FINITE ELEMENT EVALUATION OF THE EFFECTS OF LATERAL ANCHORAGE STRIPS ON THE BEHAVIOR OF CFRP-STRENGTHENED RC BEAMS

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ABSTRACT

In CFRP-strengthened RC beams, interfacial behavior between the CFRP strengthening sheets and the concrete substrate—although an important issue that could significantly affect the behavior of the beams—has not been sufficiently characterized. In this paper, an investigation of the interface and the effects of lateral anchorage strips on the flexural behavior of CFRP-strengthened RC beams, using a three-dimensional non-linear finite element model, is presented. The model uses data from a related experimental study (Zhao et al., 2005) to calibrate properties such as the interface shear strength and stiffness, which cannot be easily obtained through other means. Then, these calibrated properties are used in predicting behavior of other beams. The result of this study demonstrated that (1) lateral anchorage strips had a significant impact on the flexural behavior of CFRP-strengthened RC beams, and (2) various anchorage designs led to different load-deflection behavior and failure modes. Good agreement between the results from the analysis and experimental tests was obtained. The same model is being used in an ongoing project to further test its applicability.

KEYWORDS

CFRP, RC beams, strengthening, interfacial stresses, finite element analysis.

INTRODUCTION

Externally bonding Carbon Fiber Composite Polymer (CFRP) onto existing RC structures is gaining popularity among researchers and engineers in recent years as an effective way of strengthening and rehabilitation of structures. While it has been widely reported that this technology can improve a structure's load carrying capacity, it is also noted that the failure mode of strengthened structures will often become brittle due to debonding of the CFRP sheets. Triantaﬁllou et al. (2001) suggested that FRP strengthened members have difficulty satisfying ductility conditions while the strength factor of safety can be achieved. One of the methods that can prevent or reduce the risk of debonding is to provide transverse anchorage strips to the bottom CFRP reinforcement strips. Sharif et al. (1994) used mechanical fasteners to achieve full anchorage at the FRP plate ends, which led to concrete crushing at failure. Spadea (1998) used U-wraps (carbon fabric strips laid in the circumferential direction) to confine the plate end debonding. The failure was from debonding of the U-wraps due to insufficient anchoring effect. Teng et al. (2000) inserted glass fibers through the longitudinal fiber bundles (tows) of the fabric and into pre-drilled and pre-filled holes in concrete. This method integrated the anchorage with the layup and the anchorage was able to arrest the propagation of cracks. Naaman, et al. (2001) concluded that U-wraps and extended end anchorages do not improve loads or deflection and proposed that the strength increase due to FRP shall not be accounted for more than 20% of the nominal flexural strength of RC beams. Sagawa et al (2001) experimented with 45° U-wraps and found that full anchorage, to the detriment of the structural behavior, may in some cases reduce the deflection capacity of RC beams. Zhao et al., (2005) experimentally evaluated six beams and concluded that different anchorage configurations will yield different load-deflection response and failure mechanisms. The work presented in this paper, which is an analytical extension of Zhao et al., (2005), utilizes the finite element method to characterize the effect of the transverse anchorage strips and the interface properties on the overall behavior of CFRP-strengthened beams.
EXPERIMENTAL STUDY

Specimens Types

The experimental program (Zhao, et al. 2005) included six identical RC beams with various CFRP strengthening designs, as seen in Figure 1:

- **A**—control beam, which has no CFRP
- **B**—CFRP was attached only to the bottom surface of the beam
- **C, D, E, and F**—various anchorage strips in addition to the bottom CFRP as in B

The beams were loaded with a 4-point bending configuration with a span of 3.2 m and distance between loads of 0.31 m. All beams were 0.28-m-tall, 0.15-m-wide, and 3.35-m-long. The longitudinal reinforcement consists of three No.16 bars (16-mm-dia.) for tension and two No. 10 bars (10-mm-dia.) for compression, equivalent to reinforcement ratios of $\rho=0.014$ and $\rho'=0.0033$, respectively. Shear reinforcement was sufficiently provided.

Materials Properties

The bottom FRP laminate consisted of 5 layers of unidirectional carbon fiber reinforced polymer (CFRP) fabric. The longest anchorage strips had two layers of the same material and the rest had one layer. The CFRP composite had the following nominal properties, calculated using the modified rule of mixture method (Tsai, 1964), assuming the fiber misalignment factor $k=0.9$:

- Modulus of Elasticity, $E_1$ (GPa): 100
- In-plane shear modulus, $G_{12}$ (GPa): 5.6
- Poisson’s ratio, $\nu_{12}$: 0.23
- Ply thickness, $t$ (mm): 0.56
- Fiber volume fraction (%): 46

The concrete had a 44.8 MPa 28-day strength. Grade 60 rebar with a yielding strength of 455 MPa (from testing) was used in all beams.

TEST RESULTS

It was experimentally determined that different anchorage strip configurations significantly affected the overall strength, failure mechanisms, and the ductility of the beams. Some of the test observations are summarized as follows, as well as in Table 1.

- The control beam demonstrated a ductile behavior, failing by concrete crushing only after reaching a significant deflection of 42 mm.
- Specimen B had a strength increase of 16% over the control beam (A), but failed at a small deflection of 22 mm due to CFRP debonding. There was virtually no ductility.
- Specimen C, which had 45° anchorage strips, demonstrated the highest strength at 54% over the control beam and maintained approximately the same deflection at failure as the control beam. No debonding was observed.
- Specimens D, E, and F all showed some strength increase and, more importantly, higher ductility over Specimen B, which has no anchorage strips. Debonding occurred in a more gradual manner than Specimen B. While the amount of strength increase for these three specimens were almost identical (30%), their deflection capacity at failure was noticeably different:
  - Specimen D, which has the longer 90° anchorage strips at the ends, had a larger deflection capacity at 27 mm.
  - Specimen E, which has the 45° end anchorage strips, had the largest deflection at 33 mm. This is consistent with the observation made on Specimen C that 45° anchorage strips are effective in preventing debonding.
  - Specimen F, which had small anchorage strips at the ends, had the smallest deflection of 22 mm.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (kN)</td>
<td>94</td>
<td>109</td>
<td>145</td>
<td>124</td>
<td>123</td>
<td>121</td>
</tr>
<tr>
<td>% increase</td>
<td>N/A</td>
<td>16 %</td>
<td>54 %</td>
<td>32 %</td>
<td>31 %</td>
<td>29 %</td>
</tr>
<tr>
<td>Defl. at failure (mm)</td>
<td>42</td>
<td>22</td>
<td>38</td>
<td>27</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>Failure Modes</td>
<td>c.c.*</td>
<td>debond</td>
<td>c.c.</td>
<td>a.f./c.c.**</td>
<td>a.f./c.c.**</td>
<td>a.f./c.c.**</td>
</tr>
</tbody>
</table>

* c.c.=concrete crushing
** a.f./c.c.= shortest anchorage strip failure and then concrete crushing
It was also observed that, during the tests of Specimens D and F, in-plane shear failure of the shortest anchorage strip led to the first major load drops (Figure 1). This further caused progressive debonding of the bottom CFRP layers from the concrete substrate.

Finite Element Analysis

The Model

In this investigation a finite element model was created to simulate the load-deflection response of six RC beams with identical rectangular cross-sections and bottom CFRP reinforcement, as described in the previous section. The models, which are detailed by Perez (2005) using finite element software DIANA 8.1 (deWitte et al. 2002), are summarized as follows:

- Concrete elements: 20-node solid elements (CHX60)
- CFRP elements: 8-node (CQ40F) and 6-node (CT30F) flat shell elements (transversely isotropic)
- Steel reinforcement: embedded straight bars
- CFRP-to-concrete interface: interface elements CQ48I and CT36I, which handles interaction in the normal and shear directions, respectively

Due to symmetry, quarter models were utilized. Figure 3 shows the mesh of two selected specimens.
Material Properties

The Thorenfeldt model (Thorenfeldt et al. 1987), as shown in Figure 4a, was used for the compressive properties of the concrete. The Hordijk model (Hordijk et al. 1991), as shown in Figure 4b, was used for concrete tension. The ultimate tensile strain ($\varepsilon_{\text{ult}}$) was calculated by equating the fracture energy from the Hordijk et al.’s curve and shaded area, which is defined by the tensile strain of the concrete at its peak ($\varepsilon_t$) and the steel yielding strain ($\varepsilon_s$). The steel’s stress-strain relation is assumed to be as shown in Figure 4c, with the strain-hardening modulus $E_h$ to be calibrated. The FRP behavior was assumed linear elastic up to failure.

Interface Properties

The CFRP-to-concrete interface is the focus of this study. Based on the studies by Zhang et al. (2003), three zones as seen in Figure 5 could be differentiated when defining interfacial behavior. In the normal (out-of-plane) direction, all the zones behave as in Figure 6a. In the tangential direction, the behaviour differs depending on the zones.

- **Zone 1**: Substantial flexural cracks cause early debonding at the interface. Therefore, the shear or tangential strength was neglected for all the strengthened designs except for Specimen F, in which the anchorage closest to midspan effectively limits the crack growth.
- **Zone 2**: Due to diagonal crack opening, interfacial shear failure in this zone is often associated with the peel-off effect. Therefore, the shear behavior was assumed to be as in Figure 6b. The sudden drop after failure is associated with the peel-off effect which is illustrated in Figure 5.
- **Zone 3**: Not subjected to peel-off, the shear behavior in this zone (Figure 6c) is more ductile.
Figure 6 Interface behavior

(a) Normal
(b) Shear for Zone 2
(c) Shear for Zone 3

Figure 7 Load versus displacement comparisons

(a) Specimen A
(b) Specimen B
(c) Specimen C
(d) Specimen D
(e) Specimen E
(f) Specimen F
Calibration

Certain material properties are not easily obtainable through theoretical or experimental means. In this study, these property parameters were obtained by adjusting their value in the finite element model until the load-deflection response matches the experimental results. Table 2 describes the calibrated parameters and the specimens that were used for their calibrations. Figure 7a, b, and c show the load-deflection comparisons used in the calibration. Stress and strain comparisons were not performed in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated Values</th>
<th>Specimen</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete tensile strength, $f_t$</td>
<td>2.5 MPa</td>
<td>A</td>
<td>Figure 4b</td>
</tr>
<tr>
<td>Steel strain hardening modulus, $E_s$</td>
<td>13.5 GPa</td>
<td>A</td>
<td>Figure 4c</td>
</tr>
<tr>
<td>Interface shear strength, Zone 2, $\tau_{max}$</td>
<td>4.8 MPa</td>
<td>B</td>
<td>Figure 6b</td>
</tr>
<tr>
<td>Interface shear deformation limit, $\Delta s_{max}$</td>
<td>3.56 µm</td>
<td>B</td>
<td>Figure 6b and 6c</td>
</tr>
<tr>
<td>Interface shear deformation limit, $\Delta s_{ult}$</td>
<td>57.8 µm</td>
<td>C</td>
<td>Figure 6c</td>
</tr>
</tbody>
</table>

Prediction

Once these values are calibrated, they are used further in the prediction of the load-deflection response of Specimens D, E and F. As shown in Figure 7d, e, and f, excellent agreement was obtained in all cases.

CONCLUSIONS

Tests and analytical results demonstrated that the anchorage strips significantly affect the strength, failure mechanisms, and ductility of CFRP-strengthened RC beams.

The finite element model, using the calibrated material properties, can accurately predict the load-deflection behavior and failure mechanism of RC beams with transverse anchorage strips.

REFERENCES


