Mechanical Testing of Structural and Hybrid Epoxies

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"On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work."

Abstract

The purpose of this report is to explain in detail the procedure that was designed and implemented to test and compare results of sheer strength of different epoxies. Seven different candidates were selected as a possible means of securing components of a VIRUS unit. All of the candidates were two part epoxies except for one, and some of the epoxies tested were also potentials for optical bonding as well as structural. Samples were adhered to two-part aluminum metal facets that were designed to imitate a bonding environment similar to that of one in a VIRUS unit. Shear stress and strain was measured for each candidate using an MTS Tensile Test Machine which grasped the corresponding ends of an epoxied aluminum facet, measuring the force applied and the elongation rate of the sample as it is slowly pulled apart. The structures of the aluminum samples are conductive to this mechanism of strength testing. All seven samples were tested and individual results were determined for each and compared with one another to determine which samples would be the strongest and, therefore, most effective as means of securing components of a structure. It was found that epoxies T10-3003, Permabond ES550, Devcon 2 Ton, and Epo Tek 301-2 presented the best combination of sheer strength and stiffness. Only one epoxy, Epo Tek 301-2, was found to be a possible candidate for optical and structural bonding. Loctite Hysol 1C and the 3M epoxies were found to be inadequate for the needs exhibited by VIRUS.

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Introduction

In structural engineering there are many ways to join components of similar and dissimilar material and geometry. For each design and component situation there is an optimum fastener that provides the best combination of cost, workability, strength, and stiffness. For permanent installations that must be liquid tight one may choose a welding application. On the other hand, if a system must be made to be assembled and disassembled for transport then one may choose to use other mechanical fasteners such as bolts. One disadvantage of both of these methods of fastening is the creation of stress concentrations at the joints. These concentrations can cause sagging at the joints or provide a site for crack propagation. To this end, it has been proposed that epoxies be considered as an alternative method of component assembly for VIRUS. To satisfy this objective, various one and two part epoxies were tested using a MTS Tensile Test Machine to determine their comparative strengths. The epoxies were adhered to aluminum samples to be representative of actual system conditions. The data from these experiments would help designers to choose an epoxy that best suits their needs. The objective of this report is to present the preliminary results of the epoxies tested and to provide a framework for future testing.

Test Theory

For the purposes of experimentation it is assumed that the primary variable of study is the shear strength of epoxies. Figure 1 shows a model of a VIRUS unit with the epoxy joints highlighted. The tendency of the face plate to sag at the joints would primarily cause shear stresses before tensile, bending, or peel stresses.

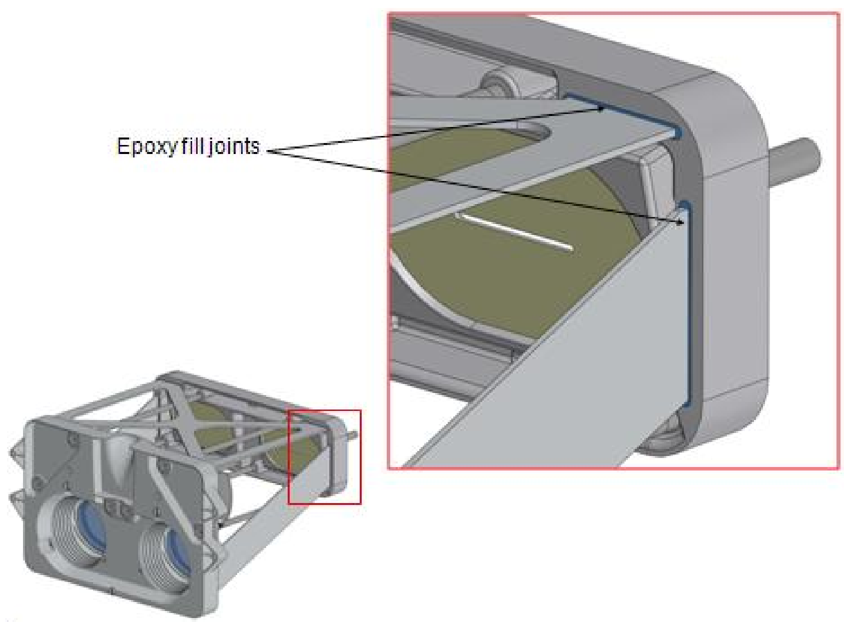

Figure 1. A VIRUS unit with epoxy joining the face plate with the top and side plates.

Shear stress can be defined as the load acting parallel to the face in question per unit of effected area as shown in the following equation:

$$\tau = \frac{F_{//}}{A}$$

where $F_{//}$ is the load acting in parallel to the element face measured in N (lbf) and A is the cross sectional area measured in m^2 (in^2). To test materials for shear strength, elasticity, toughness etc., samples are placed in a tensile test machine which measures the loads applied to maintain a preset rate of elongation. Figure 2 shows an example curve for a typical material that has been stressed to failure by a tensile test machine. To test for properties in shear, samples are built that cause a tensile force applied by the machine to act in parallel to the element. The horizontal axis represents the applied strain which is the ratio of the change in element length to its original unstressed length. The vertical axis represents the applied stress which is a function of the applied strain.

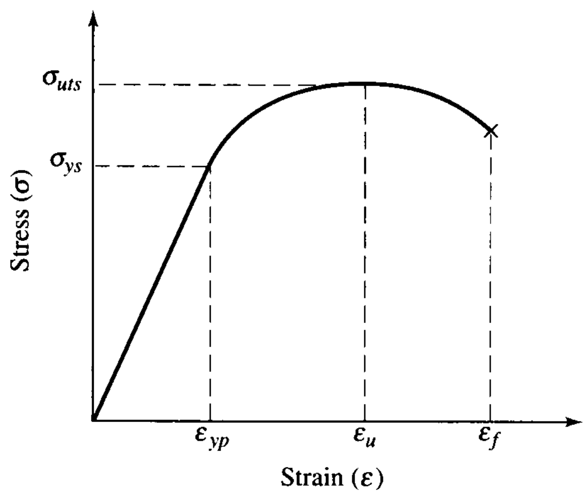

Figure 2. An example stress-strain curve for a typical material.

The linear portion of the curve represents the elastic region. Within this region all stresses are recoverable; that is as long as the applied stress does not exceed the point defined by σ_{ys}, then the element is able to return to its original shape and size. In the elastic region, the stress and strain are directly proportional as shown by the following equation:

$$\tau = G\varepsilon$$

where τ is the applied stress in Pa (psi) and ε is the applied strain. G is the shear modulus of elasticity in Pa (psi). The shear modulus of elasticity represents the stiffness of the material. A material is considered to be stiffer it has a higher shear modulus. A Typical material shear modulus can range from MPa to GPa. Once the stress strain curve reaches the point defined by (ε_{yp}, σ_{ys}), it passes into the plastic region. In this region stresses are no longer recoverable, and the deformation which is created due to the stresses becomes permanent. The stress point σ_{ys}

represents the yield strength which defines the transition stress from the elastic to the plastic region. For most engineering applications the yield strength is used as the driving strength parameter. Typically, products will be designed so that they will encounter stress levels that are orders of magnitude less than the yield strength. This is to ensure that there is no permanent deformation due to normal loading over the service life of a product.

Test Apparatus

The tensile-shear tests were performed at the Texas A&M Aerospace Materials Lab.

Aluminum Tabs

Each epoxy had to be potted into a specimen substrate for use in a tensile test machine. The specimens used for this test are shown below in Figure 3. A drawing with dimensions can be found in the Appendix. The specimens are made of aluminum to replicate the real world VIRUS design of mating aluminum plates. Each specimen was also sandblasted to increase epoxy adherence. For each epoxy a pair of aluminum test specimens were adhered together to form a single rectangular shape. Figure 4 shows a fully cured sample which is ready for testing. The epoxy model name, set date and time, and time to cure was written on the sample for ease of reference.

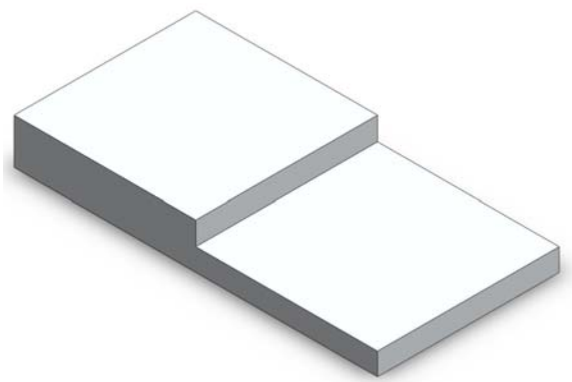

Figure 3. A model of an aluminum test specimen before epoxy is applied.

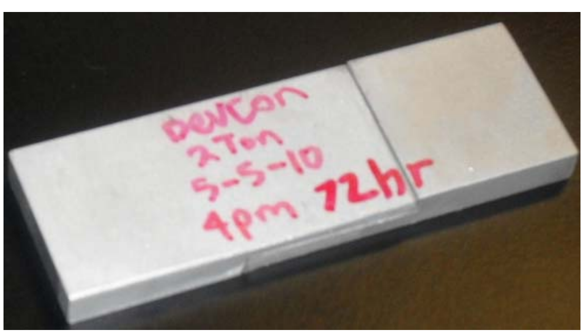

Figure 4. A fully cured epoxy sample ready for testing.

Specimen Cure Fixture

In most cases epoxies were required to cure for a period of 24 hours or more. A specimen fixture was created to maintain the specimen's relative position while the epoxy achieved full cure. The fixture consists of a plate with two clamps machined to fit one sample set. A groove was machined along the face of the plate to align each half the specimen. The clamps screwed directly into the base plate and doubled as a mechanism to squeeze out any excess epoxy. Figure 5 shows the fixture with a sample held in place. During setting, a plastic sheet is placed in between the sample and the fixture to ensure that the two are not adhered to each other.

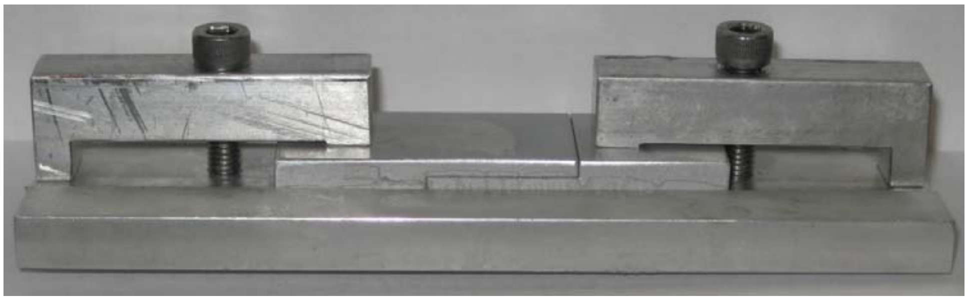

Figure 5. The specimen cure fixture with a sample held in place.

Epoxies

Table 1 shows a summary of the epoxies tested. Some epoxies are manufactured specifically for structural adhesion. These epoxies include 10-3003, ES550, and Devcon 2 ton. The other epoxies are manufactured for optical use, but the vendor data sheets showed that it would be possible to use them for structural applications as well. If a dual purpose epoxy fit the required parameters of both applications, then the overall cost of construction would be decreased and the quality of construction could be increased.

Table 1. A summary of the epoxies tested and their major characteristics.

Model	Manufacturer	1 or 2 part epoxy	Mix Ratio	Room Temperature Cure Time(~25°C)	Elevated Temperature Cure Time
2216 B/A Gray	3M	Two part	5:7 by weight 2:3 by volume	7 Days	2 Hours at 66°C or 30 Minutes at 93°C
2216 B/A Translucent	3M	Two part	1:1 by weight or volume	30 Days	4 Hours at 66°C or 1 Hour at 93°C
10-3003	Epoxies, Etc...	Two part	1:1 by volume	1 Day	30 Minutes-1 Hour at 66°C
ES550	Permabond	One part	N/A	N/A	2 Hours at 100°C, 40 Minutes at 250°C, or 20 Minutes at 300°C
Hysol 1C	LOCTITE	Two part	100:44 by weight 2.5:1 by volume	3 Days	2 Hours at 60°C, 1 Hour at 82°C, or 20-30 Minutes at 121°C
Devcon 2 Ton	Devcon	Two part	1:1 by weight or volume	16 Hours	Not listed
Epo-tek 301-2	Epoxy Technology	Two part	100:35 by weight	2 Days	3 Hours at 80°C

Procedure

Sample Preparation

Samples were prepared at the Astronomical Instrumentation lab. Each sample consisted of a two aluminum tabs which together created a 1 in^2 overlap that was filled with epoxy. The following procedure enumerates the steps taken to create a ready-to-test sample. It is vitally important that the aluminum tabs are properly blasted and cleaned as it greatly affects epoxy adherence and thus bond strength.

1. Sand / glass blast aluminum specimens.
2. Clean specimens thoroughly using warm water, degreaser, and industrial soap as needed.
3. Set the bottom half of the aluminum sample into the sample fixture. Be sure to place a plastic sheet between the sample and the fixture to prevent adherence.
4. Mix the candidate epoxy according to its data sheet and MSDS.
5. Apply epoxy to surface of both halves of the aluminum sample.
6. Press the top half of the aluminum onto the bottom half of the aluminum sample. Push the parts together along the length to squeeze extra epoxy out. Tighten the clamp until the parts are fully meshed.
7. Clean excess epoxy from the sides and top.
8. Cure the epoxy in the fixture according to the epoxy data sheet and MSDS. If heating is required, allow the epoxy to set for 24 hours before oven curing.

9. After cure remove the sample and use sand paper to clean off any epoxy residue from the joints.

Sample Testing

The tensile shear tests were performed at the TAMU Aerospace Materials Testing Lab in the Bright basement. The lab charges $35.00 per hour that the machine is running. The following procedure details how to operate the MTS Tensile Tester.

1. Turn MTS Tensile Tester on.
2. Ensure that the 30 kN load cell is installed.
3. Log into Test Works 4. The log in name is MTS and has no password.
4. Select the test method titled, "MTS Simplified Tensile - VIRUS Epoxy.msm." This test method has been specifically developed for this experiment.
5. Record the time of the test and the epoxy being tested.
6. Measure and Record the length, width, and thickness of the sample at the epoxy interface.
7. Load the epoxy sample into the load cell. The manual control remote can be activated by pushing the unlock button on the remote. The unlock button is a picture of an open padlock. If the unlock button does not light up green, click the "Motor Reset" button in Test Works 4 then re-press the unlock button on the remote.
    a. Clamp the bottom half first and ensure that the clamp is holding a roughly 1 in length of the sample.
    b. Clamp the top half by jogging the clamp into place. Ensure that a roughly 1 in length of sample is held in the top clamp as well.
    c. Record the grip space between each clamp. The grip space is measured as the distance between the inner edges of the clamps.
8. Use the remote to jog the now loaded load cell until the applied force on the heads up display of Test Works 4 reads as close to 0 N as possible.
9. Zero the crosshead and extension windows on Test Works 4 by right clicking in the respective windows and selecting "Zero Channel."
10. In the test parameter window, change the "Grip Space" value to the measured grip spacing from 6.c
11. In the test parameter window, change the "Crosshead Speed" value to 0.001 in/min.
12. Click the green arrow in Test Works 4 to begin the test. The machine will run until it detects a break or until the load cell limit is reached.
13. Export the data to Microsoft Excel.

Data Reduction

The output data file contains the cross head position as well as the load obtained at each instance of strain. These two sets of values are used to calculate stress and strain. Strain is found by dividing the cross head cell value by the initial measured grip space as shown by the following equation:

$$\varepsilon = \frac{\Delta l}{l^*} = \frac{Cross\ Head}{Grip\ Space}$$

As long as both the cross head and grip space values are in the same unit of measurement then the unit is irrelevant. The applied stress is calculated by dividing the force value by the affected area as shown by the following equation:

$$\tau = \frac{F_{//}}{A} = \frac{Measured\ Force}{Epoxy\ Tab\ Area}$$

The measured force is given in N by the machine and the epoxy tab area is machined to 1 in^2. Plotting shear stress as a function of applied strain creates the stress-strain curve which shows the characteristic strengths and stiffness's of each epoxy.

Results and Discussion

Qualitative Results

As seven different epoxies were tested, qualitative observations were made of unique factors that each epoxy exhibited. Properties such as initial color of the individual components before mixing, as well as viscosity and color of the epoxy after mixing were noted. All of the epoxies contained bubbles once mixed, and most of them became quiet warm due to the exothermic chemical reactions that take place. All were very messy to work with, some of the liquidous ones more so than others. All of the epoxies were able to be applied to the aluminum samples, cured in the expected amount of time, and yielded excellent test results. The qualitative results for the candidates are as follows:

Devcon 2 Ton's components had initial colors of light yellow and clear. The color of the mixed epoxy was translucent amber and it was viscous, similar to thick syrup.

For Epo Tek 301-2, the initial colors for both components were clear, as was the final mixture. The epoxy was quite liquidous and easy to spread on the aluminum sample.

3M's 2216 B/A Translucent had one honey colored and one clear component. The mixture was a tan color and was very liquidous.

Permabond's ES550 was the only one-part epoxy tested. Its initial color was dark metallic grey. It was extremely viscous.

The components of Hysol 1C were white and brown and were very viscous once mixed. The texture was paste-like with an off white color.

3M's 2216 B/A Gray had components of tan and grey color. The final mixture was a solid grey color and was liquidous.

Epoxy 10-3003 had initial colors of translucent gold and clear. The mixture was viscous like honey and was a translucent gold color.

Shear Test Results

For each Epoxy tested, the yield strength was recorded using the initial break method and the 0.2% offset method. The failure strength as well as the shear modulus was also found. Table 2 shows the summary of these findings. The Appendix contains the stress-strain curves for each epoxy tested.

Table 2. Characteristic data of each epoxy candidate. Dashed lines mean no point was found.

Epoxy	Shear Modulus, MPa	0.2% Yield Stength, Mpa	Yield Break Strength, Mpa	Failure Strength, Mpa
Devcon 2 Ton	962	1.92	2.54	3.8
Epo Tek 301-2	877	2.7	2.91	4.6
3M 2216 B/A Translucent	800	1.62	2.19	3.23
Permabond ES550	898	7.08	9.61	10.3
Loctite Hysol 1C	718	-	-	3.06
3M 2216 B/A Gray	401	-	-	5.23
T10-3003	982	3.13	3.59	5.84

Devcon 2 Ton

The Devcon 2 Ton data sheet claims that the cure time is 12 hours. However, first round tests showed that the epoxy actually needed cure times in excess of 48 hours. Most epoxy of this strength rating have 48-72 hour setting time as well so this is not necessarily a large problem. The epoxy had an average shear modulus of 962 MPa making it the second stiffest epoxy joint amongst the candidates tested. Under operating conditions this means that the epoxy would have little deflection over a wide range of loads. Once in the plastic range, the epoxy exhibited a linear stress-strain relationship. This indicates that joint failures in practice can detectable and predictable.

Epo Tek 301-2

301-2 was tested as a possible hybrid epoxy that could be used for both optical and structural adhesion. It was found that the epoxy had moderately high stiffness, but exhibited strength characteristics similar to the uniquely structural epoxies. The epoxy had a linear elastic and plastic region which may facilitate detection and prediction of joint deflections or failures.

3M 2216 B/A Translucent

3M 2216 B/A Translucent was originally intended for optical use only, but was then tested for possible optical-structural use. It was found that the epoxy had medium stiffness which makes it a good candidate for optical use. However, it was also found that the epoxy had relatively low yield strength of 1.62 MPa. The epoxy experienced a relatively large strain of ~0.02 while only achieving a relatively low stress. This means that 2216 B/A translucent is ductile in comparison to the other structural epoxies. From preliminary testing this epoxy should only be used for optical applications.

Permabond ES550

Of the epoxies tested, ES550 was the only one part epoxy that required elevated temperature to cure. This would make structural assembly of large components difficult since the only cure method available is a heat gun which would increase cure time and decrease the uniformity of full cure properties throughout the epoxy pot. However, the epoxy exhibited both high stiffness and high strength which make it an ideal candidate from a joint quality stand point.

Loctite Hysol 1C

Like the 3M epoxies, Hysol 1C was tested for use as both a structural and optical epoxy. Unlike other candidates, Hysol 1C exhibited an extremely linear stress-strain relationship. The shear test produced no noticeable yield point which would make predicting deformation or failure extremely difficult in most cases. The lack of a distinguishable yield point combined with the low failure strength of 3.06 MPa render Hysol 1C incapable of handling true structural situations.

3M 2216 B/A Gray

2216 B/A Gray presented similar strength performance characteristics to Hysol 1C. It exhibited a linear stress-strain relationship, but had no noticeable yield point. However, the failure strength was higher than Hysol 1C while the stiffness was lower. The quickness of the failure suggests that the material is brittle.

T10-3003

T10-3003 exhibited high strength and stiffness characteristics. It is not as strong as ES550 but is more workable because it comes in a dual syringe dispenser and will cure at room temperature. Plastic and elastic regions exhibited linear behavior which facilitates predicting deformation or failure. The viscosity allows the epoxy to easily fill spaces without being difficult to handle.

Summary

- It was found that T10-3003, Permabond ES550, Devcon 2 Ton, and Epo Tek 301-2 presented the best combination of strength and stiffness.
- It was found that Epo Tek 301-2 is the only possible candidate to be used for both optical and structural applications.
- It was found that Loctite Hysol 1C and 3M epoxies are insufficient for use as structural epoxies.

Recommendations

- Population tests should be conducted to determine the best structural epoxy of the four epoxies that have adequate structural performance.
- Further strength tests should use a redesigned aluminum tab to better isolate stresses to shear stress only.
- Strength tests should be conducted for different bond line thicknesses and for different mix ratios.

References

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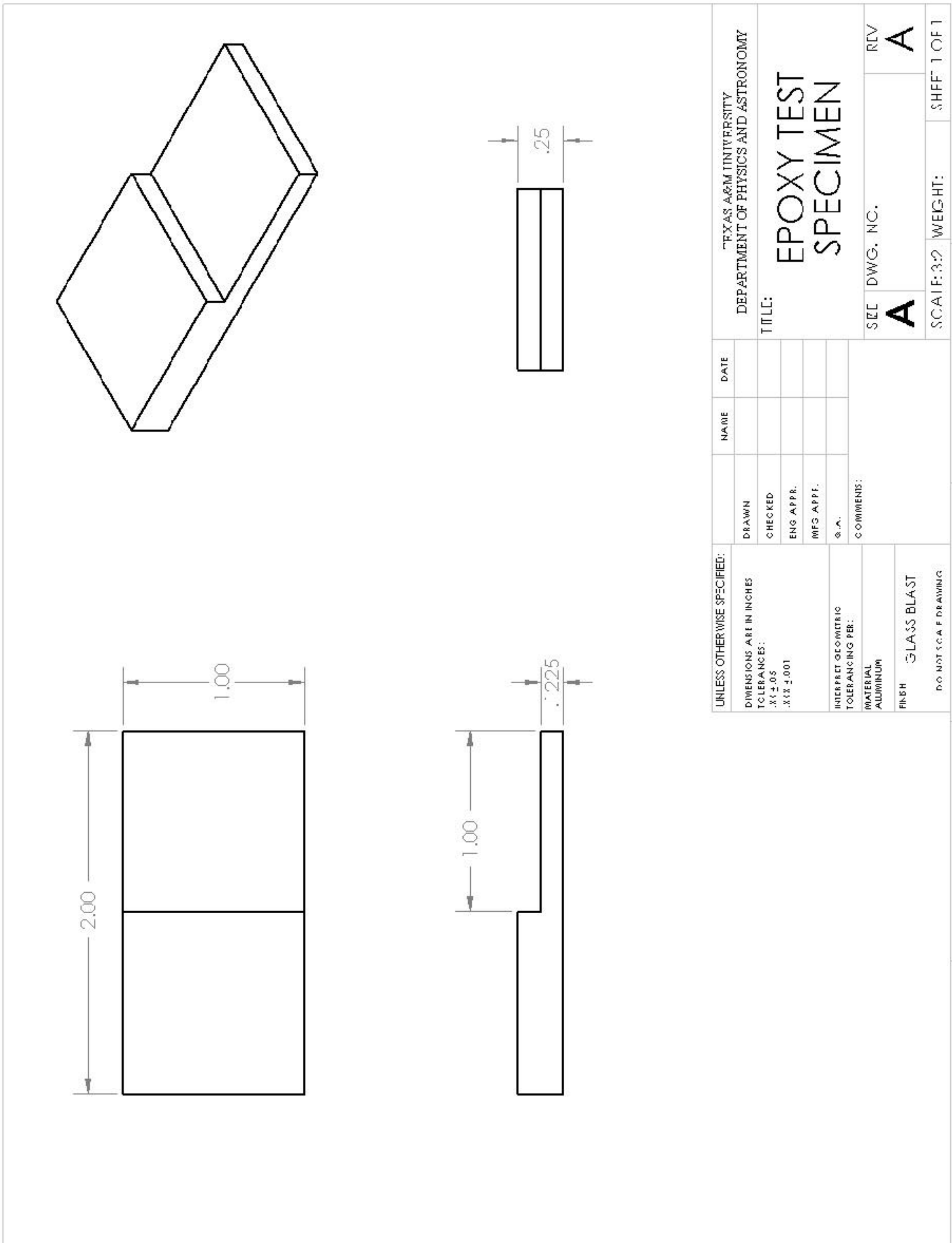
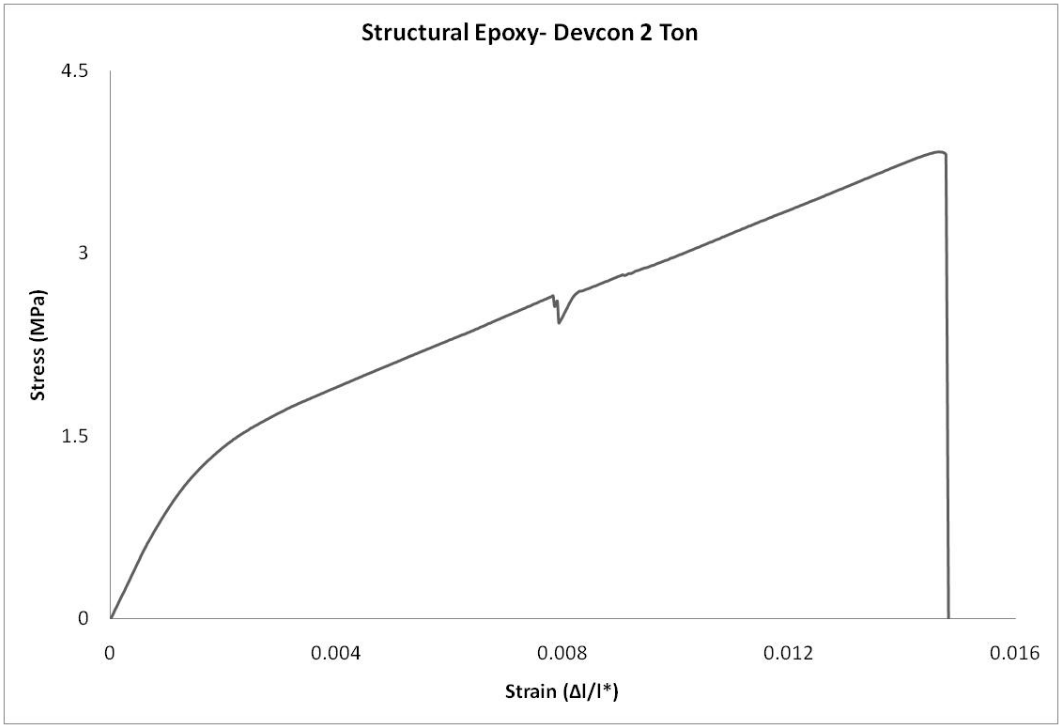
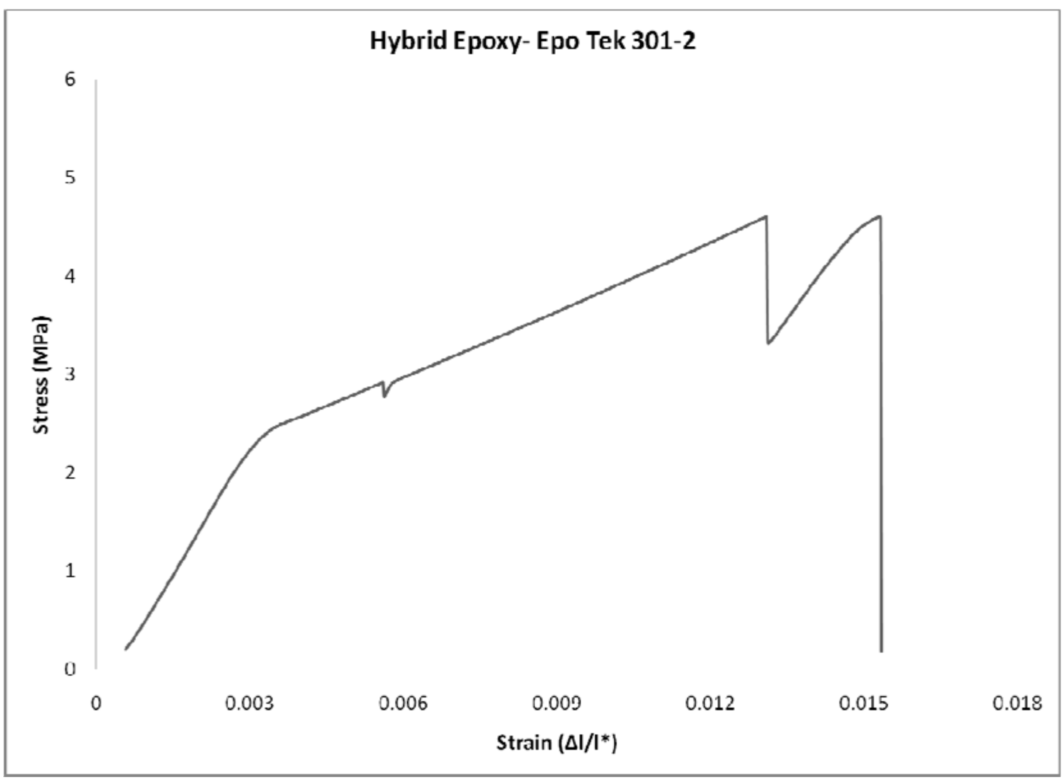
7. "Permabond ES550." *Permabond*. Permabond. Web. 05 Feb. 2010. <www.permabond.com>.

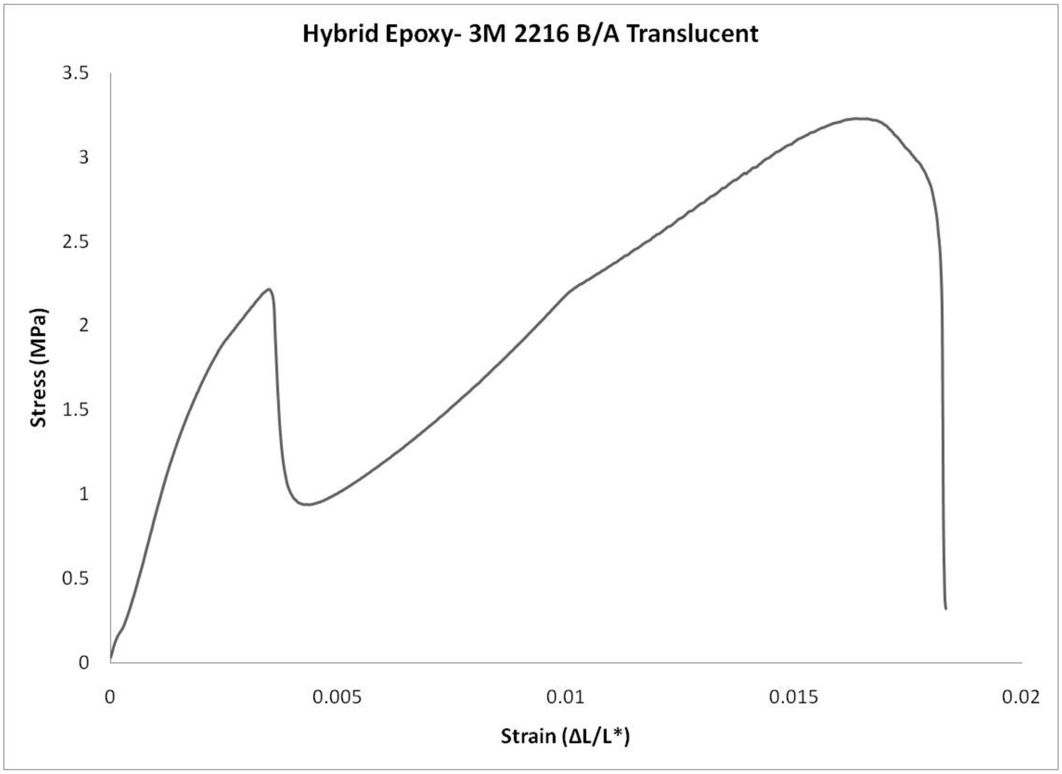
Appendix B- Sample Drawings

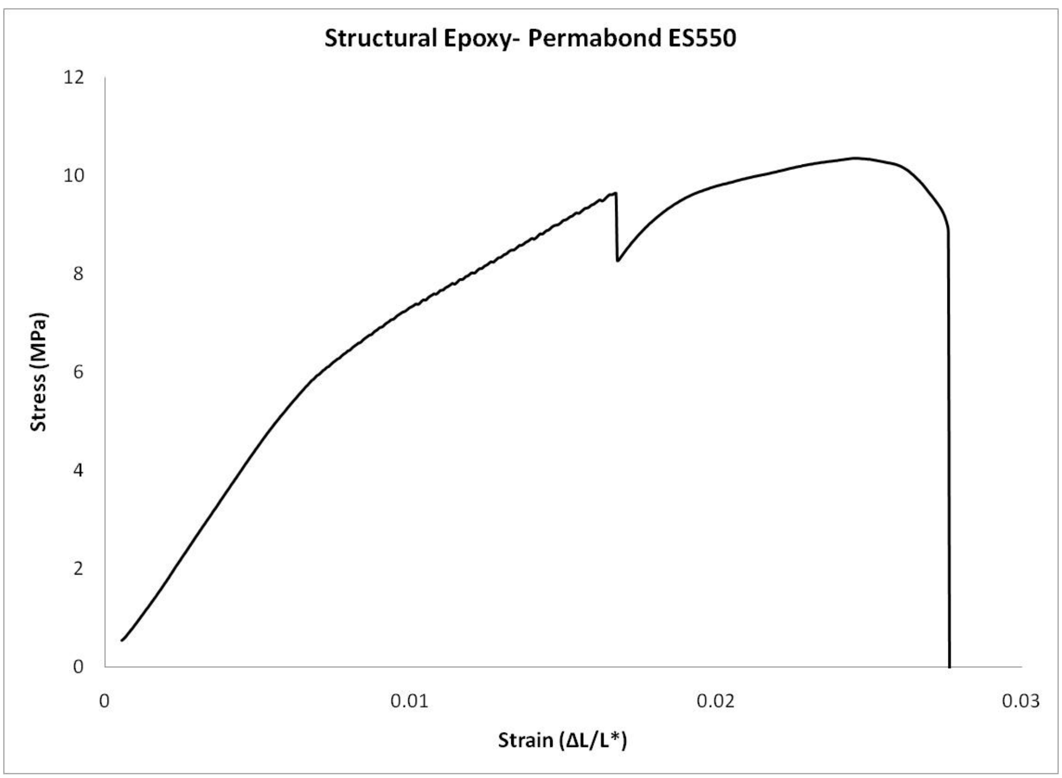


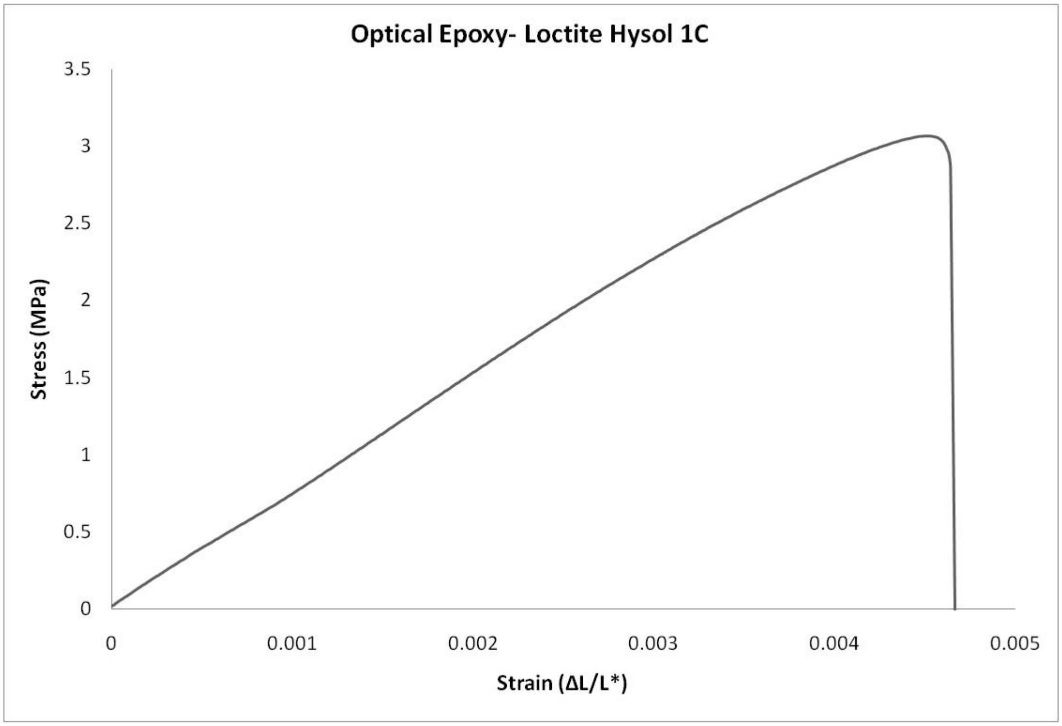
Appendix B- Epoxy Stress Strain Curves

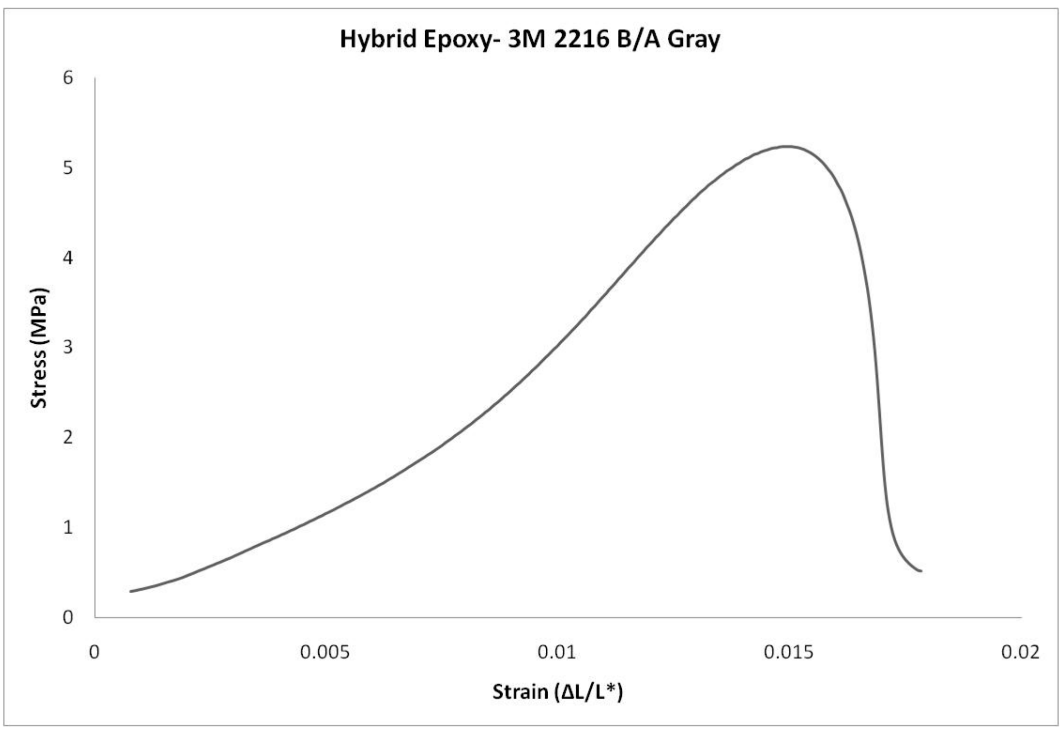





Hybrid Epoxy- 3M 2216 B/A Translucent
Stress (MPa)
Strain (ΔL/L*)
0
0.5
1
1.5
2
2.5
3
3.5
0
0.005
0.01
0.015
0.02


Structural Epoxy- Permabond ES550
Stress (MPa)
Strain (ΔL/L*)
0
2
4
6
8
10
12
0
0.01
0.02
0.03


Optical Epoxy- Loctite Hysol 1C
Stress (MPa)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.001
0.002
0.003
0.004
0.005
Strain (ΔL/L*)


Hybrid Epoxy- 3M 2216 B/A Gray
Stress (MPa)
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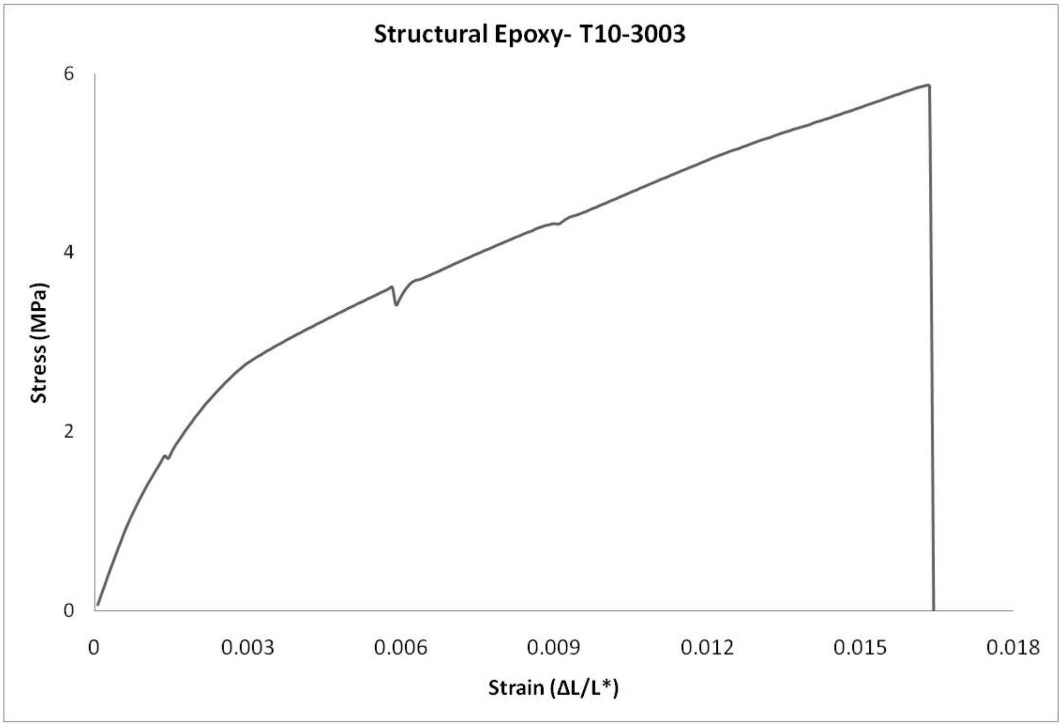
5
4
3
2
1
0
0
0.005
0.01
0.015
0.02
Strain (ΔL/L*)


Structural Epoxy- T10-3003
6
4
2
0
Stress (MPa)
0
0.003
0.006
0.009
0.012
0.015
0.018
Strain (ΔL/L*)