

DAMAGE ASSESSMENT AND RESIDUAL COMPRESSION STRENGTH OF THICK COMPOSITE
PLATES WITH THROUGH-THE-THICKNESS REINFORCEMENTS

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INTRODUCTION

The design of composite structures is rarely based solely upon the strength and/or stiffness of the composite material. The influence of temperature, moisture, and damage must be also considered. Today, damage tolerance of a material significantly limits the allowable compression strain level used in the design of composite structure. A test that is frequently used to assess the damage tolerance of a material is the compression-after-impact strength test.

Historically, composite materials have exhibited catastrophic brittle failure characteristics and little tolerance for low velocity impact damage representative of rock kick-up or tool drop impacts. New thermoset and thermoplastic matrix materials have produced "tougher" materials that have the potential for increasing the design ultimate strain by 50 percent. However, the cost of composite structures using these damage tolerant materials can be in excess of three times that of conventional metallic structures of comparable geometry.

Recent advances in textile technology and resin transfer molding have produced composite structures that have superior damage tolerance without significant sacrifice of in-plane mechanical properties. Furthermore, the structural part cost of these structures produced from textile technology can be less than the cost of a conventional metallic structure. The damage tolerance of these textile composite materials is

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achieved through inclusion of fibers through-the-thickness of the laminate. Little is understood about the mechanisms that control the damage initiation and growth in these materials with through-the-thickness reinforcements. To achieve efficient designs using these textile materials it is paramount that a fuller understanding of the mechanisms that control the damage tolerance be developed. One necessary step in developing this understanding is to assess the extent of damage at each interface after impact and prior to destructive testing.

Ultrasonic imaging techniques have been successfully employed on composite materials fabricated from tape prepreg to assess damage at different interfaces [1]. These techniques need to be extended to composite materials with through-the-thickness reinforcements.

The objective of this study is to increase the understanding of damage in composite materials with through-the-thickness reinforcements. To achieve this objective an ultrasonic imaging technique was developed to produce images of the damage at each interface of damaged composite panels having through-the-thickness reinforcements. Five different fiber architectures in a common brittle matrix are evaluated. A panel fabricated from each of these architectures was impacted, ultrasonically imaged, destructively tested, and evaluated.

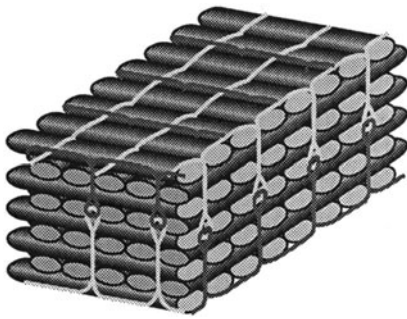
TEST SPECIMENS AND PROCEDURES

Five 9 layer [0/90/0/90/0/90/0/90/0] AS-4-3501-6 graphite-epoxy panels approximately 0.25 inches thick were evaluated in this study. Dry fiber preforms of each panel were produced, infiltrated with resin, and cured. Panel 1 was a control specimen without through-the-thickness reinforcements. Each layer of panel 1 was composed of a uniwoven fabric material. A uniwoven material is a woven material with approximately 95 percent of the reinforcement fibers oriented in the warp direction (also referred to as the 0 degree direction). In these materials the warp fibers were a 21000 filament count (21K) yarn of AS-4 graphite positioned 13 yarns per inch and the fill yarn was a fine denier E-glass yarn. The 21K graphite yarn was produced by combining 3K, 9K, and 12K yarns.

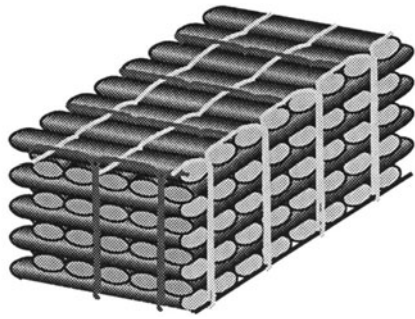
Panels 2 and 3 were of similar architecture as panel 1 except panels 2 and 3 had Kevlar and graphite fibers lock stitched through-the-thickness, respectively. A 1100 denier Kevlar and Toray graphite stitching yarn was used. Stitch row spacing was 0.25 in. in both horizontal and vertical directions producing a 0.25 in. by 0.25 in. cell. Stitch density was every 0.125 inches. A sketch of the stitch preform is shown in Figure 1.

Panels 4 and 5 were similar in appearance to panels 2 and 3 but their construction differed significantly. All the layers and through-the-thickness yarns of panels 4 and 5 were integrally woven in a single operation. Unlike the uniwoven material used in panels 1, 2, and 3 no fine denier glass fill yarn is used in panels 4 and 5 to hold the yarns in a layer together. In panels 4 and 5 the same through-the-thickness yarns (Kevlar and graphite) were used as used in panels 2 and 3, respectively. In panels 4 and 5 a "catcher yarn" embedded along the center of the preform is used in the weaving technique for incorporating a through-the-thickness yarn. A sketch of the preforms used for panels 4 and 5 is presented in Figure 1.

After the dry fiber preforms were completed a two step resin infiltration and cure process was performed. The first step is the resin infiltration step. The appropriate amount of resin was weighed out to achieve a 60 percent fiber volume fraction and poured into a mold. The preform is placed on top of the resin and the mold, resin, and preform assembly is bagged, a vacuum is drawn, and the assembly is heated in an oven and the resin infiltrates into the preform. The second step, the cure step, begins by inspecting the preform for surface dryness. If any



No-crimp 3-D weave



No-crimp stitched

Figure 1. Preform architecture for the woven (sample 4 and 5) and the stitched (sample 2 and 3) panels.

surface dryness exists then a small quantity of resin is poured onto the surface. The infiltrated preform is returned to the mold and the assembly is rebagged and placed in an autoclave for cure.

All panels were C-scanned to check for porosity and internal defects prior to machining of test specimens. Compression-after-impact (CAI) specimens were machined from each panel. Compression-after-impact specimens were 5.0 in. wide by 10.0 in. long. The CAI specimens were mounted in a test fixture and impacted with a 0.5 in. diameter aluminum ball. The test fixture simulates a simply supported condition around the perimeter of the CAI panel. The impacting of the panel is performed with a compressed air operated gun. The speed of the ball at impact was approximately 550 ft/sec which produces an impact energy of approximately 30 ft-lbs.

ULTRASONIC PROCEDURES

The ultrasonic evaluation was performed in a water bath using a 5 MHz transducer with a 0.5 inch aperture and a 2 inch focal point. The transducer was operated in a pulse-echo mode and was excited with a square wave pulser. The return signal was amplified and fed into a Time-Gain-Compensated (TGC) amplifier [2]. A digitizer with sampling rate of 50 MHz and 8 bit dynamic range acquired the signal and passed it to a computer for later analysis. The entire ultrasonic wave was digitized to include the front, interior, and back surface reflections. A spatial sampling step of 2 mm was on the order of the 6 dB point spread for the transducer as determined experimentally. A typical sampling size was 8x8 or 10x8 centimeters, depending on the size of the damage.

The TGC has a 50 MHz bandwidth, a 50 dB gain, and a control bandwidth of 5 MHz. The TGC influence on the digitized signal is shown in Figure 2. The difference between the TGC on and off is quite dramatic. The front surface reflection is attenuated and the interior and back surface signals are enhanced to the input limit of the digitizer. This increases the effective dynamic range of the digitizer.

RESULTS AND DISCUSSIONS

The data was post-processed using Fourier deconvolution and analytic magnitude signal processing techniques to provide volumetric views of the samples at any depth inside the panels. A discussion of this technique has been presented previously [1]. A Fourier deconvolution

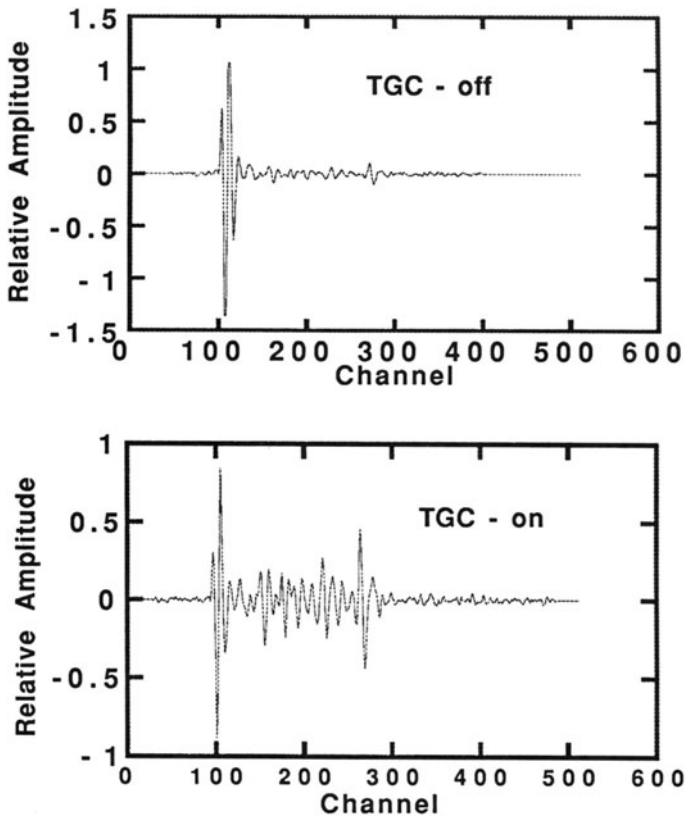


Figure 2. Waveform acquired with TGC off (top) and with TGC on. Backscatter signal corresponds to a impact generated delaminations.

increases the time and thus depth resolution by removing the system artifacts from the signal. The Fourier deconvolution was calculated by dividing the Fourier transform of a reference pulse (in this case the reflection from a brass plate) into the Fourier transform of the received signal. The result after taking the inverse Fourier transform and applying a suitable digital filter over the bandwidth of the transducer is the response of the material. Next the analytic magnitude [3] is calculated; it is a positive unipolar wave proportional to rate of arrival of energy in the detected ultrasonic wave [4]. An example of a signal processed waveform is shown in Figure 3. The front and back surface, and the 8 individual interlaminar locations are easily resolved for an undamaged region of a sample. Processed waveforms are assembled into a three dimensional array in position (x-y) and time. This array can be sliced in any manner. If we take progressive slices in time, a movie is made in which each frame (equivalent to a digitizer channel time) gives a view deeper in the composite. The signal sources at the same depth are in phase and the larger amplitude backscatter signal corresponds to an impact-generated delamination. Shown in Figure 4 are selected impact generated delaminations for a woven sample with Kevlar through-the-thickness fibers (panel 4) and a uniwoven sample (panel 1).

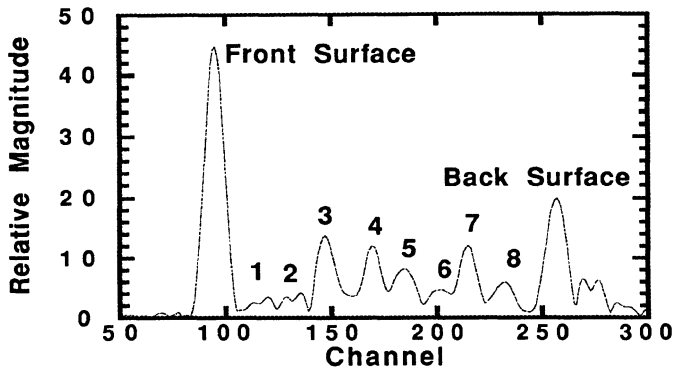


Figure 3. Result of deconvolution and analytic magnitude showing front and back surface, and 8 interfaces.

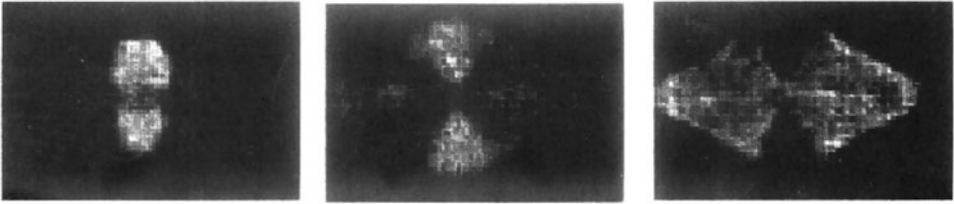
The damage of the uniwoven sample (panel 1) is almost twice that of the through-the-thickness reinforced sample.

To estimate the accuracy of the technique a separate sample similar in construction to panel 1 was impacted, ultrasonically inspected and destructively sectioned. The sections were taken at approximately every 0.15 inch across the sample, placed under a microscope and the locations of the delaminations recorded. A map of the delaminated region at each interface can be made. A comparison between the actual delamination and that measured ultrasonically is shown in Figure 5 for the second interface. The agreement was quite good. This agreement develops confidence such that fewer panels will need to be sectioned to determine the extent of damage after impact.

A graphite stitched panel was also sectioned. In this case the ultrasonic determined area was easily imaged but the classical photomicrograph revealed no delaminations. It was not until the section was soaked in dye penetrant and X-rayed that the delaminations were visible. The through-the-thickness reinforcements seem to have closed the delaminations making the classical destructive technique unreliable.

After the CAI panels were impacted and ultrasonically imaged the panels were destructively tested in compression until failure. The CAI panels mounted in the test fixture are installed in a conventional hydraulic test machine and compressed until the panel fails. Panel strain and compression force is recorded automatically by a computer controlled data acquisition system. Failure load is converted to failure stress by dividing the failure load by the cross sectional area of the panel. The failure strengths of the five panels are shown in Figure 6. All strengths were normalized to a maximum value of 39.8 Ksi, the strength of panel 3 with the graphite stitched through-the-thickness reinforcement. The through-the-thickness reinforcements, for panels 2 thru 5, provided almost twice the CAI strength of the panel without through-the-thickness reinforcement. The panel without through-the-thickness reinforcement exhibited a delamination induced instability failure as shown in Figure 7. The damage, in the form of delaminations, created by the initial impact propagated as the compressive load was applied. The failure mode of the panels with the through-the-thickness reinforcement was transverse shear failure with little visible growth of any delaminations produced from the initial impact as depicted in Figure 7.

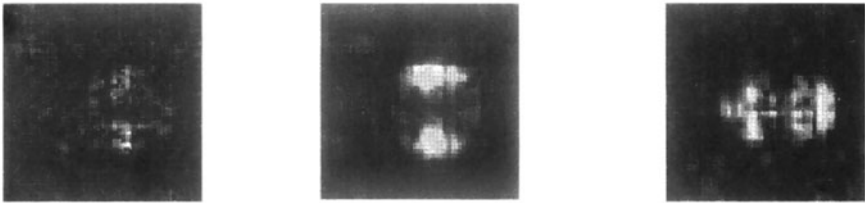
Panel 1



1

7

8



Panel 3

Figure 4. Impact generated delaminations for the 1st, 7th and 8th interfaces for panel 1 and panel 3.

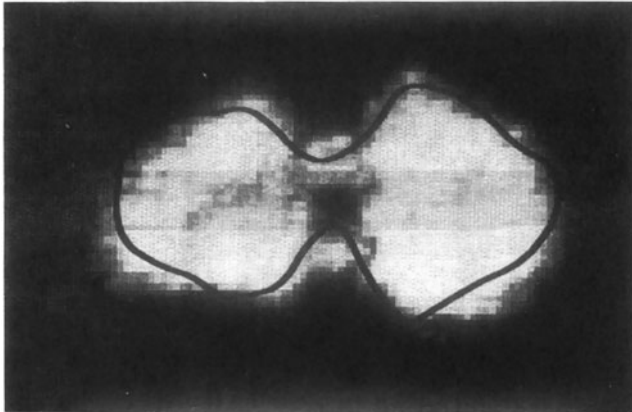


Figure 5. Delamination at the second interface for a sample similar in construction to panel 1. The line is from examination of a micrograph to determine the actual delamination area.

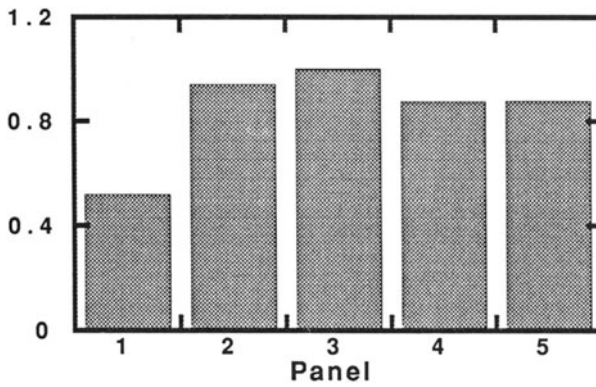


Figure 6. Normalized compression-after-impact strength for panel 1) no through the thickness reinforcements, 2) Kevlar-stitched, 3) graphite-stitched, 4) Kevlar-woven, and 5) graphite-woven.

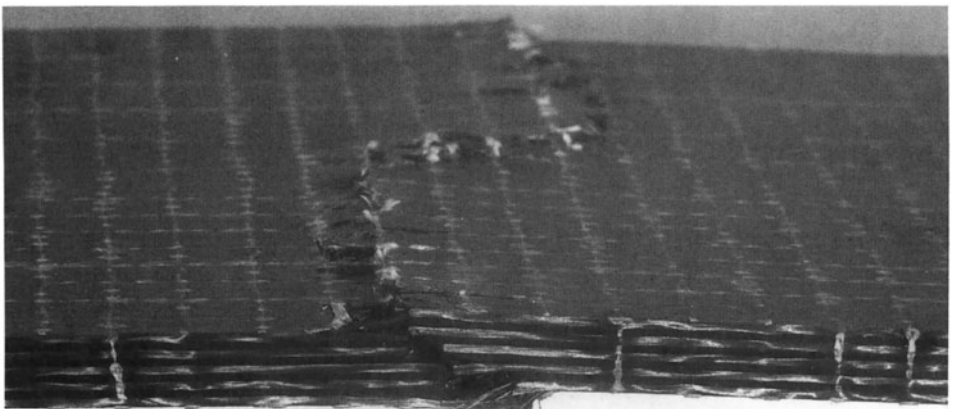


Figure 7. The failure modes for (top) panel 1 without through-the-thickness reinforcements (delamination induced local instability failure mode); (bottom) panel 2 with through-the-thickness reinforcements (transverse shear failure mode).

SUMMARY

The objective of this study was to increase the understanding of damage in composite materials with through-the-thickness reinforcements. As a first step it was necessary to develop new ultrasonic imaging technology to better assess internal damage of the composite. A useful ultrasonic imaging technique has been successfully developed to assess the internal damage of composite panels. The ultrasonic technique accurately determines the size of the internal damage. It was found that the ultrasonic imaging technique was better able to assess the damage in a composite panel with through-the-thickness reinforcements than by destructively sectioning the specimen and visual inspection under a microscope. Microscopic determination of crack location and lengths in a composite panel with through-the-thickness reinforcements was almost impossible.

Five composite compression-after-impact panels were tested. The compression-after-impact strength of the panels with the through-the-thickness reinforcements was almost twice that of the comparable panel without through-the-thickness reinforcement.

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