Fillet Characterization for Project Zephyrus

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1 Introduction

The purpose of this experiment was to characterize the strength and failure behavior of the fin-airframe fillet joint for Project Zephyrus. The Zephyrus fin design uses carbon fiber fins bonded to a fiberglass fincan with large epoxy fillets. These fillets serve two main purposes: they structurally reinforce the fin root and smooth the fin-body transition to reduce aerodynamic disturbances at the airframe-fin interface.

During flight, the fins experience aerodynamic loads that create bending moments at the fin root. If the fin attachment is insufficiently strong or insufficiently stiff, the fins may crack, debond, flutter, or fail at the airframe interface. Because of this, the fillet joint must be able to carry the expected transverse fin loads with adequate margin.

This experiment was designed as a single-fin load test. A representative fincan section with two opposing fins and epoxy fillets was mounted in an Instron universal testing machine. The Instron applied a downward load to one fin until visible damage occurred. The primary goals of the test were to determine the approximate maximum load supported by the fillet joint, observe the failure mode, and compare the measured load capacity to the expected design load.

This test should not be interpreted as a complete recreation of aerodynamic loading during flight. In flight, the fin load is distributed over the fin surface, while the Instron applied a concentrated load near the fillet termination. Therefore, this experiment is best interpreted as a local structural characterization of the fin-airframe bonded joint.

2 Equipment

The experiment used an Instron 1125 universal testing machine retrofitted with an ADMET Operator Station controller. The Instron was operated in compression, with the crosshead moving downward to apply load to the test fin. The exported test data included load, position, and time, allowing the load-displacement behavior of the test article to be analyzed after testing. The major equipment used in the experiment is listed in Table 1.

Table 1: Major equipment used in the fillet characterization test.

Component	**Description**
Instron universal testing machine	Instron 1125 UTM with ADMET Operator Station
Compression fixture	Rounded rod-like fixture attached to the Instron crosshead
Support fixture	80/20 aluminum extrusion jig bolted to the Instron base table
Test article	Fiberglass fincan tube with two opposing carbon fiber fins
Fincan supports	Short metal cylinders inserted at the ends of the tube
Data output	Instron CSV file containing load, position, and time

The programmed loading rate was not separately recorded in the test notes. However, the crosshead position in the exported Instron CSV increased linearly with time. From the slope of the position-time data, the effective loading rate was approximately 2.00 mm/min, or 0.0787 in/min. This inferred loading rate was used for the analysis in this report.

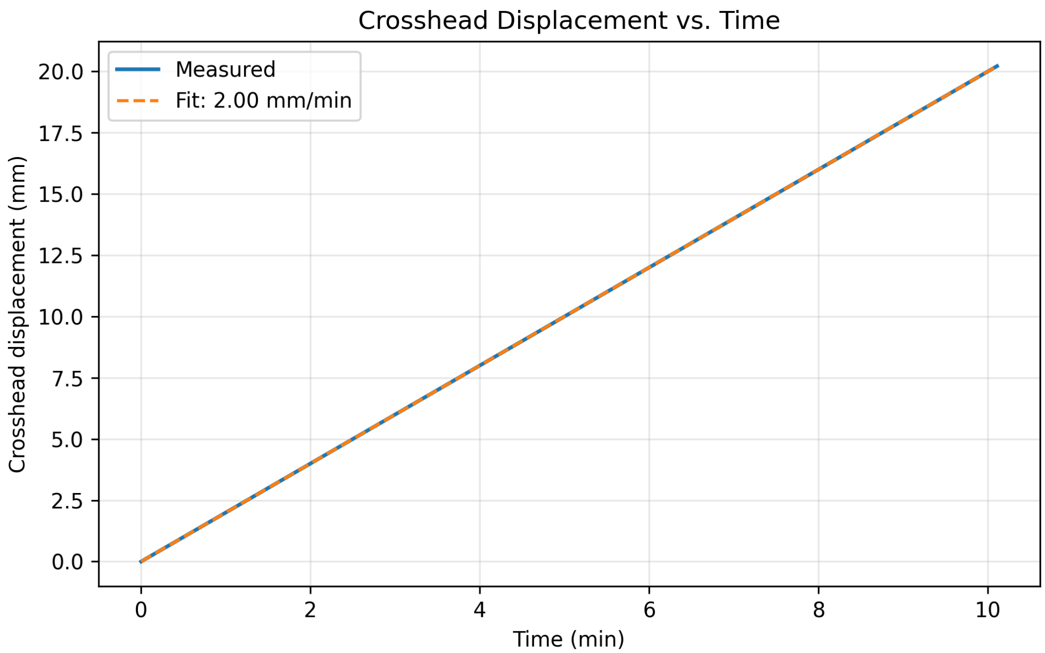

Figure 1: Crosshead displacement versus time. The approximately linear trend gives an effective loading rate of 2.00 mm/min.

3 Experimental Setup

The test article consisted of a fiberglass fincan tube with two carbon fiber fins bonded on opposite sides. The fincan inner diameter was approximately 6 in, and the tube wall thickness was approximately 0.18 in. The fincan length was approximately 12 in. The carbon fiber fins were approximately 0.25 in thick, with an estimated root chord slightly under 12 in, tip chord of approximately 9 in, and span of approximately 4 in. The fillets were made entirely from 3M DP-420-NS epoxy and had an approximate radius of 1 in. A summary of the estimated test article geometry is shown in Table 2.

Table 2: Approximate test article geometry.

Parameter	**Approximate Value**
Fincan material	Fiberglass
Fincan inner diameter	6 in
Fincan wall thickness	0.18 in
Fincan length	Approximately 12 in
Fin material	Carbon fiber
Fin thickness	0.25 in
Fin root chord	Slightly under 12 in
Fin tip chord	Approximately 9 in
Fin span	Approximately 4 in
Fillet material	DP-420-NS epoxy
Fillet radius	Approximately 1 in

The fincan was mounted horizontally in an 80/20 aluminum extrusion jig. Short metal cylinders were placed at the ends of the fincan tube to support the tube inside the fixture. One fin was oriented horizontally and left exposed for loading. The opposing fin was supported against the 80/20 fixture on the opposite side of the tube.

The Instron applied a downward force to the loaded fin through a rounded rod-like compression fixture. The load was applied near the location where the outer edge of the epoxy fillet met the exposed carbon fiber fin surface. This loading location concentrated the applied load near the fin root and fillet termination.

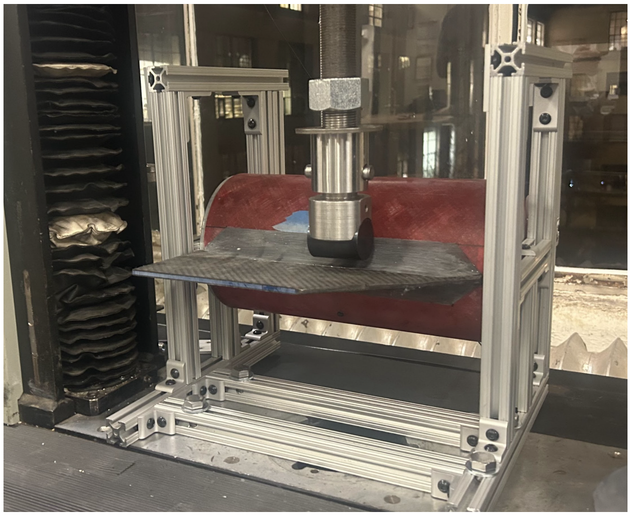

Figure 2: Overall experimental setup showing the fincan mounted in the 80/20 support jig under the Instron crosshead.

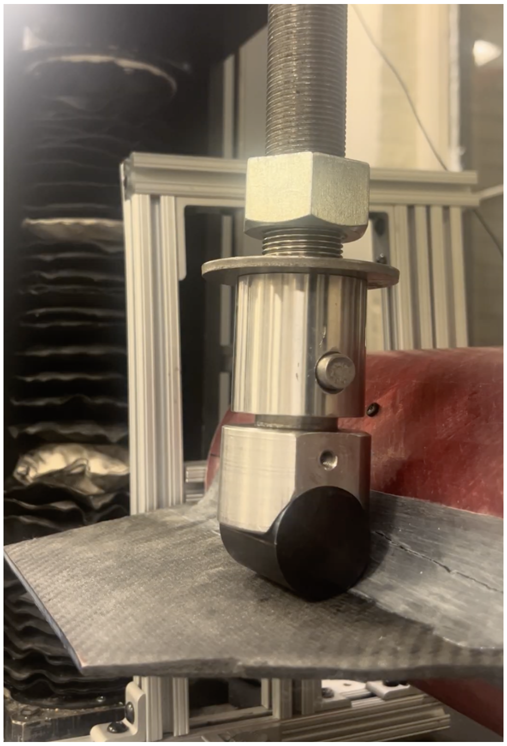

Figure 3: Close-up of the rounded compression fixture contacting the loaded carbon fiber fin near the end of the epoxy fillet.

4 Experimental Procedure

The test procedure was as follows:

1. The fiberglass fincan test article was placed into the 80/20 support jig.
2. Short metal cylindrical supports were inserted at the ends of the fincan tube to constrain the tube within the fixture.
3. The 80/20 jig was bolted to the base table of the Instron.
4. The test article was oriented so that one fin was horizontal and accessible to the Instron compression fixture.
5. The Instron crosshead was lowered until the rounded fixture contacted the exposed fin near the end of the epoxy fillet.
6. The load and displacement channels were zeroed before the test.
7. The Instron crosshead was driven downward at an inferred rate of approximately 2.00 mm/min.
8. Load, crosshead position, and time were recorded throughout the test.
9. The test was continued until cracking and visible damage occurred at the fin-airframe connection.

The primary measured quantities were load and crosshead displacement. Because the Instron records crosshead position rather than direct fin deflection, the displacement data includes deformation of the fin, deformation of the fillet, compliance of the fincan and fixture, and any rigid-body motion of the test setup.

5 Results and Analysis

The Instron test reached a maximum load of 5425 N. Converting to pounds-force:

$$F_{\max} = 5425 \text{ N} \left(\frac{1 \text{ lbf}}{4.448 \text{ N}} \right) = 1219.6 \text{ lbf} \tag{1}$$

Therefore, the measured maximum load was approximately:

$$F_{\max} \approx 1220 \text{ lbf} \tag{2}$$

This agrees with the maximum fillet strength reported in the Zephyrus CDR slides. The load-displacement data showed increasing load with increasing crosshead displacement until the peak load was reached. After the peak, the load dropped, indicating damage initiation or propagation in the test article.

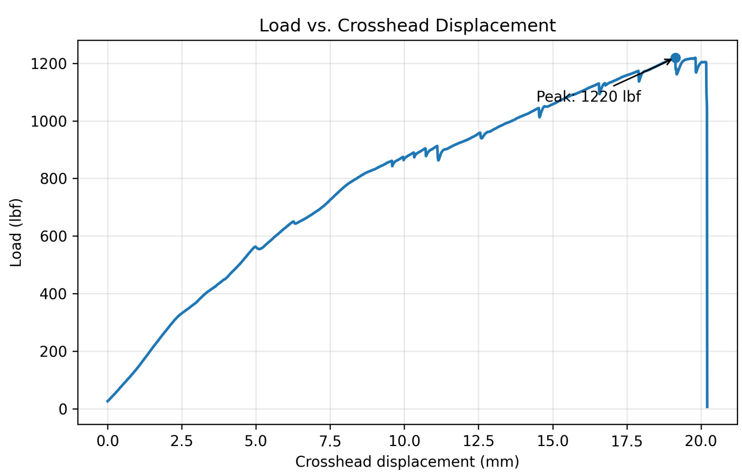

Figure 4: Instron load versus crosshead displacement for the single-fin fillet characterization test.

The failure mode was observed as cracking and splitting near the fin-airframe connection. The damage was concentrated at or near the epoxy fillet/base interface where the carbon fiber fin was bonded to the fiberglass fincan. This indicates that the test primarily loaded the bonded joint and fillet region rather than causing a simple bending failure of the carbon fiber fin itself.

Figure 5: Observed cracking near the epoxy fillet and fin-airframe connection after loading.

The Zephyrus CDR estimated that a single fin is expected to experience approximately 500 lbf of lift at maximum dynamic pressure and 5 degrees angle of attack. Comparing the measured maximum load to this expected flight load gives the factor of safety:

$$\text{FOS} = \frac{F_{\text{max}}}{F_{\text{expected}}} = \frac{1219.6 \text{ lbf}}{500 \text{ lbf}} = 2.44 \tag{3}$$

Thus, the measured load capacity corresponds to a factor of safety of approximately 2.4 relative to the expected single-fin lift load.

A summary of the main test results is shown in Table 3.

Table 3: Summary of main test results.

Quantity	**Value**
Inferred loading rate	2.00 mm/min
Maximum measured load	5425 N
Maximum measured load	1219.6 lbf
Reported maximum fillet strength	Approximately 1200 lbf
Expected single-fin lift load	Approximately 500 lbf at max q and 5 deg AOA
Calculated factor of safety	Approximately 2.4
Observed failure mode	Cracking and splitting near fin-airframe bonded joint

Because the load was applied near the end of the fillet instead of at the fin aerodynamic center, the test result is not directly equivalent to a full-fin cantilever bending test. The result is more accurately interpreted as a local joint strength measurement. However, this is still useful because the fin root and fillet are critical regions for transferring aerodynamic loads from the fin into the airframe.

The expected root bending moment during flight can be approximated using the expected fin lift load and the spanwise location of the fin center of lift. For a trapezoidal fin, the center of lift can be approximated as the centroid, or center of area, of the trapezoid. If the root chord is c_r, the tip chord is c_t, and the fin span is b, the spanwise centroid location measured from the root is:

$$\bar{y} = \frac{b(c_r + 2c_t)}{3(c_r + c_t)} \tag{4}$$

Using an approximate root chord of 12 in, tip chord of 9 in, and span of 4 in:

$$\bar{y} = \frac{4(12 + 2(9))}{3(12 + 9)} = 1.90 \text{ in} \tag{5}$$

The approximate expected root bending moment is therefore:

$$M_{\text{expected}} = F_{\text{expected}}\bar{y} = (500 \text{ lbf})(1.90 \text{ in}) = 950 \text{ lbf} \cdot \text{in} \tag{6}$$

For comparison, the local bending moment applied during the test can be estimated using the measured maximum load and the approximate load application distance from the airframe wall. If the load application distance is approximated as the 1 in fillet radius:

$$M_{\text{test}} = F_{\max}d \tag{7}$$

$$M_{\text{test}} \approx (1219.6 \text{ lbf})(1 \text{ in}) = 1220 \text{ lbf} \cdot \text{in} \tag{8}$$

Both moment estimates should be treated as approximate. The expected flight moment depends on the aerodynamic load distribution, while the test moment depends on the exact fixture contact location, which was not measured. Additionally, the Instron test applied a concentrated load near the fillet termination, while the actual flight load is distributed across the fin surface.

6 Conclusion

The single-fin fillet characterization test measured the strength and failure behavior of the Zephyrus fin-airframe bonded joint. A fiberglass fincan with two opposing carbon fiber fins and 1 in DP-420-NS epoxy fillets was mounted in an 80/20 jig and loaded in compression using an Instron universal testing machine. The load was applied downward to one fin near the termination of the epoxy fillet.

The test reached a maximum load of 5425 N, or approximately 1220 lbf. This agrees with the CDR-reported fillet maximum strength of approximately 1200 lbf. The Zephyrus CDR estimated that a single fin is expected to experience approximately 500 lbf of lift at maximum dynamic pressure and 5 degrees angle of attack. Comparing the measured maximum load to this expected flight load gives a factor of safety of approximately 2.4. The observed failure mode was cracking and splitting near the fin-airframe connection, indicating that the bonded joint and fillet region were the critical areas of the test article.

An approximate expected root bending moment was also estimated by modeling the fin as a trapezoid and using the centroid as the spanwise center of lift. Using an expected lift load of 500 lbf and a centroidal lever arm of approximately 1.90 in, the expected root bending moment is approximately 950 lbf·in. For comparison, the estimated local bending moment applied during the test was approximately 1220 lbf·in, assuming a 1 in load application distance from the airframe wall. These moment estimates are approximate because the actual aerodynamic load is distributed over the fin surface, while the Instron applied a concentrated load near the fillet termination.

Overall, the experiment supports the conclusion that the Zephyrus fillet joint had significant load capacity relative to the expected flight load. However, the test setup introduced uncertainty because the 80/20 jig lifted slightly during loading and because the exact load application point was not measured. Future testing should constrain the fixture more completely, measure the load application distance, document the loading rate before the test, and use multiple test articles to improve repeatability. A future version of the test should also consider loading the fin at a location more representative of the aerodynamic center of pressure, or comparing the measured peak load to a root bending moment derived directly from flight load calculations.

7 Limitations

Several limitations affected the accuracy and interpretation of the test.

First, the rear of the 80/20 jig lifted slightly from the Instron base table during loading. This occurred because the downward force applied to one side of the fixture created an overturning moment. The back side of the jig was not fully constrained to the table, so the fixture was able to lift as the applied load increased. As a result, the measured crosshead displacement includes not only deformation of the fin and fillet, but also motion of the test fixture. Therefore, the displacement data should not be interpreted as pure fin deflection.

Second, the exact load application point was not measured. The load was applied near the end of the fillet where the epoxy met the exposed carbon fiber fin, but the exact distance from the airframe wall is uncertain. This limits the accuracy of any bending moment calculation based on the test data.

Third, the fin dimensions used in this report are approximate. The fincan length, root chord, tip chord, and span were estimated from the test article rather than measured directly. These estimates are sufficient for describing the setup, but they should not be used for final analytical validation without confirmation from CAD.

Fourth, the test used a concentrated load applied by a rounded fixture. Actual aerodynamic loading during flight is distributed across the fin surface. Because of this, the test does not directly reproduce the flight load distribution. Instead, it provides a local characterization of the fin-root and fillet joint.

Finally, only one test article was tested. A single test provides useful information about the approximate failure load and failure mode, but it does not provide statistical confidence in the result. Additional tests would be needed to quantify variability between test articles.

8 Conclusion

The single-fin fillet characterization test measured the strength and failure behavior of the Zephyrus fin-airframe bonded joint. A fiberglass fincan with two opposing carbon fiber fins and 1 in DP-420-NS epoxy fillets was mounted in an 80/20 jig and loaded in compression using an Instron universal testing machine. The load was applied downward to one fin near the termination of the epoxy fillet.

The test reached a maximum load of 5425 N, or approximately 1220 lbf. This agrees with the CDR-reported fillet maximum strength of approximately 1200 lbf. Using the reported factor of safety of 2.4, this corresponds to an implied equivalent design load of approximately 500 lbf. The observed failure mode was cracking and splitting near the fin-airframe connection, indicating that the bonded joint and fillet region were the critical areas of the test article.

Overall, the experiment supports the conclusion that the Zephyrus fillet joint had significant load capacity relative to the estimated design load. However, the test setup introduced uncertainty because the 80/20 jig lifted slightly during loading and because the exact load application point was not measured. Future testing should constrain the fixture more completely, measure the load application distance, document the loading rate before the test, and use multiple test articles to improve repeatability. A future version of the test should also consider loading the fin at a location more representative of the aerodynamic center of pressure, or comparing the measured peak load to a root bending moment derived directly from flight load calculations.

A Data Processing Notes

The raw Instron CSV was used to calculate the peak load, effective loading rate, and load-displacement response. The primary columns used were load, crosshead position, and time. Crosshead displacement was calculated by subtracting the initial recorded crosshead position from the recorded position data.

The effective loading rate was calculated from a linear fit to crosshead displacement versus time. The maximum load was identified as the largest recorded load value in the CSV. The raw CSV should be stored with the project documentation so future team members can reproduce the analysis.

References

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