Tensile Properties of Adhesive Joints Between Alclad 2024-T3 Aluminum Sheets and Extruded 6061-T6511 Aluminum for Use in Ultralight Personal Aircraft

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Prof. Blair London
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Abstract

Cold cure two-part epoxy adhesives were tested in aluminum joints to investigate their viability for use in an ultralight aircraft. The joints consisted of Alclad 2024-T3 aluminum sheets adhesively bonded to extruded 6061-T6511 aluminum, and are part of low-load-bearing members required to carry a minimum load of 175 lbs./ft. or 14.58 lbs./in. The Alclad 2024-T3 and 6061-T6511 aluminum were prepared by sanding with 80 grit abrasive paper, the surface was cleaned with acetone to remove surface contaminants, rinsed with distilled water, and dried using paper towels. Once the surface was prepared, the test coupons were assembled using one of the three selected adhesives (Loctite E-05 MR, Loctite E-20 HP, and 3M 420DP) which were applied using a hand operated applicator gun with mixing nozzle. The samples were then placed on a jig to hold them securely while the adhesives cured. The samples were allowed to cure for several days. The samples were then loaded in tension to failure using an Instron tensile tester. The Loctite E-20HP adhesive achieved the average highest strengths of 1378.53 ± 360.25 lbs./in. The scatter is believed to be due to excessive adhesive buildup around the edges of the joint and due to variations in the machined parts. Due to its high strength, the Loctite E-20HP was used in testing 30 additional samples, with a revised joint design, to try and minimize scatter. The revised joints achieved average strengths of 1206.44 ± 584.96 lbs./in which still meets the required strength goals.

Keywords: Materials Engineering, Adhesives, Tensile Testing, Aluminum Alloys, Alclad 2024, Glue Joint, Ultralight Aircraft

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I would like to thank Samson Motorworks for the opportunity to work on this project with them. Sam Bousfield (Samson Motorworks) answered all of my questions and supplied all of the machined aluminum parts. I would also like to thank Prof. Blair London for advising me on my project.

Table of Contents

List of Figures

List of Tables

Introduction

Samson Motorworks is designing and developing a new ultralight personal aircraft. Due to the new design of the aircraft, Samson Motorworks is designing a new joint composed Alclad 2024-T3 aluminum sheets and 6061-T6511 extruded aluminum blocks. The new joint must be able to withstand loads of up to 175 lbs./ft. (14.6 lbs./in.) and remain easy to manufacture.

An ultralight aircraft is defined to have only 1 seat, weigh less than 254 pounds empty, have a fuel capacity of 5 gallons or less, limited to speeds up to 55 knots in level flight, and does not have a power off stall speed greater than 24 knots. [1] As a result of these restrictions, light-weighting is a priority to meet design requirements, improve fuel economy, and improve performance. Figure 1 shows one example of an Ultralight aircraft, although it is not the proposed design for Samson Motorworks.

Figure 1: The hummelbird is one example of an Ultralight aircraft [2] however it is not what Samson Motorworks is designing

Aluminum is an excellent choice for an ultralight for a few reasons. It is light weight with a density of 2.7g/cm^3, it is strong enough to withstand the applied loads, and is cheaper than other lightweight materials such as titanium and magnesium. The two aluminum alloys being used in the product are 6061-T6511 and Alclad 2024-T3 aluminum. The 6061 alloy is a medium strength, aerospace grade aluminum. While 6061 aluminum is not as strong as 2024 aluminum alloys, it is more resistant to corrosion. [3], [4] For applications where high strength-to-weight ratios are required, 2024 aluminum alloys are used. Because the 2024 alloys are susceptible corrosion, they are often clad with a high purity aluminum known as Alclad to increase its corrosion resistance. [5]

Joining Methods

Traditional methods of joining metals such as riveting and welding are used widely in industry today. However, these methods have disadvantages that do not make them ideal for use in this application. Rivets, even though they require holes to be drilled to use them and are used routinely on aircraft, add weight to the end product. The holes also create stress risers in the parts which can result in more material being added to increase the strength. Any addition of weight makes it difficult to meet the weight requirements for ultralight aircraft.

Welding aluminum, while possible, is not an option because the heat affected zones lose their strength due to either growth or dissolution of the precipitated phase(s). After welding, the quenching rates required for aging conditions for the aluminum to regain its strength are often unobtainable. [6] The last option for joining the pieces of aluminum together is with adhesives.

Adhesives

Adhesives have been in use for primary aircraft structures for over 50 years. Adhesives are lighter than other joining methods, improve aerodynamics, can reduce the possibility of galvanic corrosion due to the electrically insulative properties of some adhesives, and do not create heat affected zones, which is a problem with welding. While it is easy to achieve a high initial strength with adhesive bonds, it can be difficult to promote durable high strength bonds. [7] The strength and durability of an adhesive bond is determined by the adhesive used, material bonded to the adhesive, surface treatments done to the material, and joint geometry.

Many pretreatments have been developed to help increase strength and durability by promoting the bonding of adhesives to the substrate. These processes involve some combination of degreasing, etching, priming, using coupling agents (silanes), and anodizing the material. Lockheed Martin, for example, pretreats the surface of aluminum by performing a phosphoric acid anodization, priming the surface, and then finally applies the adhesive. [8]

Joint geometry, specifically bond line thickness, can have a large effect on the strength of an adhesive bond. In a study conducted by the Polytechnic University of Madrid, they determined that a difference in bond line thickness of as little as half a millimeter changed the strength of the joint by a factor of three as seen in Figure 2. The same study found that there is a large difference in the reliability of the joint depending on bond line thickness as well. [9]

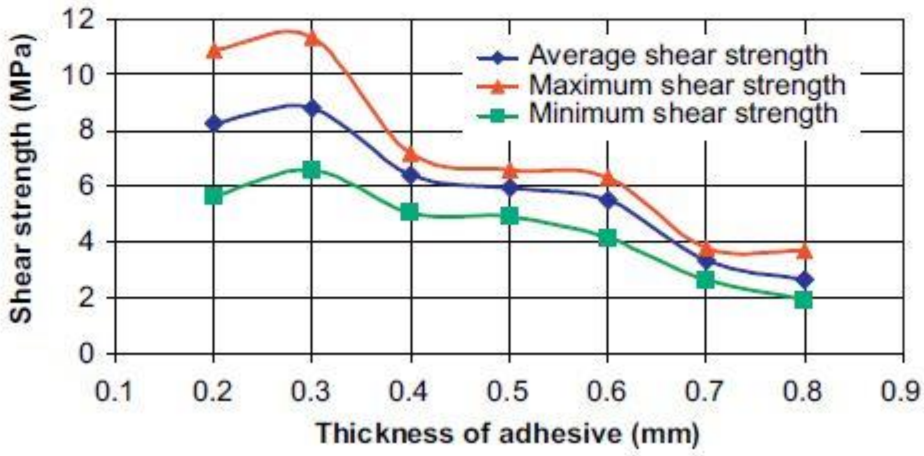

Figure 2: Graph showing the effects of bond line thickness on shear strength. The strength of the bond line for this particular adhesive changes by a factor of three when the thickness is changed by as little as 0.5mm. [9]

Adhesive selection is crucial to producing a high strength joint. There are many different kinds of adhesives being produced. Each one is better for use in different environments and with different material substrates. Table I illustrates the general qualitative properties for four different categories of adhesives. As can be seen from Table I and Table II, epoxy adhesives are good for a wide range of applications. They bond well with metals, have good mechanical properties, and can be used in temperatures of up to approximately 180ºF.

Table I: Comparison of Qualitative Values for 4 Types of Adhesives [10]

Performance Considerations	Cyanoacrylates	Epoxies	Urethanes	2 Part Acrylics
Benefits	Wide range of Applications	Wide range of Formulations	Excellent Toughness/ Flexibility	Good Impact Resistance/ Flexibility
Limitations	Low Polar Solvent Resistance	Mixing Required	Sensitivity to Moisture	Mixing Required
Operating Temperature Range	-65 to 210ºF	-65 to 180ºF	-65 to 250ºF	-65 to 250ºF

Table II: Comparison of Qualitative Characteristics for Adhesion and Mechanical Properties [10]

Adhesion to Substrates

Metals	Very Good	Excellent	Good	Excellent
Plastics	Excellent	Fair	Very Good	Excellent
Glass	Poor	Excellent	Good	Good
Overlapping Shear Strength	High	High	Medium	High
Peel Strength	Low	Medium	Medium	High
Tensile Strength	High	High	Medium	High
Elongation/ Flexibility	Low	Low	High	Medium
Hardness	Rigid	Rigid	Soft	Semi-rigid

Testing

Currently there are several American Society of Testing and Material Standards (ASTM) which have been developed to analyze and experimentally verify adhesive properties. These ASTM Standards provide a basis for testing, but do not cover every joint design.

The most widely used adhesive bond test is the single overlap shear test (ASTM D 1002-10). [11] Figure 3 shows the test specimen profile for ASTM D 1002-10. The failure mode of this test is rarely due entirely to the shear stress, but rather peel stresses induced by joint rotations and deflections. [12]

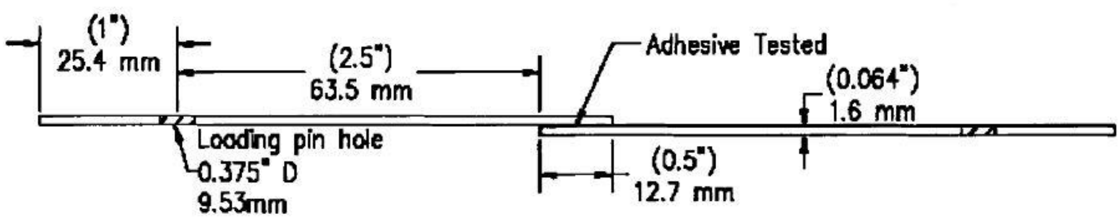

Figure 3: Specimen profile of a single overlap shear test (ASTM D 1002-10) [11]

Figure 4 illustrates the deflection of the specimen under load. To help compensate for the joint rotations and deflections, ASTM D 3165 is used. [13] Figures 5 and 6 show the specimen profiles and the profiles under load for ASTM D 3165, respectively.

Figure 4: Specimen profile showing deflection of a single overlap shear test under load (ASTM D 1002-10) [11]

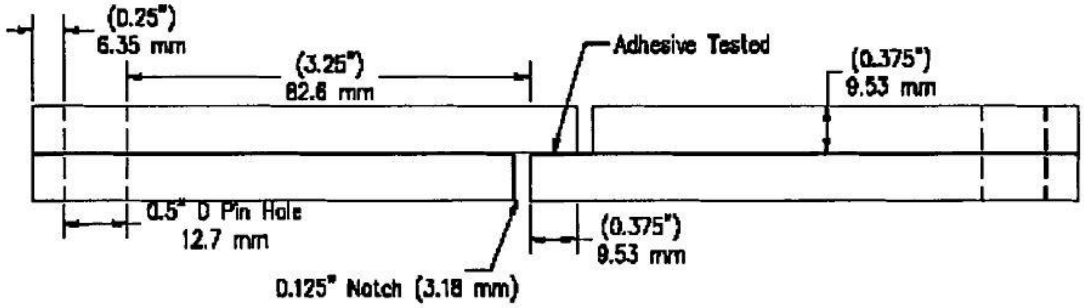

Figure 5: Specimen profile of a single overlap shear test (ASTM D3165-07) [13]

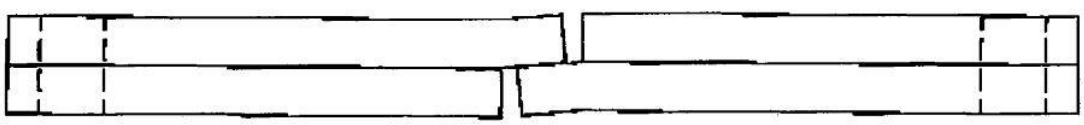

Figure 6: Specimen profile of a single overlap shear test showing deflection under load (ASTM D 3165-07) [13]

Another method for testing adhesive bonds is with a double overlap tensile test (ASTM D 3528-96R08). [14] The major difference between a single overlap and a double overlap tensile test is that instead of having one bond line between two components, there are two bond lines between three components as shown in Figure 7.

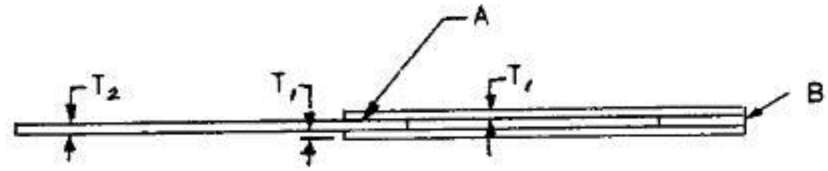

Figure 7: Specimen profile of a double overlap shear test (ASTM D 3528-96R08) [14]

Epoxy adhesives were determined to be the ideal choice for this application, due to their preferential bonding to metals, their high strength, operating temperature range, and low flexibility. Three commercially available room temperature curing epoxy adhesives were chosen to test the viability of the new joint design. These adhesives were: 3M DP-420, Loctite E-05MR, and Loctite E-20HP 2-part epoxy adhesives. Tensile testing was performed to determine if the new joint design could withstand the required loads.

Experimental Procedure

Realistic Constraints

Due to manufacturability constraints, surface treatments such as anodization are not an option. Anodization adds to the time it takes to manufacture an Ultralight. High temperature curing adhesives were also not an option due to the added time it takes and the lack of available equipment.

In addition to the manufacturability constraints, there were also economic reasons that prevented the use of some materials and procedures. Due to Samson Motorworks limited facilities and resources, anodization of aluminum and curing adhesives in ovens would have to be outsourced to other companies. This greatly increases the costs associated with building an Ultralight and reduces profitability.

Materials

The materials required were the three epoxy adhesives (3M DP-420, Loctite E-05MR, and Loctite E-20HP), a hand operated applicator gun, mixing nozzles, Alclad 2024-T3 strips, 6061-T6 blocks, 80 grit abrasive paper, acetone, distilled water, and lint free towels.

Joint Design

Two joint designs were tested, shown in Figure 8 and in Figure 9. The first joint design features a ¾″ deep slot while the second has a ¼″ deep slot. Both designs utilize the Alclad 2024-T3 aluminum sheets and 6061-T6 aluminum blocks.

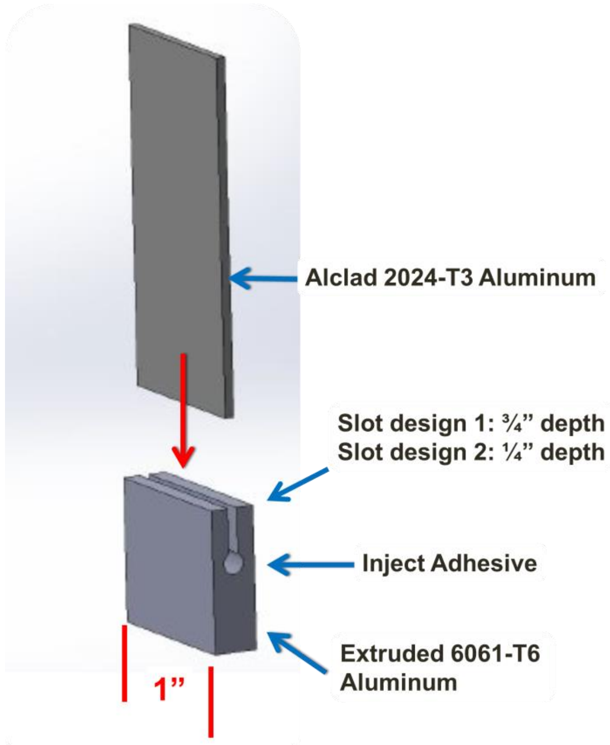

Figure 8: Schematic of the joint designs and components.

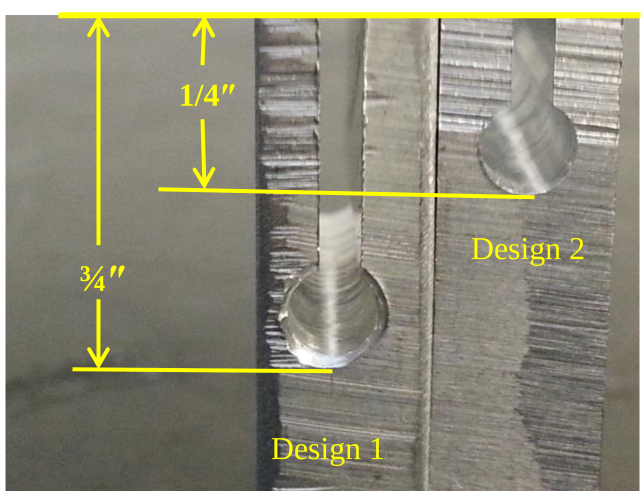

Figure 9: Two joint designs were tested. The first design (left) was 3/4″ tall while the second joint design (right) was 1/4″ tall.

Surface Preparation

Surface preparation for both joint designs was the same. Preparation of the Alclad 2024-T3 strips began with sanding the strips with 80 grit abrasive paper to increase the surface area available for bonding. This is followed by cleaning the surface to be bonded with acetone using a lint-free cloth to remove any surface contaminants. Once the surface has been cleaned with acetone, it was rinsed with distilled water and dried.

Preparation of the extruded 6061-T6 aluminum blocks is similar to that of the Alclad 2024-T3 sheets except that no sanding was performed. The size of the slot made it difficult to consistently and evenly sand the slot. Preparation began with cleaning the inside of the slot with acetone using a pipe cleaner to scrub the surface. The extruded block was then rinsed with distilled water and dried using paper towel.

Sample Assembly

Joint Design #1

Once all of the surface preparation was completed, the Alclad 2024-T3 strip was inserted into the extruded 6061-T6 aluminum block for a mock-up to measure the placement. The Alclad 2024-T3 strip was placed 1/8″ away from the bottom of the slot to allow for adhesive to bond to all surfaces, as shown in Figure 10. The Alclad 2024-T3 strip was then be marked to indicate how far it should be inserted when the adhesive was applied.

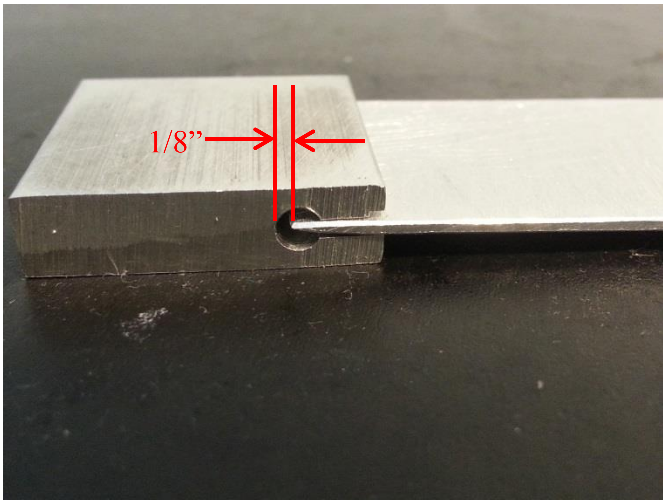

Figure 10: Mock-up assembly to mark how far to insert Alclad 2024-T3 strip.

Once the Alclad 2024-T3 strips were marked, tape was then wrapped around one open end of the slot loosely (not the top) to leave room for the Alclad 2024-T3 strips which were

slightly wider than the 6061-T6 blocks. The adhesive was then injected into the opposite end of the slot until it was overflowing, see Figure 14 for reference. The Alclad 2024-T3 strip was then inserted into the top of the extruded block to the point marked in the prior steps. More tape was then added tightly to the opposite side as the first piece to ensure no adhesive was lost. The sample was then placed in the jig in an upright position (Figure 11) to prevent movement and adhesive flow. The samples were allowed to cure for at least 24 hours prior to testing. Once cured, all tape was removed from the samples. Adhesive was then removed from the surfaces of the aluminum using a belt sander to prevent the adhesive from gumming up the test grips in the Instron tensile tester. While there was excess adhesive buildup along the sides, no excess adhesive was removed.

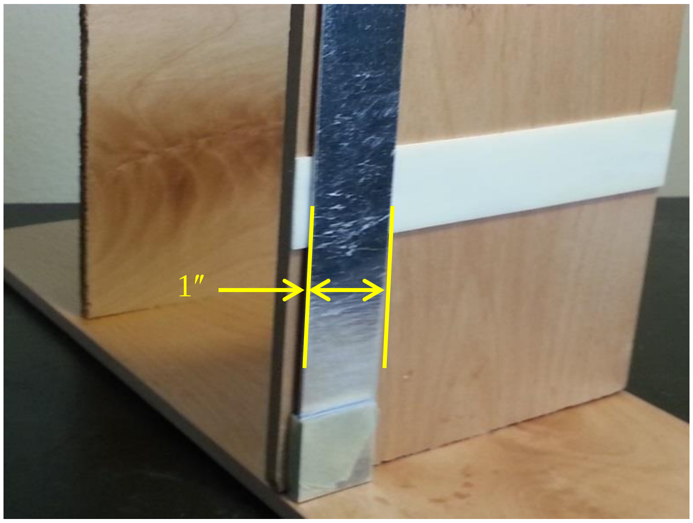

Figure 11: Sample placed in jig to cure. The sample was held in place using double-sided sticky tape.

Figure 12 shows the finished sample with excess adhesive. Due to the Alclad 2024-T3 strip being slightly wider than the 6061-T6 block, the excess adhesive was difficult to remove, and left on to eliminate any variations in results due to inconsistent adhesive removal.

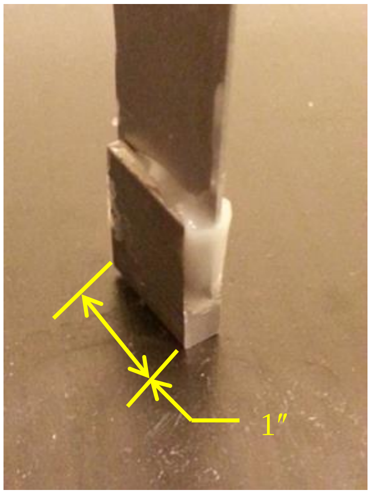

Figure 12: Image showing excess adhesive buildup due to the Alclad 2024-T3 aluminum sheet being wider than the 6061-T6 block.

Joint Design #2

Sample preparation of the second joint design was similar to the first joint design, with the exception that precautions were taken to ensure there was no excess adhesive buildup. Once all of the surface preparation was completed, the Alclad 2024-T3 strip was inserted into the extruded 6061-T6 aluminum block for a mock-up to measure the placement. The Alclad 2024-T3 strip was placed 1/8 in. away from the bottom of the slot to allow for adhesive to bond to all surfaces, as shown previously in Figure 10. The Alclad 2024-T3 strip was then marked to indicate how far it should be inserted when the adhesive was applied. Once the Alclad 2024-T3 strips were marked, tape was applied tightly around one side of the 6061-T6 block as shown in Figure 13.

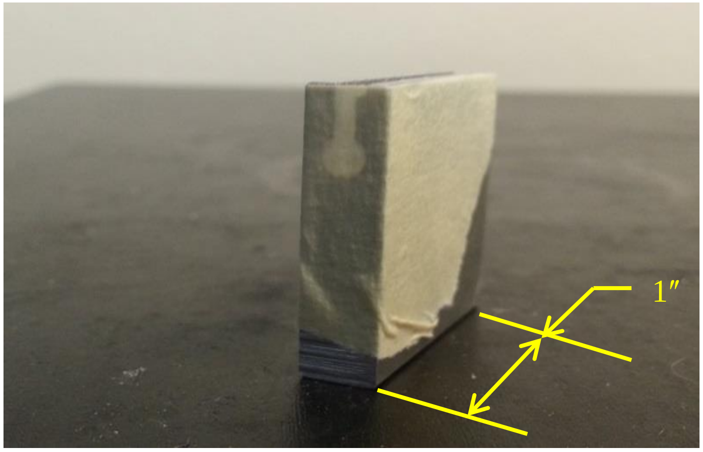

Figure 13: Tape wrapped tightly around one side to prevent adhesive flow and excess adhesive buildup.

The adhesive was then injected into the slot on the side opposite the tape until the adhesive was over flowing (Figure 14).

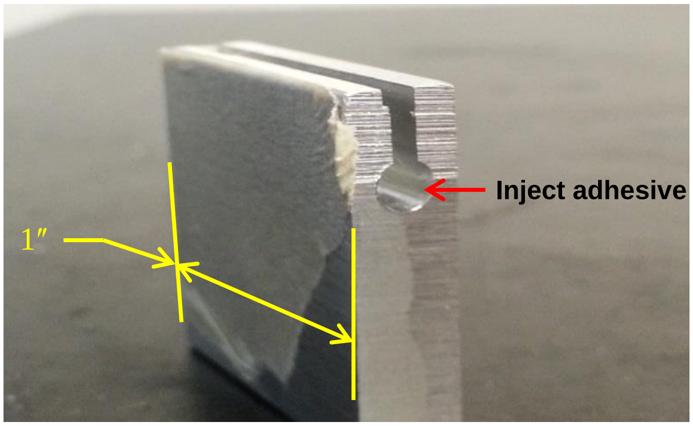

Figure 14: Inject adhesive in opposite side as the tape until adhesive is overflowing.

The Alclad 2024-T3 strip was then inserted into the top to the marked position. Once in place, tape was then tightly wrapped around the opposite side as the first piece of tape. All excess adhesive was then removed, and the samples were placed onto a jig (Figure 11) to cure for 24 hours. Once cured, all tape was removed and any remaining excess adhesive, including the sides, was removed using a belt sander. No excess adhesive buildup was present for the second joint design once sample assembly was completed.

Testing Procedure

For the first joint design, a total of 15 samples were tested. Each of the three adhesives was used in 5 of those samples. Once tested, the strongest of the three adhesives was chosen for testing in the revised joint design. For the revised joint design, 30 samples were tested.

The testing procedure was the same for both joint designs. The samples were placed in an Instron 3369 tensile tester with as much of the Alclad 2024-T3 strips in one grip as possible, and the 6061-T6 block in the other (Figure 15). Special care was taken to ensure that the joint in the extruded block was not compressed by the test grips which would have caused a falsely large test results (Figure 16). The tensile tester was programmed to pull the Alclad 2024-T3 strip and the 6061-T6 block apart at a rate of 0.05 in./min., until failure. While there are no ASTM standards for this specific adhesive joint, there are many ASTM standards for the testing of adhesive joints. The testing rate of 0.05 in./min. complied with ASTM standards D 3528 – 96R08, D 4027 – 98R11, and D 897 – 08. [14], [15], [16] These testing standards were chosen due to the similarity of

their joint designs to the ones being tested. The tests were stopped after the first indication of failure.

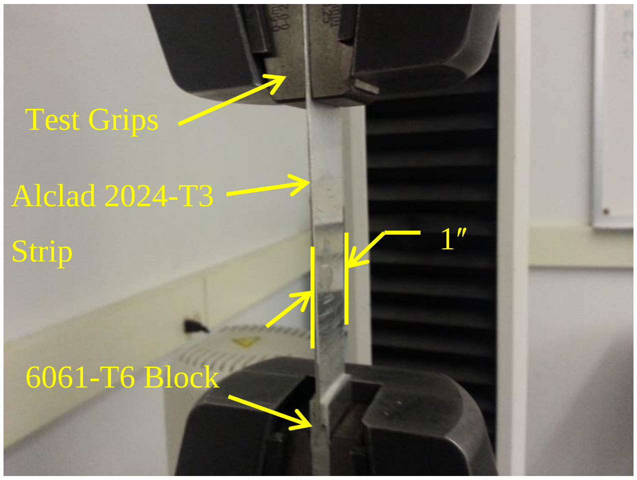

Figure 15: Schematic of sample placement in Instron tensile tester.

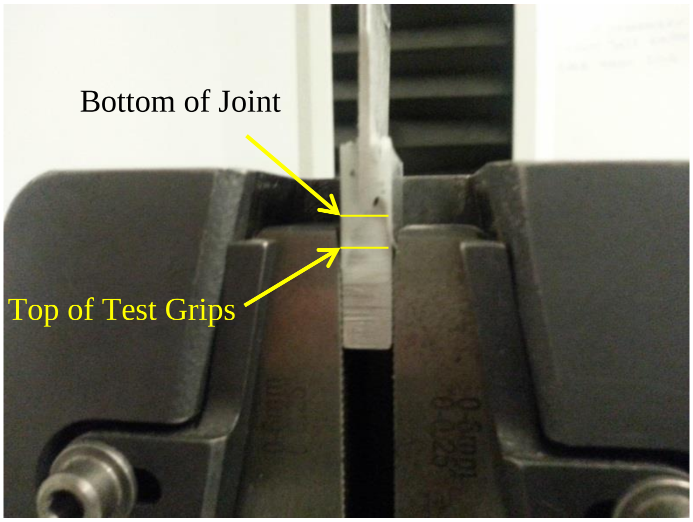

Figure 16: Ensure the bottom of the joint does not end up between the test grips to ensure accurate data.

Results

Joint Design #1

For the initial testing of the three adhesives used, the joint design included a slot that was ¾″ deep. Some samples experienced multiple failures during the test, such as all of the E-05MR samples (Figure 17). For these samples, the initial failure observed was taken to be the maximum operating load it could withstand. Figures 17-19 show the graphs of load vs. extension for all three of the adhesives during the initial tests.

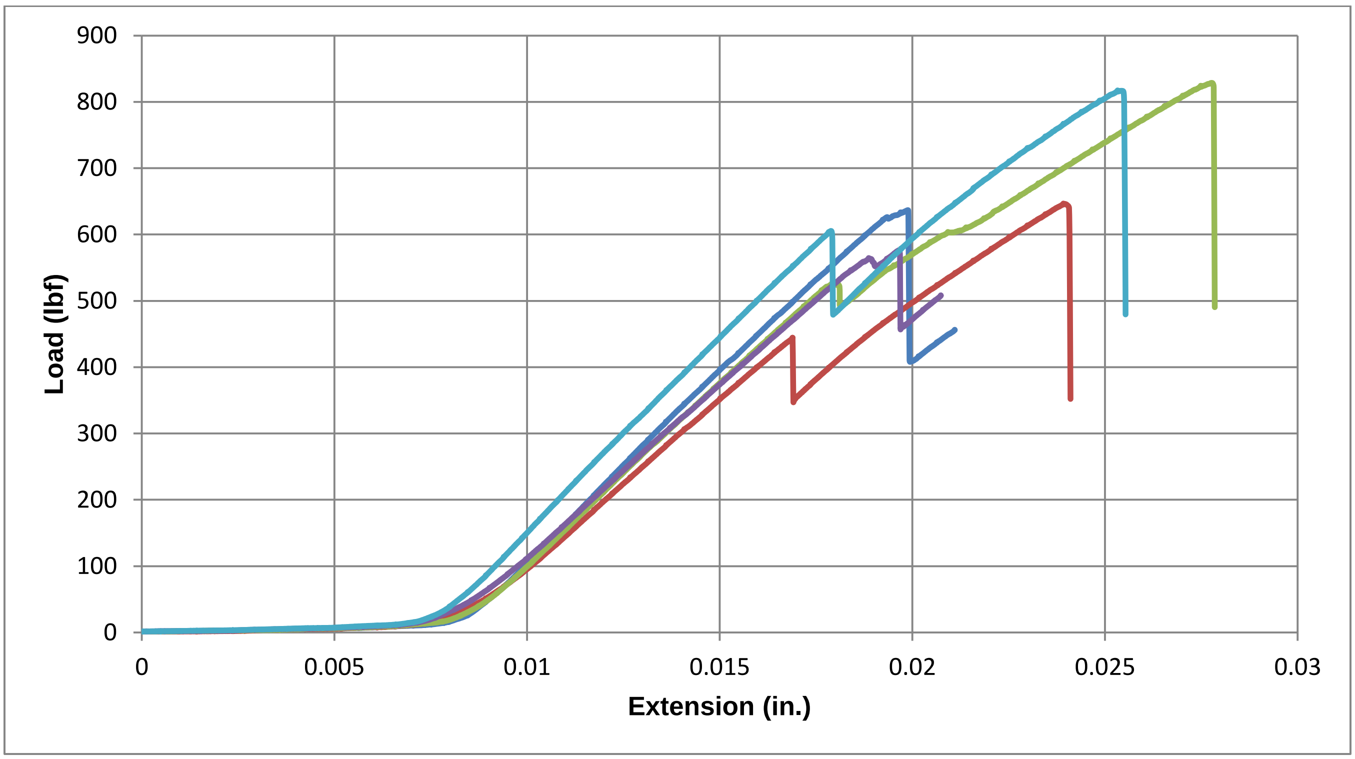

Figure 17: Graph of load vs. extension for the E-05MR epoxy adhesive. All 5 samples had an initial failure approximately 75% of the way into the test. This initial failure is what the maximum operational load is considered to be.

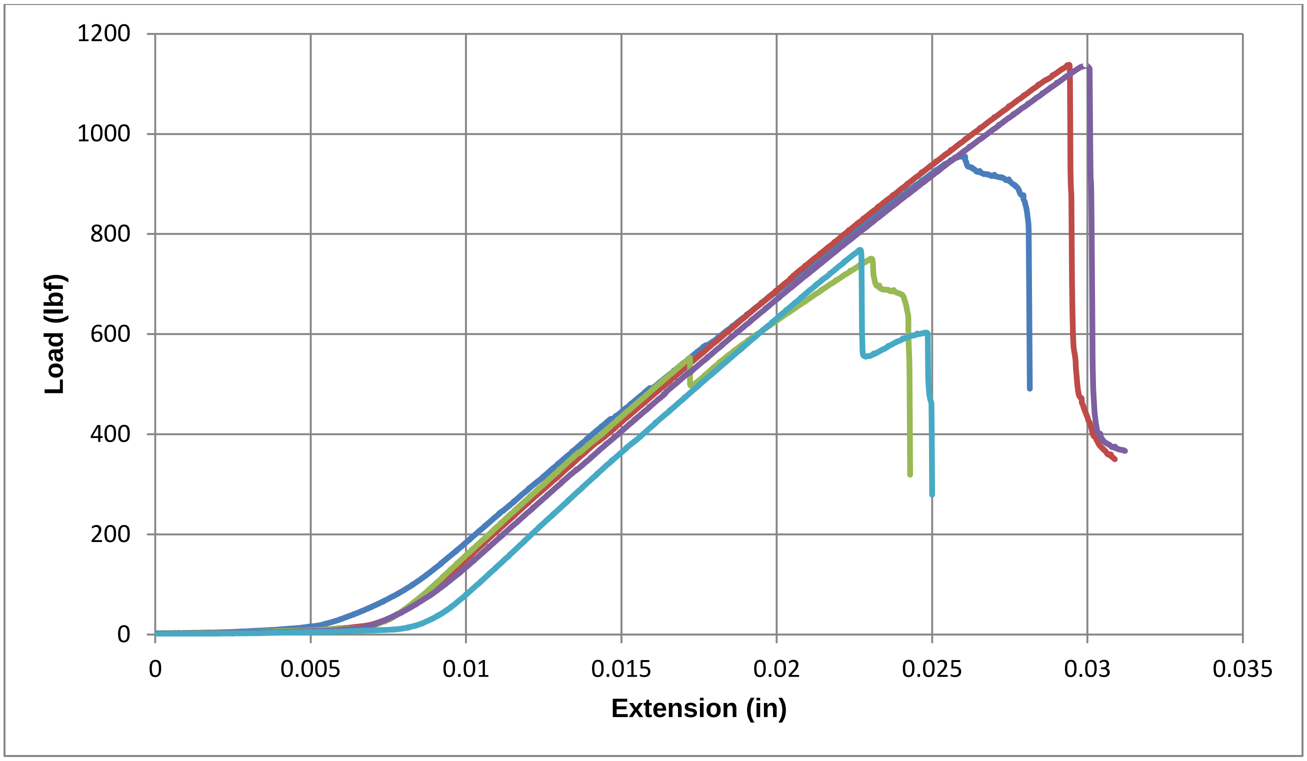

Figure 18: Graph of load vs. extension for the DP-420 epoxy adhesive. Only one of the samples had an initial failure half way through the test such as with the E-05MR epoxy adhesive. This initial failure is what is considered to be its maximum operational load achieved.

For the E-20HP epoxy adhesive, one sample (sample number 2 in Figure 19) achieved a strength value much greater than the rest of the samples. The slope of the line also changes throughout the test. While it is shown in Figure 19, this value is not included in the analysis, because it is unknown at this time what is causing this behavior.

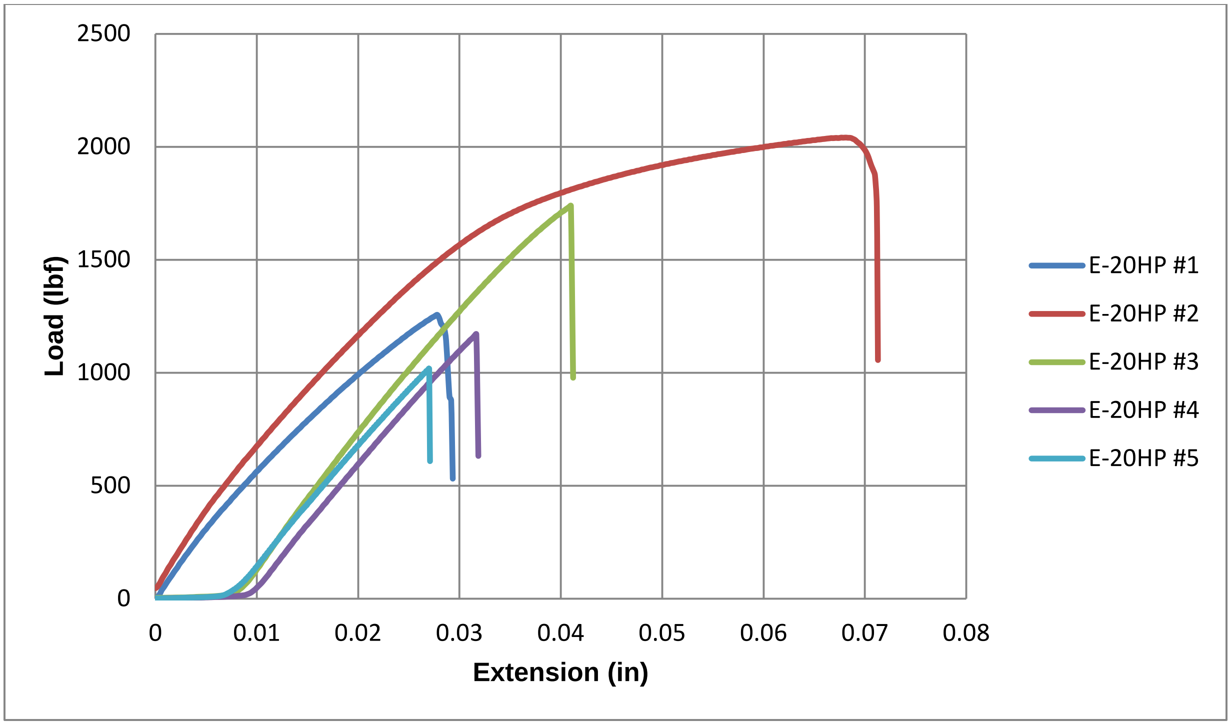

Figure 19: Graph of load vs. extension for the E-20HP epoxy adhesive. Sample number 2 reached much higher loads than the other samples. The slope for sample number 2 also changes half way through the test. This result was considered to be an outlier and not included in the analysis.

A Tukey-Kramer test used in conjunction with a One-Way ANOVA test was performed on the test results for the first joint design. This test resulted in a p-value of 0.002. Because this p-value is less than 0.05, the results for all three adhesives can be taken to be significantly different from each other with a 95% confidence interval. A boxplot of the values was constructed using Minitab software (Figure 20). The bar that extends along the bottom at the 14.58 lb_f mark was the target value the 1″ samples were required to meet. Table III shows some descriptive statistics for the testing of the initial joint design. This table shows that as the adhesives get stronger, the range of values and the standard deviation get larger.

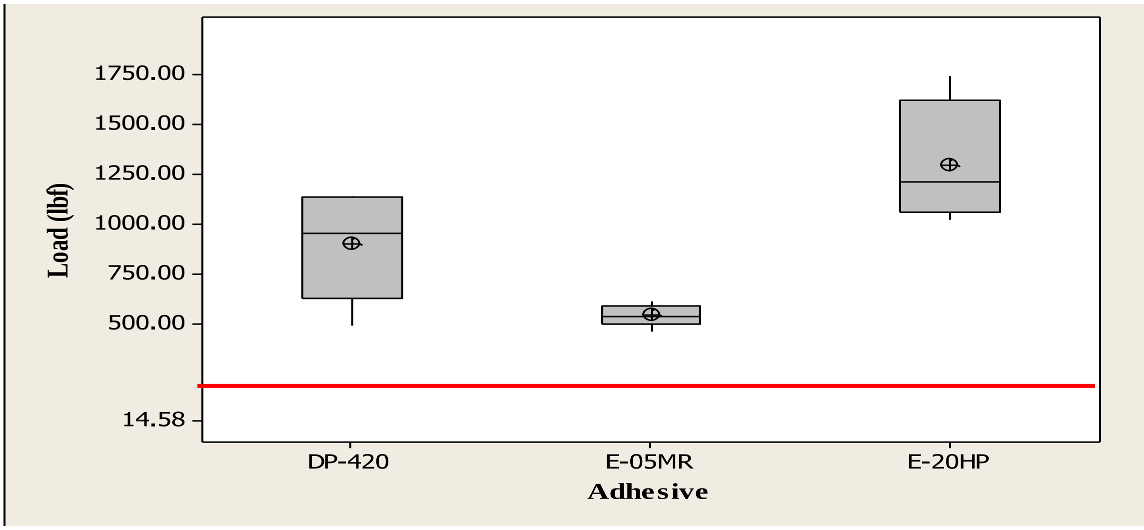

Figure 20: Boxplot comparing the tensile strengths of the three adhesives in the first joint design to the required tensile strength.

Table III: Range of Tensile Strengths Achieved for Initial Joint Design

Adhesive	Tensile Strength (lb_f)	Std. Dev.	Sample Size
Loctite E-05MR	535.24 ± 76.37	56.5	5
3M DP-420	815.65 ± 322.71	274	5
Loctite E-20HP	1378.53 ± 360.25	311	4

Joint Design #2

For secondary testing, 30 samples were tested using the strongest adhesive from the initial testing (Loctite E-20HP). Figure 21 shows a graph of load vs. extension for the revised joint with the Loctite E-20HP adhesive. The revised joint design achieved a tensile strength of 1206.44 ± 584.96 lb./in.

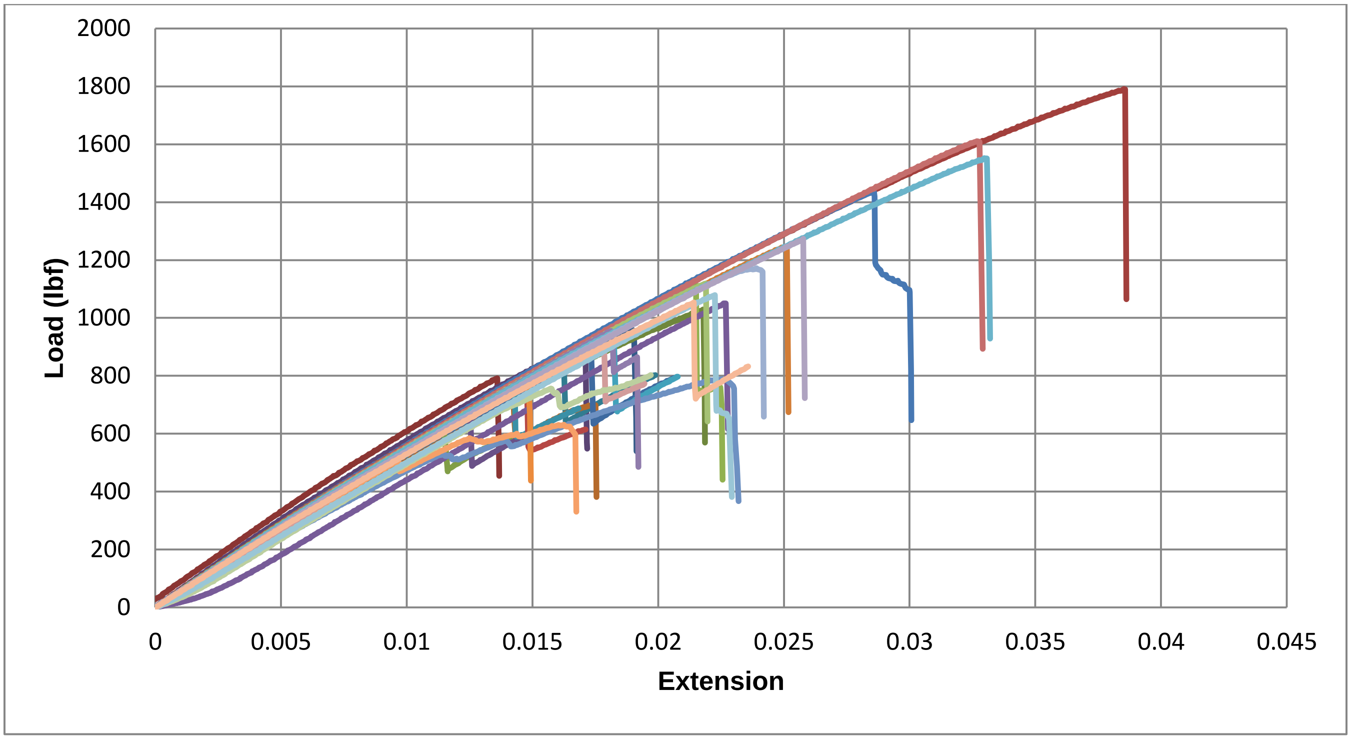

Figure 21: Graph of Load vs. Extension for the Loctite E-20HP adhesive with the revised joint design. Even though precautions were taken to reduce scatter, the revised joint design had the largest range of tensile strengths.

Figure 22 shows a boxplot comparing the tensile strength of the revised joint design to the tensile strength of the initial joint design. A Tukey-Kramer test coupled with One-Way ANOVA testing was performed between the first joint design using the Loctite E-20HP adhesive and the revised joint design using the E-20HP adhesive. This test produced a p-value of 0.078. Because the p-value is greater than 0.05, the tensile strength of the two joint designs are not significantly different to a 95% confidence interval. Table IV shows some descriptive statistics of the revised joint design in comparison the initial joint design. Table IV shows the same trend as Table III did.

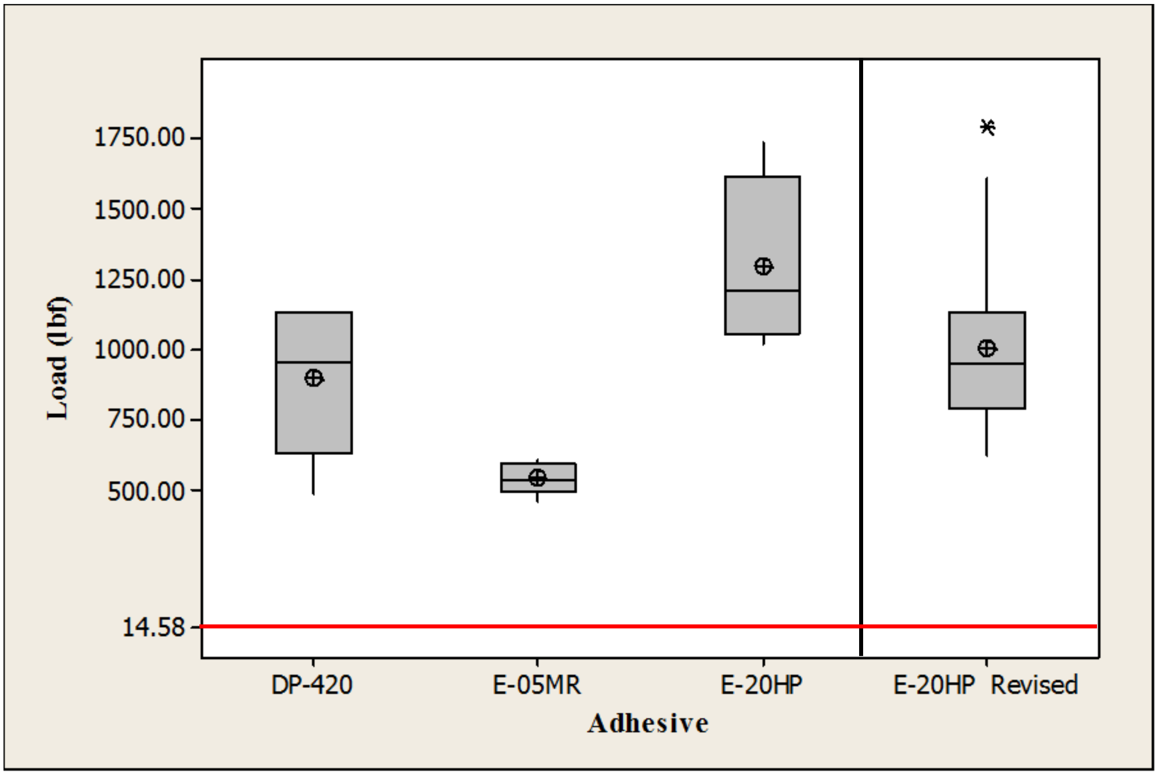

Figure 22: Boxplot comparing the tensile strengths of the revised joint design to the tensile strengths of the initial joint design and to the minimum required tensile strength. The tensile strength values for the revised joint design are not significantly different from those of the initial joint design with the E-20HP adhesive.

Table IV: Range of Tensile Strengths Achieved for the Revised Joint Design Compared to the Initial Joint Design

Adhesive	Tensile Strength (lb_f)	Std. Dev.	Sample Size
Loctite E-05MR	535.24 ± 76.37	56.5	5
3M DP-420	815.65 ± 322.71	274	5
Loctite E-20HP	1378.53 ± 360.25	311	4
Loctite E-20HP Revised Design	1206.44 ± 584.96	293.7	30

Discussion

Joint Strength

As shown previously, all of the joint design and adhesive combinations tested exceeded the design goals. The weakest of all the samples tested exceeded the design goal by a factor of

31. This success indicates that room temperature curing epoxy adhesives used in the new joint design could be a viable option for use in Ultralight aircraft, although further testing is needed. Because the revised joint design also exceeded the strength requirement, it is may be possible to reduce the material usage on the final product which will both save money, and reduce weight.

As stated earlier, the tensile strengths of the two joint designs utilizing the Loctite E-20HP adhesives were not significantly different. This suggests that the load carried by the joint is located entirely inside the red circles shown in Figure 23 and the slot height does not affect the strength. This is supported by the fact that the slot (blue section in Figure 23) is just wide enough to fit the Alclad 2024-T3 strip let alone any adhesive. This is advantageous in that shorter slots could potentially require less material, saving weight and costs.

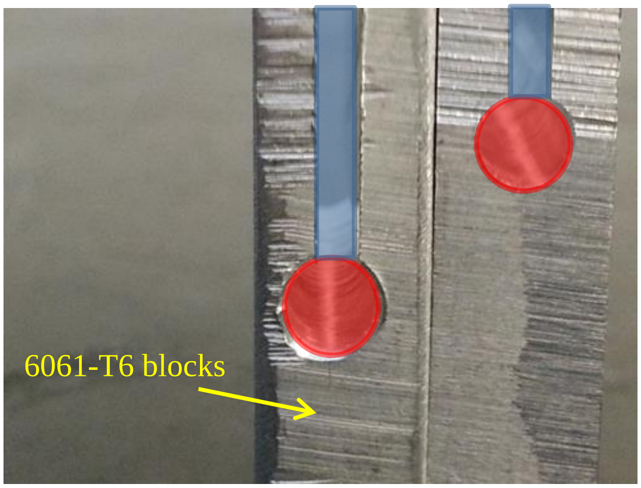

Figure 23: Schematic showing where the load is being carried in the joint. The red sections are load bearing sections.

Scatter

While scatter is inherent in the tensile testing of adhesives, there were other factors that helped contribute to the scatter. For the initial joint design, the Alclad 2024-T3 sheets were slightly wider than the 6061-T6 aluminum blocks. This made it difficult to remove excess adhesive buildup around the edges as seen in Figure 12.

It is possible that the excess adhesive buildup contributed to higher strength values than what should have been achieved. However, it is unknown how much this excess adhesive contributed to the strength, and if it was different for each sample due to variability in the amount of buildup. Any variation in tensile strength due to excess adhesive buildup is likely to be minimal, if not insignificant, due to the fact that the tensile strength of the two joint designs utilizing Loctite E-20HP adhesives was not significantly different.

A factor that adds to the scatter for both joint designs was the quality of the machining of the samples. The holes drilled in the bottom of the slots are not placed in the same position on each sample. On each sample, the hole is off centered to varying amounts. Figure 9 showed one sample with a hole slightly off center, and one sample with a hole that is placed in the correct spot. Other samples had holes that were further off center, and even tangent with the rest of the slot. This inconsistency does not change the amount of adhesive in the joint, but rather where the adhesive is located around the Alclad 2024-T3 sheet in the joint. As shown in Figure 1, the bond line thickness can have large effects on the strengths of the bond. If the hole is off center, it pushes the adhesive to one side of the Alclad 2024-T3 sheet, reducing the bond line thickness on one side. This theoretically can reduce the strength of the joint.

One final factor that helped contribute to the scatter seen in both joint designs was human error. While great care was taken to ensure all parts were made as consistently as possible, some variations occurred. Not all of the Alclad 2024-T3 strips was perfectly aligned with the 6061-T6 blocks, but rather slightly askew. This could reduce the strength values achieved due to the possibility of some rotational forces being applied during testing.

Conclusion

1. The strongest of the three 2-part epoxy adhesives tested is the Loctite E-20HP.
    - E-05MR had tensile strengths of 535.24 ± 76.37 lb./in.
    - DP-420 had tensile strengths of 815.65 ± 322.71 lb./in.
    - E-20HP had tensile strengths of 1378.53 ± 360.25 lb./in.
    - The revised joint design with E-20HP epoxy had tensile strengths of 1206.44 ± 584.96 lb./in.
2. The tensile strengths of the different joints are not statistically different.

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