AFFORDABLE PROCESSING AND CHARACTERIZATION OF MULTI-FUNCTIONAL Z-PIN REINFORCED VARTM COMPOSITES

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SUMMARY: A variety of aircraft, marine, rail and ground-transportation bodies utilize composites in their body parts and interior designs. Delamination and its growth are of critical concern in composite structures. Through the thickness stitching of composite laminates has been adopted over several years as a means of improving damage tolerance. However, this approach is time-consuming and expensive. In the current study, the focus has been to investigate Z-pin reinforcement of a composite perform that undergoes affordable vacuum assisted resin infusion / transfer molding (VARTM) processing.

A Z-pin insertion device was designed and fabricated to be hand-operated and portable enough to enable both normal and angle insertion of Z-pins into dry fibrous perform. A number of calibration experiments were run on dry and wet perform to determine insertion force for pins made of steel and brass of diameters 0.38 mm, 0.50 mm and 0.63 mm (15, 20 and 25 mil.) for various grid spacing, and for a given fabric architecture and perform thickness. The Z-pin insertion unit was then utilized to fabricate representative E-glass/epoxy laminates in a VARTM process. Experiments were performed to measure the flexural response and impact response samples "with" and "without" the Z-pin reinforcement. This paper primarily outlines the utility for a Z-pin insertion device for VARTM composites fabrication.

KEY WORDS: VARTM Processing, Z-Pin Reinforcement

INTRODUCTION

A number of advanced structural components utilize composites due to their design flexibility and lightweight characteristics. Delamination damage is a critical concern in most composite structural parts. In most instances, the damage is externally invisible, however it causes significant reduction of structural stiffness and performance [1]. Through the thickness stitching of composite laminates has been adopted over several years as a means of improving damage tolerance [2,3]. The concept of using three-dimensional reinforcement through Z-pins in laminated composites for improvement of damage resistance was introduced by Freitas et al. [4]. The study in [4] demonstrated that for compression molded pre-preg systems with Z-pin reinforcement, the Mode 1 fracture toughness increased by 18 times, the compression after impact (CAI) increased 50%, the delamination area decreased by 45-55% for a 60 J hail impact, no decrease in compression strength, 89-98% retention of tensile strength, 70% improvement in onset of edge delamination, and ability to retain stiffeners during ballistic impact. Barret [5] studied the mechanics of Z-fiber reinforced laminated composites in relation to thermal effects. Palazotto et al. [6] and Vaidya et al. [7] investigated the low velocity impact damage initiation and propagation mechanisms in hollow and foam-filled Z-fiber pin core sandwich composites with graphite/epoxy facesheets and demonstrated that Z-pin cores localized/contained LVI damage area to a system of pins.

The Z-pins may be made of steel, brass, titanium and/or pultruded tow rods of composite materials such as glass/epoxy, carbon/epoxy or kevlar/epoxy. The pins offer potential space advantages if they are hollow, and can provide multi-functionality (thermal, electrical, vibration damping etc.) The pin reinforcement of the composite laminate has the potential to not only provide transverse stiffening / strengthening, but to also carry higher shear loads. Z-pin technology also allows for light and damage tolerant designs.

The present study focuses on extending the Z-pin reinforcement of laminates from autoclave type pre-preg systems to liquid molded composites. Recently emerging liquid molding processes include resin transfer molding (RTM) and vacuum assisted resin infusion/transfer molding (VARTM) offer greater flexibility in embedding tailored features into the perform and this can be achieved at significantly reduced tooling and processing costs [8, 9]. To this end, a device has been designed and manufactured in-house (at NDSU) and implemented to produce Z-pin reinforced laminates through the VARTM process. This paper describes the features of the produced Z-pin insertion device and provides *preliminary* results from tests conducted on the VARTM laminates with 15 and 25 mil. steel Z-pins.

VACUUM ASSISTED RESIN INFUSION/TRANSFER MOLDING (VARTM)

VARTM is of interest in low cost innovative developments as it uses one-sided tooling and vacuum-bag technology [8, 9]. It is an emerging manufacturing technique that holds promise as an affordable alternative to traditional autoclave molding and automated fiber placement for producing large-scale structural parts [8, 9]. In VARTM, the fibrous preform is laid on a single sided tool, which is then bagged along with the infusion and vacuum lines (Fig. 1). The resin is then infused over a permeable mesh placed over the preform, which enables wetting in its in-plane direction. The resin gradually wets through the thickness of the preform. This process is proving to be a very attractive alternative to spray-up or impregnation methods, and it is far less expensive than conventional manufacturing methods such as autoclave and/or compression molding. Large structural parts with high fiber volume fractions

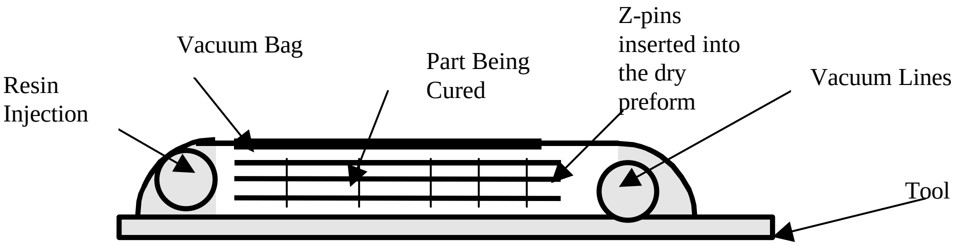


Figure 1. A Simplified Illustration of the VARTM Process

can be produced rapidly. Other advantages of VARTM are low process volatile emissions, high fiber-to-resin ratios and good process repeatability.

In the case of Z-pin reinforced composites, the VARTM process offers further flexibility, as the process of pin insertion can be performed in the perform prior to resin infiltration. The number of pins, pin density, type and spacing can be controlled and tailored into the perform, and subsequently subjected to resin infusion.

DESIGN OF Z-PIN INSERTION DEVICE

A portable hand-held Z-pin insertion device was designed and fabricated in-house for ease of use, cost efficiency, and accuracy of insertion. The device can be readily scaled-up and automated for industrial setting. The device is able to adapt to multiple wire sizes, wire types, and laminate thickness. The device consists of three basic systems integrated into a single unit. These systems are: a) wire advance mechanism, b) wire cutting mechanism, and c) device control system. Figures 2a, 2b and 3 show the schematics of the wire advance and cutting mechanisms and the device control system respectively. The specifications of the various components are provided in Table 1. The parameters of the device are provided in Table 2. A brief description of each component and assembly follows:

Wire Advance Mechanism This portion of the device design has two requirements. These requirements are to advance the wire accurately, and also provide the force necessary to insert the pins into the preform. This portion of the device is marked as 1 in Fig.2.

Wire Advance Mechanism The device was designed to accept a stepper motor actuating a friction drive wheel. The stepper motor was chosen because of the angular resolution available. With the micro-stepping motor driver, the advancing mechanism has resolution to 0.07 mm (0.003 inches), allowing the device to be adaptable to many situations.

Insertion force Stepper motors are available in many different torque ratings, and because of their design, are able to provide full torque from a standstill position. These characteristics are ideal for the insertion device application. By performing calibration tests of insertion forces, it was determined that a force of about 3.4 kgs (7.5 lbs) was required. From this data a motor was selected with an operating torque of 1.55 N-m (220 oz-in.). By using a drive wheel of 38.1 mm (1.5 in.), and applying the force through friction, approximately 3.6 kgs (8 lbs) of force is applied to the wire.

The Wire Cutting Mechanism This mechanism is designed to cut the wire flush with the surface of the composite after it has been inserted. This system is marked as 2 in Fig. 2. The device uses an air actuator to provide the force necessary to cut the wire. The cutter is built to provide mechanical advantage to the tip. By actuating the cylinder with a pneumatic solenoid, automatic cutting is achieved.

The Device Control System This portion of the device controls the actuation on demand of the device. It consists of three components. This system is shown in Fig.3.

The Programmable Logic Controller (PLC) The PLC is a programmable device used to supply the logic required to operate the device. By using built-in features of the device, instructions provided for the number of steps necessary, and then to actuate the pneumatic solenoid on demand.

The Power Supply The device utilizes electrical control, and therefore requires a device to power these units with stable, low noise energy. It provides three voltage levels, a 40-volt level to power the stepper motor, a 5-volt supply for logic voltage control, and through a voltage regulator on the 40-volt line, 12-volts to actuate the pneumatic solenoid.

The Motor Driver This component of the system provides voltage sequencing for the stepper motor. By applying a sequenced voltage to each phase of the stepper motor, the speed and direction of the motor can be controlled. The motor driver uses signals from the PLC to determine the amount of rotation needed.

TABLE 1. COMPONENT DETAILS

Transformer and Power Supply- Microkinetics PWR36
Programmable Logic Controller - Direct Logic05 model # D0-05DD
Motor Driver –MicroKinetics DM 4050
Stepper Motor – 34M220 Torque 1.55 N-m (220 oz-in.)
Air Cylinder- SpeedAire 6W078

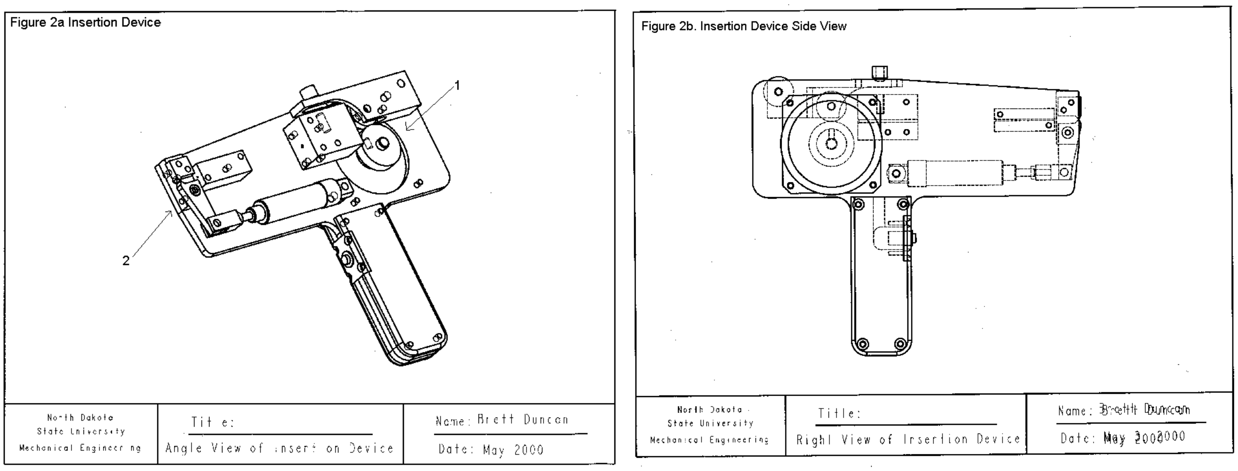
TABLE 2. PARAMETERS OF Z-PIN INSERTION DEVICE

Mechanisms	Rate
Cutter Assembly (actual cut time)	0.2 secs*
Stepper Motor	76.2 mm/sec (3 in/sec)*
Cut Length	Variable (adjusted by length control switch)
Wire tension	Adjustable by spring
Total insertion	10-15 pins per minute**

*These rates are adjustable depending on the criteria of the panel. The cut time can be adjusted to fit the exact pin diameters. The stepper motor feed rate can be adjusted to the thickness of the panel, the weave architecture and the accuracy of the insertion. These rates where determined for the insertion of pins into 15 layers of E-glass with a pin diameter of 0.38-mm (15 mil.)

EXPERIMENTAL

Calibration Experiments Preliminary tests were conducted to ascertain the extent of force required to insert a pin into an E- and S-glass perform to produce a final laminate thickness of 15.24 mm (0.6 in.) A disc was machined to accommodate a single pin (steel, brass or titanium) of 0.38 mm- 0.63 mm (15-25 mil) diameter and screwed to the movable head of a load frame. E-glass and S-glass preforms with different number of layers were placed on the bottom rigid plate of a load-frame (Q-test equipped with a 1363 kgs (3000 lbs) load cell). Compression loading at a rate of 1.27 mm/min (0.05 in/min) was applied and the force-deflection curve was monitored for pin diameters of 0.38-mm – 90.63 mm (15-25 mil) and heights of 12.7 mm – 15.24 mm (0.5-0.6 in.). Approximately ten pins were tested for each pin type. A typical force-deflection curve is shown in Fig.4. Based on the calibration experiments, it was ascertained that a force of 3.4 kgs would be required for the insertion of pins into the glass perform for a plain weave preform 10 oz/sq.yd.



a) b)

Figure 2. Z-Pin Insertion Device. a) Pictorial View, b) Detail View

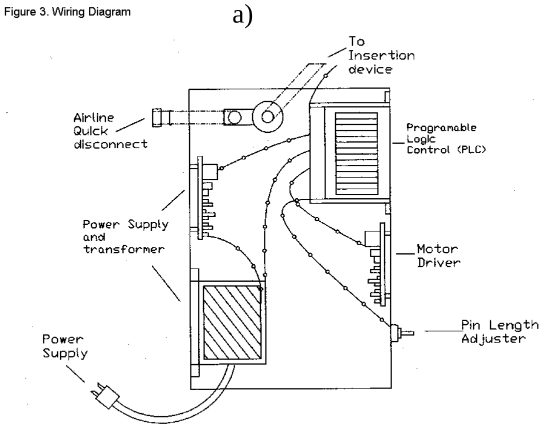


Figure 3. Electronic Components of the Z-Pin Insertion Device

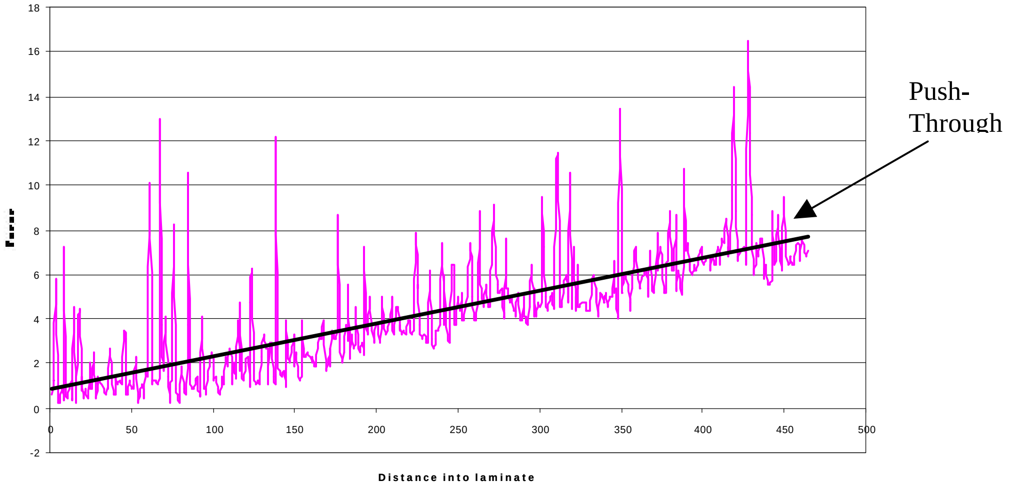


Figure 4. Calibration Curve for Z-Pin Insertion into Dry S2-glass Preform Stack of Twenty Layers (Stack Thickness ~ 25.4 mm (1”))

Manufacturing of VARTM Laminates VARTM laminates were produced using E-glass, plain weave fabric 10 oz/ sq.yd (23x24 weave) and epoxy resin E-Cast F-82 with hardener TP-41F (specific gravity of mixed system 1.13) with a mixed viscosity of 900 cps (Supplier – Eastpointe Fiberglass). Laminates of twenty layers of the perform of 45.72 cm x 50.5 cm (18"x20”) were produced in which half of the panel was unreinforced, and the other half was reinforced with steel pins of diameters 15 and 25 mil. were used. The Z-pin insertion device was used to insert pins of spacing 12.7 mm, 19.05 mm, and 25.4 mm (0.5, 0.75 and 1”) respectively, Only representative results are provided in this manuscript. During the VARTM processing, a piece of foam was placed on top of the permeable mesh,. to prevent the pins from piercing the vacuum bag. The process parameters are shown in Table 3. Laminates of average volume fraction of 52% and void content under 1% were produced as measured using the resin burn-off method. Fig. 1 demonstrates the schematic of the VARTM process.

TABLE 3. PROCESSING PARAMETERS

Process	Approximate Time
Set-up (preparing sample, vacuum, and tubing)	2-3 hours
Debulking	~2 hours
Mixing time	~ 10 minutes
Resin infusion	20-30 minutes for a 45.72 cm x 50.50 cm (18"x18") panel, 5.08 mm (0.2") thick
Curing	24 hours

Mechanical Testing : Flexure and Impact Testing

Flexure Tests Four-point bend flexure tests were conducted using an MTS 810 with a crosshead speed of 1.27 mm/min. (0.05 in/min.). Table 4 provides details of the sample geometries used in the flexure tests.

TABLE 4. DETAILS OF SAMPLES USED IN FOUR-POINT BEND FLEXURE TESTS

Dimension	Non-Reinforced mm (in.)	Reinforced 15 mil diameter (in)	Reinforced 25 mil diameter (in)
Width	86.36 (3.40)	79.24 (3.12)	89.66 (3.53)
Thickness	4.31 (.17)	4.52 (.178)	4.47 (.176)
Length	317.5 (12.5)	317.5 (12.5)	317.5 (12.5)
Pin density	N/A	19.05 (.75) grid	19.05 (.75) grid

*All dimensions have a tolerance of +/- 1.27-mm (0.05”)

Figure 5 represents the stress-strain curves obtained from the flexure tests. The flexural strength of the 0.38-mm (15 mil)-reinforced laminates was seen to be 4.22% higher than the unreinforced plate, and of the 0.63 mm (25 mil.) 11.90% higher than the unreinforced. The increase in modulus is 8% higher for the 0.38 mm (15 mil.), and 12.4% higher for the 0.63 mm (25 mil.) as compared to the unreinforced laminate. The failure of all panels was compression dominated, i.e. concentrated on the loading face.

Additional tests were performed in thicker 12.7-mm (0.5") flexural samples with a notch at the center of the panel. The Z-pins suppressed delamination growth, limiting them to the pin dimensions, while extended delaminations were observed in the case of notched samples without reinforcement.

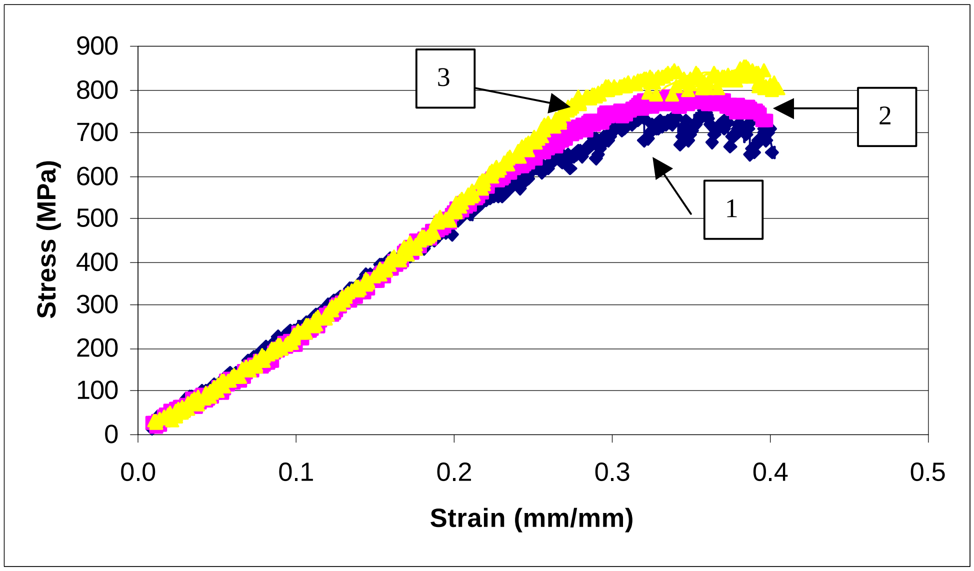


Figure 5. Stress-Strain Curves for Flexural Loading of Unreinforced and Z-Pin Reinforced Panels. 1- Unreinforced, 2 – 0.38 mm (15 mil.) Pin Reinforcement, 3 – 0.63 mm (25 mil.) Pin Reinforcement

Impact Tests Past studies [4] have demonstrated the effectiveness of Z-pin reinforcement to suppress delamination growth at high-energy impacts - 60 J. In the present work, high velocity, high-energy impact tests were conducted. A gas-gun was utilized in conducting the impact tests. The gas gun setup utilizes a pressurized chamber that releases a cylindrical aluminum projectile of mass 24 gms, 50.8 mm (2") long with 38.1 mm (1.5") diameter through a 6.09 m (20 ft) hollow barrel. The sample of 15.24 cm x 15.24 cm (6 in. x 6 in.) dimension is held in a rigid steel plate 35.56 cm x 35.56 cm x 2.54 cm (14 x 14 x 1 in.) within a capture chamber. The metal plate has an 11.43 cm x 11.43 cm (4.5" x 4.5") cut out. The composite is held in a simple supported configuration within the metal plate. Table 5 provides details of the samples tested. A chronograph Model ProChrono is strapped to the capture chamber. The capture chamber has two plexiglas windows on its bottom, 30.48 cm (12") apart to measure the velocity of the projectile through the principle of time of flight. Two light sources placed on the top of the capture chamber (which have identical windows) are used to enhance the optical path and provide accurate measurement of the inlet velocity of the projectile.

Ballistic tests were conducted at 35.96 m/s (118 ft/s). The kinetic energy input to the samples was 15 J. Figure 6 provides a projected damage state for the unreinforced samples, and the 0.63-mm (25 mil.) Z-pin reinforced samples.

TABLE 5. DETAILS OF THE BALLISTIC TEST SAMPLES

Dimension	Non-Reinforced mm (in)	Reinforced 0.63 mm (25 mil) diameter pins mm (in)
Width	15.24 (6)	15.24 (6)
Length	15.24 (6)	15.24 (6)
Thickness	4.44 (.175)	4.36 (.172)
Pin Density	N/A	19.05 (.75) grid

*Thickness has a tolerance of +/- 0.127 mm (.005")

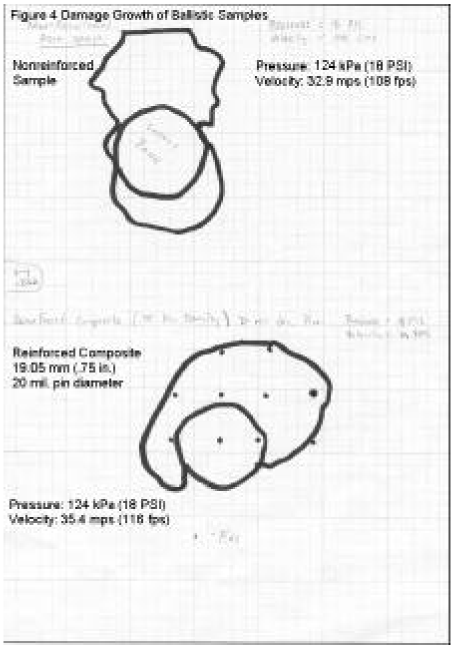


Figure 6. Ballistic Damage Profile for Unreinforced and Reinforced Laminates. Top – Unreinforced, Bottom – 0.63 mm (25 mil.) Reinforced (Dots indicate pin positions). Impactor used - Aluminum cylinder, flat head 38.1 mm (1.5") diameter, 50.8 mm (2") long

Ballistic tests indicated a preferential growth of damage influenced by the position of the pins. As seen in Fig. 6 the damage growth was observed to extend up to the periphery of a system of pins, while in the unreinforced panels, the damage growth extended in a traditional elliptical progression. The projected damage area was similar in the unreinforced and reinforced samples. This suggests that there exists a threshold of impact energy, beyond which the Z-pin reinforcement may contribute to the growth profile (shape) of the delamination, and not necessarily reduction of delamination area.   Further tests are underway to investigate perforation mechanisms under different types and shapes of projectiles.

CONCLUSIONS

A Z-pin insertion device for producing damage tolerant composite laminates with variety of pin diameters, pin types and pin lengths has been designed, manufactured and implemented in-house at NDSU. The insertion device will allow for rapid manufacturing of damage tolerant Z-pin reinforced laminates for liquid molded as well as prepreg system based composite laminates. This device has many possibilities for integration for applications as in automotive, aircraft and marine industries. The device developed is easy to automate.

The Z-pin insertion device was successfully utilized in to produce glass/epoxy composite laminates in conjunction with the affordable VARTM process. Preliminary performance evaluation studies demonstrated that the flexural strength and moduli increased by 4 % and 8% respectively, by addition of the 0.38 mm (15 mil) pins in a 19.5 (0.75 in.) grid spacing. For similar laminate condition, the addition of 0.63 mm (25-mil) pins was seen to increase the flexural strength by 11% and moduli by 12% respectively. For high-energy impacts with flat head cylinder type of sabot, the delamination area was not significantly different 'with' and 'without' Z-pin reinforcement, however, the pins influenced the delamination shape. Detailed parametric studies involving pin diameters, density, spacing and pin types are underway.

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