Bending Behavior of Concrete Beams with Fiber/Epoxy Composite Rebar

Kolten Dewayne Rice
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Bending Behavior of Concrete Beams with
Fiber/Epoxy Composite Rebar

Kolten Dewayne Rice

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Bending Behavior of Concrete Beams with Fiber/Epoxy Composite Rebar

Kolten Dewayne Rice
Department of Civil and Environmental Engineering, BYU
Master of Science

This research explores the use of carbon/epoxy and fiberglass/epoxy fiber-reinforced polymer (FRP) composite rebar manufactured on a three-dimensional braiding machine for use as reinforcement in concrete beams under four-point bending loads. Multiple tows of prepreg composite fibers were pulled to form a unidirectional core. The core was consolidated with spirally wound Kevlar fibers which were designed to also act as ribs to increase pullout strength. The rebar was cured at 121°C (250°F) in an inline oven while keeping tension on the fibers. Five configurations of reinforcing bars were used in this study as reinforcement in concrete beam specimens: carbon/epoxy rebar and fiberglass/epoxy rebar were manufactured on the three-dimensional braiding machine and cured in an inline oven while still under tension immediately after production; carbon/epoxy rebar was manufactured by IsoTruss industries on the three-dimensional braiding machine and was rolled and stored before curing; fiberglass/epoxy rebar was purchased from American Fiberglass; conventional No. 4 steel rebar was also purchased. All bars were embedded in 152 cm (60 in) long, 11 cm (4.5 in) wide, and 15 cm (6.0 in) tall concrete beams. Beams were tested under four-point bending loads after which three 30 cm (12 in) specimens were taken from the ends of each configuration to be tested under axial compression loads in order to investigate the effects of the concrete voids on the concrete strength. Concrete beams reinforced with BYU glass/epoxy rebar manufactured on the three-dimensional braiding machine exhibited 5% greater compression bending stress and 11% greater tension bending stress than concrete beams reinforced with industry manufactured glass/epoxy rebar. Concrete beams reinforced with BYU carbon/epoxy rebar manufactured on the three-dimensional braiding machine exhibited 18% lower compression bending stress and 64% lower tension bending stress than concrete beams reinforced with industry manufactured carbon/epoxy rebar. BYU glass/epoxy rebar has a 3% greater stiffness and 1% greater displacement than industry manufactured glass/epoxy rebar and BYU carbon/epoxy rebar has a 40% greater bending stiffness and 19% lower displacement than industry carbon/epoxy rebar. BYU carbon/epoxy rebar has 49% lower compression bending stress, 1% lower tension bending stress, 28% lower displacement, and a 68% greater bending stiffness than BYU glass/epoxy rebar. BYU glass/epoxy rebar has 38% greater compression bending stress, 30% lower tension bending stress, 26% greater center displacement, and a 105% lower bending stiffness than conventional steel. BYU carbon/epoxy rebar has 8% lower compression bending stress, 31% lower tension bending stress, and 22% lower bending stiffness than steel. The deflections of steel reinforced concrete and BYU carbon/epoxy reinforced concrete are comparable with steel rebar displaying a 1% greater center displacement than BYU carbon/epoxy rebar.

Keywords: Composite, carbon/epoxy, fiberglass/epoxy, rebar, FRP, reinforced concrete
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CHAPTER 1. INTRODUCTION

The purpose of this research was to examine the effectiveness of carbon/epoxy and fiber-glass/epoxy reinforcing bars (rebar) manufactured on a three-dimensional braiding machine for use in concrete members. Composite rebar manufactured on a three-dimensional braiding machine was compared with the performance of conventional steel rebar and industry manufactured composite rebar. This study builds upon previous research which explored the pullout strengths of various composite reinforcing bars from concrete members. The focus of this study was on the effectiveness of composite rebar embedded in concrete beams and tested under four-point bending loads.

1.1 Background

Composite rebar, also known as Fiber Reinforced Polymer (FRP) rebar, consists of fiber and resin components. These two components work together to create a material that is generally strong in tension by allowing multiple strands of fiber to act as a single part. Fibers can include materials such as carbon, glass, aramid, or basalt which provide high tensile strength and stiffness to the composite. Resins such as polyester, epoxy, and vinyl ester hold the fibers together and allow for the transfer of forces between fibers. In this research, tows of carbon fiber, which were pre-impregnated (prepreg tows) with an epoxy resin, were used to manufacture composite rebar. See Figure 1.1 for an example of a manufactured carbon/epoxy bar used in this research.

Rebar is regularly used in all types of construction to reinforce concrete. Concrete is strong in compression but weak in tension, and introducing rebar helps to strengthen the structure with minimal cost and effort. Steel is the most common material used for rebar due to its effectiveness, availability, and affordability. There can be drawbacks however to using steel as concrete reinforcement.
Steel will corrode when it comes into contact with moisture, which can become an issue when used to reinforce structural concrete such as footings, foundations, or bridge members. Various chemicals and salts can also damage steel rebar reducing the tensile capacity of the affected concrete member. While coating steel rebar with epoxy will help protect the material from corrosion, FRP rebar is a viable alternative due to its high strength, light weight, and ability to resist corrosion.

1.2 Related Research

Considerable research has been conducted with respect to composite structures and reinforcing members in the form of the IsoTruss®. The IsoTruss is a composite structure that can be used as an alternative to conventional structural members and has been used as reinforcement in concrete members. The IsoTruss is composed of longitudinal and helical members, the longitudinal members primarily carrying axial loads while the helical members carry any torsional and shear loads, and provides structural integrity while minimizing weight. Blake [1] used the IsoTruss in his research as a way to reinforce concrete, determining that while there was increased strength in bending, his specimens exhibited lower compression strength compared with steel bar reinforcement. Building upon Blake’s research, Jones [2] improved the IsoTruss fabrication design by placing the longitudinal members at the outer nodes of the structure and further away from the center of the cross-sectional area and was able to increase the overall strength of the structure.

Much has been accomplished in studying the properties of FRP rebar and this study seeks to build upon previous research. Mohaghegh, Silfwerbrand, and Arskog [3] determined that increasing the fiber content of basalt fiber reinforcing bars increased the shear strength of the concrete beam as a whole. Also using basalt fiber rebar, Urbanski, Lapko, and Garbcz [4] discovered that
the basalt FRP rebar had a higher critical load than conventional steel and that failure did not occur as suddenly. Kikuchi [5] embedded concrete beams with CFRP (carbon fiber reinforced polymer) rods and compared that material with conventional poly-coated (PC) steel strand wire showing CFRP reinforcement to be equal to or superior to steel. Concrete piers and columns were embedded with carbon fiber sheets by Uemura [6], who observed that CFRP worked just as well as steel in that application. Glass-fiber rods were used by Chaallal and Benmokrane [7] to reinforce concrete beams, demonstrating that with the exception of increased cracking, the glass-fiber rods behaved well in comparison to steel. Larralde, Renbaum, and Morse [8] also conducted research with concrete beams reinforced with fiberglass rebar and determined that beams with fiberglass reinforcement have less capacity than beams with steel reinforcement.

Tomlinson and Fam [9] used composite rebar stirrups in addition to longitudinal reinforcing bars in their research, resulting in FRP reinforced beams with significantly higher strengths than their steel counterparts. Elgabbes, Ahmed, and Benmokrane [10] studied the flexural behavior of concrete beams reinforced with ribbed FRP rebar. Their findings showed that beam failure occurred primarily from concrete crushing. Kassem, Farghaly, and Benmokrane [11] used a variety of FRP rebar in their research. They discovered that the composite reinforced beams behaved linearly until cracking and nearly linearly after cracking. They also found that their beams ultimately failed from the crushing of concrete.

When considering pullout strength, Belarbi and Wang [12] observed that increasing the length of embedment resulted in greater bond strength. Cosenza, Manfield, Pecce, and Realfonzo [13] looked at the development length of fiberglass FRP rebar relative to bond strength and similarly determined a relationship between the length of the embedment and the strength of the bond. Expanding upon their own research, Cosenza, Manfield, Pecce, and Realfonzo [14] also studied the roughness of the surface area of FRP rebar to find that a rough surface provided far superior bond strength compared to a smooth surface. Additionally, Machanzi [15] conducted research on the pullout strength of various FRP rebar to determine how they compare and observed that FRP rebar with a rough sand-coated surface provided greater pullout strength than FRP rebar without a sand-coated surface. Comparing FRP rebar to steel rebar, Larralde and Silva-Rodriguez [16] tested for direct pull-out strength of reinforcing bars from concrete. They found that the average bond stress was greater for steel rebar than for FRP rebar and that the slip of the
rebar was greater for the FRP rebar than for the steel rebar. Achillided and Pilakoutas [17] concluded that the bond strength of carbon FRP bars and fiberglass FRP bars were comparable to each other.

Research on the effect of longitudinal ribs on FRP rebar bonding was conducted by Akishin, Kovalovs, Kulakov, and Arnautov [18]. They experimented with the number of ribs on a bar as well as the height of those ribs and concluded that increasing the number of ribs resulted in an increased bond strength of the rebar. The height of the ribs similarly increased rebar bond strength and the reason was likely due to the overall increase in surface area.

Won, Park, Kim, Lee, and Jang [19] conducted research to determine the effect of synthetic and steel fibers in concrete on the bonding properties of FRP reinforcing bars with the concrete. Bond tests were conducted to evaluate the bond performance of fiberglass and carbon fiber reinforcing bars. They observed that the bond strength increased as the compressive strength of concrete increased, and that the fiber content in the concrete and the fiber material also contributed to the bond strength of the rebar.

In regards to the bond strength of fiber-reinforced polymer (FRP) rebar when exposed to corrosive conditions, Dong, Wu, Xu, Xin, and Taerwe [20] studied concrete reinforced with basalt fiber rebar in seawater. They concluded there was less corrosion on the bars when epoxy resin was used to bond the fibers together compared to vinyl ester resin. A similar study by Venkatesan, Palaniswamy, and Rajagopal [21] determined that basalt reinforced concrete allowed for more deflection in the member compared to steel reinforced concrete. Benmokrane [22] specifically researched fiberglass and discovered that the type of glass fibers used, along with the resin content and curing process, can affect a sample’s lifespan significantly.

In addition to corrosion, temperature is another major environmental condition that should be addressed. High temperatures from hot weather or fires can have a particularly negative affect on FRP rebar. Katz, Berman, and Bank [23] demonstrated that FRP rebar can lose up to 90% of its bond strength when its temperature is raised from 20°C (68°F) to 250°C (482°F) while steel rebar only loses about 38% of its bond strength from the same rise in temperature. They concluded that FRP rebar relies heavily on the resin content to provide bond strength. Chaallal and Benmokrane [7] also considered temperature in their research and discovered glass-fiber rebar to have a coefficient of thermal expansion similar to that of concrete. Research by Rahman, Taylor, and
Kingsley [24] focuses on the effect of temperature on FRP reinforced concrete in bridges. They observed the tensile strength and modulus of elasticity to decrease by up to 9.5% and 2.5% respectively with temperatures of 50 °C (122 °F) and can increase by 11% and 2.5% when temperatures fall to -30 °C (-22 °F).

While FRP rebar is an acceptable and useful alternative to steel reinforcing bars, it can be hard to justify the cost in the short term. Berg, Bank, Oliva, and Russell [25] conducted a cost analysis comparing FRP rebar to conventional steel rebar. While FRP rebar does have higher initial costs, the long-term cost is low due to improved durability and reduced maintenance requirements. El-Mikawi [26] created a model with material costs in mind to assess the practicality of using composites in construction and came to similar conclusions.

In summary, previous related research has shown that composite (FRP) rebar can be used as a viable alternative to conventional steel rebar for use as concrete reinforcement. Composite bars can be embedded in concrete to resist internal shear forces and to provide tensile strength for an increased load capacity. A rough surface on FRP rebar via longitudinal ribs and/or sand-coating increases pullout strength of composite rebar. FRP rebar is resistant to corrosive conditions and has a long service lifespan.

1.3 Impact of Research

This research adds to an existing store of knowledge on fiber-reinforced polymer (FRP) composite rebar by reinforcing concrete beams with carbon/epoxy and glass/epoxy rebar manufactured on a three-dimensional braiding machine and testing them under four-point bending loads. Research in how concrete beams reinforced with composite rebar manufactured on the three-dimensional braiding machine act under bending loads can help engineers to better understand how to use these materials as concrete reinforcement and how they can be effectively manufactured.

1.4 Research Scope and Objectives

The primary purpose of this research was to study concrete beams embedded with composite FRP reinforcing bars (rebar) manufactured on the three-dimensional braiding machine and compared with conventional steel rebar and pre-manufactured composite rebar when placed under
four-point bending loads. Both carbon/epoxy and glass/epoxy FRP reinforcing bars were tested in this study. The objectives of this study were to measure the effectiveness of carbon/epoxy and fiberglass/epoxy reinforcing bars for use in concrete members under bending loads, analyze how concrete beams reinforced with composite rebar perform when compared to beams reinforced with conventional steel rebar, and contribute to the existing store of knowledge on FRP reinforced concrete beams. This research was designed to answer the following questions:

- How do concrete beams reinforced with carbon/epoxy rebar manufactured on a three-dimensional braiding machine compare to concrete beams reinforced with fiberglass/epoxy rebar also manufactured on a three-dimensional braiding machine?

- How do concrete beams reinforced with fiberglass/epoxy rebar manufactured on the three-dimensional braiding machine compare to concrete beams reinforced with industry manufactured fiberglass/epoxy rebar?

- How do concrete beams reinforced with carbon/epoxy rebar manufactured on the three-dimensional braiding machine compare to concrete beams reinforced with industry manufactured fiberglass/epoxy rebar which was also manufactured on the three-dimensional braiding machine but was rolled and stored before curing?

- How do concrete beams reinforced with composite rebar manufactured on the three-dimensional braiding machine compare to concrete beams reinforced with conventional steel rebar?

1.5 Thesis Overview

This research consists of four major parts:

1. Manufacturing composite FRP rebars using the three-dimensional braiding machine located at Brigham Young University.

2. Designed construction of reinforced concrete beams which includes determining beam dimensions, constructing forms, and reinforcement placement.

3. Testing of reinforced concrete beams under four-point bending loads.

4. Analyzing and interpreting the data from test results.
CHAPTER 2. EXPERIMENTAL APPROACH

The various methods used to conduct this research are outlined in this chapter. The manufacturing of composite FRP bars and their preparation to be embedded in concrete beams are explained. The test matrix and naming convention used throughout this study are defined. The fabrication of the concrete beam specimens is described. Test procedures and data analysis methods are identified.

2.1 Rebar Manufacturing

Three of the five configurations of composite rebar were manufactured on the three dimensional braiding machine. The carbon/epoxy rope was manufactured by IsoTruss Industries and is described as rope because it was wound on an industrial sized spool after manufacturing and stored for a time before being cured. The BYU glass/epoxy configuration was manufactured by Machanzi [15] and the rebar manufacturing process in this research was based off of his process. The BYU manufactured carbon/epoxy configuration was made specifically for this research and the following information refers specifically to the manufacturing of this configuration though it may apply in part to other configurations.

2.1.1 Materials

The rebar core consisted of unidirectional carbon fiber/epoxy pre-preg tows. See Table 2.1 for manufacturer and material specification data of the core materials. See Table 2.2 for nominal mechanical properties of the core materials. The resin content of the prepgreg tow material was 27.5% as identified by TCR Composites.

Unidirectional dry aramid Kevlar was used to consolidate the core materials. See Table 2.3 for the mechanical properties of the consolidating material.
Table 2.1: Carbon/Epoxy Rebar Core Materials Specification

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Material Specification</th>
<th>Filament Diameter [µm (in)]</th>
<th>Filament Count per Tow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber</td>
<td>Toray</td>
<td>T700SC-24K-50C</td>
<td>7 (2.8E-04)</td>
<td>24,000</td>
</tr>
<tr>
<td>Epoxy (Pre-Preg)</td>
<td>TCR Composites</td>
<td>UF3369-100</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.2: Carbon/Epoxy Rebar Nominal Mechanical Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of Elasticity [GPa (Msi)]</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Compressive Strength [MPa (ksi)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T700/UF3369 Carbon/Epoxy</td>
<td>135 (20.0)</td>
<td>2551 (370)</td>
<td>765 (111)</td>
</tr>
</tbody>
</table>

2.1.2 Geometry

The carbon/epoxy rebar was produced using multiple tows of composite pre-preg carbon fiber strands with the desire to reach a cross sectional diameter of 12.7 mm (0.50 in), the size of a No. 4 typical rebar. Each tow consisted of 24,000 strands and 88 tows were used in each bar. With the 88 tows of carbon fiber and the Kevlar consolidation, a final cross sectional bar diameter of 13.2 mm (0.52 in) was achieved. A sand coating was later applied as detailed in Section 2.2.2 which increased the cross sectional bar diameter to 15.0 mm (0.59 in). Only the 13.2 mm (0.52 in) diameter is considered structural.

2.1.3 Consolidation

Consolidation was carried out using dry aramid Kevlar which was spirally wound around the core carbon/epoxy tows. This was done using two spools on bobbins that wrapped the tows in Kevlar as they were being pulled through the three dimensional braiding machine. Figure 2.1 shows this process. In addition to consolidating the carbon/epoxy tows, the spiral-wound Kevlar provided ribs similar to those on steel rebar in order to increase bonding strength with the concrete.
Table 2.3: Consolidating Kevlar Mechanical Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus [GPa (Msi)]</th>
<th>Elongation at Break %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWARON 2200 8050 DTEX</td>
<td>60 - 80 (8.7 - 11.6)</td>
<td>3.0 - 4.4</td>
</tr>
</tbody>
</table>

Figure 2.1: Two Bobbins Applying Kevlar Consolidation to Rebar.

2.1.4 Curing

After consolidation, the rebar was cured in 4.28 m (14 ft) lengths in an inline oven. The oven was placed in a way that allowed the rebar to be pulled from the three dimensional braiding machine and into the oven by a pulley system as can be seen in Figure 2.2. This assured that the tows remained in tension while curing.

Each sample was cured at 121°C (250°F). The oven required about an hour to ramp up to the desired temperature, after which that temperature was held for 90 minutes. After curing, the oven was allowed to cool for about another hour.
2.2 Rebar Specimen Preparation

This section describes the steps that were taken to prepare the cured rebar for use. This includes cutting samples to the required lengths and coating samples with sand.

2.2.1 Cutting Samples

The total length of each bar after curing was 4.3 m (14 ft) and needed to be cut into 30.5 cm (12 in) lengths for potential use in tensile tests and 144.8 cm (57 in) for reinforcing concrete beams. A LECO circular saw with a diamond coated blade as seen in Figure 2.3 was used to cut each sample. The tensile samples were first cut from the center of each cured specimen and the reinforcing bars were cut afterwards. That left about 38 cm (15 in) on each end of the cured rebar specimens that was not used. Rebar from each configuration was cut to these specified lengths.
2.2.2 Sand Coating for Bending Test Samples

Silica sand and epoxy resin were used for the sand coating. The sand was a Granusil Silica Fillers 2075 and was sieved so that only grains retained on the No. 20 sieve and above were used. The sand grains were angular in shape as is shown in Figure 2.4. The epoxy used between the sand coating and the composite rebar was Rhino 4111 Fast. See Table 2.4 for the resin material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength [MPa (psi)]</th>
<th>Ultimate Compressive Strength [MPa (psi)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhino 4111 Fast</td>
<td>572 (83,000)</td>
<td>100 (14,500)</td>
</tr>
</tbody>
</table>
A brush was used to first apply a layer of epoxy resin to the entire length of the bar. After being coated with resin, sand was poured over the rebar. The rebar was rotated and sand was applied until the whole sample was coated with sand. After all the rebar samples were coated in sand, they were placed on a temperature-safe plastic sheet and placed in an oven. The sand coating was cured using the same method described in Section 2.1.4. See Figures 2.5 and 2.6 for carbon/epoxy rebar samples before and after the application of a sand coating.
2.3 Beam Test Matrix and Dimensions

Three configurations of composite reinforcement were manufactured on the three-dimensional braiding machine, two carbon fiber and one fiberglass. The BYU manufactured fiberglass/epoxy rebar was made previously (Machanzi, [15]), the BYU manufactured carbon/epoxy rebar was made specifically for this research, and the carbon/epoxy rope with reduced diameter was manufactured by IsoTruss Industries. The IsoTruss Industries manufactured reinforcement is described as rope because it was wound on an industrial sized spool after manufacturing and stored for a time before being cured. The curing of the IsoTruss Industries manufactured reinforcement required the rope to be placed back under tension enough to ensure the bars were straight when they cured. Specimens were tested and compared with No. 4 steel rebar and sand coated fiberglass rebar obtained from American Fiberglass. The test matrix used for the beam tests is shown in Table 2.5.

An abbreviated naming convention is used to identify each tested beam. The first letter represents the fiber used in the composite reinforcing bar (“C” for carbon fiber, “G” for fiberglass). The second letter represents who manufactured the rebar (“A” for American Fiberglass, “I” for IsoTruss Industries, “B” for Brigham Young University graduate students). This is the case for all of the configurations except for the beams reinforced with plain steel rebar, which is simply represented by the letters “ST”. The ensuing number denotes which sample is being referenced, so
Table 2.5: Beam Test Matrix

<table>
<thead>
<tr>
<th>Reinforcement Type</th>
<th>Manufacturer</th>
<th>Diameter mm (in)</th>
<th>Sand-Coated Diameter mm (in)</th>
<th>Configuration Name</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/Epoxy</td>
<td>American Fiberglass</td>
<td>13.0 (0.51)</td>
<td>14.3 (0.56)</td>
<td>GA</td>
<td>5</td>
</tr>
<tr>
<td>Glass/Epoxy</td>
<td>BYU</td>
<td>12.3 (0.49)</td>
<td>14.3 (0.56)</td>
<td>GB</td>
<td>5</td>
</tr>
<tr>
<td>Carbon/Epoxy</td>
<td>IsoTruss Industries</td>
<td>9.8 (0.39)</td>
<td>11.7 (0.46)</td>
<td>CI</td>
<td>5</td>
</tr>
<tr>
<td>Carbon/Epoxy</td>
<td>BYU</td>
<td>13.2 (0.52)</td>
<td>15.0 (0.59)</td>
<td>CB</td>
<td>5</td>
</tr>
<tr>
<td>Steel</td>
<td>–</td>
<td>12.7 (0.50)</td>
<td>–</td>
<td>ST</td>
<td>5</td>
</tr>
</tbody>
</table>

“4” represents sample number 4. For example, CB-4 is used to denote the fourth sample of a beam embedded with BYU manufactured carbon/epoxy rebar, and ST-2 refers to the second sample of a beam embedded with plain steel rebar. Refer to Table 2.5 to see the naming convention assigned to each configuration.

There are five beams for each configuration of rebar for a total of 25 individual bending test specimens. Each of the five configurations were tested in four-point bending.

2.3.1 Concrete Beams Fabrication

A form was made using 2x8 and 2x10 lumber to cast the concrete beams. The concrete beams were designed to be 152 cm (60.0 in) in length, 11.4 cm (4.5 in) wide, and 15.5 cm (6.0 in) in height as shown in Figure 2.7. The form was built to accommodate those dimensions so that all 25 beams could be poured and cured simultaneously, eliminating a potential batch-dependent variable. Rebar was put into place within the form using 5 cm (2 in) chairs. See Figure 2.8 for the completed form with rebar placement and Figure 2.9 for specific form dimensions. Form oil was used on the inside of the form to help prevent bonding between the concrete and the wood while curing.
Figure 2.7: Cross Sectional Dimensions of Concrete Beams.

Figure 2.8: Completed Form with Rebar Placement.
Figure 2.9: Dimensions of Form Used to Pour Concrete Beams.
2.3.2 Concrete Properties and Curing Details

One cubic yard of concrete was ordered for delivery from Geneva Rock. A slump test was performed in accordance with ASTM C143 (Standard Test Method for Slump of Hydraulic-Cement Concrete) [27] at the time of delivery. Concrete was poured into eight cylinders with a height of 3.1 cm (8.0 in) and a diameter of 1.6 cm (4.0 in) to be used for the concrete cylinder compression test. The bulk of the concrete was used to fill the form for the beams to be used in the beam four-point bending test. The concrete vibrator was too large to fit between the reinforcing bars so a mallet was used to pound the form to help remove air pockets from the concrete beams.

A plastic sheet was placed over the concrete while it cured to help prevent water evaporation as shown in Figure 2.10. The beams were additionally wetted down throughout the curing process to help keep moisture levels up. The concrete cylinders were placed in a fog room while they cured. The concrete was allowed to cure for 28 days before testing.

![Concrete Beams Curing in Form with Plastic Sheet Cover.](image)

2.4 Test Procedures

The various tests used in this research are summarized in this section. These tests include concrete cylinder compression test and the four-point bending tests for concrete beams.

2.4.1 Concrete Cylinder Compression

The compression strength of the concrete was tested on a Forney compression machine at a loading rate of 1.27 mm (0.05in) per minute. The cylinders were capped with Hydrocal®
White Gypsum Cement one day prior to testing. Caps were added according to ASTM C617 (Standard Practice for Capping Cylindrical Concrete Samples) [28] and the cylinders were tested according to ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) [29]. See Table 2.6 for material details.

Table 2.6: Material Properties for Cement Caps

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive Strength Max Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>USG Hydrocal® White Gypsum Cement</td>
<td>41.4 (6000)</td>
</tr>
<tr>
<td></td>
<td>0.42</td>
</tr>
</tbody>
</table>

2.4.2 Beam Four-Point Bending

To test the reinforced concrete beams, a four-point bending method was chosen to maintain a uniform maximum moment in the center 46 cm (18 in) of the beam along its length. Cement caps were fixed to the load points to insure a smooth surface. Steel rods sandwiched between steel plates were placed at each load point and at the supports to allow the load to be distributed more evenly. See Figure 2.11 for details of the four-point bending layout. See Figure 2.12 for the four-point bending test shear and moment conditions.

Figure 2.11: Dimensions and Details for Layout of Four-Point Bending Test.
The test was conducted using the MTS uniaxial load frame system which has a 445 kN (100 kips) load capacity. Seven string potentiometers were attached to the underside of each beam at 18 cm (7.125 in) intervals from the center going out as shown in Figure 2.13 to measure the deflection shape. See Figure 2.14 for an example of a beam specimen loaded in the MTS system with the attached string potentiometers. Loading was applied at a rate of 1.27 mm (0.05 in) per minute. Crack propagation was measured and recorded periodically throughout testing. Each specimen was tested to failure.
Figure 2.13: Spacing of String Potentiometers Along Underside of Beams.

Figure 2.14: Four-Point Bending Concrete Beam Test on the MTS System with Attached String Potentiometers.
2.5 Data Analysis

2.5.1 Forces in Reinforced Concrete Beams from Bending Loads

The set of equations in this section are used to determine bond stress and tension force in the reinforcing bars due to four point bending loads on reinforced concrete members. The maximum shear and moment forces for a beam under a four point bending load are as shown in Equations 2.1 and 2.2, respectively:

\[ V = \frac{P}{2} \]  \hspace{1cm} (2.1)

\[ M = \left( \frac{P}{2} \right) a \]  \hspace{1cm} (2.2)

where \( V \) is the maximum shear force, \( P \) is the load applied to the beam that is distributed equally between the two load points, \( M \) is the maximum moment, and \( a \) is 49.5 cm (19.5 in) or the distance from load point to the nearest support as shown previously in Figure 2.11. The distance from the top of the reinforced concrete beam to the neutral axis can be found by rearranging Equation 2.3 to solve for \( y_t \):

\[ by_t \left( \frac{y_t}{2} \right) = (n) A_r (d - y_t) \]  \hspace{1cm} (2.3)

where \( y_t \) is the distance from the top of the beam to the neutral axis, \( b \) is the width of the concrete beam, \( n \) is the ratio of the elastic moduli, \( A_r \) is the total cross-sectional area of reinforcement, and \( d \) is the distance from the top of the beam to the center of the reinforcing bars. The dimensions for \( b \) and \( d \) are also shown in Figure 2.11 and are 10.2 cm (4.5 in) and 11.4 cm (4.0 in) respectively. The ratio of the elastic moduli \( n \) is calculated using Equations 2.4 and 2.5:

\[ n = \frac{E_r}{E_c} \]  \hspace{1cm} (2.4)

\[ E_c = 57,000 \sqrt{f_c'} \]  \hspace{1cm} (2.5)

where \( E_r \) and \( E_c \) are the modulus of elasticity of reinforcement and concrete, respectively and \( f_c' \) is the specified compression strength of concrete. Equation 2.5 is specifically for normal weight concrete and requires \( f_c' \) to be given in units of psi and gives \( E_c \) in units of psi.
The maximum tension in the reinforcing bars \( T \) for a beam under a four-point bending load can be calculated using Equations 2.6, 2.7, and 2.8:

\[
I_t = \frac{1}{3} by_t^3 + (n)A_r(d - y_t)^2 \tag{2.6}
\]

\[
f_r = (n) \frac{M(d - y_t)}{I_t} \tag{2.7}
\]

\[
T = f_rA_r \tag{2.8}
\]

where \( I_t \) is the transformed moment of inertia for a reinforced concrete beam with a rectangular cross-section and \( f_r \) is the tensile stress in the reinforcement due to beam flexure. The design shear capacity of the concrete component of the reinforced concrete beam can be calculated using Equation 2.9 and the bending stress in the beam can be calculated using Equation 2.10:

\[
V_c = 2\sqrt{f'_c(b)(d)} \tag{2.9}
\]

\[
\sigma_b = \frac{M(c)}{I_t} \tag{2.10}
\]

where \( V_c \) is the design shear capacity of the concrete portion of the reinforced concrete beam in units of pounds, \( f'_c \) is required in units of psi, \( \sigma_b \) is the bending stress in the reinforced concrete beam, and \( c \) is the distance from the neutral axis of the beam cross section to the center of the reinforcement for tension and to the top of the cross sectional area for compression. The development length \( \ell_d \) of rebar can be calculated using Equation 2.11:

\[
\ell_d = \frac{3(f_y)}{40\lambda \sqrt{f'_c}} \frac{\psi_t\psi_c\psi_e}{c_b + K_{tr}d_b} (d_b) \tag{2.11}
\]

where \( f_y \) is the yield strength of the reinforcement in psi, \( \lambda \) is 1.0 for normal weight concrete, \( \psi_t \) is 1.0 for bottom reinforcing bars, \( \psi_c \) is 1.0 for not using epoxy coating, \( \psi_e \) is 0.8 for using bar sizes smaller than No. 6, \( c_b \) is half of the center to center spacing of bars in inches, \( K_{tr} \) is 0 for not having stirrups, and \( d_b \) is the diameter of the rebar in inches.
2.5.2 Deriving Deflection Equations Using Macaulay Bracket Functions

Moment \((M_x)\) and deflection \((v)\) values were calculated at various points along the beams using the Macaulay bracket functions as described by Pytel and Kiusalaas [30]. Both sets of brackets are excluded from the equations when a point is chosen to the left of the load points, and only the second bracket is excluded when a point is chosen between load points. All brackets are used when a point is chosen to the right of both load points. The deflection equations are derived using Equations 2.12 through 2.15:

\[
EIv'' = M_x
\]
\[
M_x = \frac{P}{2}(x-<x-a>-<x-a-s>)
\]
\[
EIv' = \frac{P}{4}(x^2-<x-a>^2 - <x-a-s>^2 + C)
\]
\[
EIv = \frac{P}{12}(x^3-<x-a>^3 - <x-a-s>^3 + C(x) + C_0)
\]

where \(I\) is the transformed moment of inertia for a reinforced concrete beam with a rectangular cross-section, \(E\) is modulus of elasticity of the concrete, \(x\) is a defined point along the beam going from left to right, \(a\) is 49.5 cm (19.5 in) or the distance from the load point to the support as shown previously in Figure 2.11, \(s\) is 45.7 cm (18 in) or the spacing between the load points, \(P\) is the load applied to the beam, and \(C\) is a non-zero constant. \(C_0\) is a constant with a value of zero and is calculated by solving Equation 2.15 at the left support where deflection is zero \((x = 0 \text{ cm})\).

The maximum deflection at the center of the beam along its length, \(x = 72.4 \text{ cm} (x = 28.5 \text{ in})\), is calculated by rewriting Equation 2.15 as shown in Equation 2.16:

\[
v_{\text{center}} = \frac{P(1,868in^3) + C(28.5in)}{EI}
\]

where \(v_{\text{center}}\) is the maximum deflection at the center of the beam. By choosing to calculate deflection at the support to the right of the applied loads, \(x = 145 \text{ cm} (x = 57 \text{ in})\), the constant \(C\) can be defined as shown in Equation 2.17. By combining that with Equation 2.16 the maximum center deflection can be solved as shown in Equation 2.18:

\[
C = -P(183in^2)
\]
\[ v_{center} = \frac{P}{EI} (-3,342 \text{ in}^3) \] (2.18)

### 2.5.3 Chauvenet’s Criterion

To ensure that reliable data was obtained, Chauvenet’s criterion for rejecting a reading was employed as outlined in Holman and Gajda’s work \[31\]. The data was graphed along with an envelope indicating Chauvenet’s upper and lower limits. For 5 samples, these limits were generally calculated using Equation 2.19:

\[ \bar{x} \pm 1.65\sigma \] (2.19)

where \( \bar{x} \) is an average of a set of data points and \( \sigma \) is the standard deviation. The constant 1.65 comes from Table 2.7 where the ratio of maximum acceptable deviation to standard deviation \( (d_{max}/\sigma) \) is equal to 1.65 for a number of readings \( (n) \) equal to five. If more than half of the data points for a specific specimen fell outside of Chauvenet’s envelope, that specimen was removed from that particular analysis.

<table>
<thead>
<tr>
<th>Number of readings, ( n )</th>
<th>Ratio of maximum acceptable deviation to standard deviation, ( d_{max}/\sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.38</td>
</tr>
<tr>
<td>4</td>
<td>1.54</td>
</tr>
<tr>
<td>5</td>
<td>1.65</td>
</tr>
<tr>
<td>6</td>
<td>1.73</td>
</tr>
<tr>
<td>7</td>
<td>1.8</td>
</tr>
<tr>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td>15</td>
<td>1.8</td>
</tr>
<tr>
<td>25</td>
<td>1.8</td>
</tr>
<tr>
<td>50</td>
<td>1.8</td>
</tr>
<tr>
<td>100</td>
<td>1.8</td>
</tr>
<tr>
<td>300</td>
<td>1.8</td>
</tr>
<tr>
<td>500</td>
<td>1.8</td>
</tr>
<tr>
<td>1,000</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 2.7: Chauvenet’s Criterion for Rejecting a Reading

Table by Holman and Gajda \[31\].
CHAPTER 3. EXPERIMENTAL RESULTS

Results for the concrete cylinder compression tests and four-point bending tests for concrete beams are in this chapter. Deflections and stress-strain curves are graphed and data from these tests are summarized in tables. Discussion of the individual test results are also in this chapter. Refer to Section 2.3 for definitions regarding specimen naming conventions.

3.1 Concrete Quality Results

This section summarizes the properties of concrete ordered for delivery from Geneva Rock and discusses the test results. These include a slump test of the wet concrete at delivery and concrete cylinder compression tests.

3.1.1 Concrete Properties

A slump of 1.2 cm (3.0 in) was recorded at delivery just as the concrete beams were being cast. The compression strength cylinder test was performed on day 29 of curing and eight cylinders were tested. The cylinders had a height of 3.1 cm (8.0 in) and a diameter of 1.6 cm (4.0 in). The concrete order specified for 41.4 MPa (6.00 ksi) concrete to be delivered. The average value was recorded at 41.9 MPa (6.08 ksi) with a standard deviation of 1.5 MPa (0.22 ksi) and a modulus of elasticity of 30.6 GPa (4440 ksi). See Table 3.1 for specific results on the cylinder tests.

3.1.2 Discussion of Concrete Strength Results

Ordering the concrete to be delivered made it possible to pour all of the concrete beam specimens in one day using one concrete mix. This was done to avoid any discrepancies from mixing slightly different concrete batches during testing which would have otherwise occurred due
Table 3.1: Results from Concrete Cylinder Compression Test

<table>
<thead>
<tr>
<th>Cylinder Specimen Number</th>
<th>Maximum Load MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyl. 1</td>
<td>40.2 (5.83)</td>
</tr>
<tr>
<td>Cyl. 2</td>
<td>43.0 (6.24)</td>
</tr>
<tr>
<td>Cyl. 3</td>
<td>40.1 (5.82)</td>
</tr>
<tr>
<td>Cyl. 4</td>
<td>43.0 (6.23)</td>
</tr>
<tr>
<td>Cyl. 5</td>
<td>41.2 (5.97)</td>
</tr>
<tr>
<td>Cyl. 6</td>
<td>42.9 (6.22)</td>
</tr>
<tr>
<td>Cyl. 7</td>
<td>40.5 (5.87)</td>
</tr>
<tr>
<td>Cyl. 8</td>
<td>44.5 (6.45)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>41.9 (6.08)</strong></td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td><strong>1.5 (0.22)</strong></td>
</tr>
</tbody>
</table>

to the size of the mix and the equipment on hand. The results of this test show that the properties of the concrete matched the order specifications.

3.1.3 Visual Assessment of Cured Concrete Beam Specimens

It was discovered after curing that the concrete did not fill in completely around the reinforcement. After disassembling the forms it became apparent that most of the beams (particularly those placed in the middle of the form) had voids in the concrete located under the reinforcement. Figure 3.1 shows an example of a concrete beam with voids with the beam placed upside down for a better view of the problem area.

These voids could have been prevented by using a concrete mix with a greater slump and through better consolidation methods. Filling the voids with cement was considered as a possible way of mitigating the affects of the voids on the reinforced concrete beam but was ultimately decided against. Instead it was decided to conduct an axial compression test on the reinforced concrete beams as a way to check for negative affects of the voids. The axial compression test prisms were taken from the reinforced concrete beams after they went through four-point bending loads and were taken from the end of the beam that didn’t fail in shear. A full discussion of the prism axial compression test methods and results can be found in Appendix A.
Figure 3.1: Concrete Beam Positioned Upside Down to Display Voids Beneath Reinforcement.

Cracking of the concrete beams during testing suggested that the development length of the reinforcement was also affected by the voids. The required development length was calculated to be 35 cm (14 in) for conventional steel rebar and the actual development length for the reinforced concrete beams was 49.5 cm (19.5 in). Figure 3.2 shows how some of the beams had horizontal cracking prior to failure, which suggests that the bond between the rebar and the surrounding concrete started to fail prematurely. Voids in the concrete around the rebar would reduce the effective development length of the reinforcement. See Appendix B for all beams post bending failure.

Figure 3.2: Horizontal Cracking in the Concrete Beam Suggests Premature Bond Failure.
3.2 Four-Point Bending Test Results

The results of the four-point bending test conducted on composite reinforced concrete beams are summarized in this section. These results include load curves and deflection shapes. All of the beams failed from shear at the ends of the beams outside of where the maximum moment was applied but where maximum shear would be expected. See Appendix C for additional graphs detailing individual specimen and configuration deflections.

3.2.1 American Fiberglass Bending

The GA configuration consists of concrete beams reinforced with sand-coated fiberglass/epoxy rebar manufactured by American Fiberglass. See Figure 3.3 for the loads applied to each GA specimen during testing in relation to center displacement. The loads in the graph represent the total load \( P \) as defined in the previous chapter. The average endpoint on the graph shows the average maximum bending load and displacement at the maximum load for all specimens of the American Fiberglass configuration. The stress-strain curve for specimen GA-5 fell outside of Chauvenet’s limits of statistical acceptability. The average maximum load was 26.2 kN (5.90 kip) for all of the GA samples with a standard deviation of 2.8 kN (0.63 kip). The corrected average was 27.3 kN (6.13 kip) when excluding sample GA-5 according to Chauvenet’s Criterion. The endpoint average in Figure 3.3 was calculated and plotted without that sample.

Figure 3.7 shows the average deflection shape of the GA configuration as the load increased during testing. This same information is also shown for individual specimens as shown in Figure 3.4 and Figure 3.5 for specimens GA-1 and GA-5, respectively. Additionally, this data was stacked for all specimens of this configuration for specific load increments, an example of which is shown in Figure 3.6. The deflection shape for specimen GA-5 at 17.8 kN (4000 lb) as shown in Figure 3.6 falls outside of Chauvenet’s envelope and was therefore excluded from calculating the average configuration deflection at that load. This was done for each specimen and each configuration at identical incremental loads. Refer to Appendix C for each of those graphs.
Figure 3.3: Load vs Displacement of American Fiberglass (GA) Reinforced Concrete Beams During Bending Test.

Figure 3.4: Deflection Progression of Specimen GA-1 During Bending Test.
Figure 3.5: Deflection Progression of Specimen GA-5 During Bending Test.

Figure 3.6: Deflection of GA Specimens Under 4 kip Bending Load.

*Data that was excluded when calculating the corrected average
Figure 3.7: Average Deflection Shape of American Fiberglass (GA) Reinforced Concrete Beams at Various Loads.

3.2.2 BYU Fiberglass/Epoxy Bending

The GB configuration consists of concrete beams reinforced with sand-coated fiberglass/epoxy rebar manufactured at BYU. See Figure 3.8 for the loads applied to each GB specimen during testing in relation to center displacement. The loads in the graph represent the total load \( P \) as defined in the previous chapter. The average endpoint on the graph shows the average maximum bending load and displacement at the maximum load for all specimens of the BYU fiberglass/epoxy configuration. See Figure 3.9 for the average deflection shape of all GB specimens as the load increases during testing. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 27.0 kN (6.07 kip) with a standard deviation of 2.9 kN (0.66 kip).
Figure 3.8: Load vs Displacement of BYU Fiberglass (GB) Reinforced Concrete Beams During Bending Test.

Figure 3.9: Average Deflection Shape of BYU Fiberglass (GB) Reinforced Concrete Beams at Various Loads.
3.2.3 IsoTruss Industries Carbon/Epoxy Bending

The CI configuration consists of concrete beams reinforced with sand-coated carbon/epoxy rebar manufactured by IsoTruss Industries. See Figure 3.10 for the loads applied to each CI specimen during testing in relation to center displacement. The loads in the graph represent the total load \((P)\) as defined in the previous chapter. The average endpoint on the graph shows the average maximum bending load and displacement at the maximum load for all specimens of the IsoTruss Industries carbon/epoxy configuration. See Figure 3.11 for the average deflection shape of all CI specimens as the load increases during testing. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 27.7 kN (6.23 kip) with a standard deviation of 2.6 kN (0.58 kip).

![Figure 3.10: Load vs Displacement of IsoTruss Industries (CI) Carbon/Epoxy Reinforced Concrete Beams During Bending Test.](image-url)
3.2.4 BYU Carbon/Epoxy Bending

The CB configuration consists of concrete beams reinforced with sand-coated carbon/epoxy rebar manufactured at BYU. See Figure 3.12 for the loads applied to each CB specimen during testing in relation to center displacement. The loads in the graph represent the total load \( P \) as defined in the previous chapter. The average endpoint on the graph shows the average maximum bending load and displacement at the maximum load for all specimens of the BYU carbon/epoxy configuration. See Figure 3.13 for the average deflection shape of all CB specimens as the load increases during testing. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 28.7 kN (6.44 kip) with a standard deviation of 3.2 kN (0.73 kip).
Figure 3.12: Load vs Displacement of BYU Carbon/Epoxy (CB) Reinforced Concrete Beams During Bending Test.

Figure 3.13: Average Deflection Shape of BYU Carbon/Epoxy (CB) Reinforced Concrete Beams at Various Loads.
3.2.5 Steel Bending

The ST configuration consists of concrete beams reinforced with conventional plain steel rebar. See Figure 3.14 for the loads applied to each ST specimen during testing in relation to center displacement. The loads in the graph represent the total load \( P \) as defined in the previous chapter. The average endpoint on the graph shows the average maximum bending load and displacement at the maximum load for all specimens of the steel configuration. See Figure 3.15 for the average deflection shape of all ST specimens as the load increases during testing. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 33.8 kN (7.59 kip) with a standard deviation of 5.3 kN (1.19 kip).

Figure 3.14: Load vs Displacement of Steel Reinforced Concrete Beams During Bending Test.
Figure 3.15: Average Deflection Shape of Steel Reinforced Concrete Beams at Various Loads.
CHAPTER 4. COMPARISON OF RESULTS

Experimental results of the various configurations are compared in this chapter through average values obtained from test data. A detailed naming convention for each configurations can be found in Section 2.3 of Chapter 2. Load-displacement curves and loads applied to samples during testing are used to make comparisons in this chapter.

4.1 Comparing Stress and Load Capacity from Bending Tests

4.1.1 Maximum Applied Bending Loads

Figure 4.1 shows the maximum loads applied to each specimen by configuration. The error bars represent Chauvenet’s limits for the maximum load values. Any points that fell outside of those limits were excluded when calculating the corrected average maximum loads. See Table 4.1 for the specific maximum load values for each specimen.

Steel reinforced concrete beams (ST) experienced the largest bending loads with an average 33.8 kN (7.59 kip) force applied in four point bending. On average concrete reinforced with BYU manufactured rebar achieved slightly greater bending loads than their counterparts manufactured by other companies. Concrete beams reinforced with BYU manufactured carbon/epoxy bars (CB) experienced average bending loads of 28.7 kN (6.44 kip) while beams with carbon/epoxy rebar manufactured by IsoTruss Industries (CI) achieved average loads of 27.7 kN (6.23 kip). Additionally, concrete reinforced with glass/epoxy rebar manufactured by BYU (GB) and American Fiberglass (GA) reached average bending loads of 28.1 kN (6.31 kip) and 27.3 kN (6.13 kip) respectively when adjusted according to Chauvenet’s Criterion. Average bending loads for concrete reinforced with carbon/epoxy bars also achieved slightly greater bending loads than concrete with glass/epoxy rebar. Note that the moment, \( M \), is equal to 0.5\( P(a) \) or \( P \) times 25 cm (9.75 in).
Figure 4.1: Bending Test Maximum Loads for Each Configuration with Chauvenet’s Envelope Represented with Error Bars.

Table 4.1: Bending Test Maximum Loads Applied to Each Specimen

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>GA (kN (kip))</th>
<th>GB (kN (kip))</th>
<th>CI (kN (kip))</th>
<th>CB (kN (kip))</th>
<th>ST (kN (kip))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.1 (6.31)</td>
<td>22.6 (5.07)</td>
<td>26.6 (5.99)</td>
<td>32.8 (7.37)</td>
<td>32.2 (7.25)</td>
</tr>
<tr>
<td>2</td>
<td>21.1 (4.74)*</td>
<td>30.6 (6.87)</td>
<td>23.6 (5.31)</td>
<td>24.6 (5.54)</td>
<td>41.2 (9.27)</td>
</tr>
<tr>
<td>3</td>
<td>27.5 (6.18)</td>
<td>28.8 (6.46)</td>
<td>29.9 (6.72)</td>
<td>32.1 (7.23)</td>
<td>32.1 (7.22)</td>
</tr>
<tr>
<td>4</td>
<td>28.9 (6.49)</td>
<td>26.5 (5.97)</td>
<td>27.5 (6.18)</td>
<td>27.6 (6.20)</td>
<td>25.7 (5.78)</td>
</tr>
<tr>
<td>5</td>
<td>25.6 (5.76)</td>
<td>21.8 (4.91)*</td>
<td>30.1 (6.95)</td>
<td>26.2 (5.89)</td>
<td>37.5 (8.43)</td>
</tr>
</tbody>
</table>

Average 26.2 (5.90) 27.0 (6.07) 27.7 (6.23) 28.7 (6.44) 33.8 (7.59)
Corrected Average 27.3 (6.13) 28.1 (6.31) – – –
Std Dev 2.8 (0.63) 2.9 (0.66) 2.6 (0.58) 3.2 (0.73) 5.3 (1.19)
Upper Limit 30.8 (6.93) 31.8 (7.16) 31.9 (7.18) 34.0 (7.65) 42.5 (9.55)
Lower Limit 21.6 (4.86) 22.2 (4.99) 23.5 (5.28) 23.3 (5.24) 25.1 (5.63)

*Data outside of Chauvenet’s limits excluded when calculating corrected average.
4.1.2 Shear Forces in Reinforced Concrete Beams

The theoretical shear capacity of the concrete portion of the reinforced concrete beams was calculated to be 12.5 kN (2.81 kips). This is based on the specified beam dimensions and the measured average concrete strength from the concrete cylinder compression results. The theoretical concrete shear is lower than the actual average maximum shear experienced in the various configurations as is shown in Table 4.2. This shows that the rebar was engaged and allowed the beams to surpass the shear capacity of the concrete.

Table 4.2: Theoretical Concrete Shear and Actual Reinforced Beam Shear at Failure

<table>
<thead>
<tr>
<th>Theoretical Shear</th>
<th>GA</th>
<th>GB</th>
<th>CI</th>
<th>CB</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>kN (kip)</td>
<td>kN (kip)</td>
<td>kN (kip)</td>
<td>kN (kip)</td>
<td>kN (kip)</td>
<td>kN (kip)</td>
</tr>
<tr>
<td>12.5 (2.81)</td>
<td>13.7 (3.07)</td>
<td>14.1 (3.16)</td>
<td>13.9 (3.12)</td>
<td>14.3 (3.22)</td>
<td>16.9 (3.80)</td>
</tr>
</tbody>
</table>

4.1.3 Tension Forces in Reinforcing Bars from Bending and Pullout Loads

Tension in the reinforcing bars as shown in Table 4.3 was calculated from the maximum bending loads. These tension forces are compared with corresponding pullout tension results from research done by Machanzi [15] which are shown in Table 4.4. The American Fiberglass, glass/epoxy (prepreg), and plain steel configurations listed in Table 4.4 match the American Fiberglass (GA), BYU manufactured glass/epoxy (GB), and steel (ST) configurations used in this research respectively. The carbon/epoxy (prepreg) configuration used by Machanzi in his preliminary research is not the same as either of the carbon/epoxy configurations used in this research but is used as a general reference for comparison for both.
Table 4.3: Forces in Reinforced Concrete Beam from Four-Point Bending Loads

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Maximum Shear kN (kip)</th>
<th>Maximum Moment kN-m (kip-in)</th>
<th>Rebar Tension (Single Bar) kN (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>13.7 (3.07)</td>
<td>6.76 (59.8)</td>
<td>36.3 (8.16)</td>
</tr>
<tr>
<td>GB</td>
<td>14.1 (3.16)</td>
<td>6.95 (61.5)</td>
<td>37.4 (8.40)</td>
</tr>
<tr>
<td>CI</td>
<td>13.9 (3.12)</td>
<td>6.86 (60.7)</td>
<td>38.0 (8.54)</td>
</tr>
<tr>
<td>CB</td>
<td>14.3 (3.22)</td>
<td>7.10 (62.8)</td>
<td>40.3 (9.07)</td>
</tr>
<tr>
<td>ST</td>
<td>16.9 (3.80)</td>
<td>8.36 (74.0)</td>
<td>47.6 (10.71)</td>
</tr>
</tbody>
</table>

Table 4.4: Rebar Pullout Results from Research by Machanzi

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Diameter mm (in)</th>
<th>Sand-Coated Diameter mm (in)</th>
<th>Nominal Elastic Modulus GPa (msi)</th>
<th>Pullout Tension kN (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Fiberglass</td>
<td>13.0 (0.51)</td>
<td>14.6 (0.57)</td>
<td>47.6 (6.90)</td>
<td>35.5 (7.97)</td>
</tr>
<tr>
<td>Glass/Epoxy (Prepreg)</td>
<td>12.3 (0.49)</td>
<td>14.3 (0.56)</td>
<td>47.8 (6.93)</td>
<td>37.9 (8.53)</td>
</tr>
<tr>
<td>Carbon/Epoxy (Prepreg)</td>
<td>10.4 (0.41)</td>
<td>–</td>
<td>138 (20.0)</td>
<td>40.5 (9.11)</td>
</tr>
<tr>
<td>Plain Steel</td>
<td>12.7 (0.50)</td>
<td>–</td>
<td>198 (28.7)</td>
<td>32.7 (7.34)</td>
</tr>
</tbody>
</table>

Data from research by Machanzi [15].

The average tension force in the American Fiberglass reinforced concrete beams is higher at 36.3 kN (8.16 kip) than the 35.5 kN (7.97 kip) average pullout tension. The concrete beams reinforced with BYU manufactured glass/epoxy rebar has a slightly lower rebar tension force of 37.4 kN (8.40 kip) than the pullout tension of 37.9 kN (8.53 kip). Both carbon/epoxy configurations used in this research have lower rebar tension forces than the pullout tension of Machanzi’s carbon/epoxy (prepreg) configuration of 40.5 kN (9.11 kip). The concrete beams reinforced with carbon/epoxy rebar manufactured by IsoTruss Industries is significantly lower at 38.0 kN (8.54 kip) of tension and the beams reinforced with BYU manufactured carbon/epoxy bars are only slightly lower with 40.3 kN (9.07 kip) of tension. The 47.6 kN (10.71 kip) tension forces in the steel rebar is much higher than the pullout tension of 32.7 kN (7.34 kip) achieved by Machanzi.
4.1.4 Tensile Stress of Reinforcing Bars from Bending and Pullout Loads

The IsoTruss Industries carbon/epoxy configuration has the greatest tensile stress of 512 MPa (74.3 ksi) from bending loads. Conventional steel has a tensile stress from bending loads at 410 MPa (59.5 ksi). The bending tensile stress of BYU manufactured glass/epoxy and carbon/epoxy rebar are relatively close at 316 MPa (45.8 ksi) and 313 MPa (45.3 ksi), respectively. American Fiberglass glass/epoxy rebar has the lowest bending tensile stress at 285 MPa (41.3 ksi).

The greatest pullout tensile stress is in carbon/epoxy rebar at 476 MPa (69.0 ksi). BYU manufactured glass/epoxy rebar has a pullout tensile stress of 312 MPa (45.3 ksi) and American Fiberglass glass/epoxy rebar has a low pullout tensile stress at 269 MPa (39.0 ksi). Conventional steel has the smallest tensile stress of 258 MPa (37.4 ksi) from pullout. See Table 4.5 for the tensile stress from both pullout and bending loads.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Stress from Bending MPa (ksi)</th>
<th>Stress from Pullout* MPa (ksi)</th>
<th>Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>285 (41.3)</td>
<td>269 (39.0)</td>
<td>6%</td>
</tr>
<tr>
<td>GB</td>
<td>316 (45.8)</td>
<td>312 (45.3)</td>
<td>1%</td>
</tr>
<tr>
<td>CI</td>
<td>512 (74.3)</td>
<td>476 (69.0)</td>
<td>8%</td>
</tr>
<tr>
<td>CB</td>
<td>313 (45.3)</td>
<td>476 (69.0)</td>
<td>-52%</td>
</tr>
<tr>
<td>ST</td>
<td>410 (59.5)</td>
<td>258 (37.4)</td>
<td>59%</td>
</tr>
</tbody>
</table>

*Data from research by Machanzi [15].

4.2 Bending Load-Displacement Curves

Figure 4.2 shows the average load-center displacement curve for each configuration obtained from the four-point bending test on reinforced concrete beams. The loads in the graph represent the total load \( P \) as defined in the Chapter 2. The values for the average endpoints and stiffness for each configuration are shown in Table 4.6. Larger loads generally correspond with smaller deflections with steel reinforced concrete beams having an average center deflection of 9.73 mm (0.383 in) and beams reinforced with BYU manufactured carbon/epoxy rebar deflecting 9.60 mm (0.378 in) at the center. Beams reinforced with carbon/epoxy rebar manufactured
by IsoTruss Industries experienced an average 11.4 mm (0.448 in) center displacement while the BYU manufactured glass/epoxy and American Fiberglass reinforced concrete beams experienced the greatest deflections with 12.3 mm (0.483 in) and 12.2 mm (0.479) respective average center displacements.

The stiffness is represented by the slope of each load vs displacement curve which was calculated between 2.0 mm (0.08 in) and 8.0 mm (0.32 in) displacements for each configuration. The steel reinforced configuration has the greatest stiffness with 3.56 kN/mm (20.3 kip/in). The stiffness of the glass/epoxy configurations are the lowest with the BYU manufactured glass/epoxy configuration at 1.74 kN/mm (9.9 kip/in) and the American Fiberglass manufactured glass/epoxy configuration being the lowest at 1.68 kN/mm (9.6 kip/in). The stiffness of BYU carbon/epoxy is greater at 2.93 kN/mm (16.7 kip/in) compared with the IsoTruss Industries carbon/epoxy stiffness of 2.08 kN/mm (11.9 kip/in).

![Figure 4.2: Average Bending Test Load vs Center Displacement Curves for Each Configuration.](image)
Table 4.6: Average Bending Load, Center Displacement, and Stiffness for Each Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Center Displacement mm (in)</th>
<th>Bending Load kN (kip)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>12.2 (0.479)</td>
<td>26.2 (5.90)</td>
<td>1.68 (9.6)</td>
</tr>
<tr>
<td>GB</td>
<td>12.3 (0.483)</td>
<td>27.0 (6.07)</td>
<td>1.74 (9.9)</td>
</tr>
<tr>
<td>CI</td>
<td>11.4 (0.448)</td>
<td>27.7 (6.23)</td>
<td>2.08 (11.9)</td>
</tr>
<tr>
<td>CB</td>
<td>9.60 (0.378)</td>
<td>28.7 (6.44)</td>
<td>2.93 (16.7)</td>
</tr>
<tr>
<td>ST</td>
<td>9.73 (0.383)</td>
<td>33.8 (7.59)</td>
<td>3.56 (20.3)</td>
</tr>
</tbody>
</table>

4.3 Bending Deflection Shapes

The average deflection shape for each configuration at an applied load of 27 kN (6.0 kips) is shown in Figure 4.3. The BYU glass/epoxy reinforced concrete beams experienced the greatest average displacement and the steel reinforced concrete beams had the least displacement from these bending loads. The BYU carbon/epoxy reinforced concrete beams experienced the second lowest displacement and the glass/epoxy configurations deflected more than the carbon/epoxy configurations on average.

Predicted deflection shapes were calculated for each configuration using the derived equations as described in Chapter 2. The predicted deflection shapes for each configuration are shown in Figure 4.4 and were calculated based on 27 kN (6.0 kip) total applied loads. The average deflections are less than the predicted deflections for both fiberglass/epoxy configurations and are greater than the predicted deflections for the carbon/epoxy and steel configurations. The predictions match which configurations deflect more or less in comparison to each other. Refer to Figures 4.5 through 4.9 for graphs comparing the average deflection shapes to the predicted deflection shapes for each configuration.
Figure 4.3: Average Deflection Shape of All Reinforced Concrete Beam Configurations Under 6 kip Bending Loads.

Figure 4.4: Predicted Deflection Shape of All Reinforced Concrete Beam Configurations Under 6 kip Bending Loads.
Figure 4.5: Average Deflection Shape vs Predicted Deflection Shape of American Fiberglass (GA) Reinforced Concrete Beams Under 6 kip Bending Loads.

Figure 4.6: Average Deflection Shape vs Predicted Deflection Shape of BYU Glass/Epoxy (GB) Reinforced Concrete Beams Under 6 kip Bending Loads.
Figure 4.7: Average Deflection Shape vs Predicted Deflection Shape of IsoTruss Industries Carbon/Epoxy (CI) Reinforced Concrete Beams Under 6 kip Bending Loads.

Figure 4.8: Average Deflection Shape vs Predicted Deflection Shape of BYU Carbon/Epoxy (CB) Reinforced Concrete Beams Under 6 kip Bending Loads.
Nominal (predicted) and effective (measured) EI and EA properties were calculated for each configuration using the derived deflection equations and are shown in Table 4.7. The values for the effective properties are greater than the nominal property values for the glass/epoxy configurations. The effective property values are less than the nominal property values for the carbon/epoxy and steel configurations. The predictions match which configurations have greater EI and EA properties in comparison to each other.

Table 4.7: Effective and Nominal EI and EA Values for Each Beam Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$E_{I_{eff}}$</th>
<th>$E_{I_{nominal}}$</th>
<th>$E_{A_{eff}}$</th>
<th>$E_{A_{nominal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN·m$^2$</td>
<td>kN·m$^2$·10$^3$</td>
<td>kN (kip)</td>
<td>kN (kip)</td>
</tr>
<tr>
<td>GA</td>
<td>118 (41.0)</td>
<td>95 (33.1)</td>
<td>7.75 (1.74)</td>
<td>6.27 (1.41)</td>
</tr>
<tr>
<td>GB</td>
<td>109 (37.8)</td>
<td>89 (31.1)</td>
<td>7.08 (1.59)</td>
<td>5.82 (1.31)</td>
</tr>
<tr>
<td>CI</td>
<td>121 (42.0)</td>
<td>147 (51.3)</td>
<td>8.71 (1.96)</td>
<td>10.6 (2.39)</td>
</tr>
<tr>
<td>CB</td>
<td>168 (58.7)</td>
<td>230 (80.2)</td>
<td>13.8 (3.11)</td>
<td>18.9 (4.25)</td>
</tr>
<tr>
<td>ST</td>
<td>211 (73.6)</td>
<td>282 (98.4)</td>
<td>18.7 (4.22)</td>
<td>25.1 (5.64)</td>
</tr>
</tbody>
</table>

Figure 4.9: Average Deflection Shape vs Predicted Deflection Shape of Steel (ST) Reinforced Concrete Beams Under 6 kip Bending Loads.
The compression and tension bending stresses were calculated for each beam configuration. These stresses are shown in Table 4.8 along with the rebar structural cross-sectional area, the beam transformed moment of inertia, and the rebar modulus of elasticity for each configuration. Compression bending stress was calculated for the top of the concrete beam and tension bending stress was calculated at the center of the rebar. The glass/epoxy had larger compression bending stresses and lower tensile bending stresses in general. BYU carbon/epoxy had low bending stress both in compression and tension when compared with the other configurations.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Structural Rebar Area cm² (in²)</th>
<th>Moment of Inertia ( (I_t) ) cm⁴ (in⁴)</th>
<th>Modulus of Elasticity* ( (E_r) ) GPa (msi)</th>
<th>Compression Bending Stress MPa (ksi)</th>
<th>Tension Bending Stress MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>1.3 (0.20)</td>
<td>310 (7.46)</td>
<td>47.6 (6.90)</td>
<td>38 (5.5)</td>
<td>285 (41.3)</td>
</tr>
<tr>
<td>GB</td>
<td>1.2 (0.19)</td>
<td>291 (6.99)</td>
<td>47.8 (6.93)</td>
<td>40 (5.8)</td>
<td>316 (45.8)</td>
</tr>
<tr>
<td>CI</td>
<td>0.8 (0.12)</td>
<td>480 (11.5)</td>
<td>138 (20.0)</td>
<td>31 (4.6)</td>
<td>512 (74.3)</td>
</tr>
<tr>
<td>CB</td>
<td>1.4 (0.21)</td>
<td>751 (18.0)</td>
<td>138 (20.0)</td>
<td>27 (3.9)</td>
<td>313 (45.3)</td>
</tr>
<tr>
<td>ST</td>
<td>1.3 (0.20)</td>
<td>922 (22.2)</td>
<td>198 (28.7)</td>
<td>29 (4.2)</td>
<td>410 (59.5)</td>
</tr>
</tbody>
</table>

*Data from research by Machanzi [15].
CHAPTER 5. DISCUSSION OF RESULTS

The various configurations are compared in this chapter according to the reinforcement material and manufacturer. Comparisons are represented by percentage differences and are based on bending stress, member displacement, and stiffness. Abbreviated configuration names are used throughout this chapter for simplification purposes. All configuration names identify the type of reinforcement used in the concrete beam specimens with GA for American Fiberglass glass/epoxy, GB for BYU glass/epoxy, CI for IsoTruss Industries carbon/epoxy, CB for BYU carbon/epoxy, and ST for plain steel rebar. Refer to section 2.3 of Chapter 2 for a more detailed description of the configuration naming convention.

5.1 Comparing BYU Composite Rebar to Industry Composite Rebar in Reinforced Concrete Beams Under Bending Loads

This section focuses on the percentage differences between concrete beams reinforced with BYU manufactured composite rebar and those reinforced with industry manufactured composite rebar. Percentages have been calculated for bending stress, displacement, and stiffness.

All percent differences for the bending stress, center displacements, and stiffness between the BYU manufactured and industry manufactured configurations are shown in Tables 5.1 and 5.2. BYU glass/epoxy beams experienced 5% greater average compression bending stress and 11% greater tension bending stress than American Fiberglass glass/epoxy beams. BYU carbon/epoxy beams experienced 18% less average compression bending stress and 64% less tension bending stress than IsoTruss Industries carbon/epoxy beams. When comparing center displacements, BYU glass/epoxy has a 1% larger center displacement than American Fiberglass glass/epoxy while the IsoTruss Industries carbon/epoxy configuration has a 19% greater average center displacement than the BYU carbon/epoxy configuration. Both BYU manufactured configurations also have greater bending stiffness than their industry manufactured counterparts with the BYU carbon/epoxy stiff-
ness being 40% greater than the IsoTruss Industries carbon/epoxy and the BYU glass/epoxy stiffness being 3% greater than the American Fiberglass glass/epoxy configuration. See Figures 5.1 and 5.2 for graphs illustrating the differences between the BYU manufactured and industry manufactured configurations in terms of maximum applied bending loads and center displacements.

Table 5.1: Comparing Bending Stress, Center Displacement, and Stiffness Between GA and GB Configurations at Failure

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Stress MPa (ksi)</th>
<th>Tension Stress MPa (ksi)</th>
<th>Center Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>38 (5.5)</td>
<td>285 (41.3)</td>
<td>12.2 (0.479)</td>
<td>1.68 (9.6)</td>
</tr>
<tr>
<td>GB</td>
<td>40 (5.8)</td>
<td>316 (45.8)</td>
<td>12.3 (0.483)</td>
<td>1.74 (9.9)</td>
</tr>
<tr>
<td>Difference</td>
<td>5%</td>
<td>11%</td>
<td>1%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Table 5.2: Comparing Bending Stress, Center Displacement, and Stiffness Between CI and CB Configurations at Failure

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Stress MPa (ksi)</th>
<th>Tension Stress MPa (ksi)</th>
<th>Center Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>31 (4.6)</td>
<td>512 (74.3)</td>
<td>11.4 (0.448)</td>
<td>2.08 (11.9)</td>
</tr>
<tr>
<td>CB</td>
<td>27 (3.9)</td>
<td>313 (45.3)</td>
<td>9.6 (0.378)</td>
<td>2.93 (16.7)</td>
</tr>
<tr>
<td>Difference</td>
<td>-18%</td>
<td>-64%</td>
<td>-19%</td>
<td>40%</td>
</tr>
</tbody>
</table>
Figure 5.1: GA and GB Bending Load vs Center Displacement Curves.

Figure 5.2: CI and CB Bending Load vs Center Displacement Curves.
5.2 Comparing BYU Glass/Epoxy Rebar to BYU Carbon/Epoxy Rebar in Reinforced Concrete Beams Under Bending Loads

This section focuses on the percentage differences between concrete beams reinforced with BYU manufactured glass/epoxy rebar and those reinforced with BYU Manufactured carbon/epoxy rebar. Percentages have been calculated for bending stress, displacement, and stiffness.

Percent differences for the bending stress, center displacements, and stiffness between the BYU manufactured glass/epoxy and carbon/epoxy configurations are shown in Table 5.3. The BYU glass/epoxy reinforced concrete beams have 49% greater average compression bending stress and 1% greater tension bending stress than the BYU carbon/epoxy reinforced concrete beams. The glass/epoxy reinforced concrete beams experienced larger center displacements when compared to the carbon/epoxy reinforced concrete beams. BYU glass/epoxy has 28% greater average center displacements than BYU carbon/epoxy. The BYU carbon/epoxy has a 68% greater bending stiffness than the BYU glass/epoxy configuration. Refer to Figure 5.3 for graph illustrating the difference between the BYU manufactured glass/epoxy and carbon/epoxy configurations in terms of maximum applied bending loads and center displacements.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Stress MPa (ksi)</th>
<th>Tension Stress MPa (ksi)</th>
<th>Center Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>40 (5.8)</td>
<td>316 (45.8)</td>
<td>12.3 (0.483)</td>
<td>1.74 (9.9)</td>
</tr>
<tr>
<td>CB</td>
<td>27 (3.9)</td>
<td>313 (45.3)</td>
<td>9.6 (0.378)</td>
<td>2.93 (16.7)</td>
</tr>
<tr>
<td>Difference</td>
<td>-49%</td>
<td>-1%</td>
<td>-28%</td>
<td>68%</td>
</tr>
</tbody>
</table>
5.3 Comparing Steel Rebar to BYU Composite Rebar in Reinforced Concrete Beams Under Bending Loads

This section focuses on the percentage differences between concrete beams reinforced with BYU manufactured composite rebar and those reinforced with conventional steel rebar. Percentages have been calculated for bending stress, displacement, and stiffness.

Percent differences for the bending stress, center displacements, and stiffness between the conventional steel and BYU manufactured composite configurations are shown in Tables 5.4 and 5.5. The steel reinforced configuration has 38% less compression bending stress than the BYU glass/epoxy configuration and 8% greater compression bending stress than the BYU carbon/epoxy configuration. Concrete beams reinforced with conventional steel rebar experienced greater average tension bending stresses than either of the composite reinforced configurations. The steel configuration has 30% and 31% greater average tension bending stresses than the BYU glass/epoxy and BYU carbon/epoxy configurations, respectively. Of the BYU composite reinforced configurations, steel only has a greater center displacement when compared with the BYU carbon/epoxy
configuration, which is 1% greater. The average center displacements of the BYU glass/epoxy configuration is larger than those of the conventional steel configuration by 26%. Steel has a 105% and 22% greater bending stiffness than the BYU glass/epoxy and BYU carbon/epoxy configurations, respectively. See Figure 5.4 for graph illustrating the differences between steel reinforced concrete and the BYU manufactured composite reinforced configurations in terms of maximum applied bending loads and center displacements.

Table 5.4: Comparing Bending Stress, Center Displacement, and Stiffness Between GB and ST Configurations at Failure

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Stress MPa (ksi)</th>
<th>Tension Stress MPa (ksi)</th>
<th>Center Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>40 (5.8)</td>
<td>316 (45.8)</td>
<td>12.3 (0.483)</td>
<td>1.74 (9.9)</td>
</tr>
<tr>
<td>ST</td>
<td>29 (4.2)</td>
<td>410 (59.5)</td>
<td>9.7 (0.383)</td>
<td>3.56 (20.3)</td>
</tr>
<tr>
<td>Difference</td>
<td>-38%</td>
<td>30%</td>
<td>-26%</td>
<td>105%</td>
</tr>
</tbody>
</table>

Table 5.5: Comparing Bending Stress, Center Displacement, and Stiffness Between CB and ST Configurations at Failure

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Stress MPa (ksi)</th>
<th>Tension Stress MPa (ksi)</th>
<th>Center Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>27 (3.9)</td>
<td>313 (45.3)</td>
<td>9.6 (0.378)</td>
<td>2.93 (16.7)</td>
</tr>
<tr>
<td>ST</td>
<td>29 (4.2)</td>
<td>410 (59.5)</td>
<td>9.7 (0.383)</td>
<td>3.56 (20.3)</td>
</tr>
<tr>
<td>Difference</td>
<td>8%</td>
<td>31%</td>
<td>1%</td>
<td>22%</td>
</tr>
</tbody>
</table>
5.4 Comparing Reinforcement Tensile Stress from Pullout and Bending Loads

This section compares the bending tension in the concrete reinforcement due to bending stresses and the pullout tension achieved by Machanzi [15] in his research. The American Fiber-glass glass/epoxy, BYU glass/epoxy, and steel configurations were all used by Machanzi in his research, and while he also used a carbon/epoxy configuration in his preliminary research it was slightly different than either carbon/epoxy configurations used in this research. Machanzi’s carbon/epoxy configuration did not receive a sand coating and was 10.4 mm (0.41) inches in diameter compared to 9.8 mm (0.39 in) and 13.2 mm (0.52 in) pre sand-coated diameters of the IsoTrus carbon/epoxy and BYU carbon/epoxy configurations.

All percent differences between tensile stress from pullout and bending stresses are shown in Table 5.6. The steel configuration has the greatest difference of 59% with bending tensile stress being much higher than pullout tensile stress. Concrete beams reinforced with BYU carbon/epoxy rebar also have a large difference of 52% with pullout tensile stress being greater than bending tensile stress. The tensile stress due to bending in the glass/epoxy reinforcing bars is comparable to
the pullout tensile stress achieved by Machanzi [15] with BYU glass/epoxy having a 1% difference and American Fiberglass glass/epoxy having a 6% difference. For the glass/epoxy configurations the tensile stress from bending is larger than the tensile stress from pullout. The pullout tensile stress is 8% greater than tensile stress from bending stress for the IsoTruss Industries carbon/epoxy configuration.

Table 5.6: Bending Tensile Stress vs Pullout Tensile Stress

<table>
<thead>
<tr>
<th>Rebar Tension</th>
<th>GA</th>
<th>GB</th>
<th>CI</th>
<th>CB</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress from Bending MPa (ksi)</td>
<td>285 (41.3)</td>
<td>316 (45.8)</td>
<td>512 (74.3)</td>
<td>313 (45.3)</td>
<td>410 (59.5)</td>
</tr>
<tr>
<td>Stress from Pullout* MPa (ksi)</td>
<td>269 (39.0)</td>
<td>312 (45.3)</td>
<td>476 (69.0)</td>
<td>476 (69.0)</td>
<td>258 (37.4)</td>
</tr>
<tr>
<td>Difference</td>
<td>6%</td>
<td>1%</td>
<td>8%</td>
<td>-52%</td>
<td>59%</td>
</tr>
</tbody>
</table>

*Data from research by Machanzi [15].
CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes conclusions and provides recommendations for future research. Four-point bending tests were performed to measure the maximum bending loads and displacements of concrete beams reinforced with composite rebar. Conclusions focus on the influence of the material of the reinforcing bar, comparison with reinforcement of different manufacturers, and comparison with conventional steel rebar. All values represent configuration averages.

The BYU glass/epoxy (GB) and BYU carbon/epoxy (CB) configurations represent reinforced concrete beams with rebar manufactured on a three-dimensional braiding machine and cured in an inline oven while still under tension immediately after production. The American Fiberglass glass/epoxy (GA) configuration represents reinforced concrete beams with rebar manufactured by industry using other methods. The IsoTruss Industries carbon/epoxy (CI) configuration represents concrete beams with rebar manufactured by industry on the three-dimensional braiding machine that was subsequently rolled, stored, and then cured with enough tension to ensure straight bars. The steel (ST) configuration represents concrete beams reinforced with conventional No. 4 steel rebar. Reinforced concrete beams were 152 cm (60.0 in) in length, 11.4 cm (4.5 in) wide, and 15.5 cm (6.0 in) in height. Refer to earlier sections in this document for more details.

6.1 Conclusions

• Concrete beams reinforced with BYU fiberglass/epoxy rebar exhibited 5% higher compression bending stress and 11% higher tension bending stress than concrete beams reinforced with industry manufactured fiberglass/epoxy rebar. The BYU glass/epoxy reinforcement displayed a 1% greater center displacement from bending loads compared to industry manufactured glass/epoxy reinforcement. The BYU glass/epoxy rebar results in a 3% greater bending stiffness than industry manufactured glass/epoxy rebar. Thus, BYU glass/epoxy rebar manufactured on the three-dimensional braiding machine has a higher bending stress,
center displacement, and bending stiffness than its industry manufactured counterpart when used as reinforcement in concrete beams.

- Concrete beams reinforced with BYU carbon/epoxy rebar exhibited 18% lower compression bending stress and 59% lower tension bending stress than concrete beams reinforced with industry manufactured carbon/epoxy rebar. Industry manufactured carbon/epoxy reinforcement showed a 19% greater center displacement from bending loads than BYU carbon/epoxy rebar. The BYU carbon/epoxy rebar results in a 40% greater bending stiffness than the industry manufactured carbon/epoxy rebar. Thus, BYU carbon/epoxy rebar has a lower bending stress and greater bending stiffness than its industry manufactured counterpart when used as reinforcement in concrete beams and BYU carbon/epoxy rebar results in less deflection under bending loads than industry manufactured carbon/epoxy rebar.

- Concrete beams reinforced with BYU carbon/epoxy rebar exhibited 49% lower compression bending stress and 1% lower tension bending stress than concrete beams reinforced with BYU glass/epoxy rebar. BYU glass/epoxy reinforcement displayed a 28% greater center displacement from bending loads compared to BYU carbon/epoxy rebar. BYU carbon/epoxy rebar results in a 68% greater bending stiffness than BYU glass/epoxy rebar. Thus, BYU carbon/epoxy rebar has a lower bending stress and greater bending stiffness than BYU glass/epoxy rebar when used as reinforcement in concrete beams and BYU glass/epoxy rebar results in greater deflection under bending loads than carbon/epoxy rebar.

- Concrete beams reinforced with conventional steel rebar exhibited 38% lower compression bending stress and 30% greater tension bending stress than concrete beams reinforced with BYU glass/epoxy rebar manufactured on the three-dimensional braiding machine. BYU glass/epoxy reinforcement displayed a 26% greater center displacement from bending loads compared to steel rebar. Steel reinforcement results in a 105% greater bending stiffness than BYU glass/epoxy rebar. Thus, conventional steel rebar has a lower bending stress and greater bending stiffness than BYU glass/epoxy rebar when used as reinforcement in concrete beams and BYU glass/epoxy rebar results in greater center displacement under bending loads than steel rebar.

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• Concrete beams reinforced with conventional steel rebar exhibited 8% higher compression bending stress and 31% higher tension bending stress than concrete beams reinforced with BYU carbon/epoxy rebar manufactured on the three-dimensional braiding machine. Steel reinforcement displayed a 1% greater center displacement from bending loads compared to BYU carbon/epoxy rebar. Steel reinforcement results in a 22% greater bending stiffness than BYU carbon/epoxy rebar. Thus, conventional steel rebar has a lower bending stress, greater center displacement, and greater bending stiffness than BYU carbon/epoxy rebar when used as reinforcement in concrete beams.

6.2 **Recommendations for Future Research**

• Dry aramid composite materials should be considered for use as reinforcement to compare with prepreg composites for future research in concrete beams reinforced with composite rebar manufactured on a three-dimensional braiding machine.

• Stirrup reinforcement should be considered in any future research in concrete beams reinforced with composite rebar manufactured on a three-dimensional braiding machine as a way to prevent shear failure and focus on moment failure of the reinforced beam.

• Future research in concrete beams reinforced with composite rebar manufactured on a three-dimensional braiding machine should consider fabricating larger beams for a better understanding of large scale application.

• Concrete with a greater slump should be considered for use in future research in concrete beams reinforced with composite rebar manufactured on a three-dimensional braiding machine to allow concrete to be distributed more evenly throughout the beam.
REFERENCES


APPENDIX A. PRISM COMPRESSION TESTING

An axial compression test was chosen to be used to test the concrete beams for compression strength. This was done in response to the voids in the reinforced concrete beams to see if they might have a significant impact on the strength of the beams. Three specimens were taken from each configuration to be tested in compression for a total of 15 axial compression test specimens. Compression prism specimens were taken from the un-failed ends of the beams after they were tested in four-point bending. The procedures, results, and discussions concerning the axial compression test are outlined in this appendix.

A.1 Prism Axial Compression Test Procedures

After the bending test was complete, three 30 cm (12 in) specimens were used from each configuration to be tested in compression. These specimens were taken from the ends that did not fail on beams after they were tested in four-point bending. See Figure A.1 for examples of the compression test specimens. The ends were capped in cement in the same moment as the concrete cylinders on the day before testing. The prisms were too large for the Forney compression machine and were tested using the MTS system instead, as shown in Figure A.2. Refer to the figures in Appendix D to see each beam specimen post compression failure.
Figure A.1: Concrete Prism Compression Test Specimens.

Figure A.2: Prism Compression Testing Using the MTS Uniaxial Load Frame System.
A.2 Prism Axial Compression Test Results

The results of the axial compression tests conducted on reinforced concrete beam prisms are summarized in this section. These results include load vs deflection curves.

A.2.1 American Fiberglass Compression

The GA configuration consists of concrete beams reinforced with sand-coated fiberglass/epoxy rebar manufactured by American Fiberglass. See Figure A.3 for load and deflection curves. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 644 kN (145 kip) with a standard deviation of 52.1 kN (11.7 kip). This results in an average compressive strength of 37.0 MPa (5.36 ksi) with a standard deviation of 2.99 MPa (0.43 ksi).

![Figure A.3: Compression Test Load-Displacement Curve for American Fiberglass Reinforced Concrete.](image-url)
A.2.2 BYU Fiberglass/Epoxy Compression

The GB configuration consists of concrete beams reinforced with sand-coated fiberglass/epoxy rebar manufactured at BYU. See Figure A.4 for load and deflection curves. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 518 kN (116 kip) with a standard deviation of 86.5 kN (19.4 kip). This results in an average compressive strength of 29.7 MPa (4.31 ksi) with a standard deviation of 4.96 MPa (0.71 ksi).

![Figure A.4: Compression Test Load-Displacement Curve for BYU Fiberglass/Epoxy Reinforced Concrete.](image)

A.2.3 IsoTruss Industries Carbon/Epoxy Compression

The CI configuration consists of concrete beams reinforced with sand-coated carbon/epoxy rebar manufactured by IsoTruss Industries. See Figure A.5 for load and deflection curves. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 527 kN (119 kip) with a standard deviation of 125 kN (28.1 kip). This results in an average compressive strength of 30.3 MPa (4.39 ksi) with a standard deviation of 7.18 MPa (1.04 ksi).
A.2.4 BYU Carbon/Epoxy Compression

The CB configuration consists of concrete beams reinforced with sand-coated carbon/epoxy rebar manufactured at BYU. See Figure A.6 for load and deflection curves. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 484 kN (109 kip) with a standard deviation of 15.7 kN (3.5 kip). This results in an average compressive strength of 27.8 MPa (4.03 ksi) with a standard deviation of 0.90 MPa (0.13 ksi).
Figure A.6: Compression Test Load-Displacement Curve for BYU Carbon/Epoxy Reinforced Concrete.

A.2.5 Steel Compression

The ST configuration consists of concrete beams reinforced with conventional plain steel rebar. See Figure A.7 for load and deflection curves. All of the stress-strain curves fell within Chauvenet’s limits of statistical acceptability. The average maximum load was 735 kN (165 kip) with a standard deviation of 25.4 kN (5.7kip). This results in an average compressive strength of 42.2 MPa (6.12 ksi) with a standard deviation of 1.46 MPa (0.21 ksi).
A.3 Comparing Strength and Load Capacity from Prism Compression Tests

A.3.1 Maximum Applied Axial Compression Loads

Figure A.8 shows the maximum loads applied to each specimen by configuration. The error bars represent Chauvenet’s limits for the maximum load values. All points fell within those limits and were used in determining the average maximum loads. All of the average maximum loads are lower than would be expected based off of the results of the concrete cylinder tests. See Tables A.1 and A.2 for the respective maximum load and compressive strength values for each specimen. Note that $\sigma$ is equal to $P/A$ with $A$ being 174 cm$^2$ (27 in$^2$).
Table A.1: Prism Compression Test Maximum Loads Applied to Each Specimen

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>GA (kN) (kip)</th>
<th>GB (kN) (kip)</th>
<th>CI (kN) (kip)</th>
<th>CB (kN) (kip)</th>
<th>ST (kN) (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>576 (130)</td>
<td>—</td>
<td>681 (135)</td>
<td>—</td>
<td>765 (172)</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>738 (166)</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>555 (123)</td>
<td>—</td>
<td>486 (109)</td>
<td>703 (158)</td>
</tr>
<tr>
<td>4</td>
<td>702 (158)</td>
<td>600 (135)</td>
<td>374 (84.1)</td>
<td>464 (104)</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>654 (147)</td>
<td>398 (90.0)</td>
<td>527 (119)</td>
<td>503 (113)</td>
<td>—</td>
</tr>
<tr>
<td>Average</td>
<td>644 (145)</td>
<td>518 (116)</td>
<td>527 (119)</td>
<td>484 (109)</td>
<td>735 (165)</td>
</tr>
<tr>
<td>Std Dev</td>
<td>52.1 (11.7)</td>
<td>86.5 (19.4)</td>
<td>125 (28.1)</td>
<td>15.7 (3.5)</td>
<td>25.4 (5.7)</td>
</tr>
<tr>
<td>Upper Limit</td>
<td>716 (161)</td>
<td>636 (143)</td>
<td>698 (157)</td>
<td>507 (114)</td>
<td>770 (173)</td>
</tr>
<tr>
<td>Lower Limit</td>
<td>574 (129)</td>
<td>398 (90.0)</td>
<td>356 (80.0)</td>
<td>43 (104)</td>
<td>698 (157)</td>
</tr>
</tbody>
</table>

All data fell within Chauvenet’s limits.

*Theoretical strength of concrete beams based on cylinder tests and beam cross-sectional area.

Figure A.8: Prism Compression Test Maximum Loads for Each Configuration with Chauvenet’s Envelope Represented with Error Bars.
A.3.2 Compression Strength of Reinforced Concrete Prisms

Steel reinforced concrete had the largest compressive strength with 42.2 MPa (6.12 ksi) on average. Concrete reinforced with American Fiberglass bars had the second largest compressive strength with 37.0 MPa (5.36 ksi) and was significantly larger than the BYU manufactured glass/epoxy rebar, which reached an average compressive strength of 29.7 MPa (4.31 ksi). The carbon/epoxy bars manufactured by IsoTruss Industries also performed better under compression than the BYU manufactured carbon/epoxy rebar with average compressive strengths of 30.3 MPa (4.39 ksi) and 27.8 MPa (4.03 ksi) respectively.

Table A.2: Compressive Strength of Each Prism

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>GA</th>
<th>GB</th>
<th>CI</th>
<th>CB</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
<td>MPa (ksi)</td>
</tr>
<tr>
<td>1</td>
<td>33.1 (4.79)</td>
<td>—</td>
<td>39.1 (5.67)</td>
<td>—</td>
<td>43.9 (6.37)</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>42.3 (6.14)</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>31.8 (4.62)</td>
<td>—</td>
<td>27.9 (4.04)</td>
<td>40.3 (5.85)</td>
</tr>
<tr>
<td>4</td>
<td>40.3 (5.85)</td>
<td>34.5 (5.00)</td>
<td>21.5 (3.12)</td>
<td>26.7 (3.87)</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>37.5 (5.44)</td>
<td>22.9 (3.32)</td>
<td>30.2 (4.39)</td>
<td>28.9 (4.19)</td>
<td>—</td>
</tr>
<tr>
<td>Average</td>
<td>37.0 (5.36)</td>
<td>29.7 (4.31)</td>
<td>30.3 (4.39)</td>
<td>27.8 (4.03)</td>
<td>42.2 (6.12)</td>
</tr>
<tr>
<td>Std Dev</td>
<td>2.99 (0.43)</td>
<td>4.96 (0.72)</td>
<td>7.18 (1.04)</td>
<td>0.90 (0.13)</td>
<td>1.46 (0.21)</td>
</tr>
<tr>
<td>Upper Limit</td>
<td>41.1 (5.96)</td>
<td>36.6 (5.30)</td>
<td>40.2 (5.83)</td>
<td>29.0 (4.21)</td>
<td>44.2 (6.41)</td>
</tr>
<tr>
<td>Lower Limit</td>
<td>32.8 (4.76)</td>
<td>22.9 (3.32)</td>
<td>20.4 (2.95)</td>
<td>26.6 (3.85)</td>
<td>40.2 (5.83)</td>
</tr>
</tbody>
</table>

All data fell within Chauvenet’s limits.

A.4 Prism Compression Load-Displacement Curves

Test Figure A.9 shows the average load-displacement curve for each configuration obtained from the reinforced concrete beam compression test. The values for the average endpoints and stiffness for each configuration can be found in Table A.3. The results for the compression load-displacement curves appeared mixed. The largest average deflections were 2.77 mm (0.109 in) and 2.74 mm (0.108 in) experienced by concrete beams reinforced with steel and BYU manufactured glass/epoxy bars respectfully. However there was a significant gap in maximum compression loads.
between those two configurations with steel reinforced concrete experiencing 735 kn (165 kip) and BYU glass/epoxy reinforced concrete experiencing 518 kN (118 kips) in compression. Beams reinforced with American Fiberglass bars experienced a lesser deflection of 2.46 mm (0.097 in) than its BYU manufactured glass/epoxy counterpart, but its loads were significantly higher at 644 kN (145 kip). Both configurations of concrete beams reinforced with carbon/epoxy bars experienced lower loads and deflections. BYU carbon/epoxy reinforced concrete had deflections of 2.16 mm (0.085 in) and loads of 484 kN (109 kip) while IsoTruss Industries carbon/epoxy reinforced concrete had deflections of 2.11 mm (0.083 in) and loads of 527 kN (119 kip).

The stiffness is represented by the slope of each load vs displacement curve was calculated between 1.0 mm (0.04 in) and 1.5 mm (0.06 in) displacements for each configuration. The stiffness generally stays between 341 kN/mm (1950 kip/in) and 366 kN/mm (2090 kip/in) with the exception of the BYU manufactured glass/epoxy configuration having a noticeably low stiffness of 244 kN/mm (1390 kip/in). The American Fiberglass glass/epoxy configuration has the greatest stiffness at 366 kN/mm (2090 kip/in).

Figure A.9: Average Compression Test Load-Displacement Curves for Each Configuration.
Table A.3: Axial Compression Load, Displacement, and Stiffness for Each Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Displacement (mm in)</th>
<th>Compression Load (kN kip)</th>
<th>Stiffness (kN/mm kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>2.46 (0.097)</td>
<td>644 (145)</td>
<td>366 (2090)</td>
</tr>
<tr>
<td>GB</td>
<td>2.74 (0.108)</td>
<td>518 (116)</td>
<td>244 (1390)</td>
</tr>
<tr>
<td>CI</td>
<td>2.11 (0.083)</td>
<td>527 (119)</td>
<td>349 (1990)</td>
</tr>
<tr>
<td>CB</td>
<td>2.16 (0.085)</td>
<td>484 (109)</td>
<td>362 (2070)</td>
</tr>
<tr>
<td>ST</td>
<td>2.77 (0.109)</td>
<td>735 (165)</td>
<td>342 (1950)</td>
</tr>
</tbody>
</table>

A.4.1 BYU Composite Rebar vs Industry Composite Rebar in Compression

All percent differences for the compression strengths, displacements, and stiffness between the BYU manufactured and industry manufactured configurations are shown in Tables A.4 and A.5. The concrete beams reinforced with industry manufactured rebar have larger compression strengths when compared with their BYU manufactured counterparts. The American Fiberglass glass/epoxy configuration has the largest difference with a 24% greater compression strength than the BYU glass/epoxy configuration and the IsoTruss Industries carbon/epoxy configuration has a 9% greater compression strength than the BYU carbon/epoxy configuration. The industry manufactured configurations also have lower displacements than the BYU manufactured configurations. BYU glass/epoxy displacements are 11% larger than those of the American Fiberglass glass/epoxy configuration and BYU carbon/epoxy displacements are 2% larger than those of the IsoTruss Industries carbon/epoxy configuration. The BYU carbon/epoxy configuration has a 4% greater compression stiffness than the IsoTruss Industries carbon/epoxy configuration, and the American Glass glass/epoxy configuration has a 50% greater compression stiffness than the BYU glass/epoxy configuration. See Figures A.10 and A.11 for graphs illustrating the differences between the BYU manufactured and industry manufactured configurations in terms of maximum applied compression loads and displacements.
Table A.4: Comparing Compression Strength, Displacement, and Stiffness Between GA and GB Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Strength</th>
<th>Displacement</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa (ksi)</td>
<td>mm (in)</td>
<td>kN/mm (kip/in)</td>
</tr>
<tr>
<td>GA</td>
<td>37.0 (5.36)</td>
<td>2.46 (0.097)</td>
<td>366 (2090)</td>
</tr>
<tr>
<td>GB</td>
<td>29.7 (4.31)</td>
<td>2.74 (0.108)</td>
<td>244 (1390)</td>
</tr>
<tr>
<td>Difference</td>
<td>-24%</td>
<td>11%</td>
<td>-50%</td>
</tr>
</tbody>
</table>

Table A.5: Comparing Compression Strength, Displacement, and Stiffness Between CI and CB Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Strength</th>
<th>Displacement</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa (ksi)</td>
<td>mm (in)</td>
<td>kN/mm (kip/in)</td>
</tr>
<tr>
<td>CI</td>
<td>30.3 (4.39)</td>
<td>2.11 (0.083)</td>
<td>349 (1990)</td>
</tr>
<tr>
<td>CB</td>
<td>27.8 (4.03)</td>
<td>2.16 (0.085)</td>
<td>362 (2070)</td>
</tr>
<tr>
<td>Difference</td>
<td>-9%</td>
<td>2%</td>
<td>4%</td>
</tr>
</tbody>
</table>
Figure A.10: GA and GB Axial Compression Load vs Displacement Curves.

Figure A.11: CI and CB Axial Compression Load vs Displacement Curves.
A.4.2 Glass/Epoxy Rebar vs Carbon/Epoxy Rebar in Compression

Percent differences for the compression strengths displacements, and stiffness between the BYU manufactured glass/epoxy and carbon/epoxy configurations are shown in Table A.6. The glass/epoxy reinforced concrete beams have overall larger compression strength when compared to the carbon/epoxy reinforced concrete beams. BYU glass/epoxy has 6% greater compression strength than BYU carbon/epoxy. The glass/epoxy reinforced concrete beams also experienced larger displacements when compared to the carbon/epoxy reinforced concrete beams. The BYU glass/epoxy configuration has 27% greater average displacements than the BYU carbon/epoxy configuration. The BYU carbon/epoxy has a 49% greater compression stiffness than the BYU glass/epoxy configuration. Refer to Figure A.12 for graph illustrating the differences between the BYU manufactured glass/epoxy and carbon/epoxy configurations in terms of maximum applied compression loads and displacements.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Strength (MPa (ksi))</th>
<th>Displacement (mm (in))</th>
<th>Stiffness (kN/mm (kip/in))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>29.7 (4.31)</td>
<td>2.74 (0.108)</td>
<td>244 (1390)</td>
</tr>
<tr>
<td>CB</td>
<td>27.8 (4.03)</td>
<td>2.16 (0.085)</td>
<td>362 (2070)</td>
</tr>
<tr>
<td>Difference</td>
<td>-6%</td>
<td>-27%</td>
<td>49%</td>
</tr>
</tbody>
</table>
A.4.3 Steel Rebar vs Composite Rebar in Compression

Percent differences for the compression strengths, displacements, and stiffness between the conventional steel and BYU manufactured composite configurations are shown in Tables A.7 and A.8. The concrete beams reinforced with conventional steel rebar have larger compression strengths than either of the composite reinforced configurations. The steel configuration has 52% and 42% greater average compression strengths than the BYU carbon/epoxy and BYU glass/epoxy configurations, respectively. The steel reinforced concrete beams also have larger displacements than the BYU manufactured composite reinforced configurations. The steel configuration has 28% and 1% greater average displacements than the BYU carbon/epoxy and BYU glass/epoxy configurations, respectively. Steel has a 40% greater compression stiffness than BYU glass/epoxy, and BYU carbon/epoxy has a 6% greater compression stiffness than steel. See Figure A.13 for graph illustrating the differences between steel reinforced concrete beams and BYU manufactured composite reinforced configurations in terms of maximum applied compression loads and displacements.
Table A.7: Comparing Compression Strength, Displacement, and Stiffness Between GB and ST Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Strength MPa (ksi)</th>
<th>Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>29.7 (4.31)</td>
<td>2.74 (0.108)</td>
<td>244 (1390)</td>
</tr>
<tr>
<td>ST</td>
<td>42.2 (6.12)</td>
<td>2.77 (0.109)</td>
<td>342 (1950)</td>
</tr>
</tbody>
</table>

Difference 42% 1% 40%

Table A.8: Comparing Compression Strength, Displacement, and Stiffness Between CB and ST Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Compression Strength MPa (ksi)</th>
<th>Displacement mm (in)</th>
<th>Stiffness kN/mm (kip/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>27.8 (4.03)</td>
<td>2.16 (0.085)</td>
<td>362 (2070)</td>
</tr>
<tr>
<td>ST</td>
<td>42.2 (6.12)</td>
<td>2.77 (0.109)</td>
<td>342 (1950)</td>
</tr>
</tbody>
</table>

Difference 52% 28% -6%
A.5 Discussion of Axial Compression Results

The results of the axial compression test performed on the reinforced concrete beams are inconsistent and do not appear to coincide with engineering principles. Compression strength, deflection, and stiffness do not match what would be expected based off of reinforcement properties. Compression strength of the reinforced concrete beams are significantly lower than would be expected based off of the concrete cylinder results. The limited number of specimens used in the axial compression test, the pre-stressed nature of the samples used in compression tests, and the existence of voids in the concrete under the reinforcement do not provide confidence in these results. The results of the axial compression test from this study are therefore determined to be inconclusive.
APPENDIX B.  BENDING TEST SPECIMENS POST FAILURE

The figures in Appendix B show the post failure condition of all specimens from each configuration from the four point bending test.

B.1  American Fiberglass Bending Test Specimens Post Failure

Figure B.1: Specimen GA-1 Bending Test Post Failure.
Figure B.2: Specimen GA-2 Bending Test Post Failure.

Figure B.3: Specimen GA-3 Bending Test Post Failure.
Figure B.4: Specimen GA-4 Bending Test Post Failure.

Figure B.5: Specimen GA-5 Bending Test Post Failure.

Figure B.6: All GA Bending Test Specimens Post Failure.
B.2 BYU Fiberglass Bending Test Specimens Post Failure

Figure B.7: Specimen GB-1 Bending Test Post Failure.

Figure B.8: Specimen GB-2 Bending Test Post Failure.
Figure B.9: Specimen GB-3 Bending Test Post Failure.

Figure B.10: Specimen GB-4 Bending Test Post Failure.
Figure B.11: Specimen GB-5 Bending Test Post Failure.

Figure B.12: All GB Bending Test Specimens Post Failure.
B.3 IsoTruss Industries Carbon/Epoxy Bending Test Specimens Post Failure

Figure B.13: Specimen CI-1 Bending Test Post Failure.

Figure B.14: Specimen CI-2 Bending Test Post Failure.
Figure B.15: Specimen CI-3 Bending Test Post Failure.

Figure B.16: Specimen CI-4 Bending Test Post Failure.
Figure B.17: Specimen CI-5 Bending Test Post Failure.

Figure B.18: All CI Bending Test Specimens Post Failure.
B.4 BYU Carbon/Epoxy Bending Test Specimens Post Failure

Figure B.19: Specimen CB-1 Bending Test Post Failure.

Figure B.20: Specimen CB-2 Bending Test Post Failure.
Figure B.21: Specimen CB-3 Bending Test Post Failure.

Figure B.22: Specimen CB-4 Bending Test Post Failure.
Figure B.23: Specimen CB-5 Bending Test Post Failure.

Figure B.24: All CB Bending Test Specimens Post Failure.
B.5 Steel Bending Test Specimens Post Failure

Figure B.25: Specimen ST-1 Bending Test Post Failure.

Figure B.26: Specimen ST-2 Bending Test Post Failure.
Figure B.27: Specimen ST-3 Bending Test Post Failure.

Figure B.28: Specimen ST-4 Bending Test Post Failure.
Figure B.29: Specimen ST-5 Bending Test Post Failure.

Figure B.30: All ST Bending Test Specimens Post Failure.
APPENDIX C.  DEFLECTIONS OF BENDING TEST SPECIMENS

C.1 Deflection Progression of Each Specimen

The figures in Appendix C.1 show how the deflections of each specimen progress as loads increase during the four point bending test.

C.1.1 Deflection Progression of American Fiberglass (GA) Specimens

![Graph showing deflection progression of Specimen GA-1 during bending test.]

Figure C.1: Deflection Progression of Specimen GA-1 During Bending Test.
Figure C.2: Deflection Progression of Specimen GA-2 During Bending Test.

Figure C.3: Deflection Progression of Specimen GA-3 During Bending Test.
Figure C.4: Deflection Progression of Specimen GA-4 During Bending Test.

Figure C.5: Deflection Progression of Specimen GA-5 During Bending Test.
C.1.2  Deflection Progression of BYU Fiberglass (GB) Specimens

Figure C.6: Deflection Progression of Specimen GB-1 During Bending Test.

Figure C.7: Deflection Progression of Specimen GB-2 During Bending Test.
Figure C.8: Deflection Progression of Specimen GB-3 During Bending Test.

Figure C.9: Deflection Progression of Specimen GB-4 During Bending Test.
Figure C.10: Deflection Progression of Specimen GB-5 During Bending Test.
C.1.3 Deflection Progression of Industry Carbon/Epoxy (CI) Specimens

Figure C.11: Deflection Progression of Specimen CI-1 During Bending Test.

Figure C.12: Deflection Progression of Specimen CI-2 During Bending Test.
Figure C.13: Deflection Progression of Specimen CI-3 During Bending Test.

Figure C.14: Deflection Progression of Specimen CI-4 During Bending Test.
Figure C.15: Deflection Progression of Specimen CI-5 During Bending Test.
C.1.4 Deflection Progression of BYU Carbon/Epoxy (CB) Specimens

Figure C.16: Deflection Progression of Specimen CB-1 During Bending Test.

Figure C.17: Deflection Progression of Specimen CB-2 During Bending Test.
Figure C.18: Deflection Progression of Specimen CB-3 During Bending Test.

Figure C.19: Deflection Progression of Specimen CB-4 During Bending Test.
Figure C.20: Deflection Progression of Specimen CB-5 During Bending Test.
C.1.5 Deflection Progression of Steel (ST) Specimens

Figure C.21: Deflection Progression of Specimen ST-1 During Bending Test.

Figure C.22: Deflection Progression of Specimen ST-2 During Bending Test.
Figure C.23: Deflection Progression of Specimen ST-3 During Bending Test.

Figure C.24: Deflection Progression of Specimen ST-4 During Bending Test.
Figure C.25: Deflection Progression of Specimen ST-5 During Bending Test.
C.2 Deflections of Each Specimen at Progressing Loads During Bending Test

The figures in Appendix C.2 show how the deflections of each specimen progress as loads increase during the four point bending test.

C.2.1 Deflection Loads of American Fiberglass (GA) Specimens

![Graph of deflections of GA specimens under 1 kip bending load.]

Figure C.26: Deflection of GA Specimens Under 1 kip Bending Load.
Figure C.27: Deflection of GA Specimens Under 2 kip Bending Load.

Figure C.28: Deflection of GA Specimens Under 3 kip Bending Load.

*Data that was excluded when calculating the corrected average
*Data that was excluded when calculating the corrected average

Figure C.29: Deflection of GA Specimens Under 4 kip Bending Load.

*Data that was excluded when calculating the corrected average

Figure C.30: Deflection of GA Specimens Under 5 kip Bending Load.
Figure C.31: Deflection of GA Specimens Under 6 kip Bending Load.
C.2.2 Deflection Loads of BYU Fiberglass (GB) Specimens

*Data that was excluded when calculating the corrected average

Figure C.32: Deflection of GB Specimens Under 1 kip Bending Load.

Figure C.33: Deflection of GB Specimens Under 2 kip Bending Load.
Figure C.34: Deflection of GB Specimens Under 3 kip Bending Load.

Figure C.35: Deflection of GB Specimens Under 4 kip Bending Load.
Figure C.36: Deflection of GB Specimens Under 5 kip Bending Load.

Figure C.37: Deflection of GB Specimens Under 6 kip Bending Load.
C.2.3 Deflection Loads of IsoTruss Industries Carbon/Epoxy (CI) Specimens

Figure C.38: Deflection of CI Specimens Under 1 kip Bending Load.

Figure C.39: Deflection of CI Specimens Under 2 kip Bending Load.

*Data that was excluded when calculating the corrected average
Figure C.40: Deflection of CI Specimens Under 3 kip Bending Load.

Figure C.41: Deflection of CI Specimens Under 4 kip Bending Load.
Figure C.42: Deflection of CI Specimens Under 5 kip Bending Load.

Figure C.43: Deflection of CI Specimens Under 6 kip Bending Load.
C.2.4 Deflection Loads of BYU Carbon/Epoxy (CB) Specimens

![Graph showing deflection loads of BYU Carbon/Epoxy (CB) specimens](image)

*Data that was excluded when calculating the corrected average

Figure C.44: Deflection of CB Specimens Under 1 kip Bending Load.
Figure C.45: Deflection of CB Specimens Under 2 kip Bending Load.

Figure C.46: Deflection of CB Specimens Under 3 kip Bending Load.
Figure C.47: Deflection of CB Specimens Under 4 kip Bending Load.

Figure C.48: Deflection of CB Specimens Under 5 kip Bending Load.
Figure C.49: Deflection of CB Specimens Under 6 kip Bending Load.

Figure C.50: Deflection of CB Specimens Under 7 kip Bending Load.
C.2.5 Deflection Loads of Steel (ST) Specimens

![Graph showing deflection loads of steel specimens under 1 kip bending load.](image1)

Figure C.51: Deflection of ST Specimens Under 1 kip Bending Load.

![Graph showing deflection loads of steel specimens under 2 kip bending load.](image2)

Figure C.52: Deflection of ST Specimens Under 2 kip Bending Load.
Figure C.53: Deflection of ST Specimens Under 3 kip Bending Load.

Figure C.54: Deflection of ST Specimens Under 4 kip Bending Load.

*Data that was excluded when calculating the corrected average
Figure C.55: Deflection of ST Specimens Under 5 kip Bending Load.

*Data that was excluded when calculating the corrected average

Figure C.56: Deflection of ST Specimens Under 6 kip Bending Load.

*Data that was excluded when calculating the corrected average
Figure C.57: Deflection of ST Specimens Under 7 kip Bending Load.

Figure C.58: Deflection of ST Specimens Under 8 kip Bending Load.
APPENDIX D. PRISM COMPRESSION TEST SPECIMENS POST FAILURE

The figures in Appendix D show the post failure condition of all specimens from each configuration from the beam compression test.

D.1 American Fiberglass Compression Test Specimens Post Failure

Figure D.1: Specimen GA-1 Compression Test Post Failure.
Figure D.2: Specimen GA-4 Compression Test Post Failure.

Figure D.3: Specimen GA-5 Compression Test Post Failure.
D.2 BYU Fiberglass Compression Test Specimens Post Failure

Figure D.4: Specimen GB-3 Compression Test Post Failure.

Figure D.5: Specimen GB-4 Compression Test Post Failure.
Figure D.6: Specimen GB-5 Compression Test Post Failure.

D.3 IsoTruss Industries Carbon/Epoxy Compression Test Specimens Post Failure

Figure D.7: Specimen CI-1 Compression Test Post Failure.
Figure D.8: Specimen CI-4 Compression Test Post Failure.

Figure D.9: Specimen CI-5 Compression Test Post Failure.
D.4 BYU Carbon/Epoxy Compression Test Specimens Post Failure

Figure D.10: Specimen CB-3 Compression Test Post Failure.

Figure D.11: Specimen CB-4 Compression Test Post Failure.
Figure D.12: Specimen CB-5 Compression Test Post Failure.

D.5 Steel Compression Test Specimens Post Failure

Figure D.13: Specimen ST-1 Compression Test Post Failure.
Figure D.14: Specimen ST-2 Compression Test Post Failure.

Figure D.15: Specimen ST-3 Compression Test Post Failure.