MPC- 410
January 1, 2013- December 31, 2013

Project Title:
Predicting Fatigue Service Life Extension of RC Bridges with Externally Bonded CFRP Repairs

University:
Colorado State University

Principal Investigators:
Rebecca Atadero
Assistant Professor
rebecca.atadero@ colostate.edu
970-491-3584

Research Needs:
Externally bonded CFRP (carbon fiber reinforced polymer) is being applied as a repair technique to extend the useful life and enhance the safety of existing reinforced concrete bridges. The nature of bridge loading means that fatigue loading as well as static strength is an important design consideration. Numerous studies have considered the fatigue performance of RC beams with internal steel reinforcement strengthened with externally bonded FRP (typically carbon fibers, but in some cases glass). The review by Kim and Heffernan (2008) summarizes many of these studies. Concrete beams with externally bonded FRP subject to fatigue loads will most often fail due to fracture of the steel reinforcing bars followed quickly by debonding of the FRP from the concrete (Kim and Heffernan, 2008). When FRP is applied as an external strengthening mechanism, tensile loads are shared between the steel and FRP, and the stresses in the reinforcing steel are lower for a beam with externally bonded FRP than one without. Thus the application of FRP would be expected to extend the fatigue life of the strengthened structure by reducing the level of stress in the reinforcing steel. In their analysis of existing work Kim and Heffernan found that most studies reached this conclusion. The amount of increase can vary widely depending on the specific loading conditions and quantities such as the amount of steel and FRP. In the work surveyed, fatigue lives for strengthened beams ranged from 2.1 to 95 times the fatigue life of unstrengthened control beams and for load ranges between 30 and 50 percent of the yield strength of the reinforcement, fatigue damage did not seem to be accumulating. (Kim and Heffernan, 2008).

Although past laboratory studies have proven FRP effective at extending the fatigue life of RC beams, there remains a great deal of uncertainty about the amount of fatigue life extension and the need to consider realistic conditions for an existing structure. In the majority of situations where fatigue life is a concern FRP will be applied to a bridge that has already been in service for many years. These structures will have an existing history of cyclic loading and may be showing other signs of deterioration such as cracking and corrosion. Fatigue life of RC beams with existing damage has been considered in only a limited way, for example, recent studies by Al-Hammoud, Soudki and Topper (2011) and Davalos et.al. (2010) considered the effectiveness of FRP repair and anchorage for corroded steel reinforcement. Additional work in this area is

needed to provide designers with guidance allowing them to predict the effect of a FRP strengthening application on extending the fatigue life of an existing structure and indicating how different design choices such as amount of FRP, will affect that prediction.

Research Objectives:
The objective of this project is to collect data allowing for the development of a preliminary model to allow designers to consider the existing condition and past loading history of a RC bridge girder and properties of a CFRP repair to predict the amount of fatigue life extension provided by the CFRP repair.

Research Methods:
This research project will start by carefully considering the results of existing fatigue studies on CFRP repaired beams to identify trends in terms of how the type of loading, type of repair, and beam condition contribute to fatigue life extension. These trends will be used to develop an initial model – or at least some approximate guidance for estimating fatigue life extension. The limitations of this model and knowledge gaps in existing research will be identified for further experimental and analytical study. RC beam specimens representing aged bridge girders will be manufactured. The beams constructed for this research will be as large as feasible for lab conditions. Some of these specimens will be tested to failure under static and fatigue loading as control specimens, others will be strengthened with different CFRP repair schemes and tested under static and fatigue loading. The experimental data will be used to plot a preliminary S-N curve. Finite element models will be developed and calibrated to the results of the static loading. These models will then be combined with the experimental results to develop the preliminary model for prediction of fatigue life extension. This project will be conducted in cooperation with another MPC project at CSU: Fatigue Strength of CFRP-repaired Reinforced Concrete Bridge Girders under Service Temperature, PI: Hussam Mahmoud, in order to explore several aspects of the research question.

Expected Outcomes:
This project will result in experimental data that will enhance understanding of the effect of externally bonded CFRP repair on the fatigue life of existing RC bridge girders. The project will produce a preliminary model to predict the fatigue life extension afforded by the externally bonded CFRP. This model can be used by designers to make more educated design decisions and will serve as the basis for further research. The project team will present this model to DOT engineers and publish findings in scholarly journals.

Relevance to Strategic Goals:
Externally bonded CFRP is an attractive repair option because it is lightweight with high specific strength and stiffness, it can readily conform to the geometry of an existing structure, it can often be applied with only limited traffic disruption, and it does not corrode as a steel repair might. These advantages mean that CFRP can be an important tool in extending the safe and useful life of existing structures, thereby helping to achieve **a state of good repair** for US transportation infrastructure**.** However, in order to take best advantage of the material, designers need more information about its effectiveness – particularly with respect to fatigue performance of the strengthened structure. The knowledge gained through this project will help to improve and promote the use of CFRP.

Educational Benefits:
A graduate student will be hired as a research assistant to work on this project. Although the findings of the research will not be directly used in a specific class, they will inform class activities in courses taught by the investigators. For example, Dr. Atadero teaches an undergraduate courses in civil engineering materials and reinforced concrete design.

Work Plan:

Task 1. Literature Review to Establish Preliminary Model and Knowledge Gaps
There have been numerous tests to consider the fatigue life of RC beams strengthened with externally bonded FRP. While these tests almost universally indicate the ability of FRP to extend the fatigue life, the amount of extension is highly variable. This project will start by considering these existing studies, identifying trends between the variables and proposing a model of some form that represents these trends. Then knowledge gaps that could be filled to make the models more complete will be identified for further experimental and analytical study.

Task 2. Experimental Specimens
The literature review will also be used to describe the condition of existing RC girders, so that beam specimens can be constructed to represent damaged girders. The included damage is likely to include reinforcing steel with notches introduced, concrete with lower strengths, and pre-cracking. After the damaged specimens are constructed some of the specimens will be reinforced with externally bonded CFRP.

Task 3. Testing of Specimens
Specimens will be tested in the Structural Engineering Laboratory at the CSU Engineering Research Center. Beams with and without externally bonded FRP will be tested to failure. Some beams will be tested under static loading while others are tested under fatigue loading. The fatigue loading regimen will be established to represent traffic loading of bridge elements as closely as possible.

Task 4. Finite Element Modeling
The results of the static tests will be used to develop and calibrate finite element models. With stochastic inputs these models can then be used to extend the available data for development of the fatigue life model.

Task 5. Refinement of Preliminary Model to Predict Fatigue Life Extension
The data collected from the experimental tests and finite element modeling will be used to refine the preliminary model developed in Task 1 to relate the fatigue life extension to parameters such as the past loading history, ratio of cyclic loading to static strength, and configuration of CFRP repair will be created.

Task 6: Reporting and Dissemination
A final report will be produced describing the results of the research. A TLN seminar will be developed and presented. This seminar will be based on the research results most relevant to practicing engineers. The results will also be disseminated through publication in scholarly journals such as the Transportation Research Record or Journals of Bridge Engineering or Composites for Construction.

	Months								
Task	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
1									

2									
3									
4									
5									
6									

Project Cost:
Total Project Costs: $129,424
MPC Funds Requested: $ 64,712
Matching Funds: $ 64,712
Source of Matching Funds: PI time and effort

TRB Keywords: Reinforced Concrete Bridges, Fatigue Tests, Fiber reinforced composites

References:
Al-Hammoud, R., Soudki, K. and Topper, T.H. (2011) "Fatigue Flexural Behavior of Corroded Reinforced Concrete Beams Repaired with CFRP Sheets," *Journal of Composites for Construction*, 15(1), 42-51.

Davalos, J. F., Chen, A., Ray, I., Justice, A., and Anderson,M. (2010a). "District 3-0 investigation of fiberwrap technology for bridge repair and rehabilitation (phase-III)." FHWA-PA-2010-002-510401-014, Pennsylvania Dept. of Transportation, ⟨http://trid.trb.org/view.aspx?id=915714⟩.

Kim, Y.J. and Heffernan, P.J. (2008) "Fatigue Behavior of Externally Strengthened Concrete Beams with Fiber-Reinforced Polymers: State of the Art." *Journal of Composites for Construction,* 12(3), 246-256.