SERVICE LIFE DESIGN GUIDANCE FOR UHPC LINK SLABS

Quarterly Progress Report
For the period ending May 31, 2022

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Submitted to:
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1. Background and Introduction

Design for service life rather than just for strength is becoming more common for bridges. Multiple elements should be considered in a service life design process. One aspect of this design with potential for a large impact is minimizing the number of transverse deck joints, which can be done by using link slabs between bridge spans. Ultra-high performance concrete (UHPC) has proven potential for durable link slab construction that can be completed faster than with conventional concrete, but many designers are not familiar with the full service life potential of UHPC link slabs. This project will build on previous research sponsored by ABC-UTC and others to develop a “Guide for the Design of UHPC Link Slabs” including considerations of deformation, strength, and service life. The project will include a detailed examination of the literature available on UHPC link slabs to synthesize design guidance, including consideration of service life, and compare performance to conventional concrete construction. Data collected as part of previous research sponsored by ABC-UTC and ODOT will be combined with information from the literature to develop recommendations for structural design requirements and service life considerations required for use of both proprietary and non-proprietary UHPC. Experimental testing of link slab durability before and after service level loading will be included to fill perceived gaps in knowledge of link slab durability performance. Finally, cost analysis information will be used to examine alternative construction details. A major objective of this project will be to develop user friendly tools, that will allow use of developed information within the framework developed by SHRP2 R19A for service life design of bridges and to provide educational materials to help practitioners understand how to use those tools

2. Problem Statement

Design for service life rather than just for strength against potential overload and fatigue failure is becoming a more common consideration for bridges (Azizinamini et al., 2013). Building bridges that last longer and extending the life of existing bridges is a critical issue in the United States. Multiple bridge elements should be considered in a service life design process. One aspect of design, and often bridge retrofit, with potential for a large impact is minimizing the number of transverse deck joints. Bridge deterioration can often be traced to poor performance of these deck joints due to failure of the joint seal allowing chloride laden water onto bridge girder ends, bearings, and substructure elements. Using link slabs over the piers allows for eliminating some interior joints and moving expansion joints to the end of the bridge while still maintaining typical bridge behavior. Link slabs allow the simply supported behavior expected for many bridges, yet still transmit deformations and forces to expansion joints and reduce potential penetrations in the bridge deck. Advanced materials, such as ultra-high performance concrete (UHPC) have the potential to further improve the performance of link slabs.

UHPC is a fiber-reinforced cementitious composite with a compressive strength typically in excess of 22 ksi, excellent bond strength with reinforcement and substrate concrete, and a high post-cracking tensile strength. Together, these properties allow for the flexibility and cracking resistance needed for superior link slab performance. UHPC link slabs have great potential to simplify link slab details and substantially improve their durability. UHPC link slabs are specifically relevant to accelerating bridge retrofit in that the short required debonded lengths can significantly reduce the required amount of demolition and the overall time required for the project. Debonded lengths for UHPC link slabs can be as small as 16 in. compared to several feet for conventional construction. While the concrete in the immediate area of the joint may be deteriorated and can be removed quickly, concrete further from the joint will often be sound and take substantial time and labor to remove. Figure 1 shows an example UHPC link slab detail used by NYDOT showing the short length of UHPC material in the direction of the span (Graybeal, 2014). The high compressive strength of typical UHPC is not critical for this application and non-propriety UHPC grade materials with the required bond and flexural strengths are a potential option to obtain the desired durability. The hairline distributed cracks that form in a UHPC link slab limit pathways for water to penetrate to the bridge girders and substructure, and UHPC itself is inherently more durable than conventional concrete due to its very low permeability. UHPC link slabs have been used successfully in the field by several state DOTs and a limited number of research projects have examined structural behavior of UHPC link slabs.

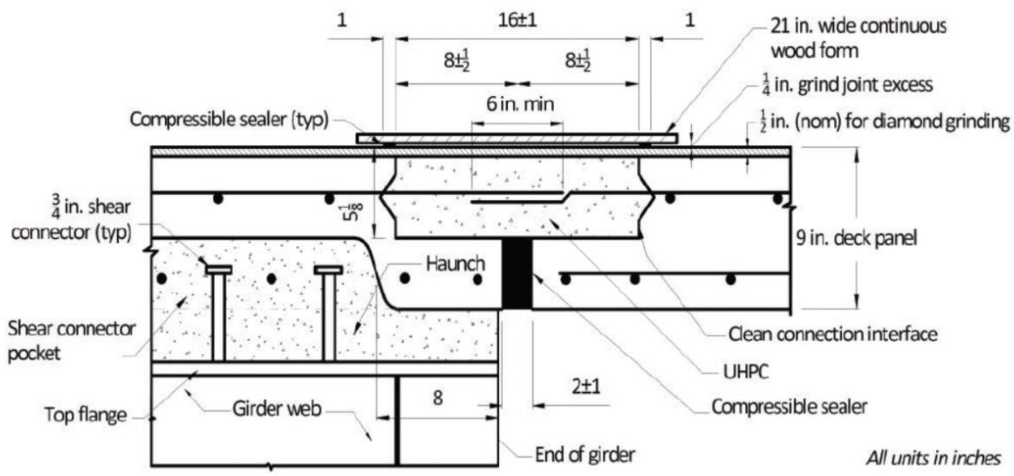


Figure 1. Example UHPC link slab detail used on a bridge project in Owego, NY, shown as a split section with the left side showing details at the girder line and right side showing details midway between girders (Graybeal, 2014)

Using UHPC for link slabs has great potential to simplify details and substantially improve durability. Several research studies have been carried out focused on link slabs and appropriate design guidelines are available in the AASHTO LRFD Guide Specifications for Accelerated Bridge Construction (2018). However, there is still some confusion about design requirements when using advanced materials such as UHPC and for quantifying the service life benefits of using UHPC link slabs compared to conventional construction.

3. Objectives and Research Approach

In order to be used with service life design recommendations (Azizinamini et al. 2013), information is needed on multiple aspects of UHPC link slabs. Bridge configurations appropriate for the use of UHPC link slabs for new construction, for repair/retrofit, and with an emphasis on accelerated construction will be identified. Failure mechanisms identified from previous research will be considered from both a structural and durability standpoint. Performance of UHPC link slabs will be examined relative to repeated traffic loading causing cracking and fatigue, and the resulting freeze-thaw durability and corrosion resistance compared to conventional construction.

This project will build on previous research to develop a "Guide for the Design of UHPC Link Slabs" including considerations of deformation, strength, and service life. This study will expand upon research sponsored by the ABC-UTC and others focused on structural behavior of UHPC link slabs and on research sponsored by the Oklahoma Department of Transportation (ODOT) on UHPC for bridge retrofit and holistic design of bridge systems. The proposed project will include a detailed examination of the literature available on UHPC link slabs to synthesize design guidance, including consideration of service life (e.g. Azizinamini et al., 2013). Data collected as part of previous research sponsored by ABC-UTC (Shafei et al. 2018, Floyd et al. 2019) and ODOT (Floyd et al. 2018) will be combined with information from the literature to develop recommendations for structural design requirements and service life considerations required for use of both proprietary and non-proprietary UHPC. Limited experimental testing will be included to fill perceived gaps in knowledge of link slab durability performance. Finally, cost analysis information will be used to examine alternative construction details.

A major objective of this project will be to develop user friendly tools that will allow use of developed information specific to UHPC link slabs within the framework developed by SHRP2 R19A for service life design of bridges and to provide educational materials to help practitioners understand how to use those tools.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Review of Link Slab Research and Practice

The project will include a detailed examination of the literature available on UHPC link slabs to synthesize design guidance, including consideration of service life (e.g. Azizinamini et al., 2013), and how that guidance fits with published guide specifications. Data collected as part of previous research sponsored by ABC-UTC (Shafei et al., 2018; Floyd et al., 2019) and ODOT (Floyd et al., 2018) will be combined with information from the literature to develop recommendations for structural design requirements and considerations required for use of both proprietary and non-proprietary UHPC. Standard practices by states currently using link slabs will be examined by leveraging the connections available through the ABC-UTC with particular emphasis placed on New York DOT, which has successfully used UHPC link slabs for a number of bridges. Typical details used by these states will be presented in the proposed Guide with guidance on application of these details to specific bridges.

An investigation of standard details and completed projects including link slabs and other deck joint types from several states was conducted. States examined include Oklahoma, Texas, Tennessee, Indiana, and New York. Standard drawings for UHPC and conventional link slabs were obtained from New York DOT. The literature reviewed on UHPC link slab research and design is substantially complete. Work on summarizing the collected literature is complete.

Task 2 – Identification of Service Life Design Considerations

Bridge configurations appropriate for use of UHPC link slabs for new construction, for repair/retrofit, and with an emphasis on accelerated construction/retrofit will be identified. Failure mechanisms identified from previous research will be considered from both the structural and durability standpoint, and performance will be examined relative to repeated traffic loading causing cracking and fatigue and the resulting freeze-thaw durability and corrosion resistance. A comparison will be made to the same properties for construction of link slab and continuous spans with conventional concrete.

The data collected from various states and the literature was distilled to identify common bridge configurations where link slabs are utilized, constraining conditions precluding the use of link slabs, critical items for design, and factors affecting durability. Bridges appropriate for use with link slabs for both new construction and repair/retrofit were considered. Work on summarizing this information into a format useful for designers for the final report was continued.

Task 3 – Cost Analysis

An analysis of the cost and comparison to other possible methods for both construction and retrofit will be conducted including the economic effects of a potential extension of service life. Other potential design details for comparison include link slabs constructed with conventional concrete or other concrete materials, simple spans with a deck construction joint, full depth continuity connections, and elimination of the deck joint without designing the connection as a link slab.

Cost data for link slabs and other joint types available from state DOT bid records were obtained from Oklahoma, Texas, Tennessee, and New York. Investigation into data from other states was conducted with limited success. Cost comparisons between states for a given joint type and between different joint types for a given state were conducted.

Task 4 – Link Slab Durability Specimen Construction and Preparation

Most of the research on UHPC link slabs has been conducted using available proprietary UHPC mix designs and little research has been conducted on durability of link slabs with potential damage from service level cyclic loads. Two full-scale link slab segments will be constructed, using non-proprietary UHPC. If possible, one specimen will be constructed with conventional concrete for comparison. Formwork and methods developed from the matching funds projects will be utilized for specimen construction. The second link slab with each material will be subjected to 3 million service level load cycles to induce a level of damage to the specimen similar to that expected in the field.

This task was delayed due to lab closures at OU associated with the COVID-19 pandemic. A phased restart of research was begun in May 2020, the students working on this project were not selected to be part of Phase 1. Students working on this task returned to the laboratory in August 2020. Work on other tasks was shifted to earlier in the project in an attempt to make up the delay.

Test specimens were designed based on details found from other states and in the literature and to fit with testing equipment available at Fears Structural Engineering Laboratory. A detail matching the New York DOT link slab design shown in Figure 2 was selected. Formwork for the full-scale slab specimens was constructed in order to create an 8 ft long joint specimen. The required block-out for the link slab section was constructed using insulation foam and the slabs were cast upside down to easily facilitate construction. Completed formwork including the slab reinforcement and block-out is shown in Figure 3. The eight conventional concrete sections required to construct four joint specimens were cast using an ODOT class AA concrete and sample specimens are shown in Figure 4. All thread bars were embedded in each end of the slab specimens (visible in Figure 4) to allow for lifting and inverting the slab specimens. Link slab specimens were then constructed connecting two of the base concrete specimens. A gasket material bond breaker was utilized to create the debonded region. Two specimens each were constructed with non-proprietary UHPC and conventional concrete. A completed conventional concrete link slab specimen is shown in Figure 5 and a UHPC specimen in Figure 6. Copper wires were connected to some of the internal bars within the link slabs to facilitate later accelerated corrosion testing, which are visible in Figure 6.

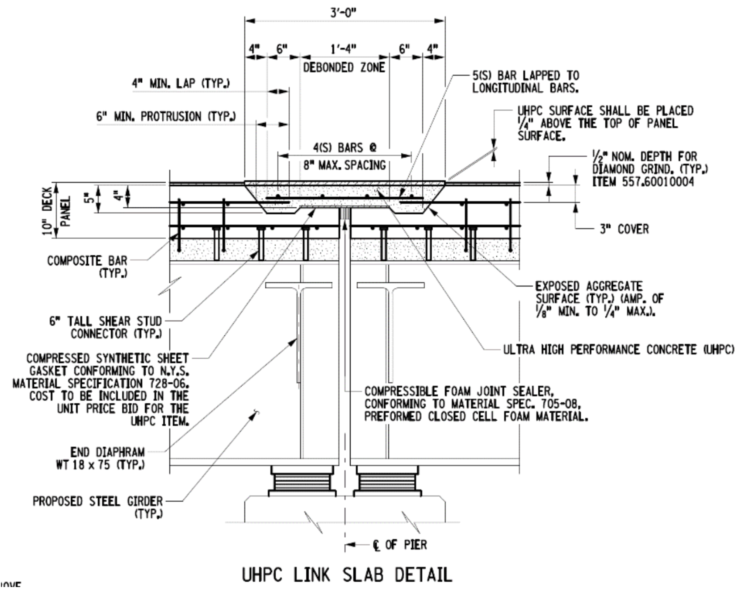


Figure 2. UHPC link slab detail used as basis for test specimen design (NYDOT)

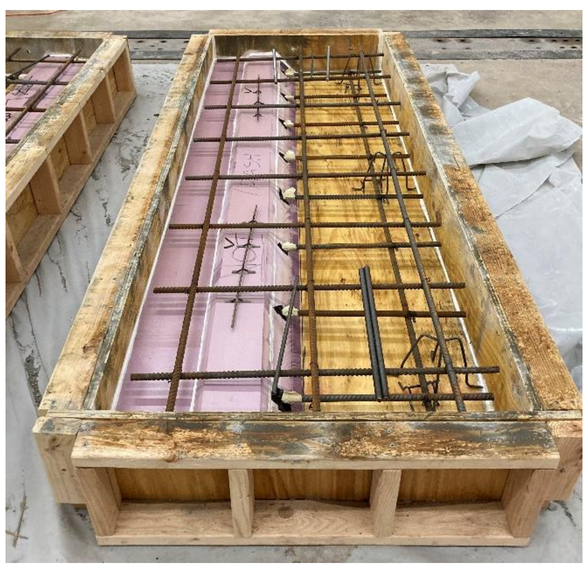


Figure 3. Base slab specimen formwork

Figure 4. Completed conventional concrete base slabs for link slab joint specimen construction

Figure 5. Completed conventional concrete link slab specimen and specimen prepared for casting link slab specimen

Figure 6. Completed UHPC link slab specimen with wires for accelerated corrosion visible

Issues with the cyclic loading apparatus delayed completion of the cyclic loading, and the targeted total number of cycles for each specimen was reduced to make up for this delay and to put less stress on the loading equipment. Specimens were loaded with a 5000 lb peak load and 1000 lb minimum load for 100,000 cycles in a configuration resulting in tension across the link slab simulating deformation from continuity over the pier (Figure 7). Specimens were loaded for 20 cycles with an 18,000 lb peak load and 1000 lb minimum load for 20 cycles in a configuration intended to represent direct loading from a design vehicle inducing compression in the link slab (Figure 8). The UHPC specimen did not exhibit visible cracking from either loading, but the conventional concrete specimen did exhibit visible cracking in the link slab.

Figure 7. Non-proprietary UHPC link slab in tension loading setup (note that this is upside down compared to service orientation)

Figure 8. Non-proprietary UHPC link slab in compression loading setup

Task 5 – Link Slab Durability Testing

Sections will be cut from one non-proprietary UHPC link slab specimen without it being subjected to any loading. The second link slab will then be cut into sections after being subjected to cyclic loading. Appropriate size sections cut from the link slab segments will be exposed to accelerated corrosion testing to examine the effect of the two different materials and the resulting interface on system durability. One set of composite conventional concrete-UHPC specimens will be exposed to a 5% saline solution ponded around the specimen, which will be connected to a DC power supply to accelerate the reinforcing bar corrosion using methods similar to Wang et al. (2014, 2017) and Abosrra et al. (2011). A stainless steel cathode will be placed in the saline solution and the anode connected to the slab reinforcement. The comparative time required to reach visible corrosion will be documented along with the location and progression of damage for each specimen. Results from previous ABC-UTC projects related to durability of UHPC in general will also be considered to provide a more complete picture of behavior.

Link slab specimens were cut into 12 in. x 8 in. x 6 ft sections for accelerated corrosion testing. Exposed ends of reinforcing bars on the cut surfaces were coated with a liquid rubber sealant to limit water intrusion to reinforcing bars to that passing through the concrete. Corrosion specimens were placed into plastic lined wood enclosures partially filled with a 5% saline solution and copper wires soldered to reinforcing bars during link slab construction were connected to an external power supply. Specimens were placed upside down on top of aluminum spacers to ensure that the top surface of the link slabs expected to be exposed in service was in direct contact with the saline solution. A stainless steel rod was placed in the saline solution to act as a cathode for the corrosion cell and a current of 0.2 amps was run through the circuit. Voltage in the system was measured over time. Figure 9 shows a UHPC link slab corrosion specimen during testing, which continued for a period of nine weeks. Specimens were removed from the saline solution baths after 5 weeks and sections of the reinforcing bars were exposed to check for visible corrosion. After the reinforcement was exposed and photographed, the void was sealed and the specimens were returned to the saline solution baths for an additional four weeks. At the end of the testing period the reinforcing bars were again exposed and photographed to examine for visible corrosion. No signs of corrosion were observed for the UHPC link slab specimens. The conventional concrete specimens exhibited cracking following the reinforcing bars after 5 weeks of testing and more extensive cracking at the end of the testing period. Signs of oxidation were also visible on the exposed reinforcing bars.

Figure 9. UHPC Link slab section at the beginning of testing

Freeze-thaw testing was conducted using ASTM C666 methods on sections cut from both the loaded and unloaded UHPC and conventional concrete link slabs for 350 cycles between December 2021 and March 2022. While it was delayed for more than two weeks due to Covid-19 cases among laboratory personnel, testing was completed in March 2022. Three specimens with dimensions of 3 in. x 4 in. by 12 in. were cut from each link slab specimen. Three of the twelve specimens (one from each of the conventional concrete link slabs and one from the non-loaded UHPC link slab) included a piece of reinforcing bar running along the 12 in. length near the center of the cross-section. Only the specimen containing a reinforcing bar was able to be cut close to the desired 12 in. length for the loaded conventional concrete link slab (AA-L). The parent link slab specimen experienced cracking along the 2 in. gap of the link slab joint during cyclic loading. This cracking caused the other two freeze-thaw specimens, which did not have rebar running along their lengths, to break into uneven sections shorter than 12 in. The resulting lengths of each specimen cut from the AA-L link slab are as follows: AA1-L was 6 in., AA2-L was 11 in., and AA3-L was 8 in. The freeze-thaw machine could only hold 11 specimens so the AA1-L specimen was selected to be the one not tested. Freeze-thaw specimens in the machine are shown in Figure 10. The resonant frequency of each specimen was measured before testing began and after each series of approximately 36 cycles using a James Instruments emodumeter setup. These frequencies were then used to calculate the relative dynamic modulus (RDM) at each testing time. Sections cut from the UHPC link slabs both showed excellent performance over time and most showed increasing RDM over the testing period, most likely from additional hydration of cement in the UHPC. However, one specimen each from the loaded and unloaded slabs exhibited a slight decrease in RDM over time. All conventional concrete specimens exhibited a decrease in RDM over time, but in general exhibited good performance relative to RDM. It should be noted that due to specimens breaking into pieces during cutting from the slabs, the effects of large cracks that formed during loading on freeze-thaw performance were not effectively captured. All conventional concrete specimens exhibited substantial scaling and deterioration of the corners and some UHPC specimens had similar damage.

Figure 10. Freeze-thaw specimens

Task 6 – Education Module Development

A series of voice annotated PowerPoint presentations and short videos will be developed that will be useful for training design professionals on design of UHPC link slabs including consideration of service life and durability.

A research seminar was conducted for the ABC-UTC at the end of October. The PowerPoint presentation developed for the seminar was updated for Clay Reed's thesis defense and will be used to record this education module.

Task 7 – Assembling Reports and "Guide for Design of UHPC Link Slabs"

Quarterly progress reports and a final report in Microsoft Word and ADA compliant Adobe Acrobat pdf will be provided at the end of the project year. A "Guide for Design of UHPC Link Slabs" will be developed incorporating the results of the research. This Guide will include user-friendly tools that will allow use of the research results within the framework developed by SHRP2 R19A for service life design of bridges.

The current report is the ninth quarterly progress report for the project and includes the activities of March 2022 to May 2022. Graduate student Clay Reed's thesis was completed in May 2022 and the final report and Guide for this project will be completed using much of the content from this thesis.

5. Expected Results and Specific Deliverables

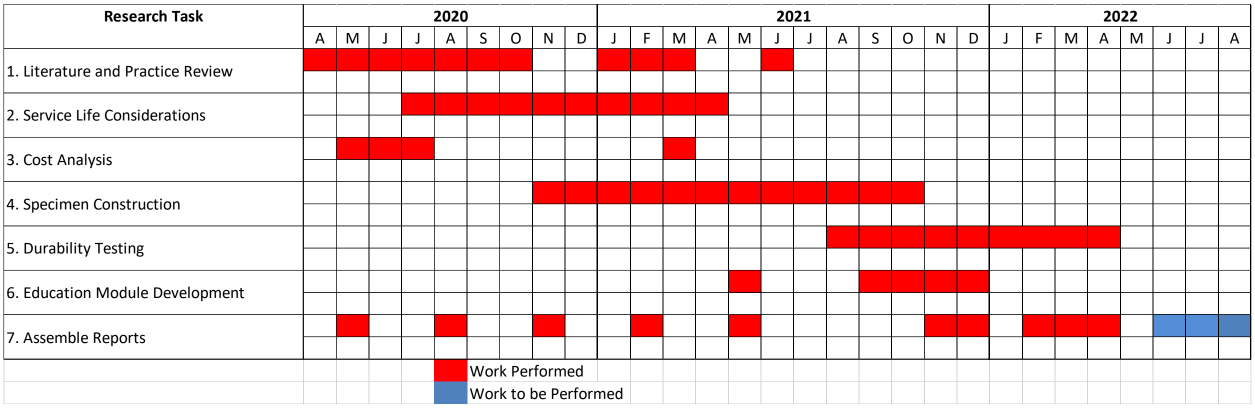
This project will develop user friendly tools that will facilitate design of UHPC link slabs within the framework developed by SHRP2 R19A for service life design of bridges. A "Guide for Design of UHPC Link Slabs" and training materials will be produced.

Success of this project would provide a track record that could lead to funding to complete similar work related to other potential design items or retrofits. As new construction methods are implemented and a greater emphasis is placed on service life design, this type of Guide will be needed. The proposed "Guide for Design of UHPC Link Slabs" will provide useful guidance for design and construction of UHPC link slabs, which have great potential for joint elimination in Oklahoma and across the country. The proposed "Guide for Design of UHPC Link Slabs" will be a useful addition to states' bridge design specifications

6. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	98%



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