Ballistic and Cyclic Rig Testing of Braided Composite Fan Case Structures

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ABSTRACT

FAA fan blade-out Certification testing on turbofan engines occurs very late in an engine's development program and is very costly. It is of utmost importance to approach the FAA Certification engine test with a high degree of confidence that the containment structure will not only contain the high-energy debris, but that it will also withstand the cyclic loads that occur with engine spooldown and continued rotation as the non-running engine maintains a low rotor RPM due to forced airflow as the engine-out aircraft returns to an airport. Accurate rig testing is needed for predicting and understanding material behavior of the fan case structure during all phases of this fan blade-out event: Impact, Spooldown, Continued Rotation (also known as windmilling) and Landing.

INTRODUCTION

The fan case on a turbofan engine provides the outer flow path for air passing through the fan and provides structure for attachment of the nacelle inlet and other engine components as shown in Figure 1. In addition to these structural requirements, the fan case must be able to contain a released fan blade in the instance of an unintended release at the engine’s highest operating speed. During normal engine operation, the additional material required for blade containment is a parasitic weight that reduces the engine thrust/weight ratio and increases fuel consumption. It has thus been of high importance to reduce the weight of large diameter engine components such as the fan case.

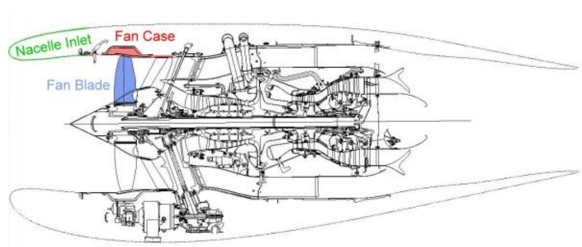

Figure 1. Cross-section of turbofan engine, highlighting locations of the fan blade, fan case and nacelle inlet.

Carbon fiber reinforced polymer composites are being used extensively in the next generation of commercial aircraft because the weight of a turbofan engine fan case can be significantly reduced.

The materials used for this application are high strength, standard modulus carbon fibers and epoxy matrix resins that are suitable for use in various resin infusion processes.

Honeywell Aerospace (Phoenix, Arizona) has worked with A&P Technology (Cincinnati, Ohio) to fabricate a series of braided composite fan cases for testing, and eventual production use on turbofan engines. In each fan case, a triaxial braid architecture with large, flat fiber bundles is used for both manufacturing efficiency and material performance. An example of the triaxial braided preform material (before resin infusion) is shown in Figure 2, and a composite fan case prototype is shown in Figure 3.

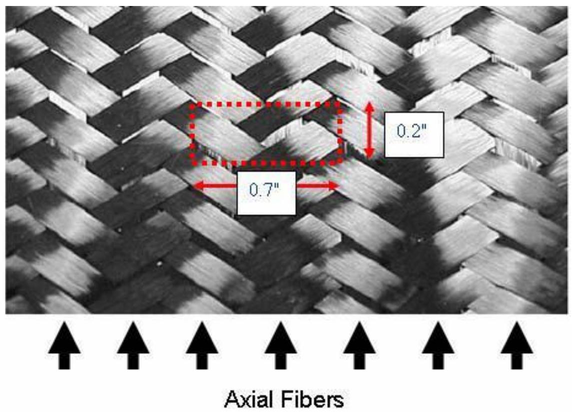

Figure 2. Triaxial braid carbon fiber material. Surface bias fibers are visible. The location of subsurface axial fibers is indicated by arrows. Unit cell size is indicated in red.


Figure 3. Braided composite fan case with aramid outer wrapping.

Honeywell Aerospace and A&P have then worked with NASA Glenn Research Center (Cleveland, Ohio) to conduct rig tests that simulate these ballistic and cyclic events. This allows for early detection of design flaws that must be corrected prior to the FAA Certification test.

BALLISTIC TESTING

Impact loads were applied to each fan case by accelerating actual engine fan blades, shot into the fan case wall with an orientation and velocity representative of a blade-out event. This was done using the single-stage gas gun configuration shown in Figure 4.

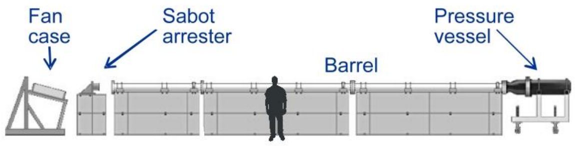

Figure 4. Schematic of the gas gun and the fan case mounted at an incline in front of the gun barrel.

The gun consists of a pressure vessel and a 12" diameter gun barrel with a length of 40 feet.

Pressure from the pressure vessel is released into the gun barrel using an electrically-heated burst disk. The fan blade projectile is supported in a cylindrical can-shaped sabot at the gun breach and is accelerated by the released pressure through the barrel. At the end of the barrel the sabot is stopped by a sabot arrester, and the projectile continues on to impact the fan case as represented in Figure 5.

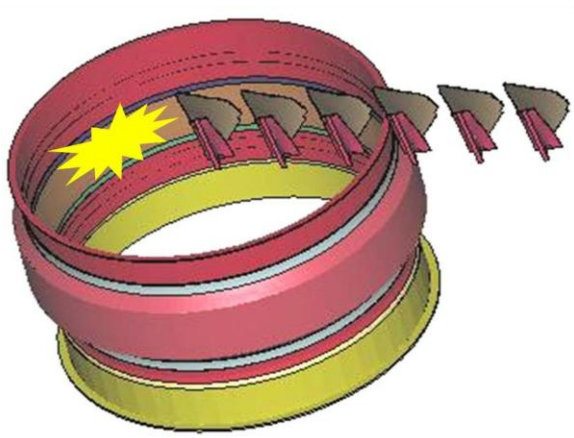

Figure 5. Fan blade flight path.

Computer simulations were performed with the commercial transient finite element code LS-DYNA (LSTC, Livermore, California) to determine the fan blade orientation within the sabot that would result in the proper impact location, as well as produce damage similar to that observed in previous engine blade-out tests.

Ballistic tests were performed on a series of aluminum fan cases to establish the validity of the test method. Composite cases were then tested using the same test conditions, with impact speeds up to 900 ft/s. In all tests the fan blade was contained by the aramid wrap surrounding the fan case.

After each ballistic test and subsequent aramid wrap inspection, the aramid was removed so the fan case could be fully inspected on its inner and outer surfaces. In addition to the damage produced by the fan blade, there was additional case damage resulting from loads caused by the aramid wrap as it deformed to contain the blade. An example of a ballistically-damaged fan case after inspection is shown in Figure 6.

Figure 6. Damaged fan case after ballistic test.

When compared to ballistically-tested aluminum fan cases, the braided composite structure had a similar amount of damage. The cyclic testing that occurred after the ballistic test is where the advantages of the braided composite fan case became further evident.

CYCLIC TESTING

The fan blade containment capability is not the only design criterion that is required for successful fan case design. After a running turbofan engine has a blade release event, the engine's digital engine control recognizes atypical parameters within the engine's operation and issues a "return to idle" command. The engine speed drops rapidly to idle, typically within two seconds and it is not uncommon for the out-of-balance fan rotor to cross a critical frequency where fan rotor deflections are exaggerated, sending large vibratory loads into the engine structure for a small number of cycles. After the aircraft pilot recognizes which engine has had the blade-out event and issues a shutdown command, the damaged engine continues to windmill at a reduced speed due to forced airflow traveling through the engine as the aircraft is headed to a safe landing location. This windmilling process can entail over 250,000 cycles of vibration on a transatlantic flight on engines in this size class.

The cyclic loads that occur during the fan rotor critical frequency, as well as those that occur during the windmilling process must be accounted for in fan case design. It is therefore important to establish a method of applying accurate deflections and cycle counts in a laboratory environment to the ballistically-damaged case. This allows for inspection of crack orientation and growth with time, to optimize the laminate architecture in subsequent case designs. A number of cyclic tests were conducted as outlined below, which brought design deficiencies to light in the 'first generation' fan case. This data was used to modify the case design, and new fan cases were fabricated and then tested ballistically and cyclically. This process continued through several generations of fan case design before arriving on a configuration which could successfully withstand all laboratory testing. During each cyclic test procedure, separate spring rate tests were conducted at specific intervals to evaluate visible vs. non-visible damage as the cyclic counts grew.

To apply cyclic loads, each damaged fan case was mounted on its aft flange to a cyclic loading fixture as shown in Figures 7 and 8.

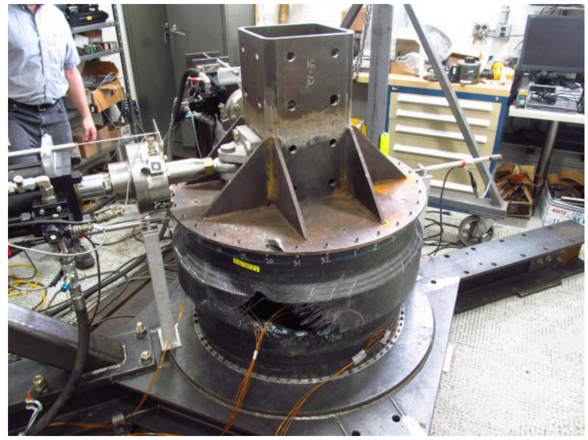

Figure 7. Ballistically-damaged fan case mounted on cyclic loading fixture.

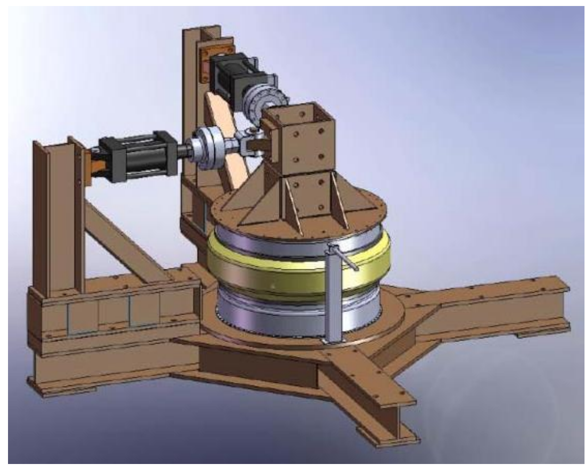

Figure 8. Simplistic representation of cyclic loading fixture.

An upper fixture was then bolted to the fan case forward flange, which connected to hydraulic actuators that provided load or displacement to the upper fixture. The hydraulic actuators were operated 90° out-of-phase in displacement control such that a circular orbit motion was applied to the upper fixture. The height at which the actuators were attached determined the ratio of shear to overturning moment applied to the fan case. Figure 9 shows the equivalent loads and overturning moments that were applied to the forward flange of the fan case.

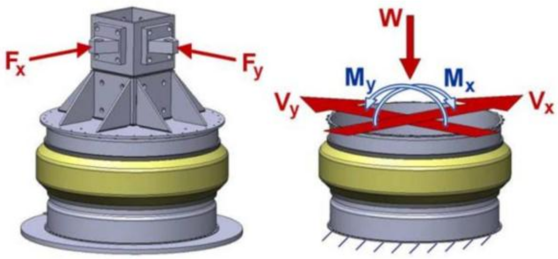

Figure 9. Loading applied to the cyclic loading fixture (left) and equivalent front flange loading (right).

By placing linear variable displacement transducers (LVDTs) around the perimeter of the fan case, the deflections of a loaded part were measured in the laboratory. Constant-deflection cycles however are not desirable as the fan case displacements in an actual fan blade-out event vary during each fan revolution as the engine decelerates down to idle. It would thus be advantageous to match this varying displacement cycle during the laboratory testing.

Instrumentation on a recent Honeywell fan blade-out test was utilized to generate a plot of radial displacement of the forward case flange, relative to the aft case flange over the spooldown cycles shown as red and black lines in Figure 10. A conservative envelope was drawn in blue around the actual data to establish a displacement-vs.-cycle goal for the laboratory testing.

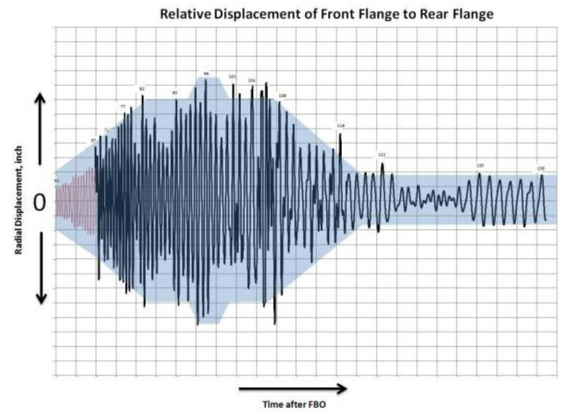

Figure 10. Measured displacements of a fan case during the cycles that follow a fan blade-out event.

NASA personnel were successful in using the LVDT deflection data as real-time feedback input for the load rams. This allowed the cyclic tests to be conducted with a different fan case deflection during each cycle (engine revolution), matching the blue highlighted area in Figure 10.

Cyclic tests were broken into two parts. The first segment matched the large case deflections yet low cyclic counts that occur during engine spooldown such as those noted in Figure 10. To determine safety margin, some cases were tested with scalar deflection multiples of not only 1.0, but also 1.5 and 1.8 times the measured values from actual engine blade-out testing.

The first segment of cyclic loading occurs when the engine is at operating temperature, and the composite structure aft of the fan blades can be over 200°F. To best simulate the event in a laboratory setting, electrical heat tapes were wrapped around the case structure aft of the fan blade plane and monitored with thermocouples. Input voltage to the heat tapes was then varied to bring the fan case temperatures into the operating range, then the spooldown cyclic tests were conducted.

The second segment of cyclic testing matched the analytically-determined smaller windmilling deflections with a high cycle count, in this case over 250,000 cycles. The windmill testing segments would take significant time as the frequency that the cycling rig can conduct without overheating its hydraulic fluid is dependent on ram displacement – typically limiting tests to a 1.5Hz maximum cyclic rate. Thus a 250,000 cycle windmilling test required nearly two days of uninterrupted clock time.

Since the turbofan engine is non-functional during the windmilling portion of the return flight, the structure of the entire case returns to ambient conditions. Thus the heat tapes were not utilized on the second segment of cyclic tests.

It was during both cyclic test segments that an additional advantage of the braided fiber structure became evident. Fan case wall crack growth during the first segment of cyclic testing was less than in comparable aluminum cases, and there was no case wall crack growth noted during any of the second segment of cyclic testing.

The braid reinforcement is highly resistant to crack growth due to the integrated multi-axial architecture. Loads at the crack front are re-distributed into other fiber directions rather than following along a linear crack path. This re-distribution mechanism is visually apparent during the quasi-static cyclic test shown in Figure 11.

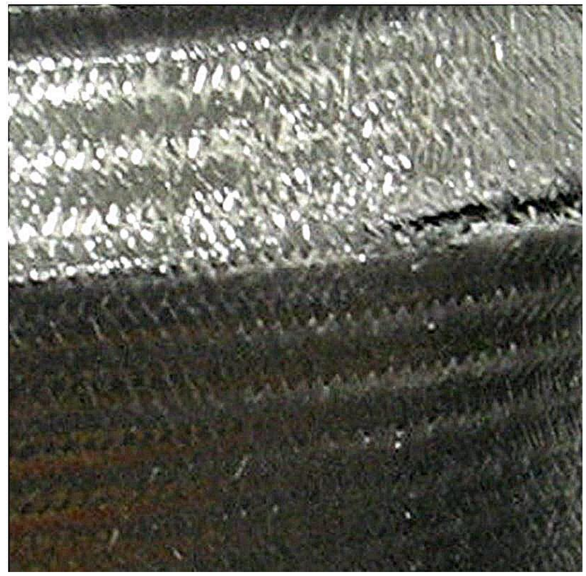

Figure 11. The braid reinforcement is highly resistant to crack growth due to the integrated multi-axial architecture.

AERODYNAMIC LOADING

The fan case also supports the aircraft nacelle inlet as shown in Figure 1, as the case carries aerodynamic loads to the rest of the engine mounting system to stay restrained to the aircraft. It is thus critical that the damaged fan case must safely withstand aerodynamic loads that occur for the remainder of the flight, as a released nacelle inlet could potentially strike an aircraft control surface. Of particular interest are the unique aerodynamic loads that occur on final approach, when the aircraft is at a high angle of attack. These loads occur after all cyclic damage has accumulated and thus have the highest chance of generating a fan case failure.

Therefore a final static load test was conducted on each ballistically and cyclically-loaded fan case. The aerodynamic loading phase of the test was viewed as a validation criterion that ensured that cumulative case damage from all ballistic and cyclic testing was not excessive, allowing a postblade-out aircraft to land safely after a windmilling diversion flight.

Prior to the static aerodynamic load test, each damaged case was inspected to determine which shear and moment loading axis would have the highest probability of causing fan case structural failure.

The static load tests were then conducted with that selected worst-case orientation. Each case successfully carried the applied aerodynamic loads. To evaluate safety margins, aerodynamic loads were increased by 400% and each case successfully carried 5 times the anticipated aerodynamic loads.

CONCLUSION

Triaxial braid composite materials have a good combination of impact performance and design flexibility that makes them suitable for use in composite fan cases. Materials selected performed well in full-scale component tests. Ballistic impact tests and structural load tests used for component testing were developed using a combined test and analysis approach based on data from previous engine blade-out tests and data acquired from full-engine dynamic analysis. The validity of the test methods was demonstrated through tests on aluminum fan cases and comparing results to previous blade-out tests. The validated test methods were used to demonstrate containment capability at reduced weight for composite cases compared to aluminum cases of similar design.

The test and analysis methods reported here provided significant risk reduction to a Honeywell Aerospace turbofan engine development program. This approach was a cost-effective method to identify unanticipated failure modes and optimize the design prior to performing an actual FAA fan blade-out Certification test.

The final generation braided composite fan case design passed all laboratory tests outlined in this report. Based on these results, an identical fan case was produced and utilized on an FAA fan blade-out Certification test in May, 2013. The ballistic and cyclic damage to the Certification test fan case was extremely similar to the damage seen in all NASA-based rig testing, further validating the test method’s effectiveness.