NASA/TM—2010-216763 TP 3188

Experimental Techniques for Evaluating the Effects of Aging on Impact and High Strain Rate Properties of Triaxial Braided Composite Materials

J. Michael Pereira, Gary D. Roberts, and Charles R. Ruggeri
Glenn Research Center, Cleveland, Ohio

Amos Gilat and Thomas Matrka
The Ohio State University, Columbus, Ohio

August 2010

NASA STI Program . . . 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 plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and 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 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 also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, 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 STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2010-216763 TP 3188

Experimental Techniques for Evaluating the Effects of Aging on Impact and High Strain Rate Properties of Triaxial Braided Composite Materials

J. Michael Pereira, Gary D. Roberts, and Charles R. Ruggeri
Glenn Research Center, Cleveland, Ohio

Amos Gilat and Thomas Matrka
The Ohio State University, Columbus, Ohio

Prepared for the
2010 Aircraft Airworthiness and Sustainment (AA&S) Conference
cosponsored by the DoD, NASA, and FAA
Austin, Texas, May 10–13, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

August 2010

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

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

Experimental Techniques for Evaluating the Effects of Aging on Impact and High Strain Rate Properties of Triaxial Braided Composite Materials

J. Michael Pereira, Gary D. Roberts, and Charles R. Ruggeri
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Amos Gilat and Thomas Matrka
The Ohio State University
Columbus, Ohio 43210

Abstract

An experimental program is underway to measure the impact and high strain rate properties of triaxial braided composite materials and to quantify any degradation in properties as a result of thermal and hygroscopic aging typically encountered during service. Impact tests are being conducted on flat panels using a projectile designed to induce high rate deformation similar to that experienced in a jet engine fan case during a fan blade-out event. The tests are being conducted on as-fabricated panels and panels subjected to various numbers of aging cycles. High strain rate properties are being measured using a unique Hopkinson bar apparatus that has a larger diameter than conventional Hopkinson bars. This larger diameter is needed to measure representative material properties because of the large unit cell size of the materials examined in this work. In this paper the experimental techniques used for impact and high strain rate testing are described and some preliminary results are presented for both as-fabricated and aged composites.

1.0 Introduction

Triaxial braided composite materials offer some advantages over laminated unidirectional composites in applications involving impact loading. One of these is that braided composites can be designed such that each layer is quasi-isotropic, thereby reducing the tendency observed in traditional composite architectures to delaminate under impact due to shear stresses caused by the differing strain response of each layer. Efficient manufacturing methods for braided composites offer additional cost benefits in certain applications. It has been demonstrated that structures such as jet engine fan containment systems manufactured from triaxial braided composites can lead to a significant weight reduction (Refs. 1 and 2) while maintaining the ability to contain a failed fan blade, required for its safety function. The materials currently being used are primarily standard modulus carbon fibers and 350 °F cure epoxy matrix materials. Various fiber/matrix combinations have been examined for static strength and impact resistance. Composites made with toughened matrix materials typically have higher static strength. The effect of matrix toughness on impact resistance is more complex because of the high rate deformation and failure processes. As an example, one composite with a very brittle matrix has exhibited low static strength, as expected, but very high impact resistance. This may be attributed to the lower-toughness resins allowing more fibers to be involved in energy absorption. The high strain rate response of the materials may also play a role in the differing impact response. Aging of the composite could result in some embrittlement of the matrix material. This would be expected to result in lower static strength, but the effect on impact resistance is not clear. To investigate these phenomena an experimental program is underway to measure the impact and high strain rate properties of triaxial braided composites and to quantify any degradation in properties as a result of thermal and hygroscopic aging typically encountered during service. Preliminary results of ongoing testing of aging on one material system has indicated a large reduction in matrix tensile strength and strain to failure (embrittlement) without an associated reduction in tensile strength of the composite after 52 weeks of repeated temperature and humidity cycles. This paper describes techniques that are being developed to investigate the impact resistance of these composite materials and how the impact resistance changes with aging.

When considering an impact involving a hard projectile with a sharp edge, local through-thickness shear failure due to the cutting action of the projectile may be the primary initial cause of failure. For the purposes of this study we assume that some technique is incorporated in the system of interest to mitigate the local initial cutting failure and that the impact energy is absorbed over a larger volume through tension in the fibers and the transfer of stresses through deformation of the resin material. Actual blade-out tests and ballistic impact tests to simulate fan blade-out in hardwall composite containment systems have shown that the deformation can be controlled to induce this type of failure (Ref. 1). A previous study conducted to investigate the impact energy absorption of braided composite systems utilized a relatively soft ballistic gelatin projectile to reduce localized stress concentrations and cutting of the composite specimens (Ref. 3). Radial deformation measurements from an actual fan blade-out test on a composite case, ballistic impact tests on composite fan cases to simulate blade-out tests, and flat composite panel impact tests using a gelatin projectile have shown qualitatively similar results (Refs. 1 and 3).

In the impact tests described in Reference 3 the composite panels were 24- by 24-in. and were held in a square fixture with a 20 in. aperture. Due to the high cost and limited availability of composite test specimens, for this study an impact test was developed that uses 12- by 12-in. panels held in a circular fixture. Impact tests are being conducted on flat panels using a projectile designed to induce deformation similar to those observed in actual composite fan case blade out tests. The tests are being conducted on as-fabricated panels and panels subjected to various numbers of aging cycles.

In addition to the impact testing, high strain rate properties of composite specimens in the as-fabricated and aged conditions are being measured using a unique Split Hopkinson Pressure Bar apparatus. The Compression Split Hopkinson Bar (SHB) technique, introduced by Kolsky (Ref. 4), is the most commonly used technique for measuring the mechanical properties of materials (stress-strain curves) at strain rates ranging from 200 to 5000 s^{-1}. In the SHB test, shown schematically in Figure 1, a short material specimen is placed between two bars.

The specimen is loaded by a wave that is generated in one of the bars (incident bar). Upon loading, part of the loading wave reflects back to the incident bar and part propagates on through the specimen to the transmitter bar. The amplitude of the loading wave and the dimensions of the specimen are designed such that the specimen is loaded to failure during the test. The incident and transmitter bars remain elastic throughout the test. The waves in the bars, which are measured with strain gages, are recorded. In the classical configuration, the stress, strain rate, and strain in the specimen during the test are determined from the recorded waves in the bars using elastic wave theory. The stress in the specimen is determined from the wave in the transmitter bar. This wave corresponds to the force that is applied to the specimen's end that is in contact with the bar. The force is divided by the cross-sectional area, which gives the average stress. The determination of the strain is more difficult. In the standard analysis of a SHB test the velocity of the ends of the bars where the specimen is placed is determined from the measured elastic waves in the bars. The difference in the velocity of the two ends divided by the specimen's length gives the average strain rate.

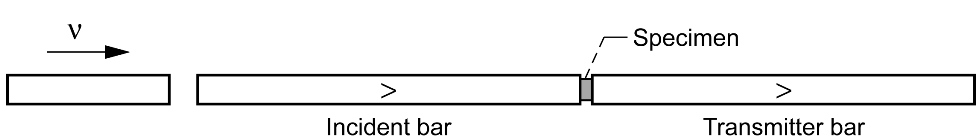

Figure 1.—Schematic of the compression split Hopkinson bar technique.

The average stress, strain rate, and strain that are measured in a standard SHB experiment are accurate if the specimen is under a uniform state of uniaxial compression. In a typical compression SHB apparatus the diameter of the bars is 0.5- to 1.0-in. and the specimen is a short (0.2- to 0.35-in.) small diameter (0.2- to 0.35-in.) cylinder. With these dimensions the main assumptions (uniform stress and strain under uniaxial compression) are valid.

The standard SHB configuration is not suitable for testing 3–D braided composites since the width and length of a specimen characteristic of these materials are large compared to the diameter of the bars. For this reason a new SHB apparatus with bars that have a diameter of 2 in. has been developed for this program. The new apparatus uses the Digital Image Correlation (DIC) technique for measuring strain directly on the specimen which eliminates the requirement of assuming that the strain distribution in the specimen is uniform spatially and temporally during the deformation process.

2.0 Methods

2.1 Materials

The composite materials considered here consist of six layers of braided fabric with a [0/+60/–60] quasi-isotropic layup made using Toray T700s fibers. Several different resins are under investigation. For the impact testing conducted in this study, the resin under consideration is Epon E-862 resin. High strain rate data is being measured on this material as well as on composites with Cytec PR520 toughened epoxy. The material is fabricated in 24- by 24-in. flat panels with a thickness of 0.125 in. using a resin transfer molding process. The architecture of the triaxial braid is shown in Figure 2. The materials have been tested in the as-fabricated condition as well as after a number of thermal and hygroscopic cycles that simulate conditions similar to those of an engine in service. The panels undergo two temperature and humidity cycles in a 24 hr period as shown in Figure 3.

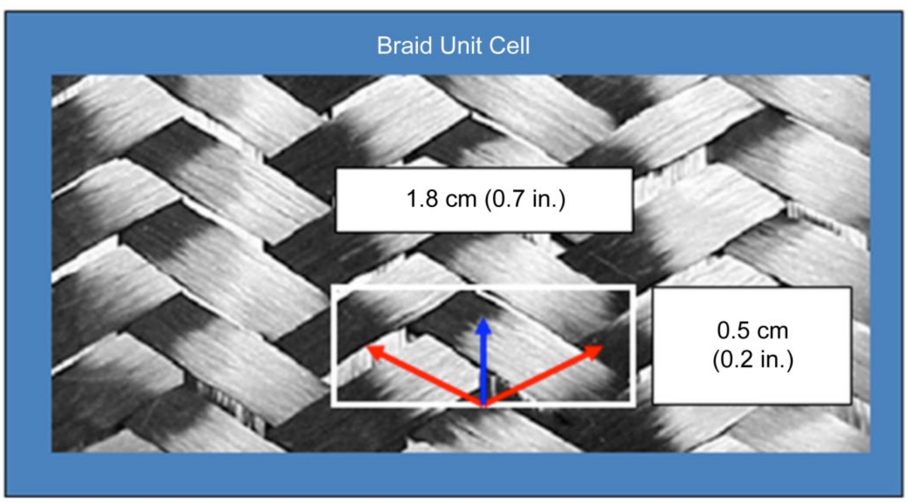

Figure 2.—Two-dimensional triaxial braided fiber architecture used for composite panels.

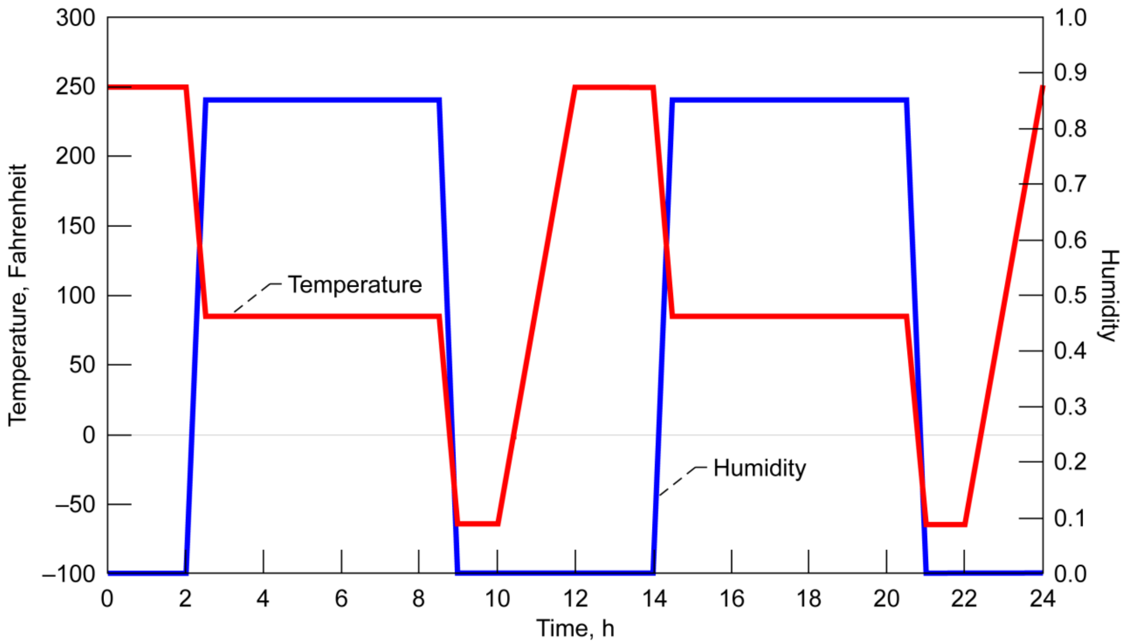

Figure 3.—Temperature and humidity aging cycle.

2.2 Ballistic Impact Testing

The ballistic impact response of the composite specimens is being measured by impacting projectiles into flat plates at a normal incidence using a single stage gas gun with a 2 in. bore and a length of 12 ft. The composite test specimens measure 12- by 12-in. and are clamped in a circular fixture with an aperture of 1 in. (Fig. 4). To eliminate slipping at the boundary, 28 bolts extend through the fixture front clamp, the specimen and the rear fixture plate. The projectile is a thin walled hollow AL 2024 cylinder with a nominal mass of 50 gm and a front face with a compound radius (Fig. 5). This projectile was designed based on a number of considerations. One is that AL 2024 is a well characterized material and its properties are independent of strain rate at least to rates up to 5000/sec. This significantly simplifies computational modeling of the impact test compared to the use of a soft body projectile. The radius of the front face of the projectile was designed such that the deformation profile and failure mode were similar to those observed in the composite plate tests described in Reference 3. The projectile underwent a design modification after the initial stages of the test program. Originally the overall length of the projectile was 1.243 in., with a length of 0.75 in. for the straight cylindrical section. However, due to some problems related to velocity repeatability and impact orientation, the overall length of the projectile was increased to 1.947 in. and the wall thickness reduced to 0.030 in. All other characteristics of the projectile, including the front face profile and overall mass remained the same. The projectiles have a diameter of 1.995 (+0/–.006) in., such that they fit inside the gun barrel with just enough clearance so that they would slide easily.

In each test the impact velocity and the exit velocity, if penetration occurs, is measured using calibrated high speed digital video cameras (Phantom V7.3, Vision Research Inc., Wayne, New Jersey). Full field displacement and strain measurements on the back side of each panel are measured using the ARAMIS digital image correlation system (GOM, Braunschweig, Germany) in conjunction with a calibrated pair of Photron model SA1.1 cameras (Photron USA, San Diego, California).

A series of impact tests has been completed on T700/E-862 composite panels. Twelve tests were conducted on 12- by 12-in. test panels cut from three separate 24- by 24-in. as-fabricated plates and eight test panels cut from two plates that had undergone 344 temperature and humidity cycles (approximately 6 months) shown in Figure 3.

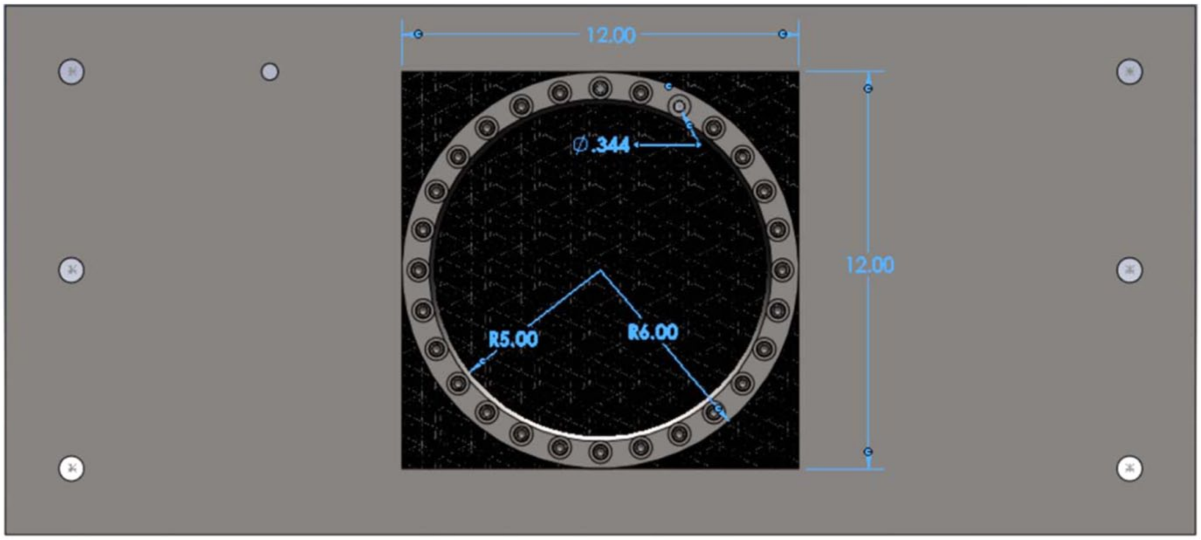

Figure 4.—Impact test fixture for 12 in. square specimens. Dimensions are in inches.

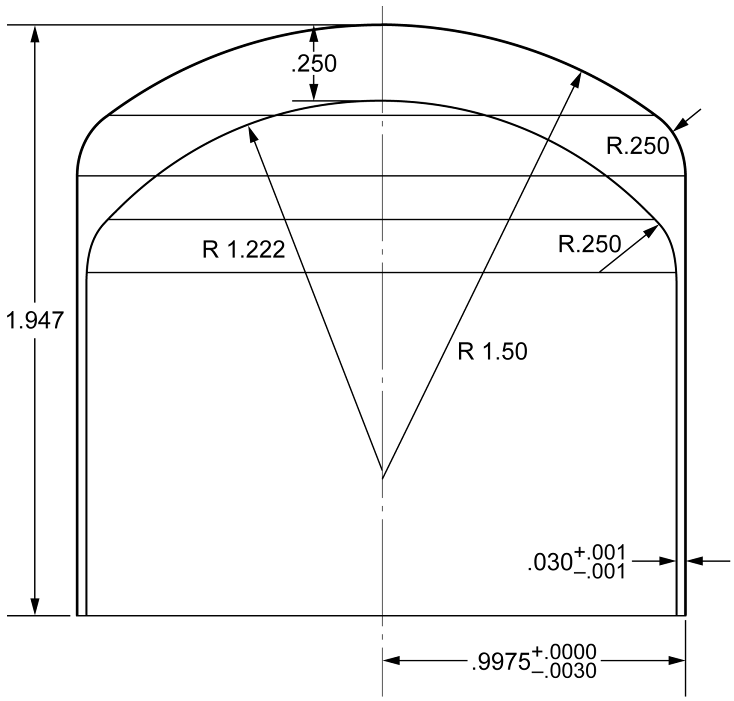

Figure 5.—Aluminum 2024 projectile. Dimensions are in inches.

2.3 High Strain Rate Testing

A series of high strain rate compression tests is being conducted on specimens machined from triaxially braided composite panels composed of Toray T700 fibers and Cytec PR520 toughened epoxy. The fiber architecture is the same as described above. Because of the relatively large fiber tows, to obtain representative high strain rate data, the specimen sizes are relatively large compared to those used in typical SHB testing. The Hopkinson bar apparatus with a bar diameter of 2 in., developed for this program, is being used to test these specimens. Tension and shear experiments using a large diameter bar have not yet been developed, but may be considered in the future.

The specimen is a rectangular coupon (1.4 in. wide, 0.5 in. long) machined from the composite panels. The coupon is glued into two adapters (Fig. 6) such that 0.062 in. of the length at each end is inside the adapters, and a 0.375 in. long section in the middle is the material that is actually tested. Specimens are being tested with the axial fibers in the direction of the loading. The specimen (painted for the DIC analysis) and the bars are shown in Figure 7.

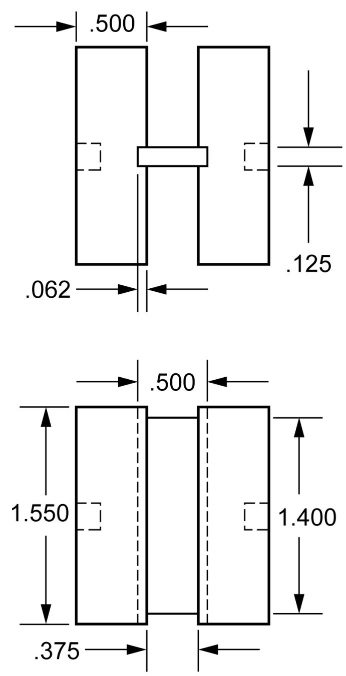

Figure 6.—Specimen and adapters.

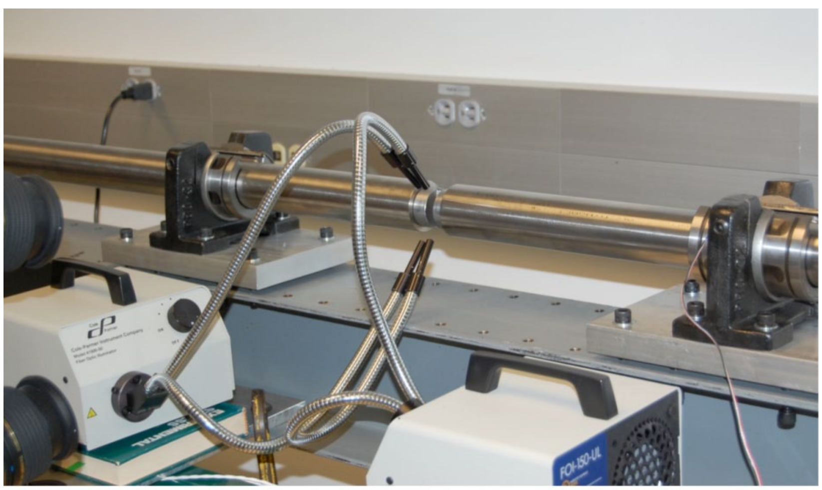

Figure 7.—Specimen in the SHB apparatus.

3.0 Results

3.1 Ballistic Impact Testing

A series of still photos taken from a high speed video camera, from just prior to impact to projectile rebound, is shown in Figure 8. In all cases, except one, the projectile orientation was straight and there was no slippage evident between the plate and the fixture. In one test the projectile was pitched downward approximately 8°. The penetration velocity for all panels is shown in Figure 9 with the as-fabricated panel data on the left and the aged panel data on the right. The data is separated into five columns, each with four data points associated with the four panels cut from a single 24- by 24-in. plate. The solid symbols indicate tests in which the projectile penetrated the panel and open symbols those in which the projectile did not. Triangular symbols indicate tests using the original projectile (designated Projectile A) and circular symbols indicate tests conducted with the modified longer projectile (designated Projectile B). The velocity required to penetrate the aged and unaged panels was in the range of 530 to 550 ft/sec. The test results indicate that there is no significant reduction in the penetration velocity for the panels after 344 cycles of aging compared with the as-fabricated panels. For each 24- by 24-in. panel there is no overlap in the penetration velocity (i.e., no cases where the projectile penetrated at a lower velocity than a non-penetration test) except for the case where the projectile orientation was not normal to the test panel as indicated in the figure. There is no obvious indication that the change in projectile length had any effects on the results.

The results indicate that there is some variation in penetration velocity between panels. An example of this variation can be seen in the second and third columns of the as-fabricated panel tests, where the penetration velocity for one set of panels is below 530 ft/sec, and in the other set above 540 ft/sec. While this variation may be considered small, it appears to be greater than any changes due to the 344 aging cycles.

Figure 10 shows the deformation profile on the back side of a panel from a typical impact test at a velocity just below the penetration velocity (544 ft/sec). The deformation is relatively localized at the center of the panel, with a maximum of 0.58 in., and is similar to the profiles observed in an actual fan case blade-out test on a composite case (Ref. 1) and to those seen in larger panel tests with a soft gelatin projectile (Ref. 3). The damage induced by the projectile is diffuse, as opposed to a cutting or shearing failure, as can be seen in Figure 11 which shows a panel in which the projectile penetrated at a velocity of 554 ft/sec.

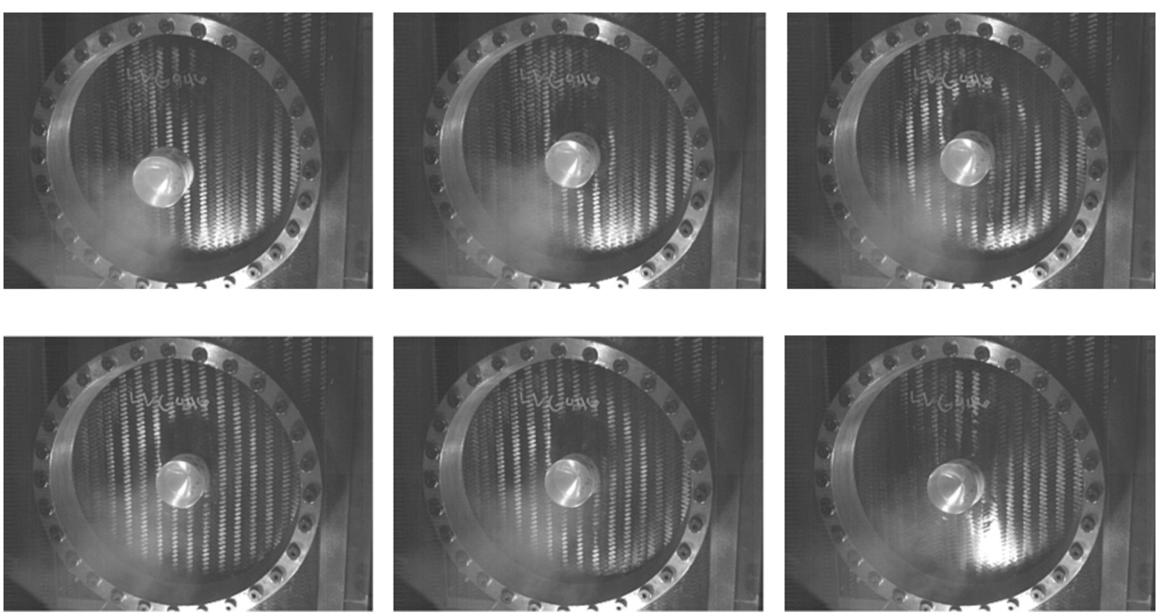

Figure 8.—Series of still images taken from high speed video of composite panel impact test.

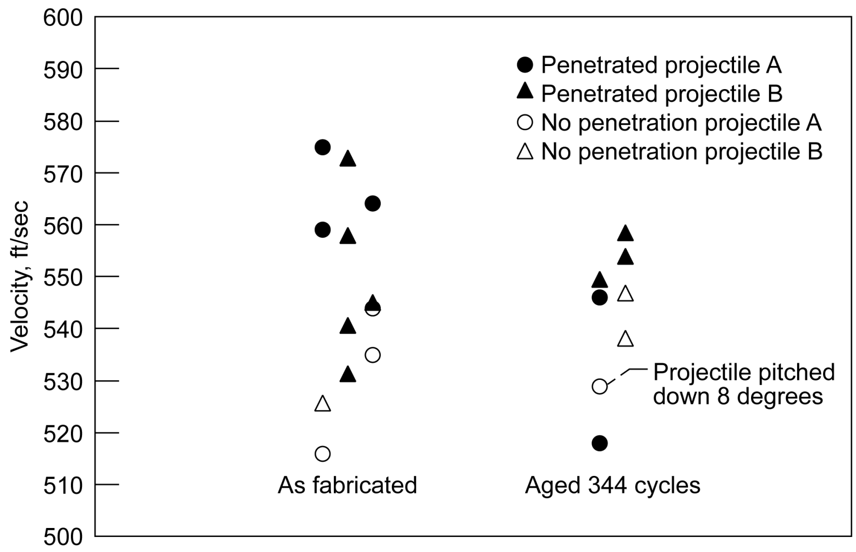

Figure 9.—Impact velocity and penetration results for composite panels.

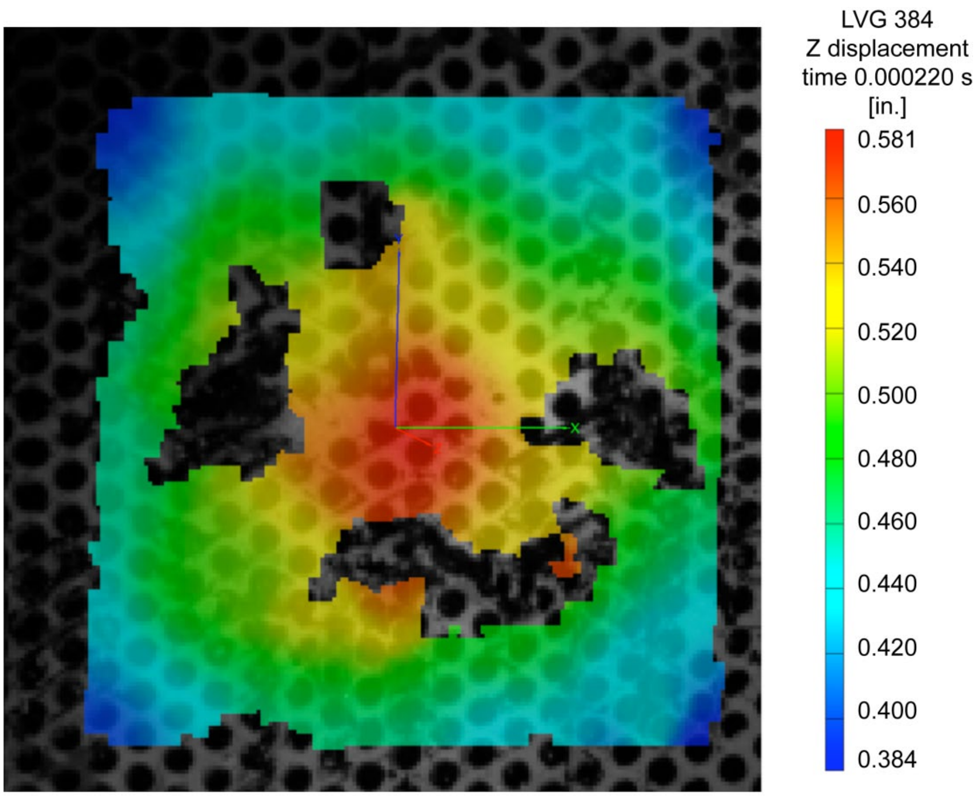

Figure 10.—Out of plane deformation pattern in composite panel at an impact speed just below the penetration threshold. Note missing areas of data due to paint pattern loss.

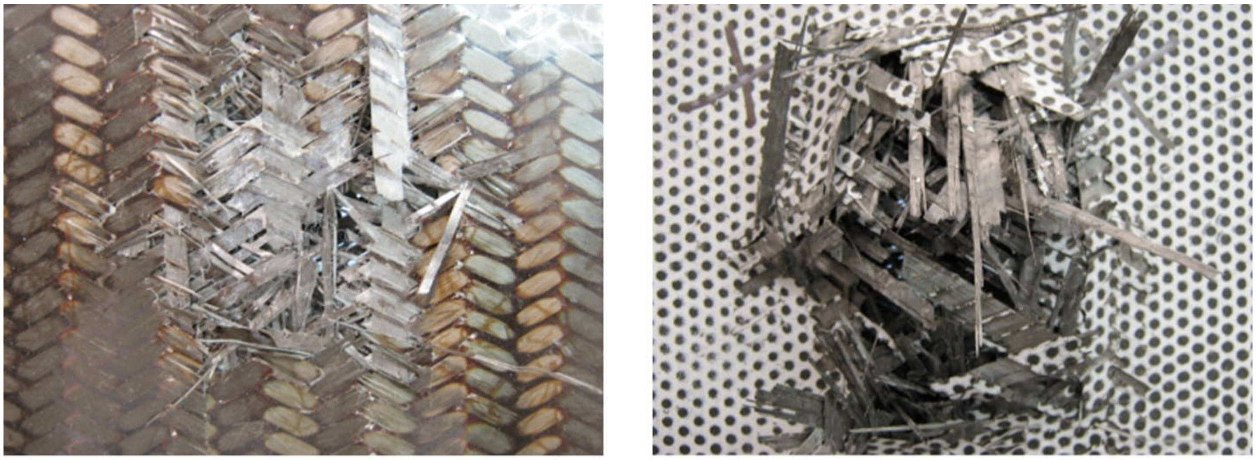

Figure 11.—Front (left) and rear (right) views of a penetrated composite panel.

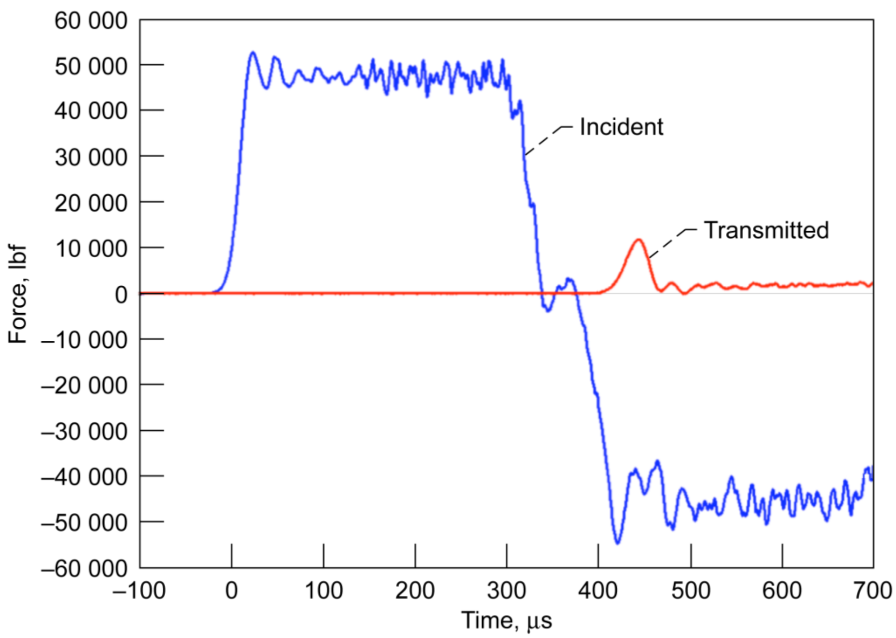

Figure 12.—Incident, transmitted and reflected waves in SHB experiment.

3.2 High Strain Rate Testing

Results from the first pilot test conducted with the new Split Hopkinson Bar apparatus are shown in Figures 12 to 15. Figure 12 shows the waves recorded in the incident and transmitted bars. Note that the amplitude of the incident wave is over 40,000 lb. The wave in the transmitter bar is actually the force transmitted through the specimen. The record shows a signal with a force that reaches 10,000 lb. The stress in the specimen is shown in Figure 13. The strain measured in the specimen (middle point) during the test with DIC system is shown in Figure 14. The average strain rate during the test (the slope of the strain versus time curve) is approximately 150 s^{-1}. The stress-strain curve is shown in Figure 15. The overall stress level appears to be significantly higher than the stress that was measured in quasi-static compression tests of specimens with the same configuration.

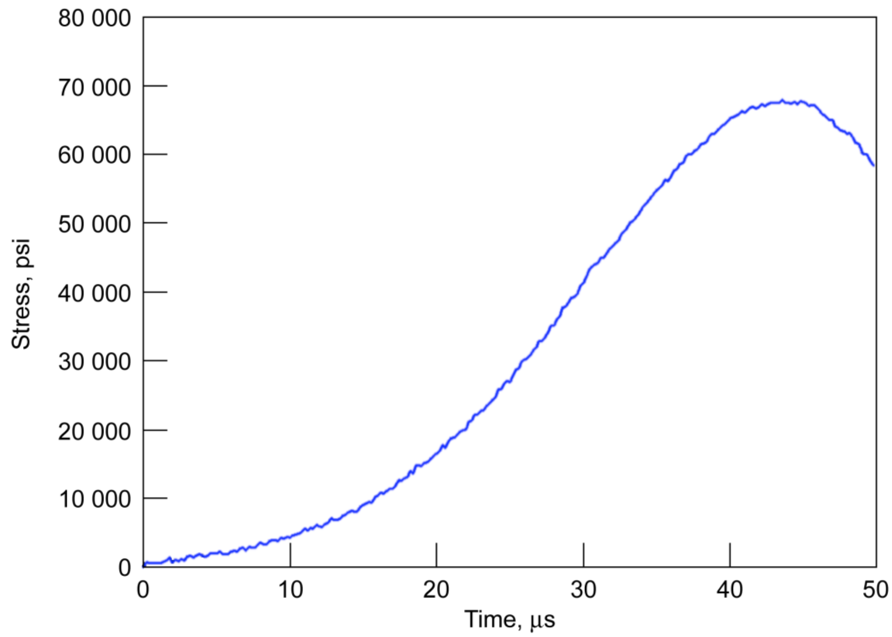

Figure 13.—Stress in the SHB specimen.

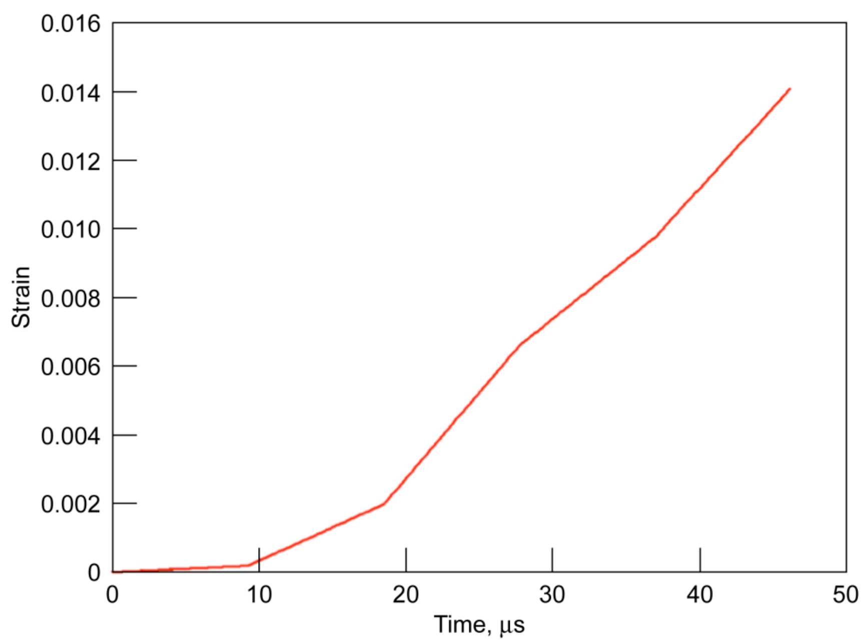

Figure 14.—Strain in the SHB specimen.

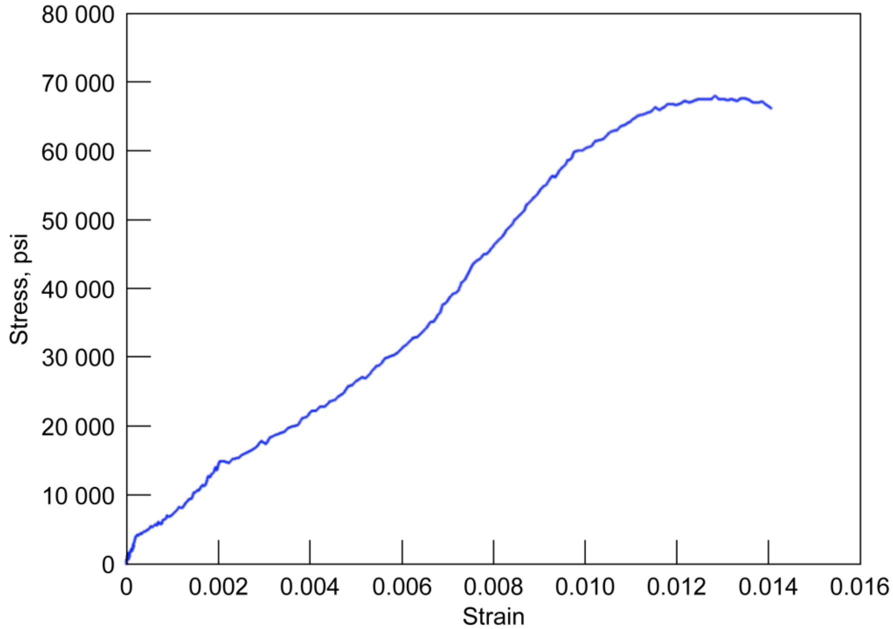

Figure 15.—Axial compression stress strain curve for triaxially braided composite Toray T700 fibers and Cytec PR520 toughened epoxy at strain rate of 420 s^{-1}.

4.0 Discussion

The impact and high strain rate tests discussed here were developed to study any changes in material properties and impact performance of composites due to in-service temperature and humidity cycles. While only preliminary results are available to date, both methods give quantitative information relevant to any degradation in performance for structures subjected to impact loading. The loading and damage modes in the impact tests are representative of those observed in actual fan case blade-out events. The relatively small panel test size allows greater statistical confidence in results due to the ability to conduct more tests. The projectile material significantly simplifies computational modeling of the test. The large diameter Split Hopkinson Pressure Bar enables the measurement of representative high strain rate data for composites with large cell sizes, such as the triaxially braided materials considered here.

The limited results to date do not indicate a significant reduction in impact performance after 344 cycles of temperature and humidity representative of typical engine service conditions. Future work will concentrate on measuring the impact performance after longer aging periods and quantifying any changes in the high strain rate properties of the composites.

References

1. Roberts, G.D., Pereira, J.M., Braley, M.S, and Arnold, W.A., “Design and Testing of Braided Composite Fan Case Materials and Components,” 19th International Symposium on Air Breathing Engines, Montreal, Sept., 2009.
2. Ogando, J., “Boeing’s More Electric 787 Dreamliner Spurs Engine Evolution,” Design News, June 3, 2007.
3. Ruggeri, C., “High Strain Rate Data Acquisition of 2D Braided Composite Substructures,” M.Sc. Thesis, The University of Akron, 2009.
4. Kolsky, H., “An Investigation of the Mechanical Properties of Materials at Very High Rates of Loading,” Proc. Phys. Soc. B 62, 676, 1949.

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

1. REPORT DATE *(DD-MM-YYYY)*
01-08-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Experimental Techniques for Evaluating the Effects of Aging on Impact and High Strain Rate Properties of Triaxial Braided Composite Materials

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Pereira, J., Michael; Roberts, Gary, D.; Ruggeri, Charles, R.; Gilat, Amos; Matrka, Thomas

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 698259.02.07.03.04.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17384

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-216763

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 24 and 39
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
An experimental program is underway to measure the impact and high strain rate properties of triaxial braided composite materials and to quantify any degradation in properties as a result of thermal and hygroscopic aging typically encountered during service. Impact tests are being conducted on flat panels using a projectile designed to induce high rate deformation similar to that experienced in a jet engine fan case during a fan blade-out event. The tests are being conducted on as-fabricated panels and panels subjected to various numbers of aging cycles. High strain rate properties are being measured using a unique Hopkinson bar apparatus that has a larger diameter than conventional Hopkinson bars. This larger diameter is needed to measure representative material properties because of the large unit cell size of the materials examined in this work. In this paper the experimental techniques used for impact and high strain rate testing are described and some preliminary results are presented for both as-fabricated and aged composites.

15. SUBJECT TERMS
Composite materials; Impact tests; Strain rate

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	17	STI Help Desk (email:help@sti.nasa.gov) / 443-757-5802