II.6

Research Results

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repair of buildings & bridges with composites

ANALYSIS OF CONCRETE BRIDGE GIRDERS STRENGTHENED WITH FRP LAMINATES UNDER SERVICE AND EXTREME LOADING CONDITIONS

PROJECT NO. II.6

SUMMARY

The project is a continuation from fiscal year 2004-2005. Previous work aimed at developing new analytical tools for analysis of RC beams strengthened with FRP laminates. The models were used to analyze several test specimens of RC beams and to investigate the corresponding failure mode, and whether it is due to CFRP fracture, debonding, or concrete crushing.

Current work focused on using the existing model to conduct a thorough analytical evaluation of current ACI-440 design specifications for RC beams strengthened with CFRP laminates. Based on these studies, a new equation for the limitation set on the strength of FRP sheets in order to prevent debonding failure has been proposed. In addition, the model has been expanded to simulate the behavior of concrete girders reinforced with FRP bars. In this case, analytical studies have been performed in order to conduct an evaluation of current ACI-440 design equations for development lengths. The effect of different parameters such as concrete strength, confinement, FRP strength, and bar diameter has been investigated and a new equation for development lengths is currently being proposed for monotonic loading conditions. Currently, the study is also focusing on evaluation of design specifications under cyclic loading conditions, typical of seismic excitations.

Note: For additional information on this project please visit : http://campus.umr.edu/rb2c/

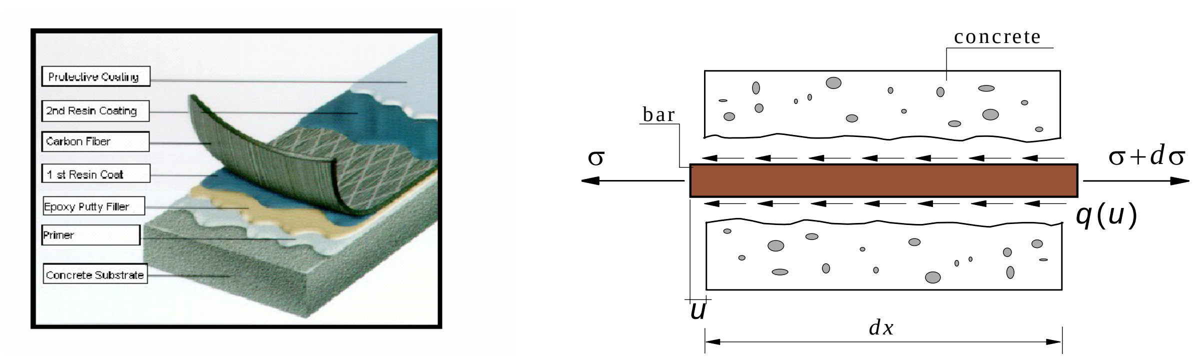

Figure 1. Beams Strengthened with FRP

BACKGROUND

Externally bonded carbon fiber reinforced polymer (FRP) laminates are a feasible and economical alternative to traditional methods for strengthening and stiffening deficient reinforced concrete and prestressed concrete girders. The behavior of bond between FRP and concrete is the key factor controlling the behavior of concrete structures that are strengthened with FRP composites. Several experiments showed that debonding failure occurs frequently before FRP rupture, and therefore the FRP strength can not be fully utilized. For design accuracy, the FRP strength must be reduce due to the debonding failure.

This research analyzes the effect of the strengthening technique on the response and failure modes of RC beams. A nonlinear RC beam element model with bond- slip between the concrete and the FRP laminates is used to study the reduction factor of FRP tensile strength of simply supported strengthened RC beams. This reduction factor is affected by the following parameters: concrete strength, thickness of FRP, modulus of FRP, bond stress between FRP and concrete interface, width of FRP laminate and FRP bond area. Two different types of bond-slip models have been used in this work: In the first, a linear model up to the point of bond failure was used. This approach is assumed to be conservative because it yielded results that are smaller than the values given by ACI-440. In the second, the bond ductility is considered through a three-stage multi-linear model up to the point of failure. This approach yielded un-conservative results with values greater than those given by ACI-440. More than 160 beams were analyzed, including beams with both rectangular and T-sections, to develop a new equation for reduction factors of FRP tensile strength due to debonding failure.

In addition, the model has been expanded to simulate the behavior of concrete girders reinforced with FRP bars. In this case, analytical studies have been performed in order to conduct an evaluation of current ACI-440 design equations for development lengths. The effect of different parameters such as concrete strength, confinement, FRP strength, and bar diameter has been investigated and a new equation for development lengths has been proposed for monotonic loading conditions. Currently, the study is focusing on evaluation of design specifications under cyclic loading conditions, typical of seismic excitations.

OBJECTIVE

To evaluate current design specifications for FRP strength reduction due to debonding failure in concrete girders strengthened with FRP laminates, and development lengths for girders reinforced with FRP bars. A newly developed finite element analysis program is used to conduct both studies. Statistical analysis of a large ensemble of specimens is conducted in both cases in order to evaluate their corresponding structural behavior.

RESEARCH APPROACH

A new nonlinear model for analysis of concrete girders strengthened with FRP laminates or reinforced with FRP bars was developed. The model was based on section discretization into fibers. Nonlinear constitutive material laws were assigned to the concrete, steel, FRP fibers, and interfacial bond between FRP and concrete. The model was used to conduct statistical studies on representative specimens in order to evaluate current design guidelines.

The results of the research showed that not only the thickness and modulus of FRP, as suggested by ACI-440, play an important role in the expression for the reduction factor due to debonding failure, but also other parameters, such as the width of the FRP strip, the bond stress between FRP and concrete, the concrete strength and the value of the bonded area, strongly affect the value of the reduction factor.

Based on the cases analyzed for beams with rectangular and T sections, a new design equation is derived for the reduction factor k_m.

For beams with rectangular sections analyzed using a brittle bond model, the equation of the reduction factor k_m is as follows:

$$k_m = \alpha \cdot E_f \cdot t^{-0.8} \cdot \sqrt{f'_c \cdot B} \cdot L'^{\,2.4} \cdot w^{0.526}$$

where E_f is the FRP modulus, B is the bond strength, f'_c is the concrete compressive strength are evaluated in MPa, t is the FRP thickness in mm, L' is the length of the FRP sheet in m and w is the ratio of width of FRP plate to width of concrete beam. The factor α equals 0.000733.

For beams with rectangular sections analyzed with a ductile bond model, the equation of the reduction factor k_m is as follows:

$$k_m = \alpha \cdot E_f^{\,0.32} \cdot f'^{\,0.4}_c \cdot (B/t)^{0.6} \cdot L'^{\,0.05} \cdot w^{0.15}$$

In this case, the factor α equals 0.028418.

For the beams having a T section and analyzed using a brittle bond model, the equation of the reduction factor k_m is given by the following expression:

$$k_m = \alpha \cdot E_f^{\,0.32} \cdot f'^{\,0.4}_c \cdot (B/t)^{0.6} \cdot L'^{\,0.05} \cdot w^{0.15}$$

The factor of α here equals 0.422.

For T sections analyzed using a ductile bond model, the results show that the reduction factor is not a key role, but a value of 0.9 is recommended for a conservative design. The proposed equations for rectangular sections are plotted in Figure (2) and compared with the ACI-440 equations.

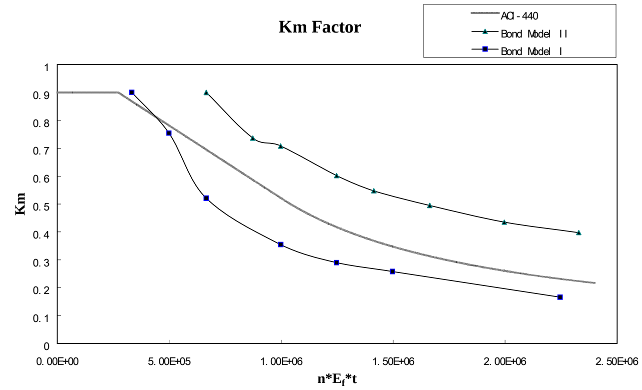

Figure 2. Reduction Factor k_m

The study resulted also in the following conclusions:

- Thinner layers of FRP plates tend to reduce the bond stress at the concrete-FRP interface, allowing a more efficient use of the FRP strength.
- FRP plate stiffness significantly affects the strengthened beam response and failure mode. A series of comparison of beams strengthened in flexure with plates of different stiffnesses and equal ultimate tensile strength showed that more rigid plates tend to have higher reduction factors.
- FRP strengthened RC beams with higher concrete strength tend to perform better than those with lower concrete strength. However, for the T section strengthened beams, the concrete strength almost had no significant influence on the reduction factor.
- As evidenced by the numerical studies, larger ultimate bond stress allows a more efficient use of the FRP plate strength. Once the ultimate bond stress exceeds a specific value, the failure mode tends to occur due to concrete failure or FRP rupture.
- The FRP plate width influences the failure mode of the strengthened beams. Wider plates with larger cross sections tend to allow concrete failure to occur

before debonding failure. For the cases of debonding failure, wider plates tend to have higher reduction factors.

- The FRP plate length plays a significant role in the failure mode of strengthened RC beams. In short FRP plates, the peak bond stress is at the plate end, while longer FRP plates allow steel yielding to penetrate, thus causing larger bond stresses under the point loads. Sufficient FRP plate length is necessary to avoid debonding failure mode.
- By comparing the analyses of beams with rectangular and T sections, the beams with T sections have more efficient use of the FRP plate strength due to the lager moment of inertia.

CONCRETE GIRDERS REINFORCED WITH FRP BARS

Analytical studies were performed for concrete girders reinforced with FRP bars in order to evaluate current ACI-440 design equations for development lengths. The effect of different parameters such as concrete strength, confinement, FRP strength, and bar diameter has been investigated and a new equation for development lengths is currently being proposed for monotonic loading conditions. As an example, Figure (3) shows the load-deformation response of a specimen with a 30" embedment length and reinforced with a #4 FRP bar. From the figure, the onset of failure starts at an end-slip value of 0.4". Further studies are currently being conducted in order to investigate failure due to bond pull-out.

CONCLUSIONS

New analytical models for concrete girders strengthened with FRP plates and bars were developed. The models were used to conduct simulations on a large number of concrete specimens in order to evaluate current design guidelines. Current work focused on monotonic loading conditions only, but cyclic loading conditions will be also investigated.

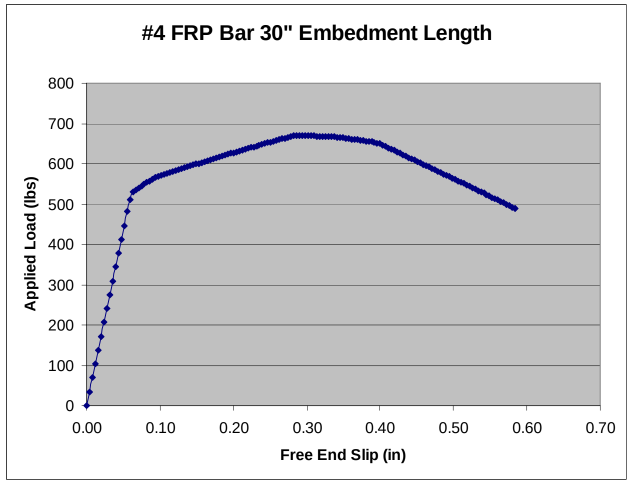

Figure 3. Load-Deformation Behavior of Specimen Reinforced with FRP Bar

WANT MORE INFORMATION?

Details on this work and additional data can be found in the final report.

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