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USDOT Region 8 University Transportation Center

A Sustainable Upgrade of Bridge Decks with Ultra-High Performance Concrete Overlays

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University

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Research Needs

Background—The safety of highway bridges is of primary concern in modern society and a huge amount of budget is required for maintenance and rehabilitation. In comparison with substructure members, bridge decks and superstructures are vulnerable to deterioration because of their direct exposure to physical and environmental loadings. Several factors accelerate the degradation of these elements such as aging, detrimental chemicals, and vehicle impact (Hao et al. 2023). Consequently, the performance of deteriorated structures becomes unsatisfactory in the context of capacity and serviceability (Zhu et al. 2020).

Rehabilitation is an effective way to extend the service life of deficient structures at affordable cost. Conventional approaches include steel plating, external prestressing, section enlargement, and supplementary supports (Rabehi et al. 2014; Valikhani et al. 2020). These are, however, valid for a limited period or demand extensive labor and special equipment that can raise construction expense. For that reason, appropriate materials should be considered to warrant the sustainability of rehabilitated members.

A new concept of concrete was proposed in the 1990's, called reactive powder concrete that did not contain coarse aggregate to increase the density and strength of the mixture (Bonneau et al.

2000). Afterward, the concept was polished and furthered to develop a state-of-the-art concrete mixture, ultra-high performance concrete (UHPC). This cementitious composite material possesses a compressive strength of at least 17.5 ksi (120 MPa) with numerous benefits (e.g., high strength, durability, fracture resistance, low permeability, favorable bond, minimal maintenance, and extended service life, Russell and Graybeal 2013; Haber et al. 2018; Al-Madani et al. 2022; AASHTO 2024). To enhance tensile resistance, about 3% of steel fibers are usually added by volume (Wang et al. 2017). One of the most distinguishable aspects between UHPC and ordinary concrete is the former's low water-to-cement ratio ($w/c = 0.2$ to 0.25). The application of UHPC is broad from primary members to joint elements (Garybeal et al. 2020) and from new construction to rehabilitation (Bertola et al. 2021).

Current challenges—As stated above, UHPC is a suitable candidate to upgrade the performance of bridge decks. By adding overlays to existing concrete slabs, synergistic benefits will follow in terms of strength (thickened slab dimension) and durability (e.g., reduced chloride ingress). Literature reports that a number of advantages are associated with UHPC overlays (Liu and Charron 2024); for example, increased load-carrying capacities, enhanced deformational characteristics, and controlled premature debonding failure. Researchers also demonstrated that UHPC overlays cast to the tensile side of reinforced concrete members increased flexural and shear resistance (Pharand and Charron 2023).

Although previous studies examined the feasibility of UHPC overlays for strengthening bridge structures (Teng et al. 2021), many of them were concerned with simple casting on top of existing concrete (Abokifa et al. 2021). Accordingly, a full load transfer was unavailable and there is room to ameliorate structural behavior by achieving composite action, so that the new and old components can act together to effectively distribute applied stresses. From a practical perspective, the bond between UHPC overlays and existing concrete is deemed crucial to ensure a composite system, which is controlled by substrate roughness, moisture, and surface preparation (Bissonnette et al. 2012).

Research justification—Placing an overlay is a convenient solution to repair or upgrade existing bridge decks and is frequently recommended to retard the ingress of chlorides (Valikhani et al. 2020); nonetheless, no practice guidelines are available for UHPC overlays. Further research is thus necessary in conjunction with the development of design recommendations. The proposed research aims to address these essential needs for the structural concrete community by elucidating the load-carrying mechanism of UHPC-overlayed deck slabs with full and partial composite actions. Subsequently, findings will be employed to suggest provisions for technical specifications.

Research Objectives

The overarching goal of the research is to explore a sustainable solution that can extend the longevity of constructed bridge decks by placing an overlay system with a state-of-the-art construction material, UHPC. Specific objectives are:

- To fundamentally understand interactive mechanisms between bridge decks and UHPC-overlays, contingent upon the degree of composite action
- To perform theoretical studies that can encompass various situations involving assorted material and geometric properties

- To develop practice guidelines for the sake of bridge engineers and government officials who are in charge of bridge management

The quality and adequacy of the proposed technical work will be measured by the feedback of practitioners and researchers who attend professional gatherings and by the reviewers of journal publications.

Research Methods

A comprehensive experimental program is planned to ascertain the effectiveness of UHPC overlays in addressing structural concerns with a focus on the capacity and stiffness of highway bridges. Analytical modeling will then be carried out for confirming the adequacy of test results, generating supplementary technical data via extensive parametric investigations, and suggesting design recommendations. To fill the gap of state-of-the-art knowledge, refined theoretical approaches will be adopted. For instance, published papers acknowledge that the strain-hardening of UHPC is generally omitted for modeling convenience, whereas such a simplification can inaccurately predict the load-bearing ability of UHPC-incorporated structures (Liu and Charron 2024). In addition, considering potential uncertainties in the field, stochastic simulations will be superinduced. Interface tests will be conducted to examine the bond behavior of UHPC and ordinary concrete. For the identification of a suitable approach, various methods will be taken into account (e.g., cylinder splitting and slanted shear). A vision-based instrumentation technique, digital image correlation (DIC), will be utilized to monitor the nucleation and progression of detrimental cracks in the overlayed deck slabs.

Relevance to Strategic Goals

The research program aligns with the two major goals of USDOT: *Safety* and *Sustainability*. The proposed rehabilitation system with UHPC overlays will significantly increase the level of safety by reducing the probability of failure. As part of the aforementioned theoretical modeling, risk levels will be quantified with and without the overlays. In so doing, specific information will be available to justify the use of the overlay system with regard to safety. As far as sustainability is concerned, the research conforms to the broadly accepted definition stipulated by the United Nations '*meeting the needs of the present without compromising the ability of future generations to meet their own needs*' because it will preserve built-environments in a rigorous manner.

Educational Benefits

The project will benefit local communities and will foster next generation bridge engineers. Technical findings will be used for a course Dr. Kim offers, CVEN4800/5800 (*Structural Rehabilitation*) at the University of Colorado Denver. The course involves three main subjects (inspection, evaluation, and rehabilitation) and the rehabilitation content will be enriched. Through technical tasks, student assistants will learn how to conduct experimental components, how to formulate theoretical models, how to interpret results, and how to draft technical guidance.

Outputs through Technology Transfer

Dr. Kim will deliver technical presentations during professional gatherings (e.g., American Concrete Institute conventions). This plan differs from routine presentations for a typical conference in that he will elaborate on research backgrounds, scientific approaches, ensuing outcomes, and practical applications. Active discussions are expected with engineers, researchers, and students. Dr. Kim will also communicate with industry people so that research can be translated into practice. Peer-reviewed publications will be another means to accomplish technology transfer around the globe.

Expected Outcomes and Impacts

By comprehending the efficacy of UHPC overlays in upgrading bridge structures under a wide variety of circumstances, bridge professionals can apply this cutting-edge rehabilitation method with confidence. The experimental and analytical approaches will result in guidelines that can be implemented in the field. The cost-effective and sustainable technique will extend the service life of bridge members and will preclude unexpected failure. The design recommendations to be drafted can be adoptable in the bridge design manuals of state DOTs. Findings will be shared with other engineers and researchers through the three bridge committees of the American Concrete Institute (ACI): ACI 342 (*Evaluation of Concrete Bridges and Bridge Elements*), 343 (*Concrete Bridge Design*), and 345 (*Bridge Construction and Preservation*).

Work Plan

Below is a succinct summary of planned tasks:

Task 1: Literature review (2 months)—A comprehensive literature search will be undertaken to collect a wide variety of papers and reports. Attention will be paid to documents that particularly handle the concepts of physics; as such, the research can better link fundamentals with applications (e.g., multimaterial interactions to account for the complex engagement between ordinary concrete and UHPC).

Task 2: Laboratory testing (12 months)—One-way slabs will be cast and cured. After hardening, the slabs will be upgraded using various overlay configurations with and without shear connectors. The spacing of the connectors will range from 0 in. to 8 in., which are necessary to assess the implications of full and partial composite actions. The effects of predamage will be studied as well by loading the slabs up to 50% of the control capacity before overlays are placed. Flexural responses will be monitored and failure modes will be documented.

Task 3: Analytical modeling (6 months)—Sectional analysis models will be formulated incorporating the degree of composite action and the consequence of preloading. To address problems that are associated with uncertainties on site, the models will be simulated stochastically.

Task 4: Technology transfer (1 month)—As stated above, Dr. Kim will share research findings with engineers, researchers, and students who attend professional gatherings.

Task 5: Design recommendations (1 month)—Results to be attained from Tasks 2 to 4 will be integrated to develop design recommendations. It is expected that adjustment factors are proposed to appropriately deal with full and partial composite actions.

Task 6: Final report (2 months)—A final report will be prepared and submitted. The contents of the report will be peer-reviewed.

Project Cost

Total Project Costs:	$120,000
CTIPS Funds Requested:	$ 60,000
Matching Funds:	$ 60,000
Source of Matching Funds:	University of Colorado Denver—$30,000 Department of Academic Attaches and Scholarship Affairs, Libya Government—$30,000 (graduate student scholarship)

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