Chapter 3
Experimental Study

The experimental study consists of examining the use of carbon fiber reinforced plastic (CFRP) bonded to the bottom of reinforced concrete beams. Each specimen was designed to resemble a typical beam that could be used as a bridge girder. They were constructed to fail due to flexure by over-reinforcing the beams for shear. The concrete, reinforcing steel, and CFRP were each tested separately to obtain the material properties. The following chapter describes in detail the experimental study.

3.1 Materials

The beams consisted of three materials: concrete, reinforcing steel, and CFRP. Each material was studied separately to acquire the properties that will later help in modeling the behavior of the specimens.

3.1.1 Concrete

One batch of concrete was used for casting the specimens. It was ordered from a local plant and arrived in a ready-mix truck. The concrete properties included Type I cement, fine aggregate, and river gravel for coarse aggregate. Also, no admixtures were present in the concrete. The slump and compressive strength requested were 4 inches and 3000 psi at 28 days, respectively. A 3000 psi strength was chosen to mimic an older bridge girder that would be subject to strengthening. Upon arrival, a slump test revealed a 4.25 inch slump, and eight cylinders were cast for monitoring strength gain.

Uniaxial compression tests were completed in accordance with ASTM C 192-95 (1997) and ASTM C39-94 (1997). The tests were performed on eight cylinders with a six-inch diameter and twelve-inch height on a compression-testing machine. After a maximum applied load from each test was recorded, the following formula was used to calculate the maximum compressive stress, f_c':

$$f_c^{'} = \frac{C}{0.25\Pi d^2} \qquad (3\text{-}1)$$

where: C= maximum compressive load

d= diameter of cylinder

Beginning with 28 days after casting, each of the cylinders were tested in pairs at different times throughout the experimental period. Table 3.1 shows the results of the compression tests. The average compressive strength is 3.08 psi with a maximum difference of five percent.

Table 3.1: Results of Uniaxial Compression Tests

Days After Casting	Maximum Load (kips)	Compressive Strength (ksi)
28	82.5	2.92
28	83.6	2.96
45	88.0	3.11
45	87.7	3.10
164	88.2	3.12
164	88.9	3.15
193	89.0	3.15
193	87.8	3.11

3.1.2 Reinforcing Steel

The longitudinal reinforcing steel used was Grade 60 with nominal diameters of 0.75 inches (#6) for the tensile bars and 0.50 inches (#4) for the compressive bars. The vertical reinforcement consisted of U-shaped stirrups with a nominal diameter of 0.375 inches (#3).

Two tension coupons from the #6 reinforcing steel were tested to acquire the yield stress and modulus of elasticity of the reinforcement. Each of the specimens were machined to remove the ribs and create a smooth surface at mid-length. The coupons were tested in tension using a testing machine with a two-inch extensiometer to record the strain. The experiment was conducted in accordance with ASTM A 370-95 (1997).

The average of the two stress-strain curves is shown in Figure 3.1. The results of the two tests were almost identical, and both exceeded the specified yield strength of 60 ksi. The average stress-strain curve showed a linear elastic behavior to a yield stress of 70 ksi and strain of 0.0038 in/in. This tested yield strain was almost double the expected yield strain of 0.002 in/in. This results in a tested elastic modulus of 19000 ksi, which is distinctly smaller than that typically used for steel reinforcement (29000 ksi). Following the linear behavior, the steel experienced strain hardening until the ultimate strength was reached. The extensiometer was remove at a strain of approximately 0.04 in/in, even though the ultimate capacity was not yet reached.

3.1.3 Carbon Fiber Reinforced Plastics

3.1.3.1 Introduction

A composite consists of two or more materials combined to produce a product that exceeds their individual properties. In particular, fiber reinforced plastics is a combination of high strength fibers and a matrix. The fiber is the strength of the composite, and the matrix is the product that holds the fibers together and acts as a load transfer median. (Norris & Saadatmanesh, 1994)

Common fibers used for civil engineering projects are glass, carbon, and aramid. The most popular is glass since it is more economical to produce. However, the prime candidate for bridge repair applications is carbon fibers. The carbon fibers are stronger and stiffer than most other fibers, and are more corrosion resistant, lower in density, and more widely available as a raw material. (Norris & Saadatmanesh, 1994)

The matrix supports the fibers, protects them, and transfers the loads through shear stresses. It’s common to use forms of polymers or plastics between the fibers for this purpose. These have advantages such as low costs and good resistance to the environment, but they can degrade rapidly due to high temperatures and moisture. (Norris & Saadatmanesh, 1994).

3.1.3.2 Description of CFRP Materials

The carbon fiber used in the tests was AS4, 3k tow, plain weave fabric. AS4 is a fiber type manufactured by Hercules with a reported nominal strength and modulus of elasticity of 500 ksi and 32 Msi, respectively; 3k tow specifies 3000 filaments per bundle of fibers in a weave; and plain weave is a simple cross weave fabric with equal tows in each direction. Two types of orientations were used in the experimental program. Each was manufactured on rolls with a six-inch fabric width. One has fibers that are equally laid parallel and perpendicular to the orientation. The other fabric has a plus and minus 45° orientation from the transverse axis and is stitched every 0.25 inches for workability. For simplicity, these fabrics and their composites will be referred to as 0°/90° and ±45°, respectively.

The adhesive will serve as both the bonding agent to the concrete and matrix of the composite. It is comprised of a two-to-one ratio of D.E.R. 383 standard bisphenol, A-based epoxy resin and Ancamide 2396 curing agent manufactured by Air Products. The tensile strength and elastic modulus are 8.60 ksi and 242 ksi, respectively. These properties were acquired from the manufactures. The CFRP volume will be approximately 50% fabric and 50% adhesive/matrix.

3.1.3.3 CFRP Testing

Uniaxial tensile tests were performed on CFRP samples to determine their properties. The testing followed the procedure outlined in ASTM D3039-95 (1997). The CFRP coupons were approximately six inches long and one inch wide. The thickness differed for the two orientations. Unlike other materials for tensile tests, the width of the CFRP was not decreased in the middle of the sample. Instead, the rectangle sample was gripped on either side and the effective length was placed in tension. The tests were performed on an Instrom testing machine, and a two-inch extensiometer was used at mid-span for strain measurements. The tensile load was applied at a displacement rate of 0.015 in/min. The dimensions and gripping of a typical sample are shown in Figure 3.2.

The tensile tests provided CFRP properties such as failure stress, strain, and modulus of elasticity. Twelve samples of each type of composite were tested, and the average data is shown in Table 3.2.

Table 3.2: Average Results of CFRP Tensile Tests

Orientation	Cross-Sectional Area, in^2	Maximum Applied Load, kips	Maximum Stress, ksi	Maximum Strain, in/in	Modulus of Elasticity, ksi
0°/90°	0.03	1.48	49.3	0.012	4108
±45°	0.10	1.29	12.9	0.039*	Tri-Linear

* This is the strain were the maximum stress occurs

The average stress-strain plot of twelve 0°/90° composite specimens are shown in Figure 3.3. The samples behaved linearly until rupture occurred at an average stress and strain of 49.3 ksi and 0.012 in/in, respectively. Rupture occurred in nine out of the twelve samples around the mid-span, while the others failed at the grips. Figures of each test are provided in Appendix A.

The average stress-strain plot of the twelve ±45° composite specimens are shown in Figure 3.4. The average maximum stress was 12.9 ksi at a strain of 0.039 in/in. Most samples possessed a semi-ductile trait. After the CFRP reach the maximum stress, the strain continued to increase. Although the maximum stress was not sustained, it dropped an average of 2.5% per 0.01in/in strain. The tests were stopped at the maximum reading of the exetensiometer of 0.1-in/in strain. However, most of the samples were still holding substantial load. The average modulus of elasticity was derived with a tri-linear approximation of the stress-strain curve. They are 747 ksi from 0 to 0.0075 in/in, 365 ksi from 0.0075 to 0.0232 in/in, and 96 ksi from 0.0232 to 0.0390 in/in. Figures of each test are provided in Appendix B.

3.2 Strengthened Beams

The strengthened beams were designed to examine their flexural behavior. Overall, seven beams were constructed; six of which were strengthened with CFRP. The other was tested without CFRP and served as the control beam. This section will describe the philosophy of the design, the CFRP application, and instrumentation.

3.2.1 Design of Beams

The beams were designed to study the flexural response of a strengthened bridge girder. The first assumption was to use a typical fraction of the balance steel reinforcement ratio, ρ_b (defined as the steel ratio that results in simultaneous yielding of the reinforcement and crushing of the concrete at the extreme compression fiber). Since reinforced concrete beams are usually designed so the steel reinforcement yields first, a ratio of $0.5\rho_b$ was deemed appropriate. This ratio would not cause the highest increase in strength after applying the CFRP. It was shown by an earlier study that for beams with the minimum steel reinforcement ratio (defined by ACI 318-95 as $200/f_y$) strength increase can be larger than 100% (An et. al, 1991). Since using the minimum steel reinforcement in a bridge girder is not typical, it seemed fitting to study the effects of CFRP strengthening on concrete beams with a higher steel reinforcement ratio.

The next step was deciding on the actual geometry of the specimens. The capacity of the available ram limited the size of beam that could be tested. Using this constraint and the analytical model discussed in Chapter 4, a maximum load was predicted. With a spreadsheet, many different dimensions were investigated until the most appropriate was chosen. This design is shown in Figure 3.5. All minimum spacing or covering requirement were satisfied according to ACI 318-95, section 7.6 and 7.7, except for the concrete cover on the bottom portion of the stirrup. Due to complications, the cover was one-inch while the code requires a minimum of one and one-half inches for cast-in-place beams. However, the cover was larger than what was specified in the code for pre-cast beams (3/8-inches). Also, a small angle was placed at mid-span on the bottom of the beam. This was used to cause crack propagation at the centerline.

A critical part of the design was ensuring the beams failed due to flexure and not shear. To accomplish this, the specimens were heavily reinforced for shear. This design was based on ACI 318-95, section 11, with the addition of a safety factor of two. A sketch with the stirrup spacing is shown in Figure 3.6.

3.2.2. CFRP Application

The most important factor in creating a composite system with the reinforced concrete beam and CFRP was assuring the bond between the materials was adequate.

Preparation of the concrete surface and the application of the CFRP are discussed in the following section.

3.2.2.1 Concrete Surface Preparation

It was necessary to have a level concrete surface to serve as a bonding plain for the CFRP. Also, the surface should be independent from all unwanted particles such as dust or lubricants. To achieve this, a hand held grinder was used to remove the surface layer on the tension side of the beam. This also helped by exposing a large portion of aggregate that would be beneficial in bonding with the CFRP. The preparation was complete by blowing the specimen with compressed air to remove any excess particles. The specimens were then covered until the CFRP was applied.

3.2.2.2 Bonding the CFRP

Applying the CFRP to the concrete surface was a learning process. The first attempt began with impregnating the fabric with adhesive, placing the layers on the floor, and lowering the concrete beams onto the CFRP. There were a few unforeseen problems with this method. First, the beam had developed a natural camber. This caused small gaps between the CFRP and concrete at mid-span. The other problem was caused when the beam was set on the CFRP layers. Since the viscosity of the adhesive was still low at the time of application, the beam slid on the CFRP. This caused the layers to move and become nonparallel with the concrete beam and each other. Although this specimen was still tested and performed acceptably (Specimen #3), a new application procedure was proposed.

The five remaining beams were strengthened with CFRP by the following method. The reinforced concrete beam was first inverted to simplify the application. After the surface was prepared (as discussed earlier), each layer of CFRP was impregnated by hand with adhesive and rolled onto the middle of the tension side of the specimen. All layers were extended past each anticipated support point to provide anchorage against debonding in the region of high shear force (Ritchie et al., 1991). After all the layers were set, the adhesive was given time to stiffen. A tear-off sheet was applied followed by bearing pads and form-fitting materials. These evenly distributed pressure throughout the length of the CFRP. Next, a quarter inch steel plate was set, followed by weights that provided 50 psi of pressure on the CFRP. Each beam was allowed to cure in this fashion for at least 24 hours.

All the composite beams except for one (Specimen #5) had adequate bond by inspection. Adequate bond was characterized by very limited amounts of fabric exposure and the CFRP centered accurately. With Specimen #5, the CFRP slipped while the weights were being set in place. This resulted in the layers of fabric being off centered.

3.2.3 Instrumentation

The composite beams were instrumented with different measuring devices to tract behavior throughout testing. This consisted of displacement, internal strain, and external strain measurements. All channels of data were recorded every eighth of a second on a MegaDac 3108 data acquisition system.

Two wire potentiometers recorded the mid-span deflection. One was attached to each bottom edge of the specimen. An LVDT was also placed at mid-span, but the total travel of this instrument is only two inches. Although this device is more accurate, some specimens were predicted to deflect more than the LVDT travels before failure. Therefore, the wire potentiometers, which have a travel length of at least ten inches, were necessary. Also, support displacement was measured during one of the seven tests, and this support deflection was subtracted from the mid-span deflection for all tests. The reported mid-span deflections are corrected for support deflection in this manner.

The internal stain was measured with three handmade and one manufactured gage. The handmade gages consisted of a Micro-Measurements CEA-13-250UW-350 strain gage placed on a six inch long, 0.75 inch (#6) piece of rebar. A hand held grinder was used to smoothed out a two inch section were the gage was attached. To prevent damage by exposure to the concrete, the strain gage was sealed with silicon. The devices are shown in Figure 3.7. The manufactured gage was developed by Micro Measurements (EGP-5-350), and was a strain gage in a protected composite case that had ribs to bond with the concrete. All four internal gages were attached to the tension reinforcement steel in the constant moment region as shown in Figure 3.8. The lead wires were tied to the reinforcement to prevent damage during the casting of the concrete.

Micro Measurement CEA-13-250UW-350 gages were used for all external strain measurements on the CFRP. They were applied to the constant moment region after curing of the adhesive was complete. Figures 3.9 and 3.10 show the gage layout for the 0°/90° and ±45° specimens, respectively. Additional gages were added to the ±45° specimens due to some inaccurate results of the 0°/90° specimens after cracks formed above the gages.

3.3 Testing Procedure

All specimens were tested to failure under four point loading as shown in Figure 3.11. Table 3.3 lists the test parameters for each of the seven specimens. This includes the specimen number, the type and number of CFRP layers applied to each beam, the area of CFRP, the loading ram used, and the type of loading control.

Table 3.3: Testing Parameters

Specimen No.	CFRP Layers	Area of CFRP, in^2	Loading Ram	Loading Control
1	None	None	MTS	Stroke
2	Two 0°/90°	0.18	MTS	Load
3	Three 0°/90°	0.27	MTS	Stroke
4	Four 0°/90°	0.36	MTS	Load
5	Two ±45°	0.60	Hydraulic	Pressure
6	Three ±45°	0.90	MTS	Load
7	Four ±45°	1.20	MTS	Load

The CFRP layers were chosen to optimize the performance of the composite beams and to compare the two different orientations. Analytical models (discussed in Chapter 4) helped to decide on the number of layers to apply. This was based on increase in strength, ductility, and desired failure modes. However, it must be noted, the area of the two CFRP orientations are not alike. The area of the ±45° orientation is over three time the area of the 0°/90° for each layer.

Two different loading rams were used for the experimental study. The first was a servo-controlled MTS ram and is shown in Figures 3.12 and 3.13. This ram can be used in either stroke or load control. Controlling the ram with stroke is a safer procedure because the load will reduce if a failure begins. This is not the case with load control, where the load is held even when the load resistance is decreasing at failure. An advantage of this is a realistic look at the failure modes and what damage they cause. The load was applied and measured using a MTS 458.10 controller.

Because of equipment problems, one specimen (#5) was tested with a hydraulic ram that was controlled with pressure. This controlling procedure is similar to stroke control in that the load will reduce when failure begins. This set-up is shown in Figures 3.14 and 3.15. The load was measured using a four-inch circular load cell.