OPTIMIZATION OF ADVANCED CEMENTITIOUS MATERIAL OVERLAYS AND UPGRADES, INCLUDING SHOTCRETE

Quarterly Progress Report
For the period ending August 31, 2019

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1. Background and Introduction

Ultra-High strength concrete (UHPC) applications have been studied as one of the many strategies in Accelerated Bridge Construction (ABC). Bridge maintenance procedures can be accelerated with the application of UHPC in specific situations. Deck overlays have been placed over deteriorated and damaged bridge decks for many years in order to extend the deck service life. Application of UHPC has the potential to reduce lane closure time during the repair process, if sufficient strength is obtained in a few hours. Typically, a concrete strength of 3000 to 4000 psi is required to open a lane to traffic. UHPC also provides a higher strength for the composite bridge deck section and mitigates additional corrosion by inhibiting penetration of additional chloride ions. Commercial UHPC mixes have been developed that have a lower slump that have been shown to hold cross slopes up to 2%. This research project addresses the design considerations required for successful application of UHPC as an alternative material for deck overlay and other deck repairs and upgrades. The research project will conduct a comprehensive literature review on bridge deck overlays, perform material level testing, perform large scale level testing for UHPC bridge deck overlays, and numerical modeling to optimize design parameters.

Recent developments in UHPC mixes have been applied with pneumatic spray applications. Such repair methods may be applicable to vertical and overhead applications, on the underside of bridge decks.

Significant research has been performed on UHPC and their applications as an overlay and upgrading material. However, as outlined later in this report, there are still a number of important questions and concerns that should be addressed and remain to be studied.

2. Problem Statement

Deterioration of bridge deck is a major issue for bridge owners. The primary causes of deck deterioration include vehicle traffic, environmental effects (i.e. freeze-thaw, salt spray), and maintenance practices (snow plows, de-icing chemical treatments). Deterioration is featured by delamination, cracking, corrosion of reinforcing steel, abrasion, scaling, and other mechanisms. Deterioration of the top deck surface is common, but in coastal areas, subjected to salt spray, the underside of the deck may also deteriorate.

One of the recent advances in UHPC application is the development of UHPC applied with pneumatic spray methods. Spraying UHPC onto the underside of a bridge deck will save the time and effort of building formwork while providing the strength and corrosion mitigation properties discussed above.

While significant research has been conducted on UHPC and their applications as an overlay and repair material, there are still a number of questions and concerns that should be addressed which include:

1. Determining the section capacity of the composite section between UHPC deck overlay, deck normal strength concrete, and bridge girder.
2. Hydro-blasting and other methods of removing deteriorated concrete and surface preparation may result in varying thickness of overlay to attain design grades. What is the effect of such variation on the overlay performance?
3. How does the roughness of the interfacial surface between UHPC and normal strength concrete impact moment capacity? What is the optimum interfacial surface roughness?
4. Overlays are typically considered for the top surface of the deck, especially in northern climates where de-icing salts are applied. Deterioration may also be found on the bottom of the deck, particularly in coastal areas where salt-spray occurs. Repair techniques should be developed for the deteriorated bottom face of bridge deck, and may include UHPC pneumatically sprayed applications.
5. UHPC mix designs typically contain 2% steel fibers, but some applications have been documented with different percentages. What is the effect of iterating steel fiber content?
6. Fatigue or cyclic loading research is lacking. More data is needed for the cyclic loading behavior on UHPC overlays.
7. The higher tensile capacity of the UHPC may allow the material to be placed over expansion joints on single span or as a link slab at intermediate supports. Covering the joints will reduce the level of maintenance needed for the joint. The advantages of reduced joint maintenance would be beneficial to bridge owners.
8. What are the optimum UHPC design mixes to retain a crowning slope up to 7%?
9. Are the recently developed non-proprietary UHPC mixtures suitable for bridge deck overlay and underside upgrade of bridge desks?

3. Objectives and Research Approach

The objective of this study is to investigate the various parameters involved in optimizing the design of UHPC overlays and upgrades, and to develop design guidelines for UHPC overlays. The activities listed below will be directed to this objective.

4. Description of Research Project Tasks

Following are description of tasks as described in the research proposal and their current status. Figure 1 shows the proposed flowchart for the project tasks.

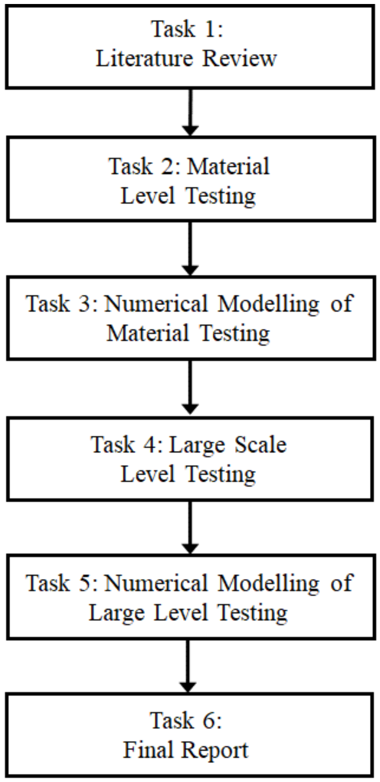


Figure 1. Flow chart of research tasks.

Task 1 – Literature Review

In this task, a comprehensive literature review is being conducted. The researchers will continue the review of the development of UHPC deck overlays and upgrades for better understanding of design challenges and issues. The literature review includes the following subject areas:

1. The current design practice of concrete overlays,
2. Material properties of UHPC,
3. Composite action of UHPC and Normal strength concrete,
4. Pneumatic Spray Application, and
5. Numerical Modeling of UHPC and composites.

The need for cost-effective and durable rehabilitation methods have been documented by many researchers [1-3]. Concrete overlays are classified as bonded or unbonded. Fowler and Trevino [1] points out the primary purpose of an overlay is to extend the life of bridge decks, and that bonded concrete overlays (BCO) have been applied since 1909. Bonded overlays can also improve the frictional surface and increase the durability of the wearing surface. Fowler and Trevino provide a simplified flow chart for developing an overlay in Figure 2.

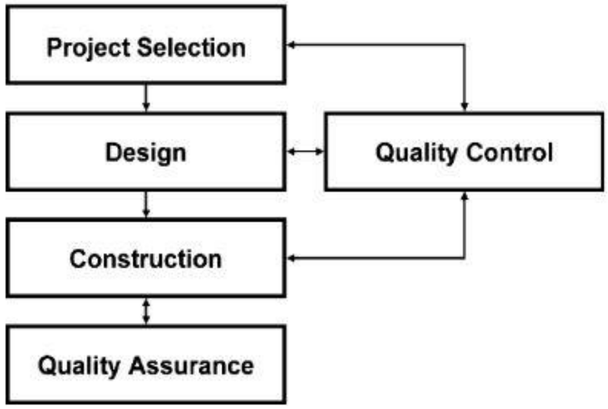


Figure 2. Simplified Flow Chart to Develop Overlay (Fowler and Trevino [1])

Bridge overlays typically are placed after concrete removal, in order to limit the increase in dead load which will reduce the live load capacity. Trevino and Fowler also [1] state, “Compatibility between the overlay and original pavement concrete is important, and the coefficient of thermal expansion and modulus of elasticity should be lower than the original concrete if possible.” This statement makes sense if overlay and original bridge deck consist of conventional concrete. UHPC is significantly stronger and stiffer than conventional concrete and must be designed with different aspects.

Wibowo and Sritharan [4] presented a study in which an existing bridge was overlaid with UHPC. They noted that bridge deterioration typically begins with cracking in the deck, which then progresses as water and chlorides have an infiltration path, eventually leading to reinforcing steel corrosion. This corrosion can initiate within 4 to 8 years. One of the issues faced by Wibowo and Sritharan was maintaining the cross slope of the UHPC overlay. LafargeHolcim provided a lower slump mix design that held a 2% cross slope in a full-scale bridge application. The mix was also placed with a conventional vibratory screed. Wibowo and Sritharan also conducted limited flexural testing on large scale specimens consisting of normal strength concrete with UHPC overlay. Increases in stiffness and ductility were noted, however, the increase in stiffness was attributed to the overall increase in depth. They did not look at a replacement depth of UHPC that would maintain the existing deck thickness. Also, no cyclic testing was performed for this study.

Graybeal, et.al. [2] and Haber, et.al. [5] studied overlays on existing bridges, with a focus on the tensile strength of the bond between the UHPC and the normal strength concrete. The overlay was placed with a proprietary UHPC mix that had thixotropic properties. Haber [8] indicates that the primary differences between typical UHPC formulations and UHPC mixes that have been formulated for overlay applications are the rheological properties. The overlay formualtions are thixotropic in shich the UHPC remains solid-like and will flow when agitated or sheared. Typical UHPC formulations are will flow freely under gravity.

Caltrans [6] provides design guidance for concrete overlays. This memorandum does not address UHPC, but the general guidelines discuss depth, bonding, live loads, and surface preparation. The memorandum also states that tapering sections should be avoided as they deteriorate quickly.

Several researchers have studied the basic properties of UHPC mixes, including compressive strength, tensile strength, creep, durability among others. Haber et al. [5] presented a table of typical UHPC properties, as shown below (Table 1).

Table 1. Typical Properties of Field Cast UHPC Concrete adapted from Haber et al. [8]

Material Characteristic	Average Result
Density	155 lb/ft^3
Compressive Strength (ASTM C39, 28-day strength)	24 ksi
Modulus of Elasticity (ASTM C469, 28-day modulus)	7,000 ksi
Direct Tension cracking strength (uniaxial tension with multiple cracking)	1.2 ksi
Split cylinder cracking strength (ASTM C496)	1.3 ksi
Prism flexural cracking strength (ASTM C1018; 12 in span)	1.3 ksi
Tensile strain capacity before crack localization and fiber debonding	>0.003
Long term creep coefficient (ASTM C512; 11.2 ksi load)	0.78
Long term shrinkage (ASTM C157; initial reading after set)	555 microstrain
Total shrinkage (embedded vibrating wire gage)	790 microstrain
Coefficient of thermal expansion (AASHTO TP60-00)	8.2 x 10^{-6} in/in/^{0}F
Chloride Ion penetrability (ASTM C1202; 28-day test)	360 coulombs
Chloride Ion penetrability (AASHTO T259; 0.5-in depth)	<0.10 lb/yd^3
Scaling resistance (ASTM C672)	No scaling
Abrasion resistance (ASTM C944 2x weight; ground surface)	0.026 oz. lost
Freeze-thaw resistance (ASTM 666A; 600 cycles)	RDM = 99%
Alkali-silica (ASTM C1260; 28-day test)	Innocuous

RDM = Relative dynamic modulus of elasticity; ASTM = American Society of Testing and Materials; AASHTO = American Association of State highway and Transportation Officials.

UHPC overlays are gaining in popularity as a rehabilitation material due to the material properties. These properties include high compressive strength and tensile capacity compared to normal strength concrete, along with lower permeability and low shrinkage. UHPC also has a high early strength that allows for reduced lane closure and construction time. Haber, et al [7] presented strengths of about 9,000 psi at 2 days.

Current research has shown that UHPC bonds well to normal strength concrete, both in direct tension test [2,7] and shear test [4]. Shrinkage stresses do not appear to be a significant design concern either [3]. UHPC has also been shown to mitigate corrosion activity [8]. Graybeal [2] presented a direct tension test methodology, illustrated in Figure 3.

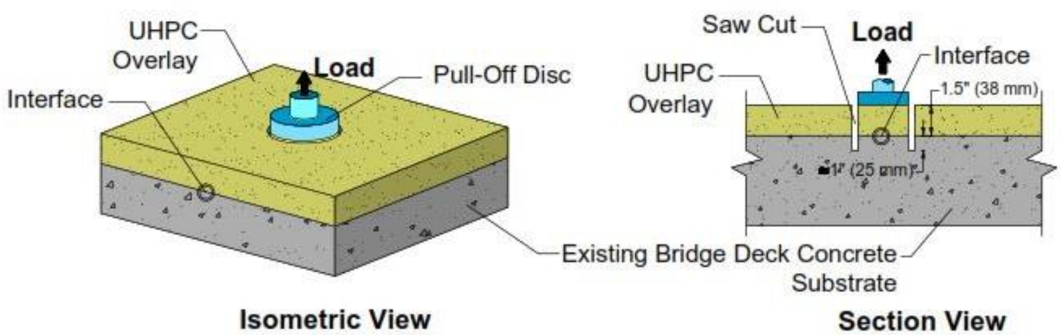


Figure 3. Illustration. Direct tension pull-off bond test based on ASTM C1583 [2].

Al-Basha, et.al. [9] performed as series of tension, slant shear and other testing to look at variations in roughness at the bond interface. Some of their results are presented in Table 2. They concluded acceptable bond strengths can be obtained between UHPC and NSC, but that strength is dependent on the surface roughness.

Table 2. Average direct tensile strengths for different textures [9].

Texture (average texture depth)	Rough (2.8 mm)	Horizontal Grooves (0.9 mm)	Chipped (1 mm)
Average Tensile Strength (MPa)	0.96	0.44	1.06

Only one study has been identified to date that included cyclic loading [7]. It appears there is a need for more cyclic load data with regard to UHPC placement.

The researcher leading this project, has spoken with “Shotcrete applicators” and attended typical shotcrete applications. In these discussions, the applicators suggest adding fly ash to the mix design to enhance the flow of the material through the hoses. Application may be possible with a smaller diameter hose, as the UHPC has little aggregate, reducing the amount of waste typically associated with spray applications. These discussions are still preliminary, as is the initial research into how the material should be applied. Ductal provided an Identity Card of Material, which summarized several material properties of spray applied UHPC, but it does not include details on the mix design or constituents.

Task 2 – Material Level Testing (in progress)

Testing of composite flexural beams will be performed. The testing will iterate various parameters such as thickness of the UHPC overlay and roughness of the concrete interface between the NSC and UHPC. Flexural strength and Modulus of Rupture of normal strength concrete (NSC) Beams with ½-inch and 1-inch of UHPC overlays will be determined experimentally. UHPC application to the beam specimens will be applied conventionally on some specimens and applied with spray application techniques on other specimens. The flexure beams will be instrumented to obtain load-deflection data.

Fabrication of the composite flexure beams began this period. Normal Strength Concrete (NSC) was placed in 18 beam molds. Eighteen flexure beams, eight 4 in. x 8 in. concrete cylinders, and three 6 in x12 in. cylinders for elastic modulus testing were cast as shown in Figure 4 and Figure 5. Two of the beams are full depth normal strength concrete as reference, to determine flexure strength of the concrete. Two bars of No. 3 were placed in each beam mold, with approximately 1-inch cover from the bottom. Testing will be conducted on sets of beams with varying roughness profiles on the interface between the NSC and UHPC. UHPC will either be placed conventionally or with spray application.

Figure 4. Beam and Cylinder Molds.

Figure 5. Casting Specimens

The roughness profiles were created on an initial set of beams. These beams serve as the basis for roughness profiles. The intent is to develop repeatable roughness profiles to allow for meaningful correlations of data. Forms were made by applying an elastomeric roofing compound to the initial beams, and removing the compound carefully after setting. A series of profile forms, also called skins, were made with this process. The interface roughness will represent:

1. Trowel finish, identified as Profile 1.
2. A trowel finish that was lightly stippled, identified as Profile 2.
3. Puddled surface to represent a typical unformed cold-joint, identified as Profile 3.
4. A puddled surface that was also chipped, identified as Profile 4.

Static load Testing will be conducted on beam sections with various UHPC thickness, interfacial surface roughness coefficients, and mix designs as shown in Table 3 below. Load-deflection data will be obtained. A set of beams will be tested with the UHPC on the upper face, and another set will be testing with the UHPC overlay on the bottom face.

Normal Strength concrete design mix typical for bridge decks was selected. The design mix had a compressive strength of 4,500 psi. Compressive strength and Modulus of Elasticity tests on NSC and UHPC cylinders will be conducted. Results of the compressive strength tests performed on NSC cylinders is shown below in Figure 6. Figure 7 shows the cylinder after 7-day compressive strength.

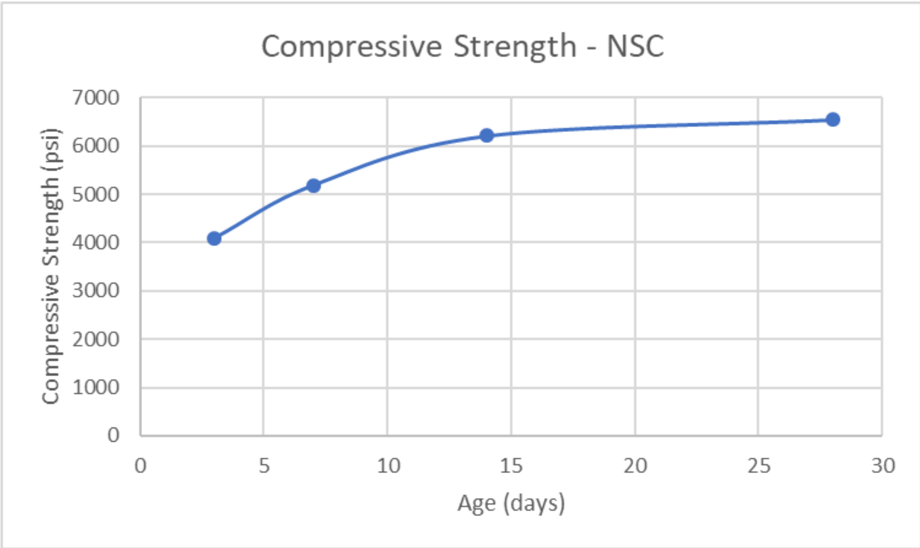
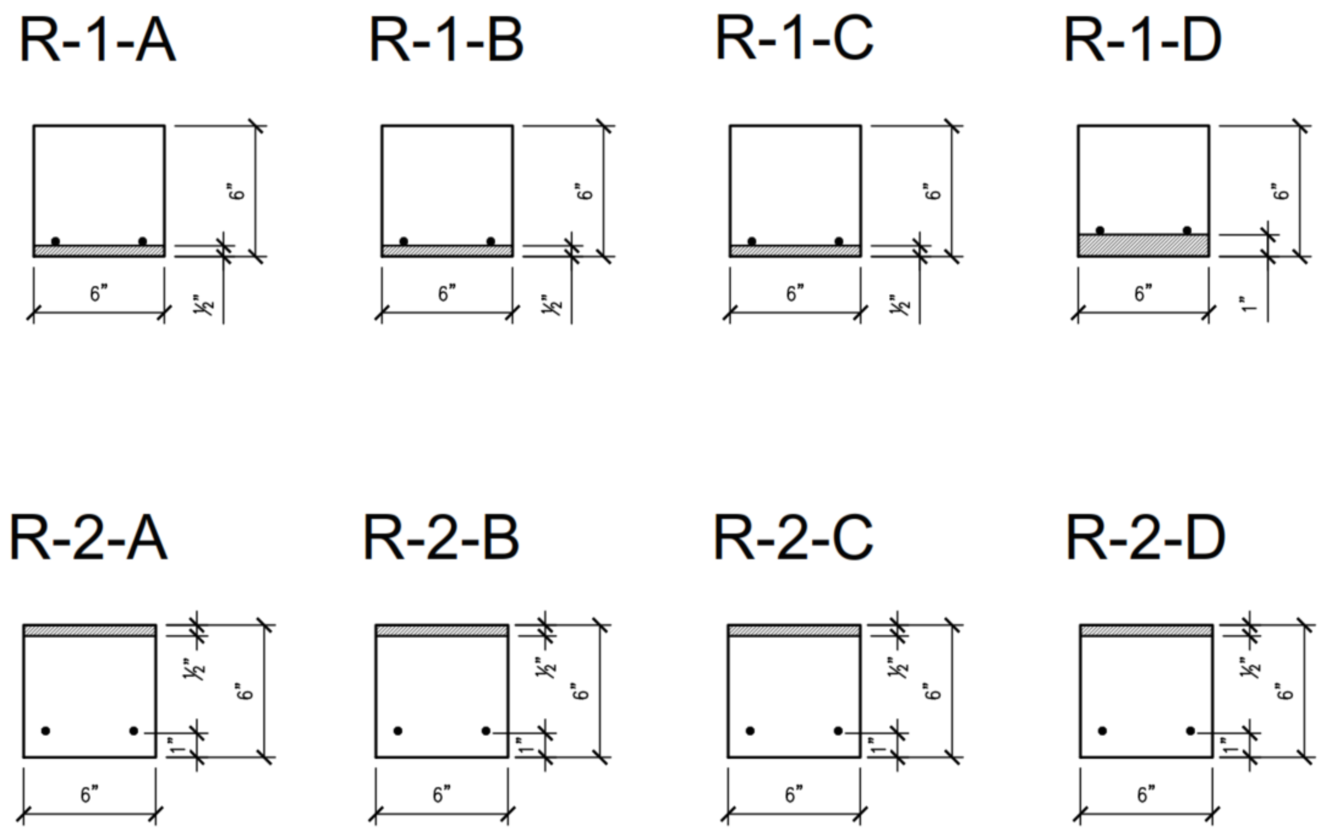


Figure 6. Compressive Strength Test Results, NSC

Figure 7. Compressive Cylinder at 7 days

Figure 8 shows cross sections of the 18 beams. Table 3 summarizes the 'as-built" conditions of the beams and presents the proposed testing program. Figures 9 to Figure 11 shows specimens after removing both roughness skin and molds. When the samples were stripped, sample R-1-C had honeycombs in the concrete. Also, the plywood spacers in the form for sample R-1-B were warped, so that the overlay thickness at the ends of the beam will be about ½ inch, but will be about 1 inch at the center.



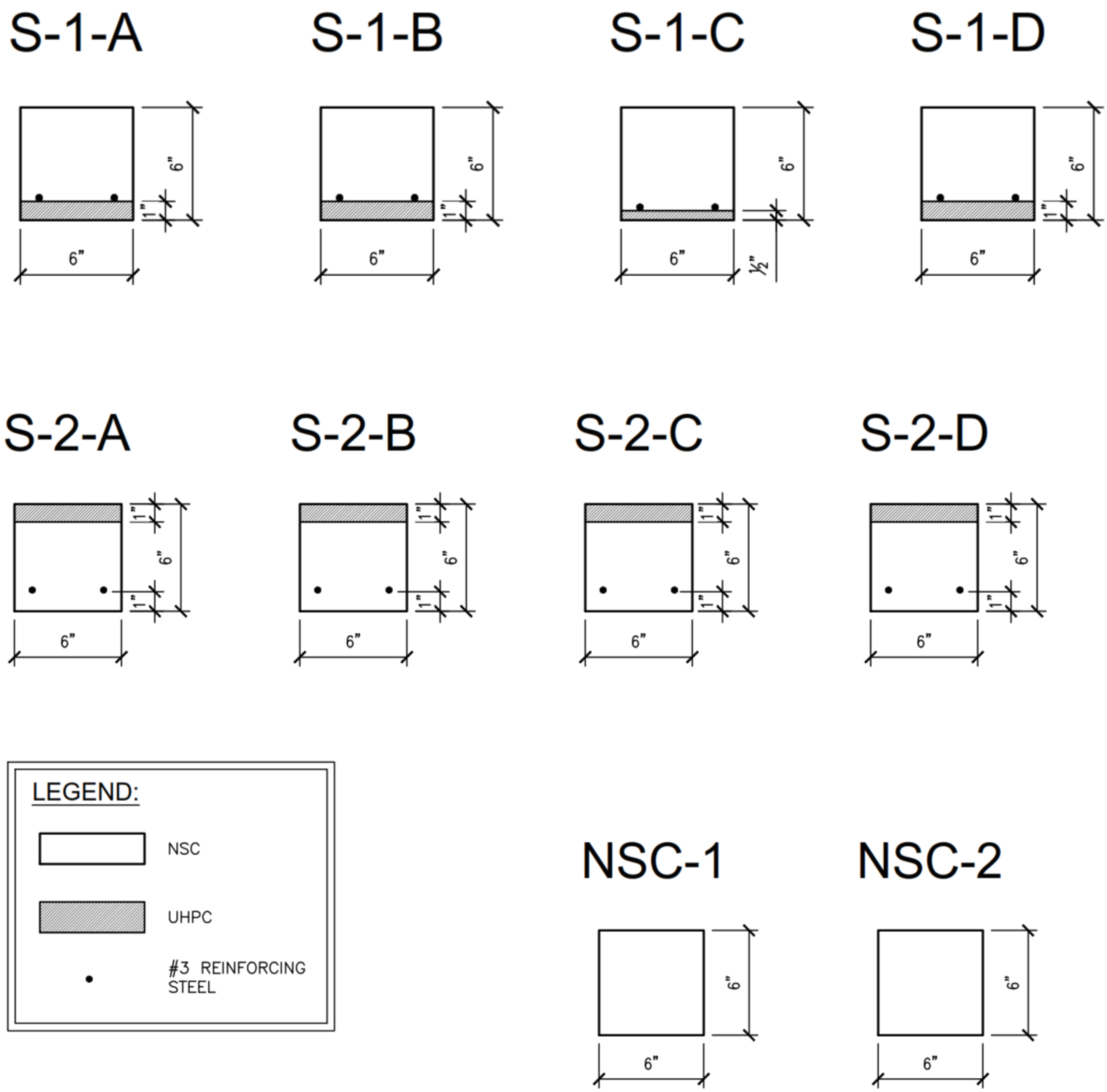


Figure 8. Flexural specimens for material testing.

Table 3. Schedule of Flexure Beam Testing

Beam Designation	Overlay thickness	Roughness profile	Re-bar location	Proposed overlay application and location
R-1-A	1/2	3	adjacent	Spray application on bottom
R-1-B	1/2	3	adjacent	Spray application on bottom
R-1-C	1/2	2	adjacent	Spray application on bottom
R-1-D	1	3	adjacent	Spray application on bottom
R-2-A	1/2	4	opposite	Conventional application on top
R-2-B	1/2	4	opposite	Conventional application on top
R-2-C	1/2	4	opposite	Spray application on top
R-2-D	1/2	4	opposite	Spray application on top
S-1-A	1	1	adjacent	Spray application on bottom
S-1-B	1	1	adjacent	Spray application on bottom
S-1-C	1/2	1	adjacent	Spray application on bottom
S-1-D	1	1	adjacent	Conventional application on bottom
S-2-A	1	2	opposite	Spray application on top
S-2-B	1	2	opposite	Conventional application on top
S-2-C	1	2	opposite	Conventional application on top
S-2-D	1	3	opposite	Conventional application on top

Notes:
Initial placement (NSC) date: 8-7-19
Beam R-1-C had honeycombing in the NSC concrete.
Beam R-1-B had a warped spacer, the thickness of the overlay will vary from ½” at the ends to about 1” in the center.

Figure 9. Flexure beam removed from form, roughness profile skin partially removed.

Figure 10. Flexure beam removed from form, roughness profile skin removed.

Figure 11. Flexure Beam R-1-C honeycombs

Transducers will be instrumented to the beams to measure force-deflection curve. Grids will be drawn on the side of beams for photo documentation before and after testing. Table 4 shows the possible comparison between the test results of the specimens.

Table 4. Anticipated Evaluations of Composite Beam Data

Samples			Comparisons	Common Attributes of Samples
S-1-C	S-1-A	S-1-B	½" vs 1"	Spray applied to bottom; profile 1
S-1-A	S-1-B	S-1-D	Spray vs Normal	Applied to bottom; profile 1; 1" thick
S-2-A	S-2-B	S-2-C	Spray vs Normal	Applied to top; profile 2; 1" thick
S-1-C	R-1-C*	R-1-A R-1-B	Profiles 1, 2, 3	Spay applied to bottom, ½" thick
S-2-B	S-2-C	S-2-D	Profiles2,3	Normal applied to top; 1" thick
R-1-A	R-1-B	R-1-D	½'' vs 1"	Spray applied to bottom; profile 3
R-2-A	R-2-B	R-2-C R-2-D	Spray vs Normal	Applied to top, ½' thick profile 4

Additions to Material Scale Testing Program

Push-out testing is proposed and added to the research program. This test provides data on the frictional resistance at an interface between specimen components. The test sample consists of 3 components placed side by side. The center component is pushed down between the other two as shown in Figure 12. The resistance to the push out is the friction generated between the components.

Similar samples will be made in other ongoing projects for UHPC repair of flexural members. The two outer samples will consist of NSC, with a roughness profile cast into one side. The UHPC component will then be cast between the two NSC components. Roughness profiles developed for the flexure testing will be adapted for a similar for this test. Five samples with roughness profiles 3 and 4 will be prepared and tested. This allows a direct measurement of the frictional resistance between component, and a direct measurement of the frictional strength at the interface. The test result will be complied with the results from UHPC repair of flexural member project which include as cast (smooth), rough surface with sand blasting, smooth with mechanical connectors, and rough surface with mechanical connectors.

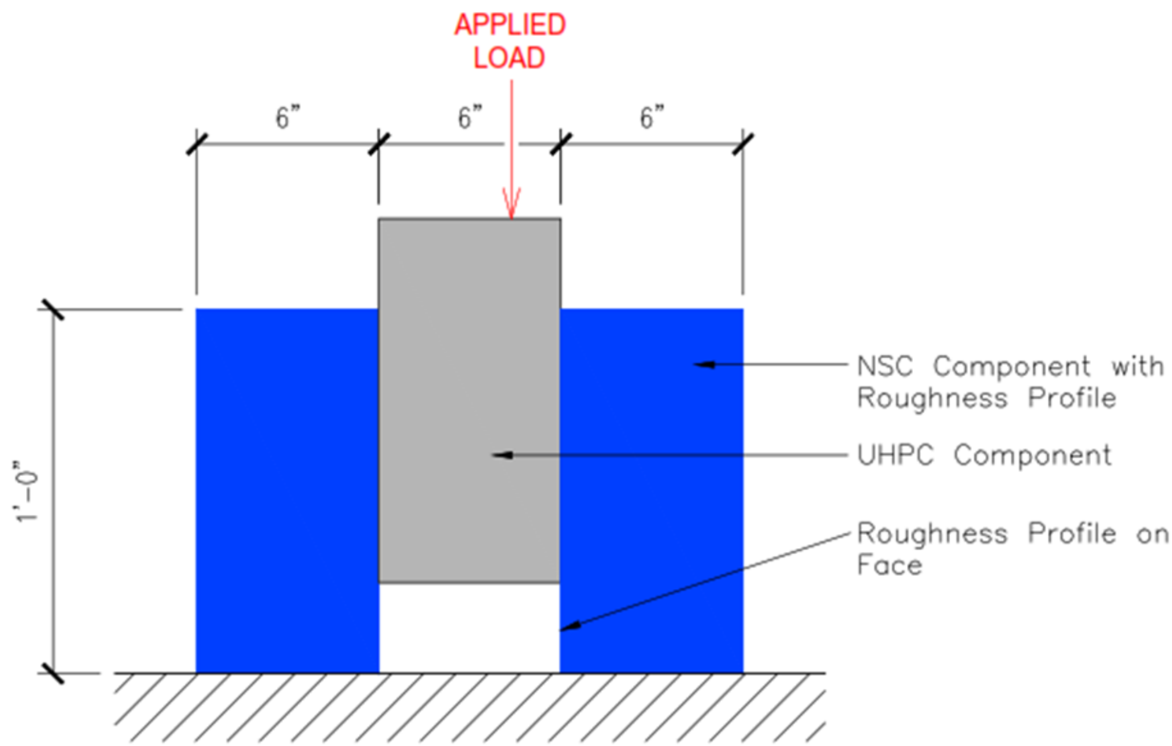


Figure 12. Schematic of the “Push-out” Test

Additional composite beams will be cast to observe formation of a sloping UHPC surface. UHPC will be applied to a 2% and a 4% slope. The roughness factor and staged application of the UHPC will be evaluated. Samples with a roughness profile 1 will be cast and placed on slopes to observe how the UHPC will react on the sloping surface. Adjustments to the UHPC mix design may be made so the sloping surface can be maintained.

Task 3- Numerical Modeling of Material Testing

In this task, non-linear finite element models will be developed and calibrated to the results of the testing performed in Task 2. The elements modeling the interfacial surface between the normal strength concrete and UHPC will be carefully considered. Modeling the appropriate interface shear behavior will be critical. Once the finite element model is calibrated, parametric studies will be performed to optimize UHPC mix by changing various properties such as f’c and E.

Task 4- Large Scale Level Testing

In this task, testing of full-scale specimens will be conducted to validate the models and incorporate parameters discussed above. Large-scale specimens with dimensions of 3 ft wide by 8 ft long will be constructed. The specimens will be 9-inches thick and reinforced with two layers (top and bottom) of No. 4 bars on 6-inch centers. A “repair -section” will be left out of the bottom side, 2-inches thick by 4 ft long, spanning the entire 3 ft width. This section will be filled with spray applied UHPC. Two specimen (Figure 13) will be prepared, and one will be statically loaded, the other will be cyclically loaded. Three additional specimens (Figure 14) will also include a surface overlay, 1- inch thick, and tested statically. A reference specimen without any overlay will also be constructed. Rebar hooks will be provided for lifting. Table 5 shows the material quantities for each specimen

Table 5 Testing Matrix and Estimated Quantities

Sample No.	Normal Strength Concrete	Reinforcing Steel	UHPC – Spray Applied	UHPC Conventional Placement	Loading
1	0.7 cy	128.3 lbs	2.0 cf	0	Static
2	0.7 cy	128.3 lbs	2.0 cf	0	Cyclic
3	0.7 cy	128.3 lbs	0	2.0 cf	Static
4	0.7 cy	128.3 lbs	0	2.0 cf	Static
5	0.7 cy	128.3 lbs	0	2.0 cf	Static
6	0.7 cy	128.3 lbs	0	0	Static

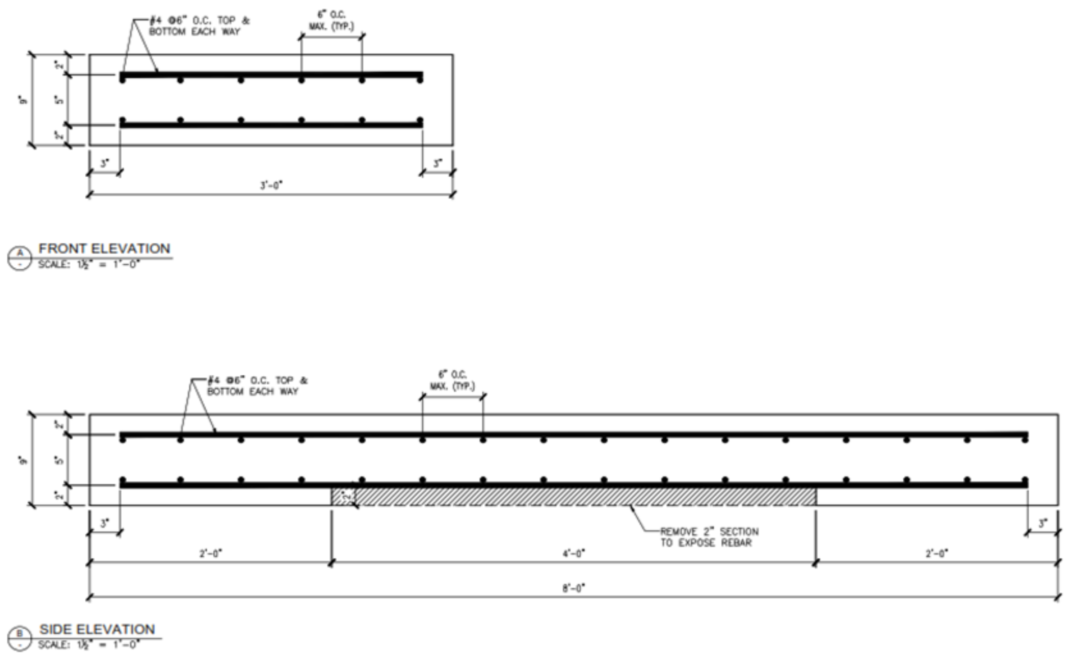


Figure 13. Large Scale Specimen Plan for Spray Application of UHPC

Figure 14. Large Scale Specimens with sloping surface for UHPC overlay.

Task 5- Development of Framework for Service Life Design

This task includes development of finite element models. The models will be calibrated to the results of the testing performed in Task 4. Parametric studies will be conducted to expand the scope of research topic.

Task 6- Final Report

Results of study are being documented. Compilation of these reports will form the final report.

5. Expected Results and Specific Deliverables

5.1 Optimized UHPC Bridge Deck Overlay Procedure

It is anticipated that UHPC will be investigated for use as overlay material, applied with traditional methods and with spray applications. The high strength of the UHPC provides a stronger deck section with higher corrosion resistance. Factors such as the required interfacial surface roughness, variable thickness and selection of a mix design will be addressed with guidelines for selection of these variables. The procedure will be presented in the form of a selection matrix or flow chart to guide the design and construction practice.

5.2 A Five-Minute Video Summarizing the Project

A short video will be prepared describing research work and findings. An ABC-UTC Guide for use of UHPC as overlay will also be developed.

6. Schedule

Duration of this project is 18 months. Timeline for various tasks is shown in Figure 15 up to the date of the second quarter report.

Item	% Completed
Percentage of Completion of this project to Date	20%

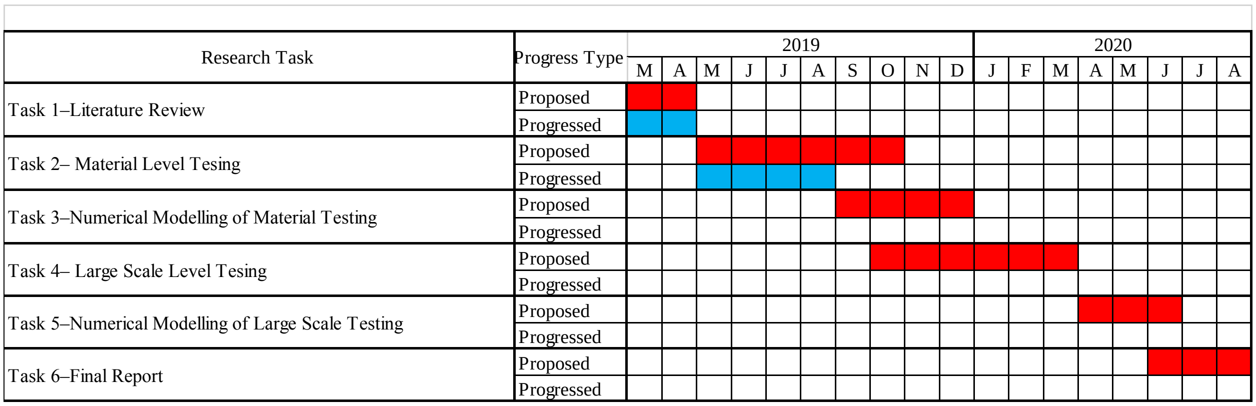


Figure 15. Project Progress.

7. References

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