The Fabrication of Carbon Fiber Frames for a Prototype GEM

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Abstract

The purpose of the research performed this semester was to manufacture carbon fiber support frames for a prototype gas electron multiplier (GEM). Test plates were fabricated in order to determine what materials would be used for the frames and how the corners would be formed. When the frames were constructed, tests were performed in order to make sure that the frames would not bend substantially. Since the frames did not deform more than half a millimeter in the z-direction when 282 Newtons were applied on parts connecting the frames, they were determined to be optimally constructed.

1 Introduction

GEM detectors are used to track the position of charged particles. Because of their high spatial resolution, these detectors are being implemented as part of the Muon Endcap upgrade to the Compact Muon Solenoid (CMS) detector complex. Similarly, GEMs are proposed to be used as part of a future electron ion collider (EIC) project in the U.S.A..

The difference between the GEMs proposed for the EIC and those constructed to upgrade the CMS Endcap is the amount of material in the active region of the detector. CMS GEMs use printed circuit boards (PCBs) to hold the drift electrode and readout structure and to provide support to the whole assembly. However, the Florida Tech EIC GEM design replaces the PCBs with foils having the drift and readout geometries on them and frames for support. This increases the amount of foils from three to five and the required tension to stretch the foils.

In order to determine the material, thickness, and width required for the support frames, a study using Inventor Professional's finite element analysis (FEA) tool was performed in the fall. These parameters were determined to be a high-modulus carbon fiber material, four millimeter thickness, and 35.5 millimeter width. With these parameters in mind, multiple test plates were constructed to practice making the composite and to tweak the design for the final product.

2 Test Plates and Frame Portion

Before the full frames were constructed, test plates and a portion of the frame were fabricated in order to test how different numbers of layers of carbon fiber fabric, kinds of epoxy, and types of making corners would effect the design. The fabrics used were IM7 high-modulus unidirectional and 090 standard carbon fiber.

2.1 Test Plates

Two different kinds of test plates were made for comparison. For one of them the use of West Marine epoxy was implemented while in the other Araldite epoxy was used. After fabrication, the plates would be put through similar tests in order to determine how strong they were.

Both plates were made in a similar process. Six layers of carbon fiber fabric were cut so that the thickness would differ along the length of the plates. Two thirty centimeter long strips of IM7 were on the bottom, one twenty centimeter strip of IM7 and a strip of 090 of the same length came next, and two ten centimeter strips of IM7 came last. In this way, different thicknesses of the composites could be tested.

Before the fabrics were laminated and cured, a table surface was cleaned and waxed with mold release. This was done so that the plates would not stick to the work area. After that, the vacuum bag for curing was preset so that no time would be wasted when laminating the fabric.

The two epoxies were made separately, both with mixing ratio of 5:2 by volume for each. This ratio was found in Amilkar Quintero's paper, under "Gluing," for the Araldite epoxy [1], and on the bottle of the West Marine epoxy resin. However, the use of this ratio for Araldite was a mistake, albeit a small one, since the ratio mentioned in Quintero's paper was by mass. Nonetheless, the ratio utilized did not impact the strength of the parts.

The first layers of carbon fiber fabric for the two plates were placed down beside each other, separated by a few inches. The West Marine epoxy was painted on the left fabric and Araldite on the right. The next layers were placed on top and metal rollers were used to squeeze excess glue through the fabrics. This process of gluing, placing another layer down, and squeezing glue through the assemblies was continued until each stack was finished.

After that, a non-stick polymer sheet with small holes across its surface was placed on top followed by a mat for soaking up epoxy. A layer of vacuum bag material was placed on top followed by another mat. This ensured than when the vacuum was started there would be no air pockets inside of the bag. A final layer of vacuum bag material was placed over the second mat and stuck to the work table using tacky tape. A hole was cut into the center of the bag and a vacuum port was attached to it via tacky tape. The port was connected to a vacuum pump and the pump was turned on. Once the bag was sealed, the plastic material shrunk tightly around the plates on the inside. Figure 1 is a view of what the curing looked like.

Once the plates were finished curing, a test was performed on them to determine how the strength of the plates compared. This test involved hanging weights varying from 4.9 to 10.5 kilograms on the end of the plate and measuring the vertical displacement of the end of the frame. An example of one data point, simulated with Inventor's FEA tool, is shown in Figure 2. Once all of the data was collected from this test, graphs relating the torque and vertical displacement of the plates at different thicknesses were generated. Error bars in these graphs were generated by propagating error in torque from the error in mass of each weight and error in displacement from the idea that a meter stick, which was used in this experiment, can only measure down to a millimeter reliably.

Figure 3 shows how the different composites compare in terms of strength. The slope of each torque equation, analogous to a spring constant, increases with thickness and as the epoxy changes. In this case, the composite using Araldite has a larger slope. In this case, the Araldite composite could handle more torque than the West Marine composite. Thus, the

Figure 1: A top view of the curing test plates, the one using West Marine epoxy labeled “W” on the left and the Araldite plate labeled “A” on the right.

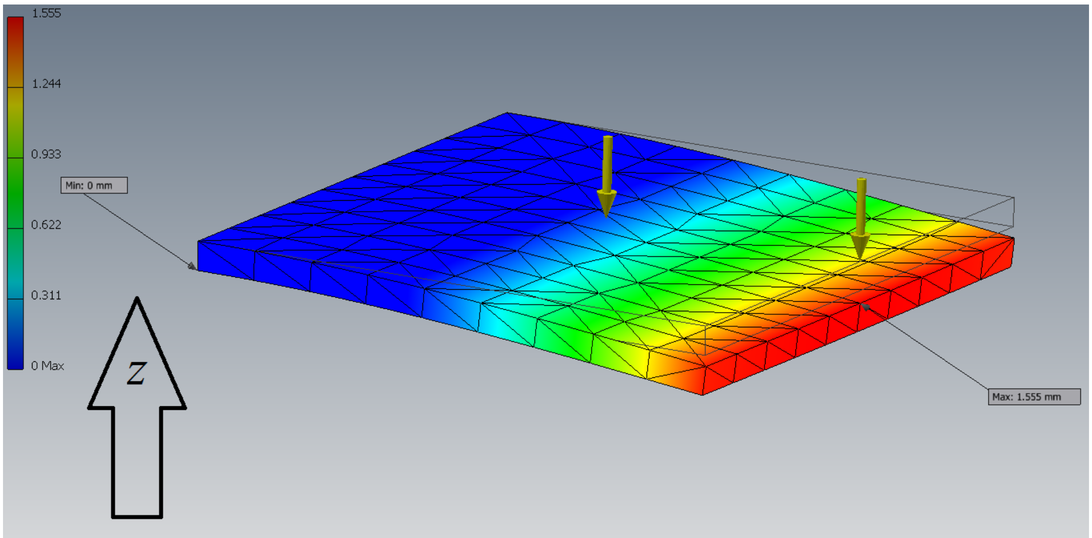

Figure 2: Simulation of Araldite test plate deflecting due to a 7.1 kilogram weight hanging on the end of the plate.

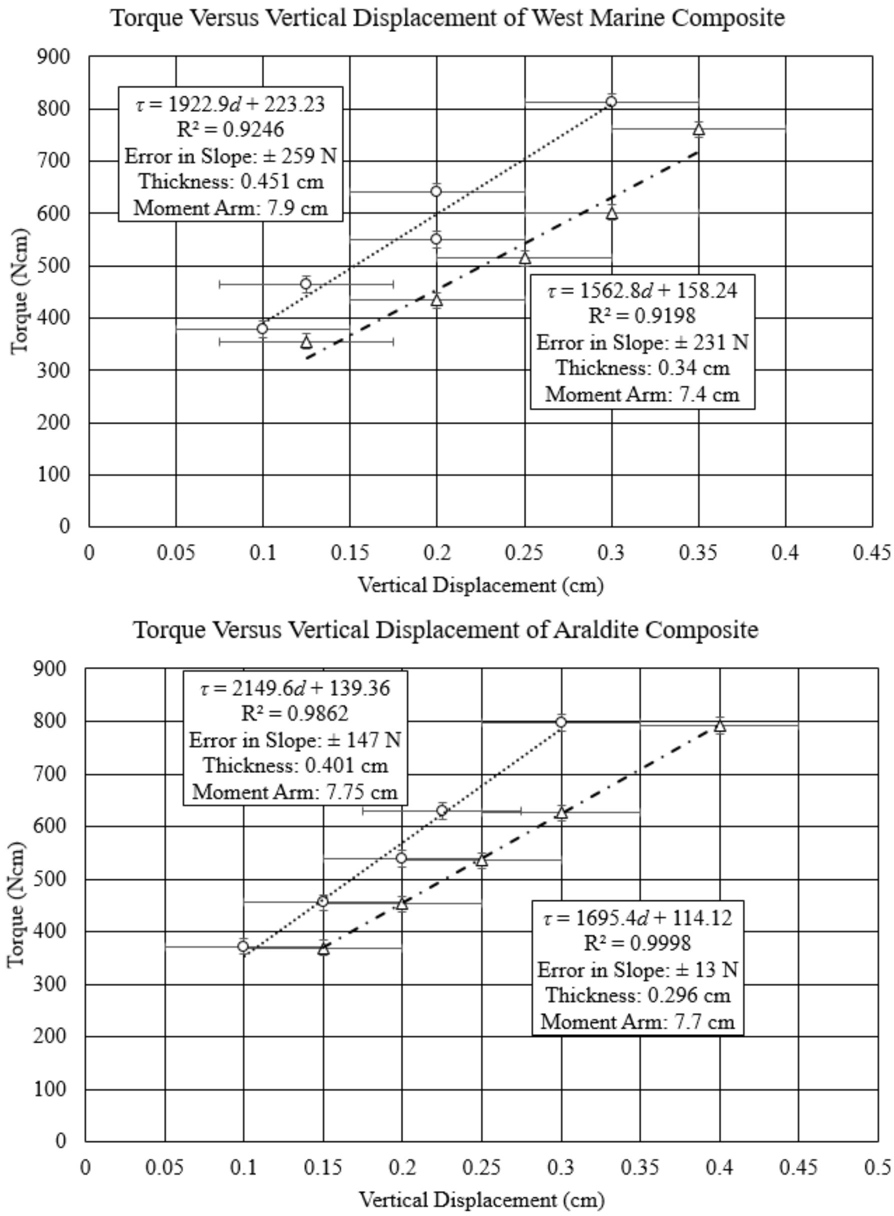

Figure 3: Comparison of West Marine and Araldite carbon fiber composites.

use of Araldite was found advantageous for making the support frames. This is fortunate since Araldite has been used in the construction of GEMs before [1]. It also has negligible out-gassing properties, which is important for gaseous detectors.

2.2 Frame Portion

Once it was determined that Araldite was most effective for the frames, a portion of the support frames was made in order to test two methods of making corners. To effectively test this, the wider end of the drift support frame was constructed. The same method of laminating the carbon fiber fabric was used and the thickness was uniform everywhere except the corners. At one of the corners, each layer overlapped the last while at the other corner subsequent layers “butted up” against each other to maintain uniformity in thickness while also making a strong structure in the corner. Figure 4 shows the laminated partial frame before the vacuum bag was constructed around it.

In addition to using two methods of making corners on the partial frame, holes for pullout posts for stretching the GEM stack were molded into the laminated piece. One of two molds, made in order to make the full frames, were used to help with this. Sixty pairs of holes of diameter 3 millimeters were drilled into a laminated rectangular plank of wood in a trapezoidal pattern such that the distance between the two bases of the trapezoid was approximately 965 centimeters. Also, the larger base was half a meter long, the smaller was a sixteenth of a meter long, and the pitch between the sides and the bases was about one and a half centimeters. Three pairs of holes made up the small base, the large base nine pairs, and the rest the sides, evenly spread out across the trapezoidal shape. When the partial frame was being made, carbon steel pins were placed into the holes associated with the large base and an arbitrary number of holes along the sides after being treated with mold release. After that, the process of laminating the carbon fiber fabric together was done around the holes. This method was used in order to preserve the uniformity of the carbon fibers in the final part.

After the frames were cured, a similar test to the one done to the test plates was conducted on the corners of the partial frames. Weights ranging from 4.9 to 10.5 kilograms were hung on the corners of the partial frame as illustrated in Figure 5. After this test was completed, a graph of the torque exerted on the frame corners was graphed as a function of deflection. This graph, Figure 6, illustrates that the overlapping method of making the frame corners is substantially more effective than the “butting” method. However, the substantial difference in thickness in the overlapping method protrudes into the area in which the pullout post holes will reside. Also, the simulations performed using Inventor Professional conclude that the deformation in the corners of the frames is negligible compared to the sides, as Figure 7 shows. Thus, the “butting” method, which would preserve thickness uniformity, was utilized due to the aforementioned motivating factors.

Before the full frames were made, another test was performed on the “butting” end of the partial frame. The same range of weights were applied to the end of the frame as with the test of the corners, and one of the data points, 70 Newtons applied to the end of the frame, was compared with a model of the deflecting portion using Inventor Professional. The Young’s Modulus of the material was changed and trends of the Young’s and Shear moduli as functions of simulated deflection were generated. The experimental value of the deflection was 1.433 millimeters and when plugged into the trends, the moduli of the composite were calculated (Figure 8). With these values, more

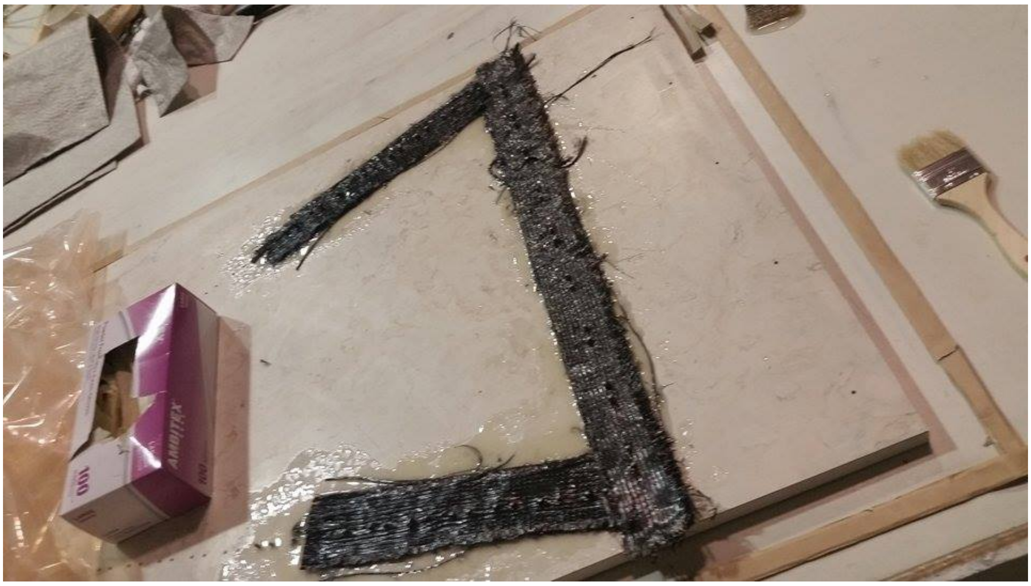

Figure 4: The laminated partial frame shown on the mold.

Figure 5: Testing the corners of the partial frame by hanging weights ranging from 4.9 to 10.5 kilograms on the corners; shown are 10.5 kilos hanging on the "butting" corner.

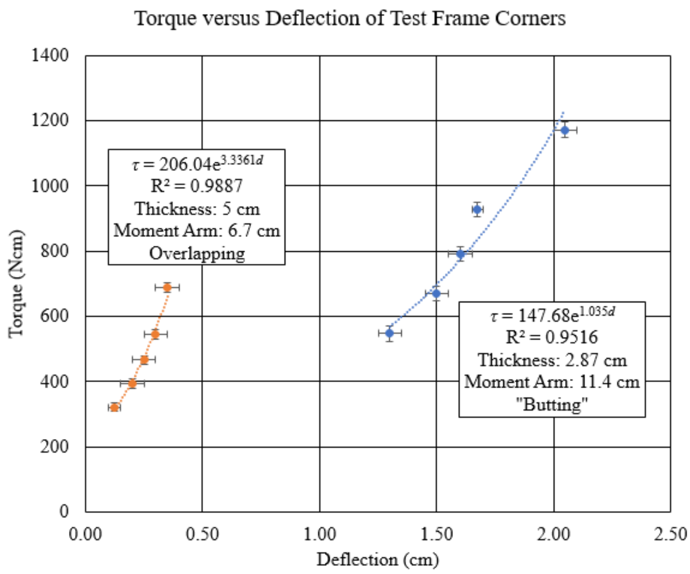

Figure 6: Torque exerted on the corners of the partial frames as a function of deflection.

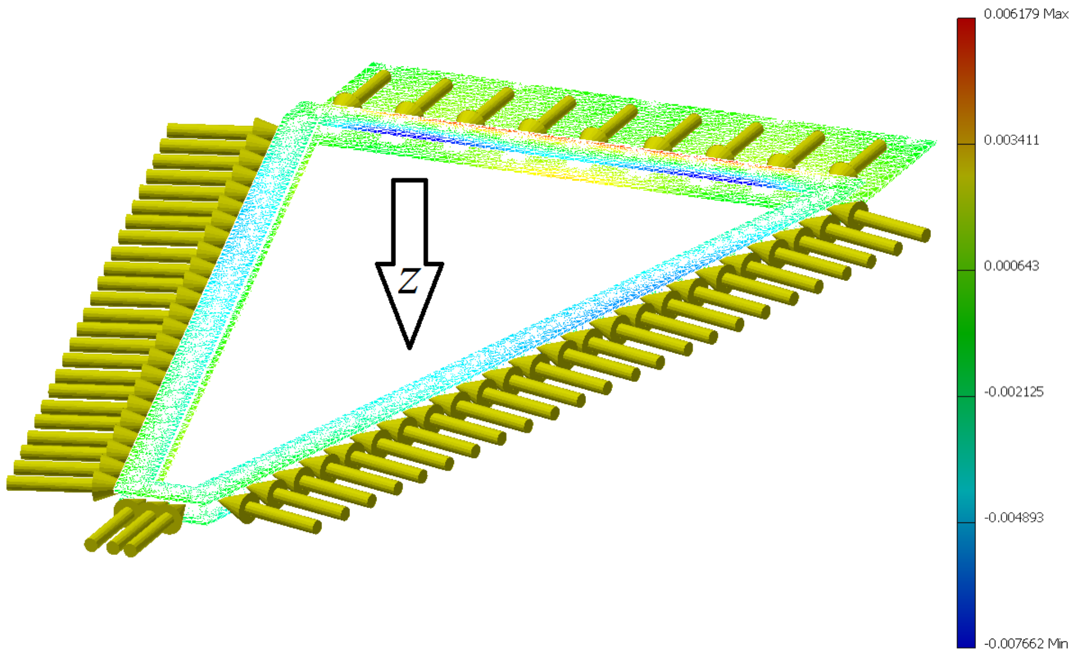

Figure 7: A simulation of the full carbon fiber frames in the z direction with 70 Newtons applied on each pullout part, emulating the foil assembly (units are millimeters); as can be noticed, the deformation in the corners is negligible compared with the sides.

accurate simulations would be performed.

3 Full Frames

With these design elements in mind, the full frames were constructed. This time, seven layers of IM7 and one of 090 carbon fiber fabrics were used in order to improve the strength of the frames. As was noticed when testing the partial frame, it deflected to a large degree compared to what was desired: Thus, more layers were utilized. Once the frames were constructed, they were trimmed in the machine shop and sanded. After that, and some brainstorming, a small experiment was conducted on the frames to see how much they would deform in the z direction.

This experiment consisted of three-dimensionally printing the pullout parts, attaching them to the frames, and using string and weights to apply tension along the length of the frames. The pullout parts were printed in Evans Library using white ABS plastic. To make sure that high tension could be maintained along the frames while not allowing the string transmitting that tension to snap, Kevlar string was ordered from Amazon.com. Using the pins that molded the frames' holes, the pullout parts were attached to the frames. Three pairs of two strings were cut and attached to three pullouts on the wide end and were strung through the three pullouts on the small end. Two clamps formed a "pulley," and a basket was attached to the strings. The small end was clamped down, weights ranging from 9 to 28.2 kilograms were placed in the basket (Figure 9), and the upwards deflection of the frames was studied. Even up to 28.2 kilograms of weight, the frames did not deform to a noticeable degree. Thus, the frames were made properly for holding the foil assembly.

Using the moduli generated through the study of the partial frame, a simulation of the material was performed using Inventor Professional's FEA tool. With applied forces on the pullout parts ranging from forty to eighty Newtons, the deformation of the frames in the z direction was studied. Thus, the force applied on the pullouts was graphed as a function of deformation in the z direction (Figure 10). The trend generated from this graph could be written in the following way:

$$z = \frac{F}{5500.5 \pm 5.6}$$

Using this formula, the deformation in the z direction when the applied force on each pullout is 282 Newtons can be easily calculated. This deformation, which is five-hundredths of a millimeter give or take half a nanometer, is well below being noticed, which confirms the experimental results implying that the frames were properly constructed.

4 Summary and Conclusions

Through trial and error, experiment and theory, it was determined that the construction of carbon fiber frames was appropriate for the prototype Florida Tech EIC GEM. Once constructed, the frames did not deform significantly. This confirmed that the concept of reducing the material in the active region of a GEM detector is possible. With this knowledge, further steps to making the prototype detector can be taken.

References

[1] A. Quintero, "Assembly 30 cm x 30 cm GEM Detectors," Procedure, Summer 2009.

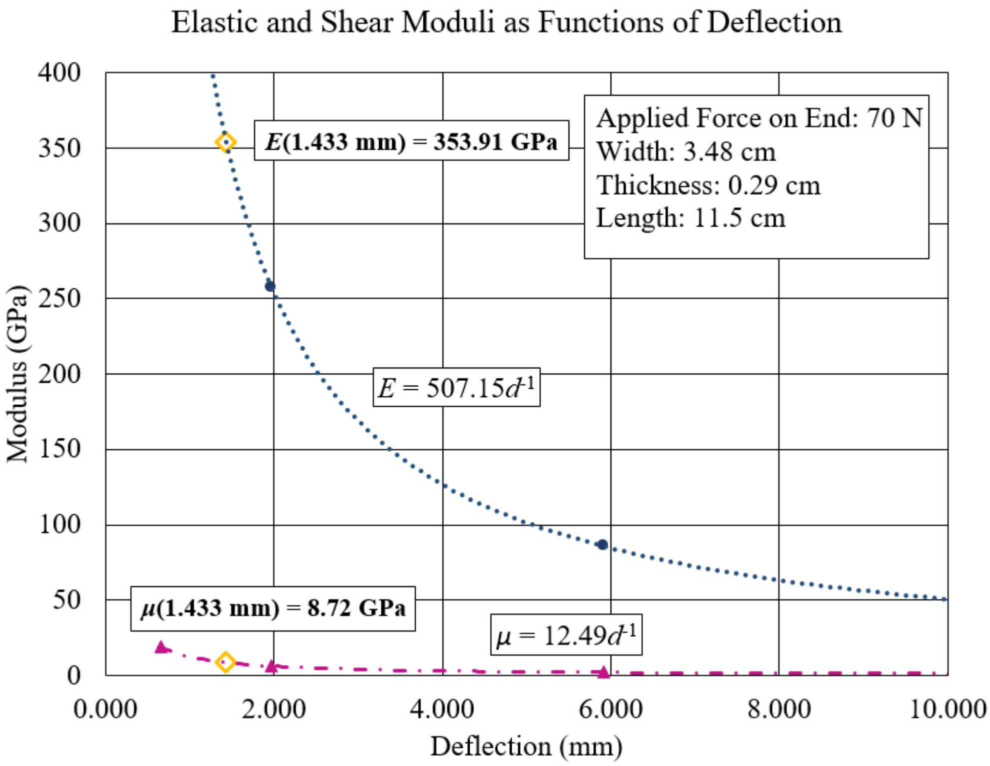

Figure 8: The Young's (elastic) and Shear moduli as functions of deflection; the yellow diamonds show the moduli of the IM7/090 with Araldite composite.

Figure 9: Setup of the full frame experiment using three pairs of lines to translate tension; shown in the basket is 28.2 kilograms.

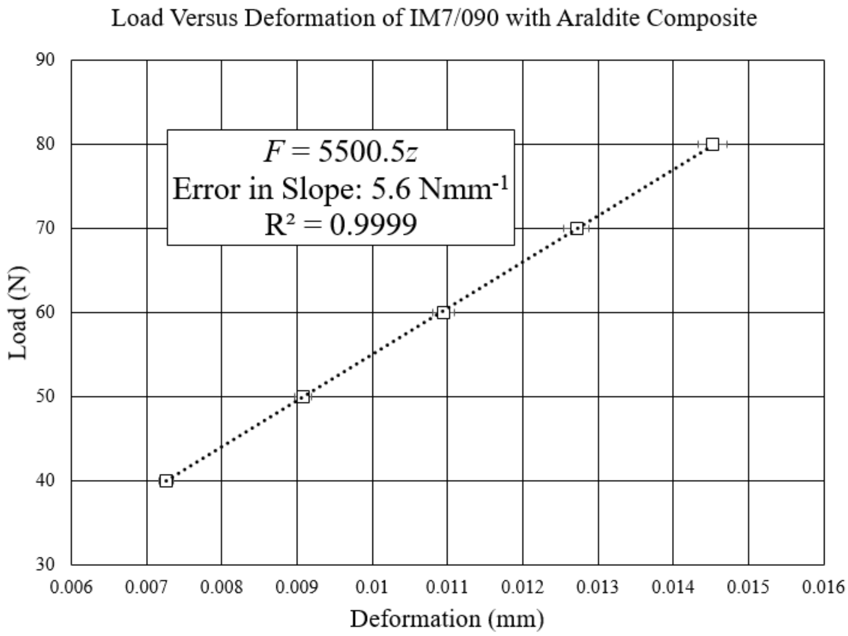

Figure 10: Applied force on the pullouts as a function of deformation in the z direction.