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Mechanical Behavior of Hybrid Concrete-Filled Fiber Reinforced Polymer Tube Columns

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Mechanical Behavior of Hybrid Concrete-Filled Fiber Reinforced Polymer Tube Columns

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B.S. Civil Engineering, University of Connecticut, 2016

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Submitted in Partial Fulfillment of the Requirements of the Degree of
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Mechanical Behavior of Hybrid Concrete-Filled Fiber Reinforced Polymer Tube Columns

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ABSTRACT

Much of America’s infrastructure is in a state of disrepair. Many bridges are approaching or have passed their designed service life. Engineers and bridge owners have an obligation to rebuild back better. This can be achieved, in part, through the utilization of novel high performance structural systems. One such technology, the concrete-filled fiber reinforced polymer (FRP) tube (CFFT) system has been extensively studied the past few decades as an alternative design for bridge columns. This column system greatly simplifies construction by eliminating the need for column formwork and associated scaffolding. It also contributes to the confinement of the concrete, improving performance. A CFFT system without the need of traditional rebar would even further simplify construction. This novel system, herein investigated, is achieved by embedding longitudinal steel fibers into the FRP tube of a CFFT. The goal of these steel fibers is to give the system the energy dissipation and ductility benefits CFFT’s gain from added rebar without the additional associated construction costs.

Hybrid metal/non-metal fiber CFFT (HCFFT) and traditional all glass CFFTs were manufactured with varying glass fiber angles and number of layers. Specimens were tested under half-cyclic concentric and eccentric compressive loading. These tests are the first in a series to understand the behavior of CFFTs and HCFFTs under different loading and to construct column interaction diagrams. Later research on larger-scale specimens will include four-point bending and combined axial and lateral loading. The addition of longitudinal steel fibers into a traditional CFFT system may offer an improvement in energy dissipation capability before failure and slow damage progression. These steel fibers may lead to a reduction in ultimate strain capacity of the CFFT, depending on manufacturing method. Mechanical properties of the specimens are presented as well as data on energy dissipation, damage progression, and recentering capability.
1 CHAPTER 1: BACKGROUND

1.1 Introduction

There is a critical need to replace much of the deteriorating infrastructure in the United States. While deferred maintenance and obsolete designs are not natural disasters themselves, they necessitate the need for urgent rebuilding. The pressing replacement of infrastructure is a chance to ‘Build Back Better’\(^1\) and adopt structural systems that are more disaster resilient than current practices. This increased resilience can be achieved through the utilization of innovative materials and structural systems. A novel structural column system that outperforms and outlasts traditional columns is studied herein. This column system, a Concrete-Filled Hybrid Fiber Reinforced Polymer (FRP) Tube (HCFFT) is first introduced in this study. Extensive experimental studies are conducted to determine the load-strain behavior, recentering capabilities, and energy dissipation of HCFFT.

This section contains a review of previous studies on fiber reinforced composites and the CFFT (Concrete Filled FRP Tube) column system, all prerequisites of this research.

1.1.1 Conventional Fiber Reinforced Composites and Resilient Design

The use of Fiber Reinforced Polymer (FRP) composites has become popular in the past few decades in industries demanding high-strength and lightweight materials. These composite materials are typically made of a thermosetting polymer, such as epoxy or vinyl-ester, reinforced with small diameter carbon or glass elastic fibers. The design of FRPs can be highly customized to meet the desired mechanical properties for a given application. Properties such as stiffness and axial and shear strengths can be adjusted by varying a composite’s fiber volume fraction and the angles of fibers in a composite matrix. Besides providing overall stability, the polymer
matrix protects the reinforcing fibers from degradation in harsh conditions such as corrosive environments.²

FRPs are often used in high-end racecars and helmets due to their lightweight and high energy dissipation. Although glass and carbon fibers are brittle, with low fracture energies, FRPs made from these fibers can dissipate large amounts energy due to the pulling out of fractured fibers from the matrix, fiber debonding, and matrix cracking³. However, these elastic glass or carbon fiber composites do not show a high energy absorption capacity prior to the onset of these failure mechanisms. These traditional FRPs are meant to be replaced following extreme loading cases. This becomes an issue when FRP materials are used in civil structural components such as bridge or building columns.

It is desirable that the next generation of structural components be designed to survive multiple hazardous loadings and remain functional after extreme loading. Current structural engineering standards specified life-safety as the requirement to be satisfied for structures during an extreme event such as a fire or an earthquake⁴. For earthquakes the International Building Code requires a building to have a maximum of one percent collapse probability over fifty years. “Collapsed” does not include a severely damaged “red-tagged” building that must demolished post-quake.⁵ But pioneering building codes aim to also protect the functionality of a structure following extreme shaking. NEHRP recommends seismic provisions aim “to avoid structural collapse in very rare, extreme ground shaking” and “to provide reasonable control of damage to structural and nonstructural systems that could lead to injury and economic or functionality losses for more moderate and frequent ground shaking.”⁶

It is learned from recent disasters that it is essential for infrastructure to remain operational following even “extreme ground shaking” in order to allow emergency response and
quick recovery of communities. Additionally, Davis and Porter have shown that there is a demand from the public to have habitable buildings after extreme earthquakes, not just have buildings that do not collapse. This study showed that the public may be willing to pay extra for this high performance.

Design of seismic resilient structures requires the use of novel materials and systems. To maintain operational after earthquakes, these structural systems need to dissipate energy under extreme cyclic loading with minimal residual displacement. This study investigates the development and performance of a novel column system for extreme loading using FRP materials.

FRP composites have previously been used in civil engineering applications such as reinforcing bars and a seismic retrofit for reinforced concrete (RC) columns. In one retrofit method, RC columns are wrapped with FRP jackets to increase strength and ductility of columns. Another application, shown by Mirmiran and Shahawy involves the use of Concrete-Filled FRP Tubes (CFFT) as bridge columns. The filament wound FRP tube increases the strength of traditional RC columns by providing confinement. There had been much interest in using these CFFT columns in marine conditions where columns are in contact with salt water. The resistant epoxy matrix of the FRP tubes prevents the degradation of concrete and steel inside. In 2012, the American Association of State Highway and Transportation Officials (AASHTO) released design specifications for these CFFT columns. But, citing current design limitations, the design specifications prohibited the use of CFFTs for use as ductile earthquake resisting members.

1.1.2 Metal Fiber Reinforced Composites
Metal fibers have been used as reinforcement in radial tires, found on all new automobiles in the United States for over four decades. A unidirectional (UD) ply of steel cords is embedded in the rubber of the tire and provides a tougher, longer lasting tire. Short steel fibers are used in Ultra-High Performance Concrete (UHPC) and allow the material to achieve tensile strengths 6 to 8 times higher than regular concrete and sustain loads after cracking.

Modern developments in manufacturing have introduced a new class of ultra-thin stainless steel fibers, with diameters of 30µm (0.0012in). These fibers are currently typically used as filler material in plastics to provide electromagnetic interference protection. Recent research has shown the potential of these steel fibers to improve mechanical properties of FRPs due to their high stiffness and large failure strain. Studies have been done at KU Leuven on the tensile and impact behavior of polymer composites reinforced with these ultra-thin steel fibers. This research studied unidirectional and cross-ply composites and examined the effect of matrix ductility, fiber packing, and fiber/matrix adhesion. Callens showed that the ultimate strain in polymers reinforced with these stainless steel fibers is three times larger than those just containing glass or carbon fibers.

1.1.3 Hybrid Composites

Traditional FRPs combine brittle but strong fibers and a ductile polymer matrix to optimize composite action. Composite hybridization advances by developing polymer composites containing multiple types of reinforcement. One type of hybrid composites, Fiber metal laminates (FML) are made by altering layers of thin metal sheet and FRP. Glass reinforced aluminum GLARE, a FML, is made with layers of aluminum and glass FRP (GFRP). GLARE was used to construct the fuselage of the Airbus A380, providing better fatigue resistance and specific strength versus aluminum. The other type of hybrid composite involves
fiber hybridization; the combination of multiple fiber types in a polymer matrix. Fiber hybridization by the combination of glass and carbon fibers has been studied extensively. Constructing composites of low elongation (carbon) and high elongation (glass) fibers can result in improvements of ductility and strain of the hybrid composite versus composites of just carbon fibers. The ‘hybrid effect’ is defined by Hayashi as the apparent improvement of failure strain in the low elongation carbon fiber of a glass/carbon hybrid fiber composite. Marom et al. later defined the ‘effect’ to be the deviation of a hybrid composite’s mechanical properties from those predicted in the Rule of Mixtures.

1.1.4 CFFT

CFFTs are bridge column systems comprised of a FRP tube filled with concrete. A CFFT has the compressive strength, stiffness, and low cost of regular strength concrete with the high durability and specific strength of FRPs. The mechanical properties of the FRP shell can be customized by altering the fibers or matrix used, fiber angle, and thickness of shell. High confinement of the concrete core provided by the FRP shell increases the column axial strength and ductility and eliminates the need for spiral reinforcing steel. Due to the lightweight of the FRP shell, it can easily be moved in place at a construction site. The shell also acts as a stay-in-place formwork for concrete casting, reducing construction time. This makes it suitable for adoption in Accelerated Bridge Construction (ABC) applications. Fam et al. studied the first field application of CFFTs in a bridge foundation on the Route 40 Bridge in Virginia. Cost analysis showed that the CFFT piles cost 77% more than RC piles initially. But due to the high durability of CFFT, they may be more economical due to reduced maintenance costs. There is currently no field application utilizing CFFT as bridge columns.

1.1.5 Previous Work at the University of Connecticut


Prior to this research project, three other relevant research projects were performed at the University of Connecticut (UConn). Echevarria et al. conducted destructive experimental testing on one-fifth scale reinforced concrete (RC) and Concrete Filled FRP Tubes (CFFT) bridge columns. The CFFT columns tested contained a small amount of longitudinal reinforcement, at 1.12% of the column cross sectional area. The outer diameter of the pipes tested was 219mm (8.64in) and six 9.525mm (0.375in) steel reinforcing rods were used. CFFT columns and control RC columns were subject to two different severities of blast and fire exposure. They were then tested to determine their remaining axial capacity. These results were compared to tests performed on undamaged columns. The experimental results showed that the CFFT columns outperformed the RC columns during and after both extreme events. These results indicated the potential benefit of using CFFT columns for the design of bridges resilient to multihazards. The study was concluded by developing a design methodology for CFFT bridge columns with minimal amounts of longitudinal reinforcing steel.

Research by A. McBride studied the potential impact of incorporating small diameter steel fibers into a glass fiber reinforced composites. This research was all conducted on thin plate composites samples. This study involved manufacturing 1” × 1” (25.4mm x 25.4mm) composite coupons for tension testing through the compression modeling technique. McBride et al. showed that glass/steel fiber hybrid composites show promise for structural applications because they have high strength, energy absorption before failure, and recentering capabilities. Another relevant research conducted at UConn consisted of corrosion tests on stainless steel fibers again identical to those used in this study. O’Brien et al. demonstrated that when
contained within an epoxy matrix, the stainless steel fibers suffered minimal corrosion and therefore loss of strength was minimized.

1.2 Document Layout

The following chapter (Chapter. 2) discusses the properties of the raw materials used in the design of the CFFT's. Testing results and manufacturing data is presented for the resin, glass fibers, steel fibers, and concrete.

Chapter Three provides details concerning the design of the FRP tubes and the whole CFFT elements. It also provides the instrumentation and experimental methodology testing performed.

Chapter Four presents the instrument data for tension and compression tests as well as descriptions and comparisons of failure mechanisms.

Chapter Five summarizes the findings of this study and suggests future work.
2 CHAPTER 2: BEHAVIOR OF MATERIALS

2.1 Introduction
The properties and behaviors of the materials used in this study are presented in this chapter. Material testing method and the results including stress-strain diagram, modulus of elasticity are discussed in this chapter. In this study a variety of materials such as resin, glass, and steel fibers were used to manufacture the FRP tubes. In addition the concrete material that was cast in the tubes to make the CFFT is explored.

2.2 Resin
A thermosetting epoxy resin was used as the polymer in the FRP pipes. This resin was composed of DER 383 liquid epoxy resin, AH 667 epoxy resin hardener, and T5000 resin additive. The FRP pipe manufacturer, Fiber Glass Systems (FGS) utilizes the same type of resin in their main line of production. It was necessary to obtain the mechanical properties of the cured epoxy independent of fibers. Therefore, pure epoxy samples were made to conduct material testing and calculate the mechanical properties.

2.2.1 Epoxy Dog Bones
An aluminum dog bone frame seen in Figure 2-1a was used to make epoxy samples per ASTM D638, Standard Test Method for Tensile Properties of Plastics. Prior to manufacturing, the mold was prepped with Meguiar’s mold release wax to assure easy release of the samples. During manufacturing of the FRP pipes, epoxy samples were made from the actual batch of resin used in the pipe manufacturing. To ensure similar curing conditions as the FRP pipe, the frame was cured at the same time in the oven with the pipe. After this stage, samples are fragile; therefore extra care is necessary during mold removal. Following removal the specimens had uneven cross sections due to the epoxy adhering to the mold walls. The specimens were polished to a uniform cross section through wet disc sanding at 400 and 800 grits. The average cross
section of the dog bone stem was 3.83mm (0.15in) thick and 6.35mm (0.25in) wide. The gage length of the specimens was 44.5mm (1.75in) long. All specimens were 114.3mm (0.45in) long and 19.1mm (0.075in) wide at the grips. Two batches of five specimens each were manufactured of the same epoxy mix used in pipe manufacturing.

2.2.2 Experimental Methodology

The finished epoxy specimens were tested on a screw-driven Instron 5869 machine (Figure 2-1c) under monolithic tensile loading as per ASTM D638. The tests were displacement controlled with the crosshead moving up at a rate of 0.078in/min (2mm/min) to achieve an acceptable strain rate. An Instron extensometer with 1 inch (25.4mm) gage length was attached in the middle of the specimen to record longitudinal strain (Figure 2-1b). The longitudinal strain, machine displacement, and load cell data were collected using Instron Bluehill software. To ensure comparable results, testing was completed on the epoxy dog bones following the testing of corresponding FRP pipes. All these tests were competed months after manufacturing. Figure 2-1d shows a typical failure specimen.
Figure 2-1: Tension Testing of Epoxy Specimens
(a) Frame with poured samples, (b) Test setup: dog bone specimen in tension grips with 1in extensometer attached, (c) Instron 5869 Testing Machine, (d) Specimen after failure
2.2.3 Results and Observations

Seven epoxy dog bone specimens were tested and failed in an acceptable manner. The average tensile properties of these tests are presented in Table 2-1. Figure 2-2 shows the stress strain behavior of each individual specimen as well as an average value.

<table>
<thead>
<tr>
<th>Epoxy Dog Bones</th>
<th>Ultimate Tensile Strength ksi (MPa)</th>
<th>Ultimate Strain (%)</th>
<th>Young’s Modulus ksi (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Values</td>
<td>5.75 (39.64)</td>
<td>2.26</td>
<td>345 (2.38)</td>
</tr>
</tbody>
</table>

Figure 2-2: Tensile Stress Strain behavior of all tested epoxy specimens

2.3 Glass Fibers

The glass fiber’s that were used in the construction of the FRP pipes was Hybon 2052, an E-glass manufactured by Nippon Electric Glass. E-glass is an electrically resistive glass made of alumina-calcium borosilicates. It is the most commonly used fiber type in FRP applications.
While not as strong or stiff as Carbon Fiber, E-glass has a longer elongation at break. It is also less than half the price per weight. The fiber tows used in the manufacturing of the FRP pipes were “250 yield”. That is, one pound (0.45 kg) of fiber tow is 250 yards (228.6 m) in length. The diameter of individual fibers in these tows is 16 microns (0.00063 in). The reported tensile modulus of these glass fibers is 10443 ksi (72 GPa)\textsuperscript{28}.

2.4 Steel Fibers

The 316 stainless steel alloy reinforcement fibers of 30 µm diameter were used in manufacturing of FRP pipes. N.V. Bekaert of Belgium manufactured and provided these fibers in the form of a quasi-unidirectional (UD) fabric. The steel fibers were oriented in the warp (90° to the length of the roll) direction. According to Bekaert the steel fibers have a density of 7.87 g/cm\textsuperscript{3} (491 lb/ft\textsuperscript{3}) and modulus of elasticity of 193 GPa (27992 ksi). The fibers were manufactured using a patented bundled drawing technique and annealed at a temperature greater than 800 °C to achieve ultimate strain without losing stiffness\textsuperscript{29}. In this process, a composite wire made out of 90 to 1000 stainless steel fibers is bundled and coated in a copper matrix material. They are then drawn to reach the desired diameter. The copper matrix is leached with sulfuric or nitric acid, leaving just the long, small diameter stainless steel fibers. The steel fibers of this fabric were kept in alignment by white polyethylene succinate (PES) cross yarns with a diameter of 15 µm (0.0006in). These PES yarns have a negligible contribution to the mechanical properties of the fabric. The woven fabric as, seen in Figure 2-3, of steel fibers and PES yarn has an areal density of 570 g/m\textsuperscript{2} (0.12 lb/ft\textsuperscript{2}). Tests conducted by O’Brien have found the yield strength of single steel fibers to be 50 ksi (344.7 MPa) with ultimate strengths up to 90 ksi (620.5 MPa). These single fibers reached strains of up to 12\%. 

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2.5 Concrete

2.5.1 Mix Design

The first series of CFFT columns were cast with a concrete mix made at the UConn structural lab. The concrete specified strength at 28 days was 8 ksi (55.2 MPa). This mix used a maximum aggregate size of 3/8 inches (9.53 mm). Limited by the size of available mixer, each batch of concrete was enough for two 2’ tall (0.61m) columns. The strength of both UConn batches as tested is detailed below. The CFFTs made with UConn’s mix were tested within a week of casting, before full strength of 8 ksi was developed. This was done to keep concrete strengths consistent with typical regular strength concrete. For the second series of CFFT’s, all columns were manufactured simultaneously with the same batch of concrete, kindly donated by Tilcon Connecticut. This mix contained a 3/8” aggregate size and had a water to cement ratio of 0.30. A mid-range water reducer was also used.

2.5.2 Experimental Methodology

Figure 2-3 Unidirectional stainless steel fibers
To determine the compressive strength of the concrete cast inside the FRP pipes, small concrete cylinders were cast from that same batch for testing. Common procedure calls for test cylinders 8 inches tall with a 4 in diameter. Due to the small max aggregate size used in the mix design, 3 inch (7.62 cm) diameter and 6 (15.24 cm) inch tall cylinders (3x6’s) were admissible. A total of 36 test cylinders were made according to ASTM C39. The samples were cured in the same location as the CFFT’s to assure similar temperature and moisture conditions. On the experimental testing day of CFFT columns, concrete cylinders were removed from plastic forms and both ends were ground with a diamond wet saw to assure a uniform and plane top and bottom. Cylinders were affixed with a cage with a vertical and horizontal transducer to measure vertical and hoop strain during testing as seen in Figure 2-4. These transducers output to a HBM data acquisition system. The cylinders were tested in a MTS 400 kip hydraulic testing machine. The tests were displacement controlled with the machine platen moving at a rate of 0.02 in (0.5 mm) per minute. The machine displacement and load cell force were output to the data acquisition system. For the Tilcon batch, three 3x6 in cylinders were tested in compression on 7, 14, 21, 28, 56, and 118 days after casting. The average strength of cylinders can be seen in Table 2-2.
Figure 2-4: 3”x6” concrete cylinder with cage for strain measurements

<table>
<thead>
<tr>
<th>Concrete Batch</th>
<th>Design Compressive Strength ksi (MPa)</th>
<th>28 day Strength ksi (MPa)</th>
<th>Test Day Strength ksi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UConn Batch 1</td>
<td>8 (55.2)</td>
<td>x</td>
<td>4.0 (27.8)</td>
</tr>
<tr>
<td>UConn Batch 2</td>
<td>8 (55.2)</td>
<td>x</td>
<td>5.05 (34.8)</td>
</tr>
<tr>
<td>Tilcon Batch 3</td>
<td>5.0 (34.5)</td>
<td>4.68 (32.3)</td>
<td>5.3 (36.5)</td>
</tr>
</tbody>
</table>

In Figure 2-5 (a) the axial stress of a concrete test cylinder is plotted versus the hoop strain as recorded by the lateral displacement transducer. In Figure 2-5 (b), the axial stress is plotted versus the vertical strain as recorded by the vertical displacement transducer. Both plots show the Stress Strain curves for 28 days after concrete casting and on the day of testing for Tilcon Batch 3.
Figure 2-5 Axial Stress vs. Strain for Tilcon Batch 3 Concrete Cylinder at 28 Days and Test Day

(a) Hoop Strain (b) Vertical Strain
3 EXPERIMENTAL STUDIES

3.1 Justification

Previous research done by McBride et al. shows that hybrid composites with glass and small diameter steel fibers ‘show promise in structural applications because of their high strength, energy absorption during loading, and re-centering capabilities.’\(^\text{26}\) An exact optimal steel percentage was not discovered but it was found that a low steel percentage ~8% performed best in terms of energy dissipation, strength, and re-centering (versus steel percentages of 16% and 23%). Additionally, the research by McBride et al. only investigated hybrid composites with unidirectional fibers. It was recommended that further research be done to optimize composite design. The goal of this research here within is to gain understanding of the behavior of hybrid glass and steel fiber composites when used as filament wound pipes and in a CFFT System. Tension tests were conducted on hollow FRP pipes not filled with concrete. Compression tests were conducted on FRP pipes filled with concrete, which contrives the CFFT system. The energy dissipation and re-centering capability of the specimens investigated here within were of particular interest. Therefore all specimens were tested until failure under half-cyclic low cycle loading.

3.2 Construction

3.2.1 Filament Winding

The FRP pipes were manufactured by the process of filament winding at a Fiber Glass Systems (FGS) factory in Little Rock, Arkansas. Glass FRP pipes are manufactured mainly for use in petrochemical industry. In filament winding dozens of tows of fibers are tension feed into a resin bath (Figure 3-1a,b). This bath is attached to a Computer numerical control (CNC) carriage that travels on rails parallel to a spinning mandrel. The rotation of the mandrel and motion of the carriage are synchronized. To start manufacturing, the bundle of resin
impregnated fibers is wrapped around the end of the spinning mandrel to engage. The carriage then travels down the rails laying the fibers along the mandrel at precise angle layups (Figure 3-1c). The angle of layers and thickness of the fiber shell can be customized to meet the designer’s needs. After fibers winding is complete, the steel mandrel is heated to completely cure the polymer resin. Finally the FRP pipe is removed from the mandrel and cut to specified lengths\textsuperscript{30}. 

(a)  
(b)  
(c)  
(d)
Figure 3-1 Filament Winding Manufacturing Process

(a) Glass Fiber tows leading out from spools towards resin bath, (b) Fibers path through resin bath and deposited on mandrel, (c) Filament Winding CNC machine, (d) Laying steel fiber scrim on top of glass layers, (e) Steel fiber scrim wrapped around mandrel. Note that steel fibers run parallel to the length of the mandrel, (f) CNC machine depositing more glass layers on top of steel layer, (g) Finished pipe in curing oven

3.3 Pipe Manufacturing Process

Almost all FRP pipes were filament wound on a lab winder with a 12 ft. (3.05 m) long mandrel at FGS. This winder allows the product development engineers at FGS to test different materials and processes on pipes of a smaller scale. Some only glass pipes tested were manufactured on the mainline at NOV and are noted. The following description is of the manufacturing process for FRP pipes on the lab winder. Prior to winding, the 6” diameter steel mandrel was heated to 150°F (65.56°C) and a thin coat of Meguiars mirror glaze wax was
applied. The epoxy resin was heated to 120°F (48.89°C) and the hardener to 250°F (121.11°C) prior to mixing. The T5000 additive was at room temperature 75°F (23.89°C) when added. The 3 components were mixed together for 3 minutes and then poured into the resin bath on the CNC carriage. This mixture had a design pot life of 45 minutes. For the pipes with a 55° wind angle, 33 tows of the 250 yield E-Glass were fed through the resin bath to make up the “band” that wound around the mandrel. For the pipes with a wind angle of 45°, 47 tows were used. Each time the carriage completed a circuit and traveled down and back on the rail, it deposited the equivalent of 1 layer of glass fibers. For pipes built of only fiber glass, the machine continuously deposited layers until the desired quantity (6, 8 or 10) was reached. To incorporate steel fibers into the other pipes, the machine (carriage and mandrel) was paused after depositing 2 layers of glass. This coincided with the carriage reaching the end of the mandrel, so that the full pipe was free from the band of fibers. A 10’ 7” (3.23m) long by 20” (.508m) wide pre-cut fabric of steel fibers was placed over the mandrel like a blanket (Figure 3-1d). The weight of this fabric was 1.98 lbs (0.90 kg). The unidirectional steel fibers ran parallel to the mandrel (Figure 3-1e). The mandrel was then slowly rotated as the steel scrim was brushed with epoxy to ensure complete fiber wet-out. Once the steel scrim completely revolved to mandrel, the carriage was started up again at full speed. Two more layers of glass were laid down and then another steel scrim was placed just like the first one. After the second layer of steel was placed, 2 more layers of glass were deposited. At this point the 6G-2S pipes were completely wound. Pipes with 8 layers of glass and 2 layers of steel, 8G-2S, were wound with another 2 layers of glass. After all fibers were deposited the fiber tows were cut. A squeegee was attached to the CNC carriage and traveled down the length of the pipe to remove excess resin and create a smoother outer surface. The mandrel was then placed into a covered oven to be cured (Figure 3-1f). It was first heated
at 250°F (121.1°C) for 1 hour and 15 minutes and then raised to 325°F (162.8°C) for 45 minutes. Following the heat cure, the mandrel was removed and allowed to cool to the ambient temperature. Once cooled, the pipe was easily stripped from the steel mandrel due to the coating of wax. The thickness of the pipes varied depending on the number of layers and the angle of winding. Thicknesses ranged from 0.11 in to 0.28 in (2.8mm to 7.1mm).

The complete FRP pipes were then cut to length with a wet saw. Pipes sections of 2.5ft (0.76 m) long were cut for tension testing and 2ft (0.61 m) long sections were cut to be used as CFFTs. The manufactured tubes had an average outer diameter of 6.2 in (15.75cm). Therefore the length-to-diameter (L/D) ratio of the 2’ CFFTs was 3.8:1. Research by Mirmiran et al. found that the “effect of length-to-diameter ratios within the range of 2:1 to 5:1 is not significant for either strength or ductility of the section.” This means that these columns can be considered short columns and the slenderness effect is not of concern.”

3.3.1 Making CFFT System

In order to make the CFFT column system, the filament wound pipes detailed in 3.3 were filled with regular strength concrete. Prior to filling, all FRP pipes were washed and all relevant dimensions were recorded. For the first series of compression tested columns, the CFFT columns were made with an 8 ksi design (55.2 MPa) mix. For the second series of compression tests all columns were made with the same batch of 5 ksi (34.5 MPa) concrete. Both series of CFFTs were made in the same manner. Each FRP tube was individually caulked to smooth ¾” (1.91cm) thick sections of ply wood with Loctite PL 500 Landscape construction adhesive shown in Figure 3-1a. This was done at least 3 days prior to casting to allow the caulk to properly set. To cast the CFFTs, concrete was scooped into a tube until it was full 1/3 of the way up (Figure 3-2c). A concrete vibrator was then plunged into the concrete, with care not to strike
the sides of the pipe. The tube was filled to 2/3’s its full height and vibrated again. The tube was then completely filled, vibrated, topped off, and then troweled to ensure a flat uniform surface. Specimens were then left to cure for 3 days before removal from the plywood. They were cured indoors at room temperature +/-75°F (23.89°C). While some FRP pipes in Figure 3-2 appear to be taller than 2 feet (0.61 m), note that these were later cut down to height.

Figure 3-2 Casting of CFFT Specimens
(a) Grouting of FRP tube to plywood, (b) Hollow FRP tubes before casting of concrete, (c) FRP tubes being filled with concrete, (d) Specimens after casting

3.3.2 Naming Convention

The individually cut pipes are named based off of the wind angle of glass fiber and the number of glass and steel layers in the pipes. The name also details the testing performed on that
Pipe. Pipe 45-6g-2s-c-1 was wound with 6 layers of glass (6g) at 45°. It has 2 layers of steel (2s) and was tested under concentric axial loading (c). It was specimen number 1 tested with that material makeup. Pipe 45-6g-2s-c-2 had the same material makeup and underwent the same testing but was specimen number 2. Pipe 55-10g-0s-0.75e was wound with 10 layers of glass (10g) at 55°. It has 0 layers of steel (0s) and was tested under eccentric axial load 0.75 in (19mm) offset from the center line of the column (0.75e). Pipe names ending in –T# were tested in tension.

3.3.3 Table of Compression Specimens and Tests Conducted

Table 3-1 and Table 3-2 list the design properties of each pipe that was tested in compression. All specimens listed in Table 3-1 were tested under concentric axial load. Table 3-2 lists the parameters of all the columns tested under eccentric axial load. Eccentric tests were performed with eccentricities of 0.75in (19mm), 1.0in (25.4mm) and 1.5in (38.1mm). The fiber angle listed is that of the glass fibers in relation to the vertical axis. Steel fibers were placed 0° to the vertical axis. End Condition of “Pin” specifies that the column end was supported on a spherical or roller bearing. In this condition the specimen was free to rotate but not translate in any direction. End Condition of “Bearing” signifies that the flat end of the column was supported on the flat immovable surface of the testing platen. For this condition the specimen was prevented from rotation as well as translation. Specifics of the test setups are explained further below in section 3.4.6. Pipes in Table 3-1 that are highlighted in gray are those in ‘Group 1’. Those not highlighted are in ‘Group 2’. The specimen end preparation and loading protocol differed between Groups.
Table 3-1: Parameters of CFFTs tested under Concentric Axial Compression Load

<table>
<thead>
<tr>
<th>ID</th>
<th>Pipe Naming</th>
<th>Glass Fiber Angle,°</th>
<th># of Glass Layers</th>
<th># of Steel Layers</th>
<th>End Conditions (Top, Bottom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55-8g-0s-c-1</td>
<td>55</td>
<td>8</td>
<td>0</td>
<td>Pin, Bearing</td>
</tr>
<tr>
<td>2</td>
<td>65-8g-0s-c-1</td>
<td>65</td>
<td>8</td>
<td>0</td>
<td>Pin, Bearing</td>
</tr>
<tr>
<td>5</td>
<td>65-8g-0s-c-2</td>
<td>65</td>
<td>8</td>
<td>0</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>6</td>
<td>55-8g-0s-c-2</td>
<td>55</td>
<td>8</td>
<td>0</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>7</td>
<td>45-8g-0s-c-1</td>
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<td>8</td>
<td>0</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>8</td>
<td>45-6g-0s-c-1</td>
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<td>6</td>
<td>0</td>
<td>Pin, Pin</td>
</tr>
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<td>9</td>
<td>55-6g-2s-c-1</td>
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<td>6</td>
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<td>6</td>
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<td>23</td>
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<td>10</td>
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</table>
### Table 3-2: Parameters of CFFTs tested under Eccentric Axial Compression Load

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<th>ID</th>
<th>Pipe Naming</th>
<th>Eccentricity (in)</th>
<th>Glass Fiber Angle, °</th>
<th># of Glass Layers</th>
<th># of Steel Layers</th>
<th>End Conditions (Top, Bottom)</th>
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<td>24</td>
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<td>0</td>
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<tr>
<td>25</td>
<td>55-8g-0s-0.75e</td>
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<td>55</td>
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<td>0</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>26</td>
<td>45-6g-2s-0.75e</td>
<td>0.75</td>
<td>45</td>
<td>6</td>
<td>2</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>27</td>
<td>45-6g-0s-0.75e</td>
<td>0.75</td>
<td>45</td>
<td>6</td>
<td>0</td>
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</tr>
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<td>55-6g-0s-0.75e</td>
<td>0.75</td>
<td>55</td>
<td>6</td>
<td>0</td>
<td>Pin, Pin</td>
</tr>
<tr>
<td>29</td>
<td>55-10g-0s-0.75e</td>
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<td>10</td>
<td>0</td>
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</tr>
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</tr>
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</table>

### 3.3.4 Table of Tension Specimens

Listed in Table 3-3 are the parameters of the pipes that were tested in cyclic tension.

‘Inner Fill’ is explained in 3.3.5.2.

### Table 3-3: Parameters of Pipes Tested in Tension

<table>
<thead>
<tr>
<th>ID</th>
<th>Naming convention</th>
<th>Glass Fiber Angle, °</th>
<th># of Glass Layers</th>
<th># of Steel Layers</th>
<th>Length of Pipe (ft)</th>
<th>Inner Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>45-8G-05-T1</td>
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<td>8</td>
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<td>4</td>
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<td>T2</td>
<td>65-8g-05-T1</td>
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<td></td>
</tr>
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<td>Al Rings</td>
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<td>2.5</td>
<td>None</td>
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<td>T11</td>
<td>45-8g-2s-T2</td>
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<td>8</td>
<td>2</td>
<td>2.5</td>
<td>Al Rings</td>
</tr>
<tr>
<td>T12</td>
<td>55-8g-0s-T3</td>
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<td>0</td>
<td>2.5</td>
<td>None</td>
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<tr>
<td>T13</td>
<td>45-8g-0s-T4</td>
<td>45</td>
<td>8</td>
<td>0</td>
<td>2.5</td>
<td>None</td>
</tr>
</tbody>
</table>

3.3.5 Specimen Preparation

3.3.5.1 Compression Test Specimens

It was critical in the compression tests that the bearing surfaces (the top and bottom) of the CFFTs were uniform and precisely perpendicular to the length of the pipe. In the process of casting the CFFTs, some minor blowout occurred in the caulk seal between the FRP pipe and plywood. As a result, multiple pipes had concrete that unevenly extended out past the height of the FRP shell on the bottom. The loss of concrete from blowout or additional concrete consolidation after topping off also affected the CFFTs at the top. To achieve a flat perpendicular bearing surface, two distinct methods were employed. In the first method, all concrete that extended out beyond the FRP shell edge was removed. This was achieved with the use of a hammer and chisel and a grinding masonry wheel. The concrete was removed so that the level of concrete was 5mm +/-2mm (.2in) below the edge of the FRP pipe. On the top surfaces the concrete was also chipped away to achieve a similar void. This void was filled with a high strength epoxy anchoring adhesive, Simpson StrongTie ET-HP. This high strength 1:1 grout
epoxy has a compressive strength over 13ksi (90 MPa) after full cure and is non-shrink. All of the CFFT specimens that were prepared in the above method are designated ‘Group 1’

![Images of specimen preparation](image1.png)

**Figure 3-3** Preparation of CFFT ends for Group 1 specimens
(a) Concrete extending beyond edge of FRP shell due to blow out of grout, (b) extra concrete removed below level of FRP shell, (c) High-Strength Epoxy spread to fill in gap of removed concrete, (d) Flat surface of CFFT finished with epoxy

The second method used to achieve a uniform and perpendicular bearing surface was to cut the ends of the CFFTs. This was done by a 16 in (40.6cm) diameter wet tile saw in the Connecticut Advanced Pavement Lab at UConn (Figure 3-4a). The cast CFFT’s were aligned perpendicular to the blade and clamped in place. No cracking was observed in the concrete following the cutting process. All CFFT specimens that were prepared using the saw cut method were designated as ‘Group 2’ of the compression tests. Preparation of the bearing surfaces was done to all the tested pipes, including those that didn’t experience blowout, to have comparable results.
3.3.5.2 Tension Tests Specimens

The first experimental testing conducted was tension tests of hollow FRP pipes. Testing of the complete pipe instead of flat cut out coupons was done in order to capture the complete system behavior of the pipe. These pipe tension tests were conducted according to ASTM D2105. Special testing grips were designed and manufactured at UConn. Further details regarding the grips and their operation are given in section 3.5.4.1.

The process for prepping the specimens for tension testing was refined and improved upon as tests were conducted. The procedure described below describes the specimen preparation method that was found to work best.

It was critical that the tension specimens failed inside their gage length, not at the grips. Therefore care was taken to reinforce the ends of the pipes. In order to prevent failure the grips, the region of the FRP pipes that were engaged by the grips were reinforced with 0.0625 in (1.6mm) thick G10 fiberglass epoxy laminate. G10 laminate is specified for its extremely high strength and high dimensional stability over temperature. Two 4in (102mm) tall strip of the G10 with length slightly smaller than the inner circumference of the FRP pipe was sanded on one side.
to roughen up the surface. The inside of the FRP pipes were smooth due to being formed around the steel mandrel (Figure 3-5a). Therefore the top and bottom 4in (102mm) of the inside of the pipe were sanded to roughen up the surface. West System G-Flex Epoxy was then spread on the roughened side of the G10 and the laminate was then placed inside the top and bottom 4in of the pipe (Figure 3-5b). After the filament winding manufacturing process the outer surface of some of the FRP Pipes had raised sections where excess epoxy had cured. Any of these bumps were sanded down so the outside of the pipe was more uniform. G10 sheets 4in tall and slightly shorter than the outer circumference of the pipe were prepared. They were epoxied to the outside of the pipe and held in-place to cure by a circular collar.

Through testing it was noticed that the hollow FRP pipes under tension would fail as the mid height of the pipe constricted. Since the main application studied was to be filled FRP pipes, it was decided to test ‘filled’ FRP pipes under tension. This was achieved by placing aluminum rings inside the pipe to mimic the concrete core of the CFFTs (Figure 3-5a). These rings were each 1.5in (38mm) tall, .375in (9.5mm) thick and had an outer diameter equal to 5.99in (15.21cm). After these rings were placed inside the pipes, the above procedure for the G10 reinforcement was performed.

In total, 13 FRP pipes were tested in tension. Four of these specimens were tested with the aluminum inner fill to simulate the effect of concrete. The specifics of each test can be found in Table 3-3: Parameters of Pipes Tested in Tension.
3.4 Instrumentation

3.4.1 400 Kip Testing Machine

All experimental testing was conducted using a Satec 400 Kip (1779 kN) hydraulic testing system. This system was controlled by a MTS FlexTest 40 Controller. Specimens were attached to grips affixed to the middle and top platens and tested in tension as the platens separated (Figure 3-6a). Specimens could also be positioned between the middle and bottom platens and tested in compression (Figure 3-6b). The movement of the machine could be
controlled in two manners. Under *displacement control* the bottom platen would displace at a constant rate in a given direction. With *force control*, the bottom platen would move to achieve a certain load on the load cell within a certain time. Under *force control* the rate of displacement is controlled by the machine and can vary. The machine load cell was located underneath the bottom platen.

![Figure 3-6 400 Kip Testing Machine](image)

(a) Tension test in 400 kip machine, (b) Concentric compression test in 400 kip machine

3.4.2 DAQ

The data acquisition system used was a Hottinger Baldwin Messtechnik (HBM) MX-1615. The software used to interface with the HBM Data Acquisition System (DAQ) was HBM’s CatmanEasy. The sampling rate for all sensor channels was 50 Hz.
3.4.3 Strain Gauges

For all specimens, FRP tubes tested in tension and CFFT in compression, two strain gauges were utilized. These two tri-axial rosette strain gauges were affixed at the mid height of the specimens, 180° across from each other. Their layout on any specimens is seen below in Figure 3-7a. TML YEFRA-5 gauges were used in all tension specimens and Group 2 compression specimens. These are 0°/45°/90° 3-element plane rosette 120 Ω gauges “applicable in the measurement of large strains up to 10~15%”\(^{33}\). All specimens of Group 1 were instrumented with TML FRA-5-11 0°/45°/90° 3-element plane rosette 120 Ω gauges\(^{34}\). For all specimens, the 0° gauge was aligned parallel to the height of the column. The 90° gauge was aligned perpendicular to the height of the column. The 0° strain gauge on side 1 (the left side in all pictures) of the column is referred to as SG-1-Vert here within. The 90° gauge on the left is named SG-1-Horz. The 45° gauge on the left is named SG-1-45°. The strain gauges on side 2 (the right) are named accordingly; SG-2-Vert, SG-2-Horz, SS-2-45, respectively.
Figure 3-7 Strain Gauges, (a) Schematic of strain gauge location on specimens, (b) TML YEFRA-5 strain gauges, (c) TML FRA-5-11 strain gauges
3.4.4 Concentric Axial Compression Tests

To more accurately measure the displacement of the machine, a displacement transducer was placed perpendicular to the bottom surface of the middle platen. This transducer, a TML CDP-50 with a stroke of 50mm (1.97 in), is seen in Figure 3-8a. This transducer had a sensitivity of 5.0mV/V. Vertical strain was measured on the column itself through the use of two 100mm (3.94in) stroke potentiometers. The potentiometer seen in Figure 3-8b is on ‘Side 1’ of the column while Figure 3-8c is 180° across, on ‘Side 2’. In Figure 3-9 and here within, these transducers are labeled as TR100-1 and TR100-2 respectively. These potentiometers were attached to bolts that were 13 in (33.02 cm) apart, centered at the mid-height of the column. These four 0.625 in (1.59 cm) diameter bolts were epoxied to the outside surface of the column with a 5 minute epoxy at least 1 day before testing. The sensor seen in Figure 3-8d was a Humboldt Large displacement transducer, HM-2310.04. It was affixed to a steel cage circumscribing the column at the mid-height. This displacement transducer measured the hoop strain of the specimen. This transducer is labeled as TR40-H in Figure 3-9 and here within.
**Figure 3-8**: Instrumentation of Concentric Axial Loaded CFFT

**Figure 3-9**: Schematic of Transducer location for Axial Compression tests
3.4.5 Eccentric compression

The instrumentation for the eccentric compression testing was the same for eccentricities of 0.75” and 1.5”. Like previously stated, all specimens were affixed with 2 tri-axial strain gauges at mid height. All transducers shown in Figure 3-9 for the concentric compression tests were also utilized in the same manner for all the eccentric compression tests.

The lateral deflection of the column was measured at two points; at mid-height and 3 in (7.62 cm) up from the bottom of the column. The mid-height lateral displacement was recorded by a TML CDP-50 with a stroke of 50mm (1.97. in) and sensitivity of 5.0mV/V (TR50-MHD in Figure 3-10). The lateral displacement 3 in (7.62 cm) up from the bottom of the column was recorded with a TML CDP-25 displacement transducer with a sensitivity of 6.25mV/V (TR25-M in Figure 3-10). These lateral displacement transducers were placed so their pistons lined up with the center line of the column. TR25-TBR and TR25-BBR in Figure 3-10, both a TML CDP-25, recorded the rotation of top and bottom the pin bearings respectively.
Figure 3-10: Layout of column for eccentric compression loading
3.4.6 Tension Tests

To measure longitudinal strain of the hollow pipe tested under tension, two Novotechnik LWG displacement transducers were affixed to the pipe at mid-height. These transducers were attached at locations 180° apart, by bolting to 5/8 in (1.59 cm) bolts epoxied to the pipe. For hollow pipes of 48 in (122 cm) length, two Novotechnik LWG-225 transducers were used, with undeformed length of 18 in (45.7 cm). For hollow pipes of 30 or 24 in (76 or 61 cm), two Novotechnik LWG-100 transducers were used, with undeformed length of 13 in (33 cm). To measure hoop strain, one Humboldt HM-2310.04 Strain Transducer with a stroke of 0.4” (10mm) was affixed at mid-height. The location and labels of these transducers are shown in

Figure 3-11: Location and labels of displacement transducers for different length pipes
3.5 Experimental Methodology

3.5.1 Compression Concentric

3.5.1.1 Test setup

Columns were tested in the 400 kip hydraulic machine. A spherical bearing was attached at the center of the middle platen, hanging down. For specimens with pin-pin boundary condition, a second spherical bearing was positioned at the center of the bottom platen (Figure 3-12). On the other tests the bottom of the column rested on the bottom platen, bearing on the surface, as seen in Figure 3-8. Regardless of end condition all specimens were aligned in the center of the machine. End conditions of each type are explained in 3.3.3 and listed in Table 3-1 and Table 3-2. All instrumentation was attached and zeroed as appropriate.

![Figure 3-12](image)

**Figure 3-12** Spherical bearing at bottom of specimen
(a) Test setup for Concentric Axial tests as Pin-Pin, (b) Close up of bottom spherical bearing
3.5.1.2 Loading protocol

There were two different loading protocols used for the separate ‘Groups’ of compression specimens. The start sequence and first cycle for both ‘Groups’ was the same. To start all concentric compression tests, a load of 2 kip (8.9 kN) was placed on the column. For the first cycle the force on the CFFT was increased from 2 kip (8.9 kN) to 50 kip (222kN) in 30 seconds. After reaching the force of 50 kip (222kN), the force was lowered back down to 2 kip (8.9 kN) again. This unloading was also performed in 30 seconds. The first cycle was completed with the machine operating under force control. The first cycle was loading to 50 kip (222kN) under force control in order to complete a full half cycle while the CFFT specimen remained elastic.

In ‘Group 1’ tests, for the second cycle, the machine operation was switched to displacement control. The bottom platen of the machine was raised at a rate of 0.2 in (0.51 cm) per minute (compressing the column). When the average strain of the left and right vertical displacement transducers reached 0.25%, the machine was paused. The machine was then switched over to load control and the bottom machine platen was lowered (reducing load on the column) until the force on the column was 2 kip (8.9 kN). This unloading sequence was performed in the same amount of time as the loading sequence. The loading/unloading cycle was then repeated with the peak of each new cycle corresponding to average vertical strains of 0.5%, 1.25%, 2%, 3%, 4%, 5%, 6% and 7%. The columns were cycled through loading and unloading until failure. Pictures were taken at the beginning, peak, and end of each cycle. Figure 3-13 shows the load and machine displacement versus time for a Group 1 specimen.

In tests conducted on ‘Group 2’ specimens, the machine operation was switched to displacement control following completion of the first loading cycle. The platen was then raised to a target machine displacement 0.1 in (.25cm) larger than the peak machine displacement
recorded under the 50 kip (222kN) of cycle one. The platen moved at a rate of 0.2 in (0.51 cm) per minute. After reaching this target displacement, the machine was switched to load controlled and the load was reduced down to 2 kip (8.9 kN). This unloading was performed in the same time it took to bring the column to the target displacement that round. After unloading to 2 kips (8.9 kN) the machine was placed back to displacement controlled. For each following cycle, the target displacement would increase by 0.1 in. Columns were cycled until failure. Figure 3-14 shows the load and machine displacement versus time for a Group 2 specimen. The target displacement in inches, $\delta_t$, for any cycle number, $n$, is given in Equation 3-1, where $\delta_{50}$ is the machine displacement at the peak of cycle one.

$$\delta_t = \delta_{50} + 0.1(n - 1) \hspace{1cm} \text{Equation 3-1}$$

Figure 3-15 displays the load versus machine displacement curve for the same test in Figure 3-14. For emphasis each individual loading and unloading half cycle is unique line style.
Figure 3-13 Machine Displacement and Load versus Time of a Group 1 CFFT specimen under half cyclic concentric compression

Figure 3-14 Machine Displacement and Load versus Time of a Group 2 CFFT specimen under half cyclic concentric compression
3.5.2 Compressing eccentric 0.75”

3.5.2.1 Test setup

The top half of the top roller bearing was bolted underneath the middle platen, directly in the center. Another roller bearing was aligned to the center of the bottom platen, with the axis of rotation of both bearings running parallel. The specimens were placed so that the centerline of the specimen was offset 0.75 in (1.90 cm) to the left of the centerline of both the roller pin bearings. The straps seen attached to the top roller bearing plate did not restrict movement but rather were there to prevent the bearing from falling in the event of violent specimen failure. A specimen at different stages of testing is shown in (Figure 3-15).
3.5.2.2 Loading protocol

First, the CFFT specimen was loaded to 2 kip (8.9 kN). To start cycle one, the force was then increased to 50 kip (222 kN) in 30 seconds. The machine displacement, at the middle platen at the load of 50 kip (222 kN), was recorded. The column was then unloaded down to 2 kip (8.9 kN). For cycle two, the column was loaded at a rate of 0.2 in (0.51 cm) per minute to a target displacement 0.075 in (0.19 cm) larger than the recorded displacement at 50 kip (222 kN). After reaching the target displacement the column was unloaded to 2 kip. Each new cycle, the target displacement was increased by 0.075 in (0.19 cm) from the previous target displacement. For the unloading of each cycle the column was unloaded to 2 kip (8.9 kN). The target displacement in inches, $\delta_t$, for any cycle number, $n$, is given in Equation 3-2, where $\delta_{50}$ is the machine displacement at the peak of cycle one.

$$\delta_t = \delta_{50} + 0.075(n - 1) \quad \text{Equation 3-2}$$
3.5.3 Compressing eccentric 1.5”

3.5.3.1 Test setup

The test setup for compression tests with an eccentricity of 1.5 in (3.81 cm) was the same as for 0.75 in (1.90 cm) eccentricity, except the offset was 1.5 in (3.81 cm). Notice that the laser in Figure 3-17 aligns with the center of the machine and therefore the roller bearings

![Test setup for Compression Tests with eccentricity of 1.5 in (3.81 cm)](image)

Figure 3-17 Test setup for Compression Tests with eccentricity of 1.5 in (3.81 cm)

3.5.3.2 Loading protocol

First, the CFFT specimen was loaded to 2 kip (8.9 kN). To start cycle one, the force was then increased to 30 kip (133kN) in 30 seconds. The machine displacement, at the middle platen at the load of 30 kip (133kN), was recorded. The column was then unloaded down to 2 kip. For cycle two, the column was loaded at a rate of 0.2 in (0.51 cm) per minute to a target displacement 0.005 in (0.01 cm) larger than the recorded displacement at 30 kip (133kN). After reaching the target displacement the column was unloaded to 2 kip. Each new cycle, the target
displacement was increased by 0.005 in (0.01 cm) from the previous target displacement. For the unloading of each cycle the force on the column was reduced to 2 kip (8.9 kN). The target displacement in inches, $\delta_t$, for any cycle number, $n$, is given in Equation 3-3, where $\delta_{30}$ is the machine displacement at the peak of cycle one.

$$\delta_t = \delta_{30} + 0.1(n - 1) \quad \text{Equation 3-3}$$
3.5.4 Tension Tests

3.5.4.1 Test setup

The tension grips were affixed to the specimen and it was positioned in the 400 kip testing machine. Each grip was attached to the testing machine by a universal swivel joint, seen in Figure 3-18. These joints accounted for any eccentricities present in the test setup. The grips used to pull the pipes in tension were built as dictated in ASTM D2105. Precise grip specifications can be found by referring to the ASTM document. The grips worked by pulling on a tapered mandrel, Figure 3-19a&b, which caused 4 tapered wedges to expand outward, gripping the inside of the pipe. The pipe was prevented from deforming due to the expanding wedges by collars placed around the outside of the column. Prior to conducting the test, the wedges were pre-engaged by tightening of 8 bolts, Figure 3-19c, so to adequately grip the inside of the pipe. The bolts were each tightened to a torque of 300 lb-in (33.9Nm), Figure 3-19d.

Figure 3-18: Pipe in machine for tension setup, universal swivel joints identified
Figure 3-19: Tension Grips, (a) Tapered mandrel (b) Close-up of bottom tension fixture, mandrel (c) Bolts for prestressing grips (d) tightening of bolts to specific torque
3.5.4.2 Loading protocol

First, the axial tension load on the specimen was increased to 2 kip under *force control*. After this, for each loading cycle, \( n \), the platen was displaced 0.25 in (0.64 cm) \( \times n \). The platen was displaced at a rate of 0.5 in/min (1.27 cm/min). For unloading cycles, the load was returned to 2 kip (8.9 kN) in the same time it took for that loading cycle.
4 EXPERIMENTAL RESULTS, OBSERVATIONS, & COMPARISONS

4.1 Introduction

In this chapter, experimental results including the observed failure mechanisms of the specimens, load-displacement response, energy dissipations, and residual displacements of specimens are presented. In addition the performance of specimens is compared. The analysis method of raw data collected during the experiments outlined in Chapter 3 is described here.

4.2 Compression Tests

4.2.1 Failure Mechanisms

There were immediately noticeable similarities between specimens of common parameters and how they failed. The glass fiber angles were the main parameter that dictated failure mode. Figure 4-1 shows the failure mechanism of three specimens made with glass wound at 45°. All three of these specimen and all other 45° specimens tested exhibited rupture along one line, parallel with the glass winding angle. Small cracks in the FRP tube were visible at the failure location on the cycles before the tube completely broke open. This area experienced bulging on cycles prior to ultimate failure. Also, the failure or crushing point was limited to one end of the column with the other end visually remaining intact. The 45° glass did not provide enough confinement to engage the entire column at failure.

The CFFT specimens with glass wound at 55° exhibited a failure mode different than those with 45° glass. These failure modes are shown in Figure 4-2. Longer length of the 55° column specimens were engaged in failure. At failure, a crack suddenly opened up in the FRP shell. This crack ran along the height of the column in a zigzag pattern. It is especially noticeable in specimens such as Figure 4-2b that the crack alternates direction at ±55°, along the wind angle.
Specimens manufactured with glass wound at 65° exhibited explosive failure as the FRP shell ruptured. These failures are shown in Figure 4-3. Note that the line of rupture does not zigzag ±65° but rather runs directly vertical for more than half the height of the column. Pictures of each tested specimen before and after testing can be found in the Appendix B.

Figure 4-1: Failure mechanism of 3 different columns with 45° glass
4.2.2 Data Filtering

When the Satec 400 kip testing machine was turned on, the machine load cell did not output a load equal to zero due to the weight of test fixtures resting on the bottom platen. This initial load was roughly 300lb (1334 N), +/- 200 lb (900 N). The column specimen was placed in the machine after it was turned on, but before data was being recorded. After precisely aligning the specimen, the bottom platen was moved up until the gap between the top of the column and the top bearing was less than 0.125 in (0.32 cm) but greater than 0 in. At this point the data collection was started to capture the time that platen first made contact with the specimen. The force value output from the 400 kip load cell was taken as the zero force in the beginning of data collection. In data processing, the ‘zero force’ value was subtracted from each force value recorded. Each specimen tested had its own unique ‘zero force’ used.
The values of the testing machine’s platen displacement also didn’t start at zero exactly when the column began compressing. Therefore the displacement data needed to be shifted to align the start of cycle one with a displacement of zero. To do this a line was fit to the linear elastic portion of the first loading cycle. The equation of this line and its x-intercept were found. The value of the x-intercept was then subtracted from each displacement data point. The load versus displacement graph of a specimen is shown in Figure 4-4. The load on the y-axis is in kips while the x-axis is machine displacement in inches. The two red dots show the linear region of the first loading cycle that the line was fit to. This line intersects with the x-axis at 0.848 in, marked by the blue arrow. Therefore in processing, 0.848 (in) was subtracted from each and every displacement point for that specimen. Each specimen had its displacement data zeroed by a unique x-intercept value. All post processing and analysis of data was done using R, a statistical computing programing language\textsuperscript{35}.

\textbf{Figure 4-4} Aligning of the displacement data on a plot of the machine load versus the machine displacement
4.2.3 Analyses Methods

4.2.4 Load versus Displacement Backbones

To easily visualize performance differences among different tests on the same plots, backbone curves were plotted for the load versus strain curves. The backbone curve directly follows the positive loading curves of the first two cycles, reaching to the peak load at cycle 2. The backbone curve then traces the maximum load point of each subsequent cycle. The backbone curve in Figure 4-5 is shown as a dashed red line, plotted over the original load versus strain curve for a cyclic concentric compression test. The load versus strain and corresponding backbone curves are found in Appendix A.

![Graph showing backbone curve for concentric compression sample with 55° glass wind angle](image)

**Figure 4-5** Backbone curve for concentric compression sample with 55° glass wind angle

4.2.5 Residual Strain Ratio

The re-centering capacity of each specimen was of particular interest. Following extreme loading, it is important that structural members are not experiencing large permanent displacement. Structures that undergo large permanent deformations are often demolished even if they are still standing. An ideal structural component could return close to its original zero
position after loading. This ability to return after loading was quantified by calculating the residual strain ratio (RSR) for each cycle. The RSR for a cycle is calculated as $\frac{\varepsilon_e}{\varepsilon_p}$; the residual axial strain, $\varepsilon_e$, at the end of a loading cycle over the maximum axial strain reached during that cycle, $\varepsilon_p$. Figure 4-6 shows where these values originate from on load versus strain graph for a cyclically loaded specimen. The RSR value is calculated for each complete loading cycle that the specimen undergoes. In Figure 4-6 the labeled strains correspond to loading cycle 5. The RSR of each cycle is plotted in Figure 4-7 on the y-axis, versus the maximum axial strain of the corresponding cycle, $\varepsilon_p$, on the x-axis. Figure 4-6 and Figure 4-7 are different plots for the exact same tested specimen, 55-6g-0s-c-1. A perfectly elastic material would have a RSR value of near zero as it would not deform plastically. The plots of RSRs for all specimens are provided in Appendix A.

![Figure 4-6: Sample Load versus Strain graph with strain labels for loading cycle 5](image)
While it is important that structural members not undergo large permanent deformations, they also need to dissipate energy. Steel dissipates energy by yielding, undergoing unrecoverable deformations. Fiber glass will not permanently deform but also won’t dissipate energy prior to the onset of failure mechanisms. Examining energy dissipation is crucial to the understanding of the proposed hybrid steel/glass system. The energy dissipation is calculated by integrating the load versus strain curve. The cumulative energy dissipated for a specimen during testing is shown in Figure 4-8. The energy dissipated is plotted on the y-axis versus each corresponding strain value on the x-axis.

For every specimen tested, an Energy Dissipation Ratio (EDR) was calculated for each completed loading cycle. This ratio compares the recorded dissipated energy for a cycle versus the maximum possible dissipated energy for the load and strain reached in that cycle. The loading and unloading curve of cycle 4 for specimen 55-6g-0s-c-1 is outlined in red in Figure 4-9. The energy dissipated during that cycle is found as the area under the curve, $A_C$, shown in

![Figure 4-7 RSR versus the maximum strain of that cycle, $\varepsilon_p$]
dark grey. For each cycle, a rectangle was made that defines the maximum possible dissipated energy. The first corner point of the rectangle is the starting strain of that loading cycle. This is marked with a green square for cycle 4 in Figure 4-9. A second point was found on the red cycle curve where the area of a rectangle bound by the 2 points was maximized. This second point is the red dot labeled 4 in Figure 4-9. The area of the rectangle, $A_R$, bound by these 2 points includes the light and dark shaded areas of Figure 4-9. The energy dissipation ratio is equal to the area under the cycle curve divided by the area defined by the rectangle: $\frac{A_C}{A_R}$.

For cycle 4, show in Figure 4-9, the strain at the end of the cycle is marked by a cyan X. The energy dissipation ratio for each cycle is plotted versus the strain reached at the end of that cycle. Figure 4-10 shows the complete plot of EDR for each cycle of the specimen tested in Figure 4-9. Plots of cumulative dissipated energy and EDRs for all tests can be found in Appendix A.

![Figure 4-8](image.png)

**Figure 4-8** Cumulative energy dissipated versus strain at that point
Damage Curves

To quantify the onset of damage through the progress of each cyclic test, damage curves were made. These curves serve to show the changing stiffness of the column specimens as cyclic
tests progressed. For each loading cycle, the slope of the load versus displacement was found. These slopes are visible as the dashed green lines of Figure 4-11a. Notice how for the slope of the loading cycles decreases are the displacement increases. The slope values were plotted on the y-axis versus the max displacement of the previous cycle, on the x-axis. Figure 4-11b shows the damage curve. The method for quantifying damage was based off of Van Paegpegem et. al’s method. Graphs like Figure 4-11b can be found for all specimens in Appendix A.

![Figure 4-11: Generation of Damage Curves (a) The slopes of each loading cycle (b) Each slope plotted versus the max displacement of the previous cycle](image)

**4.2.8 Comparison of Results**

In graphs comparing the performance of different specimens, only one design or testing change will be examined at a time. For instance, Figure 4-12 shows the load strain backbone curve for all concentric compression tests done on specimens with eight layers of glass and zero layers of steel. The title above the graph displays the standard specimen naming convention with an ‘X’ in the place of the variable that is changed for the plot. The differing variables for ‘X’ are presented in a legend below the title. In cases where there is more than one specimen with the
same design, tested in the same fashion, separate lines will be plotted with same line type.

Figure 4-12 shows the results of two separate concentric compression tests done on 65-8g-0s specimens with two solid black lines. Three tests were conducted on 55-8g-0s specimens, shown as three dashed red lines. And, two tests were conducted on 45-8g-0s specimens, represented by two dotted blue lines. A summary table of all compression tests is found at the end of the section.

4.2.8.1 Concentric Axial Load Compression Tests

4.2.8.1.1: \(X^\circ\)-8G-0S-c

\(X^\circ\)-8G-0S-c describes specimens tested under concentric compression with 8 layers of glass fibers, no layers of steel fibers, and a varying (\(X^\circ\)) glass fiber angle.

![Graph of X°-8G-0S-c compression tests](image)

**Figure 4-12:** Entire Load versus Strain backbone curves for \(X^\circ\)-8G-0S-c. Load Strain Curve for strains from 0 to 0.5%
For specimens with 8 layers of glass and no steel, load strain behavior changes based on the fiber angle of the glass. Specimens with fibers wound at 45° reached a peak load at about 0.5% strain and then underwent strain softening. While the strain at peak load is larger than the conventional 0.2% taken for unconfined concrete, the general shape of the curve follows that of unconfined concrete. The specimens with 45° glass showed almost no improvement in strength compared to the bare concrete tested.

Specimens with glass fibers wound 55° from the height of the column did not demonstrate strain softening. As the displacement was increased on these columns, the load continued to climb until failure. These tests are visible in Figure 4-12 as the red dashed lines. Specimens with 65° glass fibers experienced the most confinement as the fibers were more perpendicular to the axial loading direction than those of 45° and 55°. These specimens underwent strain hardening and failed at $F'_{cc}$ which was reached at max strain, $\varepsilon_{cc}$. Figure 4-13 shows a zoomed in view of Figure 4-12 at initial loading. On average, specimens show similar initial stiffnesses, due to same concrete being used inside the CFFT specimens. The initial stiffnesses are listed for all tests in Table 4-1.
The energy dissipation ratio (EDR) at each cycle for the 8 layer all glass specimens is shown in Figure 4-14. All specimens have low EDRs for the first cycle (first point on graph) as this is when they were still in the elastic range. Specimens with 8 layers of glass at 55° and 65° degrees have EDRs that plateau around 0.4. The specimens with 45° glass reach EDRs of around 0.8 at cycles between 1% and 2% strain. This is due to concrete crushing because of inadequate confinement. This concrete crushing does dissipate energy but is non-recoverable. It is not feasible to count on concrete crushing as an energy dissipation mechanism in design. Specimens were tested under displacement controlled loading and this crushing occurs at loads much below the peak force. In real world scenarios, once extreme crushing was reached, columns would fail rapidly if under sustained load. In Figure 4-15 is clear that while the peak EDR of 45°-8G-0S-c is large, the cumulative energy dissipated is much lower than those specimens with 55° and 65° glass fibers.
Figure 4-14: EDR curves for X°-8G-0S-c

Figure 4-15: Cumulative Energy Dissipated for X°-8G-0S-c
Figure 4-16 shows the Residual Strain Ratio of each cycle over the peak strain at the cycle. The lower the RSR, the better a specimen’s recentering capability at that strain. For comparable strains, that larger the glass fiber angle, the smaller the RSR. At 2.5% strain, the average RSR for 65° is about 0.5, for 55° is about 0.6, and for 45° is about 0.7%.

![Figure 4-16: Residual Strain Ratio for X°-8G-0S-c.](image)

The slopes of the initial loading cycle were similar for all X°-8G-0S-c specimens tested, as shown in Figure 4-12b. As more cycles were completed, these slopes deviated as the specimens accrued more damage. Figure 4-17 presents the slopes for each loading cycle versus the peak strain of the previous cycle. The construction of these curves is detailed in 4.2.7. They show the progression of damage throughout the test as the change in stiffness. Specimens of all glass angle varieties show a decline in stiffness over cycles from 0 to 1.5% strain. After this point, the stiffnesses of specimens with 55° glass and those with 65° glass remain constant. The loading slope for 45° glass specimens continues to decrease. After initial stiffness loss, 65° and
55° specimens do not undergo more stiffness loss until failure. Meanwhile 45° specimens continue stiffness loss until failure. At larger strains, specimens with 65° glass are stiffer than 55° specimens which are stiffer than 45° specimens.

![Damage Progression curves for X°-8G-0S-c](image)

**Figure 4-17:** Damage Progression curves for X°-8G-0S-c

### 4.2.8.1.2: X°-6G-0S-c

For specimens made with pipes of 6 layers of glass fibers and no steel, fiber angles of 45° and 55° were tested. The backbone of the cyclic load versus strain behavior is presented in Figure 4-18. The average maximum load for 45° specimens was 143 kip while the average maximum load for 55° specimens was 172 kip. Like with the X°-8G-0S-c specimens, the strain at maximum load was much smaller for 45° specimens than for 55° specimens. After reaching maximum load, the 45° specimens load capacity dropped sharply.
As with the X°-8G-0S-c specimens, 45°-6G-0S-c specimens had higher EDRs than 55°, as seen in Figure 4-19. This is attributable to the greater crushing of the concrete due to less confinement. Despite a higher EDR, specimens with 45° fibers over all dissipated much less energy than those with 55° as evident in Figure 4-20. Figure 4-21 presents the damage progression and shows a greater loss of stiffness for 45° specimens versus 55° specimens. Due to this damage, the 45° specimens had higher RSRs than 55° specimens as shown in Figure 4-22.
Figure 4-19: EDR curves for $X^\circ$-6G-0S-c specimens

Figure 4-20: Cumulative Energy Dissipated for $X^\circ$-6G-0S-c
Figure 4-21: Damage progression for X°-6G-0S-c specimens

Figure 4-22: RSR curves of X°-6G-0S-c
4.2.8.1.3 : 55°-XG-0s-c

Keeping the angle of fiberglass similar, tests were done on specimens with a varying number of glass layers. As seen in Figure 4-23, for similar strains, the axial load was higher for specimens with more layers of glass. This can be attributed to a higher level of confinement. As noted in previous specimens, lower confinement, 6 layers of glass versus 8 or 10 in this case, corresponds to a larger EDR, (Figure 4-24). The larger EDRs are achieved in part through unrecoverable displacement. This is seen in Figure 4-27 as specimens with 6 layers of glass have higher RSR values than specimens with 8 or 10 layers.

![Load vs. Strain backbone curves for 55°-XG-0s-c specimens](image)

**Figure 4-23:** Load vs. Strain backbone curves for 55°-XG-0s-c specimens
Figure 4-24: EDR curves for 55°-XG-0s-c

Figure 4-25: Cumulative Energy Dissipated for 55°-XG-0S-c
Figure 4-26: Damage Progression of specimens 55°-XG-0s-c

Figure 4-27: Residual Strain Ratio of 55°-XG-0S-c
4.2.8.1.4 : 55°-8G-XS-c

The variable changed for specimens 55°-8G-XS-c is the presence of longitudinal steel fibers in the FRP pipe. Specimens with zero layers of steel were designated 0S, while those with steel fibers had 2 layers incorporated in the shell, and were labeled 2S.

For all 55°-8G-XS-c specimens, the load versus strain curves show similar behavior for strains from 0 to 2%. Specimens with 8 layers of 55° glass and 2 layers of 0° steel achieved ultimate strains about half of that achieved by specimens without steel, (Figure 4-28). The average EDRs are higher for the samples with steel fibers (Figure 4-29) versus those with only glass. But the slopes of the loading cycles are also larger for the samples with 2S versus 0S, (Figure 4-31). This stands in contrast to the results of X°-8G-0S, seen in Figure 4-14 and Figure 4-17. In that case, 45°-8G-0S-c specimens had the highest EDRs and also the lowest loading slopes. This difference suggests that with the addition of the steel fibers, the 55°-8G-XS-c specimens are dissipating energy not by concrete damage but through the yielding of the steel fibers. Figure 4-32 shows that the RSR for 55°-8G-XS-c specimens with 2S is consistently larger than the RSR for 0S specimens. This can be attributed to the plastic deformation of steel fibers versus the elastic behavior of just glass fibers.

The cumulative energy dissipated for samples without steel is larger than those with steel because of the much higher strains reached before failure, (Figure 4-30). This lower ultimate strain in specimens with steel may be due to deficiencies in the method of incorporating the steel fibers. Future bending tests of HCFFTs manufactured in an alternative manner will further invest energy dissipation.
**Figure 4-28**: Load Versus Strain backbone curve of specimens 55°-8G-XS-c

**Figure 4-29**: Energy Dissipation Ratio versus the peak strain of each cycle for 55°-8G-XS-c
Figure 4-30 Cumulative Energy Dissipated for 55°-8G-XS-c

Figure 4-31: Progression of damage for 55°-8G-XS-c specimens
4.2.8.1.5  55°-6G-XS-c

The average maximum loads of the 55°-6G-XS-c specimens were approximately 20% smaller than those of the 55°-8G-XS-c specimens. The overall load versus strain behavior of 55°-6G-XS-c specimens (Figure 4-33) was similar to those of 55°-8G-XS-c. For 55°-6G-XS-c, yielding occurred at a similar point for specimens with or without steel. But again, specimens with steel included failed at strains much smaller than those without steel. For 55°-6G-XS-c specimens, there is not a noticeable difference in EDR values between 0S and 2S specimens. As shown in Figure 4-36, the cycle loading slopes for 2S specimens are slightly larger than those for 0S specimens.
Figure 4-33: Load versus Strain backbone curves for 55°-6G-XS-c specimens

Figure 4-34: EDR for 55°-6G-XS-c
Figure 4-35 Cumulative Energy Dissipated for 55°-6G-XS-c

Figure 4-36: Damage Progression for 55°-6G-XS-c
4.2.8.2 Eccentric Axial Load Compression Tests

4.2.8.2.1 55°-XG-0S-0.75e

The load vs. strain behavior of 55°-XG-0S specimens under a load at an eccentricity of 0.75in (1.90 cm) is shown in Figure 4-38. Specimens manufactured with 10 layers of fiber glass reached a load higher than those with 8 or 6 layers. In fact all specimens tested at an eccentricity of 0.75in (1.90 cm), except 55-10G-0S-c, exhibited similar peak load values and corresponding strains. These values can all be found in the third and fourth columns of Table 4-1. It is seen in Figure 4-39 that the specimen with 10G accumulated less damage during cycles than those with 6 or 8 layers.
**Figure 4-38:** Load vs. Strain backbone curve for 55°-8G-0s-0.75e specimens

**Figure 4-39:** Change of loading slope (Damage Progression) of 55°-8G-0s-0.75e
55°-6G-XS-0.75e specimens with steel fibers have a higher stiffness on loading than those without, as evident in Figure 4-40. The slope of the initial loading cycle for 55°-6G-2S-0.75e was 308 kips and was 234 kips for 55°-6G-0S-0.75e. The specimens with steel fibers also have a higher EDR achieved through a higher RSR, seen in Figure 4-41 and Figure 4-42 respectively. This is can be attributed to the yielding of the steel fibers. For these specimens the reduction in failure strain due to the inclusion of steel fibers was around 15%.
Figure 4-41: EDR for 55°-6G-XS-0.75e

Figure 4-42: RSR curve for 55°-6G-XS-0.75e
4.2.8.2.3 45°-XG-XS-0.75e

Figure 4-43 examines all 3 specimens tested under 0.75e that utilized 45° glass fibers. All three specimens had similar stiffness and as previously mentioned; peak loads and corresponding strains. Comparing the differing specimens with 6 glass layers, the addition of steel fibers prevents the carrying capacity from dropping suddenly after reaching peak load.

![Graph showing load vs. strain backbone curves for 45°-XG-XS-0.75e specimens.](image)

**Figure 4-43:** Load vs. Strain backbone curves for 45°-XG-XS-0.75e specimens

4.2.8.2.4 55°-XG-0S-1.5e
Under an axial compressive load 1.5 in (3.81 cm) offset from their center, 55°-XG-0S-1.5e specimens rank in performance similar to other test configurations. The specimen with 10 layers of 55° glass reaches a peak load 34% higher than that with 8 or 6 layers (Figure 4-44). This increase in peak load is attributed to the higher concrete confinement from 10 layers of glass. The peak load is reached at 1.0% strain for 55°-10G-0S-1.5e. Peak load is reached at 0.38% and 0.42% strain for specimens with X= 8 and 6 respectively. For X=10, the slopes of the loading cycles are consistently higher for similar strains, as seen in Figure 4-45.
Figure 4-45: Slope of Loading Cycles for $55^\circ$-XG-0S-1.5e specimens
4.2.8.2.5 55°-6G-XS-1.5e

Considering 55°-6G-XS-1.5e, the specimen with steel fibers included had a failure strain 25% smaller than the specimen without steel fibers. Initial loading stiffness and peak loads were comparable.

![Load vs. Strain Backbone curve for 55°-6G-XS-1.5e specimens](image)

**Figure 4-46**: Load vs. Strain Backbone curve for 55°-6G-XS-1.5e specimens

4.2.8.2.6 45°-XG-XS-1.5e

All 45° specimens tested at 1.5 in (3.81 cm) eccentric load reached peak load at the same strain (Figure 4-47). As with the similar specimens tested at 0.75e, the introduction of steel fibers seems to prevent an immediate reduction in load capacity after the specimen has reached peak load. Specimen 45°-8G-0S-1.5e has an ultimate failure strain larger than either specimen
with 6G. While this can be attributed to increased confinement, no specimens with 45° glass showed adequate levels of confinement.

![Graph](image)

**Figure 4-47:** Load v. strain backbone curves for 45°-XG-XS-1.5e specimens

### 4.2.8.3 Summary: All Compression Results

Table 4-1 lists a summary of results for all tests performed. $F'_{cc}$ is the peak axial load on the specimen. $\varepsilon_{cc}$ is the axial strain of the specimen at peak load $F'_{cc}$. Many of the specimens did not undergo failure at their peak load. They ruptured at a load much lower than peak due to softening. In order to compare results across all specimens, load at 1% axial strain was picked as a reference point. $F'_{c1}$ is the load on the column at when the specimen reached 1% axial strain. $S_1$ is the initial slope of the load strain curve for the first cycle. This slope is of the linear elastic portion of the curve. Column ED lists the cumulative energy dissipated (ED) during each test. This is taken as the cumulative area under the load versus displacement curve for each test.
Table 4-1: Table of Results for all Compression Tests

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<th>F'cc (Kip)</th>
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<th>F'c1 (Kip)</th>
<th>S1 (Kip)</th>
<th>ED (kip-in)</th>
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4.3 Tension Tests

During tension testing many specimens failed in an unwinding manner. These were specimens that were manufactured on the lab winder. Figure 4-48a shows a specimen after failure. A crack runs parallel to the fiber wind angle, corkscrewing around the pipe up the full height. This failure method governed in pipes that were left hollow for all glass angles tested. All tension specimen before and after testing pictures can be found in APPENDIX B: Photos. The distance between the cracks correspond to the width of the fiber tow wrapped around the mandrel in manufacturing, Figure 4-48b. Notice in Figure 4-48c the broken glass fibers running perpendicular to the failure line. In manufacturing the fiberglass was wound in +/- orientations of the winding angle. The opposing fiber angles were not enough to keep the whole pipe itself from unwinding along one strand during testing. It is believed that this failure method occurred because of an inadequate width of the fiber tow used during lab winding. All pipes
manufactured on the main line exhibited distributed failure methods such as that seen in Figure 4-49.

**Figure 4-48**: Failure of 65°-8G-0S-T1 specimen (a) Full view of specimen after failure (b) Manufacturing of pipes on lab winder (c) Close up of crack in specimen show in (a)
Figure 4-49: Tension Failure of 45-8G-0S-T1 manufactured on the mainline

All tension specimens that were tested with the aluminum core, to simulate concrete fill, underwent failure at the grips due to the much higher load achieved. Figure 4-50 shows a typical failure mode at the testing grips. Pictures of all these failure modes can be found in APPENDIX B: Photos. Due to inconsistent results from either a design flaw leading to premature failure or failure at the grips, data from tension tests is not shared.

Figure 4-50: Before and after of tension test on specimen 45°-8G-0s-T3 with aluminum rings inside
5 SUMMARY AND CONCLUSIONS

5.1 Summary
With the goal of developing a better bridge column, a Hybrid CFFT system was investigated. The feasibility of manufacturing the HCFFT shell was established through successful manufacturing runs. CFFT specimens of only fiberglass were tested with fiber angles of 65°, 55°, and 45°. The number of layers of glass was also varied. HCFFT specimens were made with FRP pipes of 45° and 55° angled glass and a varying number of glass layers. Specimens were tested under half cyclic compression at concentric and two different eccentric load configurations. The mechanical properties, cyclic behavior, and failure mechanisms were investigated.

5.2 Conclusions
The conclusions presented below are based on the results of the experimental investigation conducted on Hybrid/Non-Hybrid CFFT specimens of varying glass fiber angle and layer thickness:

- The concentric axial load capacity of a CFFT was directly proportional to the glass fiber angle. Load capacities from highest to lowest were 65°, 55°, and 45°
- For CFTTs a glass fiber angle of 45° is inadequate in providing enough confinement to unreinforced concrete. The 45° fibers offer almost no increase in load capacity and only a marginal increase in failure strain.
- For glass fiber angles of 55°, the higher the number of glass layers, the higher the level of confinement and maximum load achieved.
- Specimens made with longitudinal steel fibers and 55° glass fibers had ultimate strain values significantly smaller than specimens with only glass fibers. This reduction in ultimate strain ranged from 15 to 50% but may be contingent on manufacturing method.
- Specimens with steel fibers had higher stiffnesses than comparable specimens without steel fibers. This effect was maintained throughout half-cyclic loading.
- For similar strains and comparable specimens, those with steel fibers had higher energy dissipation ratios and residual strain ratios compared to specimens with just glass.

5.3 Future Research
The reduction in ultimate strains of CFFT specimens with steel fibers versus those without should be investigated further. Future research is recommended to explore the fiber layer interaction between glass and steel and how the steel layers may hinder the composite action of the filament wound glass. Future research is recommended on CFFTs composed of varying angles of glass for different layers. Further research to be conducted at UConn includes four-point bending and combined axial and lateral loading of CFFTs and HCFFTs.
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APPENDIX A: GRAPHS
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Energy Dissipation Ratio

Strain at End of Each Cycle (%)
APPENDIX B: PHOTOS
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4 65-8g-0s-1e | Didn’t Fail

5 65-8g-0s-c-2 | Bottom, Front

6 55-8g-0s-c-2 | Bottom, Front
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10 45-6g-2s-c-1

11 55-8g-2s-c-1

12 45-8g-2s-c-1
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16 Back
17 Back, Bottom
18 Side 1, Button
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<td>Side 1, Mid-Height</td>
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<td>Side 1, Mid-Height</td>
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TENSIØN BEFORE AND AFTER FAILURE PICTURES

T1, 45-8G-0S-T1, (hollow), mainline

The surface of specimen was painted black to facilitate digital image correlation strain measurement.
T2, 65-8g-0s-T, (hollow)
T3, 45°-8G-0s-T2, (Aluminum core), mainline
T4, 45°-8G-0s-T3, (aluminum rings), mainline
T5, 55°-8g-0s-T1 (aluminum rings)
T6,  55°-8g-0s-T2 (hollow)
T7, 55-10g-0s-T1 (hollow)
T8, 55-8g-2s-T-1 (hollow)
Inside of pipe after failure

T10, 45°-8G-2S-T1 (hollow)
Failure line after removing grips

T11, 45°-8g-2s-T2 (Aluminim rings)
T12,  55°-8G-0S-T3 (hollow)
T13, 45°-8G-0S-T4 (hollow)