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Project Title
Fire performance of bridge members retrofitted with near-surface-mounted carbon fiber reinforced polymer composites

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Research Needs
The need for an upgrade or repair frequently arises when the capacity of a member does not meet the current load-bearing requirement. Carbon fiber reinforced polymer (CFRP) composites are a promising material for upgrading or repairing existing structural members. CFRP materials are comprised of unidirectional carbon fibers embedded in a polymeric resin. The fibers provide load-carrying capacity of the composite and the resin binds the fibers so that stress transfer between the fibers is achieved. The advantages of CFRP composites include non-corrosive characteristics, prompt execution on site, reduced maintenance expenses, favorable strength to weight ratio, and good chemical or fatigue resistance (Teng et al. 2003, Kim et al. 2008, Kim and Heffernan 2008).

CFRP composites may be externally bonded to the tensile soffit of a concrete member to increase load-carrying capacity. The most critical concern of such an application is the bond performance of CFRP when the retrofitted structure is subjected to mechanical or environmental loads. Previous research has reported that premature debonding failure of externally-bonded CFRP may take place because of stress concentrations at the cut-off points (Malek et al. 1998, Bizindavyi and Neale 1999, Kim et al. 2005). A combination of normal and shear stresses along the bondline influences debonding of the CFRP (Smith and Teng 2001). An alternative retrofit method called near-surface-mounted (NSM) CFRP composites has recently been developed to improve the bond behavior of CFRP (De Lorenzis and Teng 2007).

NSM CFRP composites are an emerging technology for retrofitting existing concrete structures. A small groove is cut along the tensile soffit of a concrete member in which CFRP composites are inserted and permanently placed with a bonding agent, as shown in Fig. 1. The types of CFRP composites may be strips, laminates, and bars. Epoxy adhesives are widely used to bond the composites. The benefits of NSM CFRP applications for retrofitting concrete structures are the ease of installation, resistance to corrosion damage, reduced labor costs, improved bond characteristics when compared to externally bonded CFRP composites, and enhanced durability because the reinforcement is located inside the concrete (De Lorenzis and Teng 2007, Kotynia 2007). Given the application of NSM is still at its early stage, various technical aspects need to be examined.

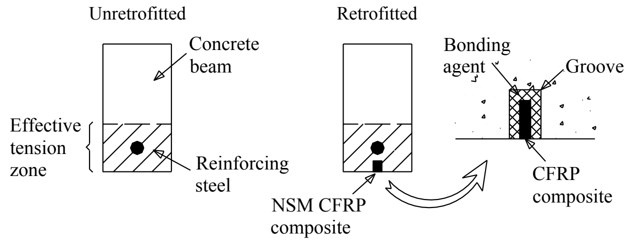

Fig. 1. Concept of NSM CFRP-retrofit (Kim and Rahman 2010)

Like other structural components, CFRP-retrofitted bridge members are exposed to potential fire hazards (Garlock et al. 2012). Repaired members must, therefore, demonstrate acceptable fire resistance to ensure adequate structural integrity until travelling vehicles are evacuated. Due to the thermal deformation of a polymeric matrix that binds carbon fibers in CFRP composites, mechanical properties of the CFRP are particularly susceptible to high temperature exposure (Bisby et al. 2005a; da Silva and Adams 2007). Although insulation materials could be applied on the surface of CFRP-retrofitted structural members (Gamage et al. 2006; Williams et al. 2006), heat transfer from a fire to the retrofit system is inevitable. In fact, CFRP repair for structural members in fire is recognized as one of the primary research needs in the rehabilitation community (Karbhari et al. 2003). Little information is currently available on the thermal performance of reinforced concrete members retrofitted with NSM CFRP composites.

The present study addresses such an identified research gap through an experimental program combined with theoretical models. The emphasis of the research is given to (1) to examining the behavior of concrete members retrofitted with NSM CFRP strips when subjected to elevated high temperatures and (2) to understanding the relationship between the performance degradation of NSM CFRP and temperature-induced distress. The emphasis of the experiment is on the residual behavior of CFRP-retrofitted concrete members, rather than the behavior during high-temperature exposure. The research program will generate much-needed test data to advance the state-of-the-art in the community.

Research Objectives

The objectives of the research are:

- To examine the performance of NSM CFRP-retrofitted concrete members at elevated high temperatures, including material characterization, bond behavior, and structural behavior
- To develop performance-based design guidelines to facilitate use of NSM CFRP technologies for upgrading constructed reinforced concrete girders and decks subjected to thermal load so that technology transfer can be as broad as possible

Research Methods

The research program deals with a practical perspective to address the occurrence of extreme scenarios for constructed bridges such as fire or blast damage. The project will examine the fundamental behavior of reinforced concrete members retrofitted with NSM CFRP composites at high temperature. Design guidelines will be suggested. The three-phase research approach is as follows:

- *Behavior*: experimental work will be conducted to understand the interaction between the NSM CFRP and concrete substrate when subjected to elevated high temperatures
- *Assessment*: performance of reinforced concrete members retrofitted with NSM CFRP composites will be rigorously quantified from material-level to structure-level
- *Technology transfer*: all technical findings will be integrated into performance-based design guidelines to address the needs of NSM CFRP applications in extreme events

Expected Outcomes
Infrastructure rehabilitation is a timely and critical area to study. The American Recovery and Reinvestment Act declared by President Obama supports the importance of infrastructure-related research. The proposed research addresses an interesting technical aspect concerning a state-of-the-art rehabilitation concept associated with extreme events such as a fire in a retrofitted bridge. The research components are unique and transferable because there has been no research on the fire performance of NSM CFRP-retrofitted concrete members. Technology transfer will result in an immediate benefit to society, including practicing engineers, industry sector, and government agencies. Overall, the proposed project will be a valuable investment to enhance the quality of our infrastructure from technical and societal perspectives.

Relevance to Strategic Goals
The proposed research program is pertinent to the theme of the regional University Transportation Center at NDSU in terms of the transportation infrastructure and the movement of large freight that may include fire-hazard materials. Focus of the research is aligned with the Secretary of Transportation's Strategic Goals (i.e., *State of Good Repair* and *Economic Competitiveness*), given that the research will address the sustainability of constructed bridges that will save significant long-term maintenance expenses and discusses the possibility of extreme events that may happen in freight-significant highway corridors.

Educational Benefits
Educational benefits from this research are two-fold. First, highly qualified personnel will be trained in the area of civil infrastructure: two graduate students will participate in the research project. Second, the research outcomes will be beneficial to the course Dr. Kim is planning to offer in 2013 or 2014: *Bridge Evaluation and Rehabilitation*. Senior undergraduate and graduate students will take this course.

Work Plan
Task 1: An extensive literature review will be conducted to better understand the state-of-the-art in fire engineering. Of interest is the fire performance of composite materials from micro- to macro-levels. An experimental program will be designed for Task 2 (Month 1-3)

Task 2: Test specimens will be constructed and tested. Three-phase tests will be conducted: i) material-level investigations for thermal characterization of the constituents, ii) bond behavior of NSM CFRP composites embedded in a concrete member subjected to thermally-induced stress states, and iii) structure-level examinations at elevated high temperatures (Month 4-10)

Task 3: A thermal-performance model will be developed based on the concept of stochastic damage. Extensive probabilistic modeling will be carried out using a Monte-Carlo simulation method. A three-dimensional finite element model will be constructed and corresponding findings will be linked with the probabilistic model prediction (Month 11-15)

Task 4: Performance-based design recommendations will be suggested and a technical report will be completed. For technology transfer, research findings will be presented in professional meetings such as American Concrete Institute conventions and international conferences (Month 16-18)

Project Costs
Funds requested from June 1, 2013 to Dec 31, 2014 (18 months): $38,000
Matching funds ($40,042):
Faculty research during academic year: $29,720(salary) + $8,332 (benefit) = $38,042; material supplies and instrumentation= $2,000

TRB Keywords: bridge, extreme event, fiber reinforced polymer, fire, near-surface-mounted, performance, rehabilitation

References (details are available upon request)
Bizindavyi and Neale (1999), Bisby et al. (2005), De Lorenzis and Teng (2007), da Silva and Adams (2007), Gamage et al. (2006), Garlock et al. (2012), Karbhari et al. (2003), Kim et al. (2005), Kim and Heffernan (2008), Kim et al. (2008), Kim and Rahman (2010), Kotynia (2007), Smith and Teng (2001), Teng et al. 2003, Malek et al. (1998), Williams et al. (2006)