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DESIGN STRENGTH OF CONCRETE BRIDGE GIRDERS STRENGTHENED WITH CFRP LAMINATES

PROBLEM STATEMENT

Externally bonded carbon fiber reinforced polymer (CFRP) laminates are a feasible and economical alternative to traditional methods for strengthening and stiffening deficient reinforced concrete and prestressed concrete girders. Although extensive research has already been undertaken to investigate both short-term and long-term behavior of CFRP strengthened bridge girders, the majority of this work has been experimental in nature. Furthermore, while some studies have proposed design models and methodologies to identify the necessary number of laminates to achieve a target strength or stiffness, many important design issues remain unresolved.

OBJECTIVES

The overall objective of this research is to use state-of-the-art numerical techniques to resolve some of the open questions; that is, to provide information that complements existing data and that will be useful for formulating comprehensive design guidelines for CFRP rehabilitation. Specific objectives include the following:

- Develop analytical models for simulating the static response and accelerated fatigue behavior of concrete beams strengthened with CFRP laminates. Use the developed models to investigate the static and the fatigue behavior of CFRP strengthened beams.

- Investigate the short-term tensile strength of CFRP laminates and establish a relationship between the fiber tensile strength and the tensile strength of CFRP laminates attached to a concrete girder. Such a relationship facilitates the design process and enables structural engineers to estimate laminate strength from fiber properties published by the manufacturer.

- Develop resistance models for reinforced and prestressed concrete bridge girders flexurally strengthened with externally bonded CFRP laminates. Use the developed models to calculate the probability of failure, the reliability index, and the flexural resistance factor of CFRP strengthened cross-sections.

FINDINGS AND CONCLUSIONS

Models for simulating the static and the accelerated fatigue behavior of reinforced and prestressed concrete beams strengthened with CFRP were developed. The models are based on the fiber section technique and account for the nonlinear time-dependent behavior of concrete, steel yielding, and rupture of CFRP laminates. Calculations take into consideration the effect of size on the tensile strength of CFRP laminates.

The models were implemented in a MatLab computer program, T-DACS (Time-Dependent Analysis of Composite Sections), and they were verified and exercised by comparing the analytical results to data from several experimental investigations. A second computer program, MACS (Monotonic Analysis of Composite Sections), was developed to run only the static portion of the developed models within a Visual Basic environment. MACS is user-friendly and features an easy to use graphical user interface.

The developed computer programs were used to investigate the static and the fatigue responses of RC and PSC concrete girders strengthened with CFRP laminates. Additional Monte-Carlo simulations (120,000 runs) were conducted, using MACS, to develop resistance models for both reinforced and prestressed concrete bridge girders flexurally strengthened with CFRP laminates. The resistance models were used to calculate the probability of flexural failure and flexural reliability index of CFRP strengthened cross-sections. The first order reliability method was employed to calibrate the proposed flexural resistance factors for a broad range of design variables.

The most important findings and conclusions from this work include the following:

- The use of coupons to obtain the in-situ strength of CFRP laminates can lead to unconservative estimates of strength if the size effect is not properly considered.

- The short-term tensile strength of CFRP laminates can be calculated by applying the Weibull Theory. Two steps are needed to compute the short-term tensile strength. The first step accounts for the size effect and predicts the tensile strength of a uniformly stressed volume that shares the size of the CFRP used in the real structure. The second step accounts for the effect of stress gradients.

- Cyclic fatigue leads to an internal redistribution of stresses similar to that obtained under static creep. To account for the increase in steel stresses due to cyclic fatigue, as well as shrinkage, creep under dead loads, and the variability in reinforcing steel strength, it is recommended that the service steel stress be limited such that $\sigma_s > 0.85 f_y$.

- The reliability index of CFRP strengthened RC cross-sections is greater than that of unstrengthened sections and increases with an increasing CFRP ratio. Although the reliability index improves with the addition of CFRP, the flexural resistance factor is recommended as ϕ =0.85, which is lower than that recommended by AASHTO-LRFD for RC sections under flexure. The reduced ϕ value results in a larger target reliability index than is normally specified, in recognition of the brittle nature of CFRP behavior.

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