MPC-516

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Project Title:
Innovative Strengthening for Deteriorated Concrete Bridges Using Embedded Composite Sheets Bonded with Polyester-silica

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University of Colorado Denver

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Research Needs:
Structural strengthening of deteriorated concrete bridges using advanced composite materials such as carbon fiber reinforced polymer (CFRP) has gained significant attention from the infrastructure engineering community. CFRP may be bonded along the tensile substrate of a concrete member with an epoxy adhesive to upgrade the load-carrying capacity of the member. Numerous advantages are expected when a structural member is retrofitted with CFRP sheets; for instance, insignificant increase in dead load, high-strength and favorable modulus, resistance to corrosion and fatigue, and reduced maintenance costs.

Although CFRP-strengthening has been broadly used for buildings and bridges over the last decade, it is recognized that premature bond failure is a critical concern, which would substantially reduce the efficacy of structural strengthening. A number of research projects were conducted to understand the bond failure mechanism of CFRP-strengthened concrete beams and to propose enhanced implementation methods (Bank 2006). The current state-of-the-art of debonding-control includes use of anchorage that can retard the failure of CFRP-concrete interface (Kalfat et al. 2013). Various types of anchor systems were suggested previously such as mechanical anchors (Ortega 2007), non-mechanical anchors (Kim et al. 2008), and CFRP U-wraps (Pham and Al-Mahaidi 2006). These approaches, however, are not a permanent solution because i) mechanical anchors are susceptible to corrosion that can cause secondary distress to the bonded CFRP; ii) non-metallic anchors need extra endeavors and will eventually fail when excessive mechanical stresses are associated; and iii) CFRP U-wraps can also debond from the concrete. An intrinsically different approach is essential to address the critical debonding problem in externally-bonded CFRP application.

A holistic research program integrating experimental and theoretical investigations is proposed to develop an innovative debonding-control method for CFRP-strengthened concrete members without using external anchorage. Unlike conventional strengthening approaches employing CFRP sheets bonded to the surface of concrete, the novel idea is that wide grooves are cut near both ends of a concrete member and CFRP sheets are embedded so that stress concentrations causing end-peeling failure are mitigated. It is important to note that this approach is different from existing near-surface-mounted (NSM) application that requires long grooves for CFRP strips. A grouting agent made of polyester-silica will be used to fill the gap between the embedded CFRP and the concrete substrate. The polyester-silica resin is believed to be a strong candidate providing sufficient bond to the CFRP-concrete interface. The proposed concept for debonding-control of externally bonded CFRP sheets has not been exploited by others previously and thus will advance the state-of-the-art of rehabilitation technologies.

Research Objectives:

The objectives of the research are:

- To develop an innovative strengthening method for deteriorated concrete bridges using CFRP sheets embedded in the substrate
- To comparatively elucidate the bond failure mechanism of the proposed strengthening approach against that of conventional externally-bonded CFRP application
- To propose design and practice guidelines for bridge professionals who are interested in repairing deteriorated concrete bridges with CFRP sheets

Research Methods:

The proposed research program is comprised of two primary components (element- and structure-level testing and corresponding theoretical investigations) that require a significantly deep understanding of interfacial interactions among the concrete substrate, embedded CFRP sheets, and polyester-silica resin. The research will address both scientific (i.e., interfacial physics) and practical engineering issues, which will be integrated into proposing design guidelines for the sake of the bridge engineering community. A three-phase research approach is summarized as follows:

- *Bond failure mechanism*: experimental work will be performed to examine the failure mechanism of bond between the embedded CFRP and concrete substrate grouted by a polyester-silica resin. Various embedment configurations (e.g., embedment angles and CFRP lengths) will be taken into consideration to identify optimal embedment conditions and corresponding failure modes. Mechanics-based investigations at mesoscale will be linked with microscale responses so that a complete understanding of interfacial damage initiation and progression can be accomplished.
- *Multi-material interaction*: provided that four different materials are integrated together to form one structural system (i.e., concrete, CFRP, epoxy, and polyester-silica), their interaction is of great interest. The principle of multi-material interaction in physics will be borrowed to explain experimental observations to be attained from the laboratory, including the transfer mechanism of potential energy among the four constituents. Microscale friction that controls the interfacial behavior at the surface level will also be studied.
- *Design guidelines*: all experimental and theoretical endeavors will cohesively be used to develop practical design guidelines. In so doing, sustainable infrastructure can be achieved with reduced long-term maintenance expenses. Technology transfer will be made through technical presentations and communications with other practitioners and researchers in conferences and professional meetings.

Expected Outcomes:

The proposed strengthening method will fundamentally reframe existing knowledge about externally-bonded CFRP application by alleviating the risk of premature debonding failure. The method will also address the aesthetic aspect of strengthened members because the CFRP is located inside a concrete substrate without the needs for external anchor systems. Detailed investigations into multi-material interaction will contribute to formulating a complete set of understanding of the embedded-CFRP system. The durability performance of the strengthened concrete members will be improved because of the reason stated above (CFRP sheets are located inside the concrete substrate where stress concentrations exist and hence the failure of the system induced by environmental or physical distress is precluded). The research will fulfill the need of bridge engineers who want to adopt state-of-the-art repair techniques and will be a valuable investment for our constructed infrastructure and associated sustainability.

Relevance to Strategic Goals:
The theme of the regional University Transportation Center at North Dakota State University (Mountain-Plains Consortium) is '*Transportation Infrastructure and Operations to Support Sustainable Energy Development and the Safe Movement of People and Goods*', which is aligned with the goal of the proposed research. Rigorous effort will be made to address critical problems facing the infrastructure of the nation, particularly for the regions experiencing aggressive weather conditions such as upper Midwest of the US. The primary interest of the current investigation meets the Secretary of Transportation's Strategic Goals (i.e., *State of Good Repair* and *Economic Competitiveness*) in terms of preserving constructed transportation structures with reduced long-term repair expenses.

Educational Benefits:
Educational components of this project are as important as research findings because new generation engineers are responsible for our constructed transportation infrastructure. The PI will train highly qualified personnel (two graduate students: Abdullah Alajmi and one more) and will integrate technical outcomes with structural engineering courses at the University of Colorado Denver. A number of undergraduate and graduate students will, therefore, benefit from the current MPC project. The PI will encourage his graduate students involved in infrastructure research to participate in conference activities and technical committees so that they can present their findings and can communicate with colleagues and potential employers. The PI will devote himself to maximizing the educational benefit of this MPC-sponsored project.

Work Plan:
Task 1: A critical literature review will be carried out to collate the current state-of-the-art and state-of-the-practice of interfacial bond between CFRP sheets and concrete substrate. An emphasis will be placed on debonding mechanisms and the effect of external anchorage as well as interfacial physics, including multi-material interaction. Also studied will be the use of polyester-silica for concrete application (Month 1-3)

Task 2: Bond tests will be conducted with isolated CFRP-concrete interface elements. Further specifically, concrete prisms will be cast and bonded with CFRP sheets at various embedment angles. The prepared interface-test elements will mechanically be tensioned until failure happens. Instrumentation will be applied to monitor the behavior of the test specimens (i.e., a load-cell, linear potentiometers, a non-contact laser extensometer, and strain gages) (Month 4-9)

Task 3: Structural testing with reinforced concrete beams strengthened using the proposed system (i.e., embedded CFRP sheets with the polyester-silica resin) will be performed. Various strengthening schemes will be evaluated such as variable CFRP-bond lengths, embedment angles, and the amounts of the polyester-silica composite. Factorial analysis will be associated to identify the respective effect of the multiple test parameters (Month 10-20)

Task 4: Design guidelines will be developed based on the findings of Tasks 2 and 3. The concept of performance-based design is employed to accomplish object-specific recommendations. Technology transfer is implemented by technical presentations and communication with other professionals in the bridge engineering community via international conferences and domestic meetings such as American Concrete Institute conventions. A final report will be prepared (Month 21-24)

Project Costs:
Total Project Costs: $99,015
MPC Funds Requested: $49.507.50
Matching Funds: $49.507.50

TRB Keywords:
bridge, concrete, damage, design, fiber reinforced polymer, girder, performance, rehabilitation, repair

References:
Bank 2006; Kalfat et al. 2013; Ortega 2007; Kim et al. 2008