Experimentally Characterizing Shear Strength of Structural Adhesives With Varying Surface Preparations

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Structural epoxies are commonly used in aerospace-grade manufacturing for adhesion for a variety of reasons, including convenience and bond strength. The strength of the epoxy bond in shear is impacted by multiple factors including surface preparation and material properties. This paper presents an experimental process to determine an effective surface preparation method for producing sufficiently strong shear bonds of structural epoxy to support Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club (RRC) at the Georgia Institute of Technology. The authors also present a novel method for surface preparation, wherein sanding is performed over uncured epoxy. The specific materials tested were woven fiberglass laminate (G10), steel, and aluminum in two different combinations: aluminum bonded with aluminum and steel bonded with G10. All pairings underwent three different surface preparations: dry sanding, wet sanding, and epoxy wet sanding. Additionally, each combination was prepared with two epoxy systems: J-B Kwik Weld and Proline 4500. The specimens underwent a single lap shear test loaded in compression on an Instron 5982 load frame. The experimental shear strength of each specimen was calculated and compared to the values provided by epoxy manufacturers. The experimental shear strengths varied from those estimated from manufacturer data sheets. Dry sanding had a higher mean shear strength for the tested epoxies when used for aluminum on aluminum. For G10 bonded with steel, wet sanding had a higher mean shear strength for J-B Kwik Weld, while epoxy wet sanding had a higher mean shear strength for Proline 4500. The results of this experiment will aid in future manufacturing of GTXR vehicles by ensuring that the preparation process chosen for flight components experiencing loads at supersonic and subsonic speeds produces sufficiently strong bonds for expected loads.

I. Nomenclature

A = bonded surface area
l = length of bonded area
w = width of bonded area
F = applied force
$\tau_{strength}$ = shear strength

II. Introduction

Epoxy is widely used throughout the aerospace manufacturing industry for its versatility in applications, such as bonding joints. Factors such as high adhesion strength and low residual stress of thermoset polymers make epoxy an attractive option for a quick, cost-effective, durable bond [1][2]. The epoxy bond strength provided by the manufacturer is often a deciding factor in choosing between epoxies for an application. This value, provided by a manufacturer data sheet, is derived from industrial strength tests under conditions that are not easily replicated by the average consumer. Furthermore, these tests are often limited to tensile and compressive strengths, not shear. Importantly, bonds in shear

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[§] Undergraduate Student, Daniel Guggenheim School of Aerospace Engineering, sdea3@gatech.edu, AIAA University Student Member 1603529 adhered with epoxy rely heavily on epoxy strength. The scope of this experiment focuses on shear bonds because of their prevalence in aerospace vehicles, such as the vehicles created by GTXR including *Fire On High* [3], *Material Girl* [4], and *Strange Magic*. In addition to the material properties of an epoxy, a crucial indicator of bond strength is the preparation of the surface, as it determines the condition of the boundary/surface interaction between the material and the epoxy. An incorrect expected strength can decrease the factor of safety without users realizing it, leading to possible deformation and tearing. The preferred failure for the epoxy would be cohesive failure, as the epoxy itself would break and indicate a strong bond between the epoxy and the bonded surface [5]. Poor or insufficient surface preparation, however, would lead to adhesive failure and result in the shear bond not withstanding the expected shear forces [5].

This experiment presents a method for characterizing epoxies based on shear strength using a single lap shear test while taking into account multiple surface preparations. Multiple 2.4 x 1.2 inch tabs of steel, G10, and aluminum were tested in two different combinations—aluminum bonded to aluminum and steel bonded to G10—all undergoing dry sanding, wet sanding, and epoxy wet sanding as surface preparations.

The specific material pairings selected for this process were based on structural components of the upcoming GTXR flight vehicle, *Live and Let Fly*. Aluminum-aluminum bonds are present in the rail guides, which are made of aluminum and used to hold the rocket to the launch rail. Additionally, other exterior components such as the 3D printed polyethylene terephthalate glycol (PETG) shrouds that protect the GPS and telemetry antennas from aerodynamic and thermal forces are attached to the carbon fiber airframe and loaded in shear by drag. Not to mention, the fins of *Live and Let Fly* are canted by 1.5 degrees, which causes the entirety of the sustainer to spin at up to 1020 rpm. The rotation causes additional aerodynamic forces on the shroud in the tangential direction which loads it in shear as well. GTXR had considered adding steel leading edges to the G10 fins for future vehicles to protect the carbon fiber from thermal heating and ablative forces, which is why the authors decided to test steel in a shear bond with G10. The fins are especially important because misalignment in the placement will cause the leading edge to be loaded in shear and would rely on the strength of the epoxy. It is important to characterize the bond strength resulting from different surface preparations in order to ensure that these crucial parts are sufficiently strong. The authors are interested in characterizing the epoxy surface preparation procedure that provides sufficiently strong bonds, which are the ones that have the most verified factor of safety, to use for the components that have been mentioned throughout this paper.

The surface preparations were chosen to address different concerns that arise during the epoxying process. Dry sanding is the most common and simplest form of surface preparation due to the usage of only a few relatively low-grit (60-120 grit) sandpapers [6]. Wet sanding works well with metals because it prevents an oxidation layer from forming on the surface of the sanded piece, thus creating a stronger bond as the epoxy adheres directly to the metal instead of the newly formed metal oxide [6]. Wet sanding also generally creates less dust, improving respiratory safety.

Epoxy wet sanding is a new surface preparation that is conceptually similar to regular wet sanding. Instead of sanding with sandpaper and a surface wetted with water, epoxy wet sanding requires the user to sand with sandpaper and a surface "wetted" with uncured epoxy. Sanding with the uncured epoxy prevents the oxidation layer from forming on the metal without having to quickly wipe off the thin layer of water before applying more epoxy. Thus, it prevents a short amount of time in which the metal is exposed to air and has the potential to oxidize. The authors also theorize that epoxy wet sanding pushes the epoxy deeper into the grooves of the sanded surface, reducing the number of vacancies within the bond.

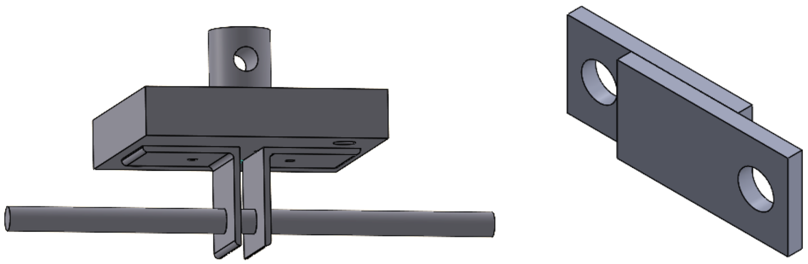
III. Experimental Setup

The experiment was set up in two main stages: surface preparation and Instron testing. For surface preparation, each half of the test article was sanded and epoxied to the corresponding other half according to the assigned surface preparation. Multiple custom Instron fixtures were designed before constructing the final fixture that properly applied a shear force on each specimen. The cured specimens were placed into these new fixtures and compressed until adhesive failure.

A. Manufacturing and Design

Simple test articles made of steel, G10, and aluminum were constructed with a water jet. Each test article was 1.2 inches by 2.4 inches with a 0.5 inch diameter hole as shown in Fig. 1b. These articles were adhered together with the respective epoxies and then were used as single lap shear test articles.

Multiple Instron fixtures were constructed before an effective test fixture was found. The initial fixtures were zero tolerance, inducing unwanted axial tension in the direction normal to the plane of the epoxy and causing the test article to experience shear before load was applied with the Instron. The next iteration of the Instron fixture introduced a degree



(a) (b)

Fig. 1 Computer Aided Designs (CAD) of a) final Instron fixture and b) adhered test articles.

of freedom in testing to isolate the lap shear force; however, unwanted tensile stress throughout the fixture, especially in the brackets, caused this design to fail.

The final fixture design (Fig. 1a) was successful, for it mitigated unwanted stresses within the fixture, and the applied force was focused on the horizontal bar and the test piece. The final iteration of the Instron attachments included a 5-by-5 inch aluminum base plate with 2 inch wide L-brackets that contained a 0.5 inch diameter hole 1.375 inches from the base of the brackets, in addition to a 0.5 inch diameter, 10 inch long steel carriage bolt through each bracket. The two L-brackets were placed 0.5 inches apart from each other and were aligned with the center of the base plate. The carriage bolt was chosen for its large tensile strength of 60,000 psi, since the bolt would not be affected by the lower tension values estimated to be exerted on the bolt itself. The larger width L-brackets were chosen to allow for more material on the sides of the 0.5 inch hole for the bolt, as the initial bracket borders were very close to the hole and snapped while testing the attachment's durability.

The single lap shear test was switched from one in tension to one in compression over concerns that the materials available to use for constructing the Instron fixtures, as well as the specimens themselves, would not withstand the estimated tensile forces experienced during each trial. These concerns arose during test trials after the Instron fixtures continued to fail in tension despite structural improvements and the presence of significant deformation of the specimens localized around the holes. There was a risk of the specimens buckling under compression; however, with precise alignment, relatively small specimens, and multiple test trials before implementation into the experiment, buckling and other unwanted deformations did not occur during the experiment's trials under compression. The single lap shear test does not have to be run under tension to still be a viable test for experimentally determining shear strength values [7].

B. Surface Preparation Procedure

In this experiment, three types of surface preparations were tested. The first preparation was traditional dry sanding. For this method, a test article was sanded with an 80-grit sanding block, followed by a 120-grit sanding block. Once the final pass of sandpaper was completed, the test article was cleaned with isopropyl alcohol (IPA) to remove dust and oils. The second preparation was wet sanding. Similarly to dry sanding, each piece was sanded with 80-grit and 120-grit dry sanding and cleaned with IPA. After this, 1000-grit sandpaper was wetted with water, and then the test articles were sanded for approximately forty-five seconds. The article was once again wiped with IPA to remove any new particles or remaining water and was immediately epoxied. The final surface preparation was epoxy wet sanding. This method also starts with an 80-grit sanding block followed by a 120-grit sanding block with standard dry sanding methods and cleaned with IPA. The epoxy of choice was then applied in equal amounts to both halves of the test article that were being adhered. This uncured epoxy was then sanded with 800-grit sandpaper until it was evenly distributed and became more viscous and the two pieces were immediately attached. All specimens were promptly vacuum-bagged and placed into the vacuum chamber to ensure consistent pressure throughout the appropriate cure time as given by the epoxy manufacturers. Immediately after placing each specimen in the vacuum bag, the halves were manually adjusted to ensure that they stayed parallel. The specimens were adjusted again immediately after pulling a vacuum to verify that the vacuum did not shift the halves.

C. Instron Procedure

Before testing, each sample was measured for its wetted length (l) and width (w) and entered into a data table. The test piece was then placed on an Instron 5982 load frame and secured on the fixture with a 0.5 inch diameter, 10 inch long steel carriage bolt as seen in Fig. 2. The specimen was checked to ensure that it was directly perpendicular to the bolts. The bolt threads were used to keep the specimen from sliding on the bolt after checking its placement. Once in place, the machine was turned on and zeroed. The articles were compressed at a rate of 0.1 mm/s until failure. The maximum force at failure, F was recorded for each article before removing the fragments from the machine. The bolts were inspected after each test for deformation.

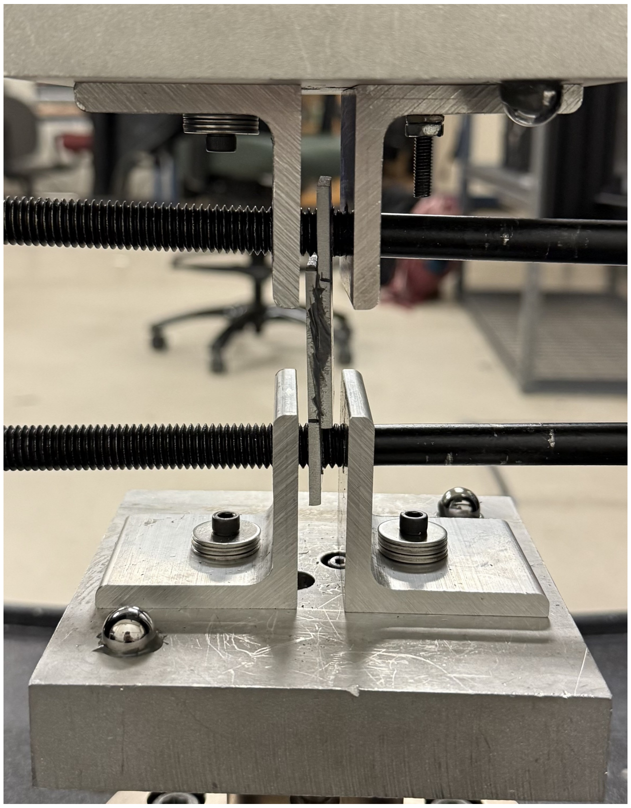


Fig. 2 Instron 5982 Setup

IV. Results

Surface Preparation	Sander 1	Sander 2	Sander 3	Mean	Standard Deviation
Dry Sanding (psi)	2078.37	2184.72	2479.97	2247.69	169.89
Wet Sanding (psi)	2565.61	2184.15	1971.59	2240.45	245.75
Epoxy Wet Sanding (psi)	1390.22	2139.385	2188.78	1906.13	365.36

Table 1 Aluminum bonded to aluminum with J-B Kwik Weld shear strength values (psi).

Surface Preparation	Sander 1	Sander 2	Sander 3	Mean	Standard Deviation
Dry Sanding (psi)	2295.21	1980.29	2221.25	2165.59	134.46
Wet Sanding (psi)	436.50	2405.59	974.54	1272.21	830.98
Epoxy Wet Sanding (psi)	1972.605	1720.66	2186.24	1959.84	190.29

Table 2 Aluminum bonded to aluminum with Proline 4500 shear strength values (psi).

The area (A) was calculated with the l and w values measured before placing the specimen into the Instron load frame. The shear strength ($\tau_{strength}$) was computed using Equation 1.

$$\tau_{strength} = \frac{F}{A} \tag{1}$$

In all results tables, the "Sander" columns indicate which of the three people doing the sanding obtained that shear strength. Each table presents the shear strength in psi of the three surface preparations across the three people sanding, as well as the mean and standard deviation of the shear strengths obtained.

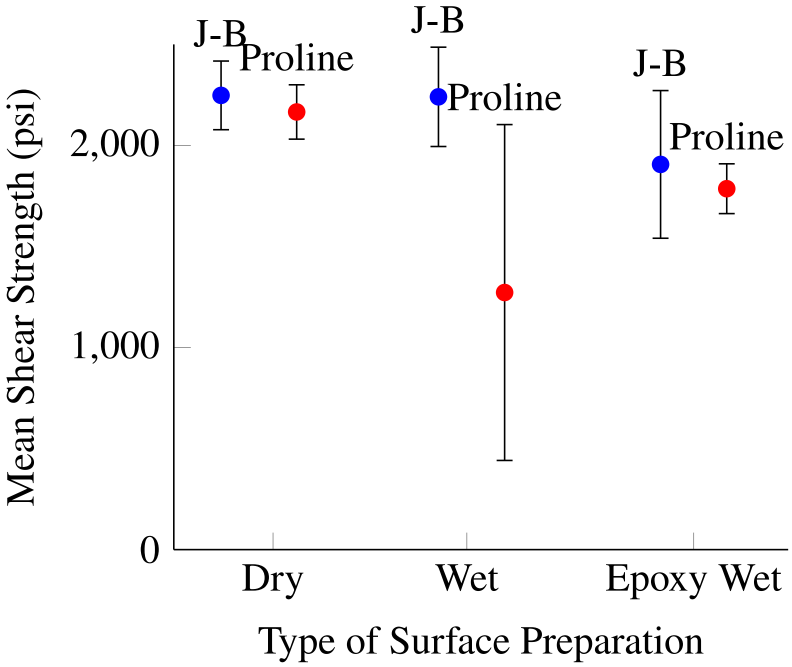


Fig. 3 Mean Shear Strengths of J-B Kwik Weld and Proline 4500 Bonding Aluminum to Aluminum

Surface Preparation	Sander 1	Sander 2	Sander 3	Mean	Standard Deviation
Dry Sanding (psi)	1619.85	2137.92	1731.28	1829.69	222.65
Wet Sanding (psi)	2271.50	1753.56	1831.68	1952.25	227.99
Epoxy Wet Sanding (psi)	1900.60	1614.96	1842.03	1785.86	123.19

Table 3 G10 bonded to steel with J-B Kwik Weld shear strength values (psi).

Surface Preparation	Sander 1	Sander 2	Sander 3	Mean	Standard Deviation
Dry Sanding (psi)	994.95	1063.88	1206.96	1088.60	88.30
Wet Sanding (psi)	1000.68	1450.37	1193.03	1214.70	184.22
Epoxy Wet Sanding (psi)	1436.96	1310.80	1323.66	1357.15	56.68

Table 4 G10 bonded to steel with Proline 4500 shear strength values (psi).

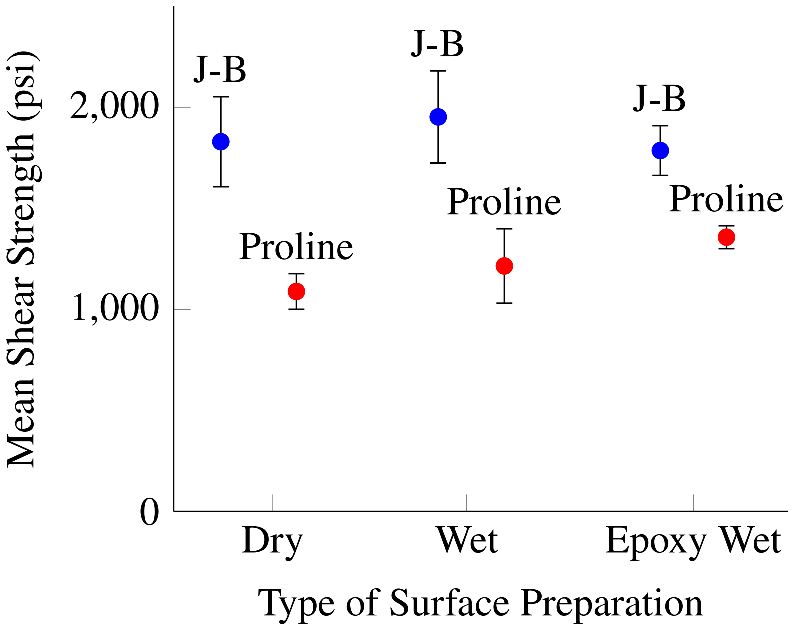


Fig. 4 Mean Shear Strengths of J-B Kwik Weld and Proline 4500 Bonding Steel to G10

V. Discussion

Table 1 presents the shear strength values obtained for aluminum bonded to aluminum with J-B Kwik Weld, with dry and wet sanding producing very similar mean shear strengths. Epoxy wet sanding with this combination had a lower mean shear strength, but a larger standard deviation in comparison to the other surface preparations. The larger variance may be due to the inability to control how much J-B Kwik Weld remained on the halves of the test pieces during epoxy wet sanding, as J-B Kwik Weld is a relatively thick epoxy and was removed by the sandpaper while sanding. Comparatively, Table 2 presents the shear strength values for aluminum bonded to aluminum with Proline 4500. Wet sanding for this combination varied substantially, indicating great error during the surface preparation and epoxying process, considering the relatively low variance in the dry and epoxy wet sanding shear strengths. Figure 3 displays the mean shear strengths and one standard deviation of each surface preparation for both epoxies tested for aluminum bonded to aluminum. The authors plan to retest the aluminum bonded to aluminum with Proline 4500 and wet sanding to investigate the unacceptably large standard deviation and produce a more accurate range of shear strength values for this combination.

Table 3 displays the shear strength values for steel bonded to G10 with J-B Kwik Weld. The mean shear strength values are relatively close with relatively small variance in strength. In comparison, Table 4 presents the shear strength values obtained with steel bonded to G10 by Proline 4500. The mean shear strengths are also relatively similar, with dry sanding and epoxy wet sanding having distinctly small variances in shear strengths across the three sanders. As with aluminum bonded to aluminum, figure 4 displays the mean shear strength and one standard deviation of each surface preparation and both epoxies tested for steel bonded to G10.

Through inspection of the specimens after the completion of testing, it is apparent that each J-B Kwik Weld bond for both material combinations, failed cohesively, while Proline 4500 failed adhesively. This indicates that the applied surface preparations of basic dry sanding, wet sanding, and epoxy wet sanding are not substantial enough to provide the bonding surface that Proline 4500 requires to reach its maximum shear strength.

Neither manufacturer of J-B Kwik Weld nor Proline 4500 directly list the shear strength of their product; however, using the von Mises criteria (Eq. 2), shear strength can be approximated as $1/\sqrt{3}$ of tensile strength [8]. Using this relationship and the tensile values provided by the manufacturers, the shear strength of J-B Kwik Weld is approximately 1876 psi; which suggests the test article is undergoing cohesive failure since the resulting shear strength was similar to the epoxy properties. The shear strength of Proline 4500 is approximately 5700 psi, which suggests adhesive failure since the bond failed long before the epoxy structurally failed.

$$\tau_{strength} = \frac{\tau_{yield}}{\sqrt{3}} \tag{2}$$

When sanding metal, a metal oxide layer is created once the surface is exposed to air which can interfere with bonding between materials. Instead of the raw materials being in contact, the oxide layers are adhered together [6]. By wet sanding with water, the water coats the piece of metal, preventing it from oxidizing, thereby creating a more direct contact between the epoxy and metal. Epoxy wet sanding was theorized to be best for composite materials due to the texture. Most composites such as G10 have rough grooved surfaces even after sanding. Therefore, by sanding with epoxy, the user is ensuring the epoxy gets into the small crevices, theoretically preventing voids in contact. Based on the results from the experiment, it appears that there might be a slight improvement in performance for wet sanding compared to dry and epoxy wet sanding, but not large enough to be significant according to a standard t-test. Thus when taking into account time, resources, labor, and raw data, standard dry sanding with J-B Kwik Weld is the preferred option for bonds between aluminum components. For G10 and steel bonds, wet sanding produced slightly better results when using J-B Kwik Weld. If one were to use Proline 4500 for a G10 and steel shear bond, epoxy wet sanding produces the stronger bond. However, the results show that Proline 4500 is not the recommended epoxy for this application, rather J-B Kwik Weld is a safer option.

Overall, J-B Kwik Weld seems to be the better choice of epoxy for the specific uses of aluminum with aluminum and G10 with steel bonds when utilizing common surface preparations. Typically, Proline 4500 is used for its thermal properties and viscosity to create fillets, and is a relatively brittle epoxy once dried. This results in a weaker shear strength despite having a higher tensile strength. It does appear that the results are based on the individual who did the sanding, therefore skill and human factor does impact this test more than previously assumed. Despite following the same procedure, including using sandpaper from the same original piece, there is still a large amount of variance between individual test articles. For certain trials, three vastly different strengths were recorded such as wet sanding aluminum with Proline 4500. Through this combination the difference between each trial was off by a factor of two. This variability stems from three different sanders each producing one specimen per combination, which may be overcome by either reducing the number of sanders to one person, or by increasing the quantity of specimens per combination per sander. This would allow a better comparison between specimens under each sander to eliminate this variance. There may also be some error in this experiment based on the materials used. For sustainability purposes, the researchers used spare aluminum and steel to create the test articles. These materials were stored outside prior to their use in this experiment. Due to this, there was uneven weathering of the multiples pieces of the steel stock used which emphasized the importance of surface preparation to the epoxying process. Through proper surface preparation, a fresh layer of material was obtained, allowing the results of this test to still be accepted. By using spare stock, the authors also do not know for certain the grade of the materials used in this experiment. The shear strength values obtained from this test can be used as a range of realistically attainable strengths, rather than a singular value assumed to be attainable in every bond.

VI. Conclusion

The purpose of this test was to experimentally characterize the shear strength of bonds between varying materials based on the style of surface preparation and type of epoxy. The results from this experiment showed that when taking into account time, resources, and calculated strengths for aluminum-aluminum bonds, J-B Kwik Weld with dry sanding was the preferred combination. For steel and G10, wet sanding with J-B Weld was the preferred combination of tested materials. This experiment showed that Proline 4500 paired with basic surface preparation is not as strong in shear strength as J-B Kwik Weld. To continue investigation of this experiment, this test will be run with additional trials with the same individual sanding to eliminate human error between trials. This will provide more data to compare against current data to reaffirm this experiment's conclusion. Additionally, this experiment will investigate more varieties of surface preparation in order to increase the adhesive strength of the Proline 4500 to the material combinations, in the hopes of finding the range of Proline 4500's actual shear strength. Additional material combinations such as PETG bonded with carbon fiber and Formlabs Rigid 10K Resin bonded with carbon fiber will be tested, as these material combinations are planned to be used for current and future vehicles of GTXR, and the organization wants to have a valid range of shear strength values before implementing these elements.

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References

[1] Jin, F.-L., Li, X., and Park, S.-J., "Synthesis and application of epoxy resins: A review," *Journal of Industrial and Engineering Chemistry*, Vol. 29, 2015, pp. 1–11. https://doi.org/https://doi.org/10.1016/j.jiec.2015.03.026, URL https://www.sciencedirect.com/science/article/pii/S1226086X15001033.

[2] Sukanto, H., Raharjo, W. W., Ariawan, D., Triyono, J., and Kaavesina, M., "Epoxy resins thermosetting for mechanical engineering," *Open Engineering*, Vol. 11, No. 1, 2021, pp. 797–814. https://doi.org/doi:10.1515/eng-2021-0078, URL https://doi.org/10.1515/eng-2021-0078.

[3] Garud, P., and Lagares de Toledo, A., "Fire on High Launch Report," Tech. rep., Ramblin Rocket Club, 2024. URL rocketry.gatech.edu.

[4] Garud, P., Johnson, C., and de Toledo, A. L., "Material Girl Launch Report," *arXiv preprint arXiv:2411.00807*, 2024.

[5] Wang, C. H., and Duong, C. N., "Chapter 2 - Failure criteria," *Bonded Joints and Repairs to Composite Airframe Structures*, edited by C. H. Wang and C. N. Duong, Academic Press, Oxford, 2016, pp. 21–45. https://doi.org/https://doi.org/10.1016/B978-0-12-417153-4.00002-5, URL https://www.sciencedirect.com/science/article/pii/B9780124171534000025.

[6] Ebnesajjad, S., "5 - Material Surface Preparation Techniques," *Handbook of Adhesives and Surface Preparation*, edited by S. Ebnesajjad, Plastics Design Library, William Andrew Publishing, Oxford, 2011, pp. 49–81. https://doi.org/https://doi.org/10.1016/B978-1-4377-4461-3.10005-7, URL https://www.sciencedirect.com/science/article/pii/B9781437744613100057.

[7] Redmann, A., Damodaran, V., Tischer, F., Prabhakar, P., and Osswald, T. A., "Evaluation of Single-Lap and Block Shear Test Methods in Adhesively Bonded Composite Joints," *Journal of Composites Science*, Vol. 5, No. 1, 2021. https://doi.org/10.3390/jcs5010027, URL https://www.mdpi.com/2504-477X/5/1/27.

[8] Help, S., "Maximum von Mises Stress Criterion," , 2016. URL https://help.solidworks.com/2016/english/solidworks/cworks/r_maximum_von_mises_stress_criterion.htm#:~:text=In%20the%20case%20of%20pure,the%20case%20of%20simple%20tension.