LIFE- CYCLE COST ANALYSIS OF ULTRA HIGH-PERFORMANCE CONCRETE (UHPC) IN RETROFITTING TECHNIQUES FOR ABC PROJECTS

Quarterly Progress Report
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1. Background and Introduction

The research project "Life-Cycle Cost Analysis of Ultra High-Performance Concrete (UHPC) in Retrofitting Techniques for ABC Projects" began on February 1, 2021. This fifth quarterly report documents the work progress from 03/01/2022 to 05/31/2022. The report includes a description of the project motivation, problem statement, research objectives and tasks, expected results with specific deliverables, and work progress schedule.

Project Motivation

Ultra-High-Performance Concrete (UHPC) is an innovative material with the potential to become a viable alternative for improving the sustainability of infrastructure components. UHPC is exceptionally cementitious material durable against freeze-thaw attack and permeation of gases and liquids. It has a low water-to-cement ratio and a low maximum grain size diameter with the addition of pozzolanic filler materials like silica fume.

Recognizing the potential benefits of UHPC technology, decision-making tools for determining when and how to use UHPC are needed. Life-cycle cost analysis (LCCA) is one of the tools that can assist to compare treatment solutions for bridge maintenance strategies to preserve ABC projects in good condition. To determine the best cost-effective maintenance strategy, it is important to understand the deterioration characteristics of the bridge components. For reinforced concrete elements, the deterioration process can be modeled as a function of the steel corrosion affecting bridge elements. LCCA can quantify the total costs of alternative investment options using software tools with deterministic or probabilistic approaches.

The life-cycle of Accelerated Bridge Construction (ABC) projects includes several phases: planning, design, construction, maintenance, rehabilitation, reconstruction or recycling. Most of the research studies for ABC projects have been focused on the design and construction phases, although maintenance and rehabilitation play an important role to preserve a bridge in good condition. This research is conducted to develop a life-cycle cost performance-based methodology to incorporate Ultra High-Performance Concrete (UHPC) applications for retrofitting techniques in ABC projects. Products from this research will support management decisions at the network and project level. It is expected that the use of new materials and timely maintenance strategies will increase the life expectancy of bridges using ABC systems.

2. Problem Statement

Accelerated Bridge Construction (ABC) projects combine construction methods and innovative systems to reduce the time to build new bridges and to rehabilitate old bridge components. Planning, design, construction, maintenance, rehabilitation, reconstruction, and/or recycling activities affect the performance of ABC projects in their service life. Research studies conducted for ABC projects have been mainly focused on design and construction, although maintenance and rehabilitation are critical for a good bridge performance.

Bridge components are affected by loads and environmental stressors deteriorating faster or even collapse without effective maintenance and rehabilitation strategies. Furthermore, wet-dry cycling and higher concentrations of chlorides in coastal areas accelerate the deterioration process reducing the life expectancy of bridges while increasing the frequency and cost of the repairs. To address this problem, innovative materials should be considered in the formulation of maintenance and rehabilitation strategies for ABC projects. Previous research efforts have identified deterioration mechanisms due to steel depassivation by chloride ions. UHPC compressive and tensile strength, ductility and modulus of elasticity are notably higher than normal strength concrete, increasing its durability under environmental stressors. Although, UHPC has higher initial costs, it is intended to lower the total life-cycle costs when compared to conventional concrete. This research project will develop a life-cycle cost performance-based methodology to analyze the potential benefits of UHPC applications on retrofitting techniques for ABC projects.

3. Objectives and Research Approach

The main objective of this research is to quantify the potential benefits of UHPC applications in retrofitting techniques to adopt long-term cost-effective maintenance strategies for ABC projects.

To accomplish this objective, a comprehensive research approach is followed in the development of the study. The approach begins investigating previous efforts seeking for potential applications of innovative materials, retrofitting methods, and software tools to conduct the life-cycle cost analysis (LCCA). Findings from this investigation are the foundation to develop a step-by-step LCCA methodology to support the bridge management decision-making process for ABC projects at the network and project level.

The research objectives are very well aligned with research efforts conducted at the Accelerated Bridge Construction University Transportation Center (ABC-UTC). The proposed research study contributes with the following ABC-UTC objectives: (a) to foster the use of new materials and timely maintenance strategies to increase the life expectancy of bridges built using ABC systems, (b) to mitigate the effects of climate change on the deterioration of ABC components throughout their service life, (c) to develop decision-making analytical tools to support ABC project implementation by local agencies, (d) to promote ABC projects implementation through research that incorporates innovative materials to improve their performance over time.

Summary of Research Project Tasks

The project activities involved a comprehensive state-of-practice review followed by the development of life expectancy and cost effectiveness models for UHPC retrofitting treatments, the development of step-by-step LCCA methodology, and a case study. In summary, the work plan was composed of seven tasks:

Task 1: Review the State-of-Practice of Bridge Retrofitting Techniques
Task 2: Side-by-Side Comparison of Concrete Retrofitting Techniques for Bridge Elements.
Task 3: Develop Life Expectancy and Cost-Effectiveness Models for UHPC Retrofitting
Task 4: Life-Cycle Cost Analysis Step-by-Step Methodology
Task 5: Case Study
Task 6: Prepare the Final Research Report
Task 7: Develop Educational Workshop Material

Figure 1 shows the task dependencies and relationships as conceived in the work plan.

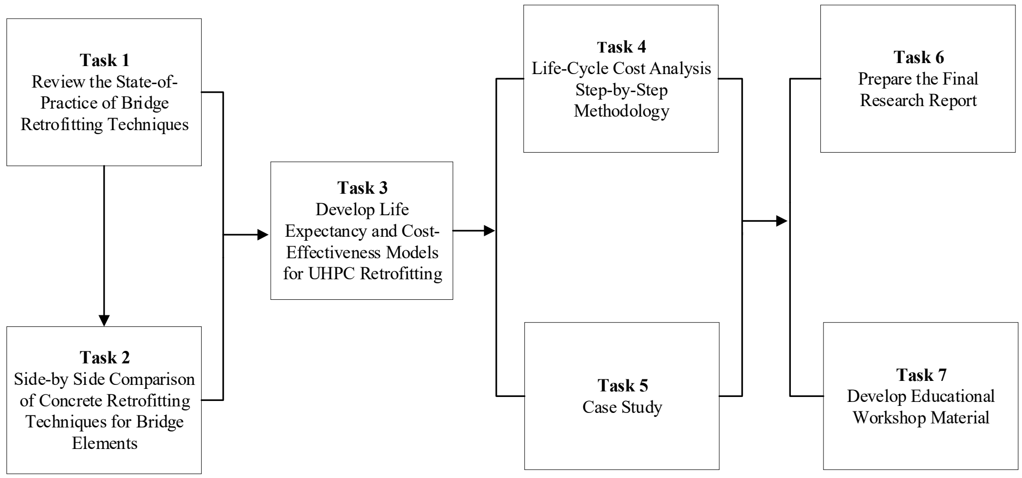

Figure 1. Overview of the research work plan.

Research Advisory Panel (RAP)

The project work has been presented to FDOT engineers for feedback and to request relevant information and data related to UHPC applications in ABC projects. The following FDOT engineers have collaborated in this effort:

Felix Padilla, P.E.
FDOT Office of Maintenance - State Structures Maintenance Engineer

Kellie Spurgeon, P.E.
Roadway Engineer Supervisor III
Florida Department of Transportation – District One

Timothy Barnard
Engineering Section Manager at Florida Department of Transportation

Xavier de la Torre, P.E.
In-House Consultant, FDOT District 4
Engineering Section Manager

4. Description of Research Project Tasks

The work followed the proposed project task descriptions. The work progress described in this report corresponds to Tasks 1, 2, 3, 4, 5, 6, and 7 as proposed for this research project.

Task 1 – Review the State-of-Practice of Bridge Retrofitting Techniques

Conventional bridge retrofitting techniques were reviewed to assess the current state-of-practice and compared to potential applications of Ultra High-Performance Concrete (UHPC). Particular attention was given to practical experiences and research findings related to ABC projects. Following the literature review, practitioners and researchers involved in the development of innovative concrete applications in retrofitting techniques have been identified.
The following questions were addressed at the end of this task:

- What are the advantages of UHPC applications in retrofitting techniques for ABC projects?
- What factors should be considered in the technical and economic comparison of concrete repair materials for bridge maintenance and rehabilitation?
- Are there data and tools to analyze the impact of UHPC retrofitting techniques on ABC performance and life-cycle cost?

As a result of this task, the findings of the state-of-practice review were organized as follows:

a) Retrofitting techniques for repairing and strengthening bridge components using UHPC.
b) Potential applications of UHPC in ABC maintenance and rehabilitation strategies.
c) Analytical approaches to model the deterioration mechanisms of UHPC applications in bridges.
d) Models to evaluate the cost-effectiveness of retrofitting techniques in ABC projects.

<u>Description of work performed up to this period:</u> Task 1 was completed as scheduled and the findings are documented in the draft of the Final Report.

Task 2 - Side-by-Side Comparison of Concrete Retrofitting Techniques for Bridge Elements.
After the comprehensive review of the state-of-the-practice conducted in Task 1, a side-by-side comparison of the concrete retrofitting techniques was conducted including factors affecting life expectancy and treatment cost-effectiveness. This side-by-side comparison allowed identify relevant parameters for modeling the performance of the UHPC retrofitting techniques in ABC projects. LCCA will require these performance models to compare the cost-effectiveness of maintenance and rehabilitation strategies in the long-term. As a result of Task 2, preliminary guidelines for the selection of concrete materials and retrofitting techniques were provided at the end of this task addressing technical and economic considerations for construction, maintenance, and rehabilitation of ABC projects.

<u>Description of work performed up to this period:</u> Task 2 was completed as scheduled and the findings are documented in the draft of the Final Report.

Task 3 - Develop Life Expectancy and Cost-Effectiveness Models for UHPC Retrofitting
Existing life expectancy and cost-effectiveness models were reviewed in-lieu of the findings from the previous tasks. There are empirical and mechanistic models to estimate life expectancy. The empirical models use statistical techniques to evaluate field and/or lab data, and the mechanistic models are based on physical properties to predict the life expectancy. Both models, mechanistic and empirical, can be combined in a Mechanistic-Empirical (M-E) approach to estimate the life.

Statistical regression, Markov chains, duration models (e.g. Weibul, Exponential, Rayleigh, and Gamma), and machine learning are common approaches for life-expectancy. For concrete steel reinforced elements, corrosion is an environmental stressor that affects the level of deterioration and impacts life expectancy. Three stages are identified in the evolution of corrosion: (1) initiation time or time for chloride ions to penetrate the concrete surface, (2) depassivation time or time for the chorides to destroy the passive film protecting the steel, and (3) propagation or corrosion time for the structural element to experiment damage (e.g. cracking, spalling). The Fick's laws and Weyers technique are used to predict corrosion stage times. Due to its low permeability, UHPC should reduce or slow the penetration of chlorides into concrete structures increasing the life expectancy. There are other life expectancy mechanistic approaches based on fatigue models and reliability analysis with the incorporation of probability analyses of the material strength.

In Task 3, a comparison of the models to predict life expectancy were conducted as a reference to develop a life-expectancy model for LCCA of UHPC applications in retrofitting techniques. Information gathered in Task 1 were used to evaluate the models, and to develop life expectancy and treatment repair cost-effectiveness models for ABC projects. Deterministic and probabilistic life prediction models will be considered in this evaluation and development of the proposed models.

Description of work performed up to this period: Task 3 was completed as scheduled and the findings are documented in the draft of the Final Report.

Task 4 – Life-Cycle Cost Analysis Step-by-Step Methodology
A LCCA methodology was developed to analyze total costs over the service life of ABC projects. The general parameters involved in the LCCA are:

- Length of the analysis period.
- Costs included in the analysis.
- Salvage value.
- Discount and inflation rates.
- Performance models.

LCCA mainly relies on the agency costs including engineering, construction, maintenance, and rehabilitation. LCCA is commonly used to compare bridge alternatives in the long-term. There are several software tools available for LCCA bridge analysis. For example, the Bridge Life Cycle Cost Analysis (BLCCA) is a non-commercial tool developed under NCHRP Project 12-43 and (Hawk 2003). A stochastic methodology is followed in BLCCA to model bridge deterioration as related to the agency and user costs. Another software tool is Life-365 with steel corrosion models to predict the service life of concrete bridge decks. There are other software tools developed in Excel platforms that incorporates LCCA probabilistic models.

In Task 4, LCCA methods and software tools were evaluated to develop a step-by-step LCC methodology for UHPC applications in retrofitting techniques for ABC projects. This methodology allowed compare maintenance and rehabilitation strategies including conventional concrete and UHPC for ABC projects.

Description of work performed up to this period: Task 4 was completed as scheduled and the findings are documented in the draft of the Final Report.

Task 5 – Case Study
A case study will demonstrate the LCCA methodology developed in Task 4. LCCA was conducted for a set of ABC maintenance and rehabilitation strategies including conventional concrete and UHPC applications. As part of the case study, a sensitivity analysis was performed to identify the factors that influence the most in LCCA results. A Tornado diagram was prepared to show the sensitivity of the parameters in the results of the analysis. Findings from the case study provided feedback to review, as needed, the performance models and LCCA methodology.

Description of work performed up to this period: This task was conducted as scheduled and it is documented in the draft of the Final Report.

Task 6 – Prepare the Final Research Report
We prepared the final report to document the research methodology followed to develop the performance model and LCCA methodology. In the final report, the LCCA methodology are described step-by-step providing recommendations for the selection of data inputs and interpretation of the results. The case study prepared in Task 5 demonstrates the application of the methodology. A summary of the findings with conclusions and recommendations are included in the final research report as part of the deliverable products. Practical guidance is provided for the incorporation of the methodology to better support bridge management practices at the network and project level. The final report provides specific recommendations on how to apply the research products for ABC project selection.

Description of work performed up to this period: This task began in December 2021 as shown in the work schedule included in the research proposal, and the draft of the Final Report is under review by the Research Advisory Panel.

Task 7 – Develop Educational Workshop Material

Workshop material for presenting the LCCA methodology and case study were developed in Task 7 to facilitate later implementation. The workshop content includes the performance modeling approach and description of the LCCA method for their introduction to potential practitioners. UHPC retrofitting repair treatments for addressing the deterioration of bridges are explained. Emphasis is given to demonstrate how to apply these methods into ABC projects. The use of the UHPC treatments and information required to conduct the LCCA are addressed in the workshop material while discussing the lessons learned from the research study.

Description of work performed up to this period: This task began in January 2022 as shown in the research proposal and it is under review for submittal.

5. Results and Specific Deliverables

This project developed a LCCA methodology for UHPC retrofitting techniques for ABC projects. Products of the research study include:

a) life-expectancy performance models for UHPC retrofitting techniques,

b) comparison of life-cycle costs of UHPC alternatives to conventional techniques with examples for ABC projects,

c) recommendations to improve the cost-effectiveness of retrofitting techniques using UHPC in ABC maintenance and rehabilitation strategies.

6. Work Progress Schedule

The project timeline with percentage of completion by task is summarized in Table 1, and Figure 2 shows the work progress schedule.

Table 1. Project timeline (percentage of completion).

Item	% Completed
Task 1 - Review the state-of-practice of bridge retrofitting techniques.	100%
Task 2 - Side-by-Side comparison of concrete retrofitting techniques for bridge elements	100%
Task 3 - Develop life expectancy and cost effectiveness models for UHPC retrofitting	100%
Task 4 - Life-cycle cost analysis step-by-step methodology	100%
Task 5 - Case study	100%
Task 6 - Prepare the final research report	90 %
Task 7 - Develop educational workshop material	90%

Figure 2. Work Progress Schedule.

Research Task	2021											2022						
	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J
Task 1-Review the State-of-Practice of Bridge Retrofitting Techniques	■	■	■															
Task 2-Side-by-Side Comparison of Concrete Retrofitting Techniques for Bridge Elements			■	■	■													
Task 3-Develop Life Expectancy and Cost-Effectiveness Models for UHPC Retrofitting					■	■	■	■										
Task 4-Life-Cycle Cost Analysis Step-by-Step Methodology								■	■	■								
Task 5-Case Study										■	■	■						
Task 6-Prepare the Final Research Report											■	■	■	■	■	■	░	░
Task 7-Develop Educational Workshop Material														■	■	■	░	░

■ Work Performed ░ Future Work

Note: The draft of the Final Report and education workshop material is under review by the Research Advisory Panel. Feedback with updates will be incorporated in the revised version of the Final Report.