CHAPTER III
METHODS AND MATERIALS

3.1: Tensile Tests

3.1.1: Introduction

The first phase of testing for the experimental program, was to conduct tensile tests of No. 4, No. 5, and No. 6 nominal diameter bars for three different manufacturers of GFRP bar. These bar sizes were chosen because they are sizes typically used in bridge decks. The tensile test consists of applying axial tension to the bars via a universal testing machine (UTM), and reading the corresponding deformations and/or strains. The purpose of this phase of the testing program was to determine the ultimate tensile strength, and modulus of elasticity of the bars. All of the tensile tests followed the same procedures and were done in accordance with the ACI 440K (1999) document, which sets standards for testing of FRP bars and sheets.

3.1.2: Materials

Several materials were needed to complete the tensile testing. First, No. 4, No. 5, and No. 6 bars were gathered from Hughes Brothers Inc, Marshall Corporation, and Pultrall. The Hughes Brothers bars are denoted by helically wrapped fibers and a mild sand impregnation. The Marshall Corporation's bars have mechanical deformations similar to those of mild steel bar. Pultrall's bars are gray in color, with no deformations, and have a heavy sand impregnation. All three bars are shown in Figure 3.1.

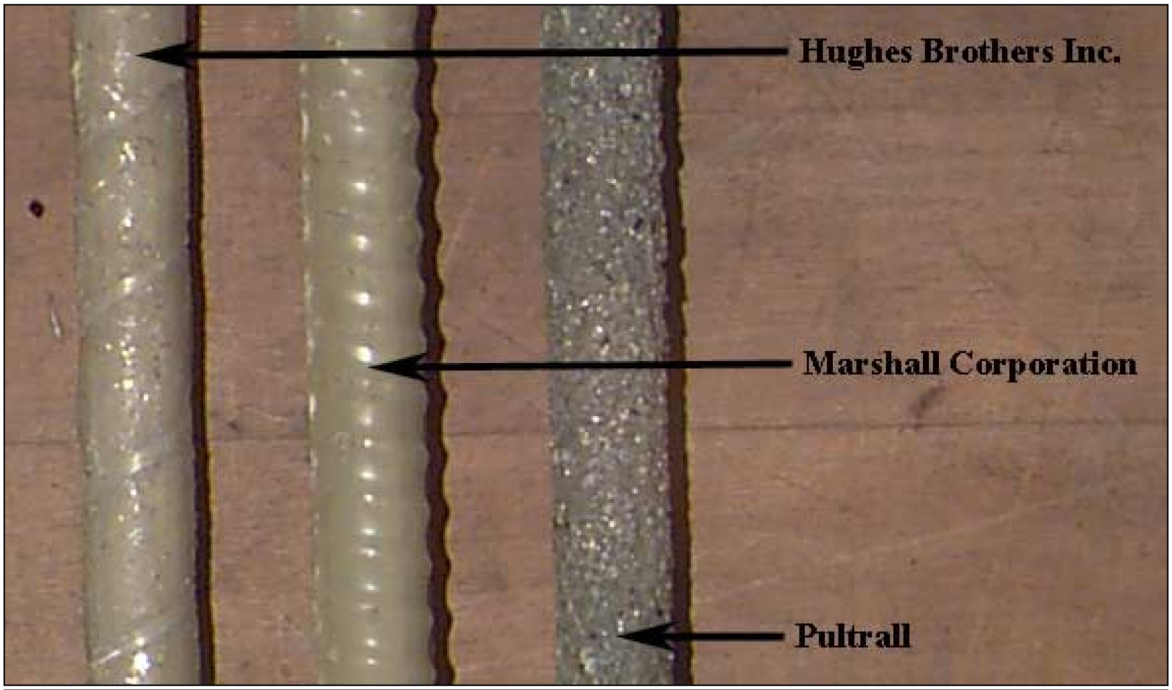

Figure 3.1: Examples of the three manufacturers' bars.

Due to the anisotropic nature of the GFRP bars, failures would be associated with an end or pinching type failure instead of tensile failures, if no precautions were taken when gripping the bars. As a result, steel tube end anchors were placed on the ends of the bars to allow for the distribution of load from the UTM to the bar. Materials for the end anchors included steel pipe, epoxy resin, and sand. Two different sizes of steel pipe were needed, 25.4 mm (1 in.), and 31.8 mm (1.25 in.) standard weight structural steel pipe. The epoxy resin was produced by West Systems, and was a two-part mixture. The bulk of the pre-measured mix was the epoxy and a small portion was the hardener (5 to 1 ratio by weight), to achieve proper set. The resin was used in conjunction with ordinary sand, which helped to improve the bond between the anchor and the bar.

3.1.3: Specimen Preparation

Initially, the bar testing length, anchor lengths, and anchor diameters were determined for the tensile tests. The total bar length includes the gage or testing length, and the anchor or cylinder length. The ACI-440K (1999) document specifies both of these lengths, as well as specifying the diameter of the anchors. The ACI-440K (1999) states that the testing length must be 40 times the nominal bar diameter, but not less than 100 mm (3.9 in.). The ACI-440K (1999) also requires that the anchor length, or cylinder length, L_g, in millimeters, be determined in accordance with Equation 3.1, but not less than 250 mm (9.8 in.).

$$L_g = \frac{f_u A}{350} \qquad (3.1)$$

Where: f_u = ultimate tensile strength, MPa
A = cross-sectional area of the specimens, mm^2

Another requirement of the ACI-440K (1999) is that the inside diameter of the cylindrical anchor be at least 10-14 mm (0.39-0.55 in.) greater than the nominal bar diameter. Adhering to these specifications, the GFRP bar lengths, anchor lengths, and anchor diameters were calculated and are shown in Table 3.1.

Table 3.1: Length and diameter specifications.

Bar Size	Gage Length (mm)	Anchor Length (mm)	Total Bar Length (mm)	Anchor Diameter (mm)
4	508	279	1070	25.4
5	635	381	1400	25.4
6	762	508	1780	31.8

With all of the necessary lengths determined, cutting of the GFRP bars and structural tubing began. After the GFRP bars and end anchors were cut to length, the inside of the end anchors were scored, and then etched with muriatic acid, to improve the bond between the epoxy/sand resin and the end anchor.

Each end anchor was covered at both ends with a PVC plumber's cap. Two caps were required for each end anchor for a total of four caps per tensile test. The exterior cap of the end anchor had a machined slot in the center, half the thickness of the cap. The interior cap, or the cap that faces the testing length of the bar, had a hole machined in the center of the cap. Both the holes and the slots were machined to 3.18 mm (0.125 in.) larger than the nominal diameter of the bar. Each cap was slightly greased, to act as a bond breaker, so that the caps could be reused when casting was complete.

Assembly and casting of the tensile test specimens began by sliding all of the exterior caps onto the ends of the anchors. Next the interior caps were placed on the FRP bars with care to ensure that no grease got on the bar. Then a quantity of sand that was mixed with the epoxy resin and hardener was measured into a bucket. The ratio of the epoxy resin/sand mix is five parts epoxy resin with three parts sand to one part epoxy hardener by weight. This ratio was used consistently throughout both phases of testing. With the sand measured, the epoxy resin was added, and mixed thoroughly. The epoxy hardener was added last and mixed with other two components. Once thoroughly mixed, the epoxy resin was poured into an anchor to approximately half full. The bar was then inserted into the anchor, and moved around in the anchor until it was seated in the machined slot in the cap. This ensured that the bar was centered throughout the anchor. Once the bar was seated in the slot of the exterior cap, more epoxy resin was added through the top of the anchor until it was full. Then the interior cap was placed over the other end of the anchor. The bar and anchor assembly was then affixed with wire ties to level vertical angles and allowed to cure for at least 24 hours. Only one end of a bar was cast at a time. Also, no more than five bar ends were cast with any given batch of epoxy resin, due to the limited pot life of the mix. An example of a typical end anchor is shown in Figure 3.2.

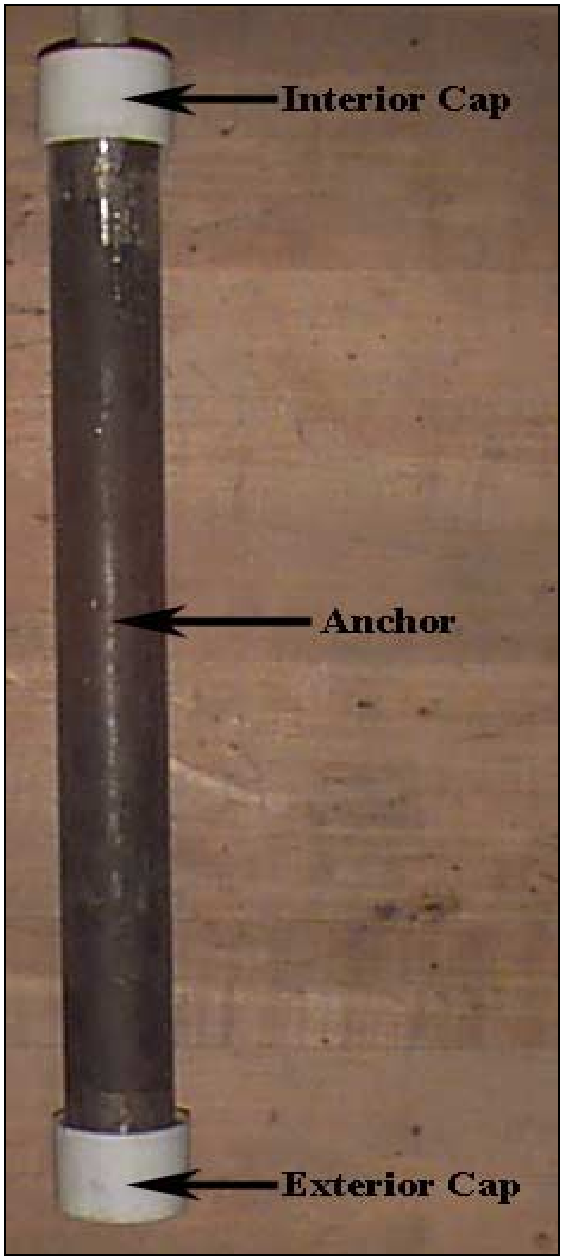

Figure 3.2: Typical end anchor.

After both anchors were attached to the tensile specimens, two strain gages were applied to each side of the bar at the center of the testing length. To do so, the center was first marked, and then all deformations or sand impregnations were ground down to a smooth surface. Measurements Group Inc. supplied the strain gages, and type CEA-13-250UN-350 was used for all the tensile tests. This type was used because its small size allowed it to adhere to a flat spot on the bar without having to wrap around the diameter of the bar. Once the gages were attached, strain gage wire was soldered onto the gages, and the specimen was ready for testing. The ACI-440K (1999) specifies that five repetitions of each type of test should be performed. So a minimum of five repetitions for each bar size, and each manufacturer was performed.

3.1.4: Universal Testing Machine (UTM) Preparation

Cross head spacing was the critical element for the hardware setup of the SATEK UTM. Since the tensile specimens' lengths ranged from 1066 mm (42 in.) to 1788 mm (70 in.), care was taken to ensure that the top crosshead was high enough on the UTM to accommodate all of the tests. With the top crosshead in place the bottom crosshead, which is mechanically adjustable can easily be moved to fit the full range of tests. Once the crossheads were in place the grips that are designed for round test specimens were inserted into each crosshead. The SATEK UTM is computer controlled, and a specific tensile test must be set up to use the machine. An existing tensile test was edited to fit the load rate, and specimen type (round) for these tests. The same test setup was used for all tests, with only the diameter of the bars changing.

3.1.5: Tensile Test Procedures

Initially, before the testing could begin, the load rate had to be established. According to the ACI-440K (1999), the load rate must fall within the range of 100 – 500 MPa per minute (14.5 – 72.5 ksi). A load rate of 300 MPa (43.5 ksi) was chosen because it is the middle of the load range. With an established load rate, focus turned toward data acquisition. The SATEK UTM has a built in load cell, and the output of the load cell is recorded by the computer. The elongation of the bar is measured by 50.8 mm (2 in.) clip on extensometer. The computer also recorded the extensometer's information. As a check for the extensometer readings, strain gage readings were taken by hand, at predetermined load levels, with the aid of strain indicator boxes.

The first step in the tensile test was placing the specimen into the UTM. Care was taken to ensure that the anchors for the specimens were centered in the grips of the UTM.

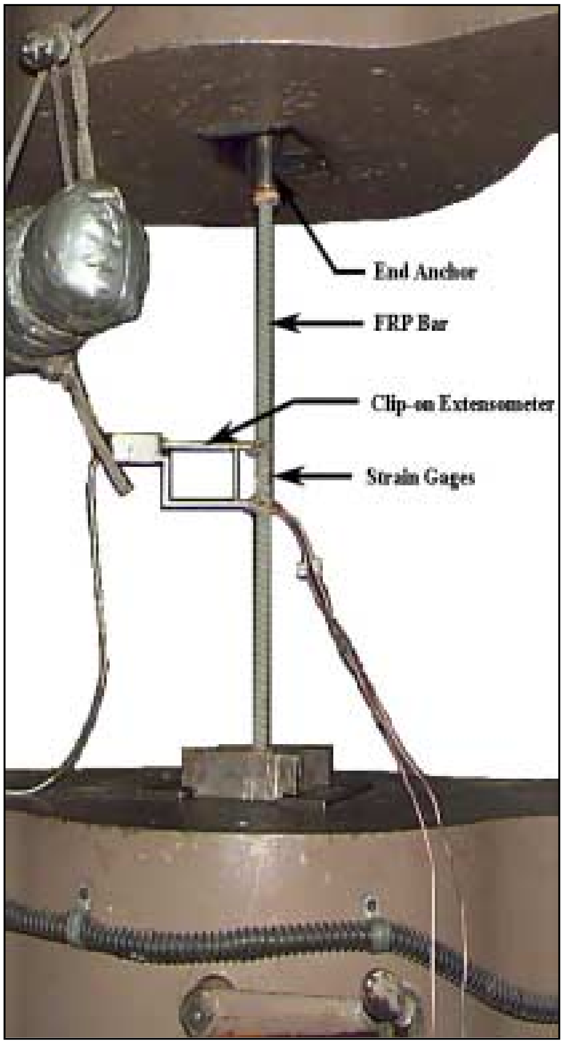

Figure 3.3: Typical tensile test setup.

Next, the strain gages were wired to the strain indicator boxes, and zeroed. The clip on extensometer was then attached at or as close to the mid-point as possible, taking care not to interfere with the strain gages. A typical test setup is shown in Figure 3.3.

The edited test procedure was selected from the computer and begun. The computer controlled the load rate throughout the test, but was manually stopped every 68.9 MPa (10 ksi) so that strain readings could be taken from the indicator boxes. The clip on extensometer was removed at approximately 70% of the guaranteed ultimate tensile strength of the bar, as determined from the manufacturers' literature. This was a precautionary measure to ensure that the extensometer was not damaged. Strain gage readings continued to be taken after the removal of the extensometer until failure of the gage. The bar was loaded until failure, and failure is defined as the shedding of at least 50% of the load with no more taken by the bar. The load was then stopped, data saved, and equipment reset for the next test.

3.2: Bond Tests

3.2.1: Introduction

The second phase of testing consisted of performing beam end bond tests. Beam end bond tests are an accurate way of simulating flexural behavior, by placing the GFRP rebar in the tensile region of the concrete. The purpose of this type of testing was to collect bond behavior and bond strength data for each type and size of bar. The process began by first casting and curing numerous concrete blocks with FRP bars embedded a specific length inside the block. After curing was complete, the blocks were placed within a specially designed test frame, and loaded in such a manner as to replicate flexural loading in a beam. As load was applied to the bar, the force in the bar was measured. As loading progressed, the elongation of the bar, the live or loaded end slip, and the free, or non-loaded end slip were measured. The procedures for this phase of testing are not specified in the ACI-440K document; rather they are similar to procedures of other literature (Johnston and Zia, 1982).

3.2.2: Test Specimen Preparations

The test specimens for this phase of testing were concrete blocks with GFRP rebar embedded in the top, and bottom of the blocks. The blocks were 914 mm (36 in.) long, 203 mm (8 in.) wide, and 381 mm (15 in.) tall. The GFRP bars were positioned in the cross-section 70 mm (2.75 in.) from the top or bottom. This allowed for the FRP bars to be inside the shear reinforcement, which had 25.4 mm (1 in.) of clear cover all the way around. Typical specimen dimensions are shown in Figures 3.4, and 3.5.

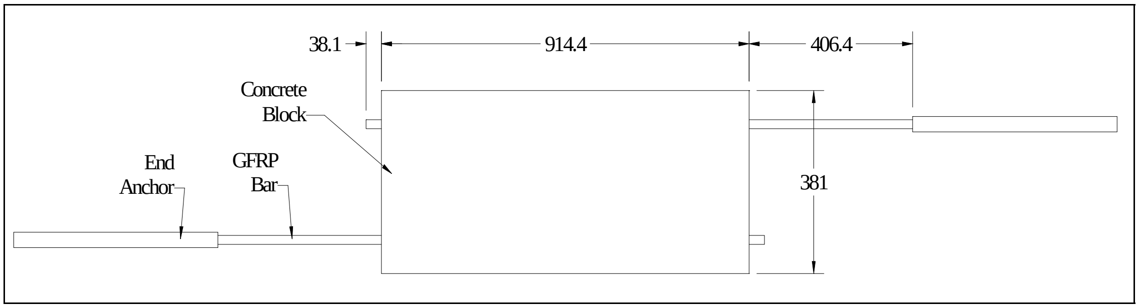

Figure 3.4: Typical specimen dimension (elevation).

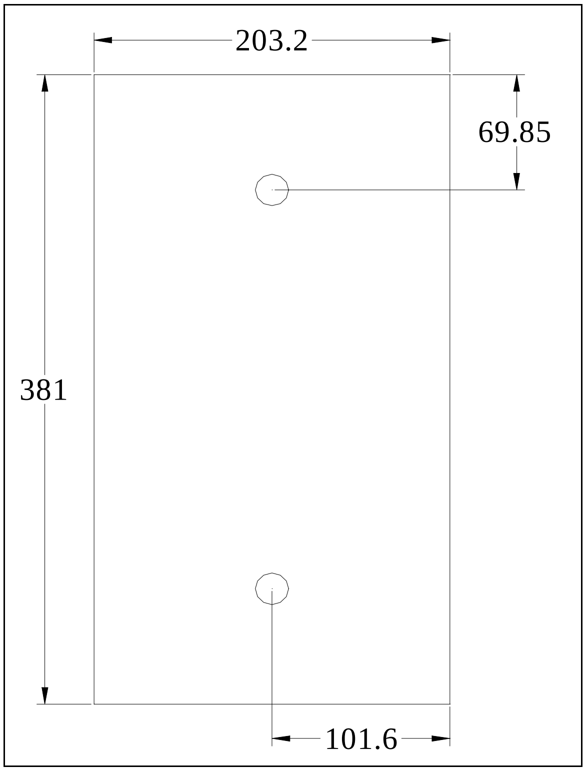

Figure 3.5: Typical specimen dimension (cross-section).

The blocks were cast on their sides, and a gang form was chosen to minimize the amount of materials needed. The gang form was made exclusively from 19.05 mm (0.75 in.) plywood, and 38.1 mm (1.5 in.) sheet rock screws. The base of each form was a standard 1220 mm (48 in.) x 2440 mm (96 in.) sheet of plywood, and 5 blocks were able to fit on each form. Four such forms were made, and used in two separate casts. Although more desirable to cast them all at once, a delay in the shipment of all of the bars made that impossible. Figure 3.6 shows a plan view of the gang form, used for casting.

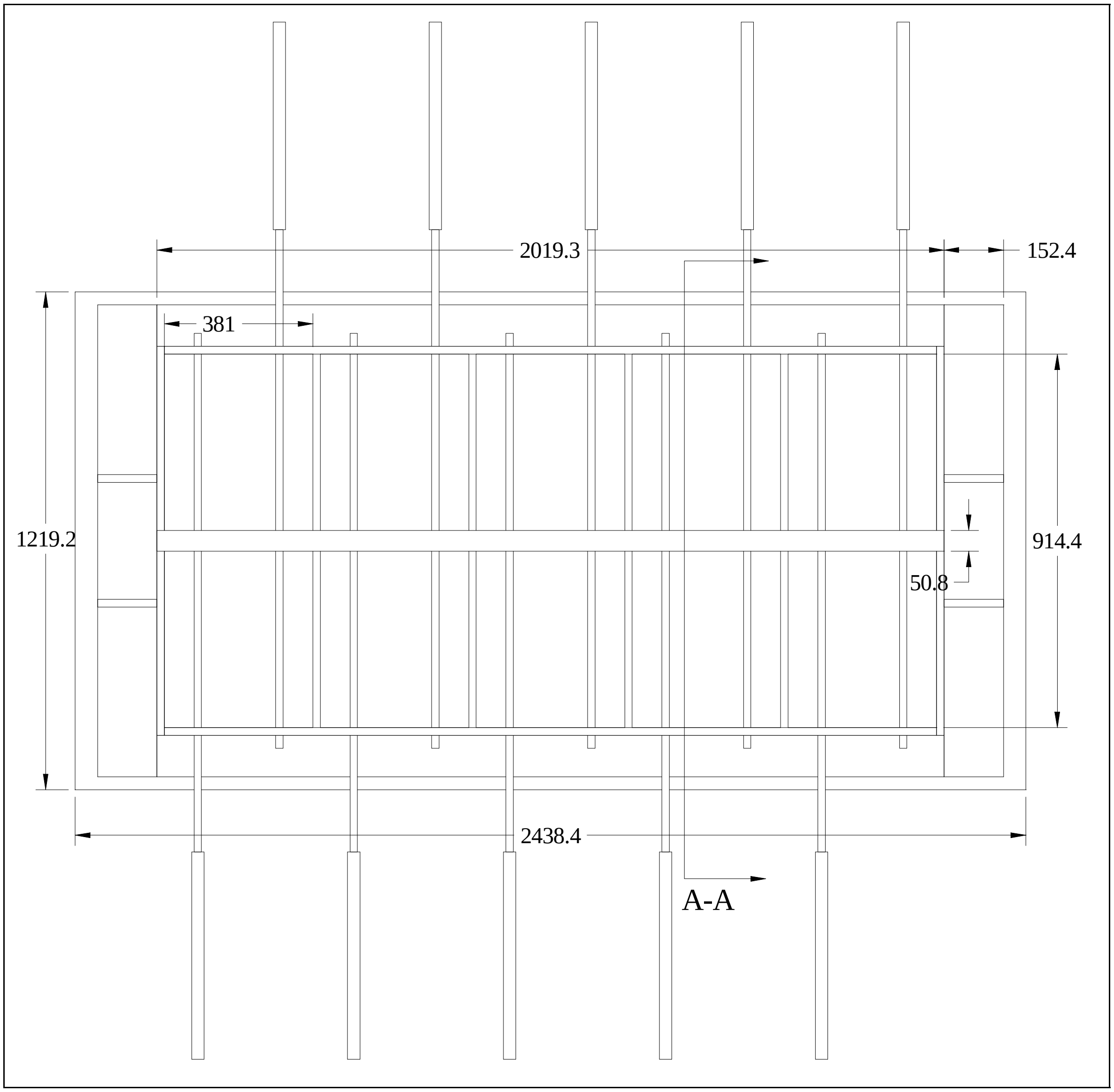

Figure 3.6: Typical gang form dimensions (plan).

Figure 3.7, and 3.8 show two other elevation views of the form.

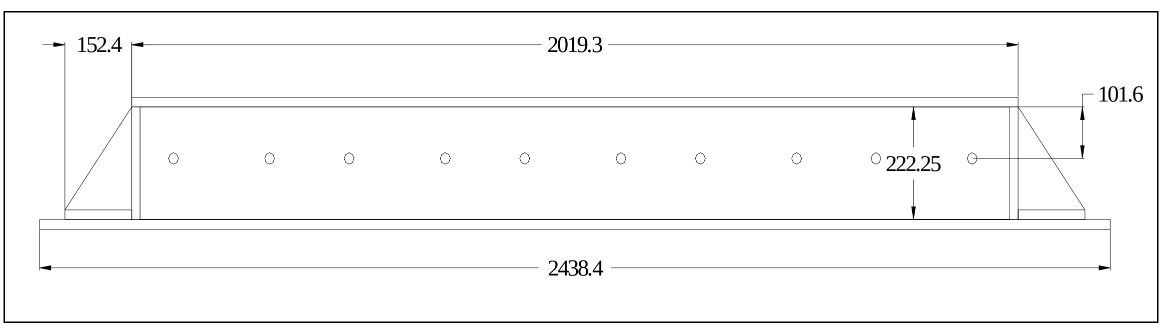

Figure 3.7: Typical gang form dimensions (elevation view).

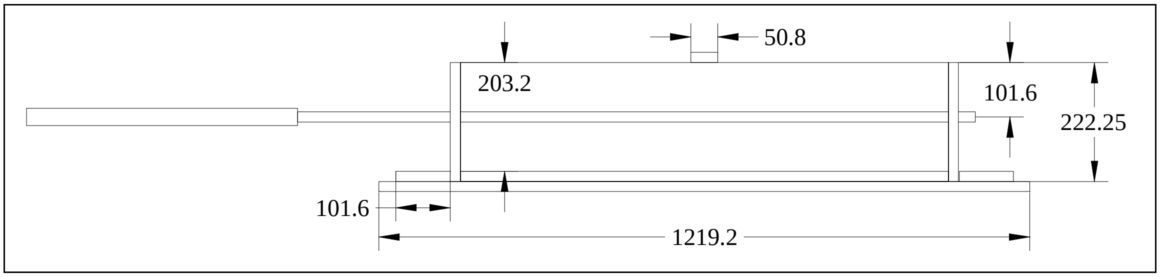

Figure 3.8: Typical gang form dimensions (elevation view, section A-A).

Along with the forms, rebar cages were constructed, of mild steel rebar, to resist the shear forces in the concrete. The cage design was taken from Johnston and Zia (1982). Their design met the ACI minimums for transverse reinforcement. The rebar cage consisted of four No. 4 bars in the corners of the cage with No. 3 closed stirrups spaced every 6 in. A small variation was made for the cage used with the No. 6 bars. Six No. 4 bars were used instead of four No. 4 bars. All of the cages were pre-assembled with standard rebar ties before being inserted into the forms. A typical cross-section of the rebar cage is shown in Figure 3.9.

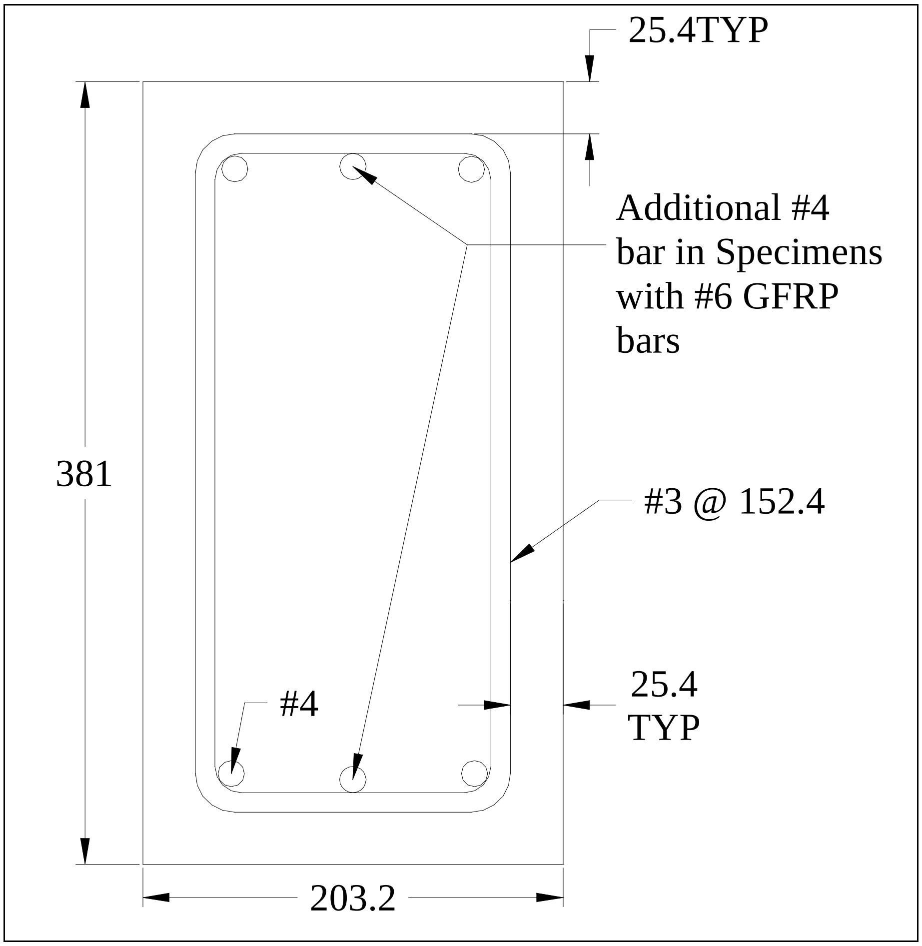

Figure 3.9 Shear Reinforcement cross-sections.

The GFRP bar preparation for the bond test was the same as for the tensile test, explained in 3.1.2, except for changes in the length of the bar, and only applying the anchors to one end of the bar. The bar length of the GFRP bars included the anchor length, space to allow for the testing equipment and instrumentation, the entire length of the block, and an extension out of the free end of the block. The anchor length was the same as for the tensile tests. The space for testing equipment and instrumentation was 381 mm (15 in). The block length was 914.4 mm (36 in.), and the free end extension was 38.1 mm (1.5 in.). So, the length of the GFRP bar was 1333.5 mm (52.5 in.) plus the length of the end anchor for a given bar size. Table 3.2 shows the length of the GFRP bars used in the bond tests.

Table 3.2: GFRP bar lengths for bond tests.

Bar Size	Bond Test Length (mm)	Anchor Length (mm)	Total Bar Length (mm)	Anchor Diameter (mm)
4	1330	279	1609	25.4
5	1330	381	1711	25.4
6	1330	508	1838	31.8

Since the object of this testing program was to determine the bond characteristics of the bar, steps were taken to ensure that failure mode was a bond failure mode. To ensure a bond failure, the amount of GFRP bar actually bonded to the concrete had to be very short. Otherwise the bar would have failed in tension. The bond stress reported in the manufacturers' literature was used in conjunction with the ultimate tensile strength found in first phase of testing to determine what the bonded lengths could be. The bonded lengths chosen for the testing program were five times the bar diameter, and 7.5 times the bar diameter. This turned out to be a very short distance compared to the length of the block. So, the rest of the length of the block had to be de-bonded. This was done with the use of bond breakers. The bond breakers are a length of pipe used to fit around the GFRP bar to allow the bar to pass through the block with little to no frictional resistance. The bond breakers used in the experimental program were either metal or PVC electrical conduit. The conduit was sized for each specific size and manufacturer of rebar. Because of the nature of the manufacturing process of the bars, each one is a slightly different size. As a result, no one size of PVC or metal conduit could be used as a bond breaker for all the bars of a particular size. So a trial and error process was used to determine the correct conduit size for each manufacturer and bar size. Also, the bonded length was chosen to be in the middle of the block, so the bond breakers were on each end.

Once the bond breakers were cut, the test specimens were ready for assembly. The forms were placed for casting, and then the chairs (support for the rebar cage) were placed inside the form. The rebar cages were then placed on top of the chairs and centered in the form. Next the GFRP bars were inserted through the pre-drilled holes, and the bond breakers were placed on the bars. The bond breakers were then sealed around the pre-drilled holes, and at the beginning of the embedment length with duct tape and/or caulk. Finally due to the weight of the end anchors, they were supported to prevent the GFRP bars from bending.

Concrete for the test specimens was ordered from a local concrete supplier, and a standard 20.7 MPa (3 ksi) mix was requested. The first batch of concrete delivered had a tested 28-day concrete compressive strength of 29.2 MPa (4.2 ksi). This concrete was used to fabricate all of the Hughes Brothers and Marshall specimens. The second batch of concrete had a tested 28-day concrete compressive strength of 23.7 MPa (3.4 ksi). This concrete was used to fabricate all of the Pultrall specimens. Concrete was placed in two layers for the blocks. Each layer was vibrated with the use of an internal vibrator. The blocks were rough finished with bull floats and trowels and allowed to set. After setting, the blocks were moist cured for seven days before being removed from the form.

3.2.3: Test Frame and Tension Rig

To simulate bending in the blocks, a special loading frame and method was required that did not allow for the use of the UTM. Instead a specially designed test frame was constructed to simulate the loading. Load was applied, in the horizontal direction, to one of the GFRP bars in the block. A horizontal reaction was required to keep the block stationary. Also two vertical reactions were needed, to resist the overturning moment. The loading is shown in Figure 3.10.

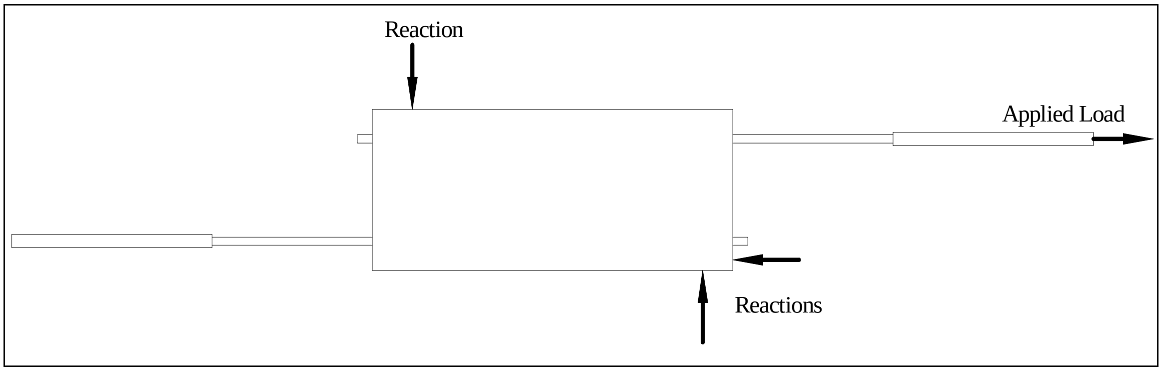

Figure 3.10: Test block loading.

The test frame consisted of two main column pieces that were connected by a single beam. The two column pieces were W21x57, and the beam was a W8x31. Both the column pieces and the beam were materials already at the Structures lab. The column pieces were used in as is condition, but the beam was cut to fit the 4343.4 mm (171 in.) space between the two columns. Two 25.4 mm (1 in.) thick plates were welded onto the ends of the W8x 31, and it was connected to the columns on each side by six 25.4 mm (1 in.) bolts. Because of the insufficient moment connection between the beam and the column, a kicker was added to the outside of the column where the hydraulic ram attached to the test frame. The test frame along with testing equipment is shown in Figure 3.11.

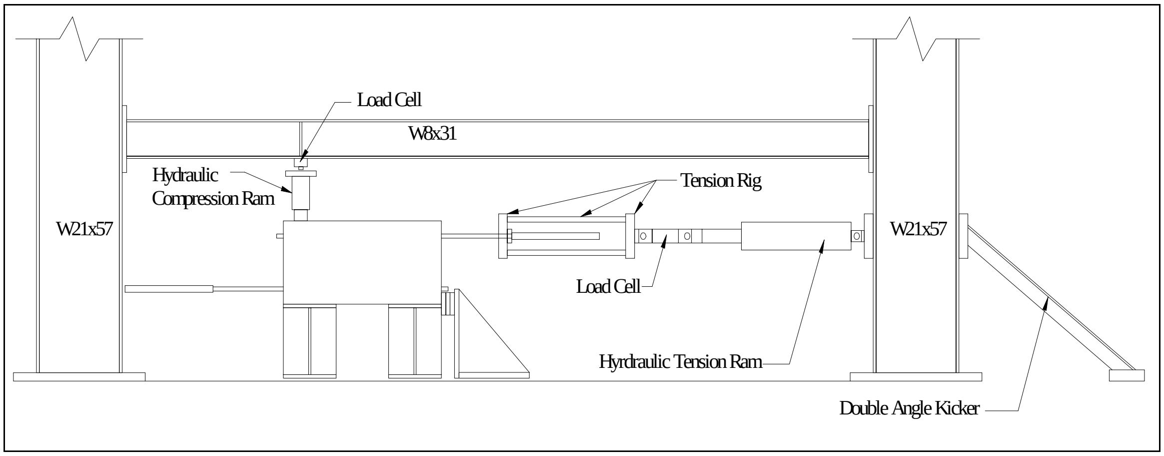

Figure 3.11: Test frame and equipment

Both load cells used in testing have a 222.4 kN (50 kip) load capacity; one was used in tension while the other was used in compression. The hydraulic tension ram was mechanically actuated (powered by an electric pump), and its function was the control the load applied to the GFRP bar. The hydraulic compression ram was actuated by hand, and was used to keep the block level during the test.

The tension rig shown in Figure 3.11 was designed for the testing program. It consists of two plates that are 50.8 mm (2 in.) thick connected together by three 25.4 mm (1 in.) diameter A572 threaded rods. The anchor plate, or the plate that goes around the end anchor of the specimen, has a 42.86 mm (1.688 in.) diameter hole in the middle of the plate, allowing it to fit around all of the end anchors in the testing program. The anchor plate is shown in Figure 3.12.

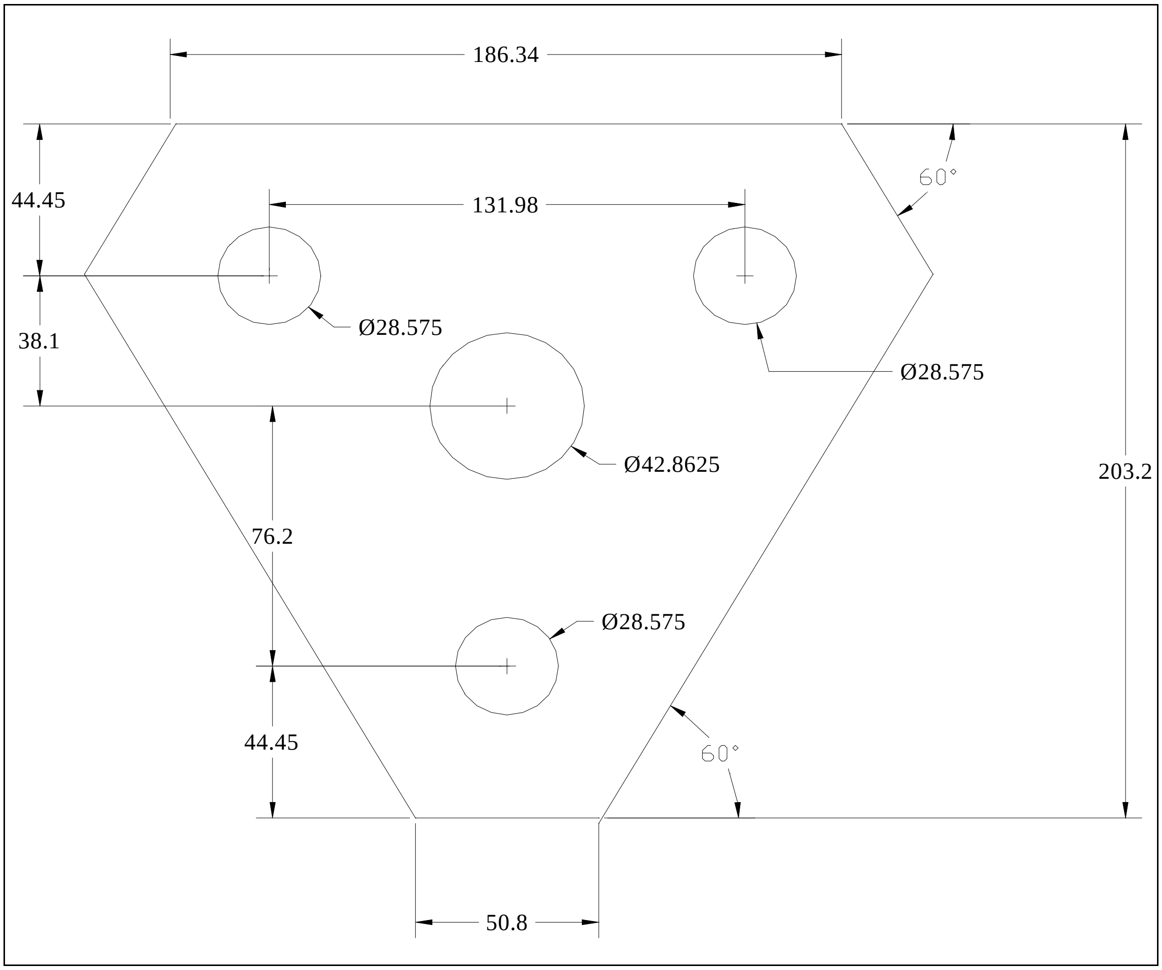

Figure 3.12: Anchor plate for the tension rig.

A washer plate is used in conjunction with the anchor plate, to allow for bearing on the inside ridge of the end anchor. The washer plate closes the diameter of the hole, from 42.86 mm (1.688 in.) to 22.23 mm (0.875 in.). This allows for the diameter of a No. 6 bar to pass though the washer plate, while the plate pushes against the inside ridge of the anchor, applying load to the specimen. The washer plate consists of a 25.4 mm (1 in.) thick plate with a 31.8 mm (1.25 in.) diameter structural steel tube welded to the center, and then split down the middle. The washer plate is shown in Figure 3.13.

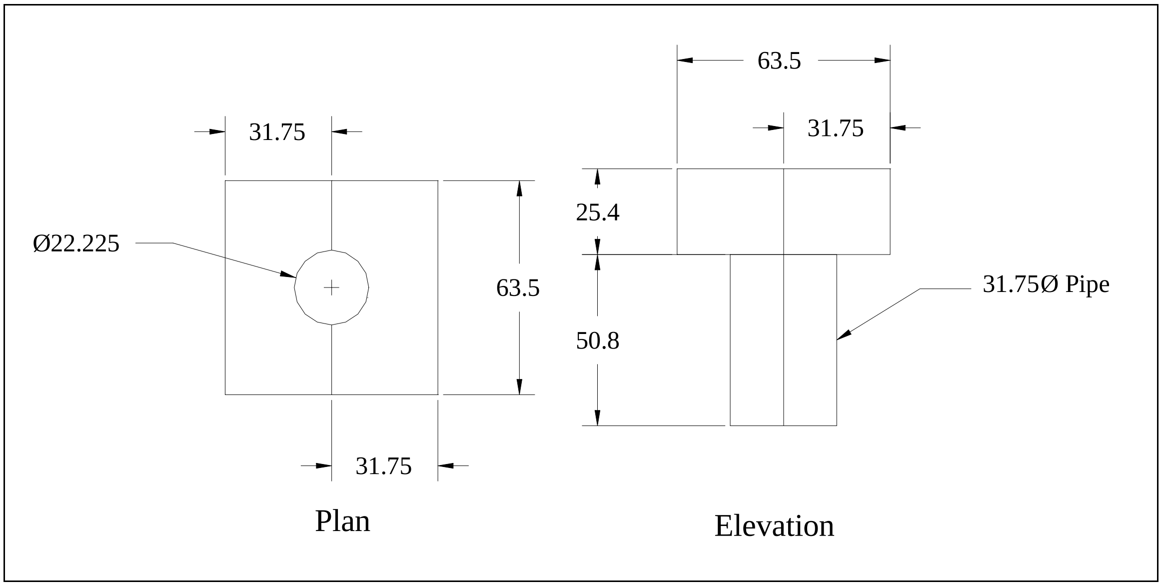

Figure 3.13: Washer plate for the tension rig.

The last plate in the tension rig is the ram plate. It attaches to the load cell and hydraulic ram. This plate is very similar to the anchor plate. The ram plate has a 25.4 mm (1 in.) thick connecter plate welded to the back (the side that attaches to the ram) of the plate. All other dimension aspects are the same, as for the anchor plate. The connector plate's purpose is to attach to the load cell, and it has a 31.8 mm (1.25 in.) diameter hole machined through it to make the connection. A plan and elevation view of the ram plate are shown in Figures 3.14, and 3.15.

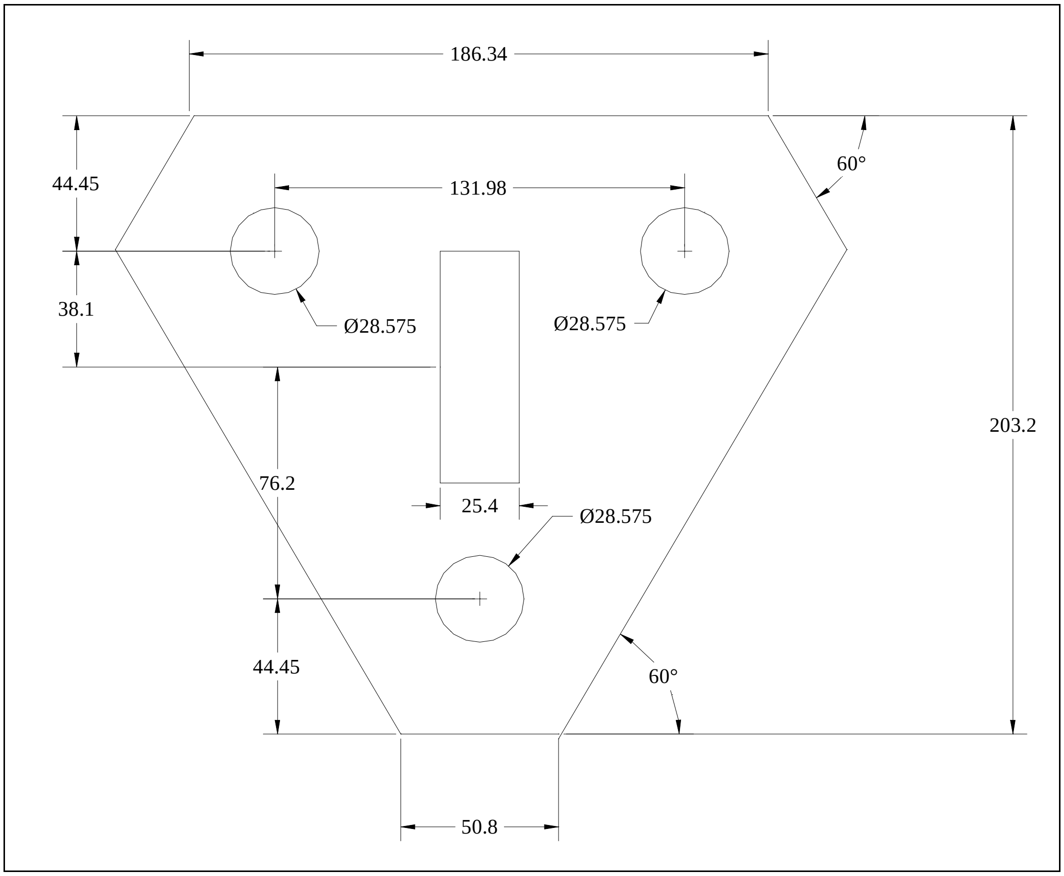

Figure 3.14: Plan view of the ram plate for the tension rig.

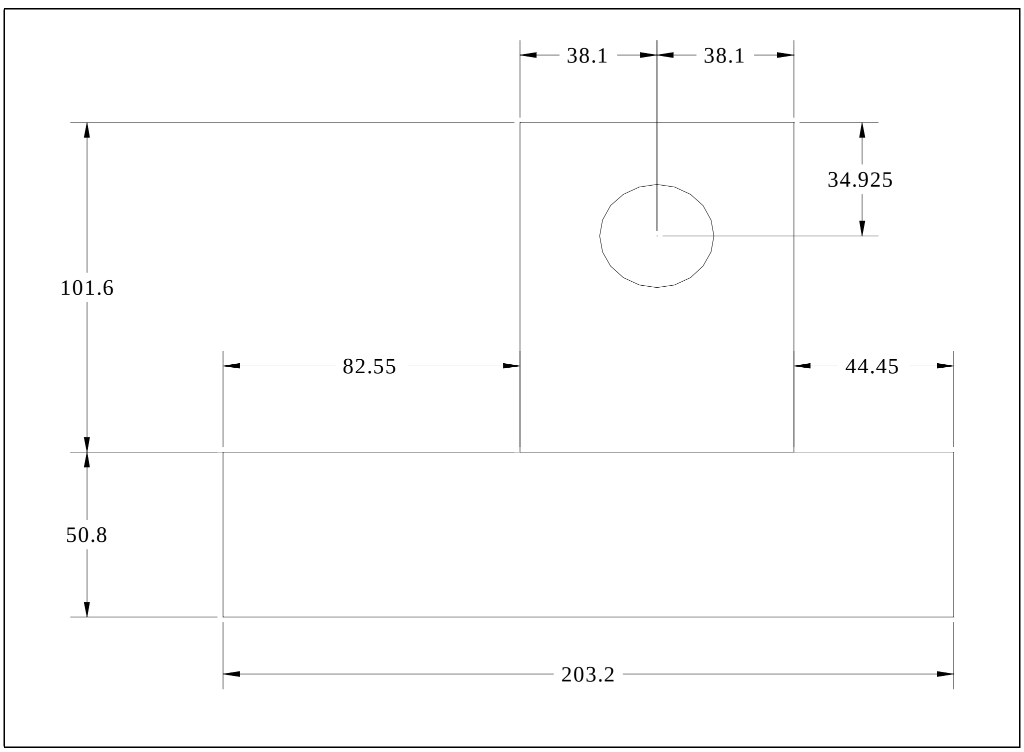

Figure 3.15: Elevation view of the ram plate for the tension rig.

LVDTs (linear variable differential transformer) were used to measure the slip of the bar on the loaded end as well as the free end. The LVDTs were also used to measure the elongation of the bar along a specified gage length. A total of five LVDTs were used for testing. Four of the LVDTs were used on the loaded end in conjunction with a specially designed bar rig. The bar rig ties all four of the LVDTs together, and attaches them to the bar. The rig consists of two aluminum clamps that hold the LVDTs to the bar, and a small aluminum pipe cut in half to attach the LVDTs to each other. The two LVDTs closest to the block are used to measure the loaded end slip of the bar. The two rear LVDTs measure the elongation of the bar over a specified gage length (typically 191 mm (7.5 in.)). The elongation measurement was in terms of strain, and it is the measured change in length over the gage length. The gage length is the distance between the two bar clamps. The elongation measurement also provided a secondary modulus check so the exact modulus for a particular bar would be known. The bar rig, and four loaded end LVDTs are shown in Figure 3.16.

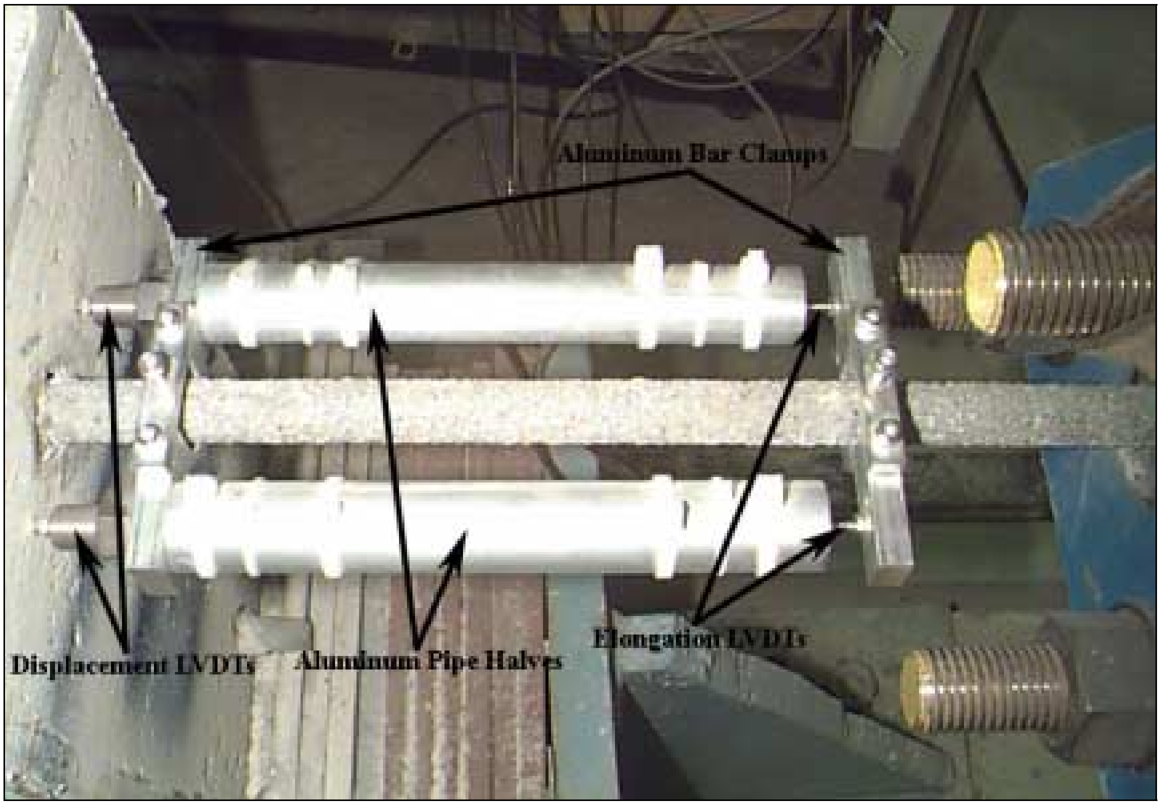

Figure 3.16: Loaded end bar rig and LVDTs.

One LVDT was used to measure the free end slip of the bar. It was attached using a steel bracket that was held to the concrete block by four bolts. The bracket provided a non-moving reference point to which the LVDT can be attached. The free end LVDT is shown in Figure 3.17.

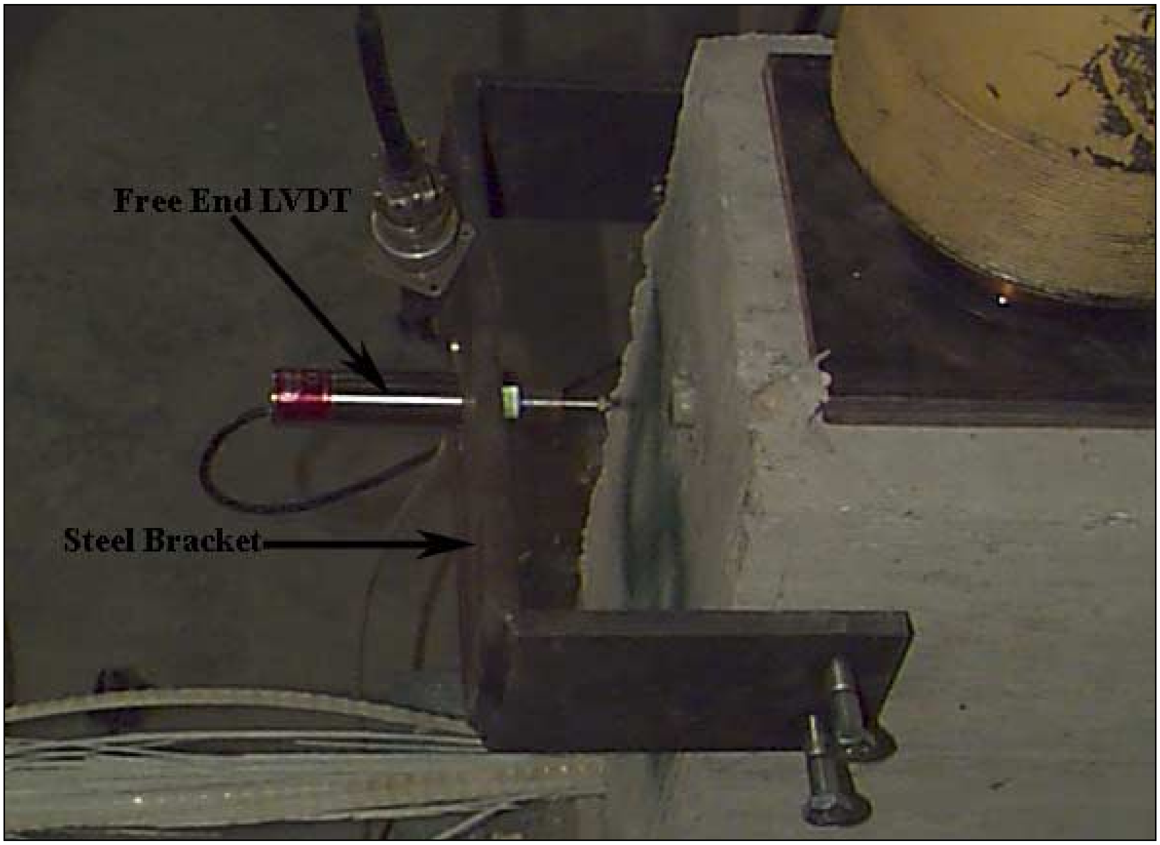

Figure 3.17: Free end LVDT.

All instrumentation was connected to Measurement Group's System 6000 data acquisition system. This system simultaneously took readings from all five LVDTs and both load cells at a rate of 10 readings per second. This system recorded the data to a personal computer using Measurements group's Strain Smart software. The Strain Smart software can also reduce the data to a desired format such as Microsoft Excel.

3.2.4: Bond Test Procedures

The first step in the testing procedure was the physical assembly of the test. It began with loading the block into the frame. This was done with the aid of an overhead crane. With the block positioned in the frame, the tension rig was placed over the end anchor of the side being tested. The tension rig, load cell, and ram remained pieced together throughout the test, and the rig was positioned on the end anchor with the aid of the ram. The ram pushed the tension rig, which was suspended from the test frame, forward and aft over the anchors. Next, the compression load cell and ram were positioned over the block 813 mm (32 in.) from the loaded end of the block. At this point, the slack was taken out of the system, and the block was leveled. Then, the loaded end LVDTs were positioned on the bar with the aluminum bar rig. Afterwards, the steel bracket, and free end LVDT were applied to the rear of the block. All of the LVDTs were fully compressed to allow for maximum elongation during testing. All instruments were then checked to ensure that they were properly connected to in the System 6000 data acquisition system. This completed the physical assembly of the testing.

The next step was setting up the data acquisition system, and running the test. The test setup was created using Strain Smart software, a relatively simple, and Window’s based program. With the test setup, the computer recorded the data at a rate of 10 readings per second once the test was started. Load was applied to the machine via the electric pump, which controlled the hydraulic ram. This was operator controlled, so the computer did not control the rate at which the load was applied. The load rates were chosen to meet the requirements of the ACI 440K (1999) document, and ASTM standard A 944-95 (1995) for beam end bond tests. ACI 440K (1999) states that load should not be applied at a rate greater than 22.2 kN (5 kips) per minute. ASTM requires that the load be applied at a rate between 10% and 33% of the published bond strength data. Both requirements were adhered to, and the load rates are given in Table 3.3.

Table 3.3: Bar loading rates.

Manufacturer	No. 4 bars kN/min	No. 5 bars kN/min	No. 6 bars kN/min
Hughes	8.9	17.8	22.2
Marshall	13.3	17.8	22.2
Pultrall	8.9	13.3	22.2

The test was initiated by beginning to record data. The operator applied load to the bar at the given load rates with the hydraulic ram. Care was taken to make sure that the load was applied at as constant a rate as possible. Data was recorded continuously through out the testing. The test was concluded when all of the displacement LVDTs had reached their maximum stroke. At this point recording was stopped, and the data was saved.

At the conclusion of the test, the tension rig was taken off of the end anchor, and the compression load cell and ram were moved out of the way to allow for room to take the block out. The block was then flipped over, and the second bar was tested in the same fashion. The procedure was repeated until all of the blocks were tested.

The bond tests were performed to acquire the bond strength characteristics for No. 4, No. 5, and No. 6 size bars for each of the three manufacturers in this program. For the most accurate simulation of flexural behavior, beam end bond tests were performed. The testing process began with constructing the specimens. This included determining the design of the forms, shear reinforcing cages, and determining the bonded lengths of the GFRP bars. That was followed by construction of all the parts, and casting of the blocks. Next the frame was designed, and all the pieces that were required for testing were fabricated. Then all of the testing equipment required for data acquisition was gathered, and setup for testing. Finally, the frame and the testing equipment were assembled with the blocks so that testing could begin.