DESIGN AND CONSTRUCTION OF AN ADHESIVE SHEAR TEST TOOL

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Abstract

The D-Zero (D∅) detector at Fermi National Accelerator Laboratory is undergoing a general upgrade in an effort to efficiently operate under much higher collision rates such as an integrated luminosity of 15 fb^{-1}. This paper reports on one of the many upgrades that is currently in progress on the Run IIB silicon detector and focuses on my contribution to the upgrade: The Design of an Adhesive Shear Test Tool.

Introduction

The physics program at Fermi National Accelerator Laboratory continues to explore the issues associated with high-energy particle physics, in an attempt to discover the Higgs boson and other particles beyond the Standard model. The advent of silicon detectors has revolutionized the field of particle physics as it facilitates the exploration of matter with ever-increasing precision. The Silicon Detector (SiDet) Laboratory offers more than 6,000 square feet of clean rooms with dozens of high-precision machines that probe, mount and connect silicon strips and electronic chips. In order to fully employ these opportunities, the D∅ detector has to be upgraded to facilitate the proper functioning of the silicon tracker layers when exposed to very high radiation levels. This apparently simple task had significant risks for both the "partial-replacement" option and "full-replacement" option. In the partial-replacement option, only the two (2) inner silicon layers would be replaced with radiation-tolerant detectors whilst the present tracker design would be maintained. Internal reviews of this option encountered many risks for the program including the risk of damage to those parts of the detector that were not replaced, difficulties in adequately cooling the inner layers and the long down time required to retrofit the existing detector.

In the full-replacement option, the entire Run IIA silicon tracker would be replaced with an upgraded version to meet the requirement that the detector withstands an integrated luminosity of 15fb^{-1} (fb^{-1} - inverse femto barn, is a measure of the number of collisions particles approximating 10^{24} cm^2). Despite that this option is more expensive and is more labor-intensive, Fermilab decided to implement the full-replacement option. The mechanical design of the Run 2B silicon detector is indeed challenging as it must satisfy strict requirements on material mass, on precision, construction and positioning and allow for signal readout and cooling of the detectors. It was the ingenuity of the engineers involved in this project who envisioned the practicality of using carbon fibers as a cooling tube. Carbon fiber is used extensively in the engineering of the D∅ detector because of its properties' of low density, low atomic number, high strength and low coefficient of thermal expansion. This presented an opportunity to design an adhesive shear stress tool to test the bond strengths of selected epoxies to the different types of plastics to be used in the D∅ detector.

Design of Adhesive Shear Test Tool

The main objective of the study of materials is to provide the engineer with the knowledge to analyze and design various types of machines and load-bearing structures. The 3M-2216 epoxy/plastic bonds being tested are to be used in various areas of the D∅ detector such as at the nozzles of the carbon fiber cooling tubes and both the plastics and epoxy were selected because of their tolerances to high levels of radiation. Table #1 provides the names of the plastics and some of their mechanical properties while Figures #1- #4 provide pictures of each of the plastics used.

	Tensile Strength (psi)	**Radiation Resistance (Gy)**	**CTE (in./in./^{0}C)**
G-10	**4000**	**1.0 x 10 $^{7..5}$**	**1.8 x 10^{-5}**
NORYL (PPO)	**9600**	**1.0 x 10 $^{5..5}$**	**3.3 x 10^{-5}**
PEEK	**5000**	**1.0 x 10 $^{6..5}$**	**4.5 – 7.0 x 10^{-5}**
KYNAR (PVDF)	**7800**	**n/a**	**7.1 x 10^{-5}**

CTE – Coefficient of Thermal Expansion

Table #1 – Mechanical properties of various plastics

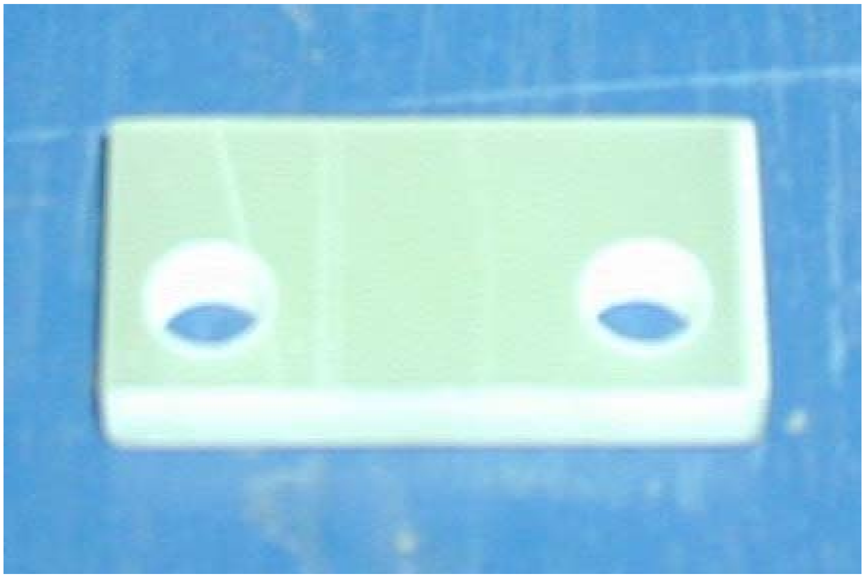

Figure #1 – G -10

Figure #2 – NORYL (PP0)

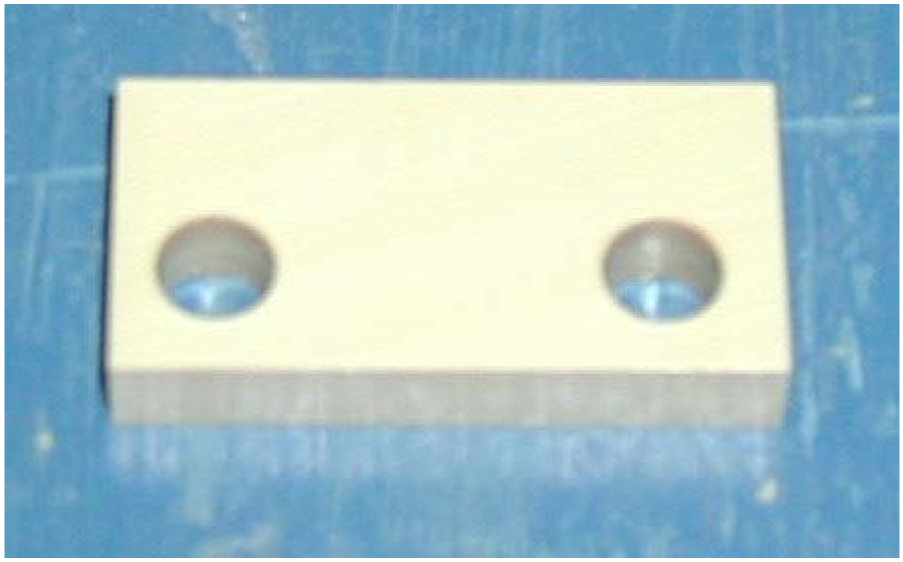

Figure #3 – PEEK

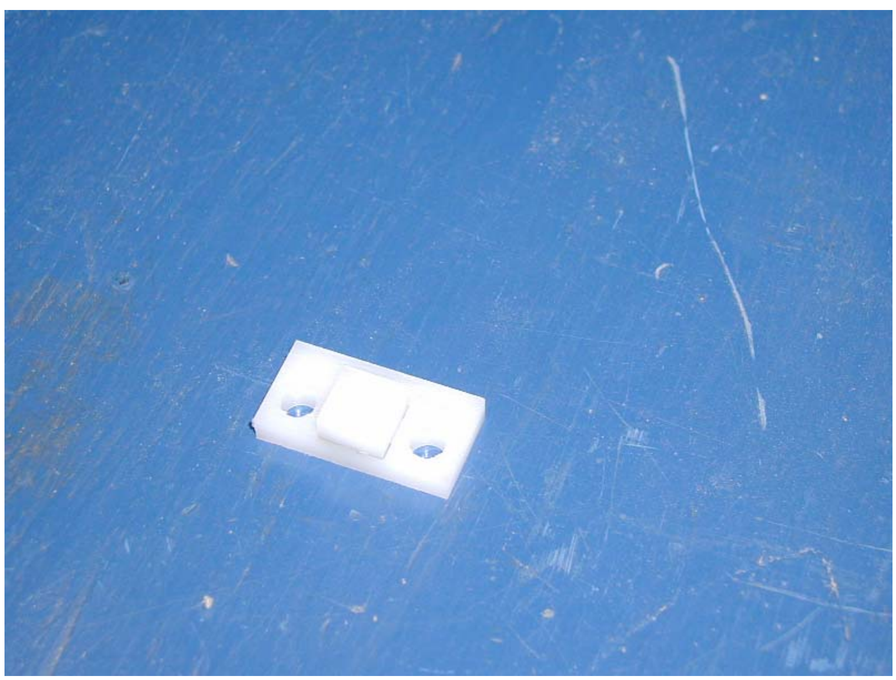

Figure #4 - KYNAR

Shear Stress

Shearing stresses are commonly found in bolts, pins and rivets used to connect various structural members and machine components. Shear forces are different types of stresses and are obtained when transverse forces P and P' are applied to a member AB as shown in Figure #5 below. Passing a section at C between the points of application of the two forces as shown in Figure #6, it is possible to generate a diagram of portion AC, as shown in Figure #7. It can be concluded that the internal forces must exist in the plane of the section and that their resultant is equal to P. These elementary internal forces are called shearing forces and the magnitude P of the resultant are the shear in the section. The formula for the shearing stress, denoted by the Greek letter tau – **(τ)** is given by

$$\tau = P/A$$

Figure #5 – Transverse forces P & P' applied to member AB

Figure #6 – Section C between points of application

Figure #7 – Portion AC

Procedure and Calculations

The first calculation was to determine the load that would shear the glue on each sample size from the plastic. Using the size of each sample as 0.50" x 0.50" and the assumption that the tensile strength is twice the magnitude of the shear strength, it can be shown that

Tensile strength = 4000 psi (pounds per square inch) ⇒ Shear strength = 2000 psi

Area of sample, A = 0.50" x 0.50" = 0.25 inch^2.

The force, P, can be calculated as follows:

$$P = \tau \times A$$

$$P = 2000 \text{ psi} \times 0.25 \text{ inch}^2$$

$$\Rightarrow P = 500 \text{ lbs.}$$

Hence, the dimensions of the handle of the adhesive shear test tool must be able to withstand the force of 500 lbs that is exerted by the 3M-2216 epoxy. A ratio of 20": 2" was used to determine the maximum weight that can be hung from the handle before shearing can occur, and this value was calculated as 50 lbs.

Beams are structural members that are designed to support loads applied perpendicular to their axes hence the handle of the shear stress tool was designed to be a rectangular beam, constructed from structural steel ASTM A36. Structural steel ASTM A36 was opted as the choice material for the handle because of its properties of high ultimate strength in tension – 56 ksi – and its high modulus of elasticity – 29 x 10^6 psi. The actual design of a beam required a knowledge of the variation of the internal shear force, V, and bending moment, M, at each point along the axis of the beam. On completion of the force and bending-moment analysis, the theory of mechanics of machines can be used to determine the beam's required cross-sectional area. The following procedure was used to construct the shear and bending moment diagram of the handle:

1. Support Reaction

All forces acting on the beam such as the forces exerted by the epoxy and weights were determined and resolved into components acting perpendicular and/or parallel to the axis of the beam.

2. Shear and Moment functions

Separate coordinates, ***x***, having an origin at the handle's left end and extending to regions of the handle between forces and where there is no discontinuity of distributed loading are illustrated in Figures #8 and #9. Section the handle perpendicular to the axis at each distance, **x,** and from the free-body diagram of one of the segments, to determine the shear force and bending moment at the cut-section as functions of x.

Section $0 \le x \le 20$

$\uparrow \sum F_y = 0 \Rightarrow$ **V = -50 lbs**

$\sum M_s = 0 \Rightarrow$ **M = -50x (lbs. inch)**

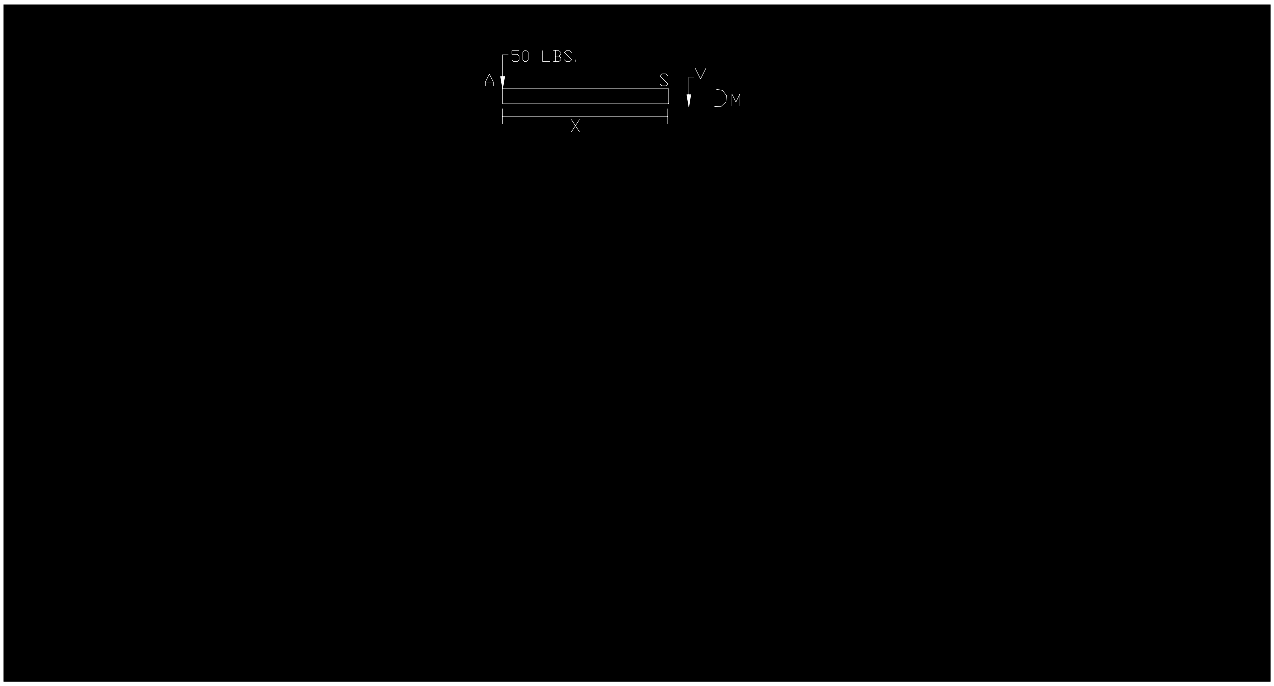

Figure #8 – Illustration of region of continuity between section $0 \leq x \leq 20$

Section $20 \leq x \leq 22$

$\uparrow \sum F_y = 0 \Rightarrow -50+550-V = 0$

$\Rightarrow$ **V = 500 lbs**

$\sum M_s = 0 \Rightarrow M + (50x) - (550(x-20)) = 0$

$M + 50x - 550x + 11000 = 0$

$M - 500x + 11000 = 0$

$\Rightarrow$ **M = 500x – 11000 (lbs. inch)**

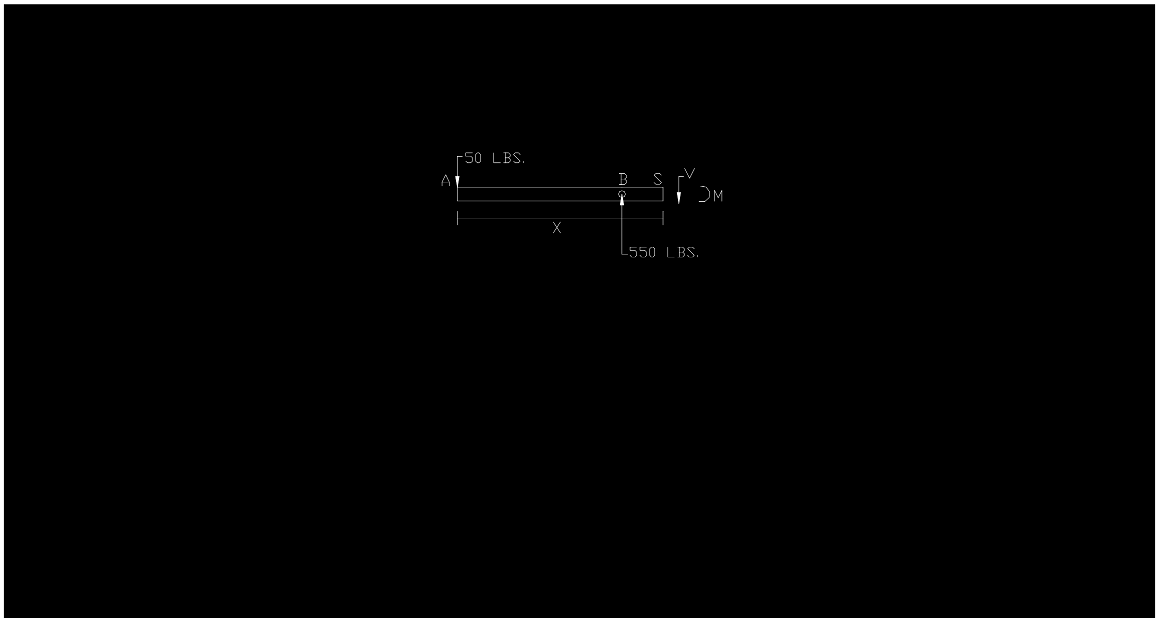

Figure #9 - Illustration of region of continuity between section $20 \leq x \leq 22$

3. Shear and Moment Diagram

A plot of the shear diagram (***V*** versus ***x***) and the moment diagram (***M*** versus ***x***) is shown in Figure #10.

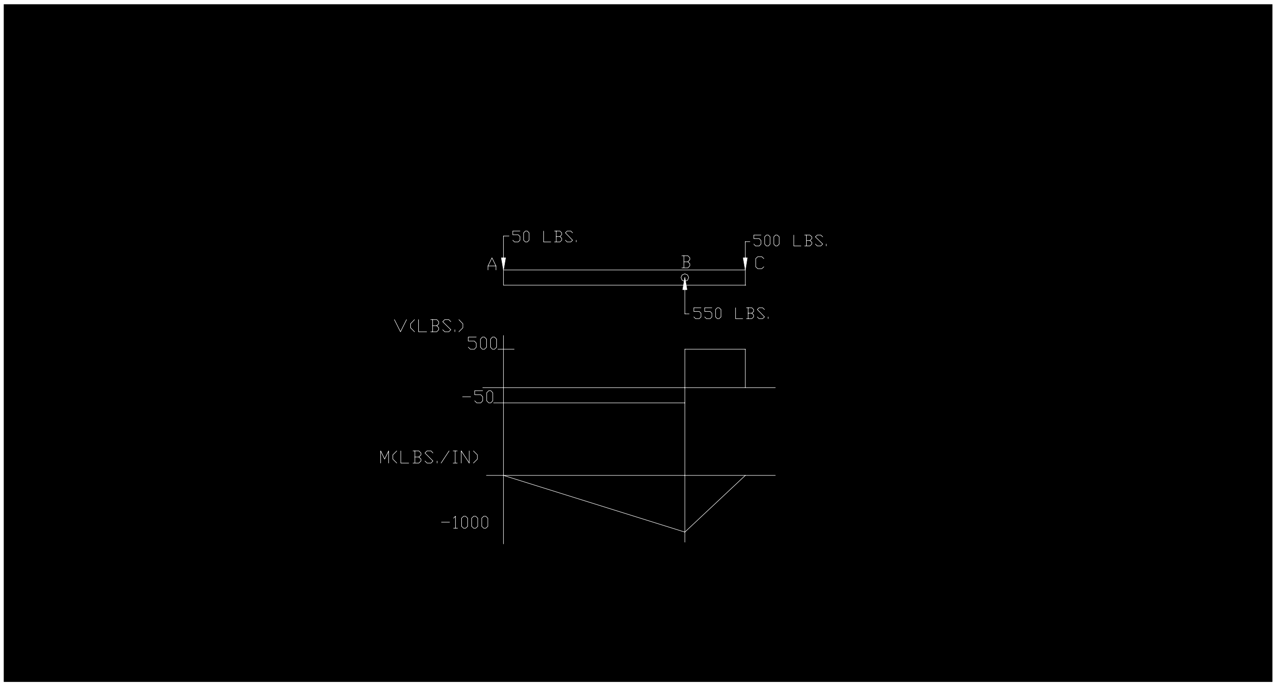

Figure #10 – Shear and Bending Moment Diagram

Having decided upon the material to be used for the handle and the sample size to be used in the shear test tool, there still remained the question of what dimensions of the steel beam would carry the given loads safely? Variations in the dimensions of the handle, pin and screws were investigated and among the calculations were stress, maximum deflection, shear stress and factor of safety. The results of the chosen dimensions are as follows:

PIN

Using: **Diameter of threads, d = 0.241”** **P = 550 lbs** $\mathbf{A = \Pi \times d^2/4}$

$= (\Pi \times (0.241)^2)/4$

$\Rightarrow \mathbf{A = 4.56 \times 10^{-2}\ inch^2}$

$\boldsymbol{\tau_{pin} = P/A}$

$= 550\text{ lbs} / 4.56 \times 10^{-2}$

$\Rightarrow \boldsymbol{\tau_{pin} = 1.21 \times 10^4\ \textbf{psi}}$

SCREW

Using **P = 500 lbs** **Area of screw = 0.032 inch^2** **No. of screws used = 2**

τ_{screw} **= P/A**

= 500 / (2 x 0.032)

$\Rightarrow \tau_{screw}$ **= 7.86 ksi**

HANDLE

Using h = 1" $\Rightarrow$ c = 1/2" **b = ½"** **M = 1000 lb.inch**

I = 1/12 x b x h^3

= 1/12 x (1/2) x (1)^3

$\Rightarrow$ **I = 4.167 x 10^{-2} inch^4**

σ **= (M x C) / I**

= ((-1000) x 0.5) / 4.167 x 10^{-2}

$\Rightarrow \sigma$ **= - 1.2 x 10^4 psi**

Maximum deflection (f_{max})

Using c = 20" **c' = 2"** **E_{steel} = 29 x 10^6 psi** **I = 1/24 inch^4**

h = 1" $\Rightarrow$ c = ½" **b = ½"** **L = 22"**

f_{max} **= ((Wc') / 3EIL) x (c (l + c') / 3)$^{3/2}$**

= ((500 x 2) / 3 x (29 x 10^6) x (1/24) x (22)) / (20 (22 + 2) / 3)$^{3/2}$

$\Rightarrow f_{max}$ **= 2.79 x 10^{-2} inch**

Pin diameter, h = 3/8” H = 1” b = ½” Ultimate Strength = 70000 psi

$$I = 1/12 \times b \times (H^3 - h^3)$$

$$= 1/12 \times ½ \times ((1)^3 - (3/8)^3)$$

$$\Rightarrow I = 3.95 \times 10^{-2} \text{ inch}^4$$

$$I/c = (b/6) \times ((H^3 - h^3) / H)$$

$$= (½ / 6) \times (((1)^3 - (3/8)^3) / 1)$$

$$\Rightarrow I/c = 7.89 \times 10^{-2} \text{ inch}^4$$

$$\Rightarrow c/I = 12.67$$

$$\sigma_{handle} = (M \times c) / I$$

$$= (1000) \times 12.67$$

$$\Rightarrow \sigma_{handle} = 1.267 \times 10^4 \text{ psi}$$

Factor of safety (F.S.) = Ultimate stress / Allowable stress

$$= 70000 / 1.267 \times 10^4$$

$$\Rightarrow F.S. = 5.50 \quad \text{(on yield)}$$

AutoCAD drawings

AutoCAD – Automatic Computer-Aided Design – is one of the many resources that were available to transposing the design of the adhesive shear test tool to a hardcopy version for its construction by the Technical Shop. Figures #11 - #14 provide sample copies of the AutoCAD drawings used in the construction of the tool.

The Adhesive Shear Test Tool

Figure #15 – Completed and assembled Adhesive Shear Test Tool

Results

In the initial stage, the samples of plastics were given to the Technical Shop to be machined and glued, using 3M-2216 epoxy. With the process of gluing the sample pieces together, certain quality control measures were used and these included:

1. The surfaces of the plastics were washed using alcohol to obtain surfaces that were very clean of fingerprints
2. After the glue was applied to the larger surface, smooth and controlled strokes using a razor blade created a uniform layer of glue on the surface.
3. The glue was not pressed down between the surfaces as this could create non-uniform contact between the surfaces; instead the smaller of the two pieces of plastics was gently placed onto the glue surface
4. All the pieces were allowed to cure for twenty-four (24) hours

5. The readings on the scale would be verified by two persons to allow the recording of accurate measurements.

Before the adhesive shear tool testing began, some safety precautions were discussed that were to be adhered in the vicinity of the testing area. These included:

1. A rag was to be placed over the tool while the bucket of water was being filled as illustrated in Figure #16; this was to act as a cover for the smaller piece of plastic because when the shear force is achieved, the force that the piece would shear from the tool might be harmful if allowed to travel anywhere in the lab.
2. All objects around or on the testing table were cleared off
3. Safety glasses should be worn by all participants involved in the testing to prevent specks of materials from entering the face area.
4. All spilled water should be cleaned up before any additional testing is conducted.

Figure #16 – Fully assembled Adhesive Shear Test tool with weight and covering

Each test was conducted with the sample being placed and tightened into position. The weight- water – was placed in a bucket attached to the handle of the tool until the plastic sheared from the epoxy as illustrated in Figure #16. The water flowed into the bucket a rate of 2.85 L/min. The water was taken and measured at a nearby hanging scale and the weight verified and recorded. A total of sixteen tests were conducted and the results are as follows:

Material Name	Material No.	Wgt. of water (lbs.)	Total wgt. (lbs.)	Total wgt. x 10 (lbs.)	Actual shearing force (psi)
PEEK	**1**	**19.0**	**20.37**	**203.70**	**814.80**
	2	**9.5≈**	**10.87**	**108.70**	**434.80**
	3	**9.0≈**	**10.37**	**108.70**	**414.80**
	4	**16.5**	**17.87**	**178.70**	**714.80**
G-10	**5**	**36.5**	**37.87**	**378.70**	**1514.80**
	6	**37.5**	**38.87**	**388.70**	**1554.80**
	7	**36.0**	**37.37**	**373.70**	**1494.80**
	8	**41.0**	**42.37**	**423.70**	**1694.80**
KYNAR	**9**	**5.0**	**6.37**	**63.70**	**254.80**
	10	**6.0**	**7.37**	**73.70**	**294.80**
	11	**6.0**	**7.37**	**73.70**	**294.80**
	12	**6.0**	**7.37**	**73.70**	**294.80**
NORYL	**13**	**13.0**	**14.37**	**143.70**	**574.80**
(PPO)	**14**	**13.5**	**14.87**	**143.70**	**594.80**
	15	**5.0≈**	**6.37**	**63.70**	**254.80**
	16	**16.0**	**17.37**	**173.70**	**694.80**

≈ - readings with dispararities

The weight of the handle - 1.37 lbs. - was incorporated into the calculations to derive the total weight. The calculations were:

Actual Adhesive Shearing Force = ((Weight of water + Weight of handle) x 10) x 4

The weight of water of the first test - Kynar #12 - was weighed a second (2^{nd}) time on an electronic scale to determine the accuracy of the spring scale that was being used. The weight of the water on the spring scale measured 6.0 lbs, compared to on the electronic scale at 6.039 lbs. This was a difference of 0.039 lbs., which concludes that the readings on the spring scale are accurate to 99.35%.

Analysis and Conclusion

From the above results, it can be inferred that the general order of the strengths of the epoxy/plastic bonds, in decreasing order is as follows:

- G-10
- Noryl (PPO)
- Peek
- Kynar

The 3M-2216/G-10 bond produced shear stresses of over one half of the maximum shear stress, thus indicating that this combination would be a suitable choice for bonds that are subjected to extremely high stresses, common in many areas of the D∅ detector. However, there were some disparities in the trend of the shear stress results especially with Peek and Noryl (PPO). Analyses of the surfaces of these plastics revealed that the pieces that produced the disparities in the readings appeared not to have been “wetted” properly. This means that the epoxy was not properly affirmed to the plastic and hence did not have full adhesion to the surfaces as was evident in the results. It was concluded that the preparation of the plastic’s surface was very crucial to the results of the adhesive shear test.

It was also observed that the coarser the surface of the plastic, the better the adhesion of the epoxy to the surface of the plastic. This was clarified with physically examining the surfaces of each of the plastic and comparing the results obtained above. Certain recommendations have been given as to improve future adhesive shear stress testing such as gently rubbing sand paper over the surfaces of the sample plastics to attain a coarser surface, which would influence the resulting adhesion results and attempting to use other types of epoxies that would increase the overall strength of the epoxy/plastic bond.

References

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[4] Juvinall, Robert C. & Marshek, Kurt M., Fundamentals of Machine Component Design, John Wiley & Sons, 2nd Edition, 1991

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Figure #11 – Base Plate

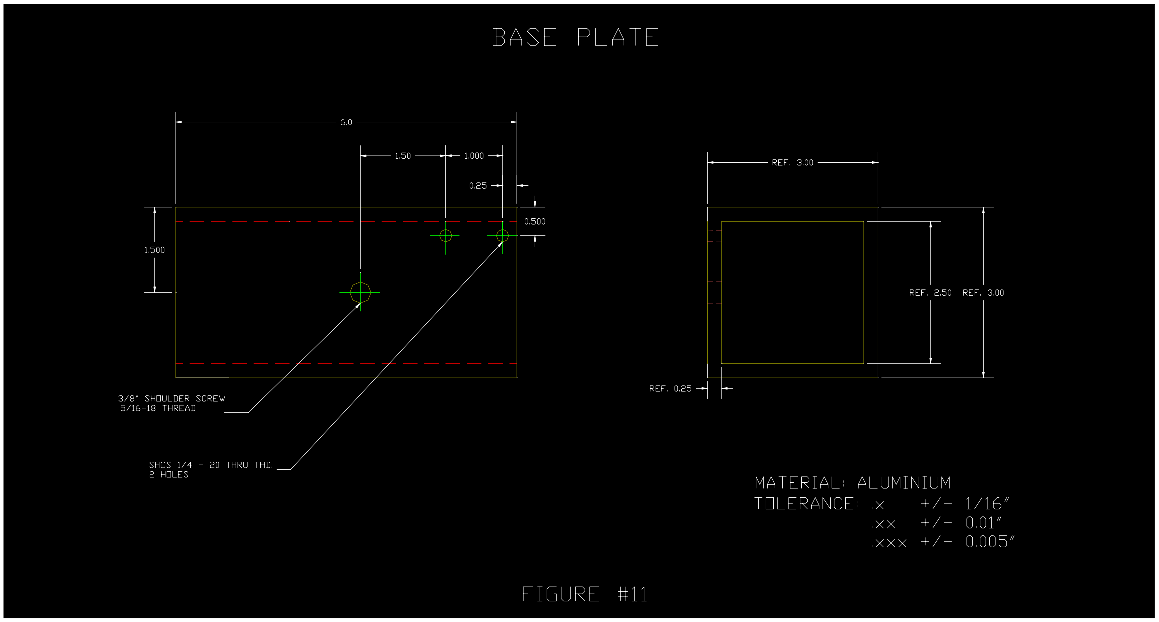

Figure #12 – Plastic Attachments

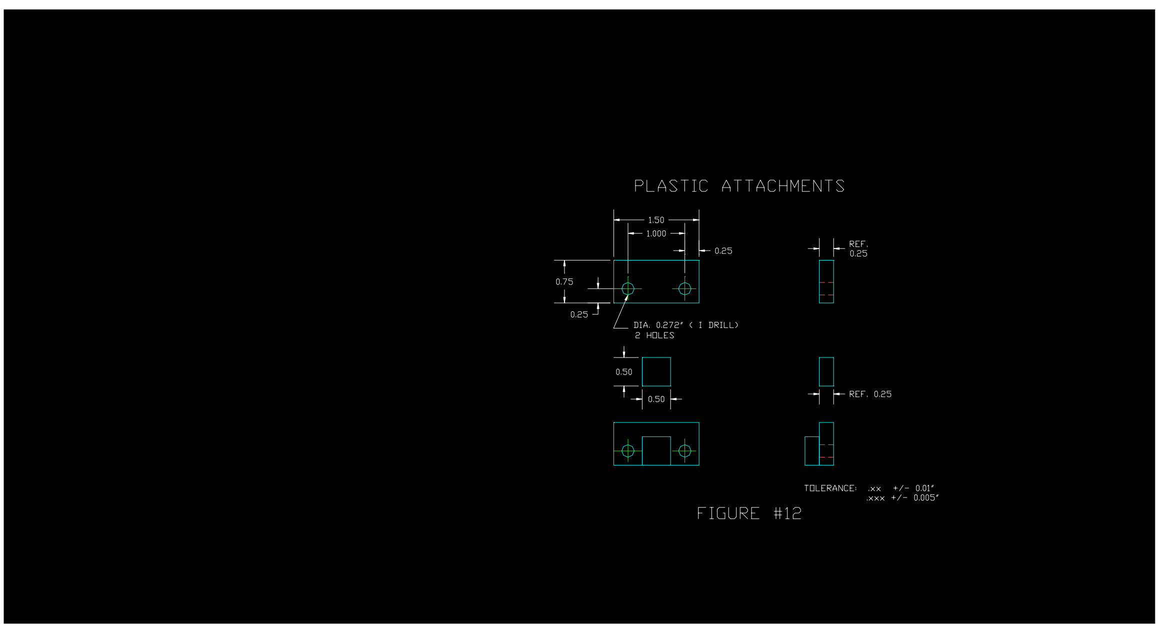

Figure #13 – Handle

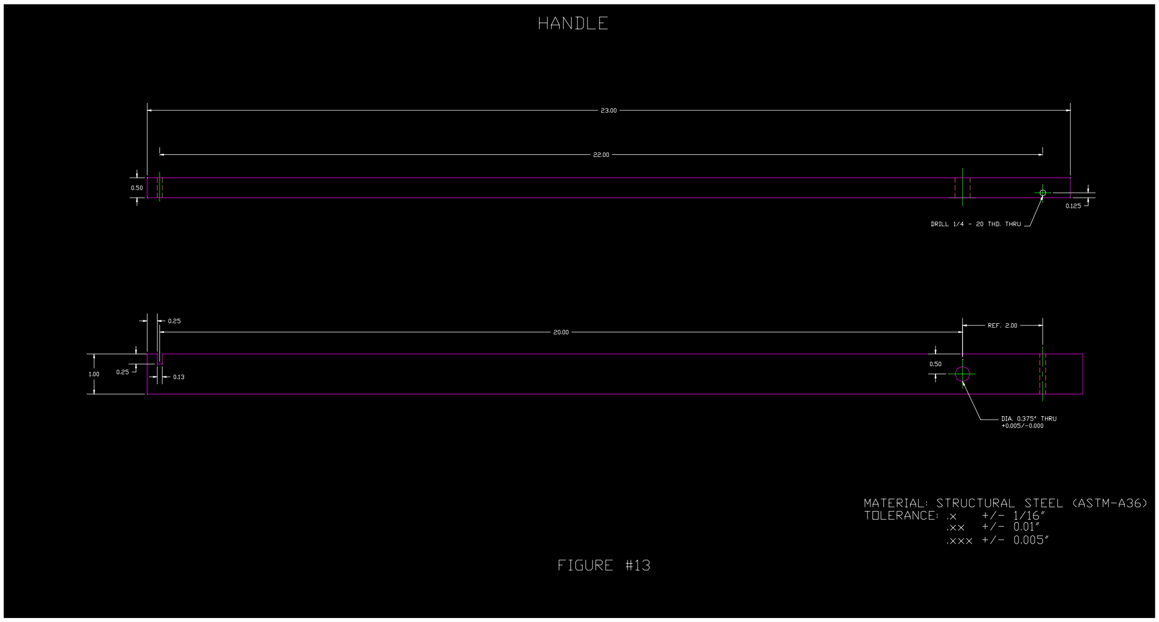

Figure #14 – Assembly