FRPRCS-14, Belfast - June 2019

Design Considerations of Anchored Carbon Fiber Reinforced Polymer (CFRP) Anchors

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Abstract

Externally applied carbon fiber reinforced polymer (CFRP) systems are ideal for rehabilitating transportation infrastructure due to its high tensile strength-to-weight ratio and speed of installation. However, CFRP material must be anchored adequately to develop its fracture capacity. In addition to developing the fracture strength of CFRP strips, CFRP anchors offer several advantages over other anchorage methods, such as system material compatibility, formability, and resilience to environmental factors.

The objectives of the presented study were to identify an anchor-to-strip cross-sectional area ratio that could develop the fracture strength of CFRP strips and to investigate the effect CFRP strip widths per anchor have on the performance of CFRP systems. Eight tests were conducted on concrete beams reinforced in flexure with anchored CFRP strips that were up to 10in. wide and up to two layers thick.

The experimental program found that an anchor-to-strip cross-sectional area ratio of 2.0 can develop the full facture strength of CFRP strips if an adequate anchor hole chamfer radius is provided. However, utilizing a larger CFRP strip area per anchors lowered the CFRP strip fracture stress.

Keywords: CFRP anchors, Rehabilitation, CFRP anchor design

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Introduction

Many transportation structures around the world are experiencing increased traffic volumes and loads. To mitigate structural deficiencies, the structural engineering community needs strengthening techniques that are cost-effective and can be applied with minimal disruption to the use of the existing structures.

Carbon fiber reinforced polymer (CFRP) materials are increasingly being used as externally bonded reinforcement to strengthen existing structures due to the material's high tensile strength-to-weight ratio and speed of installation. However, the CFRP must be adequately anchored to develop the full tensile capacity of the material. Without adequate anchorage, the material tends to debond from the concrete surface at less than half of the CFRP fracture strain [1].

For shear strengthening applications where the web of the member cannot be fully wrapped by the CFRP material, CFRP anchors can be utilized. The formability of the CFRP anchors allow them to overcome numerous geometric complications. The CFRP anchors also provide a material compatibility to the CFRP strips they anchor, which can mitigate the existence of stress concentrations at the anchor to strip interface.

Experimental Program

The objectives of the presented study were to identify an anchor-to-strip cross-sectional area ratio that could develop the fracture strength of CFRP strips and to investigate the effect CFRP strip widths per anchor have on the performance of CFRP systems. To achieve these objectives, eight longitudinally unreinforced beams were strengthened in flexure using anchored CFRP strips. The design of the test specimens, material properties, CFRP strengthening configurations, and testing setup are described in the following sections.

Test Specimen

The eight test specimens were 12in. wide, 12in. tall, and 68in. long. The length was selected such that the failure mode would be governed by flexure rather than shear.

Initially, the specimens were designed without any flexural or shear steel reinforcement. However, steel shear reinforcement was incorporated into the specimens after one test experienced an undesirable concrete shear failure. Furthermore, CFRP strips were placed on the sides of the specimens to further mitigate shear failures. Note that the steel and CFRP shear reinforcement was constructed such that the specimens remained flexurally unreinforced prior to the application of the anchored CFRP strips.

Prior to installing the CFRP strips and anchors, the concrete surfaces that was in contact with the CFRP strips were prepared by grinding off laitance and removing all dust and residue to improve the bond between the concrete and CFRP. Two holes were drilled at both ends of the tension face of the specimen for anchor installation. The anchor holes were rounded to a specific chamfer radius to avoid CFRP anchor rupture at the edge of the hole prior to fracturing the CFRP strip. A notch was cut at mid-span of the specimens to control the location of the concrete flexural cracking. Compressed air was used to remove the dust from the anchor holes and surface of the specimen. A typical CFRP layout can be seen in Figure 1.

Concrete and CFRP Material Properties

A ready mixed concrete supplier provided concrete mixtures with test day strengths ranging from approximately 3600 psi to 9900 psi. Research conducted by Jirsa et al. [2] found that the concrete strength did not affect the fracture strength of the CFRP strips or the rupture strength of the CFRP anchors.
The CFRP strip laminate used in this study had unidirectional fibers and exhibited a linear-elastic behavior until fracture. The manufacture reported the following laminate properties (parallel to the fiber direction): an expected tensile stress of 143ksi, an expected tensile modulus of 13,900ksi, an expected ultimate elongation at fracture of 1%, and a 0.02in. laminate thickness.

CFRP Strengthening Configurations

A summary of the test configurations is provided in Table 1.

Table 1: Test parameters and results

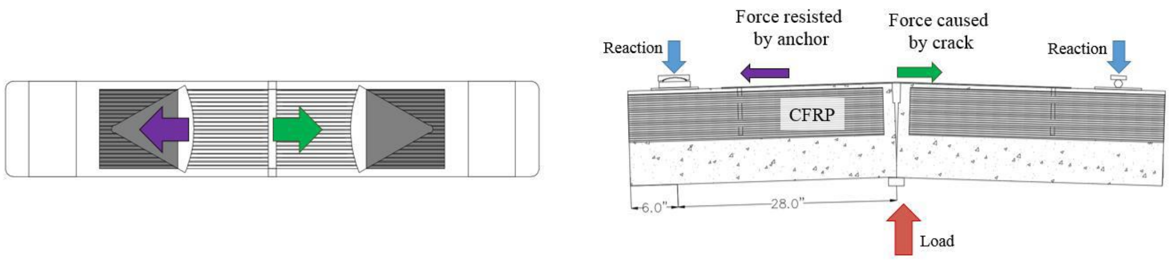
Test #	Strip width (in.)	Number of CFRP strip layers	Number of anchors per strip	Anchor material ratio (AMR)	Anchor hole chamfer radius (in.)	Anchor overlap length (in.)	Ultimate Stress per layer (ksi)	Failure Mode
1	5	1	1	1.7	0.500	6	165	Anchor Rupture
2	10	1	2	1.7	0.500	6	153	Strip Fracture
3	10	1	1	2.0	0.625	9	144	Strip Fracture
4	5	2	1	2.8	0.750	12	159	Strip Fracture
5	10	2	2	2.8	0.750	12	162	Strip Fracture
6	10	2	1	2.8	1.125	12	149	Strip Fracture
7	10	2	1	2.0	0.875	12	146	Shear Failure
8	10	2	1	2.0	0.500	12	120	Anchor Rupture

The test specimens were strengthened in flexure using 5in. and 10in. wide CFRP strips that were in a single or double layer. The 10in. wide CFRP strips were anchored with either one or two anchors.
The ratio of anchor-to-strip cross-sectional material, or anchor material ratio (AMR), is calculated as the ratio of the anchor laminate cross-sectional area divided by the strip laminate cross-sectional area. Note that this simplistic ratio is valid for this study since the CFRP anchors and strips used the same CFRP laminate material. Otherwise, the effects of the different material stiffness would need to be taken into account. Jirsa et al. [2] recommended a minimum AMR of 2.0 for anchors developing 5in. wide strips and a minimum AMR of 1.4 for anchors developing 3in. wide strips. Three ratios were used in this study: 1.7, 2.0, and 2.8.

An anchor hole chamfer radius of 1.4 times the radius of the anchor hole was used for all of the tests - except for test 8. That test used a fixed 0.5in. chamfer radius.
The overlap length of the anchors were adjusted so that the interfacial bond stress between the anchor and CFRP strips remained below 500psi as per manufacturer recommendations. In doing so, slip did not occur between the anchors and CFRP strips.

Test Setup

A three-point loading configuration was used for testing the specimens. A hydraulic ram applied a load to the specimens, which were restrained by two reaction beams. The loading method induced tensile forces in the CFRP strip and anchors on the top as shown in Figure 1.



(a) Plan view (b) Elevation View

Figure 1: Three point loading test setup

The applied load was monitored using a load cell at the ram whereas the displacements were monitored with displacement transducers at the location of the applied load and at the reactions. The strains in the CFRP were monitored with strain gages and a high-resolution optical measurement system. The data acquisition systems had a synchronized collection rate of approximately 1 second. Comparatively, the loading rate was approximately 0.1 kip/second. Additional information regarding the data acquisition systems can be found in Jirsa et al. [2].

Experimental Results and Discussion

The specimens presented in this study exhibited three distinct failure modes: CFRP strip fracture, CFRP anchor rupture, and a concrete shear failure. Of the three failure modes, CFRP strip fracture is the most desired because it results in the highest tensile capacity for a given CFRP strip. The CFRP anchor rupture implies that either the anchor was not large enough or other aspects of the anchor detailing were not adequate to develop strip strength.
The ultimate CFRP strip stress and failure mode are summarized in Table 1. The reported ultimate stress in the CFRP was calculated based on the measured applied load and the stress-strain relationship of concrete members in flexure as explained by Jirsa et al. [2].

Anchor-to-strip Cross-sectional Area Ratio

All of the test specimens that utilized an AMR greater than or equal to 2.0 experienced fracture of the CFRP strips – except for test 8. Tests 7 and 8 had identical test parameters with the exception of the chamfer hole radius. Test 8 used a chamfer hole radius of 0.5in., which is less than the chamfer of 1.4 times the anchor hole diameter used in test 7.

The test results show that the specimen with the smaller chamfer radius failed due to anchor rupture, likely caused by high strain concentrations in the anchor fibers at the chamfer. The specimen with the larger radius failed in shear. However, the CFRP strip developed a stress larger than its expected fracture stress prior to the shear failure.
Jirsa et al. [2] showed that an AMR of 2.0 can develop the tensile fracture strength of one layer of 5in. wide CFRP strips. The presented study also showed that an AMR greater than or equal to 2.0 can develop the strength of up to two layers of 10in. wide CFRP strips if a suitable chamfer radius is used.

CFRP Strip Fracture Stress

The test results have demonstrated that one CFRP anchor fractured a strip having a width of 10in., developing a tensile force of about 60 kips (two layers of CFRP laminate). However, test results also clearly indicated that the CFRP strip fracture stress reduced as the tributary width per anchor increased (Table 1). The aforementioned trend was also observed when multiple CFRP strip layers were used.
Based on an investigation of the strain data, it was observed that the largest strains in the strip occurred along the centerline of the strip when one anchor was used to develop a 10in. strip. The strains at the edges of the strip were significantly smaller than the centerline strain. Conversely, the strains along the width of the strip were more uniform when two anchors were used on a 10in. strip. The more uniform strain distribution along the width of the strip allows the CFRP to reach a higher strain (and stress) on average without experiencing localized fracture of the fibers.

Conclusions

Based on the findings of this study, the following conclusions can be made:
1. An AMR of 2.0 was shown to be sufficient to achieve strip fracture in all cases if the edge chamfer radius of the anchor hole was taken as 1.4 times the hole radius.
2. An individual CFRP anchor was shown to develop the expected strength of CFRP strips up to 10in. wide even when using two layers of fabric. However, using two anchors for a 10in. strip width (i.e., a 5in. anchor tributary width) resulted in a more uniform strain distribution in the strip. Consequently, the strips that had lower tributary widths per anchor experienced higher CFRP fracture stresses.

References

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