

## Design and Testing of Braided Composite Fan Case Materials and Components<sup>1,2</sup>

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### **ABSTRACT**

Triaxial braid composite materials are beginning to be used in fan cases for commercial gas turbine engines. The primary benefit for the use of composite materials is reduced weight and the associated reduction in fuel consumption. However, there are also cost benefits in some applications. This paper presents a description of the braided composite materials and discusses aspects of the braiding process that can be utilized for efficient fabrication of composite cases. The paper also presents an approach that was developed for evaluating the braided composite materials and composite fan cases in a ballistic impact laboratory. Impact of composite panels with a soft projectile is used for materials evaluation. Impact of composite fan cases with fan blades or blade-like projectiles is used to evaluate containment capability. A post-impact structural load test is used to evaluate the capability of the impacted fan case to survive dynamic loads during engine spool down. Validation of these new test methods is demonstrated by comparison with results of engine blade-out tests.

### **INTRODUCTION**

The fan case in a gas turbine engine provides the outer flow path for air passing through the fan and provides structure for attachment of the inlet and other components. In addition to these structural requirements, the fan case or a fan containment system must be able to contain a released fan blade during a fan blade-out event. 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. The earliest approach to fan blade containment was to provide sufficient thickness of metal in the case wall to resist penetration of the blade. This approach is called a “hardwall” design. Alternative approaches, including an approach that uses a fabric wrap on the outside of the case to provide blade containment, were investigated in the late 1970s and early 1980s (Refs. 1 and 2). The approach using a fabric wrap is called a “softwall” design, and this can be a lighter weight option for some engines. The softwall design was first used in commercial engines by General Electric on the CF-34 engine. Although there are some slight variations on the hardwall design, nearly all current commercial engines that have titanium fan blades use either hardwall cases made with metal alloys or softwall containment systems made with a metal alloy case overwrapped by aramid fibers in either a woven or braided form. A recent development by GE Aviation is the use of composite materials for hardwall fan cases in some engines that use composite fan blades.

The selection of a hardwall or softwall design for a specific engine depends on the relative weight of the two approaches in addition to other system-level design issues and overall cost. In either case, the trend in engine design has been toward higher bypass ratios for improved efficiency, reduced noise, and reduced fuel consumption. The high-bypass engines rely on a large diameter fan to provide most of the engine thrust. The fan case in this type of engine is one of the largest and heaviest structural components. As the size of the fan becomes larger, there is an increasing benefit for reducing the fan case weight. Many design and material approaches have been proposed to provide containment capability at

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reduced weight compared to the current hardwall and softwall designs. However, the cost of demonstrating these new concepts in full-scale rig or engine blade-out tests has limited the progress toward lighter weight alternative approaches.

Various types of composite materials have been considered as lightweight alternatives to metal alloys for softwall fan cases and for hardwall fan cases that must contain a titanium blade. Poor impact resistance and high fabrication cost were potential limitations for some of these approaches. The high cost of testing full-scale components using either rig blade-out tests or engine blade-out tests also limited the amount of development work on composite materials for this application. In recent work, impact testing of composite panels indicated that composite materials made with a triaxial braid architecture could have improved impact resistance compared to previous laminated composites and improved crack propagation resistance compared to aluminum (Ref. 3). In addition, a cost-effective method was developed for fabricating composite fan case structures using the triaxial braid approach and various resin infusion processes. However, the high cost of demonstrating the new technology in rig or engine blade-out tests still remained as an obstacle to implementation of this new technology.

Composite fan case prototypes fabricated as part of a NASA-funded Small Business Innovative Research (SBIR) project are shown in Figures 1 and 2. In order to evaluate the potential performance capabilities of these prototypes without performing an expensive blade-out test, new test methods were developed at NASA for characterizing materials and testing of the cases. Laboratory-scale ballistic impact tests followed by structural load tests on the impact-damaged cases were developed to overcome the obstacle of expensive rig and engine blade-out testing. This paper describes the new triaxial braid



Figure 1.—Composite hardwall fan case prototype.



Figure 2.—Composite softwall fan case prototype.

material approach and the new test methods developed to simulate fan blade-out conditions in laboratory-scale impact and structural load tests.

## **COMPOSITE DESIGN AND FABRICATION**

### **Braid Architecture and Design**

The initial braided architecture that was evaluated in this research is shown in Figure 3. This triaxial braid construction consists of three fiber orientations within a single lamina ( $0^\circ$ ,  $+60^\circ$ ,  $-60^\circ$ ). In this original design, the fiber volume in each fiber orientation is  $1/3$  of the total fiber volume for the layer. This fiber architecture results in a  $\pi/3$  quasi-isotropic construction within a single braided ply.

Other fiber architectures could be fabricated and could have advantages. However, test data was not available at the time to suggest an optimum architecture. The choice of a quasi-isotropic architecture resulted from an expectation that uniform lamina stiffness properties in all directions might result in efficient energy distribution during an impact event. Design and manufacturing efforts were also simplified by the use of this fiber architecture.

In addition to bulk laminate stiffness properties, several other lamina characteristics were defined as the initial braid architecture was designed. Decisions regarding yarn type and size, inter-yarn gap size, lamina thickness, etc., have a significant influence on both the process economics and structural performance. The use of a wide tow carbon yarn

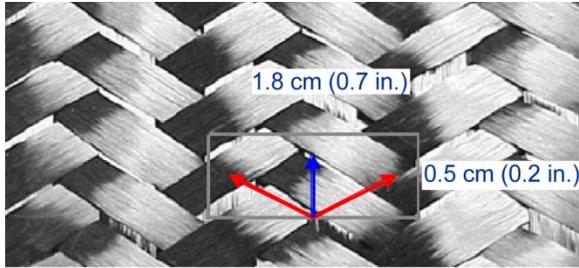


Figure 3.—Two-dimensional triaxial braid carbon fiber preform with highlighted unit cell (the blue arrow indicates the axial fiber direction, and the red arrows indicate bias fiber directions).

allowed for high yarn coverage at a low yarn density (ends/inch). Since large surface areas are covered with relatively fewer yarns, this construction enables manufacture of large structures with a smaller braiding machine at increased process speeds. Small inter-yarn gaps also have a small benefit in processing efficiency but are likely to have more of an influence on performance. These small gaps allow a reduction in fiber undulation, improved lamina stiffness, and possibly a reduced stress concentration as the fibers carry load away from the primary impact site during an impact event.

Again, in the absence of reliable data or established analytical techniques, currently the designer must make several choices in the early stages of the effort without a clear understanding of the effect on performance. However, the influence of these design choices on production capacity and process cost is very well understood.

### Braided Preform Layup

As previously discussed, the engine fan case is one of the largest structures on an aircraft engine. The manufacturing process used in this effort was specifically developed to enable fabrication of these very large structures at a reduced manufacturing cost.

Historically, the conventional braiding approach used to manufacture contoured axi-symmetric structures with integral flanges is called over-braiding. This process is shown in Figure 4. In this approach, the centerline of the braided sleeve is positioned to be coincident with the centerline of the structure. A mandrel is initially positioned below the braiding machine. As the mandrel is pulled upward



Figure 4.—Over-braiding process.

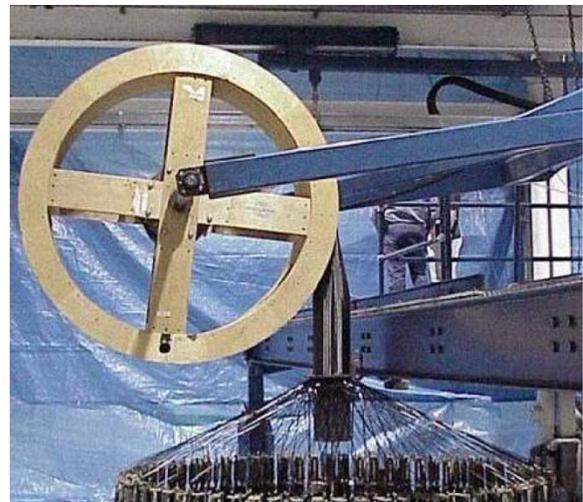


Figure 5.—Capstan winding process.

through the braid formation plane the braid sleeve is directly applied to the surface of the mandrel. This process continues until the braid covers the mandrel. The process is then repeated until a sufficient number of layers have been applied to the mandrel. Typically, over-braiding is done directly on the cure mandrel since the tooling is captured by the over-braided architecture. This necessitates the transport and manipulation of heavy, expensive tooling.

In an effort to reduce tooling and process costs relative to conventional over-braiding, this effort was focused on the development of a “capstan winding approach.” This approach is shown in Figure 5.

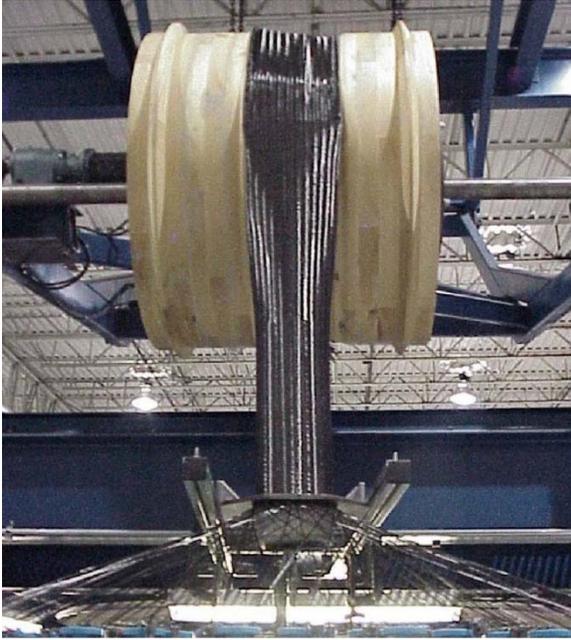


Figure 6.—Contoured braided tube being pulled over the formation point in a contoured wheel in the capstan winding process.

The capstan winding process still uses a braiding machine to form a tubular sleeve but this sleeve is now oriented in the circumferential direction of the structure. Tooling resembling a wagon wheel is rotated above the braid formation plane. Rotation of the wheel pulls the braided sleeve through the formation plane. Use of a wheel with complex geometry allows this contour to be built into the braid as it is pulled through the formation plane as shown in Figure 6. Lower radius regions in the wheel pull the corresponding fibers in the braid more slowly than higher radius regions. This creates the contoured geometry in the braid as it goes onto the contoured wheel. Since the radius changes as layers accumulate, each layer on the wheel has a different contour.

Braiding continues until material sufficient for a full preform has been applied to the wheel. The braid is then disengaged from the braider and wound back onto a small low-cost shipping spool. The start point (first ply) of the braided sleeve is now at the top of the shipping spool. Upon delivery to the molder, the contoured braid is wound off of the shipping spool and onto the complex geometry cure mandrel.

Several advantages of the capstan winding process relative to the conventional over-braiding were demonstrated in the NASA-funded SBIR contract. Tooling and shipping costs were reduced. The diameter of the case structures that could be

fabricated was significantly increased because the braid machine is now defined by the width of the structure instead of by the circumference. Material utilization and process efficiency were increased since the braid machine runs continuously. High material deposition rates were achieved since the flattened tubular sleeve deposits two layers per rotation of the wheel.

### **MULTISCALE TEST APPROACH**

The braided preforms described in the previous section can be made using a wide range of fibers and fiber architectures, and composites can be fabricated from these preforms using a wide range of layups and molding processes. There are currently no standard material test methods or reliable analysis methods that can be used for guidance on which composite materials would perform best in a fan case. Since testing of all material variations in full-scale blade-out tests is not feasible, an efficient multiscale testing approach was developed.

The types of testing that could potentially be used at various scales can be identified by considering the fan blade and case dynamics during a fan blade-out event. The dynamics of the event and the appropriate test methods depend on whether a hardwall or softwall design is being used. A hardwall fan case must stop the released blade without penetration of the case. A softwall design allows the blade to penetrate the case, and blade containment is performed by multiple layers of fabric or braid that wrap the case. The fan case must allow the blade to penetrate with a minimum size hole and with a minimum amount of secondary damage such as delamination or crack propagation. After impact, a softwall case must resist crack growth or allow for crack growth in a stable and controlled manner such that adequate structural integrity is maintained during engine spool down.

For testing at the material level, an impact test is needed that deforms the material in a similar state of strain and at a similar strain rate compared to material in the fan case during blade-out. In order to test the resistance of the material to cracking and delamination, the test must also allow a high strain energy density to accumulate in the material before failure. The following section describes a test that uses a soft projectile to impact composite panels in order to induce a high strain energy density into the composite material before penetration of the panel. This test method has been useful for screening various composite materials. Materials selected based

on these test results have been used for successful component tests, as described later in this paper.

A panel impact test that uses a hard projectile would be useful for measuring the resistance of the material to local penetration at the contact points between the blade and case. A problem with this approach is that it is not possible to define an appropriate projectile without prior knowledge of the blade dynamics and case deformation. An approach that is sometimes used is to perform impact tests with projectiles that are as close as possible to the weight and shape of a fan blade and to design the test method in a way that attempts to induce failure in a test panel that is similar to potential failure modes in a fan case (e.g., petaling, shearing, etc.). Since it was not known what failure modes would occur in the composite materials, an alternative approach was used in this work. For both hardwall and softwall designs, metal fan cases were impacted with either a real fan blade or a blade-like projectile. Finite element analysis was performed for both the impact test and previous engine blade-out tests to ensure that the impact test was conducted in a way that simulated blade-out conditions. In addition to impact testing, softwall cases were tested for post-impact structural integrity in a test rig that was designed to simulate out-of-balance loads during engine spool down. Results of this test were also compared to results from engine tests to ensure that the applied loads were representative of blade-out conditions. After the test methods were demonstrated to be a good representation of blade-out conditions using the metal cases, composite cases were fabricated and tested using the same test conditions. The containment capability of the composite and metal cases could then be directly compared.

### **PANEL IMPACT TESTING**

The impact test method for materials characterization used a gelatin projectile in order to create a large region of high strain energy density prior to failure. The projectile is made from gelatin filled with micro-balloons, similar to formulations used for artificial bird material in bird strike tests. The molded projectile is a cylinder with a length of 12.7 cm (5 in.), a diameter of 7.0 cm (2.75 in.), a mass of 450 g, and a density of 0.92 g/cm<sup>3</sup>. Composite panels were fabricated using six plies of the 0°/+60°/-60° triaxial braid preform with the 0° fibers of each ply aligned in the same direction. Panel dimensions were 61 cm (24 in.) by 61 cm (24 in.) by 3.2 mm (0.125 in.), and fiber volume fraction was

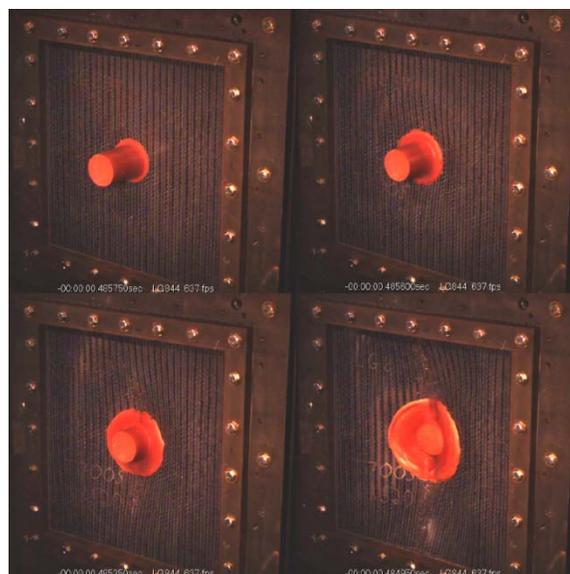


Figure 7.—Panel impact test configuration and deformation of the gelatin projectile during impact of a T700S/PR520 panel at 637 ft/s.

typically 56 percent. The panels were held between a steel fixture and a steel picture frame. A sequence of images from an impact test is shown in Figure 7.

A series of tests were conducted over a range of impact velocities to determine the penetration threshold for each material. Composites made using various fibers, resins, and resin infusion processes were evaluated.

The penetration thresholds for the various materials ranged from below 91 m/s (300 ft/s) to above 213 m/s (700 ft/s). Data obtained for panels made by resin transfer molding (RTM) using TORAYCA® T700S fiber (Toray Carbon Fibers America, Inc.) and CYCOM® PR 520 matrix (Cytec Industries, Inc.) is presented in this paper to illustrate the test method. These panels were fabricated by North Coast Composites, Cleveland, OH. The penetration threshold for this material was between 191 m/s (627 ft/s) and 194 m/s (637 ft/s). The panel shown in Figure 7 was tested at a velocity of 194 m/s (637 ft/s), which is just above the penetration threshold.

The deformation of the panels during the tests was measured using digital image correlation. In this technique the back side of the panel is painted with a dot pattern and viewed with two high-speed digital cameras. The synchronized images from the two cameras are input to computer software that is capable of calculating full field deformation by

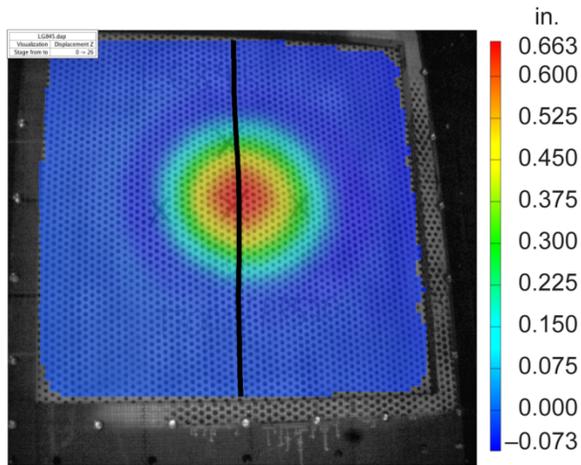


Figure 8.—Out-of-plane deflection measured by digital image correlation during a composite panel impact test. (Strains in Fig. 9 are calculated along the vertical line indicated in the picture.)

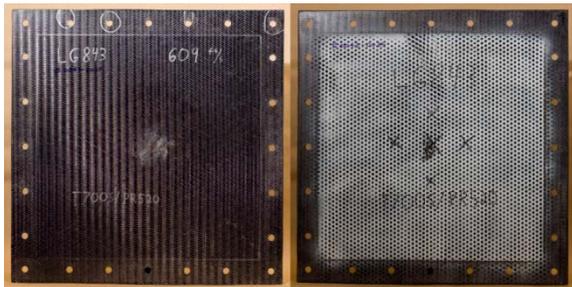


Figure 9.—Front (left) and back (right) surfaces of a T700S/PR520 panel after impact at 186 m/s (609 ft/s).

pattern recognition. A typical out-of-plane deflection pattern at a time step prior to failure is shown in Figure 8.

The strain at which damage initiates can be calculated from the full field deflection. As an example, Figure 9 shows the front and back surfaces of a panel impacted at a velocity of 186 m/s (609 ft/s), which is below the penetration threshold. Figure 10 shows a closeup view of the damage on the back side of the panel. Figure 11 shows the out-of-plane deflection and strain measured at various time steps along the vertical line shown in Figure 8. The first visible damage during the impact test is the fracture of bias braid fibers that are oriented  $60^\circ$  from vertical in Figures 9 and 10. The strain at which the fiber fracture initiates can be determined by comparing the strain measured at each time step to the high-speed video images at the same time step. Figure 11(a) shows the out-of-plane deflection of the

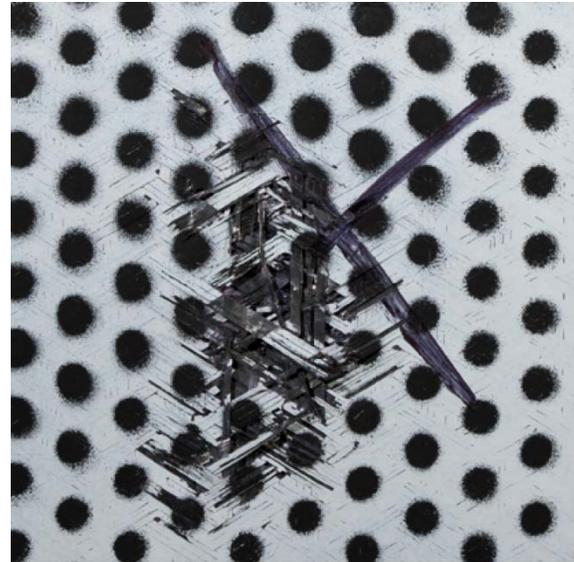


Figure 10.—Closeup image of the damage area on the back of the T700S/PR520 panel in Figure 16 after impact at 186 m/s (609 ft/s).

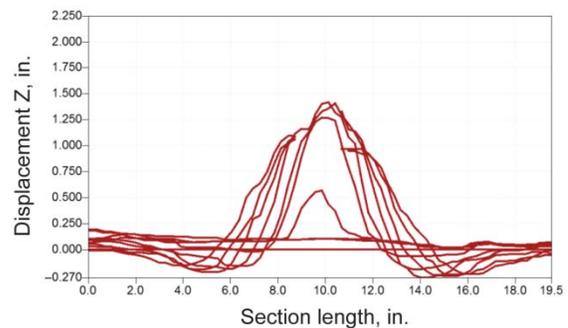
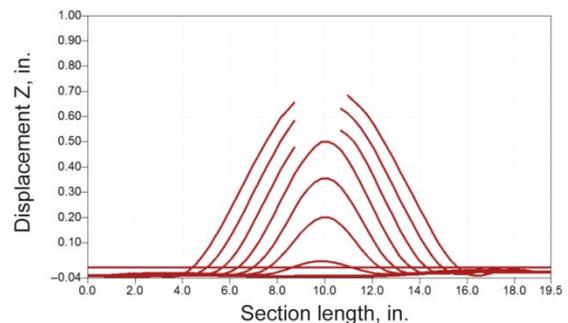


Figure 11.—Deformation (a) and transverse strain (b) during impact of the panel in Figure 9 for locations along a vertical line as shown in Figure 8.

panel along the vertical line shown in Figure 8, and Figure 11(b) shows the corresponding strain in the horizontal direction along the same vertical line. When failure occurs, the paint pattern is lost near the fracture, and the pattern recognition software can no longer track the deformation of the panel in that

region. As a result, the deflection curves in Figure 11(a) and the strain curves calculated from the deformation data become discontinuous.

In Figure 11(b) the strain in the horizontal direction reaches a value close to 1.5 percent before the bias fibers fracture. A transverse tensile failure strain of 1.68 percent was measured for the same material in a quasi-static uniaxial tensile test (Ref. 4). Even though the deformation states and strain rates are different for the impact and quasi-static tests, failure occurs at similar values of transverse strain in the braided composite material. Although the agreement is close, the accuracy of the failure strain measurement needs to be improved for both the impact and quasi-static tests. The accuracy in the impact test is limited by the time step, which is determined by the camera frame rate for a specific field of view. The accuracy in the quasi-static tests is questionable because standard coupon specimens exhibit excessive edge damage when used with triaxial braid composite materials having a large unit cell size (Ref. 4). Current research is attempting to improve the accuracy of these measurements. These improvements are needed to provide more reliable material property data for impact analysis.

Some information has been published recently about improved test and analysis methods for these triaxial braid composites (Refs. 4 and 5). Discussion of the analysis techniques is beyond the scope of this paper. However, some experimental results are presented to show some of the difficult challenges in the development of the analysis methods.

Figure 12 shows how the damage pattern changes for the T700S/PR520 material when tested at two different velocities. Figure 13 shows damage patterns for two different material systems. Current analysis methods are not able to predict these changes in damage patterns for different impact velocities and different materials.

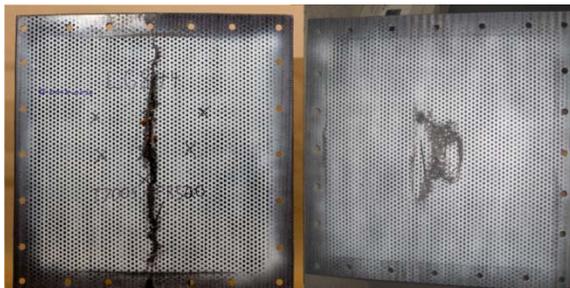


Figure 12.—T700S/PR520 panels after impact at (left) 194 m/s (637 ft/s) and (right) 230 m/s (756 ft/s).



Figure 13.—Failure modes observed for different material systems showing crack propagation along bias fiber directions (left) and fiber brooming (right).

Improvements in analysis methods will require better understanding of failure process from micro to macro levels and implementation of this knowledge into numerical methods with sufficient computational speed to be applied at the component level. Since analysis methods are not currently capable of predicting failure during impact at the panel or full-scale level, validation of new composite fan case designs must be done experimentally with guidance from analysis on deformation during impact. The following section describes methods that have been developed to evaluate composite fan cases in a ballistic testing laboratory and a structural testing laboratory.

## **COMPONENT TESTING**

### **General Test Considerations**

Hardwall cases were tested with a blade-like projectile to determine the penetration threshold. For the hardwall designs penetration of the blade is the primary concern, and it may not be necessary to test the impact-damaged cases for resistance to damage propagation during engine spool down and windmilling. For softwall designs the blade penetrates the case, and the aramid wrap applies a significant additional load to the case while stopping the blade. Therefore, softwall cases must be tested under impact conditions that simulate the hole produced by blade penetration and the load applied by the aramid wrap, as well as post-impact structural loading conditions that simulate dynamic loading from engine spool down and windmilling.

For both hardwall and softwall cases the impact loads were applied to the case by accelerating a blade or a blade-like projectile into the case in an orientation representative of a blade-out. This was done using the single-stage gas gun configuration in Figure 14. The gun consists of a pressure vessel and a gun barrel with a length of 12.2 m (40 ft). Pressure from the pressure vessel is released into the gun



Figure 14.—Schematic of the gas gun and the fan case mounted at an incline in front of the gun barrel.

barrel using a burst disk. The projectile is supported in a cylindrical can-shaped sabot at the gun breach and is accelerated by the released pressure through the gun barrel. At the end of the barrel the sabot is stopped by a sabot arrester, and the projectile continues on to impact the test article. The test article is a fan case tilted at a specific angle as shown at the left in Figure 14.

### Hardwall Case Testing

Testing of hardwall fan cases was done in partnership with A&P Technology, Cincinnati, OH, and Williams International, Walled Lake, MI. Metal fan cases from past engine development programs were provided by Williams International for the purpose of validation of the impact test method. The fan cases are representative of a small engine that has an integrally bladed titanium alloy fan disk (blisk). Because of the high strength and stiffness of the hardwall design, the impact produces large deformation of the blade. Prior to testing, computer simulations were performed to study blade and case deformation.

Computer simulations were conducted using the LS-DYNA computer code (LSTC Corp., Livermore, CA). The complete blisk and case were modeled. In the simulation a fan blade was released at the connection to the hub at a specified rotational speed. Upon impact with the case, the leading edge of the blade initially deformed to form a semicircular forward edge. Contact between this edge and the case was determined to be the most damaging event for blade containment. To simulate this damage mode experimentally, a projectile was designed in the form of a solid cylinder with a hollow tube leading edge. The deformed blade and projectile are shown in Figure 15.

A series of impact tests were conducted using this projectile. Cases were mounted at the aft flange to a stiff fixture, which was located in front of the gas gun as shown in Figure 14. This is considered to be a conservative approach for measuring penetration threshold since there is some compliance at the aft flange connection in an engine that would reduce

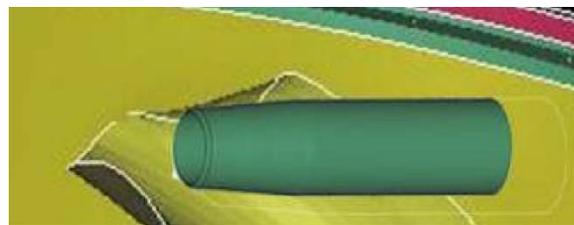


Figure 15.—Deformed fan blade and the projectile used in the hardwall case test to simulate blade impact.

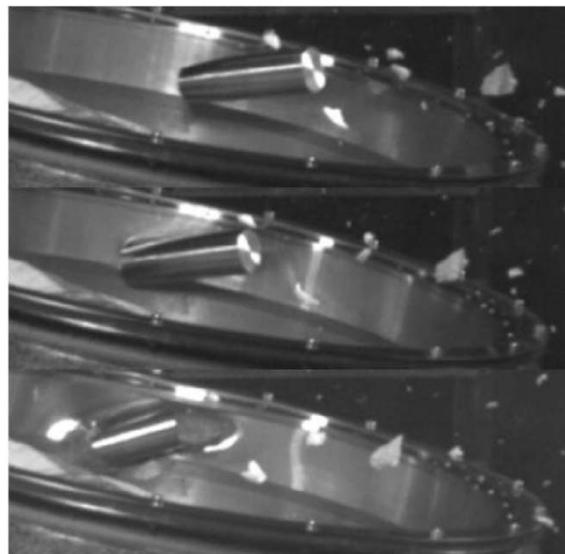


Figure 16.—Sequence of video images from an impact test on a metal hardwall fan case.

contact forces between the blade and case during impact. The cases were inclined in such a way that the projectile passed over the front flange and contacted the case from the inside in a location and orientation determined by the computer simulation. A series of tests were performed to optimize the projectile shape in order to match the case deformation and penetration threshold expected based on analysis and previous engine blade-out data. It was important to provide the correct stiffness and mass boundary conditions at the forward flange to get the correct case deformation. Ten impact tests were conducted on metal cases of three different thicknesses to determine the penetration threshold. A sequence of images from high-speed video of a test is shown in Figure 16, and results of the tests are shown in Figure 17. The data in Figure 17 apply within the range of velocities used and cannot necessarily be extrapolated outside of this range. Penetration velocities used to produce the data in Figure 17 compared closely with predictions from analysis, and case deformation in the impact area was close to that observed in previous blade-out tests. In addition a

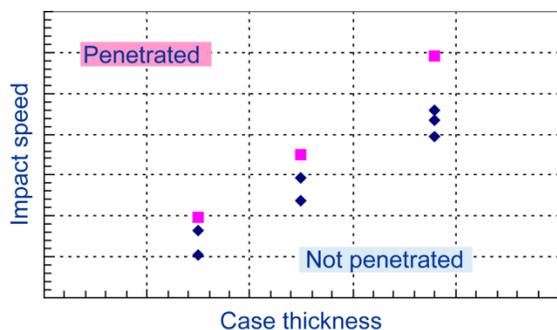


Figure 17.—Results from impact tests on metal hardwall fan cases.

slight torsion buckling resulting from the torque load applied by the blade during impact was observed in some impact tests. This deformation was similar to buckling that had occurred in some blade-out tests.

Having validated the ballistic test method using this series of tests on metal cases, the test method was applied to evaluate the performance of composite cases. The composite cases were designed to be exact replacements for a metal case with one of the wall thicknesses shown in Figure 17. In this way, a direct measure of the weight difference between metal and composite cases could be determined. The composite cases had an inner liner to prevent excessive damage to the composite material and to distribute the impact load at the inner wall of the case. Sixteen impact tests were conducted on composite cases. Slight modifications to the case design were made at different stages during the test series to achieve penetration at the desired velocity. Because of the relatively localized nature of the damage, several impact tests could be performed on a single case. The final case design was subsequently tested in an engine blade-out test. The composite case contained the released blade at a lower case weight compared to the metal case. Deformation and damage to the composite case were close to what was expected based on the ballistic impact tests and computer simulations.

A digital image correlation technique for measuring the deformation of composite panels was described earlier in this paper. The same technique was used to measure deformation of the outer wall of cases during the ballistic impact tests and during the blade-out test. A nearly circular region of out-of-plane deformation was observed for the panels and the fan cases. Initial damage, when it occurred, was in the form of fiber tensile failure on either the back side of the panel or the outer wall of the case. Deformation patterns are shown in Figure 18. The similarity of deformation patterns supports the

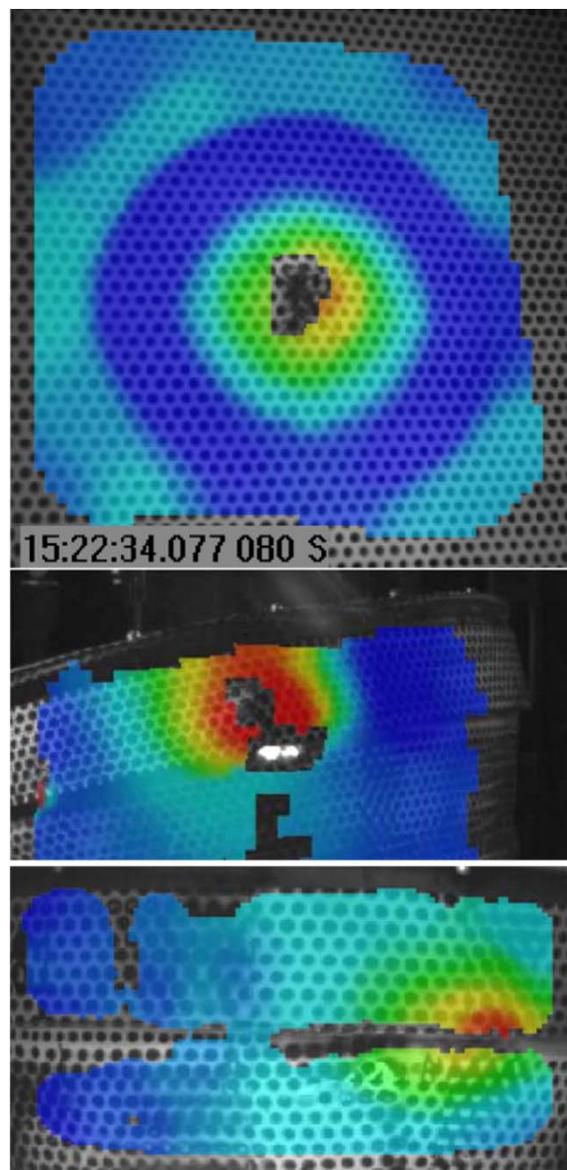


Figure 18.—Deformation pattern for a flat panel test (top), laboratory impact test on a case (middle), and full engine blade-out test (bottom).

validity of using the flat panel test method described earlier for screening of materials and for identifying failure modes and failure criteria that can be used in analysis.

### Softwall Case Testing

Softwall impact tests were performed using fan cases from a medium-sized engine and using titanium alloy fan blades from the same engine as projectiles. This work was done in partnership with A&P Technology, Cincinnati, OH, and Honeywell Aerospace, Phoenix, AZ. The tests were intended to

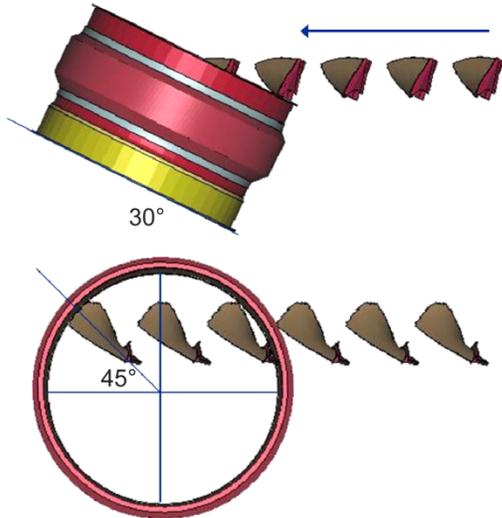


Figure 19.—Test configuration for softwall composite fan case impact testing.

evaluate the performance of the case structure rather than the containment capability of the aramid wrap. However, it was important that a realistic wrap material be used because it can apply potentially damaging loads to the case as the blade is being contained. Impact tests were conducted to induce realistic damage when the blade penetrates the case and to assess the effect of loading on the case from the aramid wrap. Structural load tests were then performed on the impact-damaged cases to simulate the dynamic loads during engine spool down. Some of the cases were then tested for crack propagation under simulated engine windmilling fatigue loads.

Softwall cases were mounted similar to the method described for hardwall cases and shown in Figure 14. Computer simulations were performed with the LS-DYNA code to determine the blade orientation and impact location needed to produce damage similar to that observed in previous engine blade-out tests. It was important to provide the correct stiffness and mass boundary conditions at the forward flange in order to induce the desired damage to the case. The test configuration is shown in Figure 19.

Similar to the approach used for hardwall cases, tests were first performed on a series of metal softwall cases to optimize the test configuration and establish the validity of the test method. Composite cases were then tested using the same test conditions. Impact tests were conducted at impact speeds up to 293 m/s (960 ft/s). In all tests the blade was contained by the aramid wrap. In addition to the damage

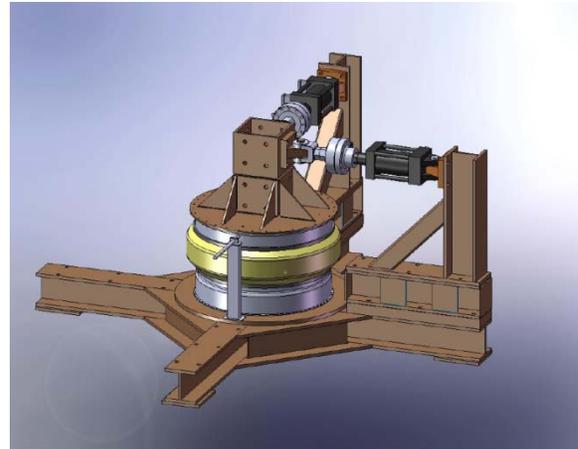


Figure 20.—Orbital Loading Frame used for simulating post-blade-out dynamic unbalance and windmilling loads on the fan case.

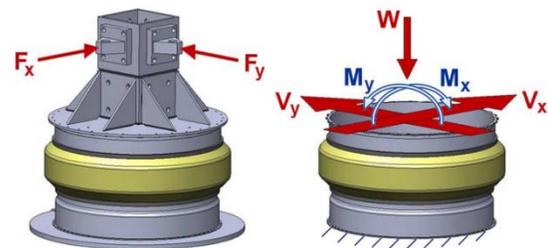


Figure 21.—Loading applied by the Orbital Loading Frame (left) and resultant loads on the case (right).

produced by the blade, there was additional case damage resulting from loads caused by the aramid wrap as it deformed to contain the blade.

After the impact tests, the fabric wrap was removed to observe the damage to the cases. The cases were then mounted in a structural loading rig, called the Orbital Loading Frame (OLF), shown in Figure 20. The OLF consists of a lower fixture to which the aft flange of the case is bolted, an upper fixture that bolts to the forward flange, and hydraulic actuators that provide load or displacement at the attachment points to the upper fixture. The hydraulic actuators were operated 90° out-of-phase in displacement control such that a circular orbit motion is applied to the upper fixture. The height at which the actuators are attached determines the ratio of shear to overturning moment applied to the case. Figure 21 shows the actual loads applied as well as the resultant loads on the case.

The test parameters in the OLF were set to simulate the expected motion of the case during engine spool down. Other test parameters also were used to simulate the much smaller loads that occur

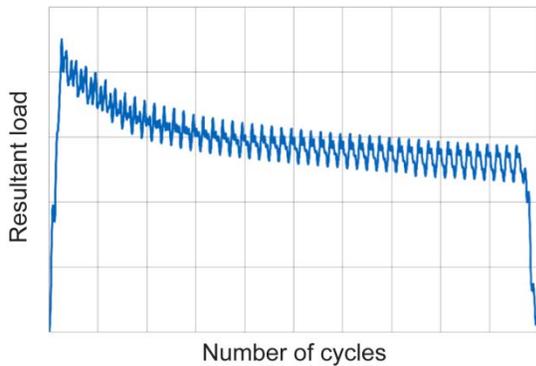


Figure 22.—Resultant load applied by Orbital Loading Frame to achieve a specified deflection.

during engine windmilling. For this work tests were required to produce this displacement was recorded. A typical output of the resultant load from the two actuators over a number of cycles is shown in Figure 22. Since it is not possible to totally eliminate damage propagation in the case during engine spool down, some reduction in load is expected. The goal is to design a case in such a way that the damage propagates in a controlled manner and stabilizes after a number of cycles as shown by the flattening of the curve in Figure 22.

Impact and orbit loading tests were conducted on three metal cases. The validity of the test method for this particular engine and fan case design was established by comparing results of the orbit load test to results from previous engine blade-out tests. The propagation of damage in the orbit load tests was close to what was displayed in previous engine blade-out tests. Different test parameters for the orbit load test would likely be needed for different engine and fan case designs.

Seven impact tests followed by orbital load tests have been conducted on composite cases. Tests were conducted in three different series, with modifications to the case design between each series. Since there is currently no blade-out data for a softwall case resembling the design of the cases tested in this work, it was not possible to anticipate all potential failure modes for the composite case. Both the ballistic impact test and the orbit load tests were valuable for identifying unanticipated failure modes as the test program proceeded. Some of these failure modes were a result of test conditions that needed to be refined to better simulate blade-out conditions. These refinements were made throughout

the test program. Other failure modes were a result of material performance or specific features of the case design. The impact and orbit load testing was very effective in identifying these potential material and design issues. The final composite case design that was tested performed better than the metal case at significantly reduced weight. Additional tests were performed on some cases to simulate engine windmilling loads, and no damage growth was observed during these tests. Engine blade-out testing of a composite case has not yet been performed.

### Future Directions

It is anticipated that the test and analysis methods reported here can provide significant risk reduction in future engine development programs that attempt to utilize new materials or design technologies for lightweight fan cases. This approach is a cost-effective method to identify unanticipated failure modes and optimize designs prior to performing a blade-out test. However, improvements are needed to make the test and analysis methods more generally applicable to a range of future engine designs. It was possible to perform the full-scale tests and analyses described in this paper because existing metal cases were available, composite cases of the same design could be fabricated, and previous blade-out data were available for the metal cases. Because of these circumstances, analysis was used to optimize test conditions, but validation of the performance of the composite case could be demonstrated by experiments. There will have to be more reliance on analysis for predicting fan case performance during future engine development programs because existing hardware and blade-out data needed for experimental validation are not available at the beginning of the development program. The analysis must be capable of providing accurate dynamic loads imparted to the fan case during blade impact, fan blade tip rub, engine spool down, and engine windmilling. Proprietary models are used by engine manufacturers for this purpose. However, it would be useful to have a nonproprietary engine model that could be used for research. One such model is a dynamic model of a full engine that can be run for quality assurance purposes as new versions of the LS-DYNA code are developed (Ref. 6). Efforts are being initiated to determine if this model can be modified to simulate the effects of rotor dynamics on fan case loading to a level of accuracy sufficient for this research.

## CONCLUSIONS

Triaxial braid composite materials have a good combination of impact performance and design flexibility that makes them suitable for use in composite fan cases. A multiscale test methodology was developed to assist in materials selection and validation testing of full-scale composite fan case prototypes. Materials selections were based on results of composite panel impact tests using a soft projectile. Materials selected in this manner 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 during the testing of components. The validity of the test methods was demonstrated through tests on metal 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 metal cases of the same design.

Future research is focused on continued validation of the test methods and improvement of the analysis methods. Improved engine models are needed to derive accurate loads on the fan case from simulation of full system dynamics. Improved material models are needed to better simulate deformation and failure of triaxial braid and other textile composites. Better test methods are also needed to quantify failure criteria under both impact and quasi-static deformation. Such improvements will allow the test methods presented in this paper to be used for development of fan case designs for future engines when existing hardware and blade-out test data are not available.

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