MPC-456
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Project Title
Performance of Steel Girders Repaired with Advanced Composite Sheets in a Corrosive Environment: A Multi-Physics Approach Leading to Practical Design Recommendations

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Research Needs

The issue of infrastructure management and rehabilitation is one of the primary interests in the civil engineering community. Constructed bridge members deteriorate because of aging, corrosion, increased service load and traffic volume, use of deicing salts, and collision of heavy trucks (Kim et al. 2008; Harries 2009; Kim and Yoon 2010). Over $180 billion is required to address structurally deficient or functionally obsolete bridges in the United States (ASCE 2005). Of particular interest are steel bridges that account for more than 43% of the substandard bridges in the nation (Tavakkolizadeh and Saadatmanesh 2003). Steel bridges are susceptible to corrosion. Structural repair of damaged members provides a viable alternative to replacement, reducing downtime and cost. Traditional repair techniques for steel bridges include use of steel plates bolted or welded to damaged girders. Although the performance of such repaired girders is generally acceptable, the repairs themselves may introduce new potential problems associated with increased dead load, corrosion (crevice and galvanic corrosion), and the introduction of fatigue-sensitive details at the junction of existing and repair materials (Lenwari et al. 2006). The application of carbon fiber reinforced polymer (CFRP) composites is proposed as an alternative to steel-plating repair methods. The advantages of CFRP materials include their non-corrosive characteristics, high stiffness- and strength-to-weight ratios, ease and rapidity of erection, and reduced long-term maintenance expenses (Bakis et al. 2002). A significant advantage of CFRP systems is that they are typically adhesively bonded, rather than mechanically connected, to the substrate steel, resulting in mitigation of the additional stress raisers associated with bolt holes or welds. Although CFRP composites have primarily been used for repairing concrete structures (Teng et al. 2003), there are relatively limited data available on strengthening damaged steel members using CFRP (Schenerch and Rizkalla 2008, Shaat and Fam 2008, Harries et al. 2010). Nonetheless, this body of work clearly indicates the promise of this technique for strengthening damaged steel members subject to monotonic loads. Cadei et al. (2004) provides significant guidance for such applications.

Notwithstanding the foregoing, very limited information is available on the behavior of steel structures repaired with CFRP composites subjected to corrosive service environments. There has been no attempt to understand the progression mechanism of corrosion for steel members repaired with CFRP, which will be a crucial issue to develop design guidelines.

Research Objectives

The objectives of the research are:

- To understand the mechanism of corrosion progression in CFRP-repaired steel bridge girders exposed to a corrosive service environment
- To examine the effect of corrosion damage on the performance of repaired steel girders in terms of load-carrying capacity and ductility as well as CFRP-steel interfacial behavior
- To develop practical design guidelines for bridge engineers who are interested in repairing in-situ bridge girders with CFRP materials

Research Methods

The proposed research program includes a multi-physics approach that requires a significant understanding of various physical phenomena associated with corrosion damage in CFRP-repaired steel bridge members. The project will cover both fundamental scientific issues and practical design recommendations for technology transfer. A three-phase research approach is summarized below:

- *Damage mechanism*: experimental work will be carried out to elucidate the damage mechanism of CFRP-repaired steel girders subjected to a corrosive service condition. Emphasis will be given to the deterioration of CFRP-steel interface with time. A combination of chemical kinetics and mechanical bond degradation will enable a multi-physics investigation environment.
- *Performance evaluation*: CFRP-strengthened steel girders with corrosion damage will be loaded monotonically to evaluate their performance in terms of load-carrying capacity, ductility, and failure modes. The knowledge gained from the first phase will play an important role in understanding the performance degradation of the damaged beams from a CFRP-debonding perspective.
- *Design guidelines*: the outcome of the aforementioned phases will be integrated into developing practical design guidelines for the benefit of the bridge engineering community. 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

Corrosion damage to steel girders is one of the most significant problems affecting the service life of existing bridges. Corrosion-induced distress is frequently observed in constructed bridge members and corresponding repair is conducted. The application of CFRP composites to repair damaged steel girders is a promising technique offering an attractive alternative to conventional repair methods (e.g., steel-plating). The performance of CFRP-repaired girders controls the longevity of the superstructure system. A technically unknown issue is the propagation mechanism of corrosion damage in CFRP-repaired steel girders and their performance with respect to the degree of corrosion. The proposed research will address this scientific challenge through a multi-physics approach in conjunction with chemical kinetics and mechanical bond degradation. The research will also fulfill the need of bridge engineers who want to adopt the state-of-the-art repair technique. This MPC project will be a valuable investment for our constructed infrastructure and its 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, in particular 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 infrastructure. The PI will train highly qualified personnel (2 graduate students: Ibrahim Bumadien and Thushara Siriwardanage) and will integrate technical outcomes with his course at the University of Colorado Denver. A number of undergraduate and graduate students will, therefore, benefit from this MPC project. The PI will encourage his graduate students involved in infrastructure research to participate in conference activities 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 literature review is done to understand the current state of corrosion research in the infrastructure community. Foci of the review are corrosion propagation in steel girder bridges and their performance degradation. Existing design documents to address corrosion-induced problems is also be studied (Month 1-3)

Task 2: Element-level investigations are conducted using steel coupons bonded with CFRP sheets. The prepared test specimens are exposed to various levels of corrosion conditions. An accelerated corrosion protocol is designed and implemented in the Structures Laboratory of the University of Colorado Denver, including electrochemical cells. Galvanic corrosion takes place with time and the test specimens are deteriorated accordingly. The rate of corrosion is quantified by measuring the loss of mass and by Faraday's law of electrolysis. Fourier transform infrared spectroscopy (FTIR) is used to understand the progression mechanism of corrosion damage along the CFRP-steel interface. Damaged specimens are monotonically loaded until failure occurs. Chemical kinetics and mechanical bond deterioration can thus be examined simultaneously (Month 4-11).

Task 3: Structure-level testing is done to evaluate the performance of CFRP-repaired steel girders subjected to corrosion damage. The accelerated corrosion protocol developed in the previous task is modified to accommodate a larger-scale girder test. Time-dependent corrosion damage is quantified and corresponding performance is studied. All conditioned beams are loaded in four-point bending. Ductility of the repaired beams is of interest because CFRP-repaired beams usually demonstrate insufficient ductility. Failure modes are characterized with the degree of corrosion (Month 12-20)

Task 4: Practical design guidelines are developed based on the findings of Tasks 2 and 3. The potential of performance-based design is assessed and hence an advanced design concept can be proposed. 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 is prepared (Month 21-24)

Project Costs ($100,105)
MPC Funds requested: $50,000.02
Matching funds ($50,105 = $46,605 + $1,500 + $2,000):
Student tuition Ibrahim Bumadien ($7,170 for SP2014, $7,170 for SU2014, $10,755 for FA2014, $7,170 for SP 2015, $7,170 for SU2015, and $7,170 for FA2015= $46,605)
Student travel support: $1,500
Material supplies: $2,000
Total Project Cost: $100,105.92

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

References (details are available upon request)
ASCE 2005; Bakis et al. 2002; Cadei et al. 2004; Harries 2009; Harries et al. 2010; Kim et al. 2008; Kim and Yoon 2010; Lenwari et al. 2006; Schenerch and Rizkalla 2008, Shaat and Fam 2008; Tavakkolizadeh and Saadatmanesh 2003; Teng et al. 2003