MPC-648
March 26, 2021

Project Title

Repairing Concrete Structures Using Near-Surface Mounted Composites with Inorganic Resins under Simulated Multihazard Damage

University

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Research Needs

In the United States, deteriorated infrastructure is one of the primary concerns. State and federal agencies spend significant amounts of dollars to maintain the quality of transportation structures. For example, the Fixing America's Surface Transportation (FAST) Act authorized $305 billion to address the immediate need of the nation (ASCE 2020). Reinforced concrete bridges are frequently constructed with surface-coated steel bars, whereas their longevity is limited and eventually a reduction in the load-carrying capacity takes place (Konecny and Lehner 2016). Advanced composites such as carbon fiber reinforced polymer (CFRP) are proven materials for repairing and upgrading constructed bridge structures (ACI 2017). The composites comprise a resin matrix and carbon fabrics, mostly made of unidirectional fibers. While the fibers are responsible for strength and stiffness, the matrix transfers stress and protects the fibers.

Organic adhesives (e.g., epoxies) are predominantly used when placing CFRP to a concrete substrate because of favorable adhesion and familiarity; however, the drawbacks of these conventional bonding agents are often recognized. Toutanji and Deng (2007) criticized that epoxy adhesives deteriorate due to ultraviolet (UV) rays and suggested cementitious inorganic resins. There are a number of advantages associated with inorganic resins: affordable costs, energy saving, easy preparation, applicability to wet surfaces, volumetric stability, prompt strength gain, durability, and thermal resistance (Li et al. 2004). Hashemi and Al-Mahaidi (2012) raised several critical issues related to epoxies, namely, moisture impermeability, flammability, chemical instability, and application period (shelf life). According to Prete et al. (2020), the use of an epoxy for structural strengthening would degrade the efficacy of CFRP at elevated temperatures. Therefore, inorganic resins can be considered to be a potential alternative for the betterment of CFRP-based repair.

Traditionally, CFRP sheets have been externally bonded to the tensile soffit of a concrete member in order to increase the flexural and shear capacities (ACI 2017). Despite the satisfactory strengthening effects of CFRP, the bonded sheets are vulnerable to high interfacial stress and premature debonding becomes a controlling factor in repair design (Al-Atta et al. 2020; Godat et al. 2020). The specifications published by the American Association of State Highway Transportation Officials (AASHTO) limit the usable strain of CFRP to $\varepsilon_f = 0.005$ (AASHTO 2012). Considering that a typical rupture strain of CFRP is around 0.015, the AASHTO limit of 0.005 is only about 30% of the CFRP's tensile strength. To address this uneconomical use of externally bonded CFRP, near-surface-mounted (NSM) CFRP technologies were proposed. The concept of NSM CFRP is that the strengthening material is located inside a concrete substrate along a precut groove and filled with an adhesive. In so doing, interfacial interactions between the concrete and CFRP increase; scilicet, the occurrence of premature debonding is precluded. Some other notable benefits of NSM CFRP are reduced in-situ labor, minimal alteration of existing concrete, and enhanced durability (De Lorenzis and Teng 2007). Similar to the case of externally bonded CFRP, epoxy resins are broadly employed for NSM CFRP application.

The rehabilitation community recently exhibited an interest in utilizing inorganic resins for NSM CFRP, with an aim to resolve the above-mentioned problems. Al-Saadi et al. (2017) examined the potential of a self-compacting cementitious adhesive for bonding NSM CFRP in a concrete groove. The performance of the proposed CFRP system was compared against that of an epoxy-bonded system. Five reinforced concrete beams were strengthened and loaded under 3 million fatigue cycles. The failure of the beams was controlled by the rupture of CFRP, rather than debonding, which confirms the effectiveness of the NSM CFRP technology. As far as composite action is concerned, epoxy-bonded CFRP showed abrupt failure at the level of concrete cover; by contrast, the case with the cementitious resin maintained full strain comparability. Although limited information is available, the present literature search convinces that NSM CFRP with inorganic resins has a great potential for repairing/upgrading bridge structures.

Research Objectives

The overarching goals of the research are:

- To evaluate the feasibility and performance of inorganic resins as a bonding agent for NSM CFRP composites, which are used to repair concrete members damaged by multihazard loadings, based on interfacial bond and structural load tests
- To propose practice guidelines for the infrastructure community, leading to expense savings in managing constructed highway bridges

Research Methods

The applicability of various inorganic resins will be studied through element- and structure-level investigations, including ordinary cement mortar, geopolymer, ultra-high performance concrete, and a polyester-silica composite. For the element-level test, simplified interface specimens will be cast and monotonically tensioned until failure. It is expected that the detailed failure mechanisms of the inorganic resins are elucidated. Afterward, structural beams suffering from multihazards will be prepared in the laboratory, repaired with NSM CFRP alongside the inorganic resins, and loaded. Because there are many types of hazards, their ramifications will be simulated by artificially reducing the cross-section of steel reinforcement; in other words, intentional structural damage will be initiated to lower the capacity of the beams (the level of damage will be identified by analytical models), which will be equivalent to the consequences of possible multihazard loadings. Theoretical modeling will be conducted to better understand the physical behavior and to numerically expand experimental results. All findings will be integrated to propose practice guidelines for the benefit of the infrastructure community.

Expected Outcomes

The research program will suggest a cost-effective and long-lasting repair method for bridge elements damaged by multihazards (e.g., corrosion, vehicular loading, tsunami, hurricane, seismic, impact, and fire interactions). Of interest are the discovery of potential in inorganic resins and their adaptability to structural rehabilitation with NSM CFRP composites. Regarding fundamental mechanics, the complex interfacial response of NSM CFRP will be comprehended, followed by the development of a practical link between the research and practice. So informed, bridge engineers can select appropriate repair methods to extend the service life of damaged bridge structures.

Relevance to Strategic Goals

The proposed research will be relevant to the Secretary of Transportation's Strategic Goals: *State of Good Repair* and *Economic Competitiveness*. Upon successful completion of technical tasks, sustainable repair will be accomplished at minimal maintenance activities, which will save the management expense of transportation infrastructure.

Educational Benefits

The direct impact of the research will be achieved through training graduate students, who will be instrumental in the bridge engineering community. Students will learn how to design structural specimens, how to cast, instrument, and test, and how to interpret recorded data. Such laboratory experiences will be valuable for their professional career: numerous design engineers in consulting firms have not received hands-on training. The results of the research will be included in one of the PI's courses, CVEN 4800/5800: *Structural Rehabilitation*, at the University of Colorado Denver. Although the course has many interesting subjects related to civil infrastructure, contents should regularly be updated in order to provide state-of-the-art education.

Technology Transfer

As President of the Bridge Engineering Institute, An International Technical Society, the PI actively participates in assorted professional activities. Furthermore, the PI chairs American Concrete Institute (ACI) 440I (FRP-Prestressed Concrete), chaired ACI 345 (Concrete Bridge Construction and Preservation) from 2012 to 2018, and is a voting member of eight national committees. The PI is often invited to give technical talks during meetings, conventions, and international conferences. For instance, the PI delivered plenary and keynote speeches for the 30th Anniversary of the Korea Concrete Institute (May 2019 in Jeju, South Korea) and the 11th Conference on Application Technology of FRP in Infrastructure (Sept. 2019 in Shanghai, China). Whenever appropriate, the PI disseminates research findings and shares insights with other researchers/engineers around the world. The PI's publications in journals and conference proceedings will be another valuable means to transfer scientific knowledge (161 journals and 79 conferences, as of Dec. 1, 2020), which can advance the state of the art of transportation infrastructure.

Work Plan

Task 1: Literature review (Months 1 to 3)
A comprehensive literature search will be carried out to identify representative distress resulting from multihazards. Emphasis will be placed on the detrimental consequences of structural damage and appropriate models for simulating the degraded behavior of existing bridge members. The mechanical and physical properties of inorganic resins will be collated and analyzed. The load-bearing mechanisms and potential failure characteristics of NSM CFRP bonded with inorganic resins will be studied.

Task 2: Element-level testing (Months 4 to 12)
Concrete blocks will be cast with a groove and CFRP will be inserted with inorganic resins. After curing, all specimens will be loaded to failure and their responses will be logged using a load cell and a linear potentiometer. A digital image correlation technique will be employed to visually assess the behavior of the specimens. The purpose of Task 2 is to examine the interfacial mechanics between the resin and CFRP, which will play a crucial role in clarifying the failure of such a heterogeneous system.

Task 3: Structure-level testing (Months 13 to 21)
Prior to preparing reinforced concrete beams, various levels of damage will be planned to represent the repercussions of typical multihazards (e.g., equivalent to reduced steel areas). A control beam and a dozen of beams repaired using NSM CFRP with inorganic resins will be tested in flexure. Expected test data include loads, displacements, compressive and tensile strains, and crack patterns. Like the case of the element-level testing in Task 2, digital images will be collected and processed to establish a relationship between the types of resins and the performance of NSM CFRP.

Task 4: Development of practice guidelines (Months 22 to 23)
The outcomes of Tasks 2 and 3 will be appraised and integrated to develop practice guidelines. Attention will be paid to the failure characteristics of NSM CFRP and the selection of adequate inorganic resins for structural repair. Depending upon test results, either prescriptive or performance-based design recommendations will be proposed.

Task 5: Final report (Month 24)
A final report will be submitted before the end of a contract date.

Project Cost

Total Project Costs:	$120,000
MPC Funds Requested:	$ 60,000
Matching Funds:	$ 60,000
Source of Matching Funds:	University of Colorado Denver, in-kind support

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