA was developing the unit costs for the overlay materials and each respective installation strategy. The estimated unit construction costs for the different materials and installation strategies are shown in table 1. These costs include materials, labor, hydrodemolition for bridge deck surface preparation, and traffic control. It should be noted that these costs are intended for overlays on the entire surface of the DMB First Structure, which as a bridge deck area of approximately 550,575 ft^2. The costs for the LMC overlays were primarily determined using existing literature and the experience of engineering consultants. Given that UHPC overlays are an emerging technology, the UHPC overlay construction costs were estimated by collecting data from previous project bid tabulations and soliciting estimated costs from a UHPC overlay contractor. Lastly, the cost of bridge deck hydrodemolition was assumed to be approximately \$15/ft^2, which was based on data from previous projects. The cost of hydrodemolition will inversely scale with the bridge deck area.

The estimated cost for IS1 using UHPC was determined using construction cost information from nine UHPC bridge deck overlays projects constructed in the United States from 2016 to 2020. The projects were in the States of Iowa, Delaware, New York, and New Jersey. Each of these projects used an installation strategy similar to IS1 described herein. The data collected from these previous projects were analyzed and normalized to the overlay installation thickness of 1.75 inches. Figure 6 depicts the relationship between cost per square ft and the overlay installation area. Each data point represents a previous project. Each project was given an identification (ID) number. Project details are listed in table 2. In general, the cost scales with the installation area, albeit not linearly. The DMB First Structure deck surface, where these overlays would be applied, is approximately 550,575 ft^2. As such, IS1 with UHPC was assigned a unit cost of \$55/ft^2.

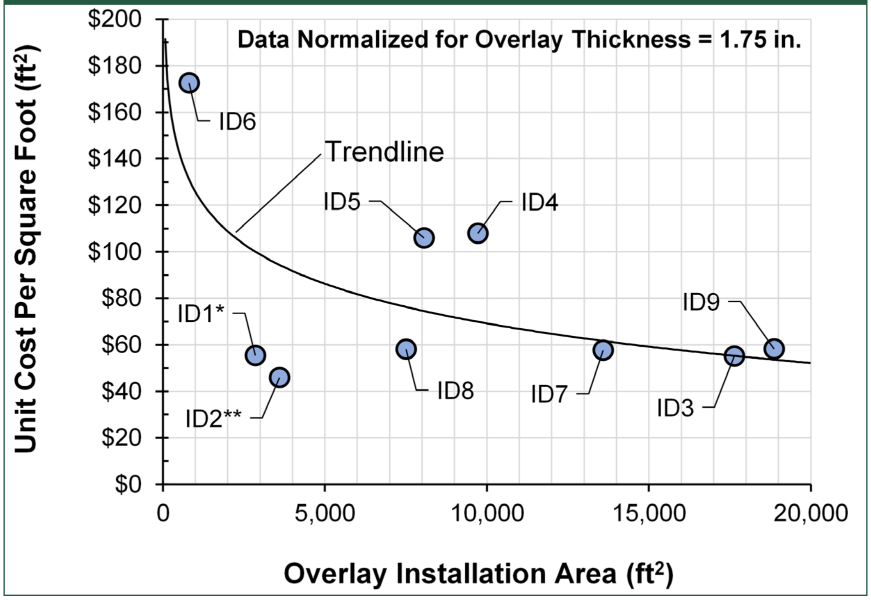
The as-built construction costs of UHPC overlay pilot projects were used to determine the estimated costs for installing UHPC overlays using IS2 and IS3. These pilot projects were completed on the DMB First Structure and the Commodore Barry Bridge (CBB). The CBB is a signature structure south of the Philadelphia International Airport, connecting New Jersey and Pennsylvania, and spanning the Delaware River. Experience from these projects revealed that removing concrete below the top mat of steel is often difficult. This type of concrete removal was specified for IS2 and IS3. Due to these removal difficulties, additional work was required by the contractor, which increased the construction costs for both pilot projects. To be as objective as possible, this work has been accounted for in the costs shown in table 1 for IS2 and IS3 using UHPC. Note that the data from figure 6 is not likely scalable for UHPC overlay installations that require concrete removal below the top mat of steel. Considering the available data and knowledge, IS2 and IS3 with UHPC were assigned unit costs of \$127/ft^2 and \$109/ft^2, respectively.

As noted in table 1, the combination of LMC and IS3 was excluded from the analysis for the following reason—asphalt is typically porous and will trap moisture and chlorides at the interface between the asphalt and the deck below. Placing asphalt over high performance concrete—without a waterproofing membrane—is avoided by most transportation agencies. It would be unadvisable to do the same with LMCs given that LMCs have a chloride ion penetrability like that of conventional high-performance concrete. Additionally, the performance objective was that the overlay material alone protected the deck, and an additional membrane or waterproof asphalt would only add further costs and future maintenance considerations.

Table 1. Estimated unit construction costs; includes cost of materials, labor, hydrodemolition for bridge deck surface preparation, and traffic control.

Installation Strategy	Brief Description	UHPC (Cost/ft^2)	LMC (Cost/ft^2)
1	1.75-inch partial depth replacement	\$55	\$23
2	3.75-inch partial depth replacement	\$127	\$39
3	2.5-inch partial depth replacement with 1.25-inch asphalt topping	\$109	Not considered for analysis

Figure 6. Plot. UHPC overlay construction costs from previous project, including bridge deck surface preparation normalized to 1.75-inch overlay thickness.



Source: FHWA.

Notes: All projects used hydrodemolition for bridge deck surface preparation with the following exceptions:

*Existing bridge deck prepared using diamond grinding.

**UHPC overlay placed atop new precast box girder with roughened surfaces.

OVERLAY SERVICE LIFE ESTIMATES

Table 3 presents service life estimates for the different overlay materials and installation strategies. It is very important to note that these numbers were developed using engineering judgement, the previous experience of the bridge owner, and the engineering consultants of the bridge owner. The numbers do not reflect all cases or situations. The reasoning behind each estimate is provided herein.

At the time of this writing, there was virtually no long-term service life data for UHPC overlays on actual bridges, mainly given that most projects globally are less than 20 yr old. As such, the expected service life of UHPC is based on existing data, laboratory testing, and testing performed in extreme environments. A few examples of known UHPC overlay performance data are provided herein.

One of the earliest UHPC bridge deck overlays was installed in Châteauneuf-Conthey, Switzerland in 2004 on a bridge spanning the Morge River. The UHPC overlay was 1.18-inch thick and an asphalt wearing surface was installed on top of it; however, a waterproofing membrane was not used between the UHPC overlay and the asphalt topping. After 10 yr of service, the UHPC overlay was still performing well. Elevated chloride levels were only found within the first 0.1 inch of the UHPC overlay. Visual inspection formally documented that the overlay was protecting the underlying deck.(15)

Research conducted by Moffatt et al. demonstrated that UHPC samples subjected to 20 yr of aggressive marine exposure had a maximum chloride content of approximately 0.25 percent (percent by mass of concrete) at a depth of approximately 0.12 inches below the surface exposed to salt water.(14) After 13 yr of exposure, reinforcing bars extracted from the samples with 0.4 inches of cover showed no signs of corrosion. Additionally, standardized laboratory testing

Table 2. Projects used to develop a cost model for UHPC overlays.

Project ID	Owner	Project Name	Year Constructed	UHPC Overlay Thickness (inches)	Approximate Installation Area (ft^2)	Bridge Deck Surface Preparation
ID1	Buchanan County (Iowa)	Mud Creek	2016	1.5	2,850	D
ID2	Delaware DOT	Blackbird Station	2017	1.5	3,600	NG
ID3	Iowa DOT	Floyd River	2018	1	17,600	H
ID4	Delaware DOT	State Road 1 Little Heaven	2019	3	9,700	H
ID5	New York State DOT	State Road 17B Hortonville	2019	1.5	8,060	H
ID6	New Jersey DOT	NJ-57	2020	1.5	800	H
ID7	New Jersey DOT	I-280 WB	2020	1.5	13,600	H
ID8	New Jersey DOT	NJ-159	2020	2.75	7,500	H
ID9	New Jersey DOT	I-295 NB	2020	1.5	18,900	H

D = diamond grinding; DOT = department of transportation; NG = UHPC overlay placed atop new precast box girder with roughened surfaces; H = hydrodemolition.

shows that UHPCs demonstrate virtually no freeze thaw deterioration.(4)

Based on this evidence, IS1 using UHPC was prescribed a 30-yr service life, and IS2 was prescribed a 50-yr service life. The service life of IS3 would likely be shorter than that of IS2 given the reduced cover of UHPC over the top mat of reinforcement. As such, IS3 was prescribed a 45-yr service life.

The service life predictions for the LMC overlay cases were based on the experience of the bridge owner, DRBA, and multiple State departments of transportation (DOTs). The service life of IS1 using LMC was prescribed as 12 yr; this arrangement is consistent with past practice on the DMB and the practices of many State DOTs. The State of Virginia has many LMC overlays with service lives approaching 20 yr, while the DRBA has been achieving only 10 yr of average service life on the DMB. A service life of 12 yr was assumed, which accounted for the longer service life in Virginia but also gave weight to past experience on the DMB.

The service life of IS2 using LMC was prescribed as 25 yr. This prescription is because most of the heavily chloride-contaminated concrete would be removed and replaced with LMC, reducing the likelihood of reinforcing bar corrosion and debonding; this assumption is supported by the experience on the Claiborne Pell Newport Bridge (CPNB) in Rhode Island. The CPNB has a similar overlay depth and uses high-performance concrete.

Table 3. Service life estimates.

Installation Strategy	UHPC	LMC
1	30 yr	12 yr
2	50 yr	25 yr
3	45 yr	—

—Not considered.

DECK REPLACEMENT OPTIONS CONSIDERED

The overlay solutions were compared to complete deck replacement. Multiple deck replacement options were considered including a full cast-in-place concrete deck, a precast concrete deck composed of precast panels connected with UHPC, a precast Exodermic deck with panels connected with UHPC, and a steel orthotropic deck; estimated construction costs, service life durations, and construction durations are summarized in table 4 for the deck replacement options. All deck replacement options included removal of the existing safety walk and railing. The railing was assumed to be replaced by new traffic railing, and space occupied by the safety walk would be replaced with a new roadway deck, which would provide a roadway shoulder. With the exception of the steel orthotropic deck, which is assumed to include integrated stringers, all deck replacement options also include the costs associated with the replacement of the existing stringers with new stringers of a similar size. Furthermore, new fascia stringers would be added to support the new roadway shoulder. Costs for traffic control were assumed to be 5 percent of the subtotal; civil, electrical, and other miscellaneous work was assumed to be 15 percent of the subtotal; and a 25 percent contingency on the subtotal was also included.

To maximize the durability, it was assumed that the cast-in-place and precast concrete decks used stainless steel reinforcement. Similarly, it was assumed that the exodermic deck used galvanized reinforcement, and the galvanized steel grid panels would be compatible with that reinforcement. To further boost durability, the concrete deck options were assumed to also have a thin polyester polymer concrete (PPC) overlay.

The service life and construction duration estimates were determined using information from the literature, previous experience of the bridge owner, and the engineering consultants of the bridge owner. Typical reinforced concrete bridge decks in cold climates with conventional mild steel reinforcement, epoxy-coated or uncoated, have a service life of 20 to 30 yr.(16) A PPC overlay installed within the first 5 yr of deck construction can lead to a 50-yr bridge deck service life, and even longer if the overlay is reinstalled every 25 yr.(17) Stainless steel reinforcement alone has been estimated to potentially provide up to 100 yr of service life.(18) Therefore, the service life for the cast-in-place and precast decks—using a combination of stainless steel reinforcement and a PPC overlay—was conservatively estimated to be 75 yr. Because the exodermic deck includes a PPC overlay but uses galvanized reinforcement, it was estimated to have a service life of 50 yr. Finally, the steel orthotropic deck was estimated to have a 75-yr service life based on published information.(19)

INITIAL COMPARISON AND ELIMINATION OF OPTIONS

DRBA performed an initial comparison of overlay solutions and the four deck replacement options based on the initial construction cost, estimated service life data, and the estimated construction durations. This initial assessment aimed to eliminate options that were not feasible or competitive based on cost, service life, and construction duration. Since this assessment was an initial assessment, only the initial construction cost was considered. The deck replacement options included an additional cost for replacement of the steel stringers. To make a fair comparison, an additional cost allowance

Table 4. Estimated bridge deck replacement cost and timing.

Deck Replacement Option	Cost of Deck (millions)	Cost of Stringers (millions)	Unit Cost Including Stringers/ft^2	Estimated Service Life	Estimated Construction Duration[e]
Cast-in-place deck[a,c]	$118.5	$48.6	$304	75 yr	3 yr
Precast concrete deck[a,c]	$123.2	$48.6	$312	75 yr	1.5 yr
Precast exodermic deck[b,c]	$142.2	$48.6	$347	50 yr	1.5 yr
Steel orthotropic deck	$273.7	$0d	$498	75 yr	2 yr

[a] Deck includes stainless steel reinforcement.

[b] Deck includes galvanized reinforcement.

[c] Deck includes a thin PPC overlay.

[d] Stringers do not require replacement.

[e] Construction duration assumes work is performed in two construction stages with no other restrictions on lane closures.

Table 5. Comparison of all overlay and new deck options.

Option	Unit Cost of Deck Per ft^2 of Deck Area U_D	Unit Cost of Stringers Per ft^2 of Deck Area U_S	Total Unit Cost Per ft^2 of Deck Area, $U_T = U_D + U_S$	Cost of Deck (millions), C_D	Cost of Stringers (millions), C_S	Total Initial Cost (millions), $C_{TI} = C_D + C_S$	Estimated Service Life, L_S	Estimated Construction Duration[d]
UHPC overlay, method 1	$55	$18[b]	$73	$30.3	$10.0[b]	$40.3	30 yr	9 mo
UHPC overlay, method 2	$127	$18[b]	$145	$69.9	$10.0[b]	$79.9	50 yr	9 mo
UHPC overlay, method 3	$109	$18[b]	$127	$60.0	$10.0[b]	$70.0	45 yr	9 mo
LMC overlay, method 1	$23	$18[b]	$41	$12.7	$10.0[b]	$22.7	12 yr	9 mo
LMC overlay, method 2	$39	$18[b]	$57	$21.5	$10.0[b]	$31.5	25 yr	9 mo
New, cast-in-place deck[X]	$216	$88[a]	$304	$118.5	$48.6[a]	$167.1	75 yr	3 yr
New, precast concrete deck	$224	$88[a]	$312	$123.2	$48.6[a]	$171.8	75 yr	1.5 yr
New, precast exodermic deck[X]	$259	$88[a]	$347	$142.2	$48.6[a]	$190.8	50 yr	1.5 yr
New, steel orthotropic deck[X]	$498	$0[c]	$498	$273.7	$0[c]	$273.7	75 yr	2 yr

Notes:

The deck area of the DMB First Structure is 550,575 ft2.

[a] Represents stringer replacement cost.

[b] Represents stringer rehabilitation cost.

[c] Existing stringers are eliminated and do not require replacement or rehabilitation for this option.

[d] Construction duration assumes work is performed in two construction stages with no other restrictions on lane closures.

[X] Eliminated from further consideration due to initial cost or estimated construction duration.

of $10 million, approximately equal to $18 per square foot of deck area, was added to the total cost of the overlay options. This additional cost allowance covers the rehabilitation of the existing steel stringers so that they can reach a condition similar to new steel stringers. Table 5 lists all overlay and new deck options, and provides a comparison of the cost, estimated service life, and estimated construction duration for each one.

After examining every overlay option, the research team determined that they all were economically competitive from an initial cost perspective. Thus, each option warranted further investigation. Of the new deck solutions, when considering both initial cost and construction duration, the precast deck option was determined to be the only competitive option. Thus, the precast deck option would be further investigated too. The new cast-in-place deck was eliminated. This decision was primarily due to the lengthy construction duration. The new precast exodermic and steel orthotropic decks were eliminated due to their high initial costs.

LCCA

The remaining options, namely the five overlay solutions and the new precast deck solution, were analyzed to examine the lifecycle costs. This analysis was performed using LCCA, which is the method for assessing the total cost of facility ownership. LCCA typically considers all costs of acquiring, owning, and disposing of a building or building system, and, in this case, a bridge rehabilitation. The primary aim of LCCA is to compare project alternatives that fulfill the same performance requirements, but differ with respect to initial and operating costs, to select the one that maximizes net savings; LCCA is not useful for budget allocation.

LCCA was performed on each option. The analysis used the estimated construction costs as the total initial cost, C_{TI}, and included major costs that would reasonably be incurred during a 50 year analysis period, which was considered the maximum remaining service life of the DMB First Structure. Costs incurred during the 50-yr analysis are defined as "future costs." There were two primary future costs that could be incurred:

1. *Asphalt wearing surface removal and replacement:* The UHPC overlay solution using IS3 included a 1.25-inch asphalt wearing surface, which requires periodic replacement. Herein, the asphalt wearing surface was assumed to be replaced every 10 yr. The future cost of removal and replacement of asphalt was assumed to be $1.93 million which includes a 15 percent allowance for maintenance and protection of traffic, equipment mobilization, and incidentals. This cost also assumes that asphalt is priced at $375 per ton.
2. *Complete deck removal and replacement:* The overlay options have service lives of less than 50 year, except for the UHPC overlay using IS2. It is possible to replace an overlay at the end of its service life with a new overlay; however, this option is considered unlikely due to the advanced age of the existing deck below and the fact that the deck has already been overlaid multiple times. As such, it is more likely that the bridge deck would be completely removed and replaced with a new bridge deck at the end of the service life of the overlay. Given cost and construction time, as previously noted, the new deck would likely be a precast concrete deck with stainless steel reinforcement. Per table 5, the future costs of the existing deck removal and replacement with a new precast deck was assumed to be $171.8 million.

Notably, the analysis did not include costs associated with the demolition and disposal of the bridge after the conclusion of the 50-yr service life, nor does it include user costs.

Table 6 shows the lifecycle cost comparison for the different solutions. All monetary values shown in table 6 are expressed in present-day values or simply "present value" denoted "*PV*." The future value, *FV*, of costs were brought to present value using the equation shown in figure 7.

Figure 7. Equation. Equation for present value, PV, based on future value, FV.

$$PV = FV \cdot F_{FV} = FV\left(\frac{1}{1 + r^{n}}\right)$$

Where:

PV = present value.

FV = future value.

FFV = future value factor.

r = real discount rate, assumed here to be 1.5 percent based on 2019 data from the Real Treasury Interest Rate for 30-yr maturity published by the White House Office of Management and Budget.[20]

n = number of year.

In table 6, "Yr 0" is considered the year where every solution has completed construction. As such, the Yr 0 cost for each respective solution is equal to the total initial cost, CTI, for that solution. The table shows a series of different years between 0 and 50, and the costs incurred during those years. Four additional values, namely, total future cost, remaining service value, net present cost, and relative net present cost, are shown at the bottom of the table and are defined below:

Total Future Cost, C_{TF} = summation of costs for anticipated maintenance (i.e., replacement of asphalt wearing surface), and eventual deck replacement if needed within the 50-yr analysis.

Remaining Service Value, RV = present value of the deck (overlay system or new deck) at the end of the 50-yr analysis period, assuming straight line depreciation occurs over the 50-yr analysis period. Except for the UHPC overlay IS2, the *RV* can be calculated using the equation for solutions shown in figure 8. This solution will have an *RV* = $0, given that the service life of the solution is equal to the duration of the analysis period. The equation in figure 8 assumes that all other solutions will require the installation of a new precast deck after the service life of the overlay solution has been exceeded. *RV* is effectively a credit applied to net present cost, which is used to compare the different solutions.

Figure 8. Equation. RV.

$$RV = \left(C_{TI,New\ Precast\ Deck}\right)\left[1 - \frac{(t_{end} - L_S)}{L_{S,New\ Precast\ Deck}}\right]$$

Where:

RV = remaining service value.

$C_{TI,\ New\ Precast\ Deck}$ = total initial cost, in present value, of a new, precast deck.

t_{end} = duration of analysis period, in years. Here, t_{end} = 51 yr, because the remaining value is assessed the end of the 50th yr.

L_s = service life of the solution for which the *RV* is being calculated.

$L_{s,\ New\ Precast\ Deck}$ = service of the new precast deck, $L_{s,\ New\ Precast\ Deck}$ = 75 yr.

Net Present Cost, C_{NP} = sum of all costs during the 50-yr analysis period, which is sum of total initial cost and total future expenditures minus *RV*. C_{NP} is expressed by the equation in figure 9.

Figure 9. Equation. CNP.

$$C_{NP} = C_{TI} + C_{TF} - RV$$

The analysis indicates that the UHPC overlay, IS2, is the most cost effective in terms of present value given the assumptions used for analysis. The primary driver of this finding is that the estimated service life is equal to the analysis period and that this solution does not require any additional costs between years zero and 50. The UHPC overlays with IS1 and IS3 are similar in cost, followed by the LMC overlay with IS2. The LMC overlay with IS1 had the lowest initial cost; however, because it has the shortest life span and hence the earliest deck replacement, it is the most expensive overlay solution over the life of the structure. Notably, the new precast deck is the costliest option over the life of the structure.

Table 6. Lifecycle cost comparison for overlay methods and new precast concrete deck.

Material/Deck Type	UHPC	UHPC	UHPC	LMC	LMC	New Precast Concrete Deck
Overlay installation strategy	Method 1	Method 2	Method 3	Method 1	Method 2	—
Estimated service life = L_S	30 yr	50 yr	45 yr	12 yr	25 yr	75 yr
Total initial cost = C_{TI}[c] (Yr 0 costs)	$40.3M	$80.0M	$70.0M	$22.7M	$31.5M	$171.8M
Yr 5 costs	$0	$0	$0	$0	$0	$0
Yr 10 costs	$0	$0	$1.6M[b]	$0	$0	$0
Yr 12 costs	$0	$0	$0	$141.6M[a]	$0	$0
Yr 20 costs	$0	$0	$1.4M[b]	$0	$0	$0
Yr 25 costs	$0	$0	$0	$0	$116.6M[a]	$0
Yr 30 costs	$108.3M[a]	$0	$1.2M[b]	$0	$0	$0
Yr 35 costs	$0	$0	$0	$0	$0	$0
Yr 40 costs	$0	$0	$1.0M[b]	$0	$0	$0
Yr 45 costs	$0	$0	$86.7M[a]	$0	$0	$0
Yr 50 costs	$0	$0	$0	$0	$0	$0
Total future cost (C_{TF})	$108.3M	$0	$91.9M	$141.6M	$116.6M	$0
RV	$59.8M	$0	$76.2M	$40.3M	$54.4M	$26.1M
C_{NP}	$88.7M	$80.0M	$85.8M	$124.0M	$93.7M	$145.7M

Notes:

All monetary values are expressed as present value.

—Not applicable.

[a] Estimated service life reached. Existing overlay and deck removed, new precast concrete deck with stainless steel rebar installed.

[b] Asphalt removal and replacement.

[c] C_{TI} is the sum of C_D and C_S.

BREAK-EVEN ANALYSIS

The research team performed a break-even analysis to determine the actual service life required such that a given overlay solution would have a net present value C_{NP} equal to that of new precast concrete deck. This analysis was only performed on the overlay solution with the lowest net present value CNP from table 6, which was UHPC overlay, IS2. The same methods and assumptions used for the LCCA were applied. The only exception is regarding the service life of the overlay solution. The results of the analysis are tabulated in table 7. Here, the actual service life of the overlay solution is a variable. This value is varied to determine the point where the net present cost of both the overlay solution and the new precast deck are equal, which is the break-even point. As shown in table 7, the break-even point occurs when the actual service of the UHPC overlay with IS2 is approximately 24 yr. That is, if the actual life span of this overlay solution ends up being less than the estimated 50 yr, but more than 24, it will still be more economical than a new precast concrete deck.

HYPOTHETICAL ALTERNATIVE SCENARIO

A reasonable followup question to the break-even analysis is: How would the net present cost change, if upon reaching the conclusion of their service lives, the overlay solutions were replaced by another overlay of the same material using the same Installation Strategy? That is, once the service life of the overlay is reached, could the overlay be removed and replaced by another overlay? Note, this example is very hypothetical given the age of the DMB First Structure and given the fact that some very practical concerns are being neglected, such as the likely need to repair or rehabilitate the existing deck or supporting superstructure before removing/installing a new overlay. For this analysis, three of the overlay solutions are considered.

The results of the LCCA are shown in table 8. Herein, both LMC overlay options were considered along with the UHPC overlay, IS1. Like the preceding analysis, all costs are expressed according to their present value. Costs incurred after Yr 0 reflect the removal and reinstallation of the overlay. The stringer rehabilitation, completed in year zero, is not included. The table also shows the cumulative construction duration, which is the sum of the construction time needed to remove and install each overlay iteration.

Herein, UHPC, IS1 and LMC IS2, are both relatively competitive on a net present cost basis and have equal cumulative construction durations. Furthermore, both options are more economical than the scenario presented in table 6. Although LMC IS2 would also be competitive economically, compared with the findings in table 6, it would require a significant amount of construction time over the course of the analysis period.

Table 7. Break-even analysis for UHPC overlay IS2 versus new precast concrete deck.

Solution	UHPC Overlay, IS2						New Precast Concrete Deck
Actual life span of the solution (yr)	10	20	24*	30	40	50	75
Total initial cost = C_{TI}[a] (Yr 0 costs)	\$80.0M	\$80.0M	\$80.0M	\$80.0M	\$80.0M	\$80.0M	\$171.8M
Yr 10 costs	\$145.8M	\$0	\$0	\$0	\$0	\$0	\$0
Yr 20 costs	\$0	\$125.7M	\$0	\$0	\$0	\$0	\$0
Yr 24 costs	\$0	\$0	\$118.4M	\$0	\$0	\$0	\$0
Yr 30 costs	\$0	\$0	\$0	\$108.3M	\$0	\$0	\$0
Yr 40 costs	\$0	\$0	\$0	\$0	\$93.3M	\$0	\$0
Yr 50 costs	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Total future cost (C_{TF})	\$145.8M	\$125.7M	\$118.4M	\$108.3M	\$93.3M	\$0	\$0
Remaining service value (*RV*)	\$38.1M	\$49.0M	\$53.3M	\$59.8M	\$70.7M	\$0	\$26.1M
Net present cost (C_{NP})	\$187.8M	\$156.7M	\$145.1M	\$128.4M	\$102.6M	\$80.0M	\$145.7M

Notes: All monetary values are expressed as present value.

[a] C_{TI} is the sum of C_D and C_S.

*Break-even point.

Table 8. Lifecycle cost comparison assuming overlay solutions are replaced with the like at the end of the service life.

Material Type	UHPC	LMC	LMC
Overlay installation strategy	Method 1	Method 1	Method 2
Estimated overlay service life	30 yr	12 yr	25 yr
Total initial cost = C_{TI}[a] (Yr 0 costs)	\$40.3M	\$22.7M	\$31.5M
Yr 12 costs	\$0	\$10.40M[b]	\$0
Yr 24 costs	\$0	\$8.72M[b]	\$0
Yr 25 costs	\$0	\$0	\$14.6M[b]
Yr 30 costs	\$15.6M[b]	\$0	\$0
Yr 36 costs	\$0	\$7.30M[b]	\$0
Yr 48 costs	\$0	\$6.11M[b]	\$0
Yr 50 costs	\$0	\$0	\$0
Total future expenditure (C_{TF})	\$15.6M	\$32.6M	\$14.6M
Remaining service value (*RV*)	\$8.63M	\$4.51M	\$0
Net present cost (C_{NP})	\$41.8M	\$50.7M	\$46.1M
Cumulative construction duration [c]	18 mo	45 mo	18 mo

Notes:

All monetary values are expressed as present value.

[a] CTI is the sum of C_D and C_S.

[b] Estimated service life of overlay reached. Existing overlay removed and placed. Cost does not include the cost of stringer repairs, C_S.

[c] Sum of the construction time required to remove and install each overlay iteration.

This construction time would significantly affect the end user, and as such would not be viable.

At the time of this writing, there has never been a UHPC overlay removed from a bridge deck. It is reasonable to assume that hydromilling could be used to remove a UHPC overlay, but it is likely to be more time and labor intensive than the removal of conventional concrete due to the high strength of UHPC. This difference could result in higher construction costs.

SUMMARY AND CONCLUDING REMARKS

This TechNote presented a summary of an LCCA study that was performed by a signature bridge owner to evaluate different overlay options for one of their bridges. The analysis examined lifecycle costs of both UHPC and LMC overlays with several thicknesses and compared them with complete deck replacement using a new, precast deck. The findings included the net present cost of the different solutions, a break-even analysis, and an alternative rehabilitation scenario. The reader may recall that the demolition costs of the structure at the end of life were not considered in the analysis. More importantly, the analysis and findings presented herein might change with different initial assumptions, structure type, and overlay performance objectives.

The results of the LCCA indicate that the UHPC overlay with IS2 had the lowest 50-yr lifecycle cost and thus is the most cost-effective option. Additionally, all five of the overlay options studied provided a lower cost over a 50-yr period than a deck replacement. The LMC overlay with IS1, which was a conventional thin overlay, had the lowest initial cost, but had higher lifecycle costs than the other overlay options. However, this finding is highly dependent on the anticipated service life of the overlay. The hypothetical alternative scenario demonstrated that the UHPC overlay with IS1 could be the most cost effective lifecycle of all solutions, if the existing UHPC overlay could be removed and replaced at the end of its service life. In closing, this study presented a method to compare the total cost of a UHPC overlay to other bridge deck overlay and replacement options. The study demonstrated a repeatable process that can be tailored to other bridges. The analysis process used demonstrates that, despite the higher initial cost compared to conventional overlays, UHPC could provide long-term cost benefits. Additionally, the cost of a UHPC overlay is significantly less than a deck replacement, outweighing the potentially shorter service life, with a shorter installation period.

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