N95- 28272

Service Tough Composite Structures Using the Z-Direction Reinforcement Process

Glenn Freitas, Constance Magee, and Joseph Boyce
Foster-Miller, Inc. Waltham, MA

Richard Bott
Naval Weapons Center, China Lake, CA

56-24 p. 7

SUMMARY

Foster-Miller has developed a new process to provide through thickness reinforcement of composite structures. The process reinforces laminates locally or globally on-tool during standard autoclave processing cycles. Initial test results indicate that the method has the potential to significantly reduce delamination in carbon-epoxy. Laminates reinforced with the z-fiber process have demonstrated significant improvements in mode I fracture toughness and compression strength after impact. Unlike alternative methods, in-plane properties are not adversely affected.

INTRODUCTION

Advanced composite materials such as carbon/epoxy are prone to delamination or splitting between the plies caused by handling or service impacts. Delamination is often internal and is difficult to detect even with sophisticated instrumentation. Critical components must be designed for conservative stress levels because of the possibility of an undetected delamination. Preventing delamination or limiting propagation under load would save weight through higher design allowables, and would reduce inspection, repair and replacement costs.

Several approaches have been evaluated for improved toughness of composite structures. Approaches evaluated to date often incur substantial cost to implement and/or result in significant reductions to in-plane properties.

Foster-Miller has developed a new approach to through thickness reinforcement called the z-fiber process. As will be shown in the sections which follow, this process has several desirable aspects including:

- No-dissimilar materials; through thickness reinforcements can match in-plane materials
- On-tool reinforcement with one side access
- Provides reinforcement locally or globally
- No specialized equipment required
- Compatible with existing tooling and process materials, equipment, and procedures
- Eliminates manufacturing steps (stitching or fastener installation)
- Potential for reduced fabrication, inspection, repair, and replacement costs
- Does not introduce any new or unqualified materials
- Increases interlaminar fracture toughness several times
- Significantly reduced delamination areas created by impact
- Minimal loss of in-plane strength

THE FOSTER-MILLER Z-FIBER PROCESS

To meet the need for control of delamination, Foster-Miller has developed a new process for inserting through thickness fibers. The process converts a 2D prepreg layup to 3D on-tool with little or no change to standard cure cycles. The process is illustrated in figure 1. A foam prefoam containing small diameter rigid fibers is placed on top of the prepreg layup on-tool. During autoclave cure, the combination of heat and pressure compacts the foam which transfers the fibers into the composite. The through thickness fibers are elastically supported by the foam to prevent buckling during insertion. After cure, the foam residue is removed along with the bleeder and release ply.

The foam preforms are produced by specialty machinery produced by Foster-Miller which can be programmed to insert fibers in any desired pattern and spacing. The foams can be produced in a variety of thicknesses, fiber densities, and fiber materials; and can be thermoformed to conform to curved surfaces. The process can be used to attach secondary structures during the co-cure as an alternative to metal fasteners (figure 2).

Foster-Miller has demonstrated the effectiveness of this technology with several different prepreg systems. Among these are AS4/3501-6, IM7-8551, and Fiberite K641 phenolic for carbon-carbon applications. The process can also accommodate several rigid rod materials as through thickness reinforcements. SiC, Boron, 30MSI carbon/epoxy, and P-100/epoxy (for thermal applications) rods have been evaluated as reinforcement materials to date. 30MSI carbon/epoxy has demonstrated the best fracture improvements in epoxy systems.

The ability of the foam to provide elastic stability to the rods allows the use of small diameter fibers. Our baseline reinforcement is 0.006 inches in diameter and is inserted at an areal density of 0.5% by area or 200 pins per square inch. The small diameter of the fibers and the ability to insert them at the point of minimum viscosity of the matrix system prevents significant fiber damage which can lead to in-plane property degradation. Small diameter fibers also maximize the laminate thickness to fiber diameter (l/d) ratio which is important in thin laminates where the primary failure mode is fiber pull-out.

MECHANICAL PROPERTY EVALUATION

The mechanical property evaluation was conducted to determine what benefits in fracture toughness can be obtained with the z-fiber process and at what cost to in-plane property data. Static tension and compression and mode I fracture properties were evaluated.

Effects of z-fiber reinforcement on static tension properties are reported by Table I. Testing was independently conducted by Rohr Industries on 0/90 woven AS4/3501-5A fabric laminates. Baseline 0.006 inch diameter 30 MSI carbon/epoxy rod stock at 200 fibers per square inch was used. Reinforced panels exhibited 98% of the strength and modulus of control panels.

Effects of z-fiber reinforcement on compression properties is reported by Table II. Testing was conducted by LTV Aircraft Products using a 4 inch x 12 inch specimen in a standard CSAI test fixture. Two different diameter reinforcement materials were evaluated. In both cases reinforced laminates retained all of their strength compared to unreinforced laminates.

Improvements in mode one fracture toughness were determined using a double cantilever beam (DCB) test specimen. In this test, the load required to propagate a fracture in peel is plotted against the tensile testing cross head extension (figure 3) of the machines. The load is reduced to zero after the crack length travels 0.10 inches along the specimen length. Loading and unloading are then repeated for several 0.10 inch crack increments. The area under the curve for each individual area (represented by cross hatch in figure 3) is used to determine mode one fracture energy G_{IC}. The data plotted in figure 3 are for AS4/3501-5 laminates and compare unreinforced specimens with specimens reinforced with boron and carbon/epoxy rod stock. Boron and carbon/epoxy reinforced specimens exhibited over two and seven times, respectively, the fracture toughness of control laminates. The boron reinforced specimens failed by fracture of the boron fiber. This is believed to be a result of the brittle nature of boron in bending. Carbon/epoxy reinforced laminates failed from fiber pull out of the transverse fibers. This suggests if a better bond between the transverse fibers and the matrix can be obtained, or if a high percentage of z-fibers is used, even higher fracture values can be expected. A summary of the effect on mode one fracture properties for 3501 and 8551 laminates is shown by figure 4.

IMPACT TESTING

Testing of AS4/3501-6 control versus reinforced laminates was conducted both with low velocity (drop weight) and medium velocity (simulated hail shot) impact.

Low velocity impact was evaluated using a 4 inch by 12 inch compression strength after impact (CSAI) specimen. The impact energy selected for testing was 20 ft•lbs (approximately 1000 in•lbs/inch). Two rod stock diameters, 0.006 and 0.008 inch diameter, were evaluated against controls. Testing was conducted by LTV Aircraft Products and the results are depicted by Table III. With both rod stocks close to 50%, improvement in CSAI was achieved.

Higher velocity impact was investigated using hail shot testing conducted by Boeing Military Airplanes. Eight inch square panels 0.125 inches in thickness were reinforced over a 5.25 inch square area about the center of the panels (figure 5). Two types of reinforcement patterns were investigated; reinforcement over the entire area, figure 5a, and reinforcement in a grid pattern, figure 5b. Areas of reinforcement contain 200 0.006 inch diameter fibers per square inch. The panels were mounted in a picture frame and impacted with 1.0 inch diameter hail balls at approximately 500 ft/sec. The resultant area of delamination for each panel condition was determined and is represented by figure 6. Area and grid reinforced panels, respectively, exhibited 44% and 57% less delamination area versus controls for the same impact level. It is theorized that grid panels were more effective because of the higher energy required to initiate delamination as the fracture approaches each group of fiber rows.

CONCLUSIONS

The effectiveness of the z-fiber process in limiting delaminations and improving fracture toughness were clearly demonstrated through the testing conducted. Also demonstrated was the advantages of this process over alternative technologies in the areas of versatility, cost-effectiveness, and limit in in-plane property degradation. In summary the Foster-Miller z-fiber process demonstrated in AS4/3501-6 laminates:

- Greater than 7.5 times increase in mode one fracture toughness
- 50% increase in CSAI
- 45-55% decrease in delamination area when subjected to 80 ft•lb hail impact
- No decrease in in-plane compression strength properties
- 98% retention of in-plane tension strength and modulus

The z-fiber process increases service toughness without increasing weight and with no introduction of dissimilar or new materials. Manufacturers of composite structures will ultimately purchase preforms which can be used for through thickness reinforcement. There will be no requirement for special machinery, keeping application costs at a minimum.

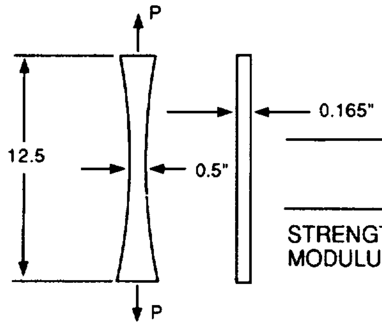
ADDITIONAL APPLICATIONS

The z-fiber process is being evaluated for applications ranging beyond service toughness. Such applications include tailoring of through thickness thermal conductivity, attachment of co-cured structures, brazed attachment of carbon-carbon structures, sandwich core constructions, and improvements in interlaminar tension strength.

ACKNOWLEDGMENTS

Work conducted for this paper was performed under a Small Business Innovative Research (SBIR) contract #N60530-88-C-0370 from the Naval Weapons Center China Lake. The technical monitors have been Mr. Burt Stull succeeded by Mr. Richard Bott. In addition, cost sharing in the terms of test services and technical support have been provided by LTV Aircraft Products, Boeing Military Airplanes, and Rohr Industries. Special thanks to Glen Williams and Scott Norwood of LTV, Jamie Childress of BMA, and Chris Saddler of Rohr for their contributions.

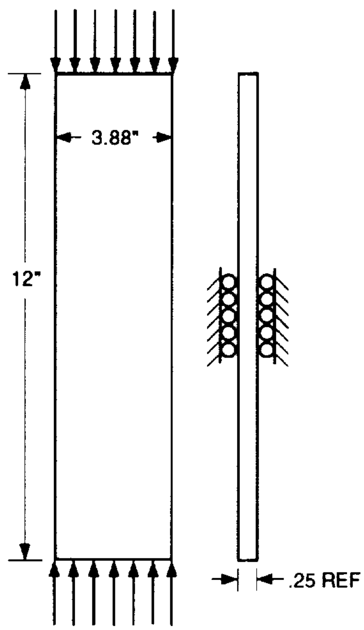
TABLE I. - STATIC TENSION DATA



	CONTROLS UNREINFORCED	REINFORCED	% OF CONTROL RETAINED
STRENGTH (ksi)	127	124	98
MODULUS (Msi)	11.9	11.7	98

61-FA-1

TABLE II. - COMPRESSION DATA



% AREA CARBON/EPOXY Z-FIBER (pins/in.^{2})	Z-FIBER DIAMETER (in.)	FAILURE STRESS (ksi)	% OF CONTROL RETAINED
NONE	NONE	92,080	---
0.5 (196)	0.006	92,936	101
0.5 (100)	0.008	93,968	102

MATERIAL: AS4/3501-6
LAMINATE ORIENTATION:
[±45/02/90±45/02/90±45/02/90±45/02/±45/0/±45]S
OR 37.5/50/12.5 PERCENT 0/45/90

60-FA-1

TABLE III. - CSAI DATA

% Z-FIBER (pins/in ^{2})	Z-FIBER DIAM (in)	FAILURE STRESS (ksi)	% INCREASE
NONE	NONE	29,267	–
0.5	0.006	43,738	49.4
0.5	0.008	43,000	46.9

MATERIAL: AS4/3501-6
LAMINATE ORIENTATION:
[±45/02/90±45/02/90/±45/02/90/±45/02/±45/0/±45]S
OR 37.5/50/12.5 PERCENT 0/45/90

61-FA-4

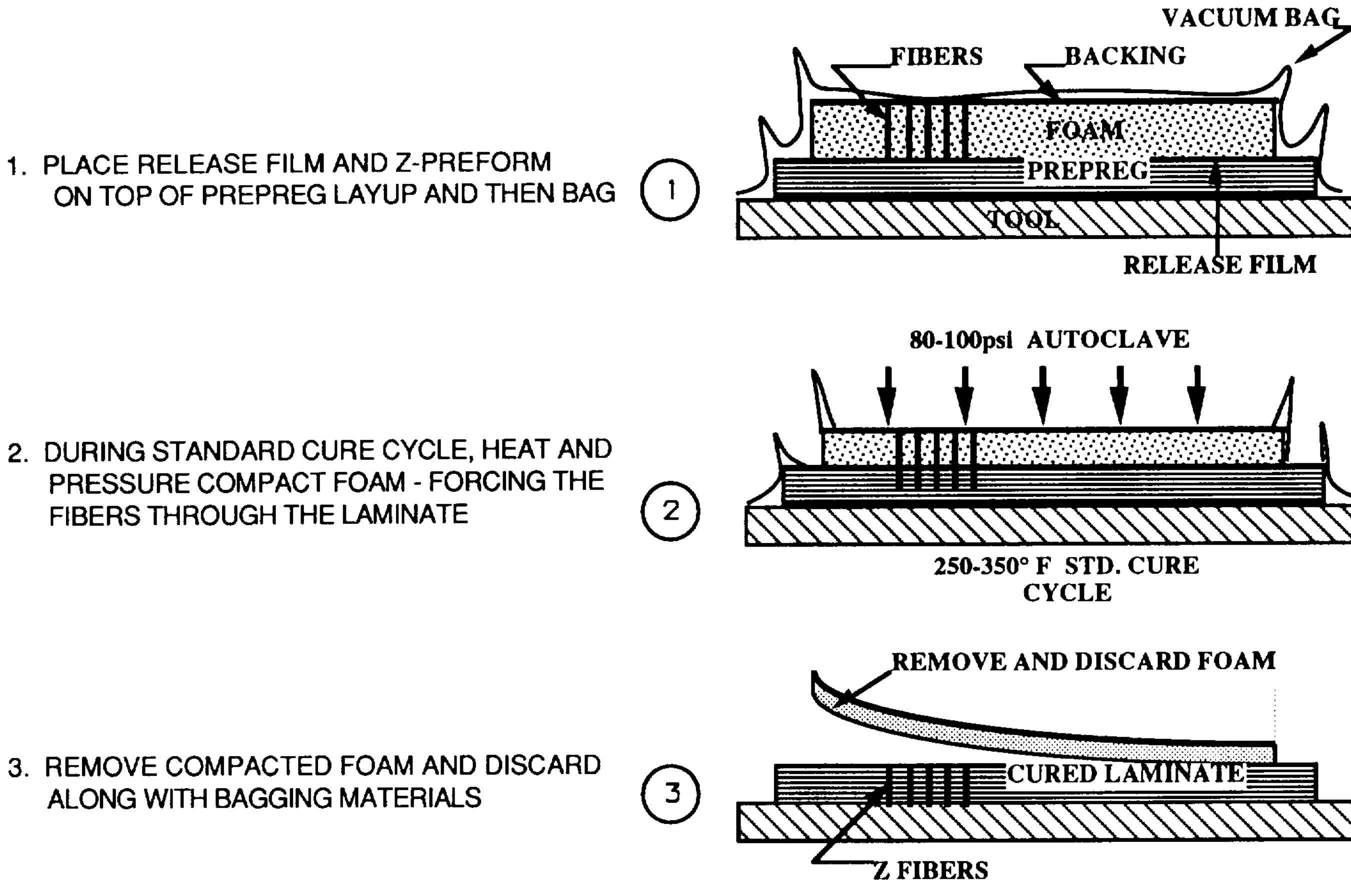


Figure 1. - Z-Fiber Process

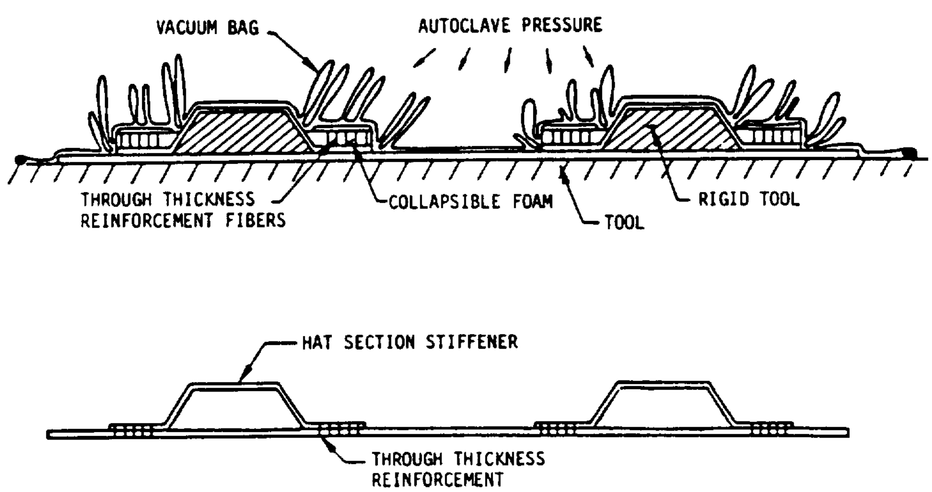


Figure 2. - Stiffener Attachment During Co-Cure

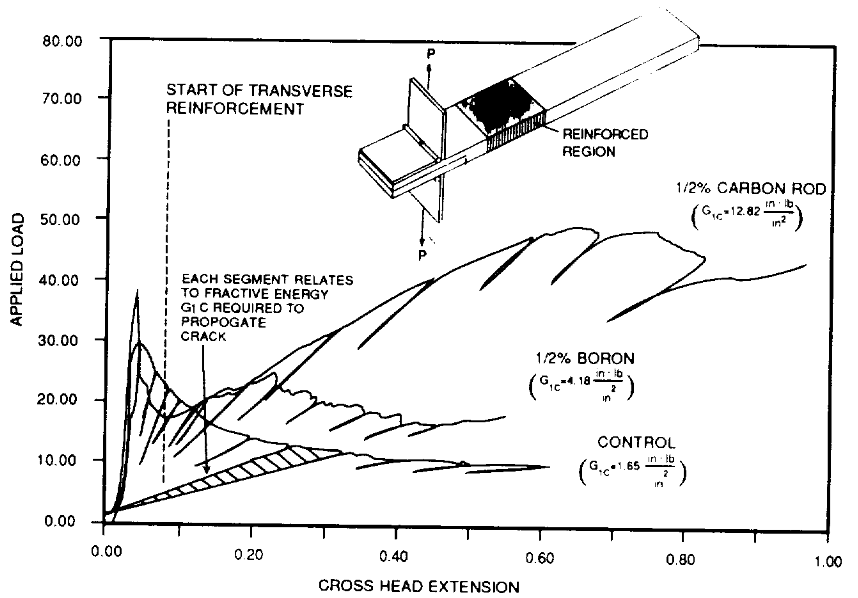


Figure 3. - DCB Plots of Various Reinforcement Materials

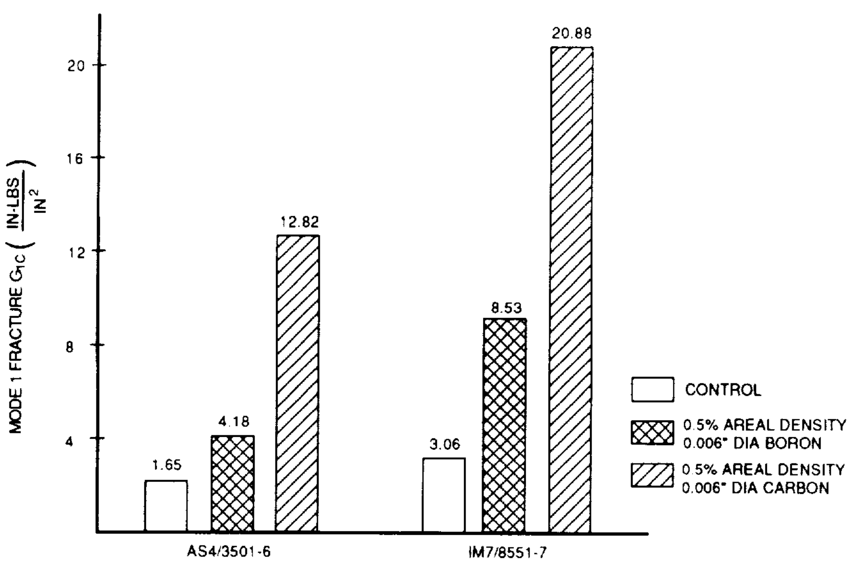


Figure 4. - Summary of Mode One Fracture Testing

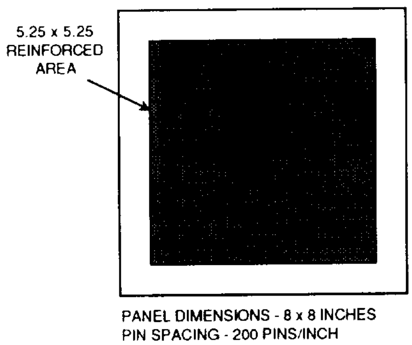


Figure 5a. - Area Reinforced Hail Shot Panel

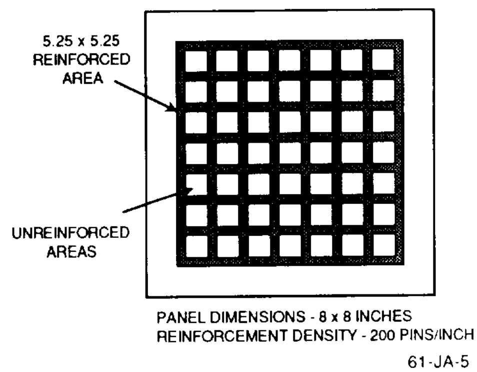


Figure 5b. - Selectively Reinforced Hail Shot Panel

Figure 5. - Hail Shot Panels

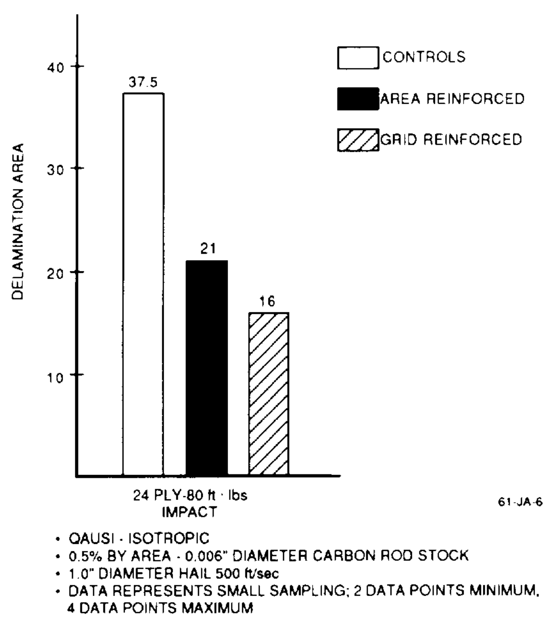


Figure 6. - Trends in Hail Shot Impact Delamination Area

THIS PAGE INTENTIONALLY BLANK