SCAN TEAM REPORT

NCHRP Project 20-68, Scan 22-01

Recent Leading Innovations in the Design, Construction, and Materials Used for Concrete Bridge Decks

Supported by the

National Cooperative Highway Research Program

The information contained in this report was prepared as part of NCHRP Project 20-68 U.S. Domestic Scan, National Cooperative Highway Research Program.

SPECIAL NOTE: This report IS NOT an official publication of the National Cooperative Highway Research Program, Transportation Research Board, or the National Academies of Sciences, Engineering, and Medicine.

Acknowledgments

The work described in this document was conducted as part of NCHRP Project 20-68, the U.S. Domestic Scan program. This program was requested by the American Association of State Highway and Transportation Officials (AASHTO), with funding provided through the National Cooperative Highway Research Program (NCHRP). The NCHRP is supported by annual voluntary contributions from the state Departments of Transportation. Additional support for selected scans is provided by the U.S. Federal Highway Administration and other agencies.

The purpose of each scan, and of Project 20-68 as a whole, is to accelerate beneficial innovation by facilitating information sharing and technology exchange among the states and other transportation agencies and identifying actionable items of common interest. Experience has shown that personal contact with new ideas and their application is a particularly valuable means for such sharing and exchange. A scan entails peer-to-peer discussions between practitioners who have implemented new practices and others who are able to disseminate knowledge of these new practices and their possible benefits to a broad audience of other users. Each scan addresses a single technical topic selected by AASHTO and the NCHRP 20-68 Project Panel. Further information on the NCHRP 20-68 U.S. Domestic Scan program is available at

https://www.trb.org/NCHRP/USDomesticScanProgram.aspx

This report was prepared by the scan team for *Domestic Scan 22-01 Recent Leading Innovations in the Design, Construction, and Materials Used for Concrete Bridge Decks*, whose members are listed below. Scan planning and logistics are managed by Arora and Associates, P.C.; Harry Capers is the Principal Investigator. NCHRP Project 20-68 is guided by a technical project panel and managed by Sid Mohan, NCHRP Program Manager.

The scan team members include the following individuals:

Donn Digamon,
Georgia DOT, Team Chair

Bijan Khaleghi (retired),
Washington State DOT

Hannah Cheng,
New Jersey DOT

Trey Carroll,
North Carolina DOT

Terry B. Koon,
South Carolina DOT

Edward Lutgen,
Minnesota DOT

Cheryl Hersh Simmons,
Utah DOT

Don Nguyen-Tan,
California DOT

Pete White,
Indiana DOT

Kevin R Pruski,
Texas DOT

Scott M. Walls,
Delaware DOT

Rick Liptak,
Michigan DOT

Harry L. White 2nd,
New York State DOT

Linh Warren,
FHWA

Pinar Okumus,
University at Buffalo, The State University of New York, Subject Matter Expert

Disclaimer

The information in this document was taken directly from the submission of the authors. The opinions and conclusions expressed or implied are those of the scan team and are not necessarily those of the Transportation Research Board or its sponsoring agencies. This report has not been reviewed by and is not a report of the Transportation Research Board or the National Academies of Sciences, Engineering, and Medicine.

Scan 22-01

Recent Leading Innovations in the Design, Construction, and Materials Used for Concrete Bridge Decks

REQUESTED BY THE

American Association of State Highway and Transportation Officials

PREPARED BY SCAN 22-01 TEAM

Donn Digamon,
Georgia DOT, Team Chair

Bijan Khaleghi (retired),
Washington State DOT

Hannah Cheng,
New Jersey DOT

Trey Carroll,
North Carolina DOT

Terry B. Koon,
South Carolina DOT

Edward Lutgen,
Minnesota DOT

Cheryl Hersh Simmons,
Utah DOT

Don Nguyen-Tan,
California DOT

Pete White,
Indiana DOT

Kevin R Pruski,
Texas DOT

Scott M. Walls,
Delaware DOT

Rick Liptak,
Michigan DOT

Harry L. White 2nd,
New York State DOT

Linh Warren,
FHWA

Pinar Okumus,
University at Buffalo, The State University of New York, Subject Matter Expert

SCAN MANAGEMENT

Arora and Associates, P.C.

Lawrenceville, NJ
June 2023

The information contained in this report was prepared as part of NCHRP Project 20 68 U.S. Domestic Scan, National Cooperative Highway Research Program.

SPECIAL NOTE: This report IS NOT an official publication of the National Cooperative Highway Research Program, Transportation Research Board, or the National Academies of Sciences, Engineering, and Medicine.

Table of Contents

List of Appendices

List of Figures

List of Tables

Abbreviations and Acronyms

AASHTO	American Association for State Highway Transportation Officials
ACI	American Concrete Institute
ASTM	ASTM International
CRR	Corrosion Resistant Reinforcement
DOT	Department of Transportation
ECC	Engineered Cementitious Composites
FHWA	Federal Highway Administration
FRP	Fiber-Reinforced Polymer
GFRP	Glass Fiber-Reinforced Polymer
HMA	Hot Mixed Asphalt
LRFD	Load and Resistance Factor Design
NCHRP	National Cooperative Highway Research Program
NEXT	Next Generation Extreme Tee
OPC	Ordinary Portland Cement
PCI	Precast/Prestressed Concrete Institute
PLC	Portland Limestone Cement
UHPC	Ultra-High Performance Concrete
US	United States

Executive Summary

The objective of this scan was to identify innovations related to concrete bridge decks and learn from the experience of transportation agencies that employ these innovations in the US. These innovations aim to improve one or more of the following aspects of concrete bridge decks: durability, crack resistance, corrosion resistance, repair and maintenance, constructability, construction speed, environmental sustainability and/or safety. Most innovations focused on addressing deterioration in bridge decks.

A workshop was held in early 2023 with the participation of the following states: California, Florida, Iowa , Kansas, Michigan, Minnesota, New York, Oklahoma, Pennsylvania, Texas, Utah, Virginia, and Washington. The topics discussed included concrete mixes and mix design development, concrete placement and finishing, curing methods, deck surface protection, fiber-reinforced concretes, corrosion resistant reinforcing bars, prefabrication, construction/design/quality control practices, workforce training, and tracking the results of innovative projects.

The scan concluded that crack mitigation relies equally on concrete mix design, care in placement, finishing, curing, structural loads, and demand. Low paste content, controlled plastic concrete temperature, restricting temperature difference between concrete and adjacent surface, limiting ambient temperature fluctuations, and wet curing without delay can help reduce cracking. Internal curing has been very effective where lightweight aggregates are available, and when their quality and conditioning can be controlled. However, successful use of internal curing requires significant involvement from owners and interaction between owners, contractors, and concrete suppliers. Discrete fiber reinforcement in concrete can provide an additional measure for crack mitigation. However, fiber type, size, and amount need to be selected for a target performance, and fiber acceptance criteria and test methods need to be developed.

Rheology and construction requirements for Ultra-High Performance Concrete (UHPC) and normal concrete differ significantly. When these differences were considered, UHPC joints between precast deck panels and between panels and girders have generally performed well and have performed like post-tensioned joints. UHPC link slabs have successfully eliminated joints in some states. Non-proprietary UHPC mixes and recent availability of new suppliers may decrease the cost of UHPC soon. Other fiber-reinforced concretes with lower cost and easier placement may be a reasonable alternative for applications that do not need the level of performance provided by UHPC.

Corrosion-resistant reinforcement provides better durability and can be used selectively when exposure is severe, when longer service life is desired, or when periodic maintenance is not an option due to difficulties with access. Several states specify corrosion-resistant reinforcement based on a target service life. For all types of rebar, field data that support laboratory data are needed to better compare bar performance under realistic and varying exposure conditions. In addition, research is needed to understand the performance of products that have improved over time, such as fiber-reinforced polymer reinforcing bars.

Partial depth precast panels are standard practice in some states and proved economical. However, success with partial depth panels depends on attention to detail during construction. Full depth precast panels accelerate construction further and may be suitable for when bridge geometry is simple, when concrete suppliers are not available nearby, and when attention is given to joint details.

Use of smaller reinforcement amounts, use of smaller bars at smaller spacing, and aligning the bars perpendicular to prevalent crack direction are practices implemented to reduce cracking, albeit with varying results. New details are developed and are being tested for haunch reinforcement when haunch thickness is large.

Best practices vary from state to state and over time due to variabilities in materials and practices. Information exchanges that discuss proper construction practices and specification development are recommended to learn from states with consistently successful experiences. Training the workforce and maintaining existing workforce knowledge is essential. This can be accomplished through development of standard practices, holding information exchange workshops, offering training opportunities for design, construction and inspection engineers and contractors, and making information accessible to the agencies or public by developing innovation-specific databases, reports, or websites.

CHAPTER 1

Introduction

1.a. Objective

The objective of this scan is to identify innovations related to concrete bridge decks and learn from the experience of transportation agencies that employ these innovations in the US. These innovations aim to improve one or more of the following aspects of concrete bridge decks: durability, crack resistance, corrosion resistance, repair and maintenance, constructability, construction speed, environmental sustainability, and/or safety. As expected, most innovations focus on addressing deterioration in bridge decks. Innovations that resulted in new materials, new construction technologies, or new design or details were of interest to the scan. Some of these innovations were introduced decades ago but improved over time based on experience, while the others were introduced very recently with limited opportunity for field evaluation. Similarly, some innovations are promising but the products may have limited availability in the US. Although deck maintenance, replacement, and rehabilitation were discussed, the scan mainly focused on new deck design and construction.

1.b. Method

A workshop was held virtually January 30–February 3, 2023. Scan team members, scan participants, and invited speakers presented research and practices related to deck materials, construction methods, design methods, and observed deck performance. The topics of the presentations and the presenters were identified through a desk scan that involved a detailed literature review. The topics discussed included concrete mixes and mix design development, concrete placement and finishing, curing methods, deck surface protection, fiber-reinforced concretes, corrosion resistant reinforcing bars, prefabrication, construction/design/quality control practices, workforce training, and tracking the results of innovative projects. At the end of each workshop day and at the end of the workshop, the scan team met to discuss the findings. The scan team members also kept detailed notes throughout the workshop. The subject matter expert compiled the discussion and notes into this report, which summarizes the findings of the scan.

1.c. Scan Team

The scan team composed of the following individuals:

- Donn Digamon, State Bridge Engineer, Georgia Department of Transportation (DOT) (scan chair)
- Cheryl Hersh Simmons, Chief Structural Engineer, Utah DOT
- Hannah Cheng, Structural Engineering, New Jersey DOT
- Don Nguyen-Tan, Chief of Office of Bridge Design, Caltrans
- Trey Carroll, Structures Management Unit, North Carolina DOT
- Pete White, Bridge Engineering Design Manager, Indiana DOT

- Terry B. Koon, Structural Design Support Engineer, South Carolina DOT
- Kevin R Pruski, Bridge Implementation Engineer, Texas DOT
- Scott Walls, Project Engineer, Delaware DOT
- Edward Lutgen, State Bridge Engineer, Minnesota DOT
- Rick Liptak, Chief Bridge Construction Engineer, Michigan DOT
- Harry L. White 2nd, Director of Structure Policy and Innovation Bureau, NYSDOT
- Pinar Okumus, Associate Professor, University at Buffalo (subject matter expert)

In addition to the individuals listed above, Dr. Bijan Khaleghi served as the scan chair during the desk scan and planning phases of the scan until he retired from Washington State DOT before the scan workshop. Mr. Harry Capers and Ms. Melissa Jiang from Arora and Associates, P.C. planned and facilitated the scan.

1.d. Scan Participants

Practices from the following thirteen states were showcased during the scan:

- California
- Florida
- Iowa
- Kansas
- Michigan
- Minnesota
- New York
- Oklahoma
- Pennsylvania
- Texas
- Utah
- Virginia
- Washington

In addition, Dr. Darwin from University of Kansas and Dr. Ley from Oklahoma State University presented on concrete mixes and placement, corrosion resistant reinforcement, fiber-reinforced concretes and in-field and laboratory test methods for concrete.

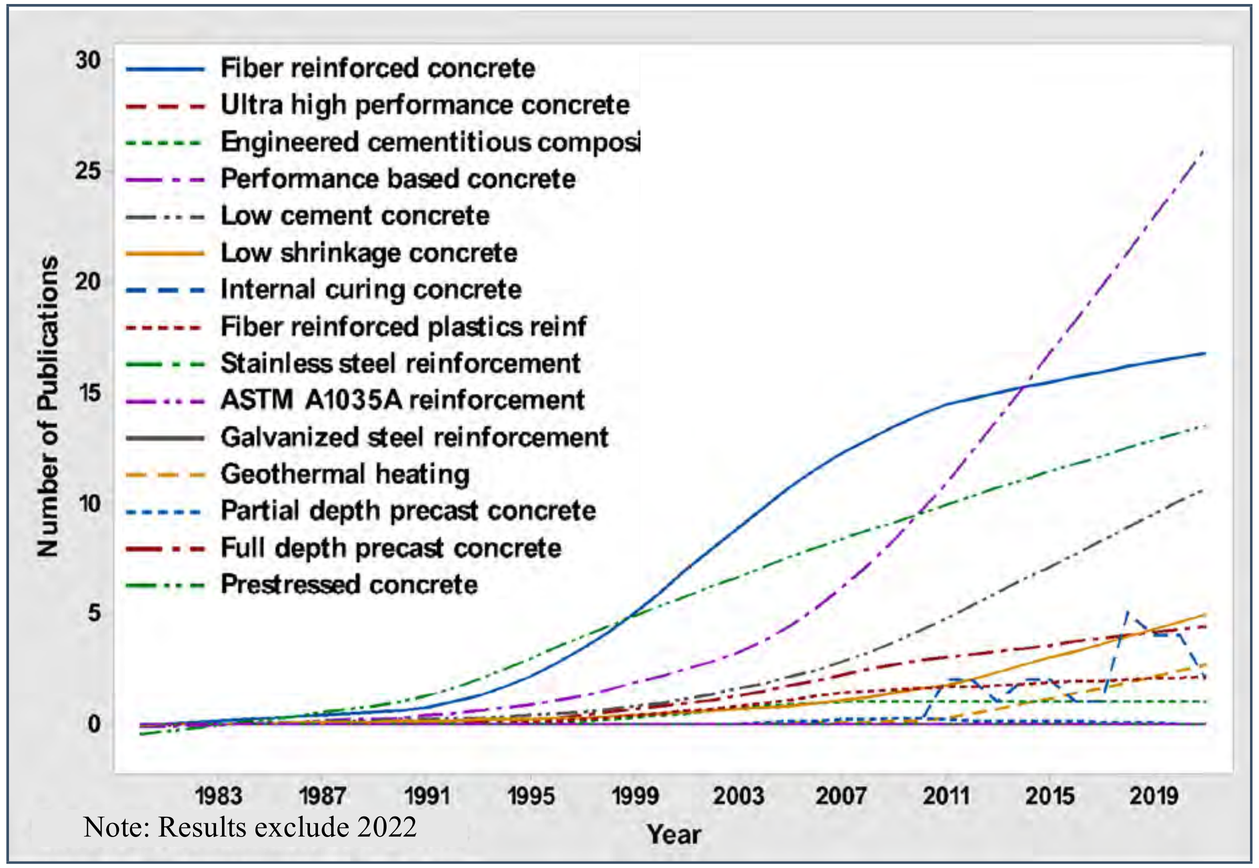
1.e. Scan Topics

An initial desk scan has identified the innovation areas shown in Table 1 through an in-depth literature review.

Fiber-reinforced concretes	● Ultra-High Performance Concrete ● Engineered Cementitious Composites ● Other fiber-reinforced concretes
Concrete mixes	● Performance-based mixes ● High performance concrete ● Sustainable concretes ● Admixtures
Curing methods	● Internal curing ● External curing
Surface protection	● Overlays/wearing surface ● Waterproofing membranes ● Sealers
Reinforcement materials	● Fiber-reinforced polymers ● ASTM 1035A reinforcement ● Stainless steel reinforcement ● Stainless steel-clad reinforcement ● Galvanized steel ● Continuous galvanized steel ● Textured epoxy coated steel ● Dual coated steel ● Cathodic protection of rebar
Decks with no internal rebar	
Prefabrication	● Partial depth precast decks ● Full depth precast decks ● Proprietary prefabricated decks
Heated decks	N/A
Design and quality assurance	N/A

Table 1. Innovations within the scope of the scan

Figure 1 shows trendlines for the number of academic publications that relate to these innovations over the last 25 years. The figure is created using data from a citation database of scholarly articles [1] using keywords shown in the legend and the word “deck”. The figure is an indicator for when innovations were first introduced to the literature as well as trends over time. The figure shows that there has been increasing interest from the academic community related to “performance-based concrete,” “fiber-reinforced concrete,” “prestressed concrete,” and “low cement concrete” for decks. Since the goal of the scan is to facilitate exchange of information between states, innovations that have been published in the literature but not yet implemented by any states have been excluded from the scan.



Note: Results exclude 2022

Figure 1. Research trends for innovations related to decks

In preparation for the scan, the scan team members ranked the innovations shown in Table 1 in the order they consider them beneficial for the scan. The results are shown in **Figure 2** and indicate that there is a strong interest in improving concrete mixes through fiber reinforcement, admixtures or performance-based designs. The scan team also expressed interest in prefabrication as well as alternative reinforcement types but the level of interest in reinforcement depended on the type. This domestic scan focused on topics that were ranked high as shown in Figure 2. For example, decks with no internal reinforcing bars or cathodic protection were not part of the scan.

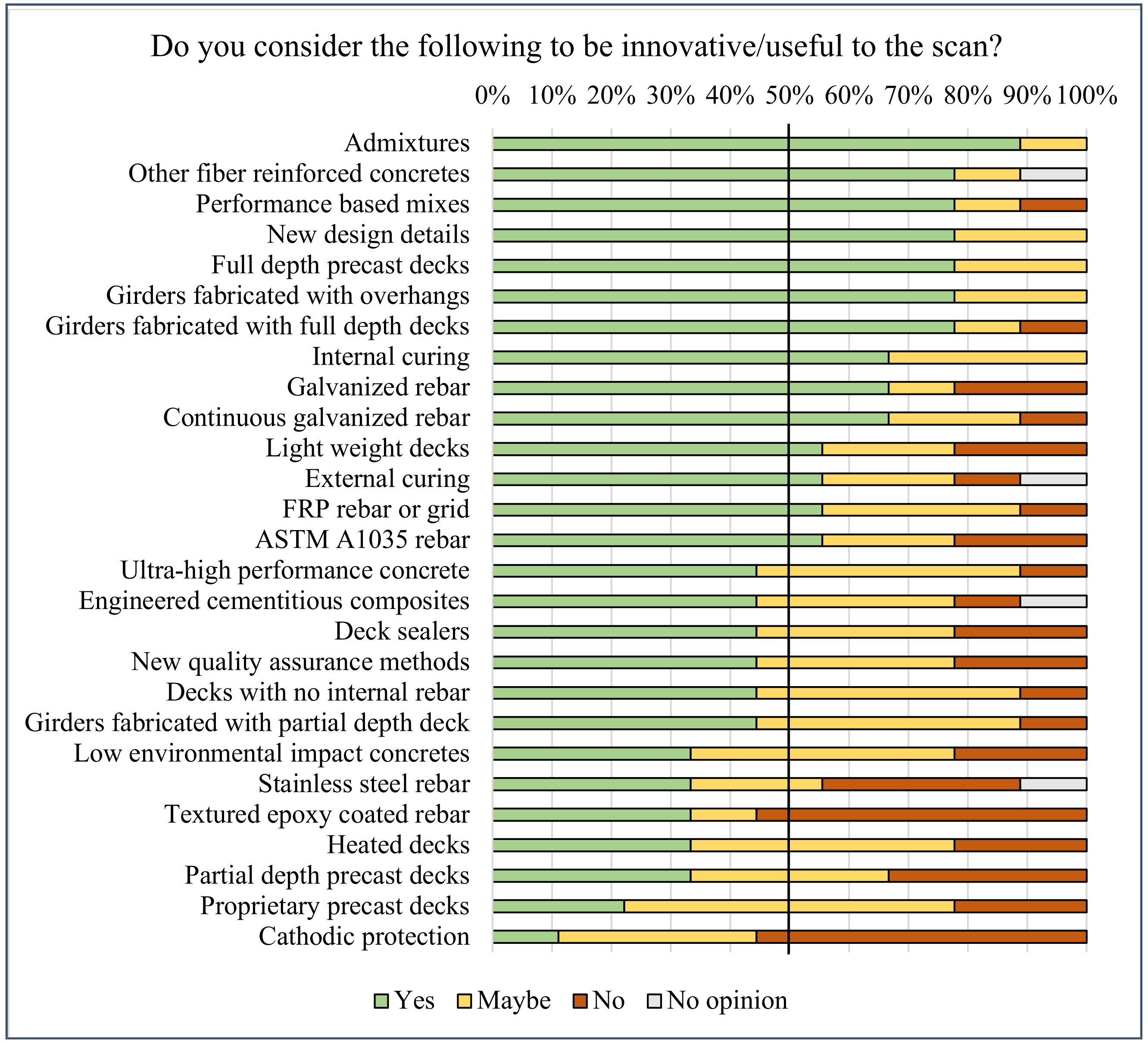

Do you consider the following to be innovative/useful to the scan?

Figure 2. Responses of 9 out of 13 DOT affiliated members of the Scan Team on whether they consider the technologies shown as innovative or useful to the scan

The following sections summarize the findings of this scan.

CHAPTER 2

Concrete Mixes, Placement, Protection

Control of deck cracks depends equally on the concrete mix and care in placement, consolidation, finishing, and curing. A common theme of the scan was to prioritize improving concrete quality (e.g., low permeability) by reducing cracking over using corrosion-resistant reinforcement. This section summarizes findings on concrete mixes and placement that can help reduce cracking.

2.a. Concrete Mixes

In an NCHRP Synthesis survey, 31 out of 39 DOTs used high performance concrete for cast-in-place concrete decks [2]. In this survey, DOTs identified that reducing drying shrinkage of mixes, together with avoiding high strength, applying wet curing immediately and continuing for at least 7 days, followed by a curing compound, reduced cracking. On the other hand, specifying maximum slump, prescriptive mixes, specifying concrete temperature ranges, curing membranes, evaporation retardants, and omitting trial casts were found to have insignificant benefits. The following subsections summarize the scan findings.

2.a.i. Paste Content

The scan participants generally agreed that keeping the paste (water and cement) content low helps reduce cracks. A pooled funded study led by Kansas DOT [3] resulted in implementation of low-cracking, high performance concrete specifications to 16 bridges in Kansas and two bridges in Minnesota. This mix has low cement content, low slump, moderate strength, and decks were constructed with temperature control, minimum finishing, and early and extended curing. When compared to control cases, most of the decks had less crack density as revealed by yearly surveys of cracks over approximately 10 years.

Mixes provided as examples during the scan included the Kansas DOT mix that limits paste content to 27%, cementitious material content to 540 lb/yd^3, and a water-to-cement ratio to a range between 0.43 and 0.45. Virginia DOT uses a mix that has a maximum cementitious content of 600 lb/yd^3, and a water-to-cement ratio less than 0.45. Pennsylvania DOT limits cementitious material content to 640 lb/yd^3 and has a water-to-cement ratio between 0.40 and 0.45. These DOTs experienced reduced cracking with these mixes, which resulted in moderate but adequate strength concretes. Cementitious material content can also be limited by specifying an upper limit for compressive strength. However, some states are reluctant to do this because of concerns with high variability of supplied concrete mixes potentially resulting in lower than specified strengths.

2.a.ii. Performance-Based Mixes

Both performance-based mixes and prescriptive mixes were discussed during the scan. According to the ACI Committee 329 [4], a performance-based specification for concrete “defines required results, the criteria to judge performance, and verification methods without requirements for how the results are to be obtained.” Therefore, performance-based specifications, also known as the end-result specifications, are an alternative to prescriptive specifications that dictate material amounts, proportions, workmanship, production, and installation processes and methods. For example, performance-based specifications commonly include requirements for permeability, minimum compressive strength, air void system parameters, alkali-aggregate reaction resistance, shrinkage limits, and abrasion resistance [5]. Because the requirements may relate to long-term performance, a challenge associated with performance-based concretes is potentially longer lead times required to develop and test concretes [5]. In addition, test methods may not be available or feasible to measure the performance within a reasonable time frame or at a reasonable cost. The scan concluded that due to difficulties and time associated with measuring the end results of true performance-based specifications, hybrid specifications with features of both performance and prescriptive mixes can provide suppliers better options, particularly for remote construction regions.

2.a.iii. Limiting Shrinkage

A common performance requirement for reduced deck cracking is low shrinkage, which can be achieved either with the mix itself or with shrinkage-reducing admixtures. Shrinkage-reducing admixtures are a type of organic chemicals called surfactants and reduce shrinkage strains in concrete by reducing the surface tension of pore fluid of concrete and capillary stresses [6]. Virginia DOT specifies a maximum 28-day shrinkage strain (350 microstrain) for their normal weight concrete, and shrinkage-reducing admixtures are allowed to achieve this requirement. Utah and Washington DOTs have the same shrinkage strain limit for their mixes. California DOT, having highly benefited from shrinkage-reducing admixtures, included the admixtures in their specifications and observed an insignificant change in total bridge cost. They limit shrinkage strain to 300 microstrain in their specifications.

2.a.iv. Supplementary Cementitious Materials

Supplementary cementitious materials, such as fly ash, silica fume, or slag cement, are used to replace cement, to lower permeability, and to increase resistance to alkali-silica reaction. Fly ash is the most common type of supplementary cementitious material and is a byproduct of the coal industry. In response to shortages of fly ash across the US due to the declining number of coal plants, harvested fly ash is being recovered from landfills [7]. Texas currently does not have supplementary cementitious materials other than fly ash readily available. However, they are considering blended supplementary cementitious materials, ground bottom ash, and harvested fly ash, with harvested landfills starting in 2023 and a slag cement grinding facility in 2024. Portland Limestone Cement (PLC), a blended cement with higher limestone content (more than 5% but up to 15% by mass of the blended cement per ASTM C595 [8]) as compared to Ordinary Portland Cement (OPC) (up to 5% per ASTM C150 [9]), can also lower CO2 emissions by reducing the Portland cement clinker amount. Texas DOT uses PLC. California DOT-sponsored research that indicated that PLC can be a suitable and environmentally sustainable replacement for OPC [10], and work is underway to implement the material in California. Ongoing research in this state is also exploring other alternative supplementary cementitious materials and sources. The recent shift in the cement industry towards production of PLC may lead to unavailability of OPC soon.

2.a.v. Test Methods for Concrete

In addition to the modern mix specifications that focus on the aspects listed above, knowledge of concrete mix and properties that impact durability is key in achieving high-quality results. Two test methods were developed at Oklahoma State University and can measure such properties for fresh concrete: air voids that impacts freeze thaw resistance and water-cement ratio that impacts strength and durability. A test method (called super air meter [11], performed per AASHTO T395 [12]) that can measure air void size distribution on site, rapidly and for fresh concrete, is specified by several states. The test can be used to develop mixes with a desired void distribution, or to verify quality for freeze-thaw resistant concrete. Specifiers can require a range of air volume and air void spacing factor.

A second test method (called Phoenix [13]) has been used by several states to rapidly measure water content in fresh concrete as an alternative or to supplement traditional slump tests. This test can serve as an acceptance criterion for fresh concrete and may be a better indicator for concrete quality compared to traditional slump tests. The test can also measure moisture content of aggregates, which can be important for lightweight aggregates used for internally cured concrete.

2.b. Placement

Construction practices (rebar placement, concrete pouring, consolidating, finishing, and curing) have significant impacts on deck quality. Minimal finishing of concrete, avoiding walking in the mix after vibrating, and avoiding finishing aids are important so that the aggregate is not disturbed, and wet curing can start without delay. For this reason, the practice of thining fresh concrete is being replaced with saw grooving of hardened concrete in most states. Specifying plastic concrete temperature ranges, pouring when ambient temperature fluctuations are small, and limiting the difference between concrete and contact surface (e.g., girder) temperatures are good practices, but achievable temperature ranges depend on the climate and specifying small ranges of plastic concrete temperatures (e.g., 55–70°F) may not be feasible for all climates. Nighttime pours can limit ambient temperature fluctuations but have challenges related to availability of labor and materials as plants do not want to operate at night. Evaporation rates can be controlled in the field using foggers and wind barriers.

2.c. Surface Finish

There are a variety of concrete surface finishes that states have used. Appropriate surface roughness is needed to prevent traffic accidents as bridge decks begin to ice up prior to adjacent pavement. The oldest and simplest surface finish is transverse tining (**Figure 3**, left). Tining can be problematic with concrete that is set up or when there is a large dosage of fibers. Some states do not use tining any longer and require cutting grooves in hardened concrete to create texture. Depths of removal and texturing range from 1/16 in. to 1/4 in. Benefits include removing high spots and allowing positive drainage to prevent water ponding and accelerated corrosion. This also allows concrete sealers to be applied if the owner uses a curing compound as part of curing. The biggest benefit is the reduction in tire noise from traffic and the good friction surface. Disadvantages include the extra cost and possible issues around drains and strip seal expansion joints combined with the possible increase in permeability from removing the concrete top skin. There are different textures that can be removed from the concrete surface. Minnesota DOT uses a technique called planing to remove the minimal top surface as seen in **Figure 3**, middle. Some states use a longitudinal grooved surface for noise and texture (**Figure 3**, right). The grooved surface leaves a portion of the original deck surface whereas planing removes the entire surface. Georgia DOT uses transverse grooving and does not allow tining for bridge decks. Michigan uses surface finishing transverse to structure centerline with the goal of applying healer or sealers with grit after two winter cycles. They have observed that epoxy overlays and the stone matrix help keep deicing salts on the surface in the winter and help prevent freezing.

Figure 3. Transverse tining (left), longitudinal planing (middle), longitudinal groove (right) in Minnesota

2.d. Curing

Curing deck concrete is critical to minimize shrinkage cracking while developing the required strength. It can be done through external curing, or internal curing followed by external curing. While external curing is common practice, internal curing is relatively new and is not practiced in all states for reasons discussed in this section.

2.d.i. External Curing

External curing is applied to maintain moisture and temperature conditions required to allow the hydration process. External curing can be applied through wet curing or curing compounds. Although wet curing can be performed by placing water on concrete (fogging, spraying, ponding), for practicality, prewetted curing blankets (sacks, cotton mats, burlap, straw, waterproof paper, some of which are proprietary products) are commonly placed on freshly finished concrete [14]. The most common duration of wet curing was identified as 7–10 days, as a balance between concrete quality and meeting construction schedule, among eighteen US states that were surveyed in a separate study [15]. As an alternative to wet curing, curing compounds can be applied to delay and reduce water evaporation. However, these do not provide additional moisture or completely prevent moisture loss [16], and consistent uniform application to obtain a membrane barrier takes effort.

The scan concluded that preventing delays in external wet curing after concrete placement is critical to quality of finished concrete. Practices that shorten this delay, as discussed during the scan, were minimal concrete finishing, applying misting, using work bridges (having multiple on site) over the wet deck concrete that allow workers to start curing as quickly as possible after deck placement, and monetary penalties that are proportional to curing delay time. Wet burlap can be applied early but may mar the surface. Extended curing (as long as 21 days in some states), using misting, presoaked burlap/burlene/cotton mats/curing blankets, spray and soaker hoses, and plastic covers are practices documented as beneficial in limiting cracking. Curing compounds are used by some states to slow down evaporation.

2.d.ii. Internal Curing

Internal curing is a method where a fraction of the aggregates is replaced with pre-wetted lightweight aggregate, although other internal curing agents such as superabsorbent polymers [17] are also being developed. During curing, water stored in the aggregate is released to help hydration or to replace moisture lost to evaporation. In other words, internal curing is a "process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water. [14]"

New York State DOT internally cures concrete on all multi-span bridge decks because they observed reduced cracks in 20 bridges built around 2008 within a couple of years of service life [18]. New York State DOT reports that the material cost of internal curing concrete is marginally higher, and the installed cost is like conventional concrete. Similarly, Virginia used prewetted lightweight coarse and fine aggregates successfully and has benefitted from internal curing. Virginia DOT also reports benefiting from the low modulus of elasticity and low coefficient of thermal expansion of lightweight concrete. They do not require shrinkage testing when lightweight concrete is used. On the contrary, other states have not used internal curing or had mixed results because either they do not have lightweight aggregate available locally or the quality of the lightweight aggregate is questionable. Lack of contractor experience and insufficient project oversight in these states have also stopped lightweight concrete use from becoming standard practice. The exchange of information between states revealed that success in this method relies on the availability, quality, and conditioning of the aggregate, and being able to determine surface and internal moisture of the aggregate on the day of mixing and adjusting the mix accordingly. This means that significant owner involvement may be needed to execute internal curing properly.

2.e. Surface Protection

Surface protection can be accomplished through overlays, waterproofing membranes, sealers, or combinations of these. Although overlays are typically used for rehabilitation, they can also be used for new decks to provide additional durability, to cover an uneven surface associated with precast deck members, or for complex geometry bridges to get a good ride that prevents water ponding. Waterproofing membranes are typically proprietary products placed on top of decks to serve as a barrier that prevents moisture and chlorides from reaching concrete. Sealers reduce the amount of water and chloride penetrating into concrete and may be effective when concrete has moderate permeability [19]. Unlike membranes or overlays, sealers leave the deck surface visible for inspections [20]. According to an NCHRP study survey with a focus on rehabilitation [21], epoxy, methacrylate, and silane sealers are the most common sealers used in the US and Canada. An NCHRP survey [19] with a focus on rehabilitation identified that asphalt overlays with membranes are the most commonly used overlays in the US and Canada. This type of overlay was used by 67% of survey respondents. Most states that participated in the scan do not use an asphalt overlay on new decks. If reduced cracking can be achieved with the deck concrete itself or if part of the deck top cover can be used as a structural overlay, an additional overlay is not recommended for new decks by these states.

The following surface protection options have been discussed during the scan. Two examples are shown in **Figure 4**. The information and numbers in parentheses are cost per square foot of the overlays as reported or estimated by New York State in upstate New York: polymer concrete overlay ($15) such as polyester polymer concrete, epoxy polymer concrete, thin polymer overlays ($5), hybrid composite synthetic concrete with fibers ($17); waterproof hot mixed asphalt (HMA) ($5); HMA and sheet ($3)/hot applied($11)/spray applied membrane ($12), Ultra-High Performance Concrete (for existing decks), concrete overlays such as latex modified concrete ($20), micro-silica concrete ($5), concrete modified with fly ash and micro-silica ($10), and silica penetrating surface treatment. Regardless of the type, overlays require proper surface preparation and proper installation to serve the life span they are intended for. In addition, low slump overlays are used in some mid-western states, but the success depends on availability of equipment and experienced contractors.

Figure 4. Thin polymer overlay, hybrid composite synthetic concrete (New York State)

Ultra-High Performance Concrete (UHPC) overlays have also emerged as an alternative and have been used in states that include New York [22], [23] and Delaware, as discussed in Section *3.b. Ultra-High Performance Concrete.*

CHAPTER 3

Fiber-Reinforced Concretes

Research and development of fiber-reinforced concretes goes back to the 1960s. According to ASTM, there are four types of fibers used in concretes: steel (stainless steel, alloy steel, or carbon steel), glass, synthetic, and natural (e.g., cellulose) [24]. Steel and synthetic fibers are the most commonly used fibers in construction [25]. Synthetic fibers include polyolefin (polypropylene, polyethylene), polyvinyl alcohol fibers, carbon fibers – among others [26] – and are suitable for bridge applications because of their resistance to deterioration. Fiber material, size, amount, orientation, and distribution have direct impacts on mix properties [27]. Synthetic fibers with diameters smaller than 0.012 in. (microfibers) are mainly used to control shrinkage cracks and do not considerably change mechanical properties [25], while larger (macro) fibers can significantly improve post-cracking properties. Combinations of fibers have been used to improve both.

3.a. Mixes with Fiber

Several states experimented with fiber reinforced concretes. A pooled funded study [28] identified 20 states with language related to fiber-reinforced concretes in their specifications. The scan showed that fiber-reinforced concretes are generally being used as an additional crack control measure to protect against material quality issues, poor curing or construction practices, or when required by loading. Among the scan participants, the use of fibers in concrete is standard practice in California. They require 1 lb. per cubic yard of microfibers and 3 lb. per cubic yard of macro fibers in their specifications. They observed insignificant changes in total project cost in pilot projects. Virginia DOT provides fibers as an option when needed, for example to address plastic or drying shrinkage or when loading or short splice lengths require fibers. The use of non-metallic fibers in concrete has been standard practice in Minnesota for the last ten years with success. The dosage depends on the fiber type and the department maintains a list of approved products.

In addition to crack control, fibers have also been used to improve the bond between concrete and reinforcement. Improved bond allows shorter splice and development lengths of reinforcement for prefabricated deck panel joints, between panels or between panels and girders. **Figure 5** shows such examples of fiber-reinforced concrete use.

Figure 5. A fiber-reinforced Engineered Cementitious Composite (ECC) mix used for a shear key (left), fiber-reinforced concrete used for a link slab (right) in Virginia

Fiber material, diameter, length, amount, orientation, and distribution impact the properties of a mix. In addition, fiber quality and properties can vary from supplier to supplier. Therefore, deck performance should not be expected to enhance by simply adding fibers to concrete. Rather, fibers should be selected for a target performance (e.g., post-cracking strength, shorter bond length) and mixes need to be adjusted for decreased workability stemming from the addition of fibers. Moreover, tests and criteria that can be used to approve fiber suppliers and fiber types are needed for states to get consistent results. Tests that can measure tensile strength, post-cracking strength, crack size, and workability were presented at the scan by Dr. Ley [29] and provide options for selecting fibers for a given performance.

3.b. Ultra-High Performance Concrete

UHPC is a tensile strain-hardening fiber-reinforced concrete with a high binder ratio and high compressive strength (e.g., larger than 17 ksi [30, 31] or 22 ksi [32, 33]). UHPC's tensile strain capacity (<0.2%) is much larger than typical conventional concrete tensile strain capacity (~0.01%) [34]. UHPCs typically employ high-strength steel fibers, although synthetic fibers have also been used. UHPCs have low matrix porosity and high particle packing density for increased durability [35]. Because the cost of UHPC is much higher than conventional concrete, UHPC has mostly been used for applications that require a small volume of materials: precast deck panel-to-panel joints, deck panel to girder joints, link slabs, and overlays (for existing bridges). The benefits include durability, better bond to concrete, and smaller joints or elimination of joints (link slabs).

3.b.i. Link Slabs

New York State presented on UHPC link slabs during the scan workshop. Link slabs are the part of the deck over the support and are used to eliminate joints that are known to cause deterioration at girder ends and piers. When there is a link slab, the rotation is assumed to occur within the link slab, and the translation takes place at the girder bearings. The link slab is designed as a hinge when assessing the global behavior of a bridge, and otherwise is designed as a flexural member with moments that are induced by girder end rotations, applied at the ends of the link slab. The length of UHPC link slabs is much shorter (2–3 ft) compared to conventional concrete link slabs (approximately 20% of the span length). The thickness of the link slab is also reduced to 4 in. (partial depth) when UHPC is used. For conventional link slabs, a bond breaker is applied to the girder surface for debonding. For UHPC link slabs, shear studs are typically retained. If shear studs interfere with the debonded zone, only the studs at the end of a girder are removed and replaced with shorter studs. **Figure 6** compares a conventional concrete link slab to a UHPC link slab. At the time of the scan workshop, New York State had built 85 UHPC link slabs and planned to build 49 additional UHPC link slabs soon. Many of the applications of UHPC link slabs in New York have been on existing bridges to replace and eliminate expansion joints. **Figure 7** shows a UHPC link slab construction and the finished link slab from New York State.

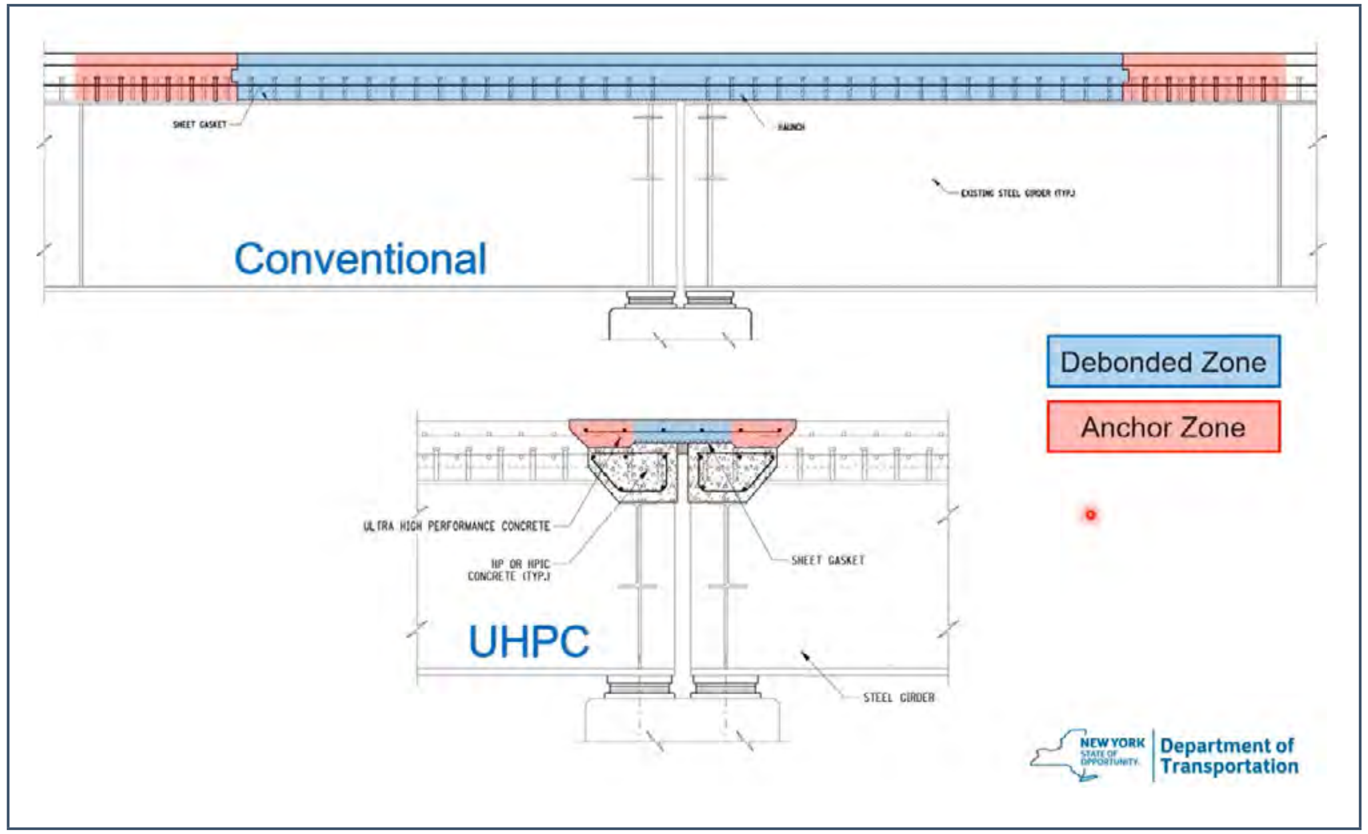


Figure 6. Comparison of link slabs with conventional concrete and UHPC from New York State DOT

Figure 7. Link slab construction (left), finished link slab (right) from New York State DOT

3.b.ii. Precast Concrete Deck Panel Joints

Utah summarized the performance of 21 bridges they built with precast concrete deck panels in a recent report [36] and presented an excerpt at the scan workshop. After experimenting with five different joint details, Utah concluded that full depth precast concrete deck joints made of UHPC can provide equivalent performance to joint post-tensioning. This is contrary to the experience of Pennsylvania, where a bridge with UHPC joints had cracks and leakage at the joint without a known cause. Although Utah used precast concrete deck panels since 2003, they used a UHPC joint detail for the first time in 2014 (**Figure 8**).

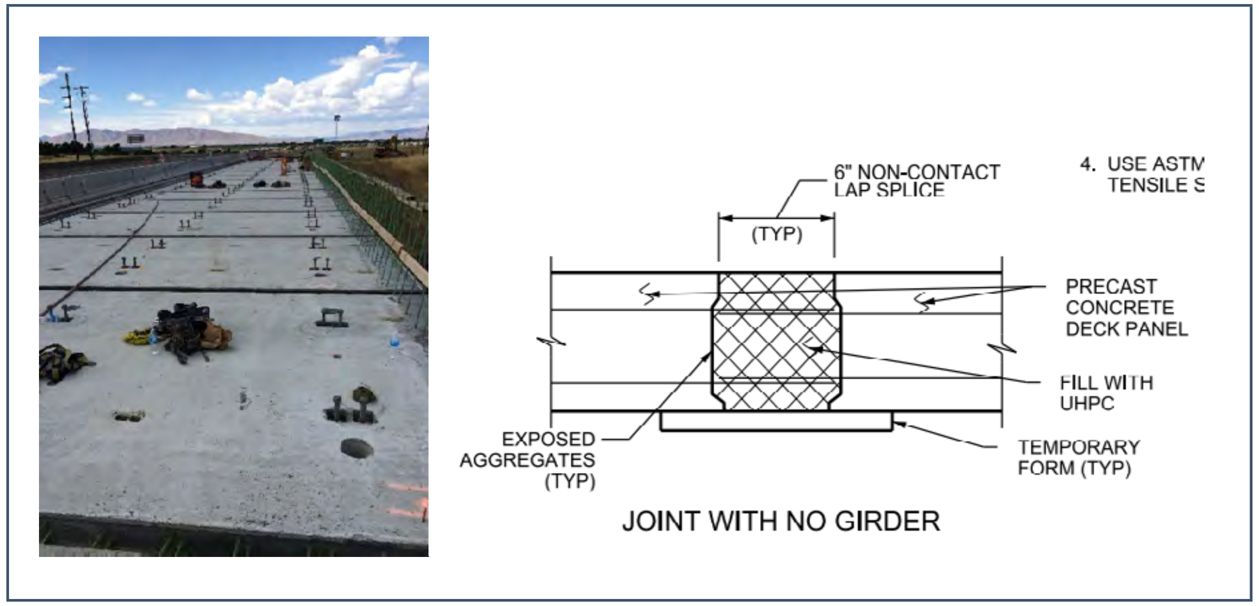


Figure 8. Transverse full depth precast concrete panel joints with UHPC from Utah

New York State has used UHPC for joints between full depth precast deck panels and for shear stud pockets since 2009, developed specifications in 2012, and standard details in 2019. New York State specifications require the contractor to have the UHPC supplier to be on site, until the contractor gains experience with the supply, mixing, delivery, placement, and curing of UHPC. They have hidden shear stud pockets as shown in **Figure 9** (left); the shear studs do not extend into the deck and eliminates interference of deck and shear transfer reinforcement. The UHPC itself transfers the shear between girder and deck.

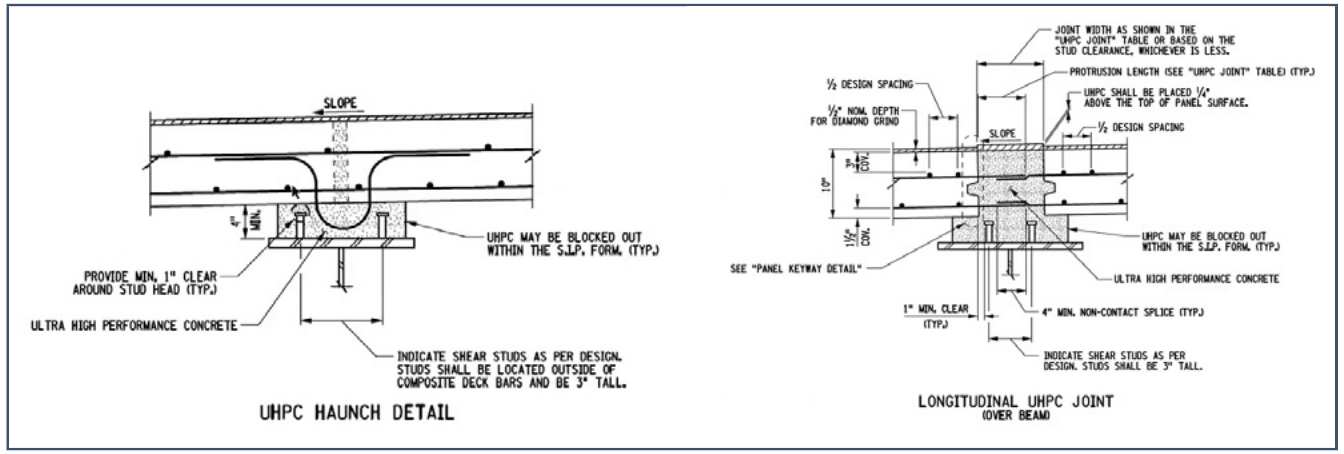


Figure 9. Full depth precast concrete panel shear stud pocked (left) and longitudinal panel-to-panel joint (right) detail from New York State DOT

Texas has initiatives to use UHPC for closure pours, allowing options for either proprietary or contractor formulated UHPC mixes. Washington used UHPC between decked girders. UHPC was placed by starting at the end of the deck with a lower elevation and gravity filled the forms. Girder joint surfaces had exposed aggregate to enhance bond between UHPC and girders. Washington also uses UHPC between full depth precast concrete deck panels, otherwise post-tensioning is required to connect the deck panels.

In general, when UHPC is used for joints, care needs to be taken so that the forms are secured and sealed against leakage and hydraulic pressure is maintained over the joints as the material settles. **Figure 10** shows formwork and buckets used to create hydraulic pressure over UHPC joints from New York State. In addition, care is needed so that fiber settlement is prevented, flow length needs to be limited to ensure fibers do not all align in the flow direction, and precast concrete surfaces need to be roughened and brought to a saturated surface dry condition before the placement of UHPC. Requiring the UHPC supplier to be present at the site may mitigate some of these potential issues.

Figure 10. Sealing of precast deck panel forms for UHPC joints (left), finished joints (right) from New York State

3.b.iii. Decks with Optimized Geometry

Most states used UHPCs in bridge decks as low-risk replacements of normal concretes or in small amounts due to the high cost of the material. The exception to using UHPC in smaller amounts is a project in Wapello County, Iowa that had an optimized deck geometry. The deck panels were prefabricated and were ribbed in two directions (waffle shape). The panels were tested by Iowa State University [37] before they were implemented in a bridge in 2011 and a design guide [38] was made available. Joints between the precast waffle deck panels and shear key pockets were also UHPC. **Figure 11** shows the prefabricated panel with shear stud pockets (top left), panel-to-panel joints (top middle), weights placed on panel-to-panel joints (top right), grinding of the excess UHPC over the joints (bottom left), and the finished deck (bottom right).

Figure 11. Prefabricated UHPC two-way ribbed (waffle shaped) bridge deck from Wapello County, Iowa

A bridge with a decked pi-shaped UHPC girders, developed and tested by FHWA [39], was built in Buchanan County, Iowa in 2008. These projects with large amounts of UHPC showed the possibility of building entire bridge elements with UHPC. However, they are not common as they are perceived to be costly despite reductions in element size and reinforcement. Since there are only a few applications to date and the applications are recent, it is too early to provide an additional cost or a service life cost estimate for projects in which entire bridge elements are made of UHPC.

3.b.iv. Overlays

Although the focus of this scan is on newly built bridge decks, overlays have also been discussed during the scan. Among the scan participants, New York and Iowa used UHPC overlays successfully. When used as an overlay material, UHPC mix rheology needs to be adjusted to prevent unintentional flow of the material without hindering workability. Achieving the required surface profile may require grinding of the overlay.

3.b.v. Non-proprietary mixes

Availability of multiple vendors and increasing experience of contractors with the UHPC are expected to bring the cost of proprietary UHPC down. To further reduce costs, multiple non-proprietary UHPC mixes are being developed across the US utilizing local materials. Iowa State University developed mixes [40] that were later used by Iowa DOT in 2022. **Figure 12** shows the proportions of the mix that used 285 ksi minimum tensile strength, 0.008 in. diameter, 0.5 in. long steel fibers at 2% by volume.

Ingredient	Cement	Sand	Masonry Sand	Silica Fume	Water
Volume Ratio (for 1.0ft^3)	0.425	0.226	0.200	0.060	0.089
Proportion (lb/yd^3)	1500	790	710	210	320

Figure 12. Proportions of the mix used by Iowa DOT

Michigan DOT funded research at University of Michigan that developed non-proprietary UHPC mixes. After an unsuccessful attempt that resulted in switching to a proprietary mix, the non-proprietary mix was adjusted to use undensified silica fume, shorter fibers, and additional high range water reducing admixtures. This mix, shown in **Figure 13**, was used for joints of decked beams by a local agency, a composite tub girder bridge and a three-stem decked girder in Michigan. Michigan DOT reports the cost of this mix to be $892 per cubic yard with 2% steel fibers and they plan to build other bridges with it.

Ingredient	Portland Cement Type 1	GGBFS	Silica Fume	HRWR	Silica Sand (Fine)	Silica Sand (Coarse)	Steel Fiber 0.5 in
0.22	0.5	0.5	0.25	3%	0.30	1.21	2.0% by volume

Figure 13. Non-proprietary mix used in a project in Michigan

Among the scan participants, Utah DOT has initiated a project with Utah State University to develop a non-proprietary mix [41] but the results are not yet available. Texas DOT sponsored research at Texas A&M University [42] that developed the mix shown in **Figure 14** with 1.5% steel fibers by volume. The fibers were 0.5 in. long and 0.008 in. in diameter. This mix was scaled up to build a 34 in. deep girder at a precast plant. The girder was tested in a laboratory, but the mix has not yet been implemented in the field.

Constituent	lb/yd^3	Material
Cement	1522	Alamo Type III
Silica fume	114	BASF MasterLife SF 100
Fly ash	158	Boral, Class F
Sand	1706	Heldenfels' sand (Max. #4)
Water	326	--
HRWR	36.6	Sika ViscoCrete 4100
Steel fiber	200	0.5" long, 0.008" diameter
w/cm	0.181	Excluded water from HRWR

Figure 14. Non-proprietary UHPC mix developed for a project funded by Texas DOT

3.c. ECC

Like UHPC, Engineered Cementitious Composites (ECC) is a type of fiber-reinforced concrete but typically has comparable compressive strengths to normal concrete. Commonly, ECCs employ PolyVinyl Alcohol or PolyEthylene fibers, at 2% by volume or less. ECCs have large tensile strain capacities, i.e., > 2% [34], and larger than UHPC's tensile strain capacity. ECC use has been much less common compared to UHPC use in the US, likely due to a lack of commercial mixes and technical guidance needed for large scale batching. ECC was developed at University of Michigan and was used by Michigan DOT on a link slab. The mix was revised based on the lessons learned on this project, but opportunities to use the material again in another bridge project have not since been identified in Michigan. Virginia DOT used ECC in shear keys and links slabs.

CHAPTER 4

Corrosion Resistant Reinforcement

Corrosion resistant reinforcement (CRR) discussed during the scan included stainless steel, ASTM A1035 steel, stainless steel clad rebar, fiber-reinforced polymer (FRP) rebar, hot dip galvanized and continuous galvanized rebar as alternates to epoxy coated rebar. Although alternative reinforcing bars can extend service life, they do not eliminate the need to repair cracked decks. For all types of rebar, field data that support laboratory data are needed to better compare bar performance under realistic and varying exposure conditions.

4.a. Fiber-Reinforced Polymers

Fiber-Reinforced Polymers (FRP) have been used as reinforcing bars in decks to increase corrosion resistance. Although aramid, basalt, carbon, and glass fibers are available, glass fibers have been the most common due to their lower cost. Glass fiber-reinforced polymer (GFRP) bars are lightweight and do not corrode. For this reason, they have been used by some states and explored by others. FRP reinforcing bars do not yield, have different concrete-bond characteristics than steel rebar and, depending on the fiber type, can have lower moduli of elasticity compared to steel rebar. Therefore, the design of bridge decks with FRP reinforcement is very different than ones with steel reinforcement. The design is often controlled by crack control requirements.

Florida DOT’s use of glass and carbon fiber polymers goes back to the 1980s. Since Florida has aggressive marine and acidic water-crossing environments, they allow FRP reinforcing bars to be used in concrete for approach slabs, bridge decks, overlays, flat slabs, as well as pile bent caps, piers, retaining walls, and railings with approval by the state structures design engineer [43], and have specifications for some of these bridge elements. Most applications have been for substructure elements. As part of their active research program on FRP reinforcing bars, Florida DOT developed a concrete railing with GFRP reinforcement and conducted impact testing [45]. A list of applications is listed on Florida DOT’s innovations webpage [44].

In 2013, Kansas used GFRP reinforcing bars in a deck (**Figure 15**, left) with a side-by-side deck that had traditional epoxy coated reinforcement. The increase in the cost of reinforcing bars was 18% and the total project was 6%. The crack density of the deck with FRP reinforcing bars was higher. In this project, the rebar used in the railing was metallic. While the light weight of FRP bars may facilitate construction in cast-in-place decks, Utah DOT used FRP reinforcing bars in precast concrete deck panels and observed that panels had to be supported from below due to the lower shear capacity of GFRP bars, which made placement harder than conventional precast concrete deck panels (**Figure 15**, middle).

Figure 15. GRP bars used for a redecking project in Kansas DOT, precast concrete deck panel with GFRP bars by Utah DOT, GFRP top mat with epoxy coated rebar bottom mat in Virginia

Washington DOT reported that, although the cost of GFRP bars is higher than conventional bars, there could be savings in installation costs due to the light weight of GFRP bars. Minnesota DOT's GFRP rebar use revealed that deck replacement and widening are not possible with GFRP bars as the bars get damaged during demolition or removal of concrete. Therefore, hydro demolition cannot be used with GFRP bars. One solution to this is to transition to metallic reinforcement near strip seals. There are other examples of FRP bars used together with conventional rebar, in which FRP is placed in regions where durability is most needed. Virginia DOT used GFRP reinforcement as the top mat deck reinforcement with epoxy-coated reinforcement for the bottom mat as shown in **Figure 15**, right [46]. Both Minnesota and Kansas had concerns about GFRP bars floating in wet concrete due to their lighter weight. This prevented Kansas from reducing the cover, even though a larger cover is not needed as GFRP does not corrode. Other material-specific concerns Minnesota DOT discussed included inability to field bend FRP bars and the dependence of the bent radius on bar diameter. For this reason, most applications in decks use straight bars or limited bents.

FRP reinforcement is largely proprietary, which has been a catalyzer for continuous advancement of the material. Consequently, FRP reinforcement products have improved and changed over time. Research is needed to understand the properties and behavior of new FRP products in bridge decks, as well as for the long-term performance of existing GFRP products.

4.b. Galvanized Reinforcing Bars

Galvanizing involves dipping rebar into a molten zinc bath (hot-dip or batch galvanizing), after surface preparation. This creates a zinc-iron alloy layer at the steel-zinc interface and a pure zinc outer layer. This outer layer largely controls corrosion performance. The coat is metallurgically bonded to steel. Coated rebar is then submerged in a sodium dichromate solution to passivate zinc coating when placed in wet concrete (to prevent reduction in bond [47]). Rebar can be galvanized before – for a majority of applications [48]0– or after fabrication; however, there are limitations in storage, quality, and bending. Galvanized rebar should not be in contact with black rebar to prevent galvanic (accelerated) corrosion [49]. Galvanized rebar was first used in the US in the 1930s [50] and there are approximately 1,000 bridges in the US [51]. It is available at more than 70 plants in North America [52].

In addition to batch galvanized rebar (ASTM A767), continuous hot-dip galvanized rebar (ASTM A1094) has been available in the US since 2018. Continuous galvanizing is the application of zinc to a blast-cleaned and pre-heated rebar as it passes through a molten zinc bath at high speeds. This process creates a thin layer of iron-aluminum-zinc layer at the steel-zinc interface and a thicker pure zinc outer layer, the latter of which is effective in corrosion protection [53]. ASTM A1094 bars are not yet widely available. Continuous galvanizing may be a faster option when lead time is a concern as galvanizing and bending takes place at the same manufacturer. However, there is only one manufacturer of this type of rebar in the US. Both galvanized bars have a better bond to concrete than epoxy-coated bars have.

Dr. Darwin from the University of Kansas presented research conducted since the late 1980s on various types of CRR. These studies showed that hot dip and continuous galvanized bars had similar performance. They both improved corrosion resistance compared to conventional uncoated bars and both needed attention to the bends. University of Kansas life-cycle cost analysis demonstrated that the initial cost of galvanized rebar is slightly higher compared to uncoated rebar, but 100-year service life cost can be as small as half the cost of the uncoated bar. Minnesota DOT considers galvanized reinforcing bars to behave like epoxy coated bars and considers this type of rebar to meet "normal service life" design requirements described in *Section 8. Service Life Approaches*. Similarly, Texas, Pennsylvania, and Utah provide galvanized bars as an alternative to epoxy-coated bars and use them when the cost is competitive. **Figure 16** shows galvanized deck reinforcement used in a bridge exposed to marine salts in the air in Washington State.

Figure 16. Galvanized reinforcing bars used in a bridge deck exposed to marine salt in the air in Washington

4.c. Stainless steel

Stainless steel (that complies with ASTM A955) is steel that has a defined minimum chromium and a maximum carbon content [54]. Level of corrosion protection highly depends on the chemical composition of the stainless-steel alloy. Therefore, it is important to include the type of stainless steel in specifications. The stress-strain curve of stainless steels has a less well-defined yield point compared to conventional steel, but design procedures are largely the same as conventional steel. Stainless steel is available in the US from multiple vendors and is more expensive than other corrosion resistant reinforcements. During the scan, Virginia DOT reported an additional 5% cost of the entire bridge amount when stainless steel was used in decks and noted that this is smaller than the cost of an overlay that may be needed for a deteriorating bridge with conventional reinforcement. Virginia DOT research [55] also showed that the cost is sensitive to the cost of the alloys that compose stainless steel as shown by data from 1999 to 2009 in **Figure 17**. In addition, because not all stainless steels are the same, Virginia DOT uses X-ray fluorescence to verify the intended alloy composition of bars as a quality control measure.

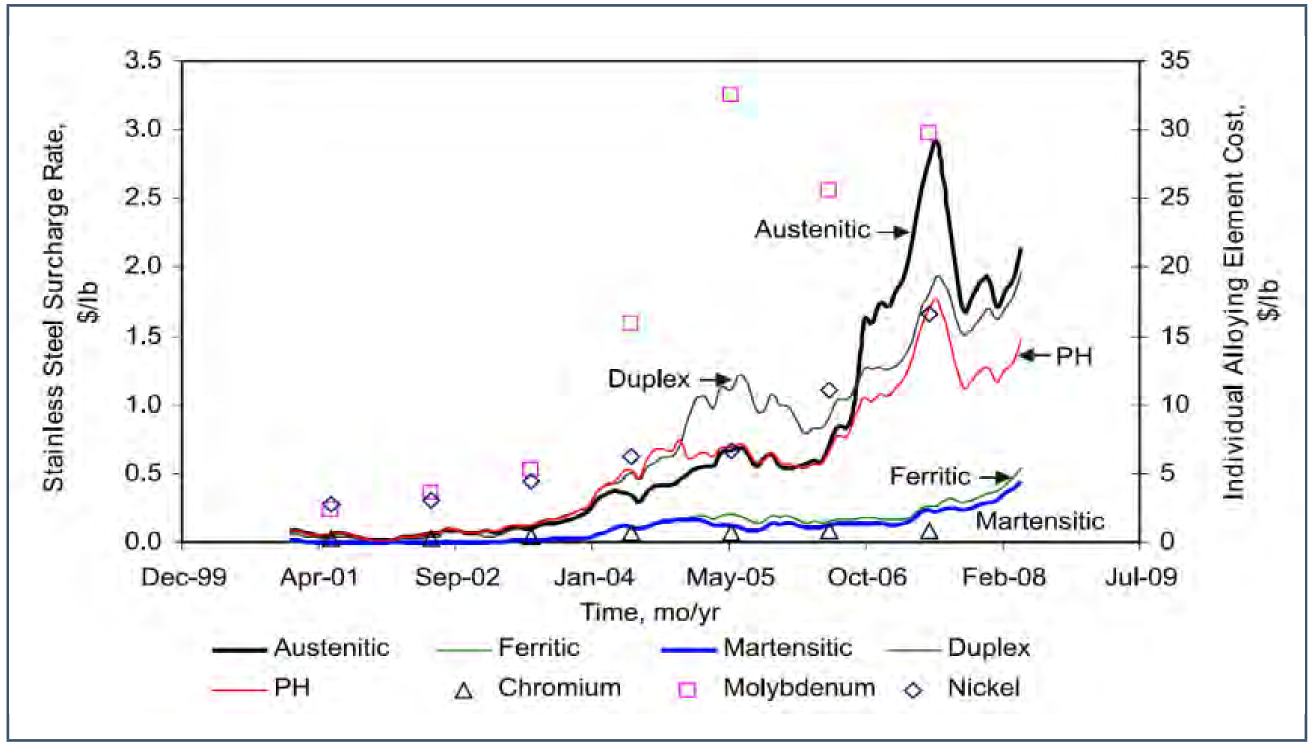


Figure 17. Change and fluctuations in cost of stainless steel and alloy over time from Virginia DOT supported research

Michigan has used stainless steel since 1983, austenitic steel before 2009, and other types since then. They reported that in 2011, the use of stainless-steel reinforcing bars added $17.43 per square foot to the cost of a conventional bridge deck; therefore, Michigan justifies the use of stainless steel when 100-year service life is needed as they assume that epoxy-coated rebar provides only 60 years of fix life. Stainless steel can be a preferred alternative to coated or galvanized reinforcement not only because it provides better corrosion protection, but also because bends do not reduce corrosion protection and its bond to concrete is the same as the one that can be achieved with black reinforcing bars.

4.d. Stainless Steel Clad Bar

A more economical alternative to stainless steel rebar is stainless steel clad rebar, which has been used by only a few states (e.g., Michigan and Virginia among the scan participants). Stainless steel clad reinforcement has a thin outer layer of stainless steel metallurgically bonded to a conventional carbon steel reinforcement, thus offering greater corrosion resistance compared to conventional steel [54]. Since the coating is metallic, it is less likely to be damaged compared to epoxy or other non-metallic coating. The ends of the bars are exposed and must be treated for corrosion resistance. Stainless steel clad rebar had a history of supply shortages and has not always been manufactured in the US, making it hard to use for projects that have federal requirements for material sourcing. Therefore, it has only been used in a few projects in the US. A new stainless steel clad bar product that has been recently introduced in the US could change this.

4.e. ASTM A1035 Steel

ASTM A1035 steel is low-carbon, chromium alloy steel [56]. There are three types of ASTM A1035 steel named according to the chromium alloy type: CS, CM, CL. According to the manufacturer [57], these steels provide varying levels of corrosion resistance according to their type and the cost increases with increasing corrosion resistance. The maximum corrosion resistance is roughly three times as much of black reinforcing bars but less than high quality stainless steel. Their yield strength meets the requirements of Grade 100 or Grade 120 steel, and the stress-strain curve is characterized by a less defined yield point as compared to lower strength steels. ASTM A1035 bars are relatively new and longer-term field data is becoming available to evaluate their performance.

Michigan DOT uses ASTM A1035 CS-type bars with 100 ksi yield strength on select bridge decks but assumes the yield strength to be 75 ksi in design or has used these bars as a one-to-one replacement for Grade 60 steel in the past. They have used ASTM A1035 bars in 17 bridges at the time of the scan workshop and 13 bridges have been planned for 2024. In 2021, bid prices for ASTM A1035 bars ranged between $2.03/lb. and $3.00/lb. while it was $1.50/lb. to $1.98/lb. for epoxy-coated bars. **Figure 18** shows a bridge deck from 2003 in Michigan. When Washington used CM-type bars in two bridges, the reported cost was $1.73/lb. as compared to $2.00-$2.50/lb. for epoxy coated reinforcing bars. Minnesota uses epoxycoated ASTM A1035 CM-type bars for decks with enhanced service life as defined in *Section 8. Service Life Approaches*. They have built over 25 decks with CM-type epoxy-coated bars in the last several years and have observed quality control issues that are being addressed by the suppliers. Utah funded a construction feasibility study [58] which did not identify any significant construction challenges and suggested considering ASTM A1035 to be a material that can be used more widely in the future. Due to lack of longer-term durability data from the field, some states choose to specify CS-type (highest corrosion resistance) rebar to be conservative.

Figure 18. Bridge deck with ASTM A1035 bars built in 2003 in Michigan (left) and in 2008 in Utah (right)

CHAPTER 5

Deck Prefabrication

Prefabricated decks enable accelerated construction and can result in higher quality, as deck panels are manufactured and cured in a controlled environment. Prefabricated elements discussed during the workshop included partial depth precast decks, full depth precast decks with post-tensioned or UHPC joints, decked prestressed girders, exterior girders prefabricated with partial overhang, and a proprietary system that compresses deck panels against girders.

5.a. Partial-Depth Precast Decks

Partial-depth precast decks are thin, precast concrete panels that are used as stay-in-place forms-made composite with the cast-in-place portion of the deck. The panels are thin (typically less than half the deck thickness), are pretensioned in the direction perpendicular to traffic, and are typically 8 ft long. The top surface is typically roughened for better bond to cast-in-place portion. A small number of DOTs that used this method mentioned reflective cracking, joint leakage, closure pour cracking, differential panel movement, concrete spalling, and excessive surface wear according to a survey [60]. A Washington DOT study [61] identified four key aspects to better performance: placement of panels on girders, extension of strands beyond panel length, development of strands, and level of composite action.

According to this scan, partial depth precast deck panels are standard practice in Texas, with more than 90% of their decks built using partial depth deck panels. Others reported cracking in the cast-in-place portion of the deck or leakage through partial depth joints. These states either limit the use of partial depth panels or provide it as an option that is often not utilized. For example, Washington DOT only allows partial depth precast deck panels in positive moment regions unless the deck is post-tensioned. The difference in experience between Texas and others appears to stem from construction practices. Texas uses blueboard bedding strips to support precast panels over girders as shown in **Figure 19**, which provides temporary support to maintain an adequate gap for the deck concrete to occupy providing permanent long-term support. The minimum thickness of the bedding strip and the precast panel overhang over the strip are 0.5 in. and 1.5 in., respectively. The key element to success is ensuring concrete is thoroughly consolidated under the panel overhang.

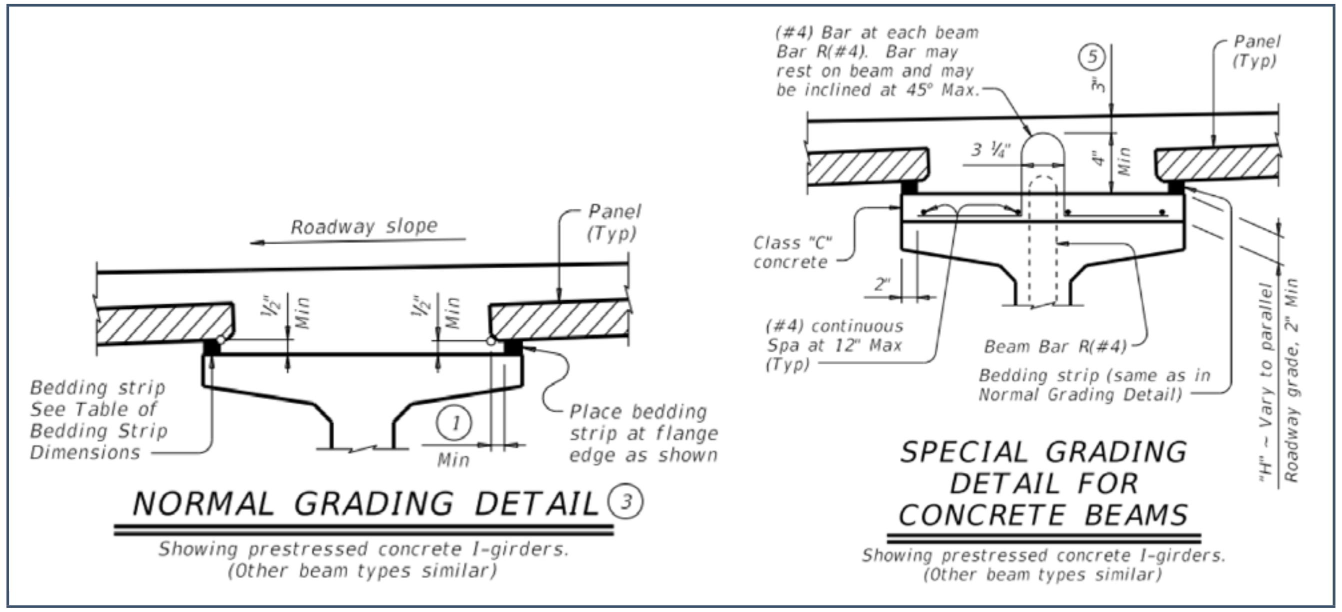


Figure 19. Partial depth precast panel placement detail from Texas DOT

Another key component of Texas's success with partial depth precast deck panels is their pre-wetting of panels to achieve saturated surface dry condition before the placement of cast-in-place part of the deck and rapid application of wet curing after concrete placement. **Figure 20** shows placement of panels on bedding strips and reinforcement for cast-in-place portion of the deck placed over the deck panels. Texas DOT requires the foam thickness to be half as thick as it is wide and allows up to 6 in. of foam thickness. Additional reinforcement is required above the beam flange when the bedding thickness exceeds 3 in. to ensure composite action.

Figure 20. Precast panels placed on bedding strips (left), and panels shown with cast-in-place deck reinforcement (right) from Texas DOT

To further accelerate construction, Texas DOT also developed partial-depth deck panels that have full-depth precast overhang. This type of panel is shown in **Figure 21** with reinforcement for railing incorporated into the deck panels. Contractors are typically given these details as an option to a traditional formed overhang, but few have chosen to use it.

Figure 21. Partial-depth precast deck panels with full-depth overhangs from Texas DOT

Finally, Washington DOT has adjacent wide flange bulb-tee girders that have a minimum 3 in. top flange, which are built with a minimum 6 in. thick cast-in-place deck. This superstructure type is shown in **Figure 22**. Like partial depth precast deck panels, adjacent girders eliminate the need for formwork and increase construction safety.

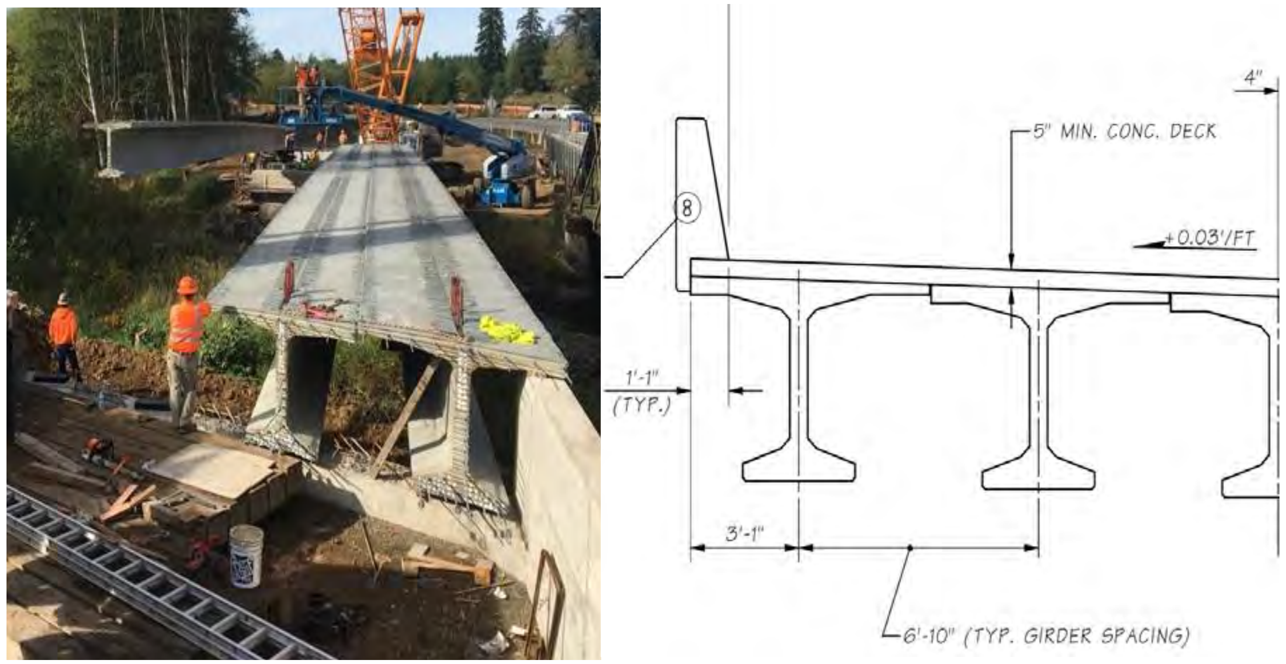


Figure 22. Adjacent wide flange bulb-tees with a cast-in-place concrete deck from Washington DOT

5.b. Full-Depth Precast Decks

Full-depth precast decks are composed of precast concrete panels that have the same thickness as the deck. The panels have pockets to house shear studs from the girders. The length of the panels (in the traffic direction) typically ranges between 8 ft. and 12 ft. The width of the panels (perpendicular to the traffic) is typically equal to the width of the bridge [62]. Panels can be pretensioned in the direction perpendicular to traffic to facilitate handling and shipping. Precast/Prestressed Concrete Institute's (PCI) State-of-the-Art report [62] provides additional details on design and construction.

Most bridges with full depth precast deck panels use post-tensioning to connect panels [63]. The next common connection detail is one with straight bars and UHPC closure pour, followed by hooked bars and conventional concrete closure pours. Mechanical or welded connections that were used in the past are largely discontinued due to concerns with performance. NCHRP 12-65 [64] developed two systems that do not require post-tensioning in the traffic direction or an overlay (one with pre-tensioning and one with conventional reinforcement in the direction perpendicular to traffic). Later, NCHRP 12-96 [65] developed simplified details for full-depth precast decks.

According to a 2019 survey [63], concerns related to full depth panels included covering construction errors or cambers, lack of contractors or bids, alignment during construction, joints between panels, higher cost, uncertainty with connection details, and long-term performance. Twenty-three respondents to the survey also provided the cost ratio of full-depth precast concrete panels to cast-in-place decks. This ratio ranged between 0.96 and 3.14 with an average of 1.8.

A 2019 survey [63] found that 31 DOTs (72% of the respondents) used full-depth precast concrete decks in the US. There were 301 projects with full-depth precast concrete decks in the US, the majority of which were in New York, Alaska, and Utah. New York and Utah participated in this scan. Utah developed several details for decks with full-depth precast concrete panels and had success with full depth precast deck panels with either post-tensioned and grouted shear key joints or joints with UHPC closure pours. Their grouted shear key detail with post-tensioning is shown in **Figure 23**. The UHPC closure pour detail is shown in **Figure 8**. In previous projects, when Utah used wide conventional concrete closure pours with straight reinforcing bar laps, they had transverse cracking and efflorescence within the joints. In these cases, issues were isolated to the closure pours and the panels performed well. Similarly, Washington DOT requires either longitudinal post-tensioning or UHPC closure pours with full-depth precast concrete deck panels.

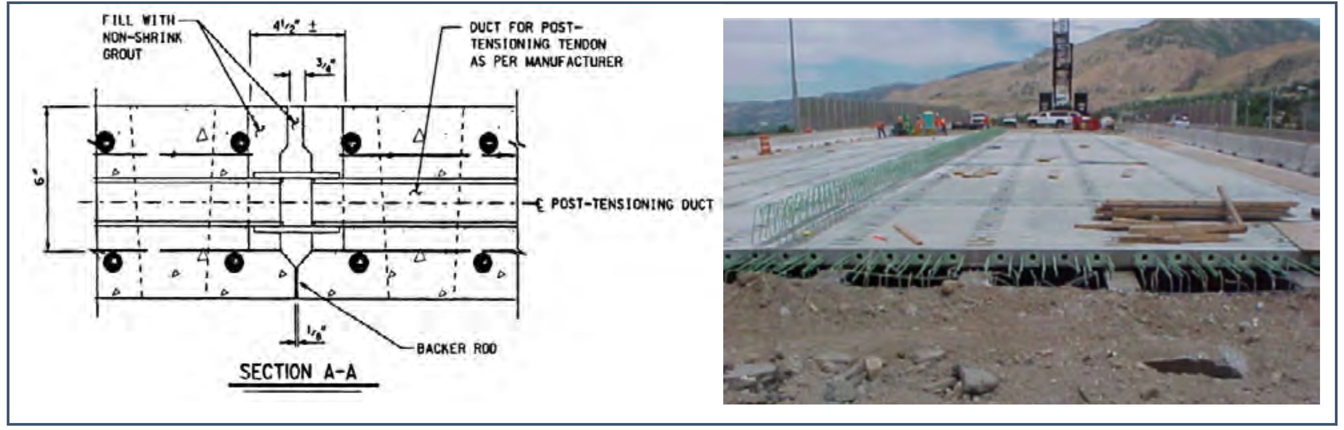


Figure 23. Grouted shear key detail for transverse joints of full-depth precast deck panels from Utah DOT

New York State DOT's earlier specifications for full-depth panels involved grouted shear stud pockets, UHPC panel-to-panel joints and an overlay. Their current specifications use UHPC for both shear stud pockets and panel-to-panel joints without an overlay. The shear stud pockets are hidden, and the panel surfaces are grinded to meet elevation requirements. Both earlier and current specifications resulted in bridges that perform satisfactorily. They use full-depth precast deck panels when high traffic volumes, limited detours, or lane restrictions necessitate accelerated construction. **Figure 9**, left, shows the hidden shear stud pocket and panel-to-panel joint details, both built with UHPC.

The scan showed that full depth precast deck panels provide a fast means to build decks for bridges that have a relatively simple geometry. More complex geometries may drive the cost higher. Full-depth precast deck panels may also be preferred when the bridge site is far from a concrete supplier. Joint details and materials are critical for deck performance; UHPC deck joints seem to be a satisfactory material for joint closure pours.

5.c. Decked Precast Girders

Although some states developed standard plans for decked girders for accelerated construction, the weight of these sections limit their wide use. A lighter option is a precast girder with a wide top flange prefabricated to include exterior parapet with rail reinforcement extending out as shown in **Figure 24** from Texas DOT. This option can eliminate overhang formwork. However, other states that participated in the scan observed that the thin overhang sections can be prone to cracking.

Figure 24. Girder prefabricated with a partial-depth deck overhang from Texas DOT

Decked girders include NEXT beams, decked bulb tee girders, adjacent decked box beams, and adjacent solid or voided slabs. New York State employs these sections for spans up to 70 ft., 130 ft., 120 ft. and 60 ft., respectively. Like New York State, Washington DOT uses decked bulb tee girders with UHPC joints as shown in **Figure 25**. These girders have straight rebar extended into the joint and roughened joint surfaces for better bond with UHPC. Washington DOT sponsored a research project to develop joint details for decked bulb tees with UHPC joints [66].

Figure 25. Decked bulb tee girders from Washington DOT

5.d. Proprietary Precast Concrete Deck Systems

A proprietary prefabricated concrete deck system, called the AccelBridgeTM, with match-cast joints was used by New York State in two projects. In this system, deck panels at the two ends of a bridge are made composite with the girders by grouting the deck pockets for shear studs. Once all panels are in place, the deck and joints are kept under compression in the longitudinal direction of a bridge by jacking the deck against the girders. This creates tension in girders and compression in deck without needing post-tensioning strands. After jacking is complete, the rest of the panel pockets and the closure between the deck panels that house the jacks are grouted to lock in compression stresses in the deck [67]. The system does not require joint closure pours as the decks panels are match cast and epoxied. New York State DOT used UHPC for shear stud panels and chose not to rely on the compression in the deck in design to allow future deck replacements. Although this is a promising system, it may be too soon to evaluate the performance and the cost of the system since there have only been a few applications to date. **Figure 26** shows the system as implemented in New York State on a bridge deck replacement project.

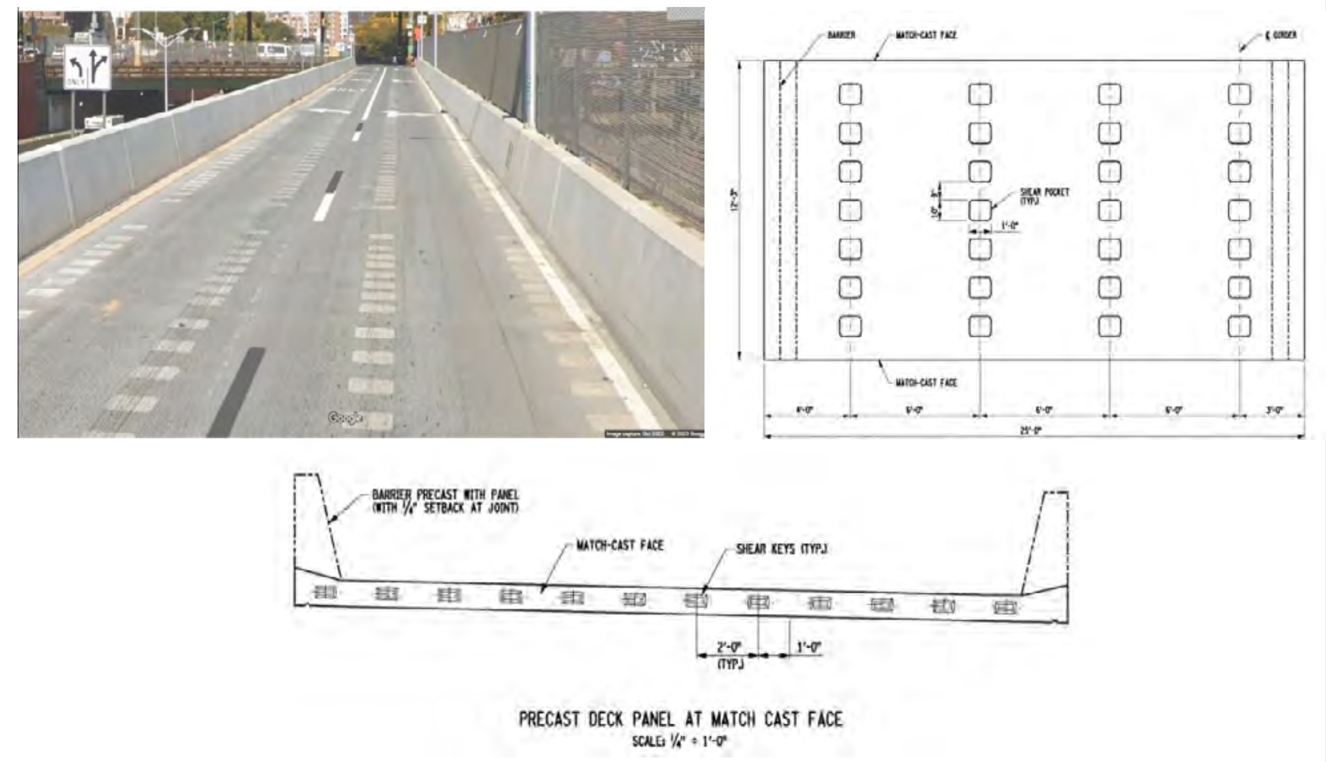


Figure 26. A proprietary precast deck system called AccelBridge™ implemented by New York State DOT

CHAPTER 6

Design and Detailing Practices

There are large variations in details and design methods used among the states that participated in the scan. These include using the empirical (e.g., Texas with modifications) or the traditional (e.g., Minnesota) deck design methods of AASHTO LRFD Bridge Design Specifications [68], designing continuous link slabs to eliminate joints over piers (e.g., New York), creating a saw cut in the deck over piers to force cracking to this region (e.g., Minnesota as shown in **Figure 27**), fully developing top mat reinforcement in the overhang by using anchors, extending the deck beyond the edge of the barrier, using higher load factors than required by AASHTO LRFD Bridge Design Specifications when designing the negative moment region of the superstructure (e.g., Minnesota). Minimum deck thickness and cover also vary from state to state and have varied over time within a state. Therefore, documenting the consequences of design changes on deck performance is essential for revisions to design details in the future. California DOT has supported a research study [69] that compared deterioration rates of decks in California to other states. This research tracked potential reasons of deck deterioration and recommended a higher amount of shrinkage and temperature reinforcement in their decks. Caltrans defined a "typical deck" and developed a standard design for this typical deck for design efficiency, ease in construction and assessment of service life issues.

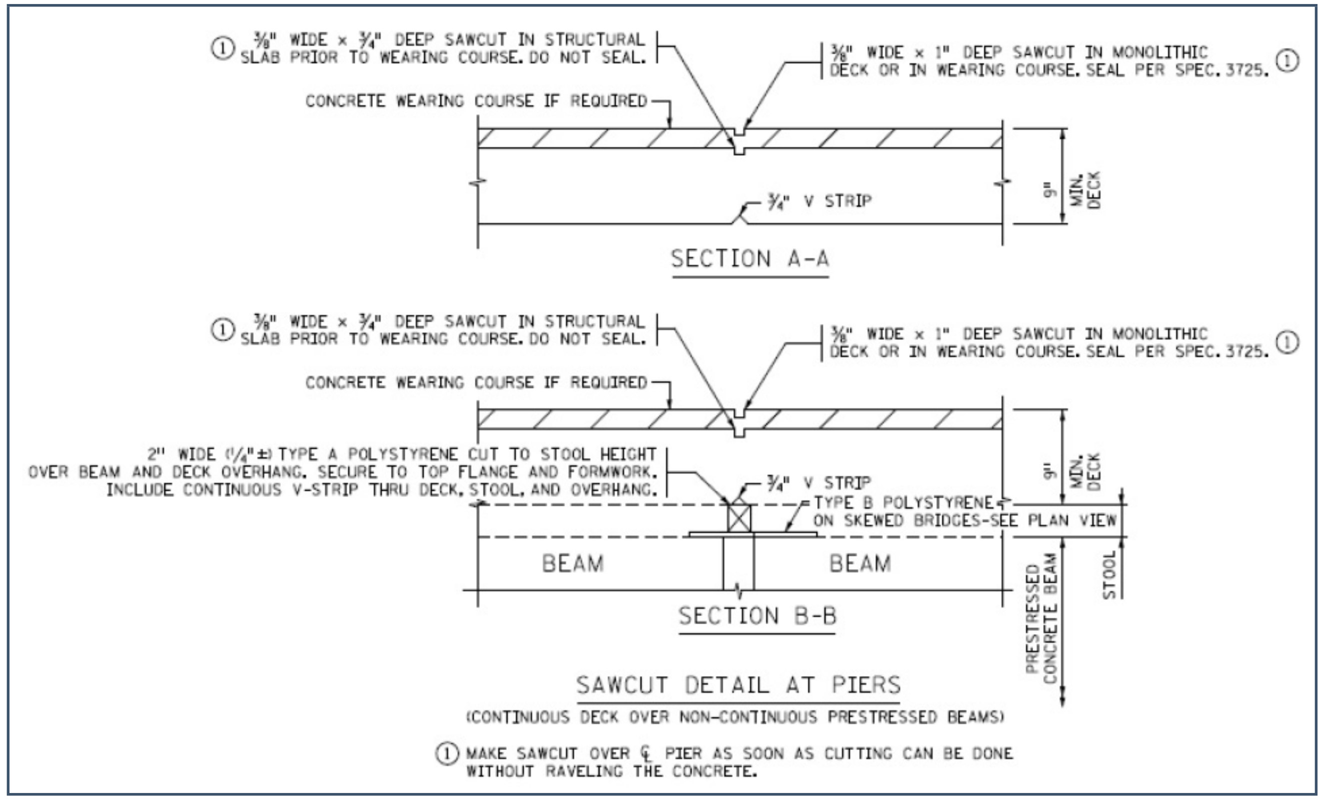


Figure 27. Sawcut of the deck between beams (Section A-A) and at beams (Section B-B) to constrain cracking to the area from Minnesota DOT

Detailing has consequences on deck durability. Using smaller reinforcing bar sizes, with small spacing and in the direction of predominant cracking can be advantageous. Increasing reinforcing bar cover may delay corrosion and extend service life but could result in wider cracks on the surface. Decks designed with the empirical design method of AASHTO LRFD Bridge Design Specifications will generally lead to a smaller rebar amount as compared to the traditional design method. Texas DOT uses the empirical method for this reason, with additional reinforcement as needed to control crack width in continuous decks over interior supports. The reasoning for this policy is reduction in the amount of metallic reinforcement that is prone to corrosion, which then leads to smaller amounts of corrosion products and less spalling [70]. The typical Texas DOT bridge deck utilizes 4 in. precast prestressed partial sub-deck panels with a 4.5 in. cast-in-place concrete and use No. 4 bars at maximum 9 in. spacing in both directions. Even though Texas construction methods do not meet all the restrictions of AASHTO LRFD's empirical method (e.g., no partial depth precast deck panels, need for diaphragms at supports, overhang length), Texas justifies these exceptions either with research or by changes in design such as using a thicker deck at expansion joints that can serve a similar purpose as end diaphragms.

Given that flexure is not the governing failure mode for decks, when transverse cracking is prevalent related to concrete drying shrinkage, placing the longitudinal reinforcing bars closer to the deck surface may restrain these cracks better. Texas DOT places longitudinal bars closer to the top surface on the top mat as shown in **Figure 28**. The scan team discussed that changing the location of the rebar may result in longitudinal cracking becoming prevalent. Texas DOT has indicated that the change resulted in reduced transverse crack tendency but increased longitudinal cracking though with an overall smaller crack density.

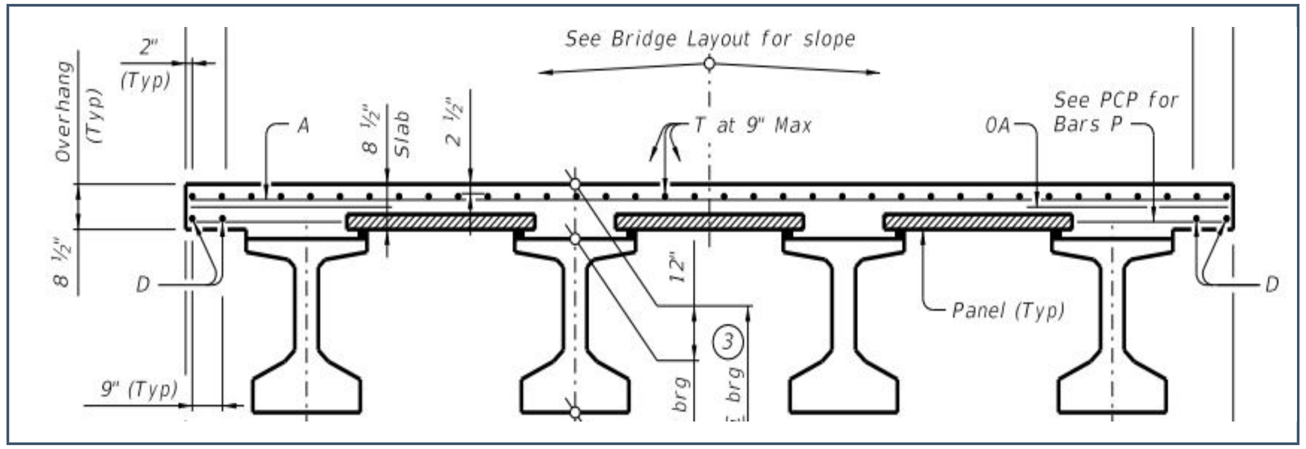


Figure 28. Deck reinforcement detail of Texas DOT

There are new options for haunch or girder-deck shear connection reinforcement when haunch thickness is large. This involves reinforcing the haunch with a U- or inverted U-shaped bars, overlapped with the stirrup from girders, reinforced with additional longitudinal bars. **Figure 29** shows details and photographs from Texas, Washington, and California. Texas DOT sponsored research that investigated the constructability and efficacy of the haunch reinforcement in transferring horizontal shear [71]. The final report, which is not yet available at the time of this scan, will develop guidance for haunch design. Washington does not use this new haunch detail when shear reinforcement is field bent (**Figure 29**, top right), but uses the detail when the shear reinforcement is pre-bent as shown (**Figure 29**, middle left).

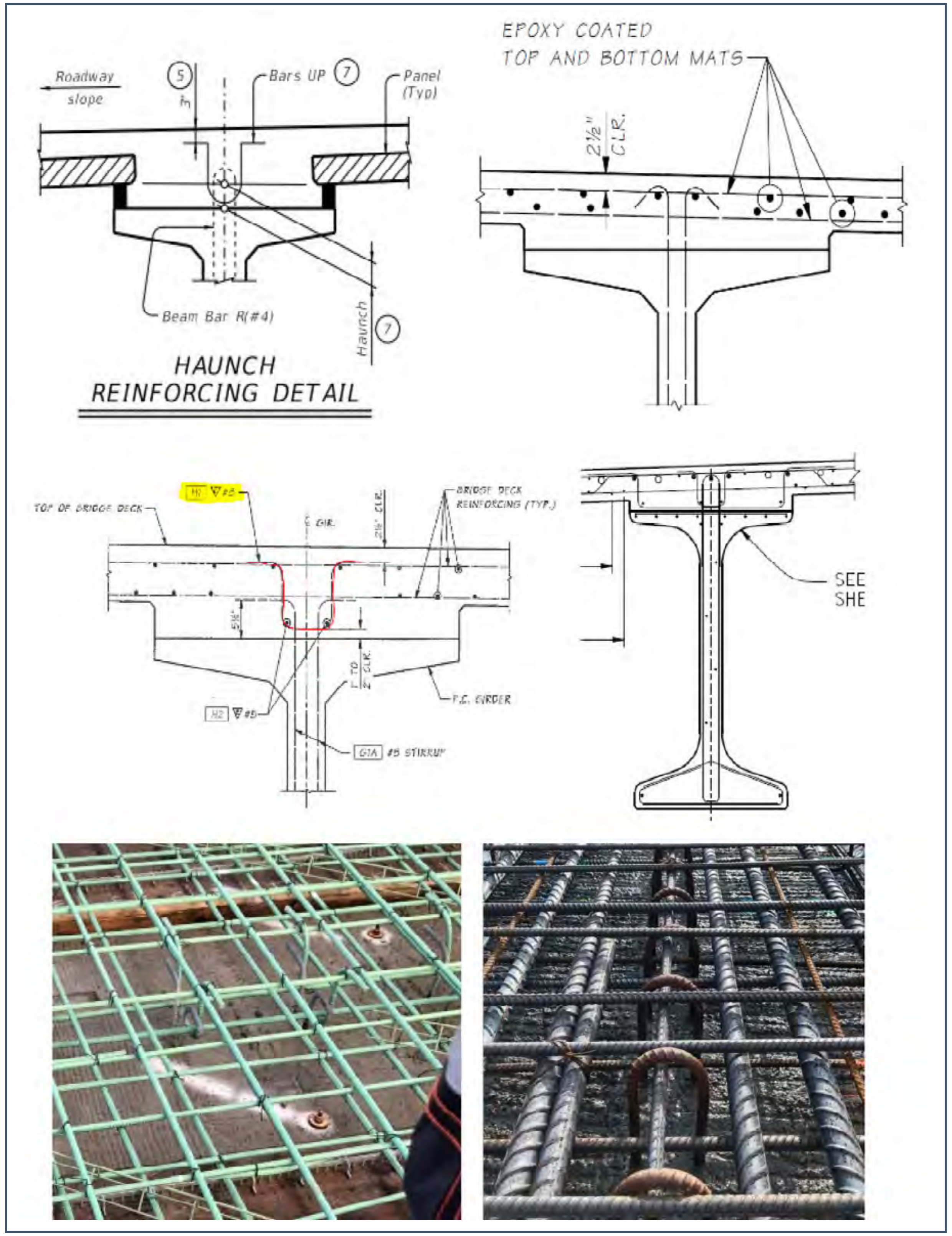


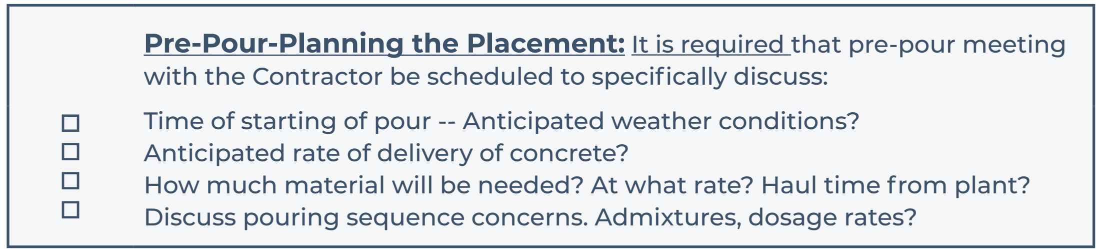
Figure 29. Haunch reinforcement from Texas (top left), from Washington (top right, middle right, bottom left), California (middle right and bottom right) DOTs

CHAPTER 7

Quality Assurance/Control, Workforce Knowledge and Continuity

7.a. Construction Quality Assurance/Control

Preparation is key, particularly when new construction methods or materials are used. On- or off-site test pours for each new mix, pre-deck pour meetings, construction checklists, training of the field crew and inspectors, slump and cylinder sampling on-site with certified inspectors in presence have helped minimize potential problems during the actual pour for the states that participated in this scan. In addition, having regional construction engineers accessible to address questions and concerns of field inspectors and engineers can prevent or solve on-site problems. **Figure 30** shows a sample from Minnesota DOT's checklist for deck concrete placement. This list includes items to be checked in the following stages: pre-pour planning (shown in the figure), before the placement, during the placement, after the placement, before falsework release, before barrier placement, and before application of heavy loads.



Pre-Pour-Planning the Placement: It is required that pre-pour meeting with the Contractor be scheduled to specifically discuss:

☐ Time of starting of pour -- Anticipated weather conditions?
☐ Anticipated rate of delivery of concrete?
☐ How much material will be needed? At what rate? Haul time from plant?
☐ Discuss pouring sequence concerns. Admixtures, dosage rates?

Figure 30. A sample from Minnesota DOT's checklist

Figure 31 shows a 10 ft. by 10 ft. test pour by Washington DOT completed a week before the actual deck placement and used to demonstrate concrete sampling, placement, temperature control, fogging, and finishing. It should be noted that test pours may be deceiving if the girders carrying the screed displace differently than the other girders.

Figure 31. A 10 ft. by 10 ft. test pour by Washington DOT

Specifying reinforcement tie points and supports for reinforcing bars can help ensure reinforcing bars are at the locations intended by the design plans. Nevertheless, there is room for technology that can help improve construction quality and placement of deck reinforcement. For example, a technology similar to laser-guided screeds can be developed to verify the location of reinforcing bars during or after they are placed because rebar mats can move from their intended position, particularly when there are no specific requirements for rebar tying or support. Alabama DOT-funded research [72] investigated whether existing laser scanners and robotic total stations can be used to measure the location of formwork and rebar during construction of two bridge decks in Alabama. Their conclusion was that while data were collected, the measurements were not precise enough to check contractors' work and processing of the large amounts of data to extract discrete locations of rebar was a challenge. They recommended revisiting this topic when the technology is improved and using the existing technology in aiding contractors with placement of formwork, rebar, and screed to save time.

For all types of CRR bars, quality control/assurance that goes beyond visual inspection is needed as rebar defects have been documented on site. It is wise to frequently sample and test alternative reinforcement bars. Technologies such as X-ray fluorescence are available as handheld devices to measure the composition of metal or alloy rebars in the field as reported by Virginia [59] and shown in **Figure 32**.

Figure 32. Hand-held X-ray fluorescence device as used by Virginia DOT

7.b. Workforce Knowledge

Because success of any traditional or innovative deck construction is highly dependent on design and construction quality, developing workforce knowledge through training of design and construction engineers, construction inspectors, contractors, and field crew are essential. Deck-specific training or certification programs appear to be smart investments that can significantly improve deck performance. Texas DOT has in the past worked to train internal and external inspection personnel as well as contractors related to bridge deck construction. They are currently working with a third-party organization to develop a bridge deck construction inspection and certification program. Similarly, Minnesota DOT developed and teaches a two-week-long inspector certification program, out of which two days are dedicated to bridge decks and a three-day-long online bridge project engineer training program. Select higher education institutes provide certificates, webinars and courses on innovative materials, design, and practices as continuous education for bridge engineers.

7.c. Knowledge Continuity

Many states explore innovative technologies. However, very few track the impacts of these innovations beyond regular inspection reports that are stored in large and general databases. Innovation requires iterations and continuous improvement, which takes time. Often, when champions of innovation leave the workforce, knowledge is lost. Therefore, it is crucial to have means (databases, innovation-specific inventories, websites, inspection reports, research studies, committees, surveys, lessons learned reports) to track and document the impacts of innovative projects. The purpose of data to be collected needs to be well defined beforehand, being mindful about the burden of collecting, storing, and maintaining such data. Utah DOT keeps an innovation-specific database that is stored on the cloud for ease of access by DOT engineers who are interested. This database stores information such as associated research documents, evaluation of the innovation, and implications of innovation. Minnesota DOT has a similar database, as well as agency-defined elements for innovative elements to be able to keep track of their longer-term performance through inspections. Florida DOT has an innovations webpage [44] with information on innovations, uses, design criteria, applications, technology transfer, and related research projects. Such online and public information provides easy access to other bridge owners or researchers who are interested in the development of new technologies, but properly maintaining online information on innovation requires time and resources.

CHAPTER 8

Service Life Approaches

Decisions for adopting innovative technologies or making design changes can be made by following a service life approach, developing state-specific service guides, and/or obtaining input from all relevant parties (design, materials, construction, asset management groups, as well as industry and academia). Guide specifications for service life design are now available by AASHTO [73], adopted by some states, and present target service life categories. With this approach, select bridges are designed with innovative materials depending on a pre-defned set of criteria that relate to factors such as the importance, exposure, cost, traffic volume, and ease of future deck repair of bridges.

Figure 33 shows bridges classified by function or target service life and associated reinforcement types from Virginia (left) and Minnesota (right). Minnesota DOT's definitions were adopted from NCHRP 12-108: Guide Specification for Service Life Design of Highway Bridges [74]. The classification is a function of bridge cost, traffic volume, and complexities in redecking [75] and impact reinforcement choice as shown in **Figure 33**, right.

Functional Classification	Class I Improved CRR	Class III High CRR
Interstate and Freeway		X
Urban Principal Arterial		X
Others	X	
Pedestrian Bridges	X	

Service life	Definition	Type of reinforcing bar and concrete cover
Normal	N/A	Epoxy coated reinforcement with 3 in. cover to the top rebar
Enhanced	100-year service life Cost>$20 million ADT>60,000 Redecking complexities (e.g., curved)	Epoxy coated ASTM 1035 with 4% chromium reinforcement with 3 in. cover or GFRP reinforcement with 2.5 in. cover to the top rebar
Maximum	100+ year service life Cost >$35 million Critical crossing (e.g., long detour) Redecking complexities (e.g., box girders)	Stainless steel reinforcement with 2.5 in. to 3.5 in. cover to the top rebar

Figure 33. Decision process for the use of CRR in Virginia (left), and Minnesota (right) [75]

Following a service life approach, Michigan DOT also defines when CRR is needed based on bridge or environmental characteristics such as high traffic volume, high importance, severe corrosion environments, relatively small deck or cover thickness, or anticipated difficulties in future repair and maintenance due to restricted access or remote locations. They use stainless steel or ASTM A1035 reinforcing bars when the deck thickness is less than 9 in., additional cost is less than 8% of the programmed structure cost, when repair and maintenance would be disruptive, or where the bridge is over hard-to-access areas.

Virginia DOT had a stricter approach and transitioned away from coated (epoxy coated or galvanized steel) steel in 2010 and only uses ASTM A1035 (Class I in **Figure 33**) or stainless steel (Class III in **Figure 33**) reinforcing bar. The decision between the two types of CRR is made based on functional classification of bridges (**Figure 33**, left). Class II was reserved for stainless steel clad rebar but is no longer used due to limited supply of stainless steel clad rebar in the US.

In addition, added cost can be used as a criterion to decide when to use alternative materials such as CRR. Pennsylvania DOT allows for CRR to be used when there is no additional cost to the department without additional criteria related to various exposure conditions or bridge types. The added cost of innovative materials can also be reduced by limiting the use of these materials to parts of decks with higher durability needs. For example, Minnesota is considering using stainless steel in targeted locations such as full depth staged construction joints. New York is using UHPC in link slabs and precast concrete deck joints.

Life cycle cost analysis has also been used to justify the initial cost of alternative materials, but the results have been sensitive to input and assumptions that are hard to substantiate. Nevertheless, these tools enable high level comparisons of various materials. Better and long-term data, possibly by tracking pilot project performance, is needed to refine analysis input, methods, and assumptions, and to generate reliable results.

CHAPTER 9

Key Findings

The following are the key findings discussed in detail in this report:

- Success of a concrete in reducing cracking depends equally on the mix, care in placement, finishing, curing, structural design, and demand. Low paste content, controlled plastic concrete temperature, restricting temperature difference between concrete and adjacent surface, and limiting ambient temperature fluctuations can reduce cracking in bridge decks. Shrinkage-reducing admixtures are effective.
- Wet curing within minutes of deck finishing is essential. Internal curing can be very efficient when quality and conditioning of the aggregate can be measured and controlled, and where lightweight aggregates are available.
- Fiber reinforcement can be used as an additional measure for crack mitigation and control. Fiber type, size, amount, and distribution impact the results. Therefore, simply adding fibers to an existing mix will likely not improve cracking. Rather, fibers need to be selected and acceptance criteria and test methods for fibers need to be defined for a desired performance and mix properties should be adjusted accordingly. A testing protocol measuring specific performance requirements of the fibers in a concrete specimen is recommended.
- Corrosion-resistant reinforcement provides better durability and can be used when exposure is severe, when longer service life is desired, or when frequent maintenance is not an option. Corrosion resistance of stainless steel and ASTM A1035 bars depends on their alloy. Glass FRP bars do not corrode, but also are problematic in deck widening or repair because of their brittle nature and susceptibility to damage during concrete removal. Newer FRP reinforcing bars are available and research is needed to understand their performance in concrete.
- Use of smaller reinforcement amounts (smaller amounts of corrosion products and less spalling), use of smaller bars at smaller spacing, and aligning the bars perpendicular to prevalent crack direction are practices implemented to reduce cracking, albeit with varying results. New details are available for haunch reinforcement when haunch thickness is large.
- Construction needs for UHPC and normal concrete are different. The performance of UHPC depends on consideration of these needs during construction. UHPC joints between precast deck panels and between panels and girders have generally performed well and have performed like post-tensioned joints. UHPC link slabs have successfully eliminated joints in some states. Non-proprietary UHPC mixes and availability of multiple vendors may decrease the cost of UHPC in the near future. Other fiber-reinforced concretes can also be more economical in applications where the higher performance of UHPC is not needed.
- Partial depth precast panels are standard practice in some states, but the success of this construction method depends on construction details and practices.

- Best practices vary from state to state and over time due to variabilities in materials and practices. Information exchanges are needed to learn from states with consistently successful experiences.
- Since deck performance highly depends on construction quality and design details, workforce training is essential. Innovation must be tracked for informed decision making and continuity of workforce knowledge. Planning and owner involvement are key in making innovation work. Development of standard practices with innovative materials and technologies may take many iterations.
- An inherent challenge in identifying the causes and solutions to deck cracking and deterioration is variability in exposure conditions (e.g., climate, deicing salt amount, traffic volume and type), local material availability and quality, construction, design, and quality assurance/control practices from state to state and between locations within a state. Even when materials are available nationwide, the quality of proprietary materials can change between suppliers or over time. Finally, design/construction/quality control practices change with time and the consequences of these changes are not always tracked. These variabilities over location and time result in innovations that are widely successful for some states to be ineffective or non-viable for others. Therefore, it is not possible to identify solutions to deck deterioration that fits the needs of all states. Rather, this report documented details of innovations that led to consistent success where they were implemented.

CHAPTER 10

Recommendations

Below are the recommendations from the scan:

1. Develop documentation strategies (websites, databases, innovation-specific inventories, etc.) to keep track of the benefits, cost, opportunities of and lessons learned from innovative projects. Maintain continuity of innovation knowledge in the workforce through documentation.
2. Invest in training and certifying bridge and construction engineers, construction inspectors, contractors, and field staff on new technologies and high-quality conventional construction practices.
3. Provide opportunities such as mock pours, pre-pour meetings, and checklists that can predict potential construction issues associated with new practices.
4. Invest in research that can refine methods, input data, and assumptions for life cycle analyses and deterioration models.
5. Prioritize improving concrete quality, which can minimize corrosion, over implementing corrosion resisting reinforcing bars. Develop modern concrete mixes that focus on reduction of cracking and test methods that can verify mix performance. Similarly, overlays may not be needed when concrete is high quality.
6. Use corrosion resisting reinforcing bars for bridges that require longer service lives following a service life approach.
7. Establish holistic approaches that span between design, materials, inspection, and construction. Allocate sufficient time, planning, budget, and incentive so that innovation is not an afterthought.
8. Explore possibilities to transfer existing automated quality control technologies (e.g., laser guided screeds) from other fields to decks and deck materials or develop new quality control methods.
9. Develop guidelines, acceptance criteria, and test methods for materials such as fibers, shrinkage reducing admixtures, and lightweight aggregates– properties of which are critical for the bridge decks.
10. Support research that can supplement laboratory data with consistent field data on the corrosion performance of deck materials.

CHAPTER 11

11.

Implementation Action

The following are the recommended implementation actions:

1. Create national dissemination opportunities (websites, webinars, etc.) for states that have consistently positive experiences with an innovation to share practices/data with others.
2. Leverage AASHTO’s Innovation Initiative website to publicize and document selected successful innovations for decks.
3. Encourage bridge owners to collect long-term data that can be used to evaluate the performance of bridges with innovations so that recommendations can be made on the most successful innovations and practices. This type of data can also be collected through an NCHRP synthesis project on any of the specific innovations, for which data already exists.
4. Write research problem statements for automated quality control methods for deck construction and materials, assessment of new deck materials considering service life, and refinement of data, methods, and assumptions of life cycle analyses.
5. Prepare training materials for construction engineers, inspectors, and contractors.
6. Encourage partnerships between universities, FHWA, internal DOT research teams, AASHTO technical committees (on concrete, technology, bridge asset management construction, safety and evaluation, and bridge preservation), and industry to foster innovation for bridge decks. These can be through research funding, pilot projects, or research problem statement development focusing on innovation and durability.
7. Develop technical publications and presentations to disseminate the results of the scan.

Appendix A:
Team Members Contact Information

Donn Digamon, P.E. -Team Chair
State Bridge Engineer
Office of Bridge Design and Maintenance
Georgia DOT
600 West Peachtree St, 24th Floor
Atlanta, GA, 30308
Phone: (470) 561-0715
Phone: (404) 631-1883
Email: dodigamon@dot.ga.gov

Bijan Khaleghi (retired)
State Bridge Design Engineer
WSDOT - Bridge & Structures Office
Olympia, WA 98504-7340
Phone: (360) 705-7181
Phone: (360) 522-2846
Email: khalegb@wsdot.wa.gov

Hannah Cheng
Structural Engineering
New Jersey DOT
Phone: (609) 963-1316
Email: Xiaohua.Cheng@dot.nj.gov

Trey Carroll
Structures Management Unit
North Carolina DOT
Phone: (919) 707-6465
Email: thcarroll1@ncdot.gov

Terry B. Koon
Structural Design Support Engineer
South Carolina DOT
Phone: (803) 737-4814
Email: koontb@scdot.org

Edward Lutgen
State Bridge Engineer
Minnesota DOT
Phone (651) 366-4501
Email: edward.lutgen@state.mn.us

Cheryl Hersh Simmons, S.E.
Chief Structural Engineer
Utah DOT
4501 South 2700 West
Salt Lake City, UT 84114
Phone: (801) 557-7846
Email: cherylhersh@utah.gov

Don Nguyen-Tan
Chief, office of bridge design
Caltrans
Phone: (916) 639-5929
Email: don.nguyen-tan@dot.ca.gov

Pete White
Bridge Engineering Design Manager
Indiana DOT
100 North Senate Ave., N758 – BRD
Indianapolis, IN 46204
Phone: (317) 232-5371
Email: PeWhite@indot.in.gov

Kevin R Pruski, PE
Texas Department of Transportation
Bridge Division
Bridge Implementation Engineer
Phone: (512) 552-5971
Email: Kevin.Pruski@txdot.gov

Scott M. Walls, P.E., M.C.E.
Project Manager, Bridge Design
Delaware Department of Transportation
Phone: (302) 760-2317
Email: scott.walls@delaware.gov

Rick Liptak
Chief Bridge Construction Engineer
Michigan DOT
Phone: (231) 590-3382
Email: liptakr@michigan.gov

Harry L. White 2nd
Director, Structure Policy and Innovation Bureau
NYSDOT
50 Wolf Road, Albany, NY 12232
Phone: (518) 485-7256
Email: harry.white@dot.ny.gov

Linh Warren, P.E.
Senior Bridge and Tunnel Construction Engineer
FHWA Office of Bridges and Structures
HIBS-10 E75-113
1200 New Jersey Ave SE
Washington DC 20590
Phone: (202) 366-8501
Email: tuonglinh.warren@dot.gov
(Mrs./She/Her)

Pinar Okumus – Subject Matter Expert
Associate Professor
Civil, Structural and Environmental Engineering
University at Buffalo, The State University of New York
Phone: (716) 645 4356
Email: pinaroku@buffalo.edu

Appendix B: Team Member Biographic Sketches

DONN DIGAMON (TEAM CHAIR) is the State Bridge Engineer for the Georgia Department of Transportation (GDOT). He graduated with a bachelor's degree in civil engineering from the Georgia Institute of Technology in 1999 and has a Georgia PE license. Prior to joining GDOT, Mr. Digamon had 15 years of experience as a consultant bridge designer, having done work in Alabama, Arkansas, Mississippi, Tennessee, and Georgia. He joined GDOT in April 2014 as a Bridge Design Group Leader in the Office of Bridge Design and Maintenance and was promoted to Senior Group Leader four years later. From 2016 to 2021, he also served as the Office of Environmental Services and Bridge Office Liaison. AASHTO (American Association of State Highway and Transportation Officials) COBS (Committee on Bridges and Structures): Construction

BIJAN KHALEGHI is Director of Implementation of the Accelerated Bridge Construction -University Transportation Center (ABC-UTC) and Research Associate Professor at Florida International University College of Civil and Environmental Engineering. He manages infrastructure research projects and implementation of accomplished research projects to state transportation agencies. He is also an adjunct professor at Saint Martin's University, teaching Bridge Engineering, Earthquake Engineering, and Prestressed Concrete. Bijan is Principal Structural Engineer with TranTech Engineering, LLC, responsible for bridge project management from TS&L to final PS&E preparation and QC/QA implementation. Before 2023, Bijan was the Washington State Department of Transportation, Bridge and Structures Office, served as member of AASHTO Technical Committees on Movable Bridges T-8, Concrete Bridges T-10, Tunnels T-20, Roadway Tunnels, and member representative of AASHTO at the Permanent International Association for Road Congress (PIARC) TC4.4 Road Tunnel Operation. Bijan was the Chair of TRB AFF30 Concrete, a member of AFF50 Seismic and AFF60 Tunnel Committees. Bijan is a recipient of PCI Robert J. Lyman award, October 2018, PCI Fellow Award, February 2018, ASCE T.Y. Lin Award, March 2014, Charles C. Zollman Award, PCI Journal 2011 and 2013, ASCE SEI T.Y. Lin Award, May 2006, Martin P. Korn Award, PCI Journal Award 2005.

XIAOHUA “HANNAH” CHENG, Ph.D., P.E., is Supervising Engineer with Structural Design Policy and Standards Unit of New Jersey Department of Transportation (NJDOT). Her primary duties include development and update of the policy, manuals, standards, and guidance for design, construction, and maintenance of state highway bridges and traffic structures through implementation of AASHTO, FHWA, and state requirements, new technologies, and lessons learned. Her duties also include development of special design and construction criteria for major bridge projects, such as extreme events and resolutions of issues encountered during construction. Her work also includes supervision and management of Bridge Resource Program (BRP), Local Aid bridge rehabilitation selection program, and staff augmentation program. She develops problem statements, reviews proposals, and oversees state research projects in various topics, such as Bridge Scour, Seismic Design, Steel Orthotropic Deck, Weigh in Motion (WIM), Multi-hazard bridge design, etc. Dr. Cheng is serving AASHTO COBS as a member representing New Jersey. She is a member of several committees, task forces, and panels of AASHTO , TRB (Transportation Research Board), NCHRP (National Cooperative Highway Research Program), and ASCE (American Society of Civil Engineers). Before joining in NJDOT, she was a researcher in bridges and structures with ATLSS Research Center, Lehigh University and Public Works Research Institute (PWRI), Japan, and worked with consultants as a structural engineer. She is a registered professional engineer in Pennsylvania.

TREY CARROLL is the Assistant State Structures Engineer. He oversees NCDOT – Structures Management Unit’s (SMU) Program Management and Field Operations. He is a North Carolina registered Professional Engineer and has worked in the Structures Management Unit for over 10 years.

TERRY B. KOON is the Structural Support Design Engineer with the South Carolina Department of Transportation. Terry graduated from the University of South Carolina in 1986 with a B.S. degree in Civil Engineering and is registered as a Professional Engineer in the state of South Carolina. He began work with the South Carolina Department of Transportation (then South Carolina Department of Highways and Public Transportation) in 1982 as a part-time employee. He served in various capacities for over 37 years in the Bridge Design Office, Midlands Regional Production Group Structural Design Office, and Structural Design Support Office. He currently serves as the Structural Design Support Engineer tasked with managing structural quality assurance reviews and the development of structural design policies and standards. Terry represents SCDOT as a voting member on the AASHTO Committee on Bridges and Structures. Also serves on the Bridge Components and Seismic Technical Committees for the AASHTO Committee on Bridges and Structures. He is a licensed professional engineer.

ED LUTGEN is the director of the Bridge Office for the Minnesota Department of Transportation. Under his direction, the office develops policy, standards, manuals, final and preliminary plans, training, and project scope for the design, construction, maintenance, and inspection for public bridges within the state. In addition, the office oversees the bridge safety inspection program for Minnesota’s 20,500 bridges. Lutgen is a member of the AASHTO Technical Committee on Bridge Preservation and chairs the Committee on Safety and Evaluation. Ed is also a member of the FHWA Bridge Preservation Expert Task Group. Lutgen is a graduate of the University of Minnesota and a licensed professional engineer.

CHERYL HERSH SIMMONS is the Chief Structural Engineer for the Utah Department of Transportation and Chair of the AASHTO Technical Committee for Construction under the Committee on Bridges and Structures. Prior to joining UDOT in 2013, she spent over 23 years in the private sector focusing on project delivery and construction as a designer, resident engineer, project manager, and design quality manager on a number of fast-track design-build projects. Cheryl earned her B.S. in Civil Engineering from Duke University and her M.S. in Structural Engineering from University of Virginia. She is a licensed structural engineer.

DON NGUYEN-TAN graduated from UC Davis in 1994 with a B.S. in Civil Engineering and received his M.S. in Structural Engineering, Mechanics, and Materials from UC Berkeley the following year. Don spent 11 years as a consulting bridge design engineer before joining Caltrans in 2006. He has held several positions within Caltrans, including structures project engineer, Senior Seismic Specialist, Supervisor of a production bridge design branch, and supervisor of a load rating branch, and is currently the manager overseeing the development and maintenance of bridge technical policies and guidance.

PETE WHITE currently serves as the Design Manager for the Bridge Engineering Department at the Indiana Department of Transportation. In his current role he is responsible for assisting with the creation of policies and standards for the agency, with the goal of better quality and increased service life for INDOT’s bridges. Prior to serving as Design Manager, Pete served as a Bridge Asset Engineer for the agency. In that position, he was responsible for evaluating approximately 20% of the state’s inventory of bridges to determine appropriate repair, maintenance, and preservation treatments. This experience provided detailed insight on the types of issues that commonly reduce the service life of bridge decks, and potential methods of mitigating those risks. Pete received his bachelor’s and master’s degrees from Southern Illinois University at Carbondale and holds professional and structural engineering licenses. He has worked on numerous structure types, including prestressed and steel beam bridges, post-tensioned box girders, tied arches, and cable stayed bridges. Pete is currently active on the INDOT/ASCE Structures Committee and serves on the PTI/ASBI Bridge Design Committee.

KEVIN R PRUSKI joined the Texas Department of Transportation Bridge Division in 1992 and has focused his career on improving bridge long-term performance. His work history includes bridge design, construction, maintenance, rehabilitation, and preservation. He is active in the department research program focusing on concrete bridge deck curing, reduction of bridge deck cracking, concrete materials, concrete coatings and sealers, long-term bridge performance, and assessing bridge deck condition to predict remaining service life. Kevin is a licensed professional engineer.

SCOTT M. WALLS is the State Bridge Design Engineer for the Delaware Department of Transportation. His primary responsibilities include oversight of the design and contract preparation of bridge rehabilitation and replacement projects. With an $80 million annual budget, the projects executed under his supervision are oriented to improve the condition and performance of the nearly 1,800 bridges in the state's inventory. He also helped shape Delaware's focus on Accelerated Bridge Construction with the expanded use of prefabricated bridge elements and Ultra-High Performance Concrete. Scott holds a master's degree in civil engineering from the University of Delaware. He is a licensed professional engineer in Delaware.

RICK LIPTAK is the Chief Bridge Construction Engineer for the Bureau of Bridge and Structures at the Michigan Department of Transportation (MDOT) in Lansing, MI. Liptak directs the Bridge Construction Unit, which includes bridge construction, fabrication, and structure modeling/research outreach. His group works with field construction engineers to assure bridge construction is done per specifications and plans. Working with the construction industry is also a key part of his unit's responsibility. Liptak has worked for MDOT since 2003 and worked as a transportation service center manager prior to the bridge construction area. Liptak also is on the advisory board of ABC-UTC with FIU. Liptak is a civil engineering graduate of Michigan Technological University and a licensed professional engineer in Michigan.

HARRY WHITE is the Director of the Structure Policy and Innovation Bureau for the New York State DOT Office of Structures. He previously led the NYSDOT Standards and Policies Unit, the NYSDOT Research and Development Bureau - Structures Unit, the NYSDOT Quality Assurance Chemistry Laboratories, and was a NYSDOT Structures Design Squad leader. He graduated from Union College in Schenectady, NY with a Bachelor of Science in Civil Engineering, and is a registered professional engineer in NY State.

TUONGLINH (LINH) WARREN is the FHWA senior bridge and tunnel construction engineer. In this position, she provides technical support to national structural engineering program areas including Load Rating, Inspection, Design, and Security of Bridges and Structures. She also supports the development, acceptance, and deployment of new and improved construction techniques. She serves as the FHWA liaison for the AASHTO Technical Committee for Bridges on Construction. She received a master's degree from The George Washington University in civil engineering. She is a registered professional engineer in Virginia.

PINAR OKUMUS (SUBJECT MATTER EXPERT) is associate professor at the Department of Civil, Structural and Environmental Engineering at University at Buffalo, the State University of New York. She conducts research related to durability, structural behavior, and design of reinforced and prestressed concrete bridges. She has more than 15 years of research experience working on projects funded by State Departments of Transportation, FHWA, University Transportation Centers, NCHRP, among other agencies such as the National Science Foundation. Examples of her work include investigations of immediate and long-term response of atypical bridges, seismically resilient bridge columns, design guidance development and monitoring of girders with posttensioning, strategic use of fiber-reinforced concretes in bridge elements and evaluation of structural response of deteriorating bridge components. Dr. Okumus holds PhD (2012) and M.S. (2010) degrees in civil engineering from University of Wisconsin, Madison and B.S. (2006) degree in civil engineering from Middle East Technical University, Turkey. She is a member and committee research coordinator of TRB's Concrete Bridges Committee, chair of the Bridge Life Cycle Cost Analysis Subcommittee, member of the Bridge Management Committee; member of PCI's Technical Activities Council, Committee on Bridges and Subcommittee on Extreme Events, Innovation Committee, Journal Advisory Committee; and member of ACI's Committee on Evaluation of Concrete Bridges and Bridge Elements.

Appendix C:
Invited Presenters Contact Information

California DOT

Craig Knapp
Senior Bridge Engineer
Email: craig.knapp@dot.ca.gov

Mark Okimura
Division of Structures
Email: mark.okimura@dot.ca.gov

Jim Ma
Prestressed Concrete Specialist
Email: jim.ma@dot.ca.gov

Jason Chou
Associate Engineer
Email: jason.chou@dot.ca.gov

Joe Harline
Phone: (916) 206-4373
Email: Joe.Harline@dot.ca.gov

Hamed Sadati, PhD, PE.
Concrete Materials Engineer
Email: seyedhamed.sadati@dot.ca.gov

Florida DOT

William Potter
State Structure Design Engineer
Phone: (850) 414-4267
Email: william.potter@dot.state.fl.us

Vickie Young
Structures Design
Phone: (850) 414-4301
Email: vickie.young@dot.state.fl.us

Steven Nolan
Senior Structures Design Engineer,
State Structures Design Office
Phone: (850) 414-4272
Email: steven.nolan@dot.state.fl.us

Iowa County Engineer’s Assoc Service Bureau

Brian P. Moore, PE
Secondary Road Research Engineer
Iowa County Engineer’s Assoc Service Bureau
Phone: (641) 777-1107
Email: brian.moore@iceasb.org

Kansas DOT

Mark Hurt
State Bridge Engineer
Phone: (785) 296-4203
Email: mark.hurt@ks.gov

Dan L. Wadley, P.E.
Chief, Bureau of Research
Phone: (785) 291-3845
Email: Dan.Wadley@ks.gov

Dr. David Darwin
Professor and Chair of the Civil, Environmental, and Architectural Engineering Department
University of Kansas
Email: daved@ku.edu
http://ceae.ku.edu/david-darwin-phd-pe
http://www.iri.ku.edu/

Michigan DOT

Steve Kahl
Supervising Engineer
Email: kahls@michigan.gov

New York State DOT

Julianne M. Fuda, P.E.
Director, Structures Design Bureau
50 Wolf Road, Albany, NY 12232
Phone: (518) 457-0704
Email: Julianne.Fuda@dot.ny.gov

Brenda Crudele, PE
Director, Structures Specialty Engineering Bureau
50 Wolf Road, Albany, NY 12232
Phone: (518) 485-0139
Email: PhoneBrenda.Crudele@dot.ny.gov

Jim Scarlata, PE
Structure Policy & Innovation Bureau, Major Projects Unit Manager
Office: (518) 485-0848
Email: Jim.Scarlata@dot.ny.gov

Eric Lantzy, P.E.
Standards and Policies Unit, Office of Structures
Phone: (518) 485-5270
Email: Eric.Lantzy@dot.ny.gov

Oklahoma DOT

Justin Hernandez, P.E.
State Bridge EngOklahoma DOT
Phone: (405) 521-2606
Email: jhernandez@odot.org

Tyler Ley, Ph.D., P.E.
Professor
Oklahoma State University
Structural Engineering
217 Engineering North
Phone: (405) 744-5257
Email: tyler.ley@okstate.edu

Pennsylvania DOT

Tyler Culhane
Senior Civil Engineer
Bridge Office
400 North Street, 7th Floor | Harrisburg,PA 17120-0094
Phone : (717) 787-7505
Email: tculhane@pa.gov

Kristin Langer
Assistant Chief Bridge Engineer
Email: klanger@pa.gov

Texas DOT

Doug Beer
Bridge Division
Bridge Construction and Maintenance Branch Manager
Phone: (940) 217-9493
Email: Doug.Beer@txdot.gov

Andy Naranjo, PE
Materials and Tests Division
Rigid Pavements and Concrete Section Director
Phone: (512) 484-6484
Email: Andy.Naranjo@txdot.gov

Steven Austin, PE
Bridge Division
Field Operations Section Director
Phone: (737) 701-4020
Email: Steven.Austin@txdot.gov

Taya Retterer, PE
Bridge Division
Bridge Standards Engineer
Phone: (512) 993-0330
Email: Taya.Retterer@txdot.gov

Seth Cole, PE
Bridge Division
Bridge Maintenance and Engineering Support Lead
Phone: (512) 539-7280
Email: Seth.Cole@txdot.gov

Daryn Sims
Bridge Division
Bridge Construction and Field Support Lead
Phone: (940) 500-8067
Email: Daryn.Sims@txdot.gov

Utah DOT

James Corney
Structures Project Engineer - Construction
4501 South 2700 West • Taylorsville, UT 84129
Phone: (702) 285-8809
Email: jcorney@utah.gov

Virginia DOT

Soundar Balakumaran, Ph.D., P.E.
Associate Director for Structures
Virginia Transportation Research Council
Phone: (434) 293-1906
Email: Soundar.Balakumaran@vdot.virginia.gov

Junyi Meng, Ph.D., PE
Asst. State Structure and Bridge Engineer
Structure and Bridge Division
Phone: (804) 786-3817 ;
Phone: (434) 566-9993
Email: junyi.meng@VDOT.Virginia.gov

Stephen R. Sharp, Ph.D., P.E
Associate Principal Research Scientist
Virginia Transportation Research Council
Phone: (434) 293-1913
Email: Stephen.Sharp@VDOT.Virginia.gov

H. Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist/VTRC
Phone: (434) 293-1977
Email: celik@VDOT.Virginia.gov

Washington State DOT

Anthony Mizumori
Concrete Specialist
WSDOT Bridge & Structures
Phone: (360) 561-9954
Email: mizumoa@wsdot.wa.gov

Andre' La Foe
Bridge Deck Manager
WSDOT Bridge and Structures
Phone: (360) 705-7393
Email: lafoelo@wsdot.wa.gov

Appendix D:
Amplifying Questions

The following are the amplifying questions developed at the scan organizational meeting and sent to scan participants. The participants addressed some or all the questions in their presentations.

For the amplifying questions, *"innovation"* or *"innovative"* is defined as new, experimental and/or alternative materials, construction practices, curing regimens, design methods, and quality assurance methods that are used to enhance deck performance.

1. General Information
   a. How many concrete decks do you have in your inventory? How many of these are innovative?
   b. How is your agency organized to support innovation for decks?
   c. What is your standard practice for deck materials, design, specifications, girder type, construction practices, and quality control? How long has this been the practice?
   d. How do you differentiate between wide bridges over narrow bridges for designing concrete decks?
   e. What is your policy regarding bridge skew angle and curvature? Please include any limitations on skew angle or radius.
   f. In skew or curved bridges, what is the threshold for orienting the concrete deck transverse reinforcement parallel to the support line, perpendicular to the girder axis, or some other way?
   g. What are the ages of your bridge decks, and what issues do you encounter on a regular basis that can be attributed to the age of your decks?
   h. Are deck performance and maintenance issues in your organization related to environmental conditions? Which one(s) of the following are the most common types of damage, deterioration, or quality control issues that you see?
      - Construction cracking
      - Shrinkage cracking
      - Potholes
      - Corrosion
      - Spalling/delamination
      - Lack of cover
      - Poor drainage
      - Others (please specify)
   i. What processes do you follow to evaluate innovation before implementation?
2. Design, Detailing and Specifications Related to Innovations
   a. Do you use traditional design, empirical design, or other design methods for your innovative concrete decks?
   b. What design and other standards do you use for innovative bridge decks, e.g., AASHTO, others?
   c. How are maintenance and repair considerations worked into the design of an innovative deck?
   d. Do you recommend any particular concrete innovation based on past experience?
   e. Do you explicitly consider life cycle costs when considering investing in innovations? Or do you consider them but not include them in cost estimations?
   f. What concrete cover do you require for top and bottom deck reinforcement when using innovative rebar or concrete materials?
   g. Do you alternate the top and bottom reinforcement locations in innovative or standard decks? Where do you locate bar supports and ties?
   h. Do you place the transverse or the longitudinal reinforcement closer to the deck surface in innovative or standard decks?
   i. Do you use stay in place forms?
   j. Do you provide any test/condition data with bid documents or in another manner?
   k. Have you developed unique design methods or adopted any existing ones that are specifically for innovative decks?
3. Concrete Deck Types
   a. Do you use or have you used fiber-reinforced concrete for bridge decks?
   b. Do you use or have you used partial depth or full depth precast concrete decks?
   c. Do you use or have you used prestressed concrete decks?
   d. Do you or have you used precast girders pre-topped with decks (e.g., decked bulb-tee)?
   e. Do you or have you used steel girders pre-topped with deck?
   f. If you use any alternative concretes of construction methods, have you identified limitations and opportunities with any of them?
   g. Have you developed specifications/guidelines for any deck innovation?
   h. What was the initial cost of the innovation compared to a conventional deck? If there was a cost difference, how was this justified?
4. Deck Concrete and Reinforcement Materials
   a. What are the constituents of your innovative concrete mixes for decks?
   b. What are the limitations on the water/cement ratios of innovative mixes?
   c. What are the concrete compressive strength requirements for innovative mixes?

   d. Do you use lightweight concrete for bridge decks? Is this standard practice or for evaluation purposes?
   e. Do you use performance-based concrete mixes? If you do, what performance criteria do you specify? Is this standard practice or for evaluation purposes?
   f. Do you use admixtures in your mix for crack reduction or corrosion prevention? Is this standard practice or for evaluation purposes?
   g. Do you use engineered cementitious concrete (ECC) for bridge decks, and what is the rationale for using ECC?
   h. Do you use ultra-high performance concrete (UHPC) for bridge decks, and for what purposes?
   i. Do you use high performance concrete for bridge decks? Is this standard practice or for evaluation purposes?
   j. What are your policies for providing extra corrosion resistance to rebar?
   k. Do you use or have you used epoxy coated reinforcement for bridge decks? Do you require repair of damaged epoxy coating? If so, please describe.
   l. Do you use or have you used stainless steel reinforcement?
   m. Do you use or have you used stainless steel clad reinforcement?
   n. Do you use or have you used galvanized reinforcement or any other coated reinforcement?
   o. Do you use or have you used MMFX bars (ASTM A1035)?
   p. Do you use or have you used non-metallic GFRP or FRP reinforcement?
   q. Do you use or have you used any other materials not mentioned above?
   r. If you use any alternate concrete mixes, have you identified limitations and opportunities with any of them?
   s. If you use any alternate reinforcing types, have you identified limitations and opportunities with any of them?
   t. Have you developed unique specifications/guidelines for any alternative concrete mixes or reinforcing bars?
   u. What was the initial cost of the innovation compared to a conventional deck? If there was a cost difference, how was this justified?

5. Concrete Deck Construction Practices
   a. Do you have a policy for deck pouring sequence?
   b. What are your best practices for concrete deck curing methods and duration?
   c. What are your best practices for the ambient temperature limit?
   d. What are your best practices for the concrete temperature requirements?
   e. What test requirements and methods do you use for innovative materials?
   f. What are your practices for accelerated deck construction?
   g. For installation of precast concrete decks, do you consider environmental effects, such as installation temperature, creep, and shrinkage?
   h. Do you have special procedures for installing precast concrete decks in skew or curved bridges?
   i. Do you have specific requirements for finishing machines for skewed and curved bridges?
   j. What are your best practices for waterproofing/sealing systems for concrete bridge decks?
   k. Do you have pre-construction and/or post-construction quality control procedures?
   l. What training resources do you provide to construction inspectors? Do you require certifications for construction inspection?
   m. Do you have any criteria in the contract for when and how to repair new bridge decks?

6. Concrete Deck Safety Inspection and Maintenance
   a. How do you record and keep track of inspections (including deficiencies) of innovative concrete decks?
   b. What inspection methods do you use when you build innovative decks with alternative materials or new technologies?
   c. At what frequency do you inspect the innovative decks?
   d. How do you measure, monitor, and track the performance of innovative decks?
   e. What differences in inspection, repair, or maintenance practices have you observed for innovative decks?
   f. What differences in inspection, repair, or maintenance frequency have you observed for innovative decks?

7. Research
   a. Do you conduct in-house research?
   b. Have you conducted or funded any research on concrete bridge decks? If so, please provide references. If a reference is not available, please indicate the topic of research.
   c. Have you implemented research results?

8. Summary
   a. What are the three innovations you used that are the most promising for research or deployment?

Appendix E:
Case Studies

CASE STUDY TITLE:

Controlling Shrinkage Cracking

NAME OF AGENCY OR ORGANIZATION:

California Department of Transportation (Caltrans)

DESCRIPTION AND SUMMARY:

To extend service life, Caltrans treats cracked bridge decks with methacrylate. Methacrylate deck treatments have cost Caltrans $50 million annually. Over half of the bridge decks treated were less than 4 years old. About half of those were flagged for treatment at the first biennial inspection. Starting in 2001, our objective was to reduce maintenance costs of concrete bridge decks by eliminating or greatly reducing the presence and size of deck cracks. This was accomplished.

KEY RESULTS:

Through research and experience, a relationship between 28-day shrinkage performance and the cracking behavior of in-place concrete was established.1 Cracking in concrete bridge decks can be significantly reduced if the concrete mixtures used have 28-day shrinkage values below 0.030% (when tested in accordance with AASHTO T160 using 4"x 4" prisms). With the readily available shrinkage-reducing admixtures (SRA) on the market, it is now practical to routinely meet this requirement.

CHALLENGES:

If the concrete is allowed to crack while plastic, the deck will be cracked and the efficacy of reducing the longer-term drying shrinkage will not be verifiable. To address this issue, Caltrans specifies that an atomized mist be applied continuously to the deck surface from the time of finished strike-off until curing blankets are applied. To assist in preventing plastic shrinkage cracks, fiber reinforcement is also required. Caltrans specifies a blend of polyolefin fibers, 1 lb./cy of microfibers, and 3 lb./cy of macro fibers. The macro fibers also serve as additional restraint if any drying shrinkage crack does occur.

SRAs can interfere with air-entraining admixtures. Fortunately, the admixture industry has developed compatible SRAs for use in air-entrained concrete so that both air entrainment requirements and shrinkage requirements can be met. If there is an issue, consult with the admixture supplier for assistance with resolution.

RESOURCES:

When implemented via a change order, costs increased for non-air-entrained concrete, on average, by about $50/cy. $25/cy for the SRA and $25/cy for the fibers (the SRA used for air-entrained concrete is about twice the price of non-air-entrained concrete). When these specifications were included in the contract as part of a bid item, there was no measurable change to structure concrete bid prices. Better quality at no perceptible bid price increase is attributed to reduced contractor-assigned risk for crack remediation and market forces of competitive bidding.

LESSONS LEARNED:

It has been our experience that for concrete with equal 28-day shrinkage performance, those that contain SRA exhibit less crack intensity, width, and depth, than those that do not. Therefore, a minimum SRA dosage of ¾ gal/cy is included in Caltrans specifications. This also serves to avoid establishing any significant competitive advantage between aggregate suppliers.

Before these requirements were made Standard Specifications, extensive piloting of projects across California's various aggregate sources provided confidence that the shrinkage requirement was realistically achievable in all areas of the state. Still, some concrete suppliers were concerned they could not meet the shrinkage requirement. To mollify this concern, Caltrans specifications state that if all the concrete's material requirements are met AND the admixture manufacturer's published maximum SRA dosage rate is used, the shrinkage test results need not be below 0.030%. To date, we are unaware of a case where it was necessary to employ this waiver.

FUTURE PLANS:

- Reduce the minimum cementitious material requirement for bridge decks.
- Implement performance requirements for fiber reinforcement to verify performance and accommodate alternative fiber materials.
- Establish a lower shrinkage requirement for fully restrained applications that are more at risk of cracking (e.g., deck on deck overlays and decks with permanent steel deck forms).
- Implement shrinkage limitation requirements for concrete pavement.
- Reduce the duration of water cure of concrete decks from seven days to three days when advisable for Accelerated Bridge Construction projects.
- Specify placement sequences for decks to limit strain accumulation in longer spans.
- Study the potential for reducing deck thickness due to the increased durability and life cycle performance using the CRACK-Less deck specification, decreasing dead load, cost, and greenhouse gas emissions.

REFERENCES:

Controlling Shrinkage Cracking (ca.gov)

Appendix F: References

1. Clarivate. *Web of Science. 2021* [cited June 2022; Available from: www.webofscience.com.
2. Russell, H.G., NCHRP SYNTHESIS 441: *High Performance Concrete Specifications and Practices for Bridges*. 2013. p. 73.
3. Darwin, D., et al., *CONSTRUCTION OF CRACK-FREE BRIDGE DECKS: FINAL REPORT*. 2016.
4. ACI Committee 329, ACI 329-14: *Report on Performance-Based Requirements for Concrete*. 2014: Farmington Hills, MI.
5. Kurtis, K.E., L.F. Kahn, and E. Nadelman, *Viability of Concrete Performance-Based Specification for Georgia DOT Projects*. 2013. p. 107.
6. Rajabipour, F., G. Sant, and J. Weiss, *Interactions between shrinkage reducing admixtures (SRA) and cement paste's pore solution*. Cement and Concrete Research, 2008. 38(5): p. 606-615.
7. Kaladharan, G., A. Gholizadeh-Vayghan, and F. Rajabipour, *Review, Sampling, and Evaluation of Landfilled Fly Ash*. ACI Materials Journal, 2019. 116(4).
8. ASTM C595/C595M – 21, *Standard Specification for Blended Hydraulic Cements*. 2021: West Conshohocken, PA.
9. ASTM C150/C150M – 22, *Standard Specification for Portland Cement*. 2022: West Conshohocken, PA.
10. Bharadwaj, K., et al., *CALTRANS: Impact of the Use of Portland-Limestone Cement on Concrete Performance as Plain or Reinforced Material - Final Report*. 2021, Oregon State University: https://doi.org/10.5399/osu/1150.
11. Under Construction. *Concrete Air Entrainment | Super Air Meter.* 2023 [cited May 2023; Available from: https://www.superairmeter.com/.
12. AASHTO Committee on Materials and Pavements, AASHTO T395-22: *Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method.* 2022.
13. Robertson, J.B., M.T. Ley, and D. Cook Marllon, *Measuring the Change in Water-to-Cement Ratio in Fresh and Hardened Concrete*. Journal of Materials in Civil Engineering, 2022. 34(4): p. 04022016.
14. ACI, *CT-20: ACI Concrete Terminology*. American Concrete Institute, 2020.
15. Azizinamini, A., et al., B*ridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems, and Components*. 2014: Washington, DC.
16. Armaghani, J. and T.L. Cavalline, *NCHRP Synthesis 544: Concrete Technology for Transportation Applications*. 2019: Washington, DC.
17. Adams, C.J., et al., *Super-absorbent polymers for internally cured concrete*. 2022. p. 48.
18. Carpenter, D. and M. Royce, *Internal Curing Concrete Bridge Decks in New York State*. PCI Aspire, 2019. **Summer**: p. 48.
19. Krauss, P.D., J.S. Lawler, and K.A. Steiner, *GUIDELINES FOR SELECTION OF BRIDGE DECK OVERLAYS, SEALERS AND TREATMENTS*. 2009: Washington, DC. p. 111.
20. McGovern, M.S., *A clear view of sealers*. Concrete Construction, World of Concrete, 2000. **45**(1): p. 53-58.
21. Krauss, S., et al., *Mechanical Function of a Complex Three-Dimensional Suture Joining the Bony Elements in the Shell of the Red-Eared Slider Turtle*. Advanced Materials, 2009. 21(4): p. 407-412.
22. White, H.L. Bridge Deck Overlay Options. in *Statewide Conference on Local Bridges*. 2019. Syracuse, NY.
23. Haber, Z.B. UHPC Overlays: An Emerging Repair Solution. in *UltraHigh Performance Concrete (UHPC)* Workshop. 2017. Albany, NY.
24. ASTM C1116/C1116M-10a, *Standard Specification for Fiber-Reinforced Concrete*. ASTM International, 2015: p. 7.
25. ACI Committee 544, *ACI 544.4R-18: Guide to Design with Fiber-Reinforced Concrete*. American Concrete Institute, 2018: p. 44.
26. Banthia, N., et al., F*iber-reinforced concrete in precast concrete applications: Research leads to innovative products*. PCI Journal, 2012. **57**(3): p. 33-46.
27. Zollo, R.F., *Fiber-reinforced concrete: an overview after 30 years of development*. Cement and Concrete Composites, 1997. **19**(2): p. 107-122.
28. Amirkhanian, A. and J. Roesler, *Overview of Fiber-Reinforced Concrete Bridge Decks*. 2019. p. 37.
29. Dickey, M., *Use of Fibers to Improve the Performance of Concrete, in Department of Civil and Environmental Engineering*. 2019, Oklahoma State University: Stillwater, OK. p. 89.
30. Tadros, M. *Fundamentals and Application on PCI Ultra-High Performance Concrete. in GCPCI-PCEF Meeting*. 2021. Precast/Prestressed Concrete Institute.
31. Portland Cement Association. *Ultra-High Performance Concrete.* 2019 [cited June 2022; Available from: https://www.cement.org/learn/concrete-technology/concrete-design-production/ultra-high-performance-concrete.
32. Graybeal, B., *FHWA Tech Note: Ultra High Performance Concrete*. 2011.
33. Perry, V.H., P. White, and T.M. Ahlborn. *The First North American Broad Based Structural Design Guide on UHPC - ACI 239C*. in First International Interactive Symposium on UHPC. 2016. Des Moines, IA.
34. Li, V.C., *Introduction to Engineered Cementitious Composites (ECC), in Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure*, V.C. Li, Editor. 2019, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 1-10.
35. Graybeal, B., *Tech Brief: Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector*. 2013. p. 8.

36. Utah Department of Transportation, Performance of Accelerated Bridge Construction Projects in Utah As of October 2019: Lessons Learned Report. 2019. p. 258.

37. Aaleti, S., et al., *Structural Characterization of UHPC Waffle Bridge Deck and Connection*. 2014, Iowa State University: Ames, IA. p. 91.

38. Aaleti, S., B. Petersen, and S. Sritharan, *Design Guide for Precast UHPC Waffle Deck Panel System, including Connections*. 2013: Washington, D.C.

39. Graybeal, B.A., *Structural Behavior of a 2nd Generation Ultra-High Performance Concrete Pi-Girder*. 2009. p. 114.

40. Shafei, B. and R. Karim, *Non-Proprietary Ultra-High Performance Concrete Mix Design for ABC Applications*. 2022. p. 96.

41. Sorensen, A. and S. Banerji, *Durability and Volumetric Stability of Non-Proprietary Ultra High Performance Concrete Mixes Batched With Locally Sourced Materials*. 2022, Utah State University: Ongoing Project.

42. Texas Department of Transportation. *Utilization of UHPC Bridge Superstructures in Texas, Project 0-6982*. 2023 [cited May 2023.

43. Florida Department of Transportation. *Structures Design: Fiber Reinforced Polymer Reinforcing*. 2022 [cited May 2023; Available from: https://www.fdot.gov/structures/innovation/frp.shtm.

44. Florida Department of Transportation. *Structures Design Innovation*. 2022 [cited May 2023; Available from: https://www.fdot.gov/structures/innovation.

45. Chen, Y.U., *Development of GFRP Reinforced Single Slope Bridge Rail, in Department of Civil and Coastal Engineering*. 2021, University of Florida: Gainesville, FL. p. 263.

46. Phillips, K.A., et al., *Performance of a Bridge Deck with Glass Fiber Reinforced Polymer Bars as the Top Mat of Reinforcement*. 2005, Virginia Transportation Research Council: Charlottesville, VA. p. 68.

47. American Galvanizers Association. *Galvanized Rebar: Frequently Asked Questions About Galvanized Rebar*. N/A [cited 2017; Available from: http://www.galvanizedrebar.com/frequently-asked-questions/.

48. International Zinc Association. *Case Studies*. N/A [cited June 2022; Available from: https://www.galvanizedrebar.com/.

49. Virmani, Y.P. and G.G. Clemena, *Corrosion Protection - Concrete Bridges*. 1998: McLean, VI.

50. Concrete Reinforcing Steel Institute, *Frequently Asked Questions About Hot-Dip Galvanized Reinforcing Bars*. 2016: Schaumburg, IL. p. 6.

51. Epoxy Interest Group. *Use & Applications: Manufacturing Process*. 2017 [cited 2017; Available from: http://epoxyinterestgroup.org/use-applications/manufacturing-process/.

52. *American Galvanizers Association*. American Galvanizers Association. 2017 [cited 2017; Available from: https://www.galvanizeit.org/.

53. Ross, B., et al., *Textured Epoxy Coated and Galvanized Reinforcement to Reduce Cracking in Concrete Bridge Decks and Components*. 2021. p. 141.

54. Concrete Reinforcing Steel Institute, *Frequently Asked Questions (FAQ) About Stainless Steel Reinforcing Bars*. 2018: Schaumburg, IL. p. 7.

55. Presuel-Moreno, F., J.R. Scully, and S.R. Sharp, *Identification of Commercially Available Alloys for Corrosion-Resistant Metallic Reinforcement and Test Methods for Evaluating Corrosion-Resistant Reinforcement*. 2008, Virginia Transportation Research Council. p. 51.

56. Concrete Reinforcing Steel Institute, *Frequently Asked Questions (FAQ) About Low-Carbon, Chromium ASTM A1035 Type CS, CM and CL Steel Reinforcing Bar*, in CRSI Technical Note. 2017: Shaumburg, IL. p. 6.

57. Hennings, B. *Design and Specifying A1035 Corrosion Resistant and High Strength Reinforcing Steel. in Presentation to Alaska* DOT. 2017.

58. Barr, P. and K. Wixom, *Feasibility of Using High-Strength Steel and MMFX Rebar in Bridge Design*. 2009, Utal State University: Logan, UT. p. 84.

59. Sharp, S.R., et al., *Acceptance Procedures for New and Quality Control Procedures for Existing Types of Corrosion-Resistant Reinforcing Steel*. 2011, Virginia Center for Transportation Innovation and Research: Richmond, VA. p. 78.

60. Jones, J., K. Ryan, and M. Saiidi, *Toward Successful Implementation of Prefabricated Deck Panels to Accelerate the Bridge Construction Process*. 2016. p. 283.

61. Hieber, D.G., et al., *State-of-the-Art Report on Precast Concrete Systems for Rapid Construction of Bridges*. 2005. p. 112.

62. PCI Committee on Bridges, *STATE-OF-THE-ART REPORT ON FULL-DEPTH PRECAST CONCRETE BRIDGE DECK PANELS*. 2011. p. 151.

63. Garber, D. and E. Shahrokhinasab, *Performance Comparison of In-Service, Full-Depth Precast Concrete Deck Panels to Cast-in-Place Decks*. 2019. p. 152.

64. Badie, S.S. and M.K. Tadros, *Full-depth Precast Concrete Bridge Deck Panel Systems*. 2008: Washington, D.C.

65. Badie, S.S., G. Morcous, and M. Tadros, *Simplified Full-Depth Precast Concrete Deck Panel Systems* 2018.

66. Peruchini, T.J., J. Stanton, and P. Calvi, *Investigation of Ultra-High Performance Concrete for Longitudinal Joints in Deck Bulb Tee Bridge Girders*. 2017, Washington State Transportation Center: Olympia, WA. p. 100.

67. He, E., J. Whittaker, and J. Gonyea. *REPLACING AN INTERSTATE BRIDGE DECK WITHIN A WEEKEND CLOSURE – CASE STUDY OF ACCELBRIDGE DECK SYSTEM*. in *Virtual Accelerated Bridge Construction Conference*. 2021. Virtual.

68. AASHTO, *AASHTO LRFD Bridge Design Specifications, US Customary Units, 9th Edition*. 2020, American Association of State Highway and Transportation Officials: Washington, DC. p. 1716.

69. Nowak, A.S., et al., *Deck Design Loads and Analysis*. N/A, Auburn University.

70. Holt, J.M., *Reducing Steel in Bridge Decks*. Concrete Bridge Views, 2014. **Septembe/Octobe**r(78).

71. Helwig, T., *Develop Guidance for Structural Behavior of Tall Haunches in TxDOT Beam and Girder Bridges*. Ongoing Project: https://library.ctr.utexas.edu/Presto/content/Detail.aspx?ctID=M2UxNzg5YmEtYzMyZS00ZjBlLWIyODctYzljMzQ3ZmVmOWFl&rID=NjU5&sID=MQ==&qrs=VHJ1ZQ==&q=KHJwLlN0YXR1czooYWN0aXZlKSk=&rrtc=VHJ1ZQ==.

72. Richardson, J., et al., *Measurement of Bridge Deck Layout Prior to Concrete Placement*. 2017, University Transportation Center for Alabama: Montgomery, AL. p. 29.

73. AASHTO, *Guide Specifications for Service Life Design of Highway Bridges, 1st Edition*. 2020.

74. Murphy, T., et al., *Guide Specification for Service Life Design of Highway Bridges*. 2020: Washington, DC.

75. Minnesota Department of Transportation, *MnDOT Service Life Design Guide for Bridges*. 2023. p. 21.