NASA/CR—2005-213969

Smart Fan Containment System

General Electric Aircraft Engines
Cincinnati, Ohio

November 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/CR—2005-213969

Smart Fan Containment System

General Electric Aircraft Engines
Cincinnati, Ohio

Prepared under Contract NAS3–01135, Work element 3.3, Task order 23

National Aeronautics and
Space Administration

Glenn Research Center

November 2005

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Work Element 3.3 - "Smart" Fan Containment System

Input from Stephen Mitchell stephen.mitchell@ae.ge.com
Brian Rice, University of Dayton Research Institute

Objectives

GE Aircraft Engines uses the two basic types of fan containment concepts shown in Figure 1. The hardwall fan case concept uses a thick shell to stop, deflect and prevent the radial escape of any blade fragments. The softwall fan case concept uses an energy absorbing flexible belt to stop, deflect, and sometimes capture blade fragments. The distortion of the energy absorbing belt during impact is shown in Figure 2. Although a variety of system and configuration requirements determine the possibility of using either hardwall or softwall, the softwall design generally demonstrates the lightest weight.

Therefore the primary objective is to develop an innovative "smart" softwall containment system that capitalizes on the anisotropic nature of composites. The key technologies of this new "smart" system include the development of new "smart" braid material systems with capability of localized strength enhancement in response to applied loads, and diagnostic capability of shell damage and disbond through nanofiber circuitry. The result of this program is an ultra lightweight structure with improved toughness, performance, lower cost and diagnostic capabilities.

A secondary objective is to capitalize on the Ohio-based resources of small businesses, and universities to develop, analyze, fabricate and test the "smart" containment system. A&P Technology (Cincinnati) will develop the braiding, ASI (Xenia) will produce the nanofibers, Webcore (Dayton) will fabricate components, University of Dayton (Dayton) and the University of Akron (Akron) will conduct analysis, and UDRI (Dayton) will conduct testing.

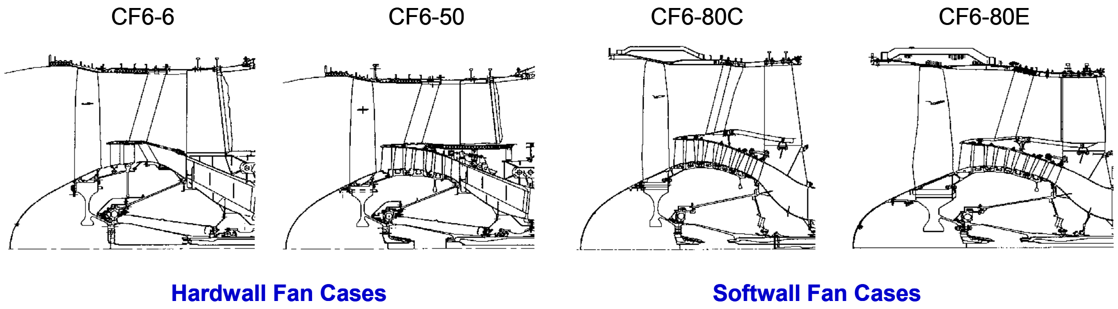
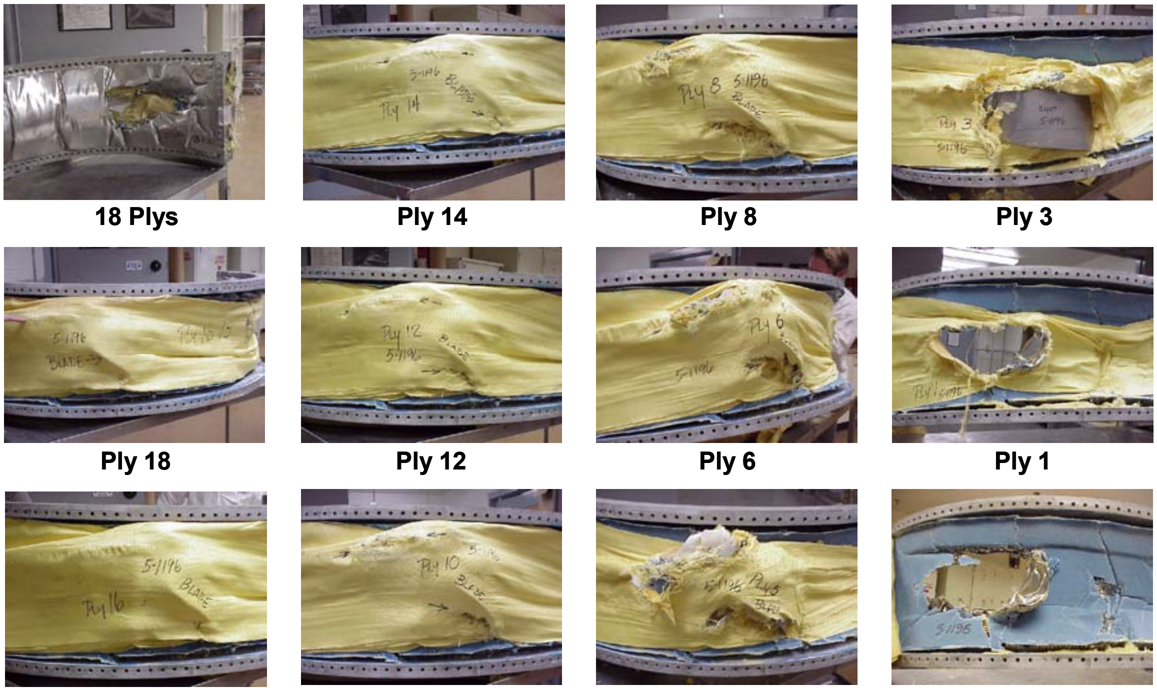


Figure 1. Various Fan Modules.



18 Plys
Ply 14
Ply 8
Ply 3
Ply 18
Ply 12
Ply 6
Ply 1
Ply 16
Ply 10
Ply 5
Honeycomb

Figure 2. Sequence of Containment Case Damage.

1. Technical Progress

Sub Task 3.3.1 – "Smart" Containment System Design

Based on extensive past experience, the design of the prototype softwall case was completed and shown in Figure 3. The case is a 360 continuous conical braided shell with a forward diameter of fifty six (56) inches, an aft diameter of fifty four (54) inches, and a length of twenty-five (25) inches. The forward and aft ends of the case have integral upright bolted flanges, and the center portion of the shell is a honeycomb sandwich. The outside of the case is wrapped with a containment belt of continuous dry braided fiber. Data captured from previous fan blade-out rig tests was used as the baseline to compare material properties, impact results, containment capabilities and weights.

The weights of the full scale hardwall baseline and several softwall designs are listed below. The weight of the all composite softwall case reflects the results of the ballistic testing conducted in this program.

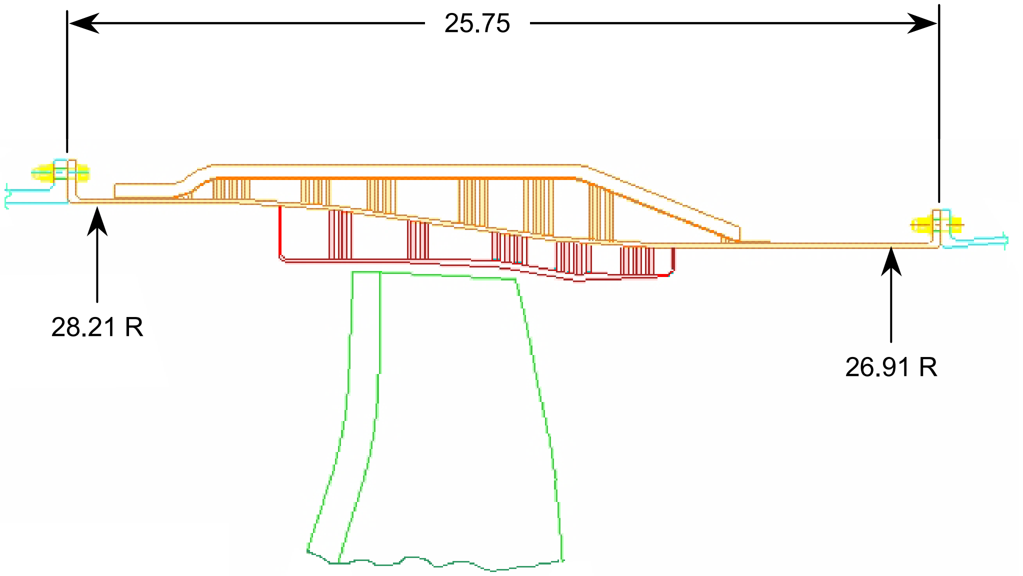


Figure 3. Prototype “Softwall” Fan Case.

Containment Approach	Case	Material Containment	Fan Case Weight (lb)	Savings lbs. / %
Hardwall	Aluminum	Aluminum	1127	Baseline
Softwall	Aluminum	Kevlar	858	269 / 24
Softwall	Carbon/Epoxy	Kevlar	727	400 / 35
Softwall	Carbon/Epoxy	Zylon	640	487 / 43

Sub Task 3.3.2 – Braid Preform Development & Subscale Test

Task 1 – Fabrication

A&P Technology completed the manufacturing of a wide variety of Carbon, Aramid (Kevlar) and PBO (Zylon) braided preforms needed to fabricate the panels and half cases. Three (3) different resins (5208, M36 and 977-3), compatible with the RFI process, were initially evaluated. Viscosity flow tests were conducted on several six (6) inch wide, forty-eight (48) long braided preforms. The length of the preforms was determined from the projected axial length of the full scale case. The preforms were mounted in a vertical position with all of the resin positioned at the bottom end of the panel. The panels were bagged and heated to the proper resin film infusion (RFI) cure cycle. The untoughened 5208 resin flowed the entire vertical length of the panel, whereas the toughened M36 and 977-3 resins flowed to 15% and 55% respectively of the total length. Based on these results, the M36 resin was eliminated as a candidate for use in this program.

The fabrication of twenty (20) subcomponents was completed in this time period. The configuration of the subcomponents was comprised of seven (7) flat panels, two (2) curved panels, nine (9) sandwich panels and three (3) half cases. Both the flat and curved panels were approximately 2 ft. by 2 ft. The sandwich panels were 120 degree arcs on a 22.25 inch radius and 25 inches wide. The half cases were 180 degree arcs on a 22.25 inch radius and 16 inches wide. A summary and depiction of the various subcomponents is shown in Figure 4.

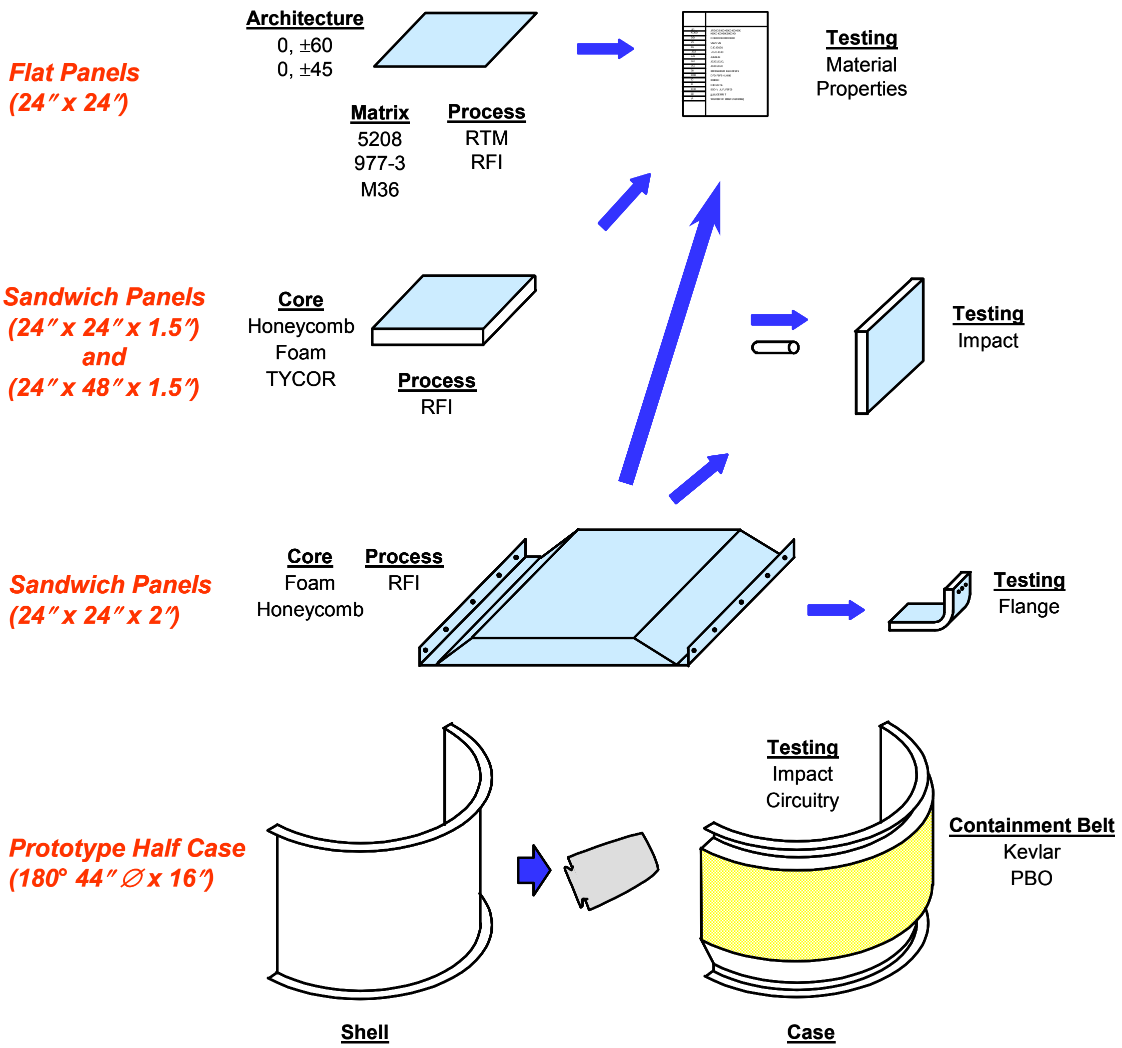


Figure 4. Composite Fan Case Subcomponents.

Task 2 - Impact Testing

The results from separate subcomponent tests was incorporated into the critical softwall half case. Three (3) “Softwall” Half cases were fabricated and ballistically tested.

Each half case has an inner radius of 22.24 inches, a width of 16 inches, and a containment belt width of thirteen (13) inches. The construction of each bonded sandwich half case consists of a .125 inch thick inner shell of braided T700 Carbon / Epoxy, a 2 inch thick Aluminum “Flexcore” honeycomb, and a thin (.050 inch) Glass / Epoxy outer shell. The containment belts are located on top of the curved sandwich panel, and are attached at the two short (16 inch) ends of the case.

Case 1

The containment belt consisted of three (3) braided sleeves of Kevlar 49 material, and the inner shell was T700 / 977-3 Carbon Epoxy.

Case 2

The containment belt consisted of two (2) braided sleeves of Zylon material, and the inner shell was T700 / 977-3 Carbon Epoxy.

Case 3

The containment belt consisted of three (3) braided sleeves of Kevlar 49 and 29, and the inner shell was T700 / 5208 Carbon Epoxy.

Each case was mounted in a curved metal frame fixture and radially bolted along the entire perimeter on both sides of the case. This setup is shown in Figure 5. The titanium blade was potted into a foam sabot (Figure 6), and ballistically impacted into the case approximately ten (10) inches from the short end. After the initial (Shot 1) test, the case was turned over, any excess sleeving was removed, and the opposite end of the case was impacted (Shot 2).

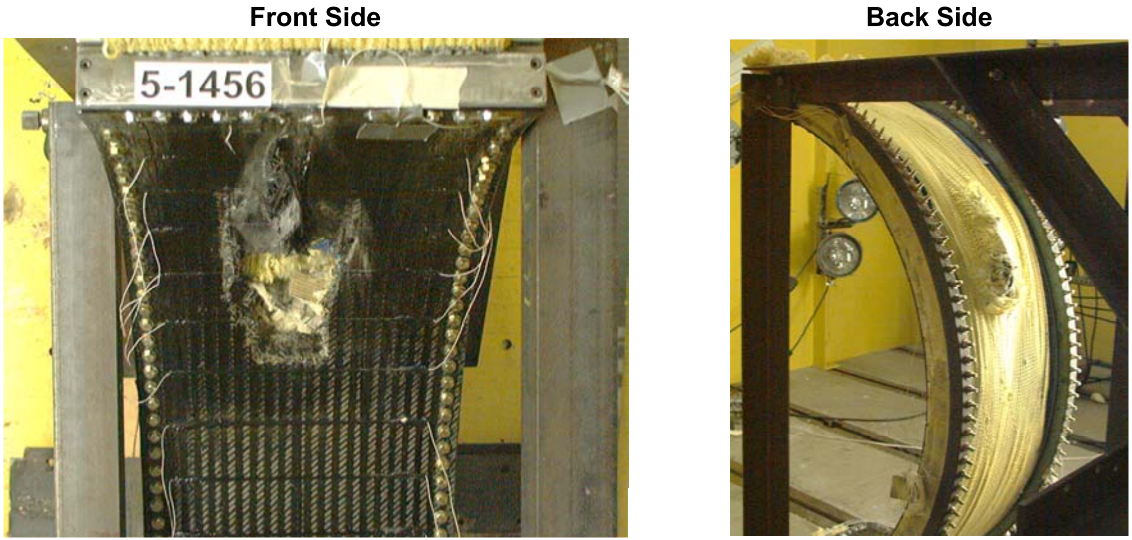
The results of the tests are summarized in the following table, and the accompanying Figures show the damage to both the front and back of the half case.

Case	Shot	Sleeves	Blade Wt.	Velocity	Result	Figures
1	1	**3**	2.060 lb.	770 fps	**Contained**	7
1	2	**2**	1.990 lb.	787 fps	**Uncontained**	8
2	1	**2**	2.042 lb.	779 fps	**Contained**	9
2	2	**1**	2.002 lb.	775 fps	**Uncontained**	10
3	1	**3**	2.014 lb.	768 fps	**Uncontained**	11
3	2	**3**	2.071 lb	776 fps	**Contained**	12

Based on these preliminary results, the Zylon absorbs significantly more energy than the Kevlar 49, and results in a 33% weight savings over the Kevlar 49 material.

Figure 5. Ballistic Test Set-up for Halfcase.

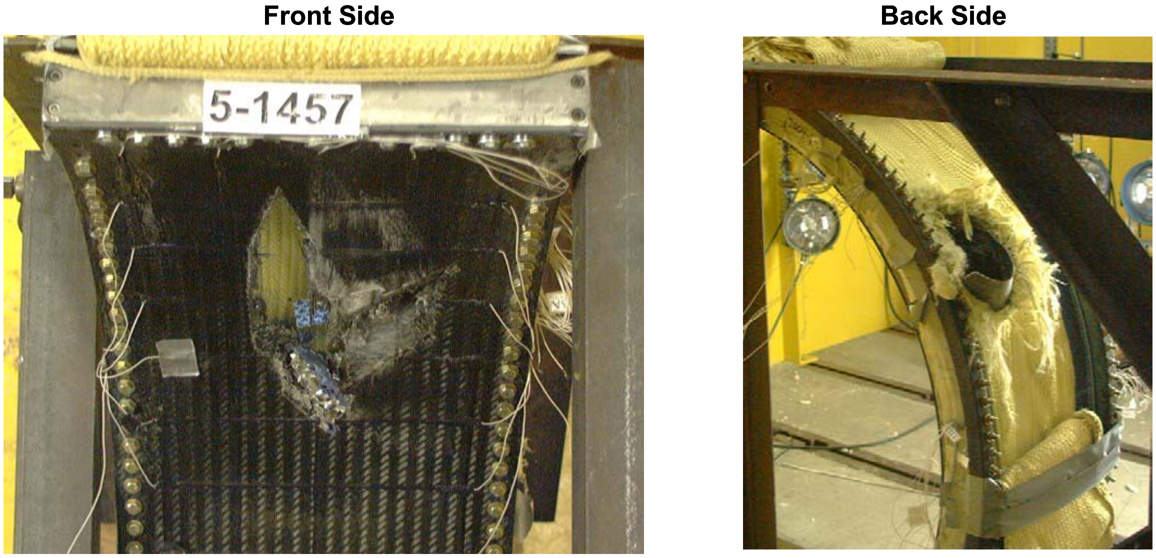
Figure 6. Titanium Blade Projectile and Sabot.



Front Side

Back Side

Figure 7. Kevlar 49® Contained Blade.



Front Side

Back Side

Figure 8. Kevlar 49® Uncontained Blade.

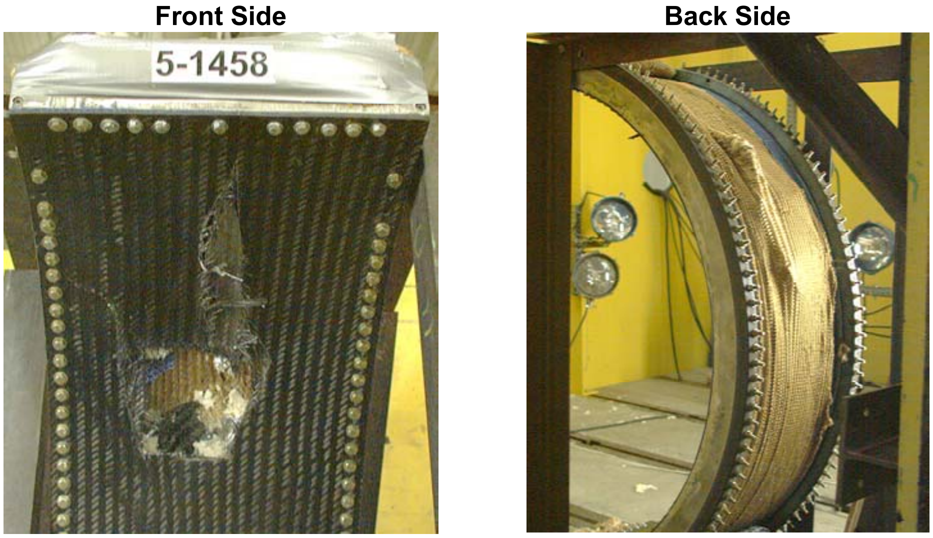

Front Side Back Side

Figure 9. Zylon® Contained Blade.

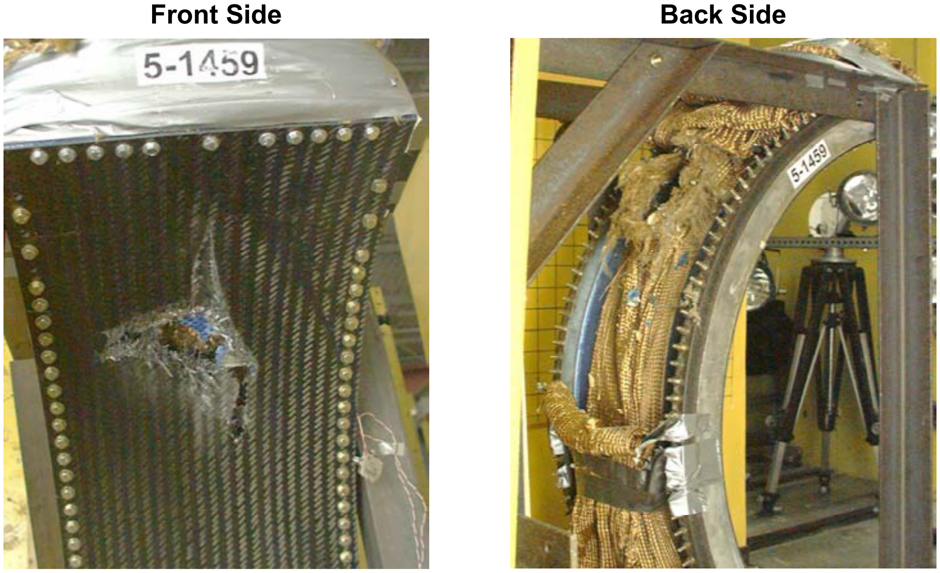

Front Side Back Side

Figure 10. Zylon® Uncontained Blade.

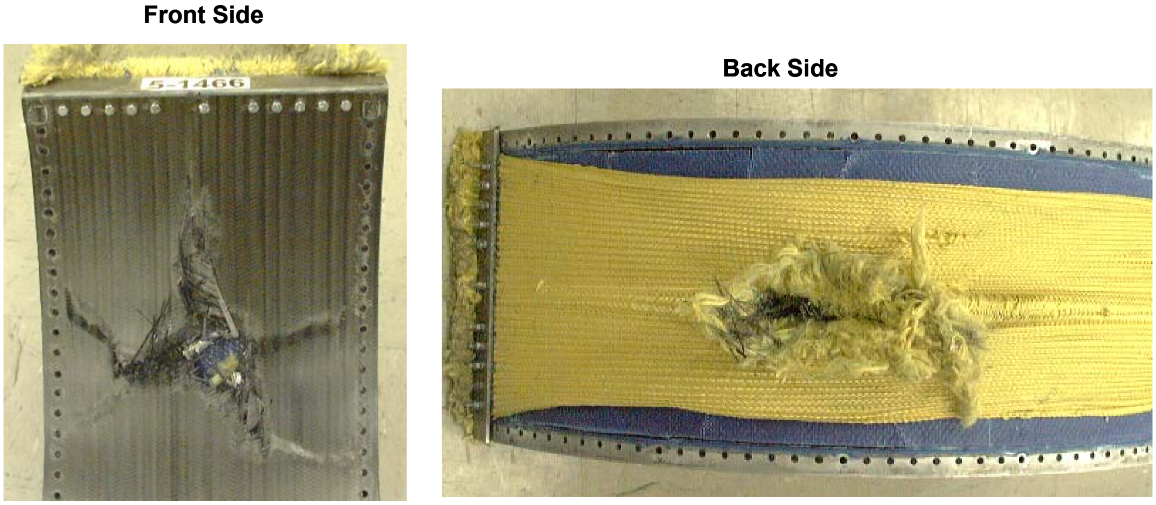


Figure 11. Kevlar 49/29® Uncontained Blade.

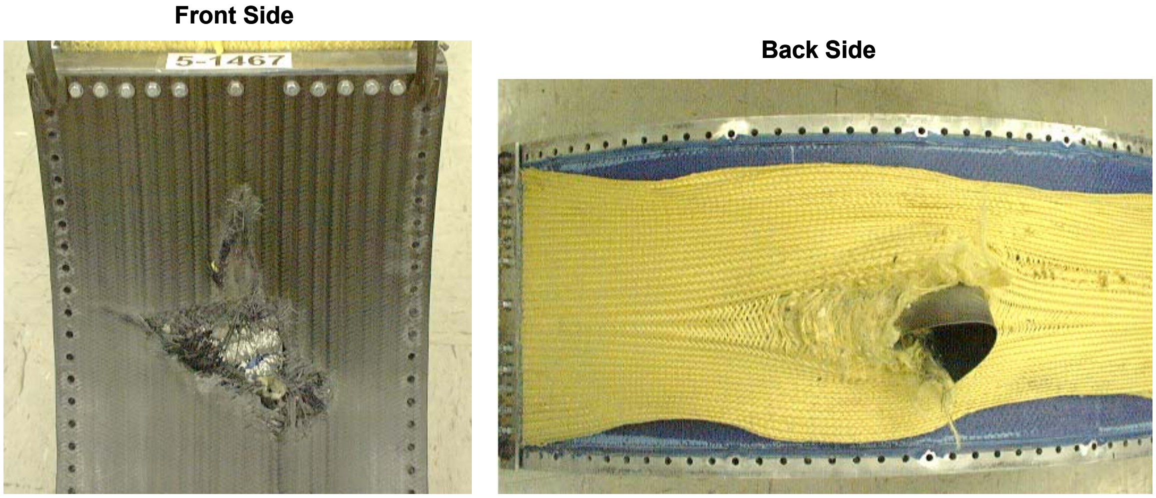


Figure 12. Kevlar 49/29® Contained Blade.

Sub Task 3.3.3 – Nanofiber Grid & Stitch Development & Subscale Tests

The purpose of this project is to develop and evaluate the use of conductive inks as a damage detection system for composite parts such as an engine fan case. The conductive inks are formulated from highly conductive vapor grown carbon nanofibers supplied by Applied Sciences Inc. This project consists of five tasks: Task 1 Inks & Beams, Task 2 Smart Panels, Task 3 Smart Sandwich Panels, Task 4 Nanofiber-filled Tow, and Task 5 Smart Half Case.

Task 1 – Inks and Beams

Previous research, shown in Figure 13 has demonstrated that the conductivity of polymers can be tailored by blending the host matrix with modest amounts of vapor grown carbon nanofibers, VGNF. For this project we have selected the PR24-HHT fiber type because of its high electrical conductivity and product maturity. After evaluating several ink formulations we have selected a composition of X wt% PR24-HHT/Epon 862/D230. This formulation results in a resistance of approximately 1000 ohms/inch for an ink strip of approximately 3mm width and 0.5mm thickness. All results presented below are based on this formulation. Figures 14 and 15 depict a stress induced crack in the ink with exposed nanofibers.

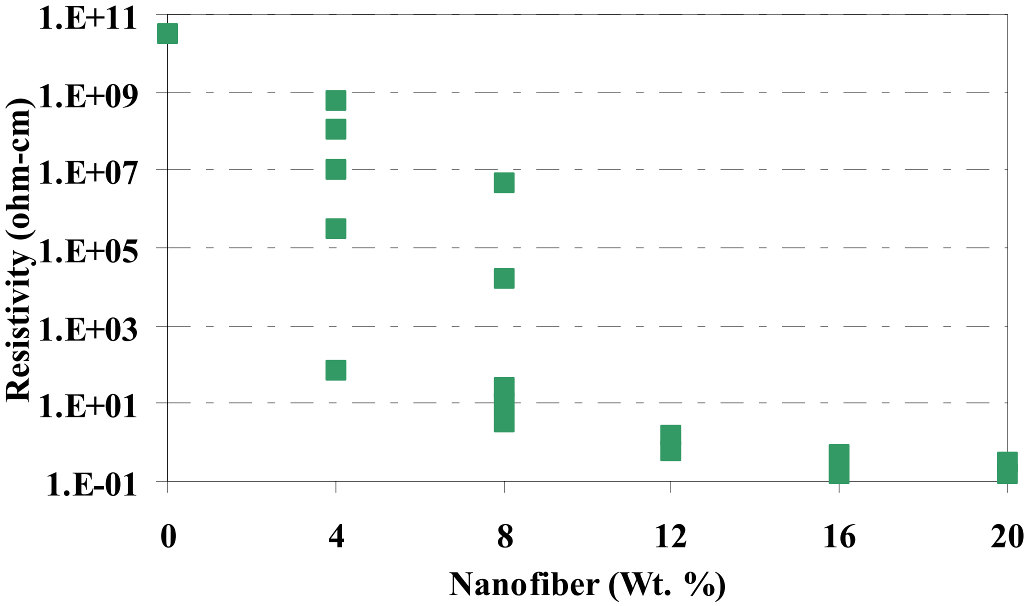


Figure 13. Resistivity of epoxy matrix as a function of VGNF type and loading

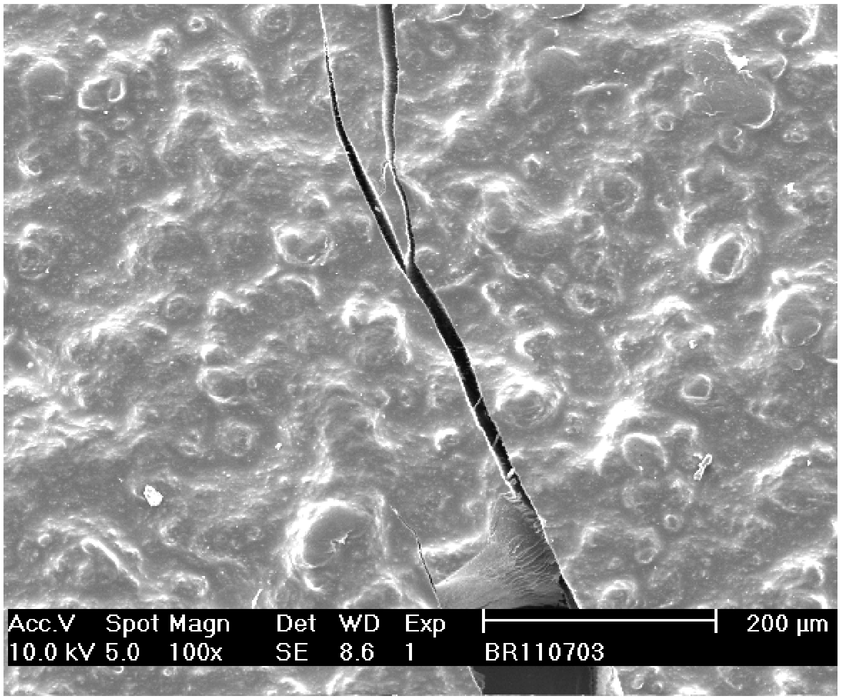


Figure 14. Crack in ink strip 100X

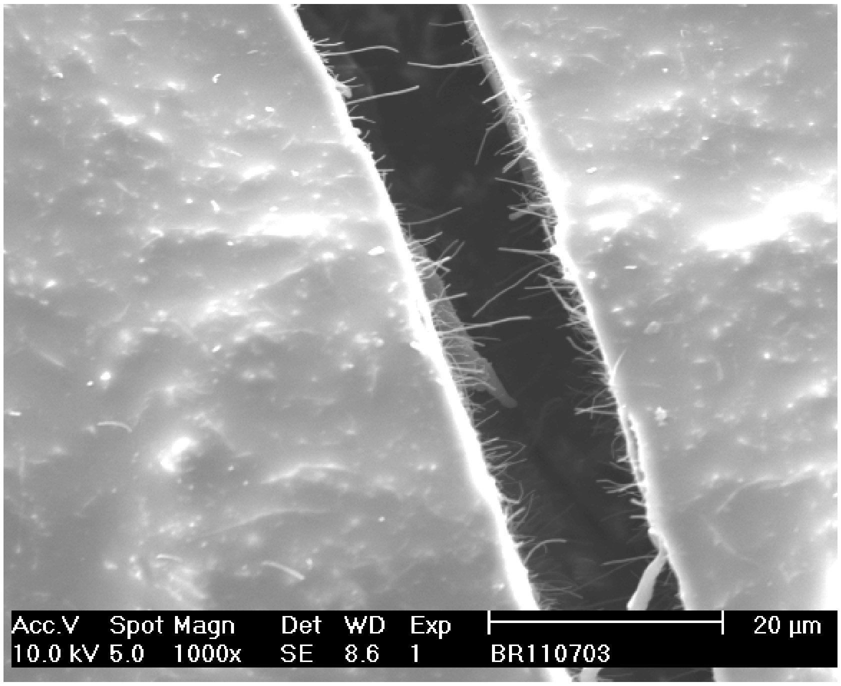


Figure 15. Crack in ink strip showing conductive nanofibers 1000x

Task 2 - Smart Panels

Previously 12" x 12" 16 ply and 32 ply quasi-isotropic laminates were instrumented with a conductive ink grid consisting of 5 x 5 lines as shown in Figure 16. Static indentation/penetration demonstrated, and shown in Figures 17 and 18, that the grid was sensitive to the deformation/damaged state. Another panel was shot with a 7/8" diameter steel ball with a velocity of 1000 feet/second to verify the impact test configuration. This "practice" test indicated that the sensor grid would survive the impact event and that the high speed data acquisition system was able to record the event.

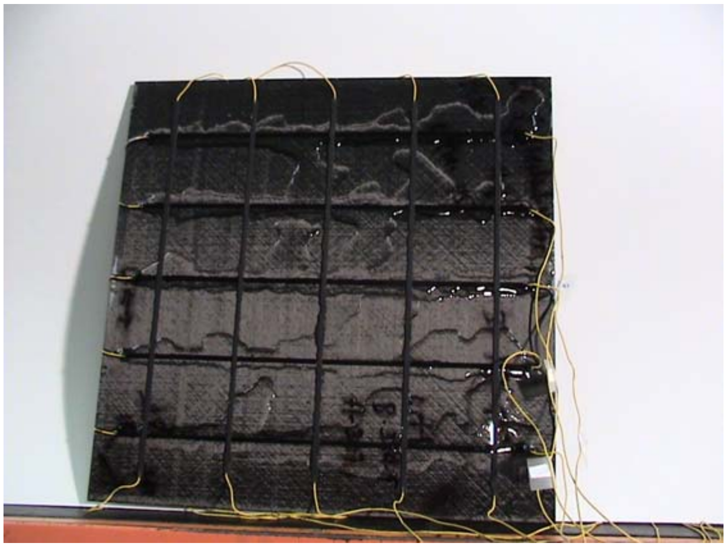


Figure 16. Sensor grid of "nano" conductive ink on panel 112503D

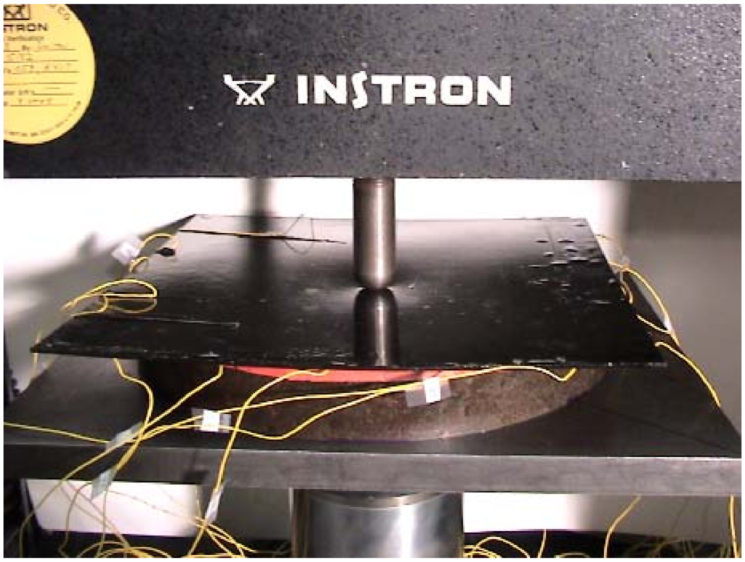


Figure 17. Photo of plate 112503D with one inch indenter initiating plate deflection

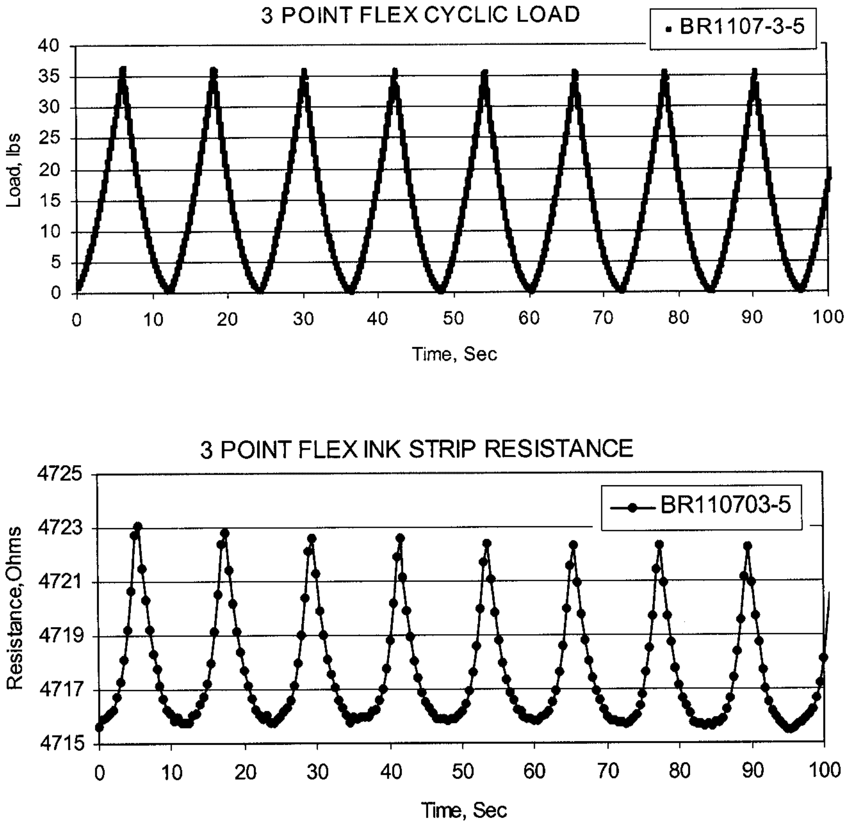


Figure 18. Load and resistance curves during cyclic flex test

Task 3 - Smart Sandwich Panels

A Tycor® foam core sandwich panel fabricated by Webcore and supplied by GEAE was prepared with a 5 x 5 sensor grid and exposed to an impact test using a 7/8" diameter steel ball. Figure 19 shows the steel ball and sabot, the support assembly for the sandwich panel and the subsequent damage. The damage was centered at the intersection of the center lines X3 and Y3. The damage did not extend much more than an inch from this node. Figure 20 shows the resistance readings of Y3 and Y4 taken at a rate of 1 MHz. The maximum upper range of the data acquisition system was set to a value of approximately 26 K-ohms to achieve a higher resolution at the lower bounds. We see that the resistance of Y3 increased rapidly at 0.0025 seconds and dropped back down briefly before rising off-scale (26 K-ohms) permanently. The brief drop in resistance could be a result of the steel ball passing through the hole and completing the circuit of the Y3 grid line.. The adjacent grid line Y4 shows almost no effect except one point of increased resistance at 0.003 seconds which may indicate the effects of a stress wave in the panel.

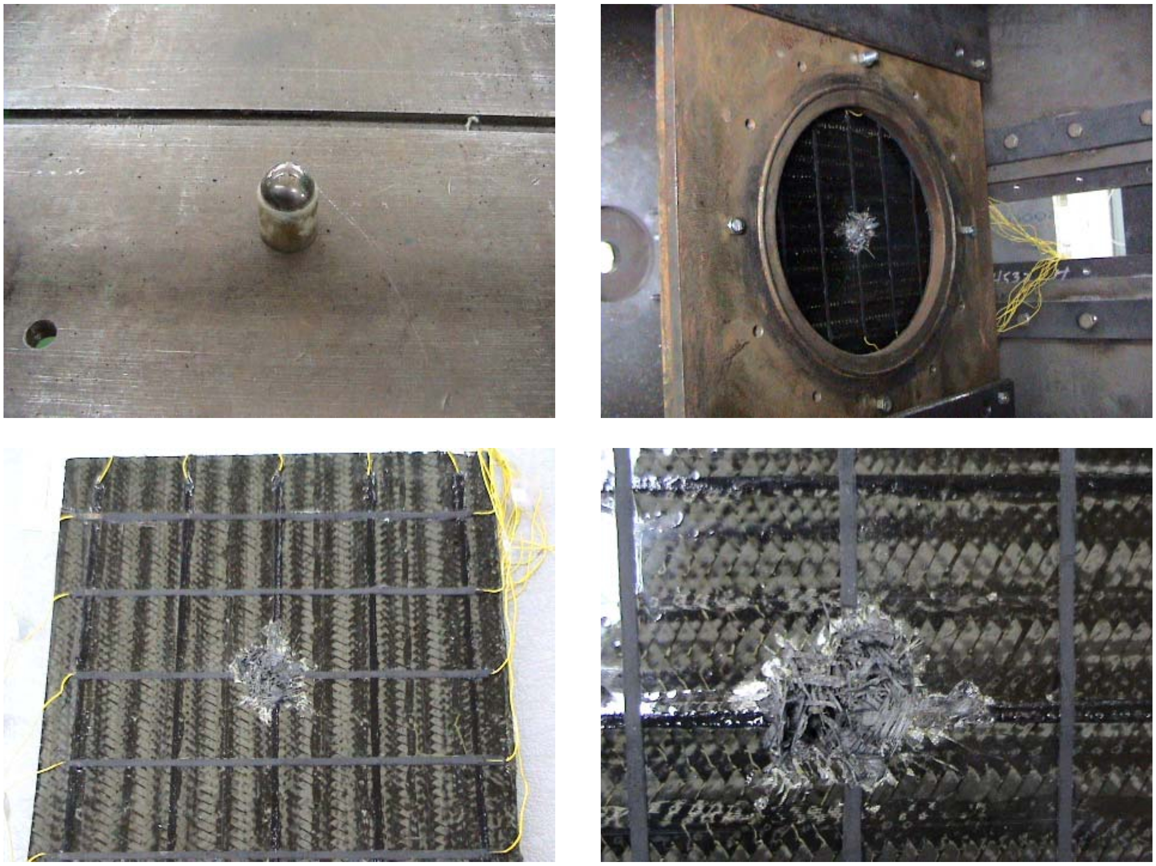


Figure 19. Picture of projectile, impact test cell, whole plate after impact, and damage location centered at X3 - Y3.

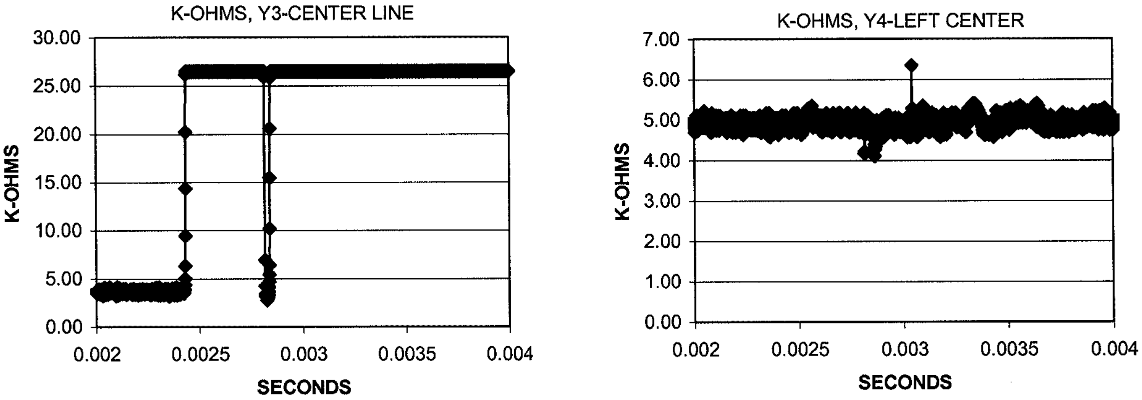


Figure 20. Resistance readings taken at 1Mhz during the impact event at locations Y3 and Y4.

Further review of the other grid lines will need to be conducted to substantiate this possible secondary effect. Figure 21 shows a table of the resistance values measured before and after the impact event. We see that Y3 has a value of near infinity while X3 has a value of 73 K-ohms. The interaction of the carbon fibers around the hole can provide a high resistance circuit which would explain why X3 has some measurable value; keeping in mind the resistance has increased about 15X following impact.

Task 4 - Nanofiber-filled Tow

Glass tow was coated with a similar composition of the conductive ink to determine whether or not it could be used as a "smart weave" sensor grid in stitched sandwich structure. A target resistance value of 20K-ohms/foot of fiber was selected because that is only a slightly higher resistance than that of the sensor grid lines. Figure 22 illustrates the method used to achieve this goal. Essentially the glass tow was drawn across a table and the nano-ink was brushed on by hand followed by winding onto a mandrel, where it was allowed to cure. This product form was previously tested by Webcore to have the ability to be used as stitching thread in their equipment. Approximately 650 feet was delivered to Webcore. We consider this application method to be a "brute force method" which can certainly be improved upon once better methods of spreading the heavily sized tow are developed.

Task 5 - Smart Half Case

A half case was instrumented with five circumferential lines and nineteen width lines using a spacing of three inches. The sensor grid for the case was prepared using the same methods as the flat panels. Unfortunately, we did discover that there was some cross talk between the circumferential lines, meaning at some locations the conductive ink came in contact with the underlying composite structure. We'll need better methods to check the insulating coating before applying the sensor grid but in any case it did not seem to hurt our results during impact. The sensor lines going across the width had no cross talk. Figure 23 illustrates 1) engine half case as received, 2) application of masking tape used to define sensor grid, 3) first set of finished grid lines, 4) completed case with sensor grid ready for impact test, 5) case after first impact event, 6) case after second impact event. During impact 1 lines 15-19 across the width were severed as well as 3 and 4 on the circumference. During impact 2 width lines 1-4 were severed and line 5 was damaged. The two impact damage sites are illustrated in Figures 23-5 and 23-6. Table 1 provides a summary of the resistance readings before and after test 1 and after test 2. We see the grid lines not severed during the impact remain unchanged. Therefore the grid system gives an accurate account of the damage zone. We had issues with broken sensor wires during test-setup which need to be addressed in the future.

Branch Code	Av. Resis before shootinh, Ohm	Av. Resis. after shooting, Ohm
X1	4024	3844
X2	2615	3984
X3	4663	72792
X4	4362	4192
X5	5571	5051
Y1	2555	2563
Y2	3688	3640
Y3	3534	infinity
Y4	4523	5400
Y5	4087	3952

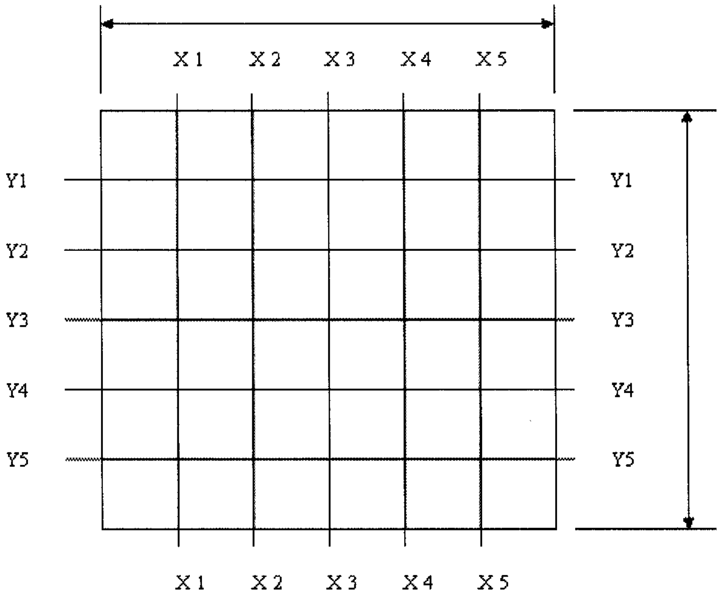
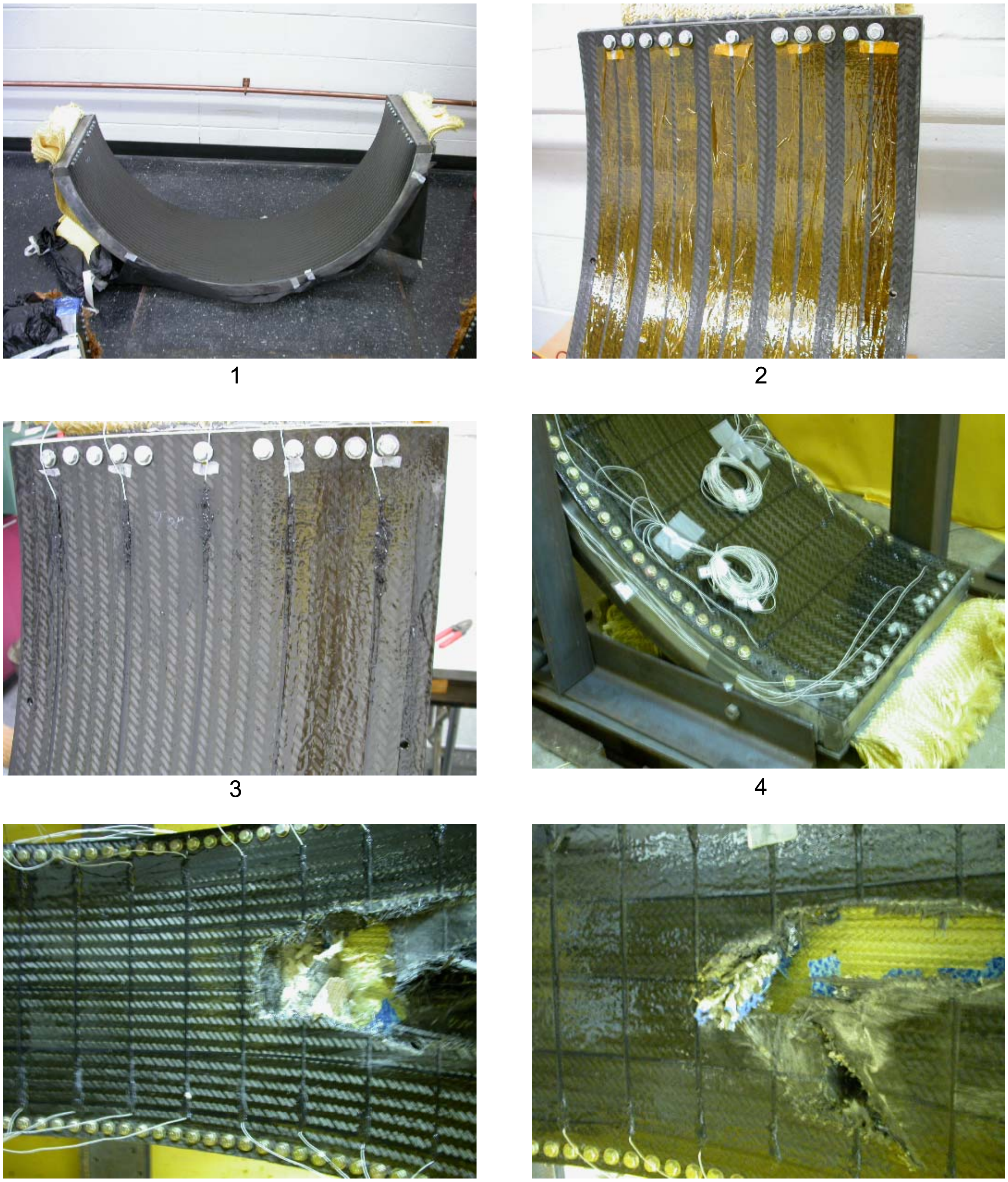


Figure 21. Static resistance readings taken before and after impact event. Center lines X3 and Y3 were broken during impact with a 7/8" diameter steel ball.

Figure 22. Filament winding set-up for producing a conductive glass tow using a conductive carbon nanofiber coating.



1 2

3 4

5 6

Figure 23. Series of pictures depicting 1) engine half case as received, 2) application of masking tape used to define sensor grid, 3) first set of finished grid lines, 4) completed case with sensor grid ready for impact test, 5) case after first impact event, 6) case after second impact event.

HORIZONTAL SENSOR GRID LOCATION	BASE LINE RESISTANCE, OHMS	FIRST IMPACT RESISTANCE, OHMS	SECOND IMPACT RESISTANCE, OHMS
1	4.48		SEVERED
2	5.40		SEVERED
3	4.68		SEVERED
4	5.31		SEVERED
5	6.63		111000
6	5.80		6.58
7	5.45		N/A
8	4.81		5.05
9	5.71		N/A
10	6.15		N/A
11	3.56		N/A
12	4.85	4.84	
13	3.64	3.98	
14	4.95	13.65	
15	5.60	SEVERED	
16	3.92	SEVERED	
17	5.23	SEVERED	
18	4.08	SEVERED	
19	4.43	SEVERED	
CIRCUMFERENTIAL SENSOR GRID LOCATION	**BASE LINE RESISTANCE, OHMS**	**FIRST IMPACT RESISTANCE, OHMS**	**SECOND IMPACT RESISTANCE, OHMS**
1	8.21	9.33	8.53
2	9.98	8.33	8.31
3	30.1	SEVERED	
4	28.6	SEVERED	
5	12.9	N/A	

Table 1. Resistance values of the half case grid taken before and after impact events.

2. Summary and Accomplishments

In less than one year, a variety of successful developments have occurred under this program that have advanced the containment technologies for the next generation of aircraft propulsion. Braided materials have proven their improved fiber architecture efficiency in restricting crack propagation and absorbing energy. Zylon has exhibited improved energy absorption over Kevlar for titanium blade impact events. Carbon nanofibers have demonstrated their ability to form efficient data circuits for diagnostic purposes. The combination of all of the above developments provides the groundwork for evolving the next generation of “Smart” containment engine systems. Listed below is a summary of the critical accomplishments for this program.

- Identified a fiber / resin system (T700 / 977-3) to satisfy both impact and manufacturing requirements for a containment case
- Developed braided shell fiber architecture with high crack resistance and structural efficiency
- Quantified energy absorption and weight savings of braided Zylon® vs. Kevlar containment belt
- Developed nanofiber enriched ink as diagnostic grid for braided composites and sandwich structures
- Initiated development of selective nanofiber enriched tows for use in braided architectures
- Identified potential use of nanofiber grid for validation of impact analysis codes

3. Recommendations

- Demonstrate the “smart” containment case technologies in blade-out prototype rig test
- Scale-up the manufacturing and controls for the nano fiber circuitry
- Developed improved ballistic structural composites using nano fibers
- Demonstrate the “smart” containment case design on a full scale engine

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** November 2005	**3. REPORT TYPE AND DATES COVERED** Final Contractor Report

4. TITLE AND SUBTITLE Smart Fan Containment System	**5. FUNDING NUMBERS** WBS–22–714–92–50 NAS3–01135 Work element 3.3, Task order 23
6. AUTHOR(S) General Electric Aircraft Engines	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) General Electric Aircraft Engines One Neumann Way Cincinnati, Ohio 45215–1915	**8. PERFORMING ORGANIZATION REPORT NUMBER** E–15287
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546–0001	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER** NASA CR—2005-213969

11. SUPPLEMENTARY NOTES

Project Manager, Clayton Meyers, Aeronautics Division, NASA Glenn Research Center, organization code PRV, 216–433–3882.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 07 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.	**12b. DISTRIBUTION CODE**

13. ABSTRACT *(Maximum 200 words)*

In less than one year, a variety of successful developments have occurred under this program that have advanced the containment technologies for the next generation of aircraft propulsion. Braided materials have proven their improved fiber architecture efficiency in restricting crack propagation and absorbing energy. Zylon (Toyobo Co., Ltd., Kita-Ku, Osaka, Japan) has exhibited improved energy absorption over Kevlar (Dupont, Wilmington, DE) for titanium blade impact events. Carbon nanofibers have demonstrated their ability to form efficient data circuits for diagnostic purposes. The combination of all of the developments provides the groundwork for evolving the next generation of "Smart" containment engine systems. A summary of the critical accomplishments for this program are: (1) Identified a fiber/resin system (T700/977–3) to satisfy both impact and manufacturing requirements for a containment case, (2) Developed braided shell fiber architecture with high crack resistance and structural efficiency, (3) Quantified energy absorption and weight savings of braided Zylon versus Kevlar containment belt, (4) Developed nanofiber enriched ink as diagnostic grid for braided composites and sandwich structures, (5) Initiated development of selective nanofiber enriched tows for use in braided architectures, and (6) Identified potential use of nanofiber grid for validation of impact analysis codes.

14. SUBJECT TERMS Propulsion systems (aircraft)	**15. NUMBER OF PAGES** 26
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**