Full Scale Validation Testing for Legacy Aircraft Finite Element Models

Mr. D. Wieland
Southwest Research Institute, United States of America

Abstract

As the US military extends the service life of aging weapon systems, the need for accurate models of aircraft structures has become critical. The original finite element models (FEMs) used during the development of these legacy systems were either not procured by the military or not maintained, necessitating the development of new FEMs from 2D drawings and scanned parts. Given that many weapon systems were tested up to 60 years ago, the absence of original test data presents significant challenges for model validation. This has led to the United States Air Force (USAF) performing full scale test for model validation.

This paper delves into SwRI's recent experiences in performing full-scale validation test for the T-38 and A-10 aircraft finite element models. To achieve this, a diverse array of measurement techniques, including deflection potentiometers, strain gages, fiber optic strain sensors, and digital image correlation, were employed.

Depending on the component, the validation tests often are performed on structure that will be returned to active service. This necessitates extra caution to ensure the structure is not damaged and can limit options for methods to attach to and load the structure. The presentation will discuss the specific test setups, the resulting data, status of the validation effort, and key lessons learned from the validation process.

1. Background

Southwest Research Institute (SwRI) has been a leader in aircraft testing for over 30 years, during which they have primarily focused on certification requirements. The main types of testing include static strength testing to determine the aircraft's ability to withstand applied forces without permanently deforming, and fatigue life testing to estimate how long the aircraft components will last under repeated loads. These tests have also historically generated valuable data used for finite element analysis (FEA) validation, although this was not the primary reason for conducting these tests. Recently, however, SwRI has shifted its focus towards testing specifically for the validation of legacy aircraft digital twins. In particular, SwRI has conducted validation testing for the T-38 and A-10 FEA digital twins.

2. T-38 Background

The T-38 is a supersonic jet trainer that was designed in the late 1950s. Introduced into service between 1961 and 1972, the T-38 is now entering its fourth 20-year lifetime. However, its usage has changed radically over the years. For the T-38 to remain in service beyond 2035, various modification programs have been performed and new wings have been implemented, leading to a loss of the original analytical baseline. Therefore, there is a significant desire to update the structural analysis baseline. Northrop Grumman (NG) is developing a detailed finite element model (FEM) for the aircraft, while SwRI is providing full-scale testing support to ensure the FEM is accurate and validated against real-world test data.

3. T-38 Finite Element Model (FEM)

The T-38 FEM was developed over several stages, with most sections modelled separately at major production breaks. These sections include:

- The fuselage
- The boattail
- The vertical stabilizer
- The horizontal stabilizer
- The wings
- The speed brake package

The full model comprises over 2 million elements and nodes and possesses more than 12 million degrees of freedom. With a mesh size of approximately 1 inch, the model is highly detailed, with every structural part and fastener being modelled. The major components of the FEM are shown in Figure 1: .

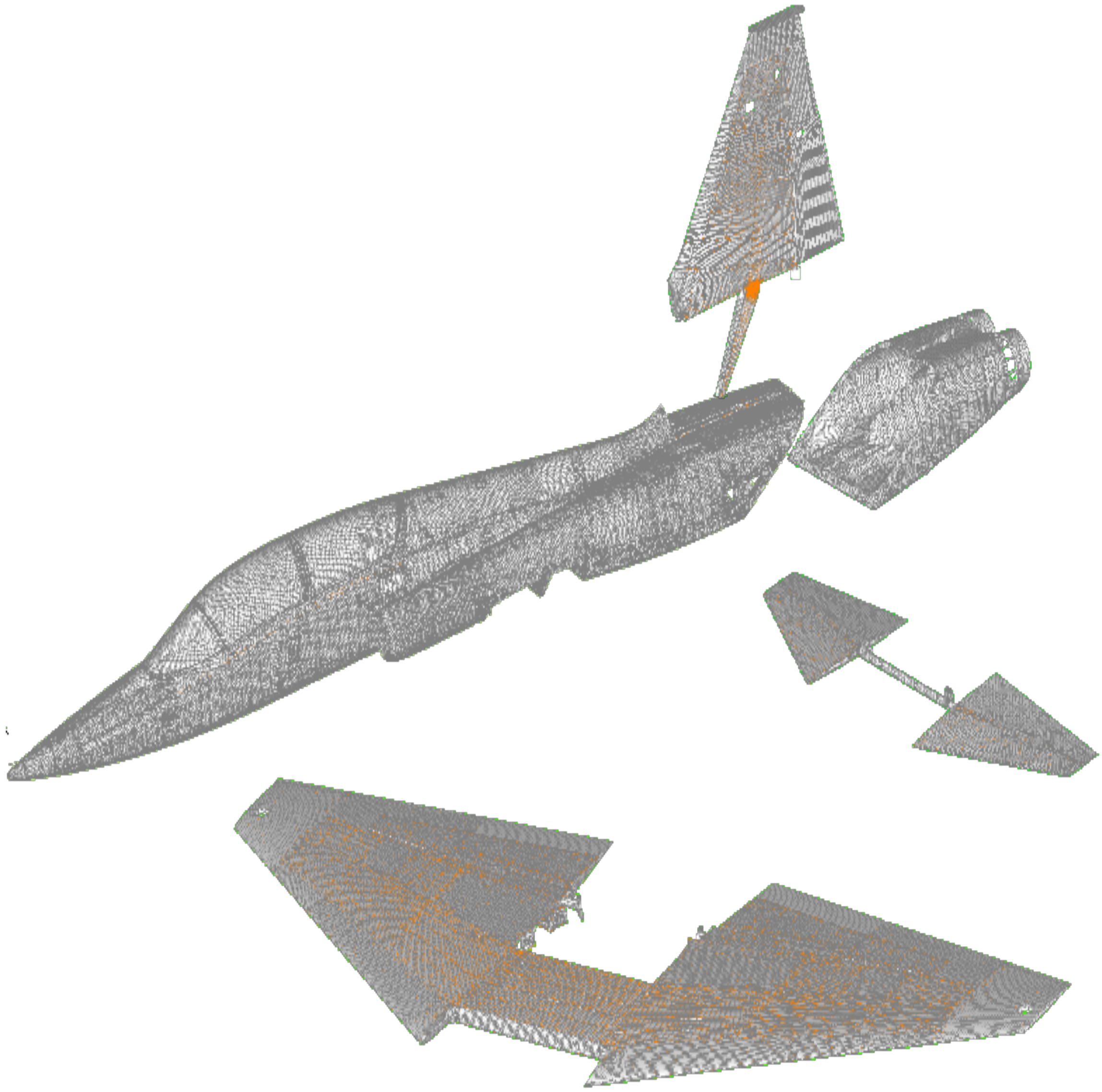

Figure 1: T-38 FEM Major Components

4. Previous T-38 Tests

The T-38 has undergone many full-scale tests in the past including the original component certification test performed in the late 1950s and early 1960s. A redesigned wing (-29) was tested in the early 1990s and the fuselage underwent a fatigue test in the 2005 timeframe. In 2014 a fatigue test of the -29 wing was performed. The data from the original certification testing was of limited use due to the major structural upgrades performed to the fuselage and the redesigned wings since then.

Although recent fuselage and wing fatigue tests provided valuable validation data, their primary focus on fatigue testing resulted in relatively low strain levels compared to limit load for most recorded events, limiting their usefulness for detailed model correlation. This led to issues with validations due to the low strain readings.

The primary purpose of the Fuselage Fatigue Test was to determine the certified fatigue life of the fuselage with all the major structural modifications. This resulted in strain gages being concentrated near fatigue critical locations, especially the upper longerons. Only limited gages were installed for items like load path validation. Strains were measured at every test endpoint in the fatigue spectrum and recorded. In addition, a strain survey of four load cases was conducted every 1,000-hour test block, with data also recorded at each test endpoint.

The purpose of the -29 wing fatigue test was also to determine the certified test demonstrated fatigue life. Two -29 wings were fatigue tested, each subjected to different fatigue usages. Again, strain gages were placed near fatigue critical locations, with additional gages deployed for FEM validation. Due to budget limitations the number of strain gages for FEM validation were limited. Similarly to the fuselage test, strains were measured at every test endpoint in the fatigue spectrum and recorded. A strain survey of eight load cases was conducted every 1,000-hour test block, with data recorded at each test endpoint. Figure 2: shows the T-38 -29 wing being tested.

Figure 2: T-38 -29 Wing Test Undergoing Loading

5. T-38 -33 Wing Validation Test

All this data was valuable for validating the T-38 fuselage and -29 wing components, but the T-38 fleet is currently undergoing wing replacements. The new wings (−33) include several modifications to enhance fatigue resistance.

The USAF decided to perform a strain survey of a brand-new production -33 wing. This test was specifically performed for the purpose of gathering data for FEM validation.

To validate the redesigned -33 wing FEM, SwRI performed a strain survey using an existing test fixture. The test used a new, undamaged wing, an MTS Aero ST DAC, and 12 simplified fatigue load conditions (9 wing up bending and 3 wing down bending). Figure 3: compares the target and applied wing bending moment diagram. NG specified the locations for 100 strain gages which were placed using flat pattern mylars to ensure precise positions aligned with the FEM mesh. Additionally, 14 deflection transducers were used to measure wing deflections. Figure 3: shows a sample of the test set up.

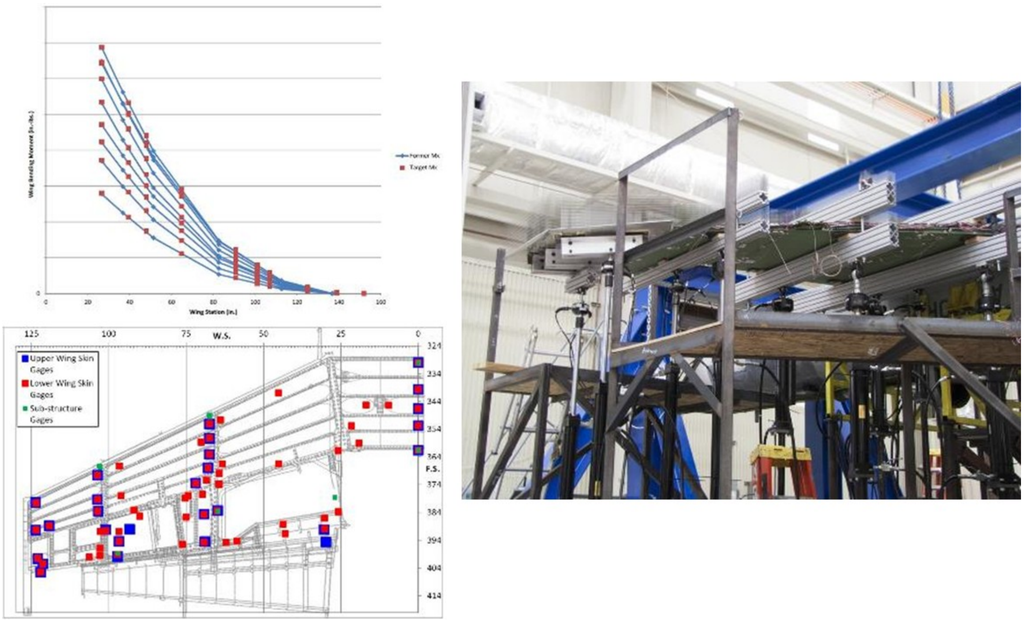

Figure 3: T-38 -33 Wing Test, Upper left is a chart showing the T-38 -33 Wing Test Applied Wing Bending Moment as Compared to Target Wing Bending Moment for the 9 Wing Up Bending Conditions, lower left is the strain gage map and right side is a photograph of the test undergoing loding.

The strain survey involved repeating 12 load cases five times, yielding very repeatable results. The average strain standard deviation was found to be 3.7 microstrain, which is indicative of the consistency and repeatability of the test setup. These results are now being used in the ongoing correlation and validation of the T-38 FEM. NG is using the USAF structures bulletin for model correlation and validate for this effort [1]. Figure 4: shows a sample of strain gaged data and a correlation plot.

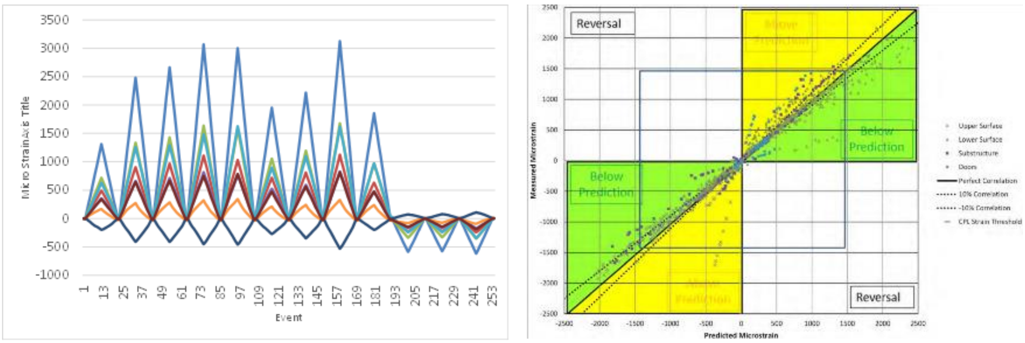

Figure 4: Sample of T-38 Wing Strain Gage Measurements (left) and Strain Gage Correlation Plot (right)

6. T-38 Empennage Test

Previous testing focused on the main fuselage and did not include the vertical stabilizer or boattail (collectively referred to as the empennage structure). To validate the empennage FEM, SwRI performed a strain survey using a retired fuselage recovered from desert storage, with a boattail removed from service. The test setup included the use of an MTS Aero ST DAC and six design limit load distributions, comprising three symmetric fuselage bending conditions, one vertical stabilizer case, and two rolling conditions. Strain measurements were taken using 332 strain gage channels and six fiber optic strain measuring channels. Reaction load measurements involved eight instrumented bolts holding the boattail onto the aft fuselage and multi-axis load reaction measurements at four primary wing interface joints. Additionally, 23 global deflection measurements were made using string potentiometers.

The strain survey was successfully completed, with each load case repeated multiple times. Unit loads were also applied to each actuator. All test setups and survey data were supplied to the USAF and NG, who are currently in the process of validating the FEM for the empennage area. A sample of results are shown in Figure 5: .

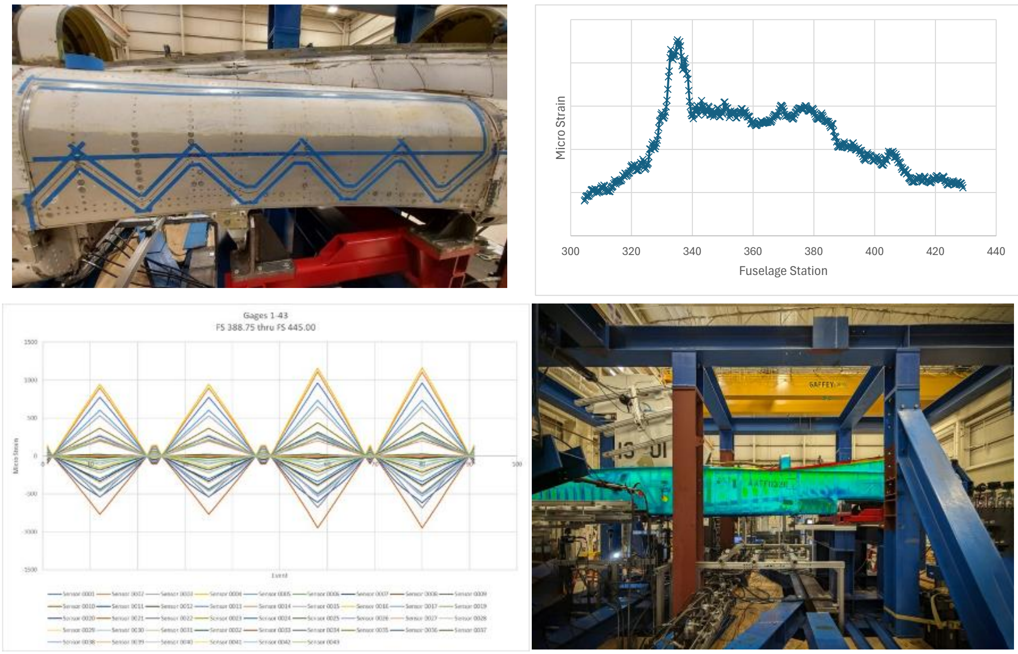

Figure 5: T-38 Empennage Test, Upper left fiber optic strain location, upper right sample fiber optic strain results along dorsal longeron, lower left sample strain gage date for different load cases, lower right FEA strain contours overlaid on test fuselage

7. A-10 Background

The Fairchild Republic A-10 Thunderbolt II is a single-seat, twin-turbofan, straight-wing, subsonic attack aircraft developed by Fairchild Republic for the United States Air Force (USAF). In service since 1977, it is expected to remain in service until 2028. The SimCenter Nastran FEM for the A-10 was developed in stages by the USAF A-10 Analysis group, rather than the OEM. Similar to the T-38 model, it was modelled in sections at major production breaks, including fuselage sections, nacelles, empennage, and wings. The full model consisted of over 2.5 million elements and nodes, with more than 12 million degrees of freedom and a 1-inch mesh size.

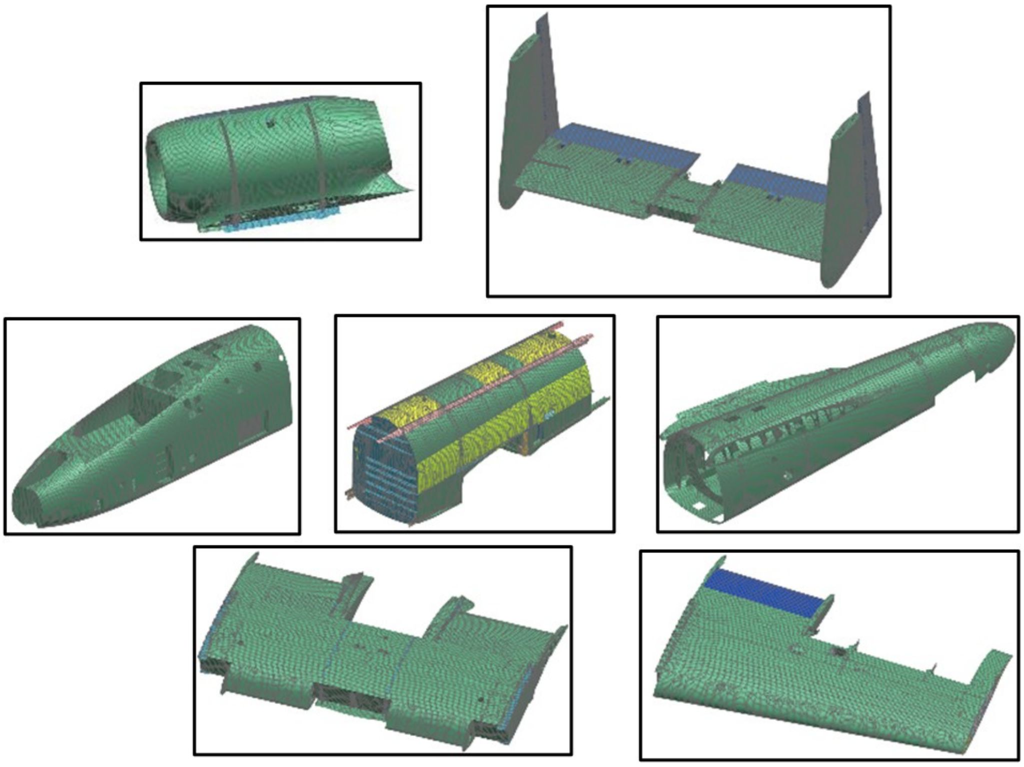

Figure 6: A-10 Finite Element Model Major Components

Previous A-10 tests included a Fuselage & Empennage Fatigue Test and a Thick Skin Wing strain survey. The fuselage test involved 510 unique load conditions, using 46 actuators, 318 strain gages, and 7 deflection potentiometers. The Thick Skin Wing Strain Survey was performed for three load conditions, utilizing 149 strain gages, and 24 deflection potentiometers. More details on these test results are available in the 2019 ASIP presentation [2].

8. A-10 Empennage Strain Survey

A strain survey was performed on the A-10 empennage structure in 2020 in order to develop additional data for the A-10 FEM correlation and validation. The survey only included the horizontal stabilizer, vertical stabilizers and the elevators. The rudder was simulated with a rod spanning the lower and middle attach lugs. Twelve actuators were strategically located with load distribution closely matching NG's design loads used during the fuselage full-scale fatigue test. Data collection included 190 strain gages across 6 load cases, with each load cylinder individually loaded to maximum extension and retraction loads to isolate strain gage response. Figure 7: shows a photograph of the empennage test set up and a sample strain gage map.

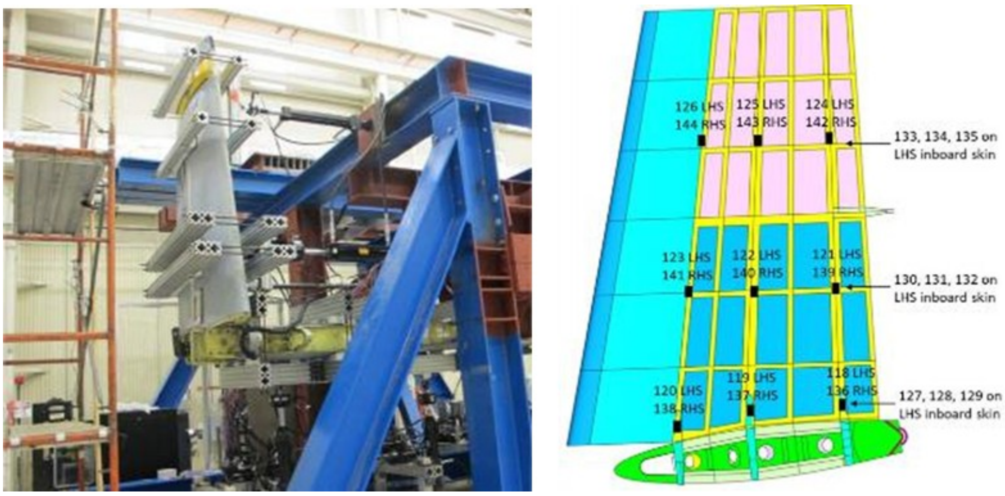

Figure 7: Right Side of the A-10 Empennages Strain Survey Test and A Sample of The A-10 Vertical Stabilizer Strain Gage Map.

The strain gage response was largely as expected, exhibiting linearly elastic behaviour. However, evidence of elastic nonlinear responses was observed in spar webs and other unexpected locations, such as some skin gages and the spar cap at BL 108. In some cases, the non-linearity followed the same path in both loading and unloading phases, while in others, the paths diverged. The A-10 analysis group is corelating and validating the model. Figure 8: shows a sample of the strain gage response as compared to the predicted strains for a load case.

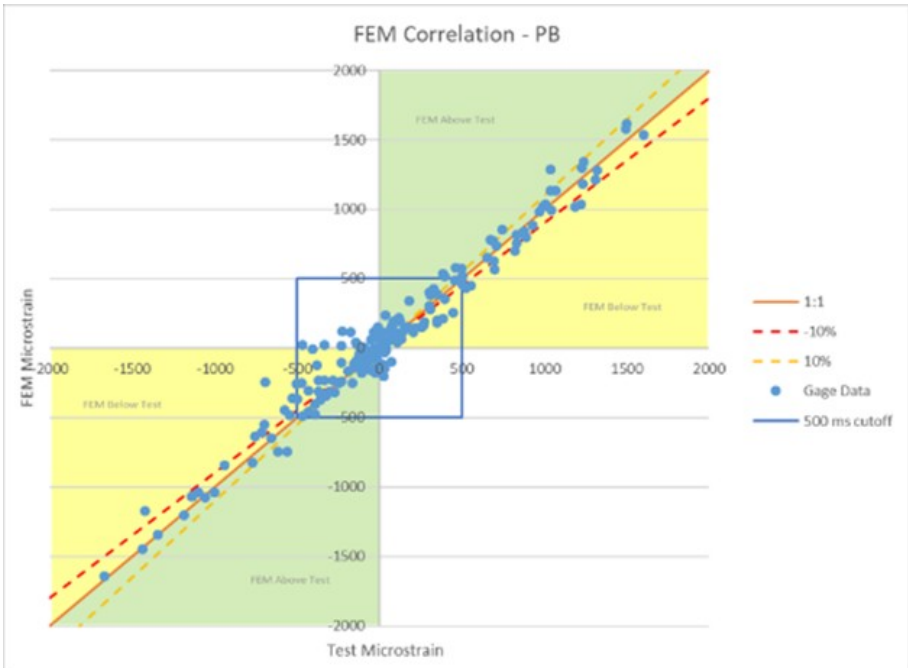

Figure 8: A-10 Empennage Sample Correlation Plot

9. A-10 Nacelle Strain Survey

A strain survey of the A-10 engine nacelle was performed in 2023-2024 focused solely on producing large strains suitable for model validation. In previous testing of the A-10 nacelle, flight loads were applied to the test article resulting in low strain reading. This resulted in difficulty validating the models. So it was decided to test the nacelle again but this time applying large loads to the major structural components at various location to ensure larger strain responses. The test setup included four configurations and eight load cases, with two actuators and four multi-axis loadcells to measure reaction loads. A total of 66 axial strain gages and 42 rosettes were used for the strain measurements.

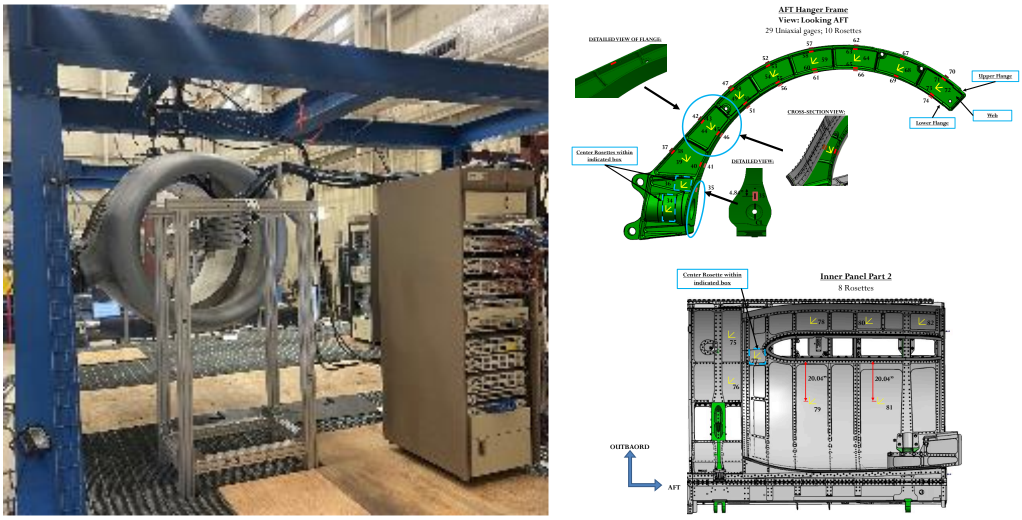

Figure 9: A-10 Nacelle Test Set Up and Sample Strain Gage Maps

Four different test configurations were tests to investigate the stiffening effects of secondary structure. The four configurations were the flight configuration, the aft cowling on with doors open, the aft cowling off with doors closed and the aft cowling off with doors open.

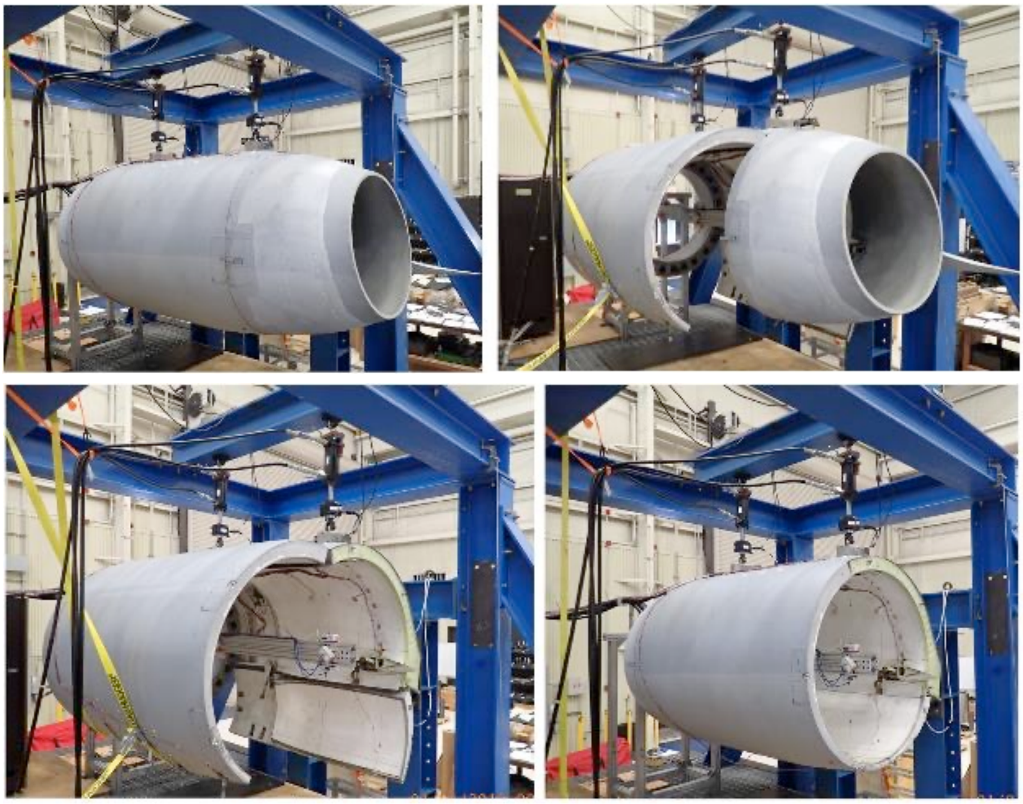

Figure 10: The four test configurations, aft cowling on doors shut, aft cowling on doors open, aft cowling off doors open and aft cowling off doors closed

The strain survey was successfully completed, with each load case repeated three times. Unit loads were also applied for each actuator. All test setup and survey data were supplied to the USAF A-10 analysis group, which is currently validating the nacelle FEM. Is a sample comparing strain gages results with the nacelle doors closed and open.s

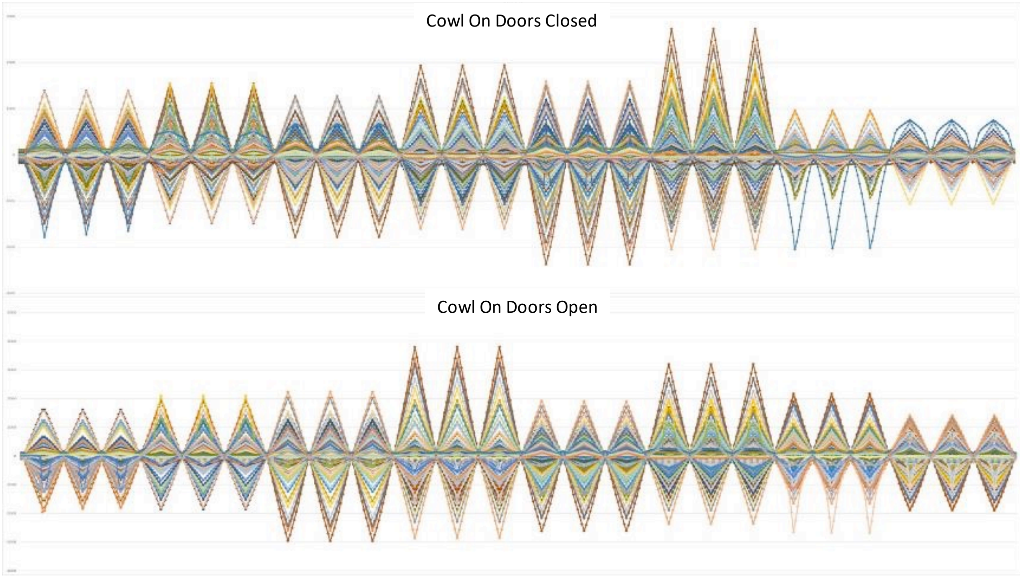

Figure 11: Sample A-10 Nacelle Strain Gage Data for two Test Conditions

10. Testing Lessons Learned

SwRI has been performing full scale testing for over 30 years and during that time we have learned a few lessons on validation testing. They are discussed below.

Well defined deflection measurement locations are critical. This includes global deflections such as string pots and measurements of very small deflection via strain gages. Since structural FEMs are basically predicting deflections based on the stiffness of the structure and the applied loads, it is a good idea to think about how to measure the overall deformation of the model.

For example, ideally the analysist may want a perfectly rigged test fixture constraint. Since that is frequently not possible in the test lab, measuring test fixture deflections may be important in order to correct for rigid body rotations and translations due to the test fixture deflections.

Measuring the global deflection response of the model such that the analysis can validate against more than only of few deflects is often desirable to determine if the model is deforming correctly. For example, on a wing multiple deflections along the chord and the span would be measures so that both wing bending and torque can be measured.

Strain gage placement should be chosen carefully. Ideally the strain gage should be above 25% of the material yield strength for at least one of the validation load cases without being in a high stress gradient. Strains below

25% can result in large percentage errors when correlating strain to FEM results even though the delta strain is small. Placing gages in high strain gradients can also be problematic for several reasons. The FEM may not be refined enough to capture the gradient, which would make it difficult to correlate to and possibly lead to needing to refine the model or to use detailed breakout models. Multiple gages should be placed on cross-sections to better assess overall load distribution.

Applying unit load cases for all load actuators can be very beneficial for model validation. It can help localize what is causing specific issues with the model that may be harder to identify when there are multiple loads being applied. They can also be used to verify the linear elastic response of the test article. In theory applying each load separately and then summing up their responses should give the same results as when all the loads are applied at the same time.

For surveys intended for FEM correlation, simplifying the load and constraints as much as possible reduces the chances of error in modelling the test setup and the chances of the test being performed wrong. In addition, designing the test specifically for model validation can allow more freedom in the applied loads to exercise areas of the structure that may not get strained under design loads. For example, structure that is primarily sized for stiffness may have low strain response for a typical design case. This can make it difficult to validate due to low measured strains, but if special loads can be applied to the test that exercise that structure without damaging other structure it can help with model validation.

11. Conclusion

SwRI’s extensive experience in aircraft testing has transitioned to a more data-driven approach aimed at validating digital twins for legacy aircraft. The detailed and thorough testing processes ensure reliable and repeatable results, contributing to the continued serviceability and improved performance of legacy aircraft. SwRI's pivotal role in the advancement of modern aerospace technology is demonstrated by its meticulous approach to testing and validation.

12. References

[1] “Structures Bulletin: Guidance on Correlating Finite Element Models to Measurements from Structural Static Tests,” AFLCMC/EZ , Bldg 28, 2145 Monahan Way, WPAFB, OH 45433-7101 , Feb. 2020.

[2] M. Worley, “Validation of the A-10 Full- Scale Finite Element Model Update on Development and Planned Future Use Cases AFLCMC,” presented at the ASIP Conference, San Antonio, TX, Dec. 04, 2019.