ME - I9800:

Independent Study - Research Project

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STUDY OF THE ENVIRONMENTAL EFFECTS ON PERFORMANCE OF ADHESIVE-BONDED SINGLE-LAP JOINTS UNDER STATIC LOADS

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1. Objective

The objective of this study was to determine the Tensile Breaking Strength of a Single-Lap Joint under Quasi-static Uniaxial Tension Loading, using a High Performance Structural Epoxy Adhesive on Aluminum adherends under four different environmental conditions:

a. Room Temperature - Dry Conditioning
b. Low Temperature (-51°C)
c. High Temperature (63°C)
d. High Humidity (95% Relative Humidity)

The purpose of this report was to provide a baseline for future studies on dynamic single lap joint testing.

The subject of study was the Epoxy identified as LOCTITE EA 9309NA QT AERO epoxy (aka Hysol EA 9309 NA QT SYSTEM) which was used to adhere two plates of Aluminum 6061 T6 following ARL-ADHES-QA-001.01 REV. 2.2 document [1] for surface preparation and bonding procedure of the lap joint. The sample dimensions and testing methodology conformed to ASTM D1002 [2], with the exception of the Aluminum plate thickness which were increased to 4 mm (refer to section 3.1. Methodology).

The specifications of the Epoxy are as follows:

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Manufacturer Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Lap Shear Strength (-55°C) - MPa</td>
<td>37.7</td>
</tr>
<tr>
<td>Tensile Lap Shear Strength (25°C) - MPa</td>
<td>32.8</td>
</tr>
<tr>
<td>Tensile Lap Shear Strength (82°C) - MPa</td>
<td>6.4</td>
</tr>
<tr>
<td>Tensile Lap Shear Strength (25°C) - Hot/Wet - MPa</td>
<td>32.8</td>
</tr>
<tr>
<td>Tensile Strength (25°C) MPa</td>
<td>32.2</td>
</tr>
<tr>
<td>Tensile Modulus (25°C) MPa</td>
<td>2303</td>
</tr>
<tr>
<td>Shear Modulus (25°C) MPa</td>
<td>841</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table1. Typical values of mechanical properties of the adhesive sourced by manufacturer [3].
2. Previous Work

Extensive studies have focused on the analysis of properties of adhesive-bonded joints. This section intends to gather existing literature about the static tests that are currently carried to study shear stress in different joint configurations. Special attention will be dedicated to the joint of choice in this report, and some stress analysis theory of adhesive-bonded lap-joints will be gathered.

2.1. Shear Tests

The tests intended to study the shear properties in adhesives can be divided into bulk and joint tests. Bulk tests use specimens which are made entirely of cured adhesive material. They provide accurate results for the properties of the material but do not represent the adhesive properties in a joint. This is the reason why joint tests are performed: joint test specimens use two substrates which are connected by a thin layer of adhesive. They are designed to provide a meaningful study of the properties of a joint in different loading scenarios, which is a closer simulation of the real application of adhesives. However, accurate measurements in joint tests where small adhesive thicknesses are used are difficult to obtain due to the small displacements typically encountered in the experiments (da Silva et al. [5]).

Bulk Specimens

Bulk Torsion

This test uses a solid or tubular bar with square sections at the ends. The specimen is gripped by the square ends where a torsional load is applied. The torque and twist provided by the test machine can be measured along the length of the specimen, which, along with the geometrical dimensions of the specimen, provide the parameters necessary to calculate the shear stress $\tau$ and shear strain $\gamma$.

V-Notched Beam Shear Method (for composites ASTM D5379)

Also known as Iosipescu, this test is performed on a conventional tensile testing machine. It uses a 4 mm thick rectangular specimen with two V-notches at its center, which is loaded on the top and bottom with a bending moment on each side. The moments cancel out at the middle section of the specimen creating an area of uniform shear at the cross section of the notches. This test is subject to deflections of the specimen that can lead to misleading results, and is not adequate for flexible adhesive materials. There are also stress concentrations at the notches that compromise the accuracy of the results. This test permits the use of strain gauges and is used to calculate the shear stress $\tau$ and shear modulus $G$ from the load applied by the machine, the cross-section of the specimen, and the strain $\varepsilon$ recorded by the strain gauges.
Notched Plate Shear Method

This test is also known as the Arcan method and is similar to the losipescu. The specimen also contains 2 notches in the middle section but with the addition of a fillet meant to reduce stress concentrations. It has two holes placed vertically on both sides, which allow the application of two opposing forces to create a shear load. In this case, an extensometer can be used to measure displacement between the two notches, as well as strain gauges.

Joint Specimens

Tests with Thin Sheet Adherends

There are several tests which use thin adherends in a Lap Joint configuration (Single Lap - ASTM D 1002, Double Lap, Butt Strap etc [6]). The Lap Joint specimens generally use a 25.4 mm wide, thin plate (adherend A) which overlaps on its end with one or more plates (adherend B) where they are joined by the adhesive. The two loose ends of the specimen are gripped in a tensile test machine where loads are recorded. However, peeling stresses (stress normal to the bondline) occur in the adhesive layer on these tests due to unavoidable bending created by the misalignment of the tensile forces on the specimens. As a result, the shear strength calculated from the loads at failure are a poor representation of the actual values of stress through the area of the bond and can only be used for comparison and quality control of adhesives [5,6].

These are the type of joint configurations that are most commonly used in engineering. In addition to their low cost and simple methodology, their tests have become a benchmark in many industries despite their inability to provide reliable mechanical properties of the adhesives. This is due to the complexity of the stress state caused by bending effects that the adhesive undergoes during the test. This subject is discussed further at the end of this section, where the stress distribution found in a single-lap joint is shown.

Thick Adherend Shear Test (ASTM D 3983)

This test method is similar to the single-lap joint, but it uses stiff and thick metallic adherends which puts the adhesive in a state of uniform shear, reducing the peel stresses under the loads of the testing machine. The use of a dedicated extensometer is required to measure the small displacements that occur in the bondline, and it provides the accuracy necessary to calculate the strain of the adhesive. In this technique it is also required to measure the strain of the adherend by performing a tensile test on a “dummy” specimen made of the same material as the adherend. The displacement measured on the adherend is used to correct the measurements extracted from the joint specimen. Some variations of this method are able to determine the maximum of the stress-strain curve of the adhesive [5].
Butt Joint in Torsion (ASTM E 229)

This method uses solid substrates or tubes which are joined by the adhesive with a butt joint. A torque is applied to the free ends of the substrates until failure of the adhesive occurs. In this method the stress concentrations do not exist, recording larger strains than in other tests. The use of extensometers is also available with a correction to remove the displacement of the substrates. This is considered the most accurate method to obtain the shear stress-strain curve, which provides the shear strength and shear modulus of the adhesive.

2.2. Shear Stress in Single-Lap Joints

Adhesively-bonded lap joints provide a non-uniform shear stress along its bondline under tensile loads. This is a consequence of the bending caused by the non-axial loading on the two extremes of the substrates which are not aligned with each other, and provide normal stresses to the adhesive. The difference in strain between the adherend and the adhesive also contribute to the complexity of the shear stress, as well as the tensile and compressive stresses experienced at the corners of the adhesive layer that add up to the normal stress induced by the bending effect [7].

R.D. Adams et al. take into account these three factors during the stress analysis of a metal-to-metal adhesive-bonded lap joint using a high-strength epoxy. In their study the analysis is carried by a finite-element method and compared to practical results obtained with a model.

Below is an example of a typical shear stress distribution of a single lap joint under tension.

![Shear-Stress distribution from finite-element models](image)
3. Experimental Results

3.1. Methodology

3.1.1. Specimen Dimensions

Originally, the intention of this study was to conform to the standard test method ASTM D 1002. However, the tensile testing of such specimens revealed plastic deformation of the adherends before failure of the adhesive, due to the bending moment caused by the tensile loads over the geometry of the single lap configuration.

Figure 2. ASTM D 1002 Lap Joint specimen adherends yielding before reaching failure by shear strength of the adhesive.

In order to avoid this undesired effect, the thickness of the metal adherends was modified. The criterion to determine the thickness of the adherends intended to minimise the effects of the deformation of the metal under tensional forces provided by the testing machine. Therefore, the thickness was determined by the maximum dimension allowed by the grips of the available equipment: \( t = 4 \) mm. A drawing of the specimen is shown in Fig. 3, with an adherend thickness of \( 4 \pm 0.125 \) mm, and with an overlap length of \( 12.7 \pm 0.25 \) mm, the bondline thickness was set to \( 0.25 \pm 0.125 \) mm. The material of the metal adherends was Aluminum alloy 6061-T6. Specimen engineering drawings are provided in Appendix A.
3.1.2. Specimen Manufacturing / Preparation of Test Joints

Aluminum Adherend Plates Preparation

The adherend plates were machined from 6061-T6 Aluminum, 4 ± 0.178 mm thick x 30 mm wide bars (McMaster part # 9146T34) to the dimensions specified in Figure 3.

The method followed for the surface preparation of the adherends is summarized in this section of the report. However, a detailed process is described in document ARL-ADHES-QA-001.01 rev 2.2, section 8.3.4 Silane Coupling Agent Pretreatment Preparation.

In this method, the first step was the removal of debris from the fabrication residuals on the adherend plates and cleaning of the surface preparation area by wiping with acetone solvent. Next, the bonding surface underwent a grit-blasting process. Residue from the blasting process was spray-cleaned with an inert gas. A commercial compressed-air duster in aerosol can format was used throughout this experiment for spray-cleaning surfaces. This concluded the preparation of the aluminum adherend plates for the application of the GPS Silane Coupling Agent.

Figure 3. Form and Dimensions of Test Specimen utilized in this study. All dimensions appear in mm, with a tolerance of 0.127 mm (5 thousands of an inch).
Figure 4. (TOP LEFT) Machining process of 18 stacked Aluminum plates. (TOP RIGHT) Aluminum plates being sandblasted in the chamber. (BOTTOM) 18 plates ready for the Coupling Agent bath.

GPS Silane Coupling Agent

The preparation of the GPS Silane Coupling Agent followed the steps described below, for the four batches of specimens used for the experiments:

1) Combination of 135 ml of Ethyl Alcohol and 15 ml deionized water (9:1 ratio).
2) Adjustment of pH of solution to pH = 4.5 by adding Acetic Acid and controlling the values with pH strips. Most times this step was not necessary as pH already measured 4.5.
3) Addition of 1% by solution weight of GPS Silane coupling agent material (3-glycidoxypropyltrimethoxysilane) with a syringe.
4) Addition of a stir bar and stir on a magnetic stir plate during 20 minutes.

Once the coupling agent was prepared, the aluminum plates were immersed in the agent for 90 s. The excess of coupling solution after the bath was removed immediately with inert gas. On the last step of the surface preparation the plates were introduced in an oven at 100°C for 1 h (Figure 5.).
Figure 5. Application process of the GPS Silane coupling solution on the adherends. TOP LEFT - overview of the station during the bath of the coupling agent. TOP RIGHT - Adherend plates being submerged in coupling agent for 90 s. BOTTOM LEFT - adherends being dried off of any excess coupling agent immediately after the bath. BOTTOM RIGHT - adherends being placed in the oven.

Specimen Bonding

A tooling fixture was utilised to achieve a consistent bondline thickness during the bonding process of the specimens. In order to accommodate the dimensions for the specimens of this study, a series of modifications were made to the available fixture:

In order to allow the use of individual 25.4 mm (1 in) wide Aluminum plates during the bonding process, a specimen carrier was manufactured (Figure 6). A set of shims were used to accommodate the thickness of the plates and adjustment of the bondline thickness.
Figure 6. Specimen carrier during manufacturing (LEFT). Finished carrier being tested with a set of specimens (RIGHT).

The Epoxy mixture was performed in the ratio of 100:23 by weight, as specified in the manufacturer’s specification bulletin [3]. The Aluminum plates were placed on the specimen carrier before an even layer of the epoxy mixture was applied over the previously prepared bonding area. The fixture was later assembled with distributed weights over the top, to apply pressure to the bonding area (Fig. 7). The specimens were left to cure in the fixture for 12 h and extracted after polymerization to measure dimensions. The specimens were left to cure outside the fixture at room temperature for a minimum of 5 days.

Figure 7. Bonding fixture assembly holding 9 specimens. From Left to Right: application of Epoxy and placing of adherends on the specimen carrier. Enclosed fixture with weights on top.
3.1.3. Tension Loading Testing

The tension loading test followed the ASTM D 1002 methodology. The specimens were gripped by inserting the ends 25.4 mm inside the jaws, allowing a distance of 138.7 mm at the crosshead. A set of 4 mm thick tab ends were used at the grip areas of the specimens to ensure the alignment on the machine. The lap joints were tested at a rate of 1.27 mm/min. The equipment used for the tension loading tests was the MTS 810 Material Test System.

An identification system for the specimens was established with the format X_Y, where X indicates the bonding batch, and Y identifies the slot on the bonding-fixture’s specimen carrier in which the sample was bonded.

As a preliminary measure to the single lap tests, a tensile test was performed on a sample of aluminum 6061-T6 in order to obtain its Young’s Modulus. A stress-strain plot with two different curves were obtained for the adherend material from the two readings measured by the crosshead and the extensometer. The goal was to compare the two measurements and analyse the precision of the readings of deflection provided by the crosshead. For this test, a plate of 6061-T6 alloy with dimensions 119.06 x 29.8 x 4 mm was tested.

<table>
<thead>
<tr>
<th>Area of Cross Section (A) - mm²</th>
<th>119.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of Sample (L) - mm</td>
<td>119.06</td>
</tr>
<tr>
<td>L. of Extensometer (L_ext) - mm</td>
<td>25.4</td>
</tr>
<tr>
<td>Width of Sample (b) - mm</td>
<td>29.8</td>
</tr>
<tr>
<td>Thickness (t) - mm</td>
<td>3.930</td>
</tr>
</tbody>
</table>

Table 2. Geometry of Aluminum Sample

To obtain the Young’s Modulus (E) of the aluminum, the Tensile Stress (σ) made by the uni-axial load P over the cross section of the sample A must be calculated with equation (1). For this calculation, a point in the middle section of the elastic region in the Load - Displacement plot was chosen. The corresponding values of Load P and Displacement d are presented in Table 3. The strain of the aluminum (ε) is calculated using equation (2), where the length L is set for the length of the sample L or the length of the extensometer L_ext from table:

\[ \sigma = \frac{P}{A} \]  \hspace{2cm} (1)

\[ \varepsilon = \frac{d}{L} \]  \hspace{2cm} (2)

Finally, the value of E is calculated with the following equation:

\[ E = \frac{\sigma}{\varepsilon} \]  \hspace{2cm} (3)
Figure 8. Stress-Strain curve for “dummy” specimen with readings from crosshead and extensometer (LEFT). “Dummy” specimen under tensile testing with mounted extensometer (RIGHT).

<table>
<thead>
<tr>
<th></th>
<th>Empirical Load (KN)</th>
<th>Displacement (mm)</th>
<th>Tensile Stress of Alu. (MPa)</th>
<th>Strain of Alu.</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensometer</td>
<td>9.073</td>
<td>0.02957</td>
<td>76.11577181</td>
<td>1.16E-03</td>
<td>65,381.826</td>
</tr>
<tr>
<td>Crosshead</td>
<td>9.073</td>
<td>0.227</td>
<td>76.11577181</td>
<td>1.91E-03</td>
<td>39,922.219</td>
</tr>
</tbody>
</table>

Table 3. Results from tensile test of Aluminum specimen

The data collected by the extensometer led to a calculated Young’s Modulus of 65.4 GPa (close to the value provided by the database ASM.MATWEB of 68.9 GPa). On the other hand, the Young’s Modulus derived from the cross-head measurements was 39.9 GPa. This experiment verified that the use of an extensometer is necessary for the calculation of the Elastic and Shear Moduli. An extensometer suitable to the single lap configuration is not contemplated in the ASTM D 1002 methodology, therefore “Single lap shear joint is mostly used for comparison and quality control of adhesives, [...] it is not suitable for the determination of the true adhesive properties.” - da Silva et al. [5]
3.1.3.1. Room Temperature

Five specimens were tested at room temperature following ASTM D1002 and the procedure described in sections 3.1.2 and 3.1.3 of this report. No additional preparation was required for the room temperature specimens. Load and displacement values were recorded. Specimens were identified and stored for inspection. Selected specimens were branded from 2_3 to 2_7.

3.1.3.2. Low Temperature

Five specimens were tested at -51°C following ASTM D1002 and the procedure described in sections 3.1.2 and 3.1.3 of this report. The specimens and end tabs were placed in an MTS 651 environmental chamber which contained the grips, at a temperature of -51°C for 1 h. The specimens were clamped to the top grip leaving the bottom ungripped and allowing 20 min to reach testing temperature after sealing the chamber. The bottom jaw was gripped prior to starting the test. Load and displacement values were recorded allowing 20 minutes between opening and closing the chamber. Specimens were identified and stored for inspection. Selected specimens were branded from LT_4_1 to LT_4_5.

3.1.3.3. High Temperature

Five specimens were tested at 63°C following ASTM D1002 and the procedure described in sections 3.1.2 and 3.1.3 of this report. The specimens and end pieces were placed in the environmental chamber as in the previous test at 63°C for 1 h. The specimens were clamped to the top grip leaving the bottom ungripped and allowing 20 min to reach testing temperature after sealing the chamber. The bottom jaw was gripped prior to starting the test. Load and displacement values were recorded allowing 20 minutes between opening and closing the chamber. Specimens were identified and stored for inspection. Selected specimens were branded HT_3_8, HT_3_9, HT_4_6, HT_4_8 and HT_4_9.

3.1.3.4. 95% Relative Humidity

Five specimens were placed at an environmental chamber at 95% relative humidity for 10 days. Within 20 min after exposure, testing was performed at room temperature following ASTM D1002 and the procedure described in sections 3.1.2 and 3.1.3 of this report. Load and displacement values were recorded. Specimens were identified and stored for inspection. Selected specimens were branded RH_3_1 - RH_3_7.
3.2. Test Results

The readings measured during the experiments were used to calculate the value of the Shear Strength of the lap joints (τ). The Shear Strength has been considered the stress at which the adhesive starts yielding, and it has been referred to by stakeholders and references as the Tensile Breaking Strength of the Lap Joint (TARDEC), the Apparent Shear Strength of the adhesive (ASME), or Tensile Lap Shear Strength of the bond (LOCTITE). This parameter is calculated as follows:

\[ \tau = \frac{P}{A_{ovlap}} \]  

Where \( P \) is the Tensile Load at failure and \( A_{ovlap} \) is the area of the overlap of the adherends.

<table>
<thead>
<tr>
<th>Length of Overlap - mm</th>
<th>12.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of Sample (b) - mm</td>
<td>25.4</td>
</tr>
<tr>
<td>Area of Overlap ( (A_{ovlap}) ) - mm(^2)</td>
<td>322.58</td>
</tr>
</tbody>
</table>

**Table 4.** Geometrical parameters for calculation of Shear Stress.

This section presents the Load-Displacement graphs from all the experiments performed on the lap-joint specimens in each of the environmental conditions. A table collecting tensile loads at failure and corresponding displacements are included, with the shear strengths for each specimen calculated using equation (4). A picture has been included illustrating the nature of the failure of each one of the specimens.
3.2.1. Room Temperature

![Load-Displacement curves from tests performed at Room Temperature](image)

**Figure 9.** Load - Displacement curves from tests performed at Room Temperature

<table>
<thead>
<tr>
<th>Lap Sample</th>
<th>Joint Load at Failure (KN)</th>
<th>Displacement at Failure (mm)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 2_3</td>
<td>8.164</td>
<td>0.4188</td>
<td>25.308</td>
</tr>
<tr>
<td>Sample 2_4</td>
<td>8.373</td>
<td>0.4205</td>
<td>25.956</td>
</tr>
<tr>
<td>Sample 2_5</td>
<td>8.794</td>
<td>0.45</td>
<td>27.261</td>
</tr>
<tr>
<td>Sample 2_6</td>
<td>8.429</td>
<td>0.4435</td>
<td>26.130</td>
</tr>
<tr>
<td>Sample 2_7</td>
<td>9.118</td>
<td>0.4539</td>
<td>28.266</td>
</tr>
<tr>
<td>Avg. Values</td>
<td>8.5756</td>
<td>0.43734</td>
<td>26.584</td>
</tr>
</tbody>
</table>

**Table 5.** Calculated Shear Strength at failure at Room Temperature
At Room Temperature, the strength of the specimens averaged at 26.58 MPa. The measurements of load at failure remained consistent, as did the stiffness represented by the slope observed in the elastic region in Figure 9. Most samples showed plastic deformation with very variable deflection. All samples experienced an elastic fracture.

Figure 10 shows the adhesive was the cause of failure in all the specimens tested, except for the specimen 2_5 which failed at the interface between adhesive and adherend.
3.2.2. Low Temperature

![Load - Displacement curves from tests performed at -51°C](image)

**Figure 11.** Load - Displacement curves from tests performed at -51°C

<table>
<thead>
<tr>
<th>Lap Sample</th>
<th>Joint</th>
<th>Load at Failure (KN)</th>
<th>Displacement at Failure (mm)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 4_1</td>
<td></td>
<td>14.05</td>
<td>0.6556</td>
<td>43.555</td>
</tr>
<tr>
<td>Sample 4_2</td>
<td></td>
<td>13.07</td>
<td>0.6426</td>
<td>40.517</td>
</tr>
<tr>
<td>Sample 4_3</td>
<td></td>
<td>12.94</td>
<td>0.6572</td>
<td>40.114</td>
</tr>
<tr>
<td>Sample 4_4</td>
<td></td>
<td>13.96</td>
<td>0.7126</td>
<td>43.276</td>
</tr>
<tr>
<td>Sample 4_5</td>
<td></td>
<td>13.7</td>
<td>0.7206</td>
<td>42.470</td>
</tr>
<tr>
<td>Avg. Values</td>
<td></td>
<td>13.544</td>
<td>0.67772</td>
<td>41.986</td>
</tr>
</tbody>
</table>

**Table 6.** Calculated Shear Strength at failure at -51°C
At Low Temperature, the strength of the specimens averaged at 41.98 MPa. The measurements of load at failure remained consistent, as did the stiffness represented by the slope observed in the elastic region in Figure 11. All of the samples showed a brittle behavior with no plastic deformation recorded. All samples experienced an elastic fracture.

Figure 12. shows the adhesive was the cause of failure in all the specimens tested.
3.2.3. High Temperature

Figure 13. Load - Displacement curves from tests performed at 63°C

<table>
<thead>
<tr>
<th>Lap Joint Sample</th>
<th>Load at Failure - Yield (KN)</th>
<th>Displacement at Failure (mm)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 3_8</td>
<td>1.341</td>
<td>0.2052</td>
<td>4.157</td>
</tr>
<tr>
<td>Sample 3_9</td>
<td>1.184</td>
<td>0.1527</td>
<td>3.670</td>
</tr>
<tr>
<td>Sample 4_6</td>
<td>1.965</td>
<td>0.1989</td>
<td>6.092</td>
</tr>
<tr>
<td>Sample 4_8</td>
<td>1.918</td>
<td>0.266</td>
<td>5.946</td>
</tr>
<tr>
<td>Sample 4_9</td>
<td>1.917</td>
<td>0.2258</td>
<td>5.943</td>
</tr>
<tr>
<td>Avg. Values</td>
<td>1.665</td>
<td>0.20972</td>
<td>5.162</td>
</tr>
</tbody>
</table>

Table 7. Calculated Shear Strength at failure at 63°C.
At High Temperature, the strength of the specimens averaged at 5.16 MPa. The measurements of load at failure presented significant fluctuations relative to the low values of load recorded. The slope of the curves in the elastic region are fairly consistent, indicating a similar stiffness among the specimens. All of the samples experienced a ductile fracture.

Figure 14 shows the failure of the specimens was at the interface between adhesive and adherend, except for sample 4_9.
### 3.2.4. 95% Relative Humidity

![Load - Displacement curves from tests performed at 95% Relative Humidity.](image)

**Figure 15.** Load - Displacement curves from tests performed at 95% Relative Humidity.

<table>
<thead>
<tr>
<th>Lap Sample</th>
<th>Joint</th>
<th>Load at Failure - Yield (KN)</th>
<th>Displacement at Failure (mm)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 3_1</td>
<td></td>
<td>5.158</td>
<td>0.294</td>
<td>15.990</td>
</tr>
<tr>
<td>Sample 3_2</td>
<td></td>
<td>5.533</td>
<td>0.2927</td>
<td>17.152</td>
</tr>
<tr>
<td>Sample 3_4</td>
<td></td>
<td>5.758</td>
<td>0.3107</td>
<td>17.850</td>
</tr>
<tr>
<td>Sample 3_5</td>
<td></td>
<td>5.799</td>
<td>0.3195</td>
<td>17.977</td>
</tr>
<tr>
<td>Sample 3_7</td>
<td></td>
<td>5.426</td>
<td>0.3018</td>
<td>16.821</td>
</tr>
<tr>
<td>Avg. Values</td>
<td></td>
<td>5.5348</td>
<td>0.30374</td>
<td>17.158</td>
</tr>
</tbody>
</table>

**Table 8.** Calculated Shear Strength at failure at 95% Relative Humidity.
At High Humidity, the strength of the specimens averaged at 17.16 MPa. The measurements of load at failure remained consistent, as did the stiffness represented by the slope observed in the elastic region in Figure 15. All of the samples showed a brittle behavior with no plastic deformation recorded. All samples experienced an elastic fracture at the interface between adhesive and adherend (Figure 16).
4. Analysis of Results

![Figure 17](image-url)  
**Figure 17.** Load - Displacement curves of samples exposed to four different environmental conditions.

<table>
<thead>
<tr>
<th>Environmental Condition</th>
<th>Load at Failure - Yield (KN)</th>
<th>Displacement at Failure (mm)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp. (25°C)</td>
<td>8.794</td>
<td>0.45</td>
<td>27.261</td>
</tr>
<tr>
<td>Low Temp. (-51°C)</td>
<td>13.07</td>
<td>0.6426</td>
<td>40.517</td>
</tr>
<tr>
<td>High Temp. (63°C)</td>
<td>1.918</td>
<td>0.266</td>
<td>5.946</td>
</tr>
<tr>
<td>95% Rel. Humidity</td>
<td>5.426</td>
<td>0.3018</td>
<td>16.821</td>
</tr>
</tbody>
</table>

**Table 9.** Calculated Shear Strength at failure from samples exposed to four different environmental conditions.
This study takes the values and results from the Room Temperature tests as the normal conditions. Therefore, this is the test which will be used as a reference to the rest of the environmental conditions.

The Elastic Modulus is mentioned in this report despite the fact that it is not possible to calculate with the single-lap joint tests. However, the slope on the elastic region of the curves shown in Figure 17 are a good way to compare this parameter among the different tests.

The Elastic Modulus and Shear Strength increase significantly in colder temperatures (a 48.6% increase in strength), while they decrease dramatically in high temperatures (78.2% decrease in strength). In this study, the stiffness (Young Modulus) of the joint suffered small variations when exposed to 95% Relative Humidity, but its strength decreased by 40.7%.

At Room Temperature, the lap joints experienced plastic deformation describing a ductile behavior which was accentuated at high temperatures with ductile failures in all the specimens. At cold and high humidity conditions, however, the adhesive seems to have become brittle as they showed no signs of plastic deformation before failure.
5. Conclusion and Discussion

A big difference in the performance of the adhesive has been observed in the different environmental conditions. These results were somehow to be expected, except for the results obtained under 95% Relative Humidity. While the stiffness observed in the curve shows an expected behavior, the value of Shear Strength and the nature of the failure documented leads to an unexpected result.

Scholars and mentors of this study suggest an abnormal behavior when comparing the values of Shear Strength obtained: The single-lap joints under High Humidity have never presented such poor performance compared to the joints at Room Temperature. Typically the adhesive is almost unaffected by humidity, which suggests a misleading conclusion potentially attributed to manufacturing defects during the bonding process of the specimens. As an observation to reinforce this hypothesis, all of the samples used for the High Humidity tests were manufactured in Batch 3. Two specimens from Batch 3 were also used on the High Temperature tests, which coincidentally registered the lowest loads at failure, compared to the rest of the specimens on that same test. For this reason, no conclusions can be made either about the nature of the failure of the specimens exposed to high humidity. These describe an unexpected brittle behavior in comparison to the specimens at room temperature.

To conclude, the mechanical properties of the adhesive are heavily affected by the environmental conditions in which they perform. Specifically, the subject of study shows alarming unsuitability for higher temperature applications. However, further experiments shall be conducted to reinforce the results obtained in this study. The author suggests dedicated monitoring of the geometry of the overlap and adhesive mixture: special attention must be paid to the thickness of the bondline and mixing ratio in prospective experiments in order to guarantee consistency in data acquisition.
6. References


7. Appendices