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SMARTweave Sensors for Assessing Ballistic Damage: a Feasibility Study

by Daniel J. Snoha, William O. Ballata, and Shawn M. Walsh

ARL-TR-1674
May 1998

Army Research Laboratory
Aberdeen Proving Ground, Maryland 21005-5069

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Abstract

SMARTweave technology, developed and patented by the U.S. Army Research Laboratory (ARL), has been applied to monitor resin flow and cure progress in composite laminate processing. It has since demonstrated the capacity of being a viable sensing mechanism in other critical applications. In this feasibility study, for example, SMARTweave sensors have successfully shown the potential for detecting ballistic-impact-induced damage in a composite laminate. A sensing grid of electrically conductive graphite fibers was embedded in the composite specimens during lay-up of the glass-fabric preforms. The results of electrical resistance measurements preformed before and after ballistic impact, with the difference indicating the detection of induced damage (delamination), are presented herein. For purposes of qualitative comparison, a traditional, ultrasonic, nondestructive, evaluation technique was also used to capture the effects of the induced damage. This research was conducted during the period that the Materials Division was in transition from ARL, Watertown, MA, to the Rodman Materials Research Laboratory, Aberdeen Proving Ground (APG), MD.

Acknowledgments

The authors' appreciation goes to Clarissa DuBois and Suhas Malghan of the University of Delaware (UDel) for their assistance in manufacturing the test specimens, to Tom Carlson at the Aberdeen Test Center (ATC) for doing the ballistic testing, and to Knut Kreiger (UDel) and Patrick Sincebaugh (U.S. Army Research Laboratory [ARL]) for performing the ultrasonic inspection and interpreting the results.

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1. Introduction

1.1 Background. Over the last decade, the U.S. Army has initiated a number of programs specifically dedicated to exploring the potential of polymer composites as primary structural elements in a variety of critical and noncritical applications. Polymer composites present a number of attractive features with, perhaps, the most important being the weight savings offered by substituting composites for more traditional structural materials, such as steel or aluminum. Indeed, the "lightening of the force" has been and remains a fundamental goal of the Army. Every pound shed from an Army materiel system increases its ease and effective deployment while reducing cost associated with intermittent transportation. The major concern with polymer composites is whether or not they can effectively preserve, if not fortify, the performance of the material and systems that they replace; increasingly, prevailing economic constraints impose limits on the cost of delivering such composite systems affordably.

Traditionally, the U.S. Air Force has been the leader in the development and application of polymer composites, but, until recently, these have largely been relatively thin, graphite, fiber-reinforced materials. Conversely, the Army has been interested in thick-section, glass-reinforced composites for use not only as structural members but also for providing an additional measure of ballistic integrity. The distinction between "thin" and "thick" is still a largely debated issue. Suffice it to say that general agreement has established that a thick composite is one with a thickness of greater than a half inch; though, often attached to this statement is the provision that the type of reinforcement employed will give variance to this definition. It is important to note, however, that thickness is only one component in determining both processing and structural performance parameters for a given composite system.

While weight savings is the primary goal, there are other concerns that drive the development of Army-specific composite material. For example, the polymer itself must exhibit some degree of flame retardance. Additionally, once ignited, the polymer should not discharge a lethal concentration of fumes. These concerns, in fact, have driven both resin formulation and selection for prototype versions of the composite infantry fighting vehicle (CIFV) and the composite armored vehicle (CAV). This has prompted the notion of "coinjection" to achieve the desired exterior ballistic and structural properties while minimizing safety and health risks.

Delamination is the prevalent mode of failure in composites. However, the physics involved offer a unique and highly effective means for absorbing large amounts of energy delivered to a structure, which may occur during ballistic impact. The process of impact-induced delamination initiates when the "lamina" within the composite begin to peel away from each other due to the enormous shear force acting on the composite. Pulling each of these lamina apart involves breaking the adhesive bonds that exist between the matrix and the reinforcing medium. Furthermore, delamination occurs over an increasing large surface area so that the amount of energy necessary to effect substantial delamination is even more significant depending on the duration of the applied force. At impact, the kinetic energy (KE) of the threat is transferred to the composite in milliseconds, while the delamination-associated mechanisms act as energy sponges absorbing and dissipating the damage produced by projectile penetration. It is the energy-absorbing feature of polymer composite laminates that, with proper design and fabrication, can result in a new generation of lighter, primary, structural armor materiel.

1.2 SMARTweave Technology. SMARTweave [1] is a novel system designed to efficiently and economically retrieve "state" data from a distributed array of sensors. "State" refers to the parameter, or series of parameters, that one may wish to monitor and track during a series of prescribed or witnessed events. For example, the state of resin flow is a desired parameter in the assessment of the resin-transfer molding (RTM) process; the event is the physical impregnation of the fibrous preform by the polymer resin. Similarly, monitoring the progress of cure in the resin over an array of sensor points is another desirable set of data; the event in this case is the curing of the resin, and the state is defined as the instantaneous degree of cure in the resin.

Generally, the SMARTweave system consists of a sensing grid, a multiplexer designed to rapidly interrogate the grid, an electrical circuit designed to measure an electrical property (e.g., resistance, capacitance, voltage, etc.), and a software-based computer platform to control, record, and display the flow of sensor data. The sensing grid itself is composed of electrically conductive filaments arranged to produce sensing "gaps" at each of the junctions in the grid. As a conductive material fills these gaps (e.g., resin, moisture, etc.), an electrical measurement is made. If no material is present, the state remains unchanged; if material has arrived, its electrical properties cause a change in state indicating the arrival. This process may be repeated continuously over all the sensing gaps in the grid with the aid of a multiplexer; the result is a discrete representation of material location and material property at any point and at any instant in the grid.

The U.S. Army Research Laboratory (ARL) has developed and applied this patented technology to the RTM process. Monitoring resin flow in the RTM process is critical inasmuch as the flow is responsible for the final mechanical properties of the part. Formation of dry spots due to poor configuration and operation of the RTM process is a common problem. The SMARTweave system has been used successfully to monitor this resin flow and, for the first time, provide an in-situ, real-time assessment of the RTM impregnation process. Most notably, the SMARTweave system was used in the prototype fabrication of the lower hull and crew capsule, two critical components of the Army-sponsored CAV program directed by the U.S. Army Tank-automotive and Armaments Command (TACOM) and contracted to the United Defense Co., San Jose, CA.

The SMARTweave technology has since been demonstrated to possess the potential for other critical applications. For example, as part of an Army Science and Technology Objective (STO), the SMARTweave system was tasked to provide gross-damage information in composite laminates. This gross damage is designed to simulate, for example, the effects of projectile penetration sustained during a conflict. The concept is to ultimately deploy the SMARTweave system as an on-line, real-time, battle-damage detector. Other potential applications include damage detection in marine structures and moisture detection in the charcoal filtration systems of chemical/biological protective suits. These applications could benefit from the SMARTweave's ability to inexpensively and rapidly detect anomalies in the host system environment.

In the present study SMARTweave was investigated as potential in-situ means for determining damage in a polymer composite laminate. Specifically, the research focuses on embedding a sensing grid composed of commercially available graphite fibers in an array (e.g., 5 × 5) so as to produce 25 unique sensing elements. Each of these elements is uniformly distributed over the surface of the laminate. The goal is to effectively assess the performance of the SMARTweave sensing grid as a means for determining damage induced by ballistic impact.

2. Experimental Procedures

2.1 Specimen Description. Three different specimen types were created for ballistic-damage detection. First, four thin, flat panels were fabricated using a vacuum-assisted RTM process called Seemann Composite Resin Infusion Molding Process (SCRIMP) (see Walsh [1] and Appendix A). A 6 × 6 SMARTweave sensor grid was installed in each of these nominal 0.25-in-thick panels. The second specimen was a 0.5-in-thick, SCRIMP-produced, flat panel containing an 8 × 8 SMARTweave grid. The third specimen was a full-linear-dimensional prototype of the XM194 gun mount shield, except for the wall thickness, which was quarter scale. The XM194 gun mount shield (see Figure 1), from this point on referred to as the "ballistic shield," protects the cooling and recoil mechanisms of the XM297E1 cannon assembly of the 155-mm, advanced, solid propellant, armament system.

2.2 Specimen Fabrication. The first set of specimens (four thin, flat panels) were made using a one-sided aluminum tool and standard, vacuum-bagging technology. The specimens consisted of a 10-ply lay-up of 24-oz, 5 × 4, plain-weave, E-glass fabric. After the fourth ply, six graphite filament "tows," used as SMARTweave sensors, were placed in the horizontal direction and at an equal distance from each other. Following the sixth ply, six additional graphite tows were placed equidistant in the vertical direction. A release-coated nylon fabric (peel ply) was then placed on top of the 10 glass plies. The function of the peel ply is to facilitate removal of the distribution media, which is a nylon cloth material that speeds up the resin infusion process. Next, a single ply of very high-permeability distribution media was laid over the peel ply. This was followed by fitting a helical-cut polyethylene tube alongside one perimeter end and in contact with all the plies. A similar tube was likewise fit to the opposite end of the plies. One of the tubes acted as a "leaky pipe" to

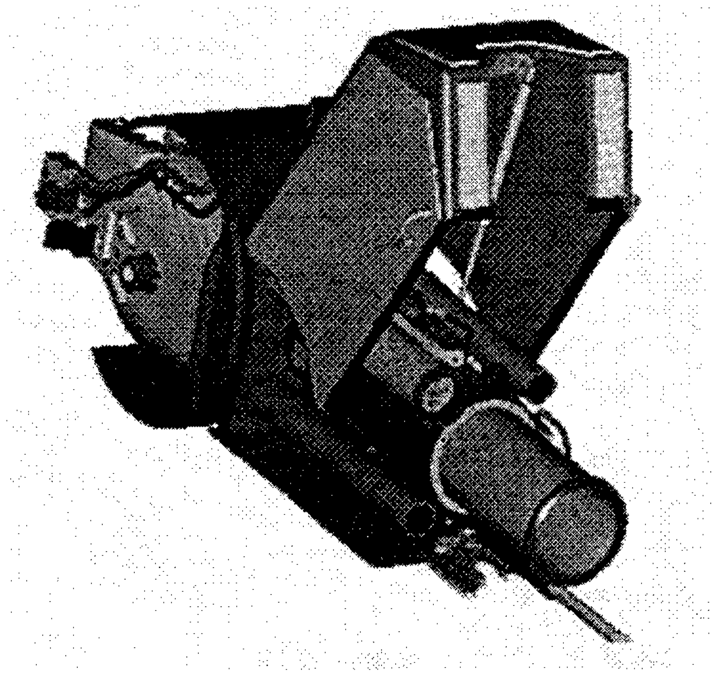


Figure 1. XM194 Gun Mount "Ballistic" Shield.

uniformly introduce resin to the preform; the other acted as the vacuum line. The mold was evacuated and held at full vacuum (29 in of Hg) to provide a pressure gradient for initiating and maintaining resin flow and also to compress the preform. The resin system, Dow Derakane 411-C50, was a vinyl ester resin specially formulated to have a low viscosity for RTM operations. This system also requires a catalyst, Akzo Chemicals Trignox 239A, and a promoter, cobalt napthalate salt (CoNap) solution at 6%. After the resin system was prepared, the feed tube was immersed into the resin and the pinch clamp was released, allowing the vacuum to draw the resin into the preform. The composite panels were cured at room temperature followed by postcuring at 212° F for 2 hr. Appendix B contains the composite processing data sheet for producing the thin panels.

The second specimen, a 23-ply, 0.5-in-thick panel, was fabricated following similar procedures that were used for producing the thin, 10-ply panels (see Appendix B); however, a larger (8 × 8) SMARTweave sensor grid was installed. Eight sensors were placed in the horizontal direction on top of the 11th glass fabric ply and eight sensors were placed vertically after the 13th ply. Figure 2 is a schematic representation of the sensor grid lay-up.

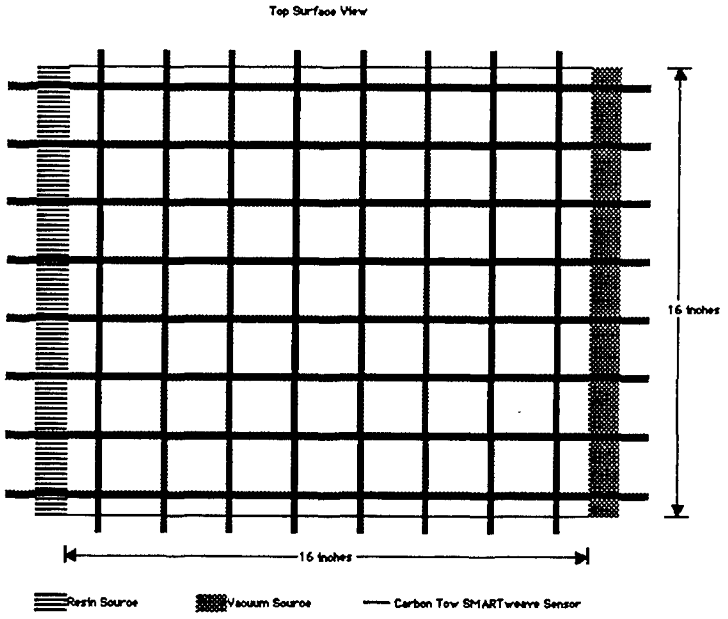


Figure 2. Schematic Representation of the SMARTweave Sensor Grid Lay-Up in the 23-Ply Composite Panel Specimen.

The ballistic shield specimen was manufactured in a composite female tool using the SCRIMP process, and made of 10 plies of 24-oz, 5 × 4, plain-weave, E-glass fabric. SMARTweave sensors (Hercules Magnamite AS4 graphite tows) were placed in the lay-up after the seventh and ninth plies. The graphite tows were laid into the mold in a 16 × 16 grid. The ballistic shield was cured at room temperature and then postcured at 170° F for 3 hr. A photograph of the ballistic shield is shown in Figure 3.

2.3 Ballistic Testing. The four thin panels (specimen nos. 1–4, see Appendix C) and the one thick panel (specimen no. 5, Figure 4) were individually clamped to a test stand 30 ft from the rifle barrel. Specimen no. 1 was tested against the 0.30-cal., 44-grain fragment-simulating projectile (FSP), specimen nos. 2, 3, and 5 were tested against the 0.50-cal., M2 Ball, and specimen no. 4 was tested against the 7.62-mm ball. All of the specimens were tested at 0° obliquity, and each was subjected to no more than three impacts. The impact points were at or near the nodes of the SMARTweave sensor grid, where the full-penetrating projectile damaged the graphite tows, thereby altering electrical continuity. The nodes are pseudo junctions of the orthogonally embedded

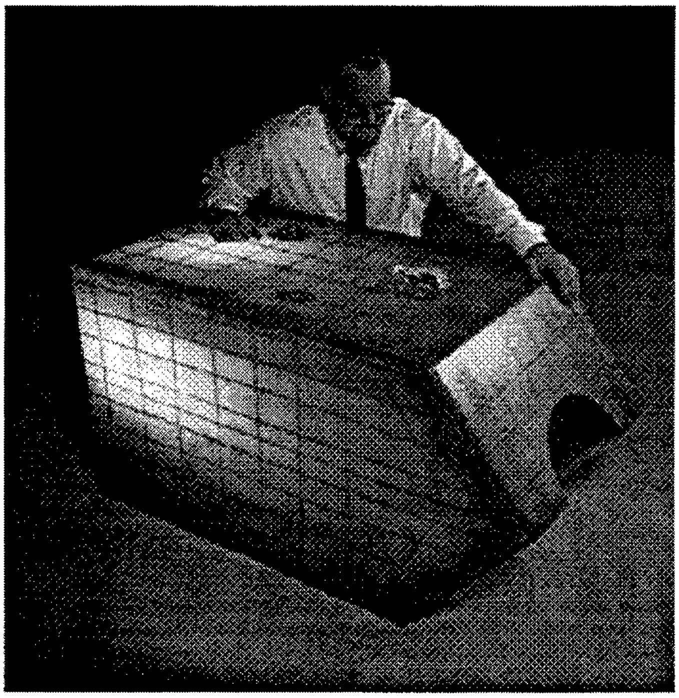
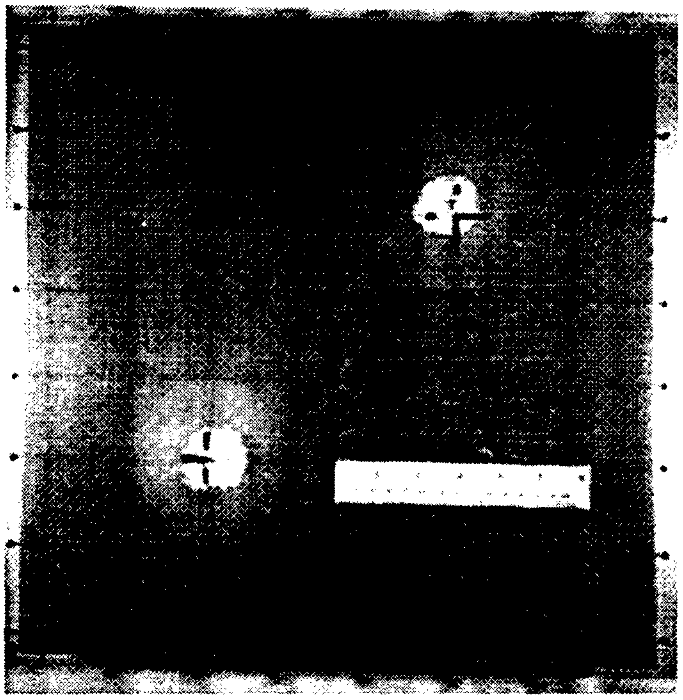


Figure 3. SCRIMP-Manufactured Ballistic Shield Specimen.

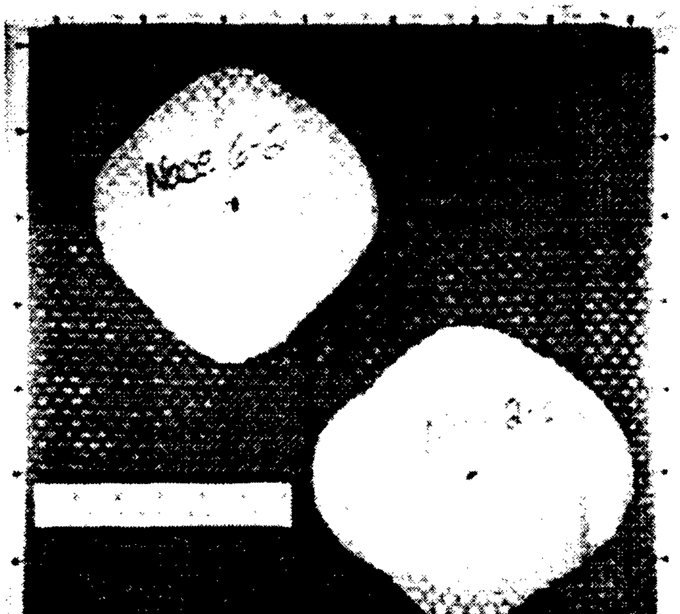
filaments (i.e., they are in close proximity to each other but are not in physical contact). The objective of this test was not to assess the ballistic performance of the fiber/resin composite laminate, but, rather, as stated earlier, to determine if the SMARTweave sensing grid can effectively detect damage induced by ballistic impact.

2.4 Damage Detection. Damage is determined when a statistically significant difference in the electrical resistance is observed between the undamaged and damaged states of the sensors within the laminate. The damage is approximated by considering each of the sensors as having at least four neighboring sensors, both vertically and horizontally. The neighboring sensors not only provide additional spatial sensor information but also serve to corroborate the integrity of a given sensor signal. By multiplexing through all the sensors, one can obtain a sufficient approximation of the damage.

2.5 Ultrasonic Inspection. Specimen no. 5 (0.5-in-thick, 15-in-square, 23-ply composite panel) was nondestructively evaluated before and after ballistic impact by performing an ultrasonic



(a) Impact View.



(b) Back View.

Figure 4. Photographs of the Impacted 23-Ply Composite Panel.

immersion test using the pulse/echo method with a 5-MHz transducer. An automated scanner was utilized to collect A-scans (amplitude vs. time signals) at an interval of 0.0375 in, resulting in a total of 160,000 A-scans. The magnitude of the back surface reflection of each A-scan was measured to determine the relative attenuation of the ultrasonic signal. Attenuation variations are due to signal absorption and scattering within the specimen and can be attributed to inherent characteristics such as density variations, porosity, delaminations, and inclusions. The attenuation of each ultrasonic signal was measured and mapped into a C-scan (a graphical representation of all A-scan attenuation data).

3. Results

3.1 Damage Detection. The electrical resistance data in Figure 5 and Appendix D are the resistance values (in ohms)of each graphite filament sensor (16 total from eight rows and eight columns) measured before and after ballistic impact. The after-ballistic-impact values are shown in parenthesis. The change in resistance is the result of projectile penetration at or near a sensor causing partial separation or complete fracture of the fibrous material. Evaluating all the sensors identifies the location of damage. In the case of the 23-ply composite panel (see Figure 4) the resistance of row nos. 3 and 6 and column nos. 3 and 6 before ballistic impact was approximately 160 Ω. The resistance of these filaments after impact was infinite. Matching up the damaged rows and columns in their respective grid placement allows one to locate the region of ballistic impact. This change in resistance signifies a complete local destruction of the sensor. In thin specimen nos. 1, 3, and 4, the sensors were not damaged at all, which results in the resistance before and after being unaffected. This illustrates that carbon tows, although ideal for process monitoring, are not optimal for ballistic damage detection. However, the resistance change in row no. 4 of thin specimen no. 2 (Figure C-2) went from 167 Ω to 739 Ω, which represents a partial fracture of the sensor and gives promise to the potential of detecting nonterminal damage. To maximize the information regarding damage, a sensor-material substitution could be made. In this study, carbon tows are used as the sensor material; if a sensor material was more sensitive to strain, then smaller changes in strain

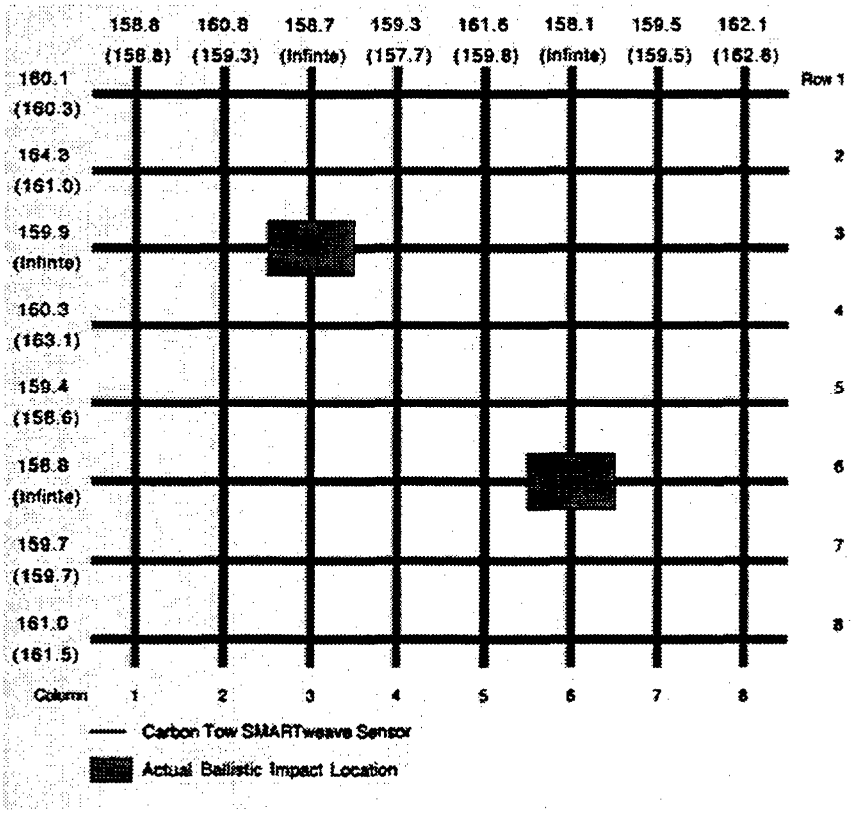
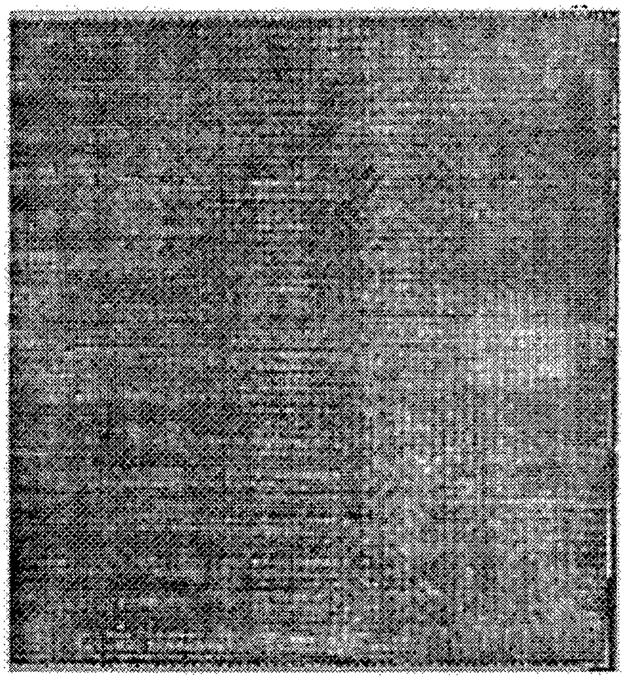


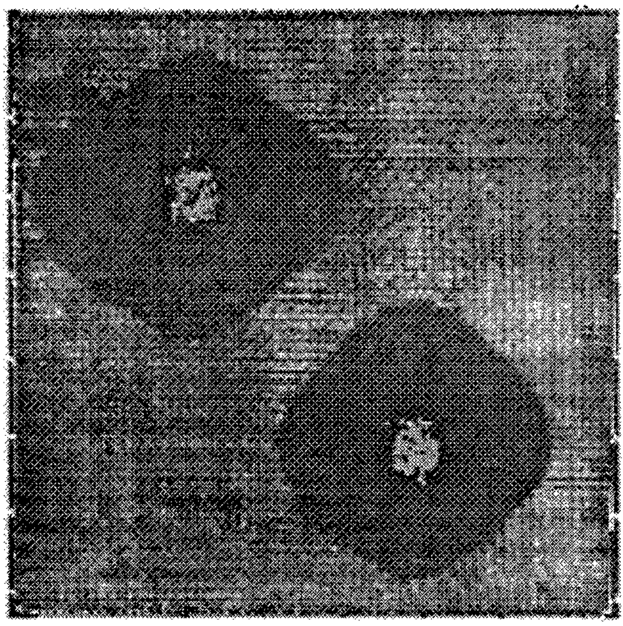
Figure 5. Electrical Resistance Values From the 23-Ply Composite Panel Specimen.

would allow for more significant changes in resistance, which would in turn lead to more detailed damage information.

3.2 Ultrasonic Inspection. Figure 6a presents the attenuation map of the 23-ply panel before ballistic impact. Analysis of the C-scan indicates that the panel was relatively homogeneous with no significant resin-rich areas, dry spots, nor anomalies detected. The attenuation map of the panel after ballistic testing, shown in Figure 6b, depicts the extent of damage (delamination) that occurred as a result of the 0.50-cal. M2 ball impact. The darker (black- and brown-colored) zones represent areas of high attenuation. Due to the large acoustical impedance mismatch between air and the composite material, the ultrasonic signals are almost completely reflected at the delamination interface, resulting in very low-magnitude back reflections. It can be concluded from the analysis of this nondestructive inspection that the detected damage can be attributed to the ballistic test and not to preexisting irregularities within the specimen.



(a) Before Ballistic Impact.



(b) After Ballistic Impact.

Figure 6. Ultrasonic Attenuation Map From the 23-Ply Composite Panel Specimen.

4. Summary

Though preliminary, this study has successfully demonstrated the use of commercial-off-the-shelf (COTS) graphite fibers in a SMARTweave sensing grid as a means for detecting gross ballistic damage. It must also be concluded that the use of a graphite grid for observing resin flow and cure during composite processing is not necessarily optimized for in-situ damage detection in the finished part. Indeed, this study appears to confirm the need for reformulating the SMARTweave sensing grid so that it is properly "tuned" to detect the variations induced by ballistic damage. These modifications might include, but are not limited to, exploring new types of conductive materials, new designs of the sensing elements (i.e., comb configurations to increase local surface area), and alternative electrical property measurements such as capacitance and frequency. However, it should also be noted that any future damage-detection array should preserve the most attractive features of the SMARTweave approach: ease of installation, economic interrogation of large numbers of nodes, and sensor compatibility with the primary structural material.

5. Future Work

Current research efforts are focused on developing and evaluating a variety of alternative sensor materials and configurations specifically formulated for detecting delamination and adhesive-bond failure. While these technologies are designed to provide real-time information on the relative structural integrity of a composite component subject to ballistic impact, increased sensitivity in the grid may also contribute to health monitoring of fielded material subject to less traumatic but, nevertheless, severe environmental or structural loading. The efficient, global interrogation features of the SMARTweave system demonstrated in this study will contribute to the development of future sensing systems that are increasingly viable and cost effective.

6. References

1. Walsh, S. W. "In-Situ Sensor Method and Device." U.S. Patent No. 5,210,499, 11 May 1993.

2. Seemann, W. H. "Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, 20 February 1990.

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Appendix A:

Seemann Composite Resin Infusion Molding Process (SCRIMP)

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The Seemann composite resin infusion molding process (SCRIMP)[1] is a process by which a thermosetting resin is infiltrated into a fibrous preform. The advantages of this process are (1) SCRIMP is a low-cost, repeatable composite process method utilizing only a one-sided tool (mold) and standard vacuum-bagging technology and (2) dependent on the fabric architecture, SCRIMP can yield excellent volume fractions of fibers on the order of 50–55%. Complex three-dimensional (3-D) and trussed structures and thick-section composites (on the order of 6 in thick) can be manufactured. The primary disadvantage of SCRIMP is that only one side of the component has a good (or smooth) surface finish due to the fact that only one-sided tooling is employed. Figure A-1 shows a schematic of SCRIMP.

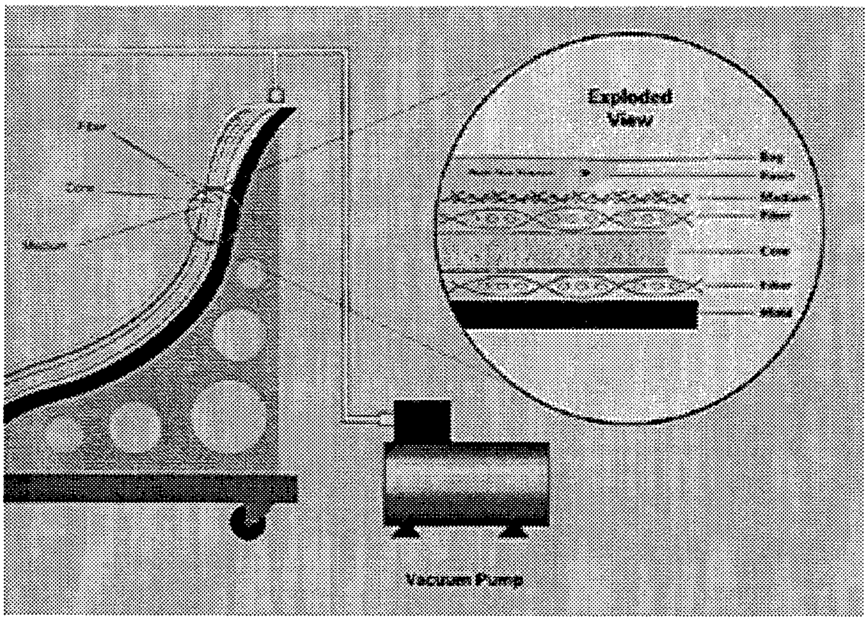

Figure A-1. Schematic of SCRIMP, courtesy of Seemann Composites, Inc.

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[1] Seemann, W. H. "Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastic Structures." U.S. Patent No. 4,902,215, 20 February 1990.

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Appendix B:

Composite Processing Data Sheets

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DATE: 10 April 1996

PERSONNEL: Bill Ballata and Dan Snoha

OBJECTIVE: To produce a thick composite panel with SMARTweave sensors that can be ballistically tested to evaluated its ability to detect damage.

LAY-UP SEQUENCE (from top surface to bottom surface):

(1) Vacuum bag
(2) Distribution media
(3) Peel ply
(4) 5 × 4 glass fabric, 9 plies, 17 in × 17 in
(5) SMARTweave sensors, 8 carbon tows, horizontally oriented
(6) 5 × 4 glass fabric, 3 plies, 17 in × 17 in
(7) SMARTweave sensors, 8 carbon tows, vertically oriented
(8) 5 × 4 glass fabric, 9 plies, 17 in × 17 in
(9) 5 × 4 glass fabric, 2 plies, 17 in × 19 in
(10) Tool

RESIN SYSTEM:

Component	Concentration (%)	Mass (g)	Volume (ml)
Total Resin	100.00	2552.15	2416.86
411-C50	97.80	2496.00	2400.00
Trigonox	2.00	51.04	56.71
CoNap	0.20	5.11	5.16
Gel Time: 30 min			

NOTES:

(1) The feeder tube was wrapped in distribution media.
(2) There seemed to be a small point leak where a few bubbles were able to get into the part. This leak occurred at the opposite end of the feeder tube from the inlet point. In the final part, some small voids were noticed along that edge. From this note, it is suggested to use two boundaries of tacky tape in the future.
(3) 3M Super 77 spray adhesive was used along the edges to help hold the preform in place. It was noticed on the final part that the spray adhesive, used extremely sparingly, did have some type of negative effect on the part quality.
(4) The part was postcured at 100° C for 2 hr.
(5) The glass fabric is 5 × 4 E-glass in a plain weave. The sizing on the fabric is unknown but probably a general-use epoxy/polyester sizing. The resin is a vinyl ester from Dow, 411-C50. The volume fraction of the E-glass is between 52% and 54%. The SMARTweave sensors are carbon tows (graphite fiber bundles).

DATE: 02 July 1996

PERSONNEL: Bill Ballata and Clarissa DuBois

OBJECTIVE: To produce a panel with SMARTweave sensors that can be ballistically tested.

LAY-UP SEQUENCE (from top surface to bottom surface):

(1) Vacuum bag
(2) Distribution media
(3) Peel ply
(4) 5 × 4 glass fabric, 4 plies, 30 in × 30 in
(5) SMARTweave sensors, 6 carbon tows, horizontally oriented
(6) 5 × 4 glass fabric, 2 plies, 30 in × 30 in
(7) SMARTweave sensors, 6 carbon tows, vertically oriented
(8) 5 × 4 glass fabric, 3 plies, 30 in × 30 in
(9) 5 × 4 glass fabric, 1 ply, 30 in × 34 in
(10) Tool

RESIN SYSTEM:

Component	Concentration (%)	Mass (g)	Volume (ml)
Total Resin	100.00	2233.13	2154.13
411-C50	97.80	2184.00	2100.00
Trigonox	2.00	44.66	49.62
CoNap	0.20	4.47	4.51
Gel Time: 30 min			

NOTES:

(1) The feeder tube was wrapped in distribution media.
(2) There seemed to be a small point leak where a few bubbles were able to migrate into the part. This leak occurred at the opposite end of the feeder tube from its inlet point. In the cured part, some small voids were noticed along that edge.
(3) 3M Super 77 spray adhesive was used along the edges to help hold the preform in place. It was noticed on the cured part that the spray adhesive, used extremely sparingly, did have some type of negative effect on the part quality.
(4) The part was postcured at 100° C for 2 hr.
(5) The glass fabric is 5 × 4 E-glass in a plain weave. The sizing on the fabric is unknown but probably a general-use epoxy/polyester sizing. The resin is a vinyl ester from Dow, 411-C50. The volume fraction of the E-glass is between 52% and 54%. The SMARTweave sensors are carbon tows (graphite fiber bundles).

Appendix C:

Photographs of the Thin-Panel Specimens After Ballistic Testing

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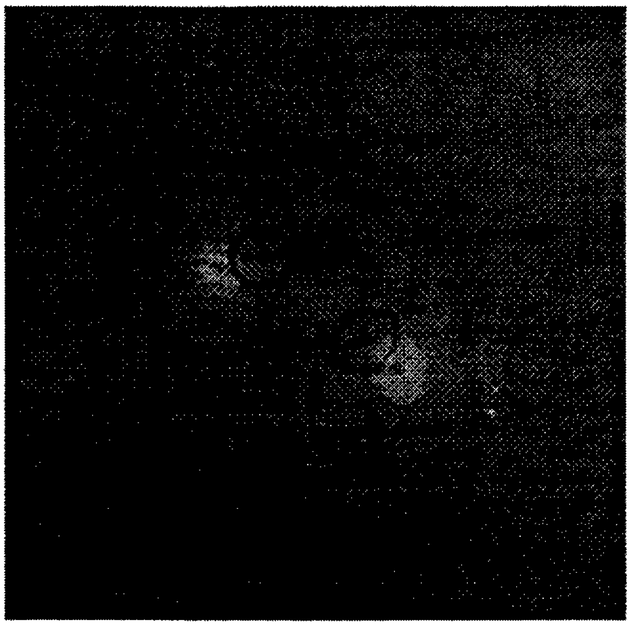
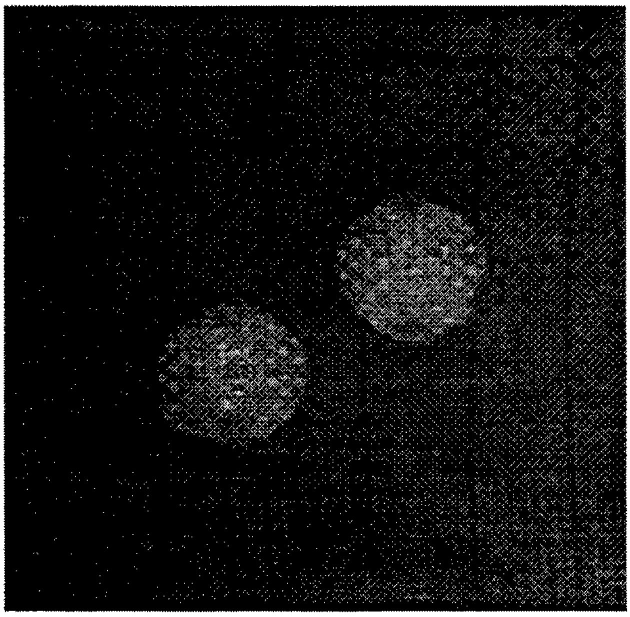
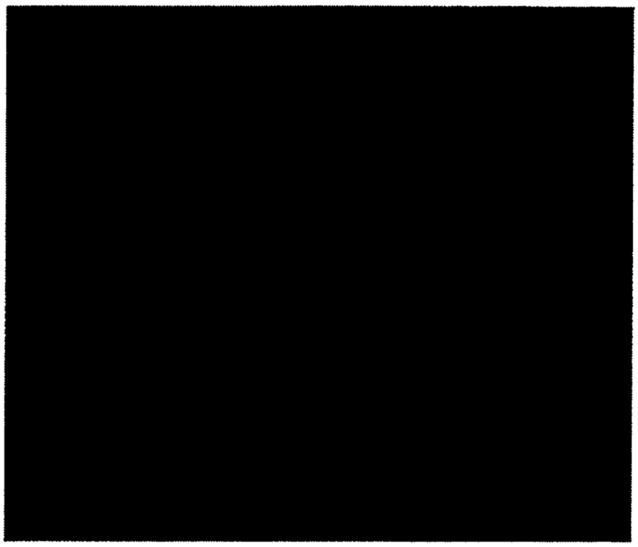


(a) Impact View.

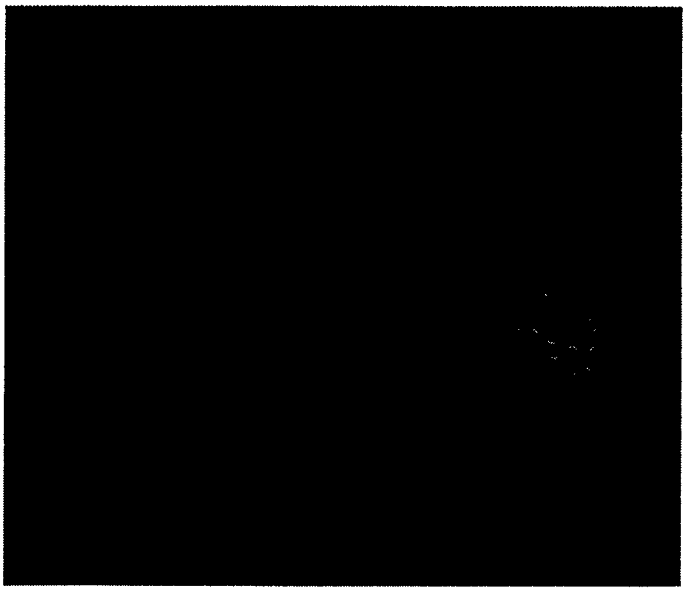


(b) Back View.

Figure C-1. Thin-Panel Specimens After Ballistic Testing, Panel 1.

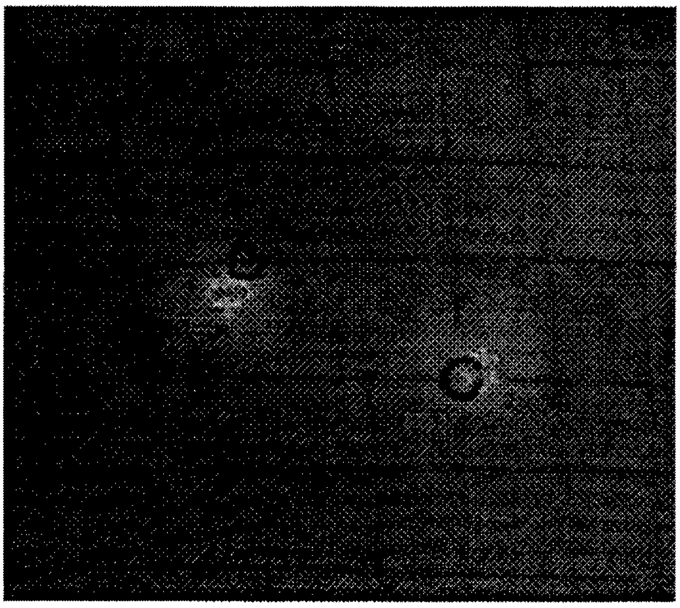


(a) Impact View.

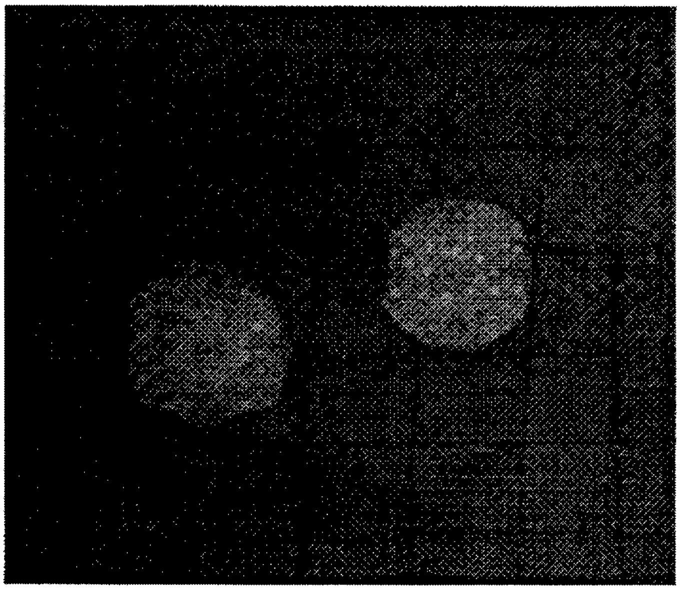


(b) Back View.

Figure C-2. Thin-Panel Specimens After Ballistic Testing, Panel 2.

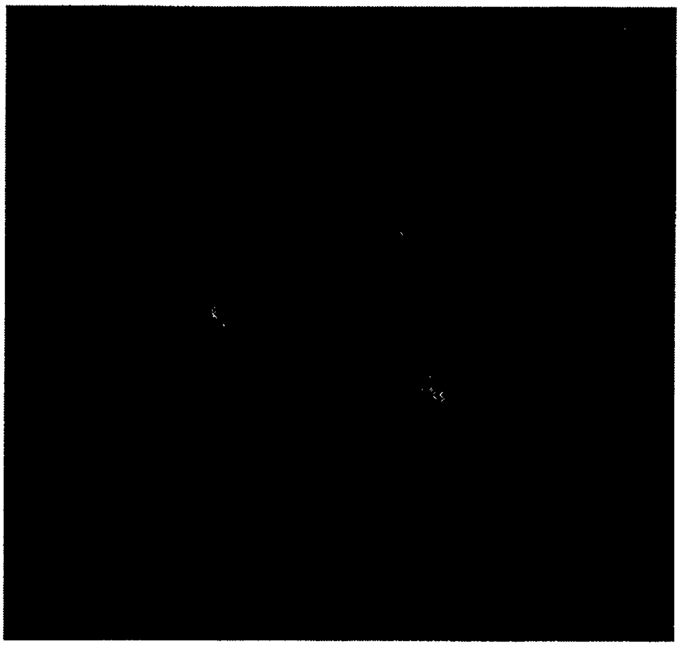


(a) Impact View.

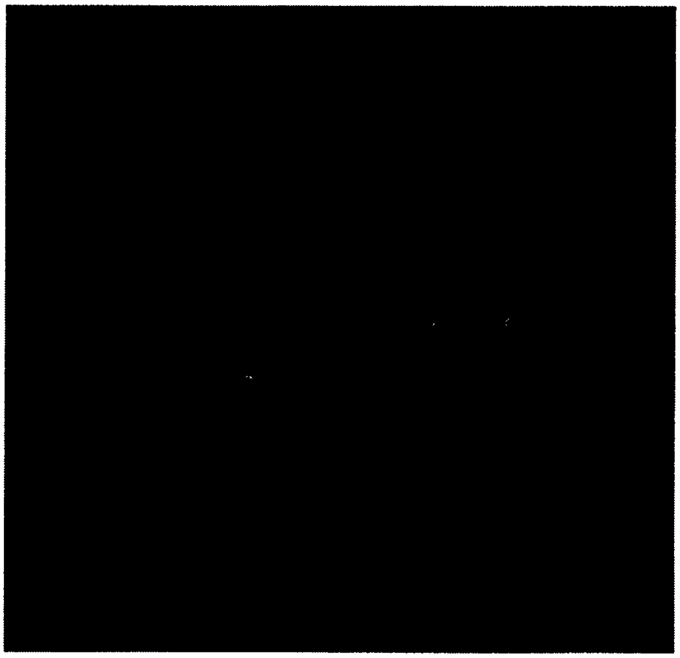


(b) Back View.

Figure C-3. Thin-Panel Specimens After Ballistic Testing, Panel 3.



(a) Impact View.



(b) Back View.

Figure C-4. Thin-Panel Specimens After Ballistic Testing, Panel 4.

Appendix D:

Electrical Resistance Values From the Thin-Panel Specimens

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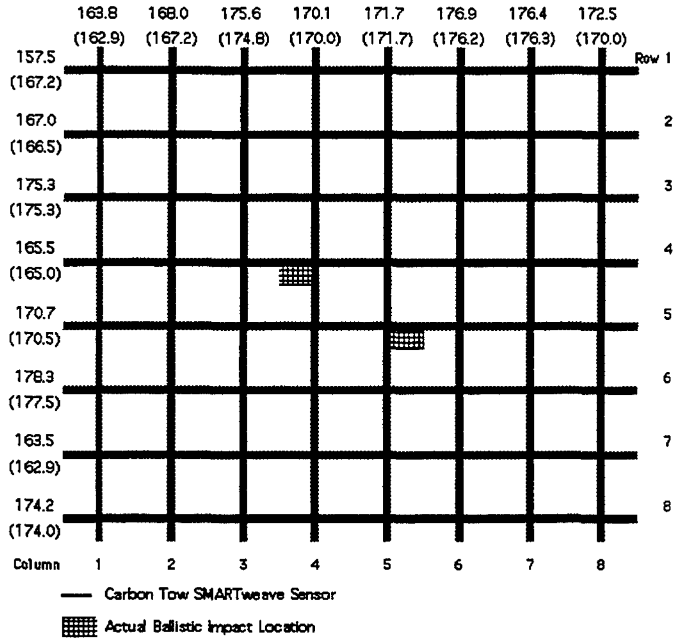

Figure D-1 Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 1 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

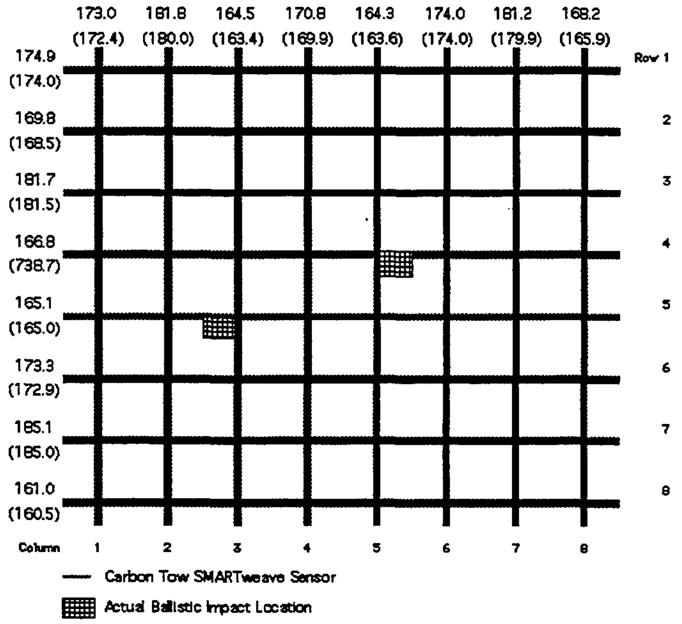

Figure D-2. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 2 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

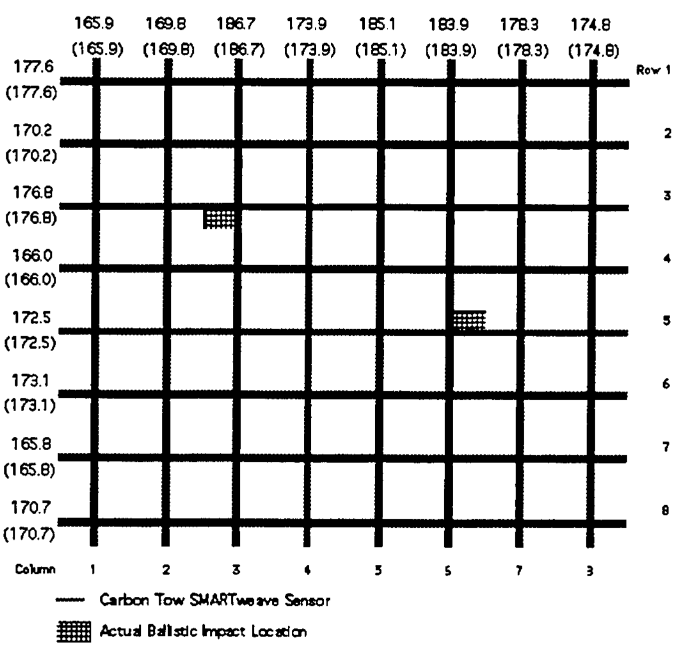

Figure D-3. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 3 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

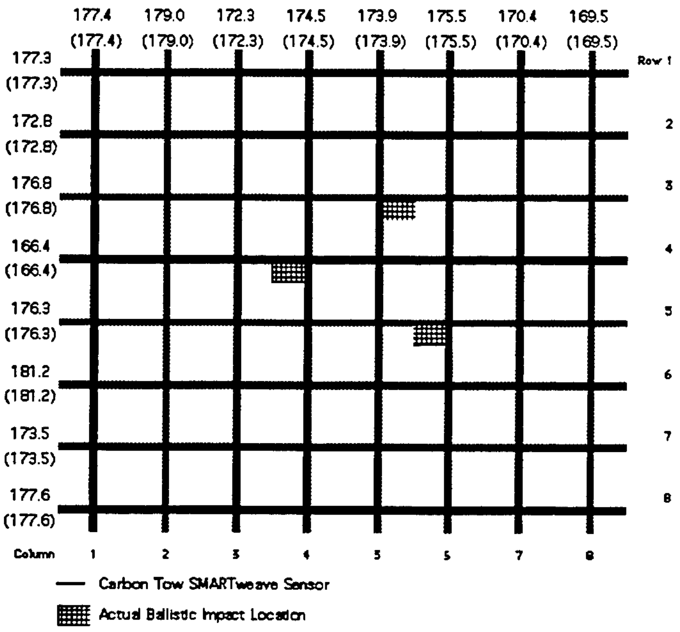

Figure D-4. Electrical Resistance Values of the Carbon Tow Sensors in Thin-Specimen Panel 4 (Resistance in Ohms). Before Impact Is the First Value (Top), While the Second Value (Bottom, in Parentheses) Is After Impact.

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REPORT DOCUMENTATION PAGE

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2. REPORT DATE
May 1998

3. REPORT TYPE AND DATES COVERED
Final, Jun 96 - Nov 97

4. TITLE AND SUBTITLE
SMARTweave Sensors for Assessing Ballistic Damage: a Feasibility Study

5. FUNDING NUMBERS
COMPO2

6. AUTHOR(S)
Daniel J. Snoha, William O. Ballata, and Shawn M. Walsh

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1674

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

SMARTweave technology, developed and patented by the U.S. Army Research Laboratory (ARL), has been applied to monitor resin flow and cure progress in composite laminate processing. It has since demonstrated the capacity of being a viable sensing mechanism in other critical applications. In this feasibility study, for example, SMARTweave sensors have successfully shown the potential for detecting ballistic-impact-induced damage in a composite laminate. A sensing grid of electrically conductive graphite fibers was embedded in the composite specimens during lay-up of the glass-fabric preforms. The results of electrical resistance measurements preformed before and after ballistic impact, with the difference indicating the detection of induced damage (delamination), are presented herein. For purposes of qualitative comparison, a traditional, ultrasonic, nondestructive, evaluation technique was also used to capture the effects of the induced damage. This research was conducted during the period that the Materials Division was in transition from ARL, Watertown, MA, to the Rodman Materials Research Laboratory, Aberdeen Proving Ground (APG), MD.

14. SUBJECT TERMS
SMARTweave, damage detection, health monitoring

15. NUMBER OF PAGES
34

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
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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