

BOND BEHAVIOR OF CFRP STRENGTHENED FULL-SCALE PRESTRESSED CONCRETE BRIDGE GIRDERS

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ABSTRACT

This paper presents the bond characteristics of carbon fiber reinforced polymer (CFRP) flexural strengthening systems for prestressed concrete. Two large-scale prestressed concrete bridge girders were strengthened with externally bonded CFRP precured strips and tested monotonically to failure. Both girders failed due to FRP debonding propagating from intermediate flexural cracks. The main test variable considered in the experimental program was the amount of FRP debonding mitigation provided. Test results show that using transverse anchorage wraps along the length of the girder can increase the debonding strains of the longitudinal CFRP strips by over 20 percent. The full program with testing of five girders is described along with preliminary analytical results.

KEYWORDS

Reinforced concrete, prestressed concrete, FRP, debonding.

1. INTRODUCTION

Strengthening concrete structures with CFRP materials is becoming attractive solution to strengthen existing bridges. While the flexural failure modes due to concrete crushing and FRP rupture are well known (Rosenboom et al., 2006), the bond behavior of large-scale plated structures can still not be predicted with confidence. For long-span FRP plated reinforced concrete, with the longitudinal strengthening extending to near the supports, the common failure mode is interface debonding propagating from flexural cracks around midspan towards the supports. Various analytical models have been proposed to predict the strain in the FRP at debonding including fracture based models (Teng et al., 2000) and models based on mechanics (Sebastian 2002).

As part of an extensive research project funded by the North Carolina Department of Transportation examining the cost-effectiveness and value engineering of CFRP repair and strengthening for prestressed concrete, a study has been initiated to determine the bond characteristics of CFRP strengthening systems for prestressed concrete. Two girders were strengthened with CFRP precured strips and tested to failure, which occurred due to FRP debonding propagating from the midspan region. The main test variable examined was the amount of debonding mitigation provided. Test results show that debonding strain could be increased with a properly designed anchorage system.

2. EXPERIMENTAL PROGRAM

2.1 Test Girders and Strengthening Configuration

Two 45 year-old 9140 mm long prestressed concrete test girders were extracted from a bridge and delivered in good condition prior to strengthening with no visible cracks. Both girders were prestressed with ten 1723 MPa stress-relieved strands with an average prestressing force of 71.7 kN per strand measured experimentally. The strand configuration consisted of both straight and harped prestressing strands as shown in Figure 1. Concrete core samples were taken after testing and the average concrete compressive strength for both girders was 61.4 MPa. For both girders the main longitudinal CFRP strengthening was two CFRP precured strips ($A_{FRP}=119 \text{ mm}^2$), having a

modulus of elasticity of 164.8 GPa and a tensile strength of 2800 MPa. The strips were bonded to the concrete with a high-modulus, high-strength 2-part structural adhesive with a shear modulus of 1.03 GPa provided by the manufacturer. Transverse wet lay-up CFRP sheet “U-wraps” 152 mm wide were provided on each web at a spacing of 914 mm along the length of girder EB1S. Similar U-wraps were provided for girder EB1SB on *one side only*, to study the bond characteristics without U-wraps. The 1.3 mm thick U-wrap material was also tested, and the modulus of elasticity was found to be 51.7 GPa with an ultimate tensile strength of 710 MPa. The CFRP was installed according to NCHRP Report 514 (Mirmiran et al. 2004) under simulated field conditions by experienced contractors.

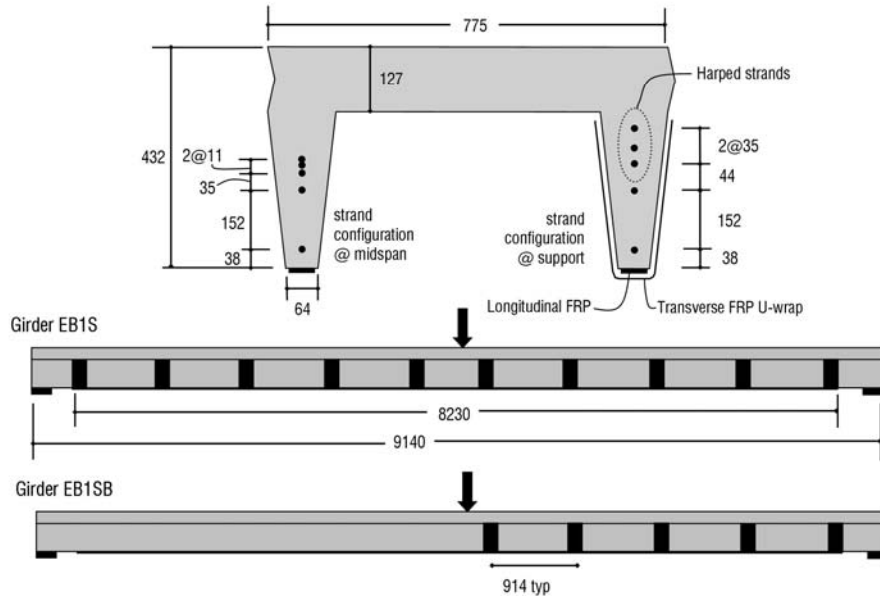


Figure 1: Girder cross-section and strengthening configuration (in mm)

2.2 Test Setup and Instrumentation

The girders were supported by concrete blocks and tested using a 490 kN actuator in 3-point bending with 216 mm elastomeric bearing pads provided on each side. Displacement was measured through the use of potentiometers at midspan and at the support sections. Strain gauges were used to measure concrete compressive strain and were also applied to the longitudinal CFRP along the length of the girder to measure FRP tensile strains for girder EB1SB. Each girder was loaded up to the cracking load then unloaded to determine the effective prestressing force, and then the girder was loaded at a rate of 2.5 mm per minute up to failure.

3. TEST RESULTS

The cracking load of girder EB1S was 57 kN. The effective prestress force per strand, determined from crack re-opening load, was found to be 72.1 kN. At yielding of the prestressing strands (at a load of 102.3 kN), numerous flexural cracks had formed around midspan at a stabilized spacing of approximately 100 mm. Near failure the flexural cracks bifurcated at the bottom of the web due to the plating constraint. Failure occurred due to intermediate crack debonding which propagated from the midspan towards the supports at a load level of 176 kN. The experimentally measured debonding strain at failure was 0.0122 mm/mm, 72 percent of the ultimate strain measured from tensile tests. The interface along which the debonding propagated was mixed: in certain locations around midspan the failure surface was the concrete paste layer just above the longitudinal CFRP, whereas closer to the supports the failure surface was either at the CFRP-adhesive interface or within the strip (interlaminar failure).

The cracking load of girder EB1SB, with debonding mitigation on one side only, was 57.8 kN. From the crack re-opening load, the effective prestress force was determined to be 71.2 kN. The behavior of this girder was similar to

girder EB1S before and after cracking and yielding of the prestressing strands, which indicates that the presence of the U-wraps did not influence flexural cracking. The girder failed due to intermediate crack debonding at a load level of 161.9 kN as shown in Figure 2b, with an experimentally measured debonding strain of 0.0100 mm/mm, which is 59 percent of the tensile strength of the CFRP. The debonding initiated near midspan on the side without U-wraps and propagated towards the support. The failure interface initially was the concrete paste layer at the bottom of the web and then shifted to the CFRP-adhesive interface towards the supports. The increase in FRP strain at debonding due to the presence of the U-wraps at 914 mm spacing was 22 percent higher. The load versus deflection curves for girders EB1S and EB1SB along with a control girder described in Rosenboom et al. (2005) are shown in Figure 2a. The increase in ultimate load compared to the control girder was 19.3 percent for girder EB1SB and 9.6 percent for girder EB1S. The measured axial tensile strain in the externally bonded CFRP strip versus the distance along the beam is shown in Figure 3a.

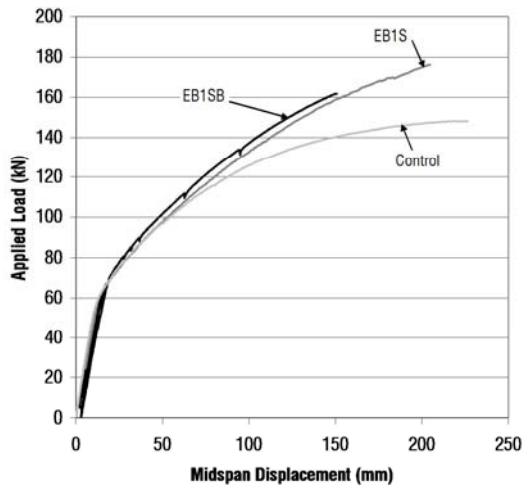


Figure 2a: Load-deflection behavior of tested girders

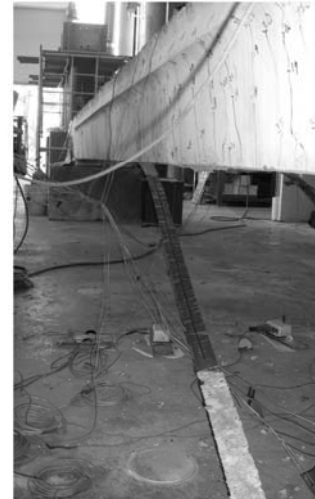


Figure 2b: debonding failure of girder EB1SB

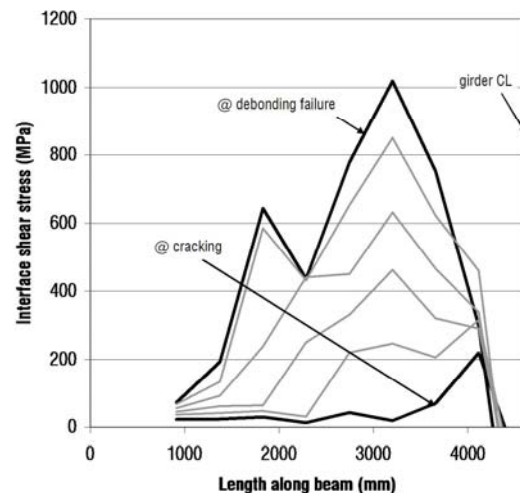
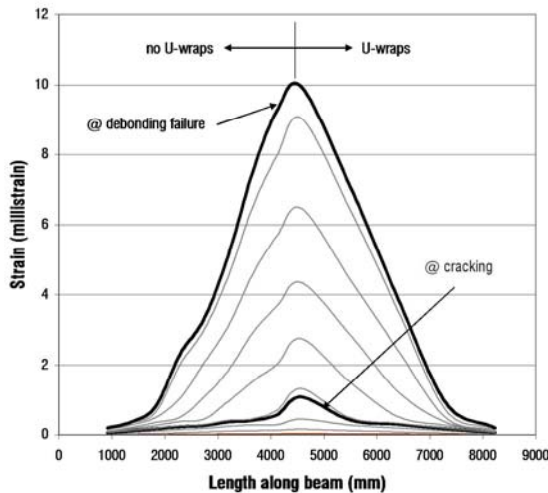


Figure 3a: Length along beam v. tensile strain in FRP Figure 3b: Length along beam v. interface shear stress

4. ANALYTICAL MODELING

There are several behaviors of prestressed concrete that make strengthening with externally bonded CFRP is more effective than regular reinforced concrete. The effective prestress force in the beam imposes an initial compressive strain in the beam soffit that is present regardless of whether the beam is propped during strengthening. This initial strain in the beam soffit is directly translated into extra CFRP force that can be developed prior to debonding failure compared to what is traditionally developed for a reinforced concrete beam. Most of the developed models assume that the member is already cracked at the time of strengthening, which is rare for typical prestressed concrete

members. Even if the prestressed concrete member has been subjected to overloading conditions during its service life and is cracked at the time of strengthening, the prestressing force will promote crack closure increasing the debonding strains of the CFRP at failure.

From equilibrium of the axial forces along the length of a plated beam the interface shear stress (τ_i) can be determined by the following equation:

$$\tau_i = t_p E_p \frac{d\varepsilon_p}{dx}$$

where t_p and E_p are the thickness and modulus of elasticity of the plate and ε_p is the axial strain in the plate along the length of the beam, x . Application of this equation to the measured strain values for girder EB1SB are shown in Figure 3b. The predicted strain gradient in the externally bonded FRP material along the beam can be found by conducting a moment-curvature analysis of the section assuming flexural failure. Since the axial strain gradient is an important factor affecting the bond behavior, the stress-strain characteristics of the longitudinal steel reinforcement becomes very important. Stress relieved prestressing strands, with a less abrupt transition from elastic to plastic behavior than regular reinforcing steel, place less of a demand on the interface shear stress in this transitional zone along the beam. At the plate termination point a different state of stress exists, with shear and normal stresses acting together due to many factors including the abrupt termination of the plate. At a large distance away from the termination point, peeling stresses become smaller in magnitude, and are influenced mainly by aggregate interlock once debonding propagates. Therefore, an assumption can be made that intermediate crack debonding is mainly due to mode II interface shearing stresses, not an interaction between shear and normal stresses.

Future tests will include three additional prestressed concrete C-Channel girders to examine the effect of the number of CFRP layers and the type of CFRP material (pre-cured or wet lay-up). In each case the tensile strains along the length of the girder will be measured and used to identify failure criteria to an analytical model which will be presented at the conference.

5. CONCLUSIONS

As part of a comprehensive research project sponsored by the North Carolina Department of Transportation, five prestressed concrete bridge girders are considered to evaluate the bond behavior and performance of CFRP strengthening systems. Test variables include the amount of CFRP material, type of CFRP system (pre-cured or wet lay-up), and presence of transverse U-wrap anchorage. The test results of two girders are presented in this paper showing that increases in debonding strain of 22 percent can be achieved through the use of transverse wet lay-up CFRP U-wrap anchorage.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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