

“Establishing a Ballistic Test Methodology for Documenting the Containment Capability of Small Gas Turbine Engine Compressors”

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Abstract

A test methodology currently employed for large engines was extended to quantify the ballistic containment capability of a small turboshaft engine compressor case. The approach involved impacting the inside of a compressor case with a compressor blade. A gas gun propelled the blade into the case at energy levels representative of failed compressor blades. The test target was a full compressor case. The aft flange was rigidly attached to a test stand and the forward flange was attached to a main frame to provide accurate boundary conditions. A window machined in the case allowed the projectile to pass through and impact the case wall from the inside with the orientation, direction and speed that would occur in a blade out event. High speed, digital video cameras provided accurate velocity and orientation data. Calibrated cameras and digital image correlation software generated full field displacement and strain information at the back side of the impact point.

Introduction

Both the United States Army (US Army) and the Federal Aviation Administration (FAA) require that turbine engine manufacturers demonstrate full containment of shed rotor blades in an engine (Ref 1, 2 and 3). In a rotor with inserted blades, the engine must contain a blade failure occurring at the root section in the fillet below the blade platform. For an integrally bladed rotor, the entire blade from the blade root fillet must be contained. The engine manufacturer is required to show by analysis that the containment system can absorb the kinetic energy of the released blade and contain the blade to satisfy qualification or certification requirements. The analysis must be substantiated through testing.

For an engine contractor to validate an engine's containment capability to the US Army, the requirements that are listed in paragraph 3.3.8.9.1 of General Specification for Engines, AV-E-8593 (Ref 3), must be demonstrated. The engine must contain a compressor, inlet particle separator (IPS) blower and turbine blade. The damage caused by the blade failure cannot initiate an uncontained engine fire; the bearing and lubrication systems cannot allow the rotor to become uncoupled; the structures supporting the rotors must accommodate potential imbalanced rotating masses; and, the disk must have a burst speed margin of 5% greater than the maximum predicted free rotor overspeed should shaft decoupling occur.

The containment qualification requirements listed in paragraph 4.6.6.3 of the above document specify that containment must be demonstrated by an engine test on the power turbine and compressor rotor assemblies. Spin pit testing is allowed on the gas generator turbine rotor assemblies. The tests must demonstrate that all damage is contained.

The FAA requirements are similar. Paragraph 33.94 of Federal Aviation Regulation (FAR) Part 33 (Ref 1) requires that blade containment must be demonstrated by an

engine test and that the engine must contain all of the damage without catching fire and without failure of its mounting attachments. Under some conditions, analysis may be an acceptable substitute for a test if the analysis has been validated to be equivalent to the test. Thus, in the end, qualification and certification of an engine's containment capability must be rooted in test data.

In satisfying containment requirements, the US Army has often had difficulty acquiring substantiating data. Analyses to justify containment capability are often based on large engine data extrapolated to lower kinetic energies. In addition, when containment capability is based on fielded engine data, the failed blade weight and the operating conditions are generally not known. It is only when a controlled engine blade out test is performed that there is some certainty in the data.

NASA Glenn Research Center (GRC) has ongoing programs to document ballistic containment capability (Ref 4, 5, 6, 7, 8), both for the space program and aircraft engines. The US Army's Aviation Engineering Directorate initiated a study with the NASA GRC Ballistic Impact Laboratory to adapt their rigs to address the size and energy requirements of small gas turbines. Tests were conducted to determine the ballistic energy limit of small compressor cases.

Test Method

Facility

Impact tests were conducted using the Large Vacuum Gun facility at the NASA GRC Ballistic Impact Laboratory (Figure 1.a). A schematic of the test installation is shown in Figure 1.b. This facility consists of a gun barrel connected to a vacuum chamber in which the test fixture is located. For these tests a 3 in diameter gun barrel with a length of 22 ft was used. The pressure vessel has a volume of 1644 in³ and a maximum pressure of 300 psi. Because of the relatively high speeds required in these tests, compressed helium was used as the propellant.

Projectile

The projectiles used in these tests were actual blades machined from stage 1 and 2 integrally bladed rotors. The projectile was supported in a specially designed sabot (Figure 2) which carried it down the gun barrel. The sabot was designed to be light weight, strong enough to withstand the pressure loads and to support the blade in an orientation representative of engine operation. The blade support conforms to the low pressure profile or suction side of the blade. The sabot was stopped at the end of the gun barrel by a sabot stopper (Figure 3) in the form of a diverging cone designed to deflect the majority of the sabot material away from the target and allow the projectile to continue on its path toward the target.



Figure 1.a. Large Vacuum Gun at the NASA GRC Ballistic Impact Facility.

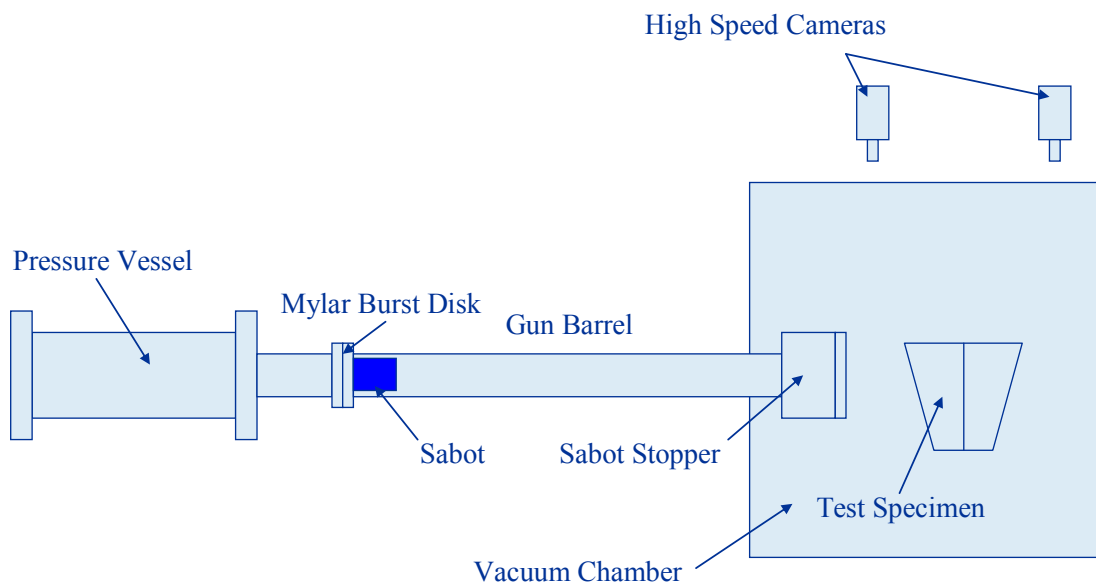


Figure 1.b. Schematic of Large Vacuum Gun Facility.

To shoot the projectile, the gas from the pressure vessel was released using a burst disk consisting of a Nichrome wire sandwiched between two or more sheets of 0.005 in thick Mylar®. The vessel was filled to the required pressure and a voltage applied to the Nichrome wire which caused it to heat up and break the Mylar® disk, releasing the pressurized gas and accelerating the sabot down the gun barrel.



Figure 2.a. Sabot used for Stage 2 blades.



Figure 2.b. Stage 2 blade mounted in sabot.

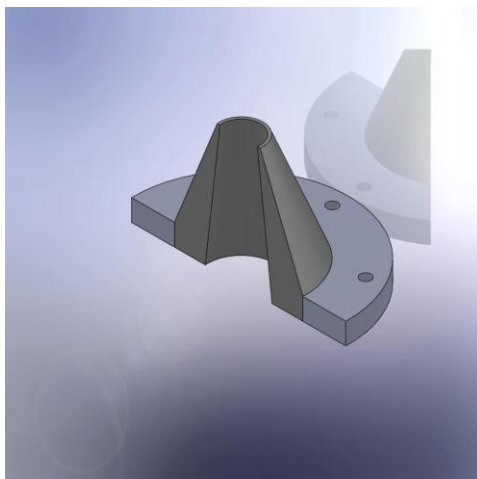


Figure 3. Schematic of the cross section of the sabot stopper. In this view the sabot would be traveling from top to bottom and the blade would pass through the center hole.

Test Article/Target

The test articles were compressor cases from a small gas turbine engine. In the particular engine tested the case is split axially, and the two halves are bolted together. It was important that the test article configuration incorporate stiffnesses representative of the actual engine hardware. To accomplish this, the full compressor case was mounted on a stiff fixture in front of the gun barrel such that its centerline was vertical and the plane in which the two case halves are joined was normal to the path of the projectile. A portion of the engine main frame was bolted to the compressor front flange. A window was machined in the half of the case closest to the gun barrel (the front half) so that the projectile could travel through the window and impact the back half of the case. The case was offset laterally so that the radial location of the projectile at impact was the same as would occur if a blade separated from the rotor near the split line of the case. The test setup is shown in Figure 4.

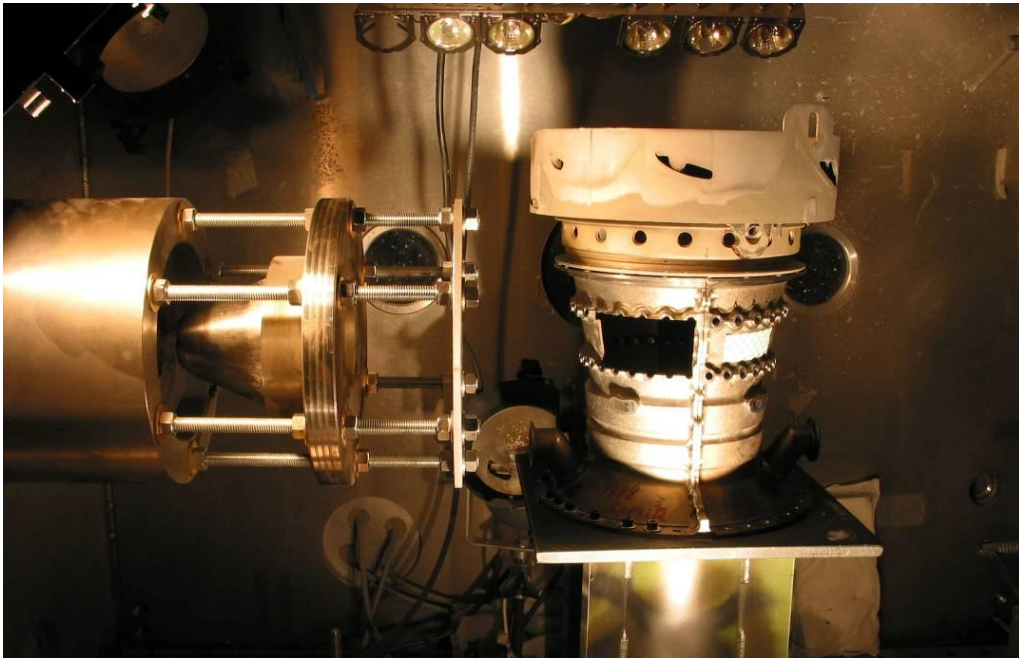


Figure 4. Test article shown in vacuum chamber in front of the gun barrel. The figure shows the sabot stopper on the left and the window in the test article through which the blade travels before impacting the back half (on right) of the case from the inside.

Instrumentation

The impact velocity of the projectile was measured using a high speed digital video camera (Phantom 7-3, Vision Research, Inc., Wayne, NJ) which was set to capture images at 40000 frames/sec. It was calibrated to determine the ratio between image pixels and distance by using a round bar with machined calibration marks placed in the plane of the projectile's travel. The camera was mounted facing normal to the path of the projectile. For each test, a point on the projectile in the same lateral plane as the

calibration bar was tracked as a function of time. Two additional high speed cameras were mounted orthogonally downstream of the test article to capture the velocity of any blade fragments that penetrated the case. In addition, several high speed cameras were used to obtain case full field displacements (for strain determination) and also other qualitative information from the impact tests.

Discussion of Test Issues

Successful demonstration of containment requires that a case will contain a failed blade throughout the test. Tests of actual engine hardware have traditionally been either engine tests or spin pit rig tests. For these traditional tests, a fully bladed rotor is assembled with a weakened blade designed to fail at a predetermined test speed. These traditional tests document the ability of the compressor case to contain the failed blade as it impacts the case, as it is pushed by adjacent blades, and as secondary failures impact the case. In the current test, the affects of adjacent blades are not present. In addition, there are no upstream or downstream stators to retain the blade in the same axial plane of rotation. In the current ballistic tests, the blades typically impacted the case at the blade tip, rotated and struck the case at the blade root, and then followed a spiral course around the inside of the compressor case and exited the case at the front of the main frame (upper end in test setup). For all successful test shots in this study, the root impact was always the site of the worst case damage. In an actual engine, the spiraling would be restricted by adjacent hardware and energy would continue to be input to the compressor case in the general region of the initial impact.

As a result, no blade impacts resulted in a blade exiting through the case thickness, even when a large fragment of the case was punched out or when the front flange failed (Figure 5).



Figure 5. Uncontained impact with no blade exit.

Through the course of the tests it was observed that as impacts progressed from the lowest to the highest energies, the resulting damage progressed from simple scuffing to a brittle crack to a crack with plastic deformation, tearing or flowering along the circumference of the compressor case. Further, at the higher energy impacts, the main frame flange that was attached to the front of the compressor case would also fail. Once

a tear began, the incremental energy required to propagate the tear appeared to be relatively small compared to the energy required to initiate a brittle crack. Therefore, for ballistic testing, the US Army defined the boundary between uncontained and contained impacts as case cracking in which the crack has not progressed from a more brittle crack to a more ductile crack (resulting in more plastic deformation) based on engineering judgment. It is expected that if the damage progressed beyond this limit, an actual engine test with the inclusion of the rotor and adjacent hardware would result in an uncontained failure. This is due to the influence of adjacent blades/stators and/or the resulting collateral damage from the event.

The test articles were illuminated with high intensity lights that made the cloud of remaining sabot material that traveled with the blade to the impact site appear to be very large. There was a concern that this material might invalidate the results of these tests. Therefore, separate, sabot only tests were performed on cases that had already been used in impact tests. In one of these tests, the sabot was fired at a velocity greater than 2000 ft/sec. Before and after photos indicated no noticeable increase in damage to the case (Figure 6). In addition, the maximum strain measurement during the impact showed a peak strain of 2.6 % at the sabot material impact location. This is less than 1/3 of the ultimate strain of the case material at the test temperature. It was concluded that the remaining sabot material that traveled with the blade to the impact site had no impact on test results.

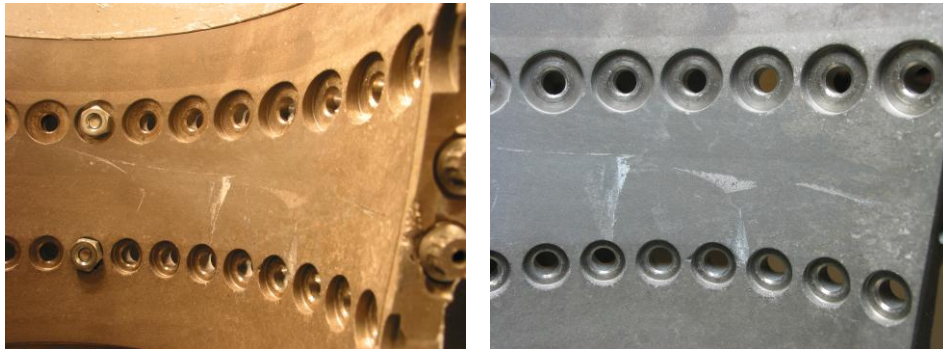


Figure 6. Damage on case before impacting with sabot only (left) and after impacting with sabot only (right) at a speed of 2197 ft/sec. Case had been previously impacted by a stage 2 blade at a low velocity.

Analysis Method

This test program required analysis of the data both during testing and at the completion of the program. Data analysis was required during testing to guide the test program and again after all the testing was completed to interpret their results for future efforts..

Unlike many ballistic tests where projectiles are fired at flat plates, this test used actual engine hardware. Typical flat plates and projectiles are controlled to tighter tolerances and have less variability than the hardware that was used for these tests. Our case thickness values varied from case to case as did blade fragment weight. Since containment is dependent on the thickness of the case and the kinetic energy of the blade

(function of its mass/weight and test velocity), blade fragment test velocities had to be calculated for each test to arrive at the ballistic limit for the case material.

Several empirical relationships were evaluated throughout the course of testing. Two specific ones in which kinetic energy is a function of thickness to some power are located in FAA-RD-77-44 (Ref 9). A simplified form of each follows.

The first is based upon a curve fit to previous test data.

$$E = f(t^{2.56}) \quad (1)$$

Where,

E = kinetic energy of fragment

t = case thickness

The second is an equation for energy absorption that has been used frequently by the FAA in years past.

$$E = f(t^2) \quad (2)$$

Each of these methods, and other similar variants, were assessed for their applicability as the testing progressed.

Results

Fifteen impact tests were conducted on cases at the stage 2 location and 18 tests at the stage 1 location. Impact velocities ranged from approximately 1000 ft/sec to 2200 ft/sec. As discussed previously, the blade did not completely penetrate through the case wall in any test. However in a number of cases the damage was severe and portions of the case were ejected. In several tests, cracks due to the blade impact extended through the compressor case front flange and through the mating flange of the main frame. While the blade did not pass through the case in any test, many of the tests were labeled as uncontained based upon the US Army definition for the containment boundary. Photographs of the contained stage 1 boundary points are shown in Figure 7 below and the uncontained stage 1 boundary points are shown in Figure 8. In addition, a non-dimensional plot of the kinetic energy of the projectile as a function of thickness is shown in Figure 9. This plot includes the critical stage 1 and stage 2 test points. As seen below, a form of equation 2 resulted in a good fit through the critical points for both stages.

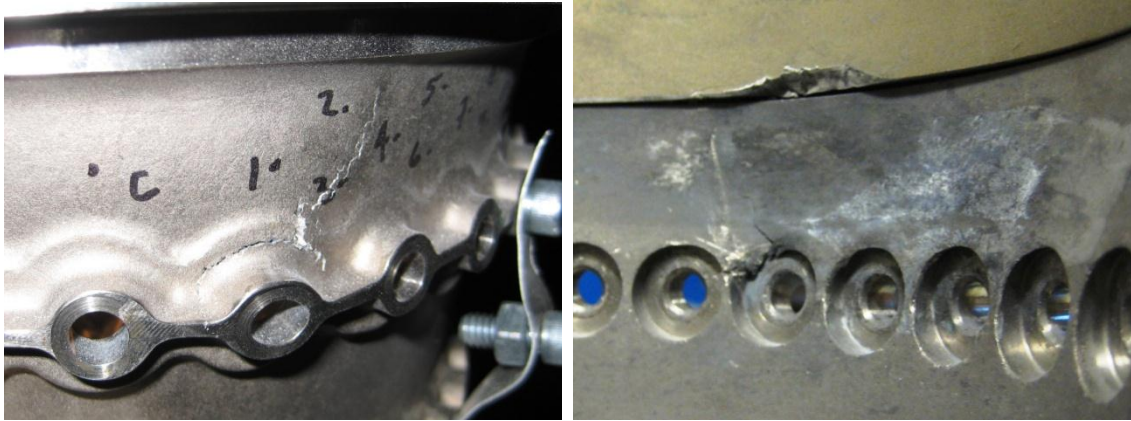


Figure 7. Stage 1 contained boundary point.

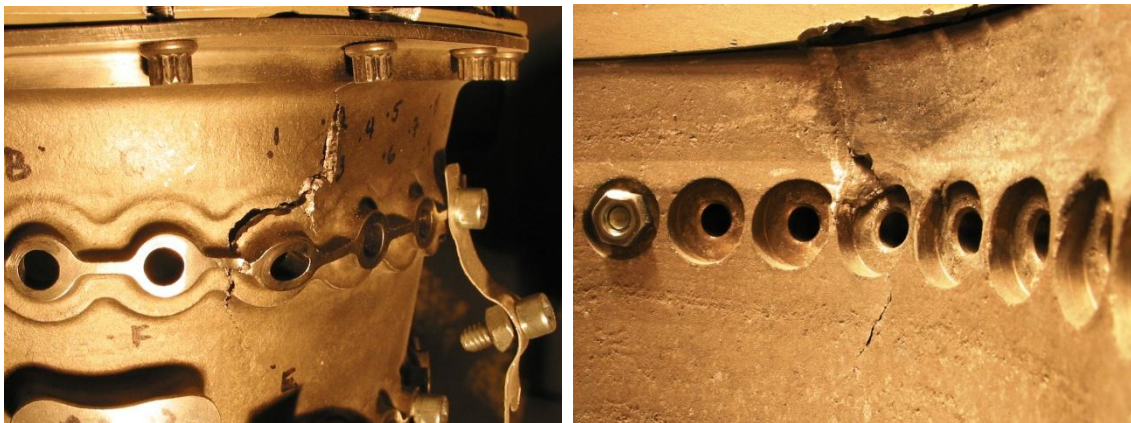


Figure 8. Stage 1 uncontained boundary point.

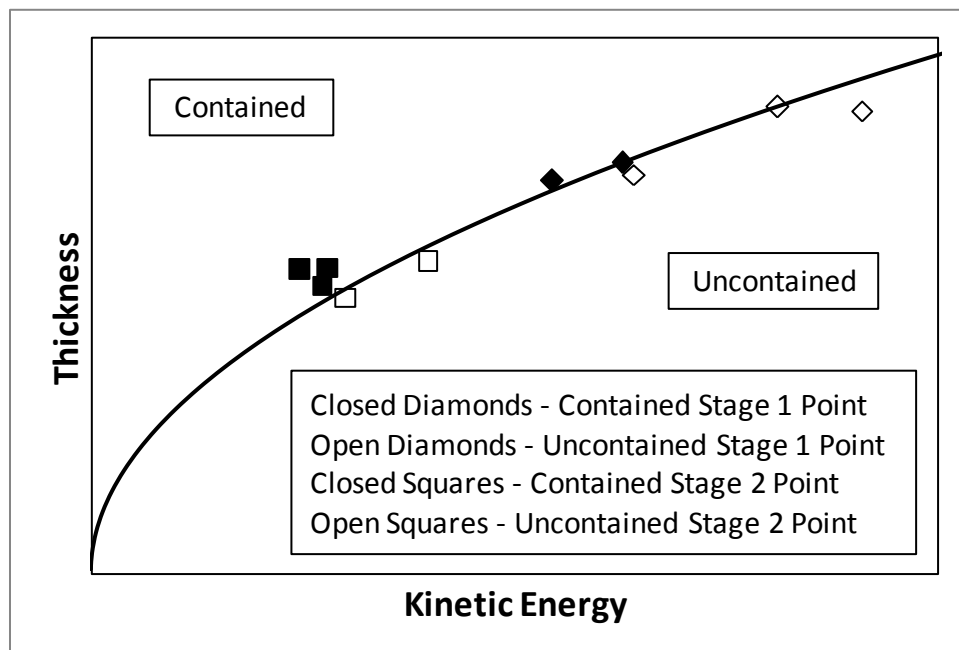


Figure 9. Plot of thickness versus kinetic energy.

Summary

The test setup described in this report provides a repeatable method for impacting a case with a blade in an orientation and speed similar to a blade out event. The kinematics of the blade in the test, with the tip impacting first, followed by a root impact is similar to what would be expected in the real event. The majority of the damage is due to the root impact. This test methodology is an important tool in establishing the containment boundary of small engine compressor cases.

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