To the Graduate Council:

I am submitting herewith a thesis written by Jay Randall Sayre entitled "The Effects of Bias Angle and Fiber Volume Fraction on the Mechanical Properties of Filament-Wound, Polypropylene-Glass Tubes." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the Master of Science degree, with a major in Polymer Engineering.

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THE EFFECTS OF BIAS ANGLE AND FIBER VOLUME FRACTION ON THE MECHANICAL PROPERTIES OF FILAMENT-WOUND, POLYPROPYLENE-GLASS TUBES

A Thesis
Presented for the
Master of Science
Degree
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Jay Randall Sayre
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DEDICATION

This thesis is dedicated to my wife, Kara, and my parents, Jim and Jeanne Sayre. Without their love and support this would not have been possible.

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The list of acknowledgments for such an undertaking is seemingly endless, yet, there are a few that stand out above the rest. I would like to thank the members of my Advisory Committee, Dr. Roberto Benson and Dr. Joseph Spruiell, for their time and expertise. In particular, I would like to thank Dr. John F. Fellers, my major professor. Through his guidance and teachings I have taken away much more than I would have ever imagined from this institution. I would also like to thank the Center for Materials Processing for their gracious funding and support. Lastly, I would like to thank the University of Tennessee for providing me the opportunity to fulfill a dream.

ABSTRACT

This thesis discusses the uninterrupted, filament winding of a continuous, fiber-reinforced, polypropylene cylinder using raw materials (not a prepreg) at start-up. The objective was to increase the understanding of the process by yielding defensible conclusions regarding its operation in achieving engineering structures possessing high mechanical properties. Primarily, the effects of the bias angle wrap and the fiber volume fraction on the mechanical properties of the composite laminates were studied. The experimental values were compared against a theoretical mechanics model for the force resultants and the moduli of the laminate. It was found that the highest tensile and flexural strengths were achieved for the lowest bias angle value obtainable, 54°. Similarly, it was also found that the highest tensile and flexural moduli belonged to the 54° tube. The strength and modulus for fiber volume fractions of 0.34, 0.37, and 0.46 did not appear to vary significantly from one sample to the other. Therefore, it was determined that the fiber volume fraction was not a controlling factor in regards to the mechanical properties of the products in this experiment.

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Chapter I. Introduction

Polymeric Composite Fundamentals

When observed three dimensionally, composite materials consist of one or more discontinuous phases (reinforcement) embedded in a continuous phase (matrix). These phases are physically distinct and mechanically separable. The joining of these phases is accomplished in a controlled manner in order to achieve mechanical properties that are superior to the individual components. There are several types of composite materials on the market. Along with metal and ceramic composites, polymeric composites are widely utilized. In addition to factors such as low cost and chemical resistance, there is another major advantage in polymeric composite materials. This advantage lies in the high strength-to-weight ratio.

The strength-to-weight ratio is, in essence, the specific strength of the given material. The specific strength, by definition, is simply the strength of a material divided by its density. This value is, dimensionally, work per unit mass. This means that for materials with a high specific strength it takes more energy per unit mass to cause a failure. Materials with high specific strengths can also support higher loads at values less than their failure strengths. This is because they have little weight of their own to support when compared to the payloads they are capable of supporting. For polymeric composites, they yield considerably higher values when compared to conventional materials such as low alloy steels. These high strength-to-weight ratios mean high energy savings, which equals lower costs.

Since a polymeric composite's weight and strength are highly dependent on the type of reinforcement used, it is necessary to make comparisons between reinforcements and conventional materials to see the true benefit in polymeric composites. Composite reinforcements have been compared to traditional materials in Table I.

Table I. Typical Reinforcing Materials versus Conventional Materials [1]

Material	*Modulus*[1]	*Strength*[2]	*Density*[3]	*Sp. Modulus*[4]	*Sp. Strength*[5]
Steel	30	600	0.282	11	21
Aluminum	10.6	90	0.097	11	9
Titanium	16.7	280	0.170	10	16
Carbon*	46	339	0.065	71	52
Glass**	12	300	0.092	13	33

Note: [1] 10^6 lb_f/in^2, [2] 10^3 lb_f/in^2, [3] lb_m/in^3, [4] 10^7 $(lb_f \cdot in)/lb_m$, [5] 10^5 $(lb_f \cdot in)/lb_m$
*Magnamite-HMS4 [2]
**Data from PPG [3]

It can be seen from this table that glass has a high specific strength and a comparable specific modulus when compared to materials such as steel. When glass is placed in a low-density, polymer matrix like polypropylene (density = 0.033 lb/in^3 [1]), it gains the benefits of toughness and other matrix serving functions without the addition of much weight.

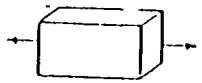
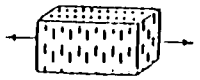
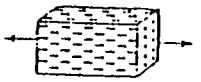
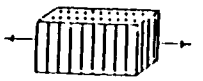
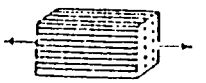
In general, there are two reinforcement classifications of composites, particulate and fibrous (organic or inorganic). Fibrous composites may have short, long, or continuous fibers. Continuous fiber composites, although anisotropic, yield higher strength values in the direction of fiber orientation than do short or long fiber composites (see Table II.). These fibers are available in a variety of end use forms depending on the

materials, process, and product. Rovings are common in filament winding processes when a number of strands of continuous fibers are required to be wound onto a mandrel without twisting.

Typically, the reinforcement is stronger than the matrix. Although the reinforcement serves as the load bearer, the matrix also serves several functions. Coupled with binding the fibers together and transferring the load to them, the matrix protects the fibers against environmental attack and damage due to handling, and it imparts toughness to the composite. The more energy the composite can absorb before fracture, the higher the toughness will become. The matrix imparts toughness by making the composite more ductile. This ductility causes a yielding in the composite, thereby, increasing the amount of energy that needs to be input into the system to cause a fracture.

Polymeric composite matrices can be either thermoplastic or thermoset. Thermoplastics soften upon heating, and, via liquid flow, can be reformed several times without degrading. They are characterized by linear or branched molecules having strong intramolecular bonds and weak intermolecular bonds. They can exist in crystalline and/or amorphous phases. Thermoplastics derive their strength from the intrinsic properties of their molecular weight. Thermosets, on the other hand, consist of multifunctional monomers that form a network. These network polymers are insoluble and usually noncrystallizable. They are characterized by the strong covalent bonding that is pronounced throughout the network. They are usually isotropic and do not melt or flow upon heating.

Table II. Stress-Strain Data for a Variety of Glass-Epoxy Systems [4]

	System (Stress Direction)	Filler Shape and Orientation	Strength σ (MPa)	Stiffness E (GPa)	Ultimate Strain ϵ (%)	Volume Fraction Filler V_f
1	Unfilled resin		69–83	2.1–2.8	4–5	0
2	Bead-filled		62–72	10.3–11.7	2.0–2.5	0.50
3	Short fibers (transverse)		38	9.6	0.4–0.5	0.50
4	Short fibers (longitudinal)		276	31.0	0.6–1.0	0.50
5	Continuous fibers (transverse)		28–41	12.4–14.5	0.4	0.60
6	Continuous fibers (longitudinal)		896–1103	43.4–46.9	2.0	0.60

Processing of Thermoplastic Composites

In the past, continuous-fiber, polymeric composites have been made with a thermoset as the matrix. It was not until the past decade that greater effort was placed into the processing of thermoplastic composites [5]. Thermoplastics offer great advantages over conventional thermoset matrices. Some of these advantages include unlimited shelf life of preforms, recycle ability, and high toughness for better damage tolerance (Damage tolerance is basically a design notion used in the prediction of the remaining life in a material due to time-dependent flaws.). The main problem is in the processing difficulties attributed to the fact that thermoplastics have high melt temperatures and high melt viscosities [5].

Advanced thermoplastic composites have been shown to require over 70% of the total production cost in the processing step alone [5]. This is due to the problems encountered with the high temperatures and viscosities. Until a suitable and economical process for manufacturing thermoplastic composites is discovered their use will remain limited. Some of the current processing technologies of thermoplastic composites include filament winding, pultrusion, and injection molding [5].

Filament winding batch techniques that involve thermoplastics offer the potential for a rapid production method with high fiber orientation and high mechanical properties in the manufacturing of hollow cylinders. The successful production of thermoplastic composites using a prepreg has already been accomplished [6,7,8,9,10]. In this process, a continuous-fiber prepreg is placed under tension, heated to a consolidation temperature, and then wound onto a rotating mandrel. This may be an automated or manual operation in which the formation of the product is done in a predetermined and controlled manner.

Since these techniques are insitu processes, they eliminate the curing time that thermosets require, which results in higher production speeds.

Chapter II. Literature Review and Discussion of Topics

Thermoplastics as a Composite Material

Thermoplastics have been under consideration for replacing thermosets as composite matrix materials for quite some time. Table III lists some of the common advantages and disadvantages of thermoplastics when compared to thermosets.

Table III. Thermoplastics versus Thermosets [6]

Aspect	*Advantage*
Viscosity	Thermoset
Temperature	Thermoset
Cycle Time	Thermoplastic
Post Cure	Thermoplastic
Repair and Post Forming	Thermoplastic
Storage	Thermoplastic
Toughness	Thermoplastic

One of the primary goals in any manufacturing process is to reduce fabrication costs (i.e. time, labor, and raw material cost). Thermoplastics have the potential to reduce the time and the amount of labor in their production. Unlike thermosets, there is no need for curing thermoplastics, thus, they have the possibility to reduce the process time. The reduction in labor is due to the ability of thermoplastic processing to become automated, since "hands on" application of a resin is unnecessary [6].

Advanced thermoplastic materials have been too expensive in the past to be considered in the replacement of thermosets. There is now a bridge between low cost materials and the production of high-tech composites. Techniques are now available which produce inexpensive thermoplastic prepregs for cold draping and hot forming that have promising mechanical properties when compared to conventional materials [11]. Simple cost analysis has been performed based on the amount of material needed for structural integrity in combination with material price [11]. Although these prepregs are becoming less expensive, there is still a need to reduce material cost for other processing techniques, such as, filament winding.

The advantages of repair and storage lie with thermoplasts. Since there are weak intermolecular bonds in thermoplastics, they can be easily reformed to correct for flaws [12]. The shelf lives of these reformable plastics are extensively longer than for thermosets. This is true because they are consolidated insitu [12]. Therefore, thermoplastic products do not require the curing step that is required by thermosets after production.

The fracture toughness (i.e. the resistance to crack propagation) of thermoplastics is often much larger than for thermosets [13]. Although thermosets having high degrees of crosslinking provide excellent strength and modulus values, they are often brittle. Thermoplastic resins have no crosslinks, large amounts of free volume, and can have high molecular weights. These facts allow energy to be dissipated in thermoplastic matrices that would otherwise promote a crack growth in more brittle materials.

One of the main advantages of polymers is the weight savings when compared to other materials. Although acceptable mechanical properties for thermoplastic composites use to require products with a fiber volume fraction of 0.6 or greater [6], current

technologies are being investigated which yield good results with fractions of 0.5 or less [14]. Obtaining these numbers requires a low viscosity resin to prevent fiber damage and distortions. Thermoplastics generally have high melt viscosities (in the range of 0.0145 - 145.0 $lb_f \cdot s/in^2$ [14]), therefore, current technology forces one to turn to expensive prepregs that already contain the desired fiber volume percentages to use as start-up materials for processing.

To contemplate thermoplastics as a viable ingredient in advanced composite production, consideration must be given to the high temperature applications, as well as, the high melt viscosities that will be encountered. There are two areas of concentration in regards to temperature applications for thermoplastics that must be discussed. The first is the processing temperature. Thermoplastics have high melting temperatures that must be dealt with in an insitu consolidated process. These temperatures must be taken into account to meet the design requirements. The second area of concentration is the usage temperature. Thermoplastics structural uses are generally limited to well below their glass transition temperature [11]. Most thermoplastics retain comparable mechanical properties to thermosets when below their glass transition [6].

The Fiber-Polymer Interface

To a large extent, end-product mechanical properties are dependent on the degree of fiber wetting. High interfacial adhesion is needed to realize the advantages of properties like the toughness potential, for example. The degree to which a fiber adheres to the matrix is a function of the void content and the area of contact [15]. This degree can be maximized by decreasing the porosity between the fibers and "fanning" these fibers out.

By lowering the void content and increasing the area of contact, the wetting of the fibers will become a more uniform process.

The wetting of the fiber bundle is also dependent on the viscosity of the polymer used. In general, the lower the viscosity, the better the chance the polymer has in wetting the bundle. The high melt viscosity of thermoplastics presents problems in on-line impregnation. Current technology in the processing of thermoplastics involve a separate step in order to accomplish impregnation (prepregs). This idea is not without its faults [8]. It is difficult to control the heating for impregnation, and the time for this heating action limits the processing speed. A pre-heater and a heater at the consolidation point are extra equipment that is necessary in this procedure. It has also been found that the amount of time the matrix is heated before it is consolidated must be long enough to insure complete, homogeneous matrix flow through the fiber bundle [8].

In order to improve the contact at the interface the ways in which the polymer can bond to the fiber must be observed. There are two major types of bonding that can occur at the interface. These types are mechanical and chemical bonding [13]. In chemical bonding a coupling agent is used to produce a "chemical bridge" between the fiber and the polymer. In glass fibers a silane coupling agent is generally used. See Figure 1.

The rule of mixtures is an excellent way of determining the achievable strengths and the degree of wetting in composites [16]. Before using the rule of mixtures, some basic assumptions about the composite must be made:

i. composite fracture is fiber controlled

ii. the modulus of elasticity of the fiber is greater than the matrix

iii. the strain to failure of the matrix is greater than the fiber

iv. the evaluation is for unidirectional composites

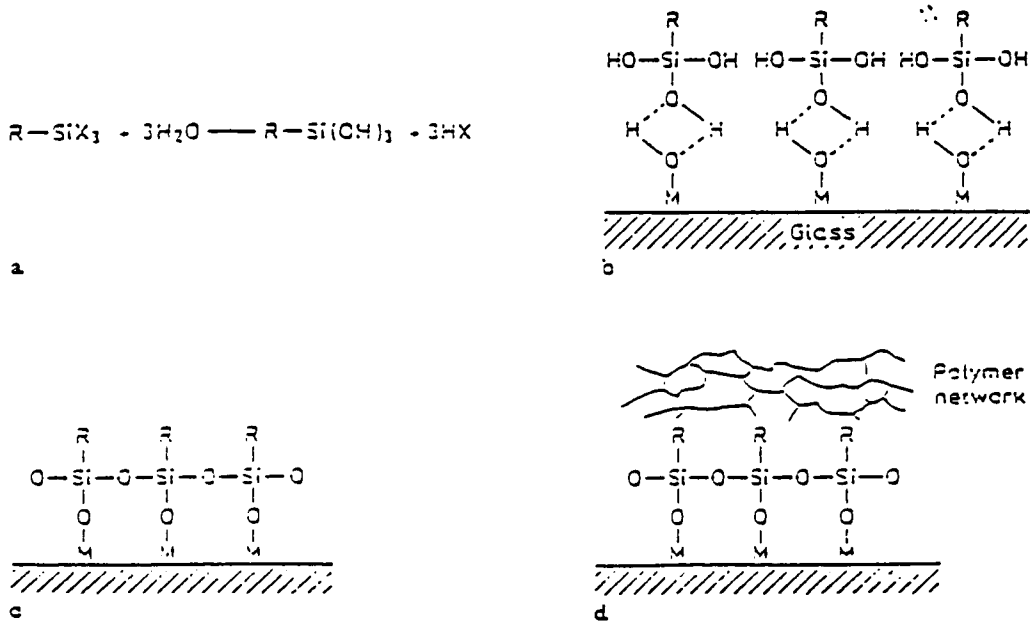


Figure 1. Function of a silane coupling agent: **a** hydrolysis of silane to silanol; **b** hydrogen bonding between hydroxyl groups and a glass surface; **c** polysiloxane bonded to a glass surface; **d** resin-compatible functional R groups after reacting with polymer matrix [13].

The first estimation that needs to be carried out is the fiber critical volume, $V_{f(crit)}$:

$$V_{f(crit)} = \frac{\sigma_m - \sigma_m^*}{\sigma_f - \sigma_m^*},$$

where σ_m = the ultimate tensile strength of the matrix

σ_m^* = the tensile strength of the matrix at the corresponding strain value of the ultimate tensile strength of the fiber

σ_f = the ultimate tensile strength of the fiber

This critical volume is the volume above which the fiber will strengthen the matrix, rather than weaken it.

Once this starting point for the fiber volume is realized, other characteristics can be estimated for the composite. Two cases need to be considered. Case I. is for the stress induced in the fiber direction, and Case II. is for the stress induced transverse to the fiber direction.

Case I.

i.) ultimate tensile strength of the composite, σ_c:

$\sigma_c = \sigma_f V_f + \sigma_m^*(1-V_f)$, where σ_f is the ultimate tensile strength of the fiber, σ_m^* is strength of the matrix at the corresponding value of strain for σ_f, and V_f is some fiber volume fraction greater than $V_{f(crit)}$.

ii.) modulus of elasticity of the composite, E_c:

$E_c = E_f V_f + E_m(1-V_f)$, where E_f and E_m are the moduli of elasticity for the fiber and matrix, respectively.

Case II.

i.) ultimate tensile strength of the composite, σ_c:

$\sigma_c = \sigma_m$, where σ_m is the ultimate strength of the matrix

ii.) modulus of elasticity of the composite, E_c:

$E_c = E_f E_m/(V_f E_m + V_m E_f)$, where E_f and E_m are the moduli of elasticity for the fiber and matrix, respectively.

The rule of mixtures provides a tool for the prediction of composite properties based on the properties of its constituents. This micromechanical prediction, from a mechanics point of view, is a precursor to the actual physical measurement of the composite's properties. Once the physical data is collected, macromechanical analysis of the system can take place. Therefore, the rule of mixtures is very important in the design considerations of any composite material. The rule of mixtures is depicted graphically in Figure 2. Any composite whose values fall below this line has prematurely failed. This failure may be due to inadequate wetting, broken/damaged fibers, areas of stress concentration, and/or voids in the matrix. It is possible to reach this upper bound, and even surpass it. This is done when the matrix has adhered to the fibers to a high degree, allowing a stress coupling effect between the constituents when a load is applied. Figure 3 displays the mechanical benefit of a composite that undergoes stress coupling. It can be seen from this figure that, as a high degree of wetting is achieved, it is possible for a composite to have better mechanical properties (i.e. larger strain at failure and larger stress at failure) than predicted by the rule of mixtures. This occurs from the idea that, as the fibers are breaking when their ultimate tensile stress values are reached, the matrix is undergoing plastic flow at the break region. This response by the matrix enables the load to be transferred to a more continuous section of the fiber. See Figure 4. This load transfer

works well in increasing the damage tolerance of the composite, thereby, allowing higher mechanical properties to be fulfilled.

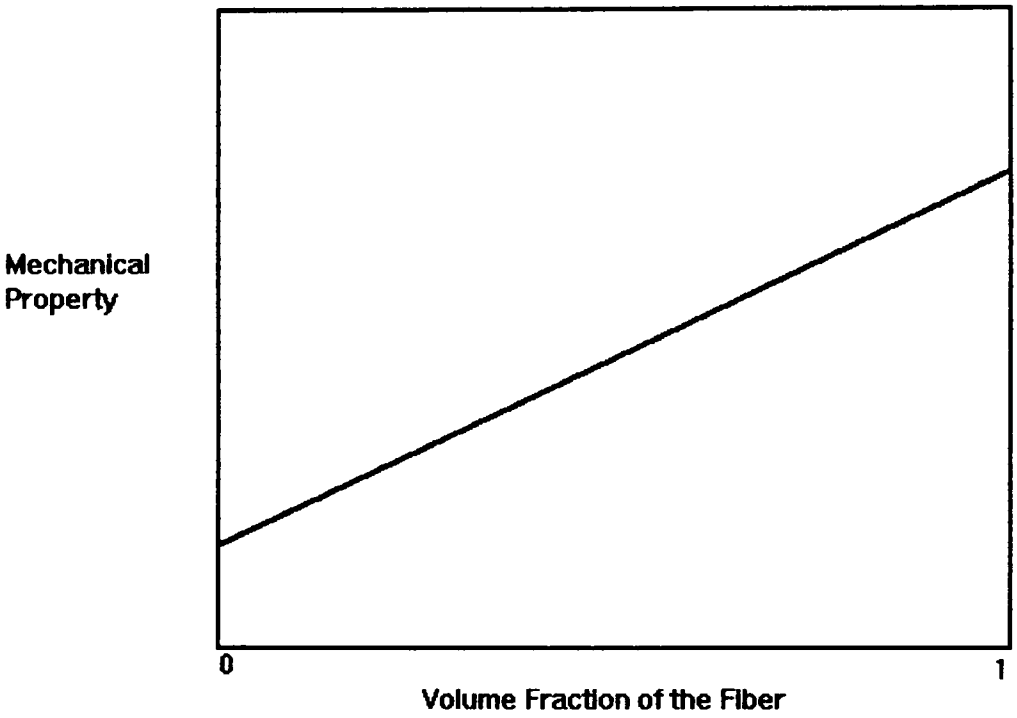


Figure 2. The Rule of Mixtures Generalized for a Two-Phase System [1]

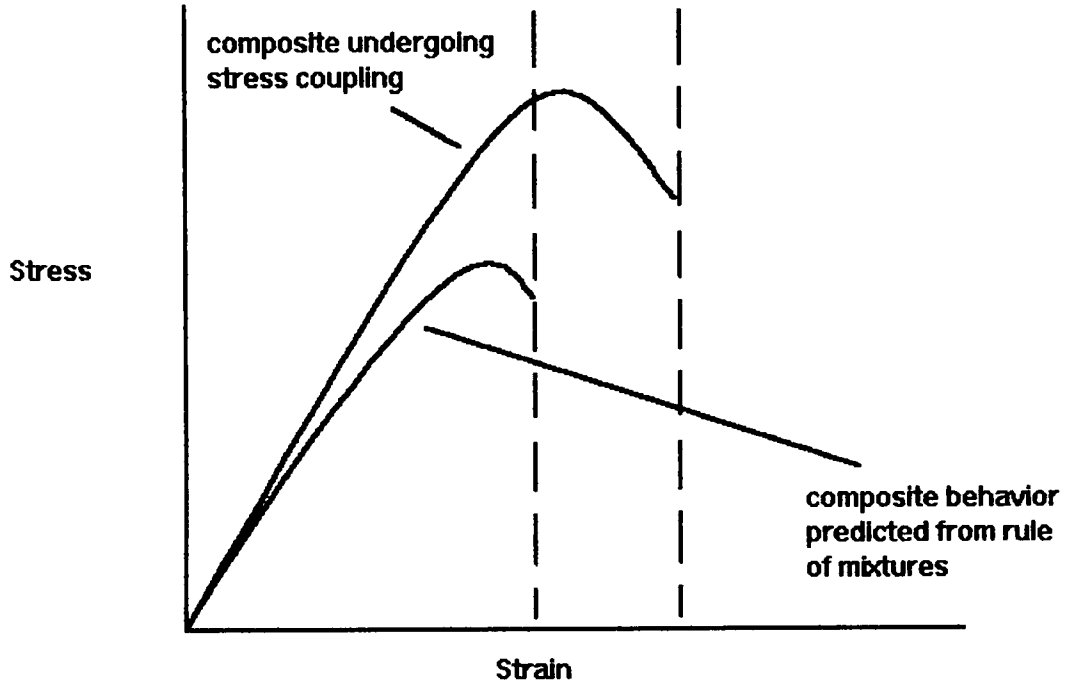


Figure 3. Stress vs. Strain of a Generic Glass Thermoplastic Composite

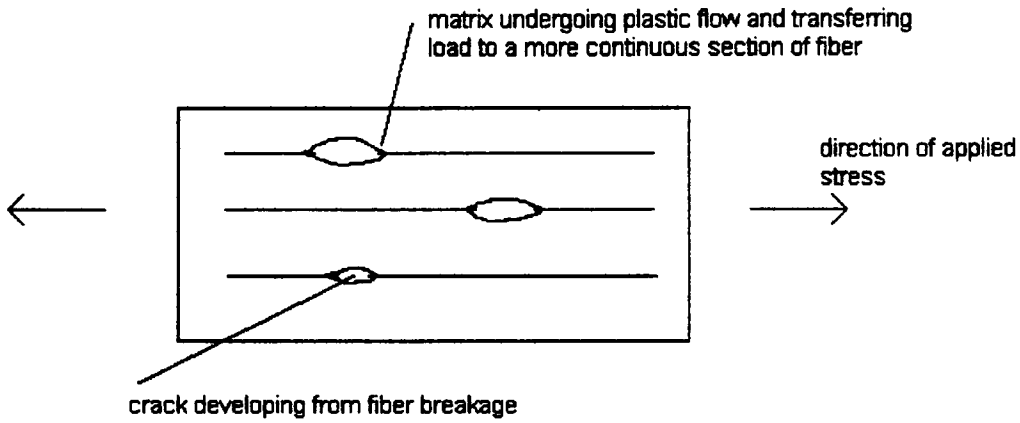


Figure 4. A composite matrix undergoing a transfer of load to a more continuous section of fiber after several breaks have occurred.

Filament Winding Processing

Filament winding techniques have been examined which use continuous-fiber, thermoplastic prepregs as the start-up material [6,7,8,9,10]. The process models for these materials incorporate compaction forces, melt temperature profiles, and take-up winding velocities. Material costs and processing speeds (i.e. 120 ft/min for current composite processing speeds that utilize thermosets as the matrix material) need to be enhanced for these processes to match present epoxy systems [7]. The main problem has been in the time that it takes between the heating of the impregnated tow and consolidation. This limiting factor needs to be overcome by either advancing current heating/consolidation technology or implementing on-line impregnation.

Advances in glass/polypropylene tape laying, which use a robotic arm in the filament winding workcell, have been developed to aid in faster and more precise production [9]. This research has also yielded composite winding patterns of 90° and ±45° for composites of a pre-determined length. To the author's knowledge, a filament winding process still has not been developed which incorporates an uninterrupted product, a raw material start-up, and a variable bias angle winding pattern.

Bias Angles

Bias angle wraps play a major role in the strengthening of composites [1]. Composites that are wrapped in a 90° wrap will show great strength in compression and tension in the fiber direction. However, when these composites are tested in applications that do not lie in the reinforcement direction (i.e. transverse tension and bending), they

will fail readily. A method must be devised that can increase the failure strength of the product by varying this bias angle wrap.

A composite cylinder may be optimized to provide strength in both the longitudinal and hoop directions. Such a cylinder must consist of an optimum bias angle wrap. This bias angle wrap can be determined by developing the following model [17]:

$f = Pr/t \sin^2\theta$, where f is the force applied to the cylinder
P is the internal pressure against the cylinder
r is the inner radius of the cylinder
θ is the bias angle wrap from the longitudinal axis
and t is the thickness of the cylinder wall.

Let f_1 be the hoop stress and f_2 be the longitudinal stress, then:

$f_1 = f \sin^2\theta$ and $f_2 = f \cos^2\theta$

Now, let the hoop stress be equal to twice the longitudinal stress and solve for θ. The result shows that the optimum angle for reinforcement in both the hoop and longitudinal directions is 54.7°. By using this model it also shows that as the angle approaches 90° the composite can withstand greater hoop stress relative to longitudinal stress. When the angle approaches 0°, the composite can withstand greater longitudinal stresses.

Varying bias angles (between 0° and 90°) is a way that can add strength and stiffness to a composite in loading that is not in the direction of the reinforcement. When angles are varied from ply to ply, shear coupling must not be ignored, or significant deviations from predicted modulus calculations will occur [1]. The varying of bias angles

from ply to ply can also affect the predicted values of the strength. It has been recorded that as the angle is varied from 0° to ± 45° (the direction of load is in the 0° direction), the strain at failure is actually several times larger than what is predicted from corresponding unidirectional composites [1]. At greater angles the opposite is known to occur. A process must be developed which can produce a product with a bias angle wrap that promotes greater mechanical properties under several loading applications.

Chapter III. Experimental

Objective

The objective was to increase the understanding of the process by yielding defensible conclusions regarding its operation in achieving engineering structures possessing high mechanical properties. Products were made in order to study two process variables:

i.) the influence of the bias angle on the mechanical properties at a fixed total volume fraction of glass fiber and a fixed ratio of bias angle/radial wrapping, and

ii.) the influence of the volume fraction on the mechanical properties at a fixed bias angle and a fixed ratio of bias angle/radial wrapping.

In addition to these variables another feature of the process was examined. This was the effect of the slight alteration of the rotational velocity (which created a product that had a corrugated appearance rather than a smooth one at the same bias angle) on the mechanical properties.

Materials

The raw materials used in this experiment were glass fiber and polypropylene. The glass fiber was supplied by PPG in the form of rovings. This fiber was chemically treated by PPG for use with polypropylene. The main reason that glass fibers were used is because they have the following desirable inherent qualities:

- inexpensive
- isotropic, three dimensional structural network
- high tensile strength and modulus
- high chemical resistance

- The glass fibers used for this thesis had the following physical properties [3]:

- density 2.54 g/cm^3
- tensile strength 300,000 psi
- tensile modulus 12,000,000 psi

(It should be noted that the value for the tensile strength of the glass fiber was provided by PPG, and that this value is considerably lower than what is usually reported for glass. This value was determined by PPG, given the processing parameters and other data provided by the author.)

This Polypropylene also has desirable inherent characteristics which justifies its use:

- good chemical, moisture, and heat resistance
- inexpensive
- low density
- good flex life

The polypropylene used for this thesis had the following physical properties [18]:

- density 0.9 g/cm^3

- melting point 160-175 °C
- glass transition -20 °C
- extrusion range 200-260 °C
- tensile strength 4,500-6,000 psi
- tensile modulus 165,000-225,000 psi

(The values for the tensile strength and modulus of the polypropylene were determined by testing dogbone samples prepared from pellets of the resin. These test samples all behaved within the limits provided by Modern Plastics Encyclopedia [18]. Therefore, the limits provided by MPE were the values to be used in the analysis of the composite.)

Equipment

The equipment used in the development of this thesis was as follows:

- a laboratory scale extruder
- an aluminum fiber-wetting die
- a tensioner made of aluminum, brass, and rubber tubing
- an aluminum-based, brass-pin delivery eye
- a brass mandrel
- an aluminum heating block for the mandrel
- an approximate 20" long, 5/8" diameter lead screw and ball nut
- a base made of aluminum that supported the mandrel, the lead screw and ballnut, and the delivery eye
- two computer-driven stepping motors
- three temperature controllers
- a 386 microprocessor computer

Figure 5 shows a general block diagram of the experimental setup. Figures 6 and 7 show more detailed photos of the winding facility.

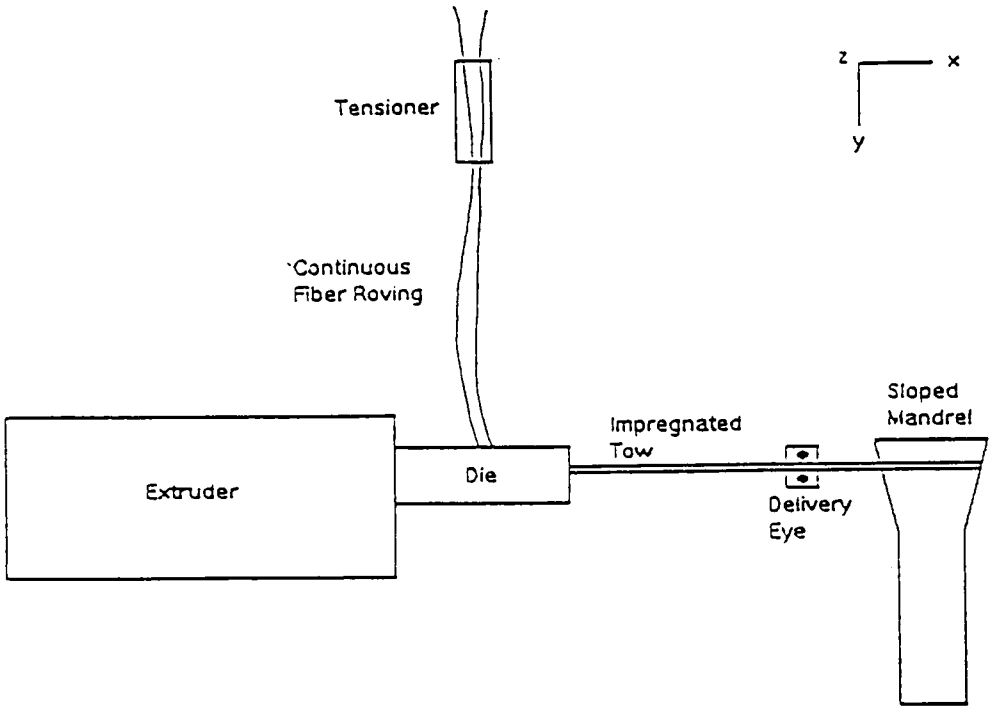


Figure 5. Overall Schematic of Thermoplastic Composite Winding Process

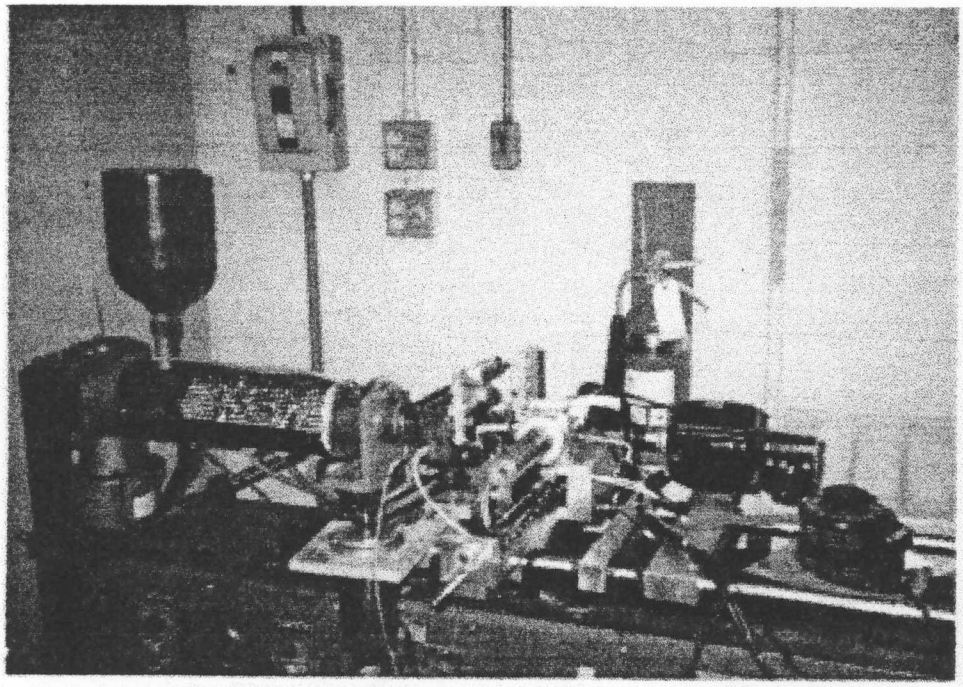


Figure 6. A Photograph of the Complete Winding Facility

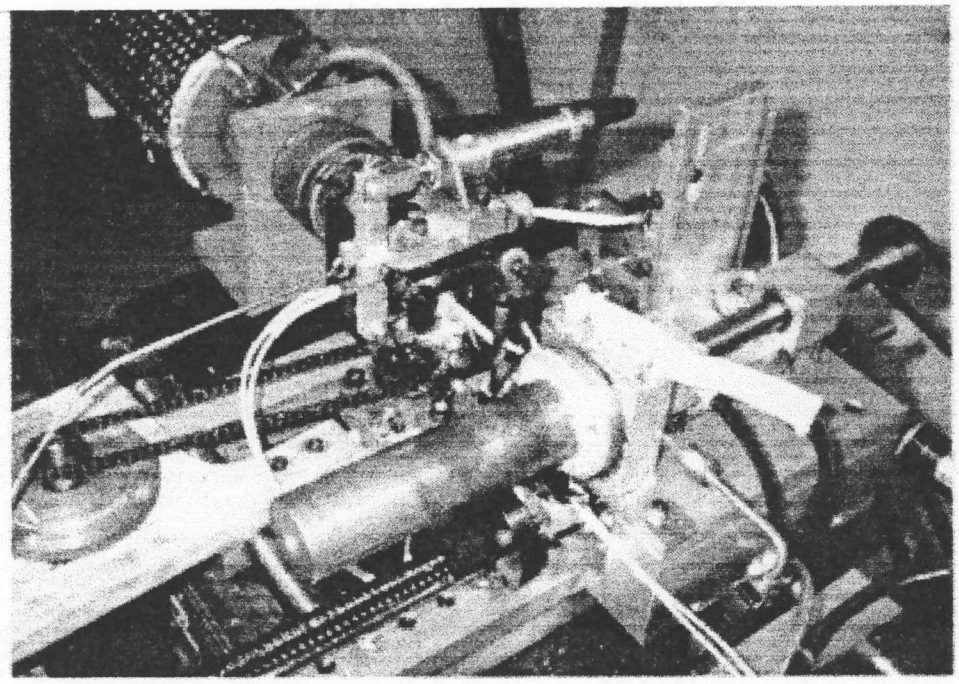


Figure 7. A Close-Up of the Mandrel, the Tensioner, and the Delivery Eye

Methodology

Computer-aided control was placed on the experimental setup. The computer controlled the action of the tensioner and the translating delivery eye. The speed of the mandrel was controlled by a DC controller that was manually adjusted to the desired RPM. The fiber bundle was fed through the tensioner where the computer-driven stepping motor would activate a brass plunger. This plunger would push the fiber bundle against a piece of rubber tubing while the bundle was being pulled in order to vary the tensioning force and periodicity. Once the fiber bundle went through the tensioner it proceeded to the fiber-wetting die. It was at this point that the tow was impregnated with polypropylene. The impregnated tow then proceeded through the delivery eye and onto the mandrel.

Tensioning was variably controlled to induce a translational movement in the composite product. This motion occurred because the increased tension would reach a value that promoted a slippage of the composite down the sloped portion of the mandrel. This velocity is a function of the mandrel's rotational velocity, temperature profile, slope, and the amount of tension in the tow. The delivery eye translational velocity and the rotational velocity of the mandrel were also controlled in order to explore the mechanical properties due to bias angle variations during the consolidation of the composite cylinder plies during winding.

One-hundred-stroke products were made for evaluation. A stroke consisted of one run of the program SLOWTRAN.BAS, which is found in the appendix. The steps involved in the production of a one-hundred-stroke tube are outlined below:

1.) All of the equipment was brought up to operating temperatures.

2.) The program TENSION.BAS, which is found in the appendix, was used repeatedly to apply a completely radial wrap to the entire mandrel before any translations were allowed to take place. This program allowed tensioning to be applied without any translations by the delivery eye.

3.) Once the mandrel was completely wrapped with product, the program, SLOWTRAN.BAS, was activated. This program applied a period of tensioning to the tow, followed by no applied tension and a delivery eye translation in the +y-direction. Then the delivery eye would travel in the -y-direction to complete one stroke and, therefore, one bias wrap.

4.) SLOWTRAN.BAS would continue on for ninety-nine more strokes. It would take approximately one hour for one hundred strokes to complete, yielding a product of ~29-39" long.

Three bias angles ($\pm\theta$) were used for the evaluation of the effect of the bias angle on the mechanical properties. (See Figure 8. for the orientation of the bias angle.) These bias angles were obtained by varying the rotational velocity of the mandrel from 11.8-24.2 RPM. The range of bias angles achieved was from 53-70°. Three volume fractions (V_f) of the 59° tube were used for the determination of the effect of the volume fraction on mechanical properties. The volume fraction of fiber was altered by making minute adjustments to the gate at the fiber exit of the wetter. The volume fractions used were 0.34, 0.37, and 0.46. In order to examine the process feature of corrugation, a corrugated tube was made with a bias angle of 59° at a volume fraction of 0.37, and compared against its smooth surfaced counterpart.

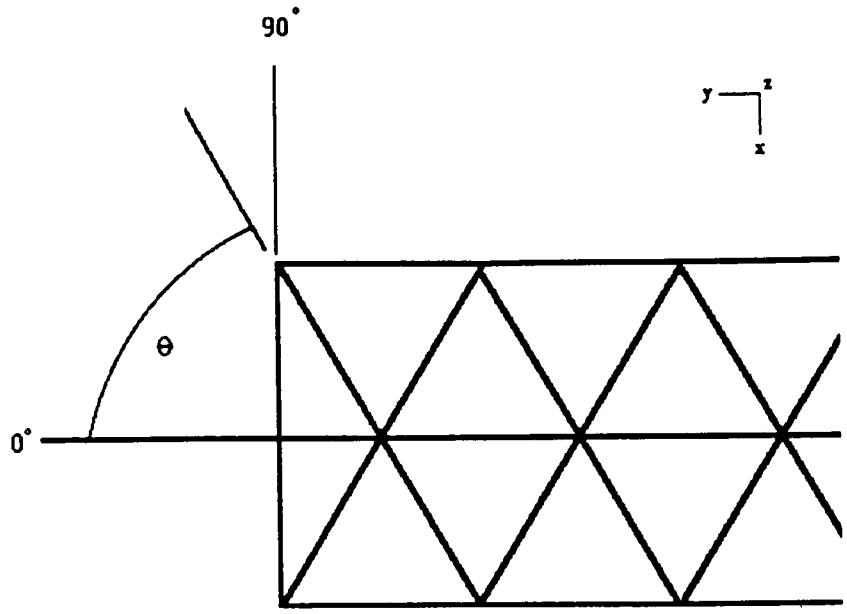


Figure 8. The Angle of Orientation in a Cylindrical Composite

Some additional important process constants include:

- mandrel dimensions:

length	6 3/8 in
diameter	1 3/4 in
degree of slope	~1-2°
length of slope	2 in

- distance from extruder die to point of contact on mandrel ~4 in
- delivery pin diameter 5/16 in
- delivery eye translational velocity ~1-2 in/sec
- delivery eye translation distance 5 3/8 in

Samples of the lamina were prepared by producing a flat tape. This tape was created by drawing the fiber bundle through the wetter and across only one delivery pin with no filament winding. The tape was then cut into five inch long (0.217" wide and 0.054" thick) specimens for the testing of lamina properties in the direction of fiber orientation. Another tape was produced to yield a tape that was as wide as possible for testing transverse to the fiber. This was done by cooling the tape with an air stream as it exited the fiber wetter. One inch long (0.478" wide and 0.013" thick) specimens were cut from this tape to test the lamina properties transverse to the fibers. Five samples were taken from each tape to study the mechanical properties of the lamina in both directions. These samples were taken at a 0.37 volume fraction.

Samples for the effects of the bias angles and the volume fractions on the mechanical properties were prepared by cutting sections from their respective tubes in the axial direction. These samples were cut into beams with a width of 1" and a length of 5". Fifteen samples were taken from composite tubes at a volume fraction of 0.37 at the three different bias angles. Ten samples from each angle were compression molded, while five were not post-formed. The compression molding took place by inserting the samples in a hydraulic press at 195 °C for 1/2 hour while under pressure. Samples were similarly created for the corrugated tube and the three tubes at 59°, whose volume fractions were 0.34, 0.37, and 0.46. For these samples only ten were created for each tube since only compression molded samples were needed.

Volume fractions of each tube were obtained by burning off the polymer from one inch wide cylindrical samples. One sample was taken from both ends of each tube by cutting them off radially. These samples were then placed in an oven at 550 °C for four

hours. The volume fractions were calculated by using before and after composite weights and the densities of the polymer and glass. These fractions had a deviation of $\pm$ 0.01.

Uniaxial tensile testing and four-point bending tests were performed on all sample specimens by using an Instron testing machine. The test methods were derived from accepted ASTM standards. The established ASTM standards that were used as a guideline were ASTM D 638 and ASTM D 790 [19]. The grips of the Instron were such that special care needed to be taken in the mounting of the lamina samples. All of the lamina samples needed to be altered in order to be used in the mechanical grips. The sample edges were treated with molten polypropylene in order to deter the grips from cutting through the samples. The remainder of the tensile samples were gripped by merely clamping down on their ends. All of the samples tested in tension had a 3 inch gage length except for the lamina that was tested transverse to the fibers. Due to the size of this sample the gage length was 0.25 inches. The four-point loading testing was done with a 4 inch span length and a 1.33 inch load length. All samples were centered with the loading axis and allowed to lay against the lower loading points with the bias wrap facing down.

These testing procedures yielded values for the tensile and flexural strength, as well as the tensile and flexural moduli of all specimens. The results from these tests were used in determining the effect of the bias angle, the volume fraction, and the feature of corrugation on the mechanical properties of the tubes. This examination provided logical conclusions that lead to an understanding of the production of polypropylene-glass composite cylinders with high mechanical properties.

Chapter IV. Results and Discussion

The Relationship Between the Mandrel and Translational Velocities

The mandrel velocity and the delivery eye translational velocity play a key role in the processing of the composite cylinders. These two velocities are related to one another and to the bias angle, θ. The relationship of the delivery eye translational velocity to the mandrel rotational velocity is given by the following equation:

(1) $\tan\theta = (2\pi \bullet R \bullet \omega)/V$,where R is the radius of the mandrel,
ω is the rotational velocity of the mandrel,
and V is the translational velocity of the delivery eye.

The translational velocity of the delivery eye was ~1.2 in/sec. This velocity was left unchanged because of equipment limitations. It was the fastest obtainable speed for the system. The rotational velocity of the mandrel was altered to yield products with different bias angles. The best three velocities for ω were determined to be 11.8, 18.1, and 24.2 RPM. These velocities were chosen because they developed products that were consistent in laying down the tow in a particular manner. This manner was one in which the impregnated tow wound onto the mandrel by laying as close to the previous tow as possible without causing an overlap. If an overlap of the tow line had begun, the speed of the mandrel had to be adjusted to correct this. An overlap caused the product to build a "ridge" over time. This "ridge" gave the tube a corrugated, spiral appearance which increased as the tube production continued. Over time the tube no longer appeared to be a constant diameter cylinder, which was the desired product for this study.

The velocity outer limits were the minimum and the maximum limits of operation. Any velocity that was lower than 11.8 RPM would not allow the tow to be wound onto the mandrel without having an excess of slack in the line. This slack would cause the product to lose its uniformity, and, therefore, produce unacceptable piping. Any velocity that was higher than 24.2 RPM would cause excessive fiber damage and insufficient wetting. This occurred because the fiber line was being pulled too fast through the fiber wetter. Products that were made at faster rotational velocities were consistently longer than for slower speeds. This happened because the amount of tension in the system increased and caused a higher degree of product slippage. However, this slippage was not great enough to overcome the amount of fiber per unit time, thus, these products had an increased wall thickness also. The dimensions of the tubes produced are shown in Table IV.

Table IV. Product Thicknesses and Lengths

RPM	Average Thickness [in]	Average Length [in]
11.8	~1/16	29
18.1	~1/8	35
24.2	~3/32	39

Adhesion and Cohesion

The degree to which the matrix adhered to the fibers was determined by taking experimental tensile measurements and comparing them to the rule of mixtures. The experimental measurements were performed on a polymer impregnated tape that was

subjected to two separate loading conditions. The tape was loaded in the direction of fiber reinforcement and transversely to the fiber direction. This tape was considered to be representative of a single lamina in the composite structure. Figures 9 and 10 show the mechanical response for the tape under both loading conditions. The experimental results are compared to the theoretical values in Table V. Individual test results and standard deviations are located in the appendix.

Table V. The Rule of Mixtures vs. Experimental Values for a Single Lamina at a Fiber Volume Fraction of 0.37

	Rule of Mixtures [longitudinal]	*Experimental [longitudinal]*	*Rule of Mixtures [transverse]*	*Experimental [transverse]*
Strength [psi]	114,000	78,200	5,250	154
Modulus [psi]	4,560,000	3,380,000	307,000	1,650

The lamina that was tested in the fiber direction yielded a strength value that was 68% of the theoretical value, and a modulus that was 74% of the theoretical value. This may be partially attributed to the damage to the fibers during processing and in handling in general. The fibers that were already broken in the lamina before testing represented areas where cracks began. It is postulated that these cracks were initially blunted by the matrix which reduced the value of the modulus. As the stress rose, the matrix could no longer support the load, and the interface failed at a critical stress value. When the interface failed there was no longer a sufficient way for the stress to be transferred between the fibers, and individual fibers began to fracture. The lamina never fractured entirely. Once enough of the fibers fractured to cause an unloading, the test stopped.

The lamina that was tested in transverse loading did not hold up to much loading at all. It was noted that all of the samples had several voids in them when placed under a microscope before testing. These voids were merely breaks in the continuity of the

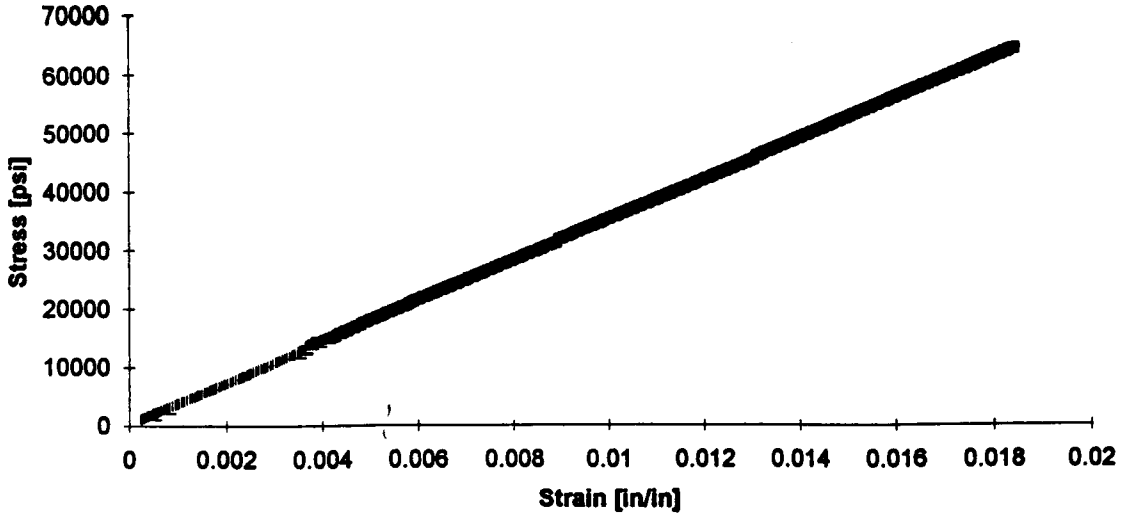


Figure 9. A Typical Stress-Strain Diagram for a Lamina Tested in Longitudinal Tension

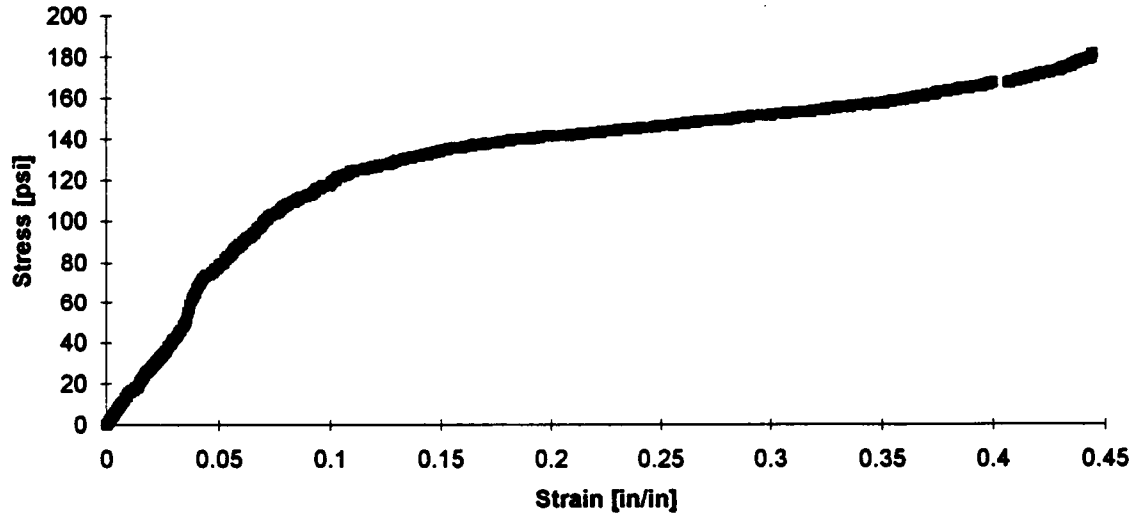


Figure 10. A Typical Stress-Strain Diagram for a Lamina Tested in Transverse Tension

polymer that appeared as holes when light was passed through the sample. These voids played a significant role in the reduction of the modulus. They made the samples less rigid by increasing the flexibilty of the material due to the reduction of continuous polymer segments. These holes (flaws) also generated a large stress concentration around them. The load at which failure can occur is highly dependent on the length of the cracks in the material ($\sigma_{failure} \propto 1/(\text{crack length})^{0.5}$ [17]). The fracture of the material is controlled by the longest crack. The longer the crack, the less stress required to cause a failure. Although these holes cause stress concentrations that may lead to premature failure, it is more likely that these samples failed because of another factor. The reasoning behind this is because of the large difference in the rule of mixtures strength when compared to the experimental strength in the transverse direction. The visible voids were not long enough to cause a failure at such a low stress. The transverse samples were very difficult to load because of the short gage length used. This difficulty in loading could have placed cracks along the samples that were undetected by the naked eye moments before testing. These cracks could have been put into the sample at a length that would be sufficient to cause a failure at under 200 psi.

The cohesion of the laminas in the formation of the composite was examined by placing samples of all three bias angle cylinders in tension. Samples that had no post-forming were compared against samples that were compression molded after production. It was found that samples from all bias angles benefited in improved mechanical properties due to compression molding. Figures 11. through 13. display the comparisons of these samples for each angle. All of the compression molded samples had higher modulus values and broke at higher stresses than the samples that were not post-formed. Post-forming improved the response of the samples by removing some of the voids, and by allowing the laminas to bond more efficiently.

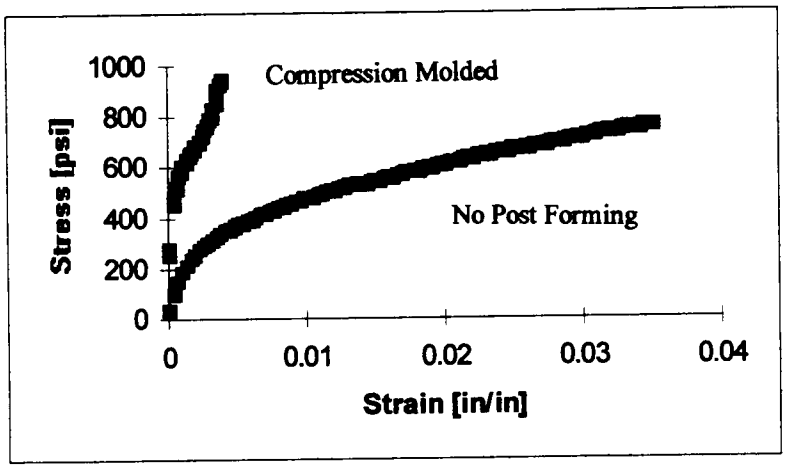


Figure 11. The Tensile Properties of a Typical 54° Compression Molded Sample Compared to a Non-Post-Formed Sample at a 0.37 Volume Fraction

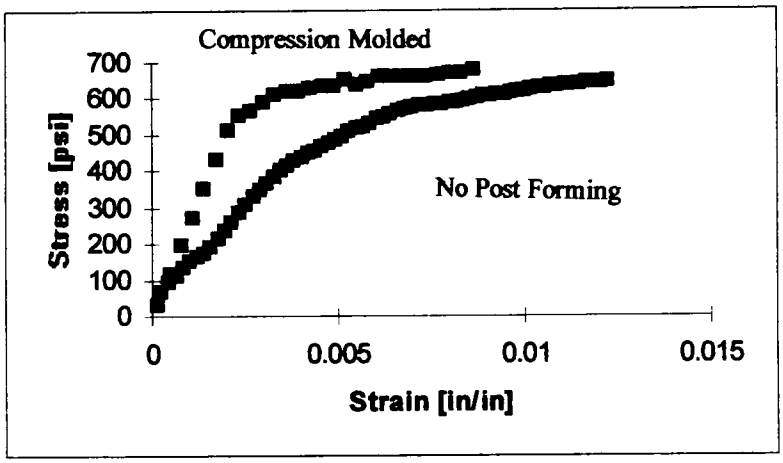


Figure 12. The Tensile Properties of a Typical 59° Compression Molded Sample Compared to a Non-Post-Formed Sample at a 0.37 Volume Fraction

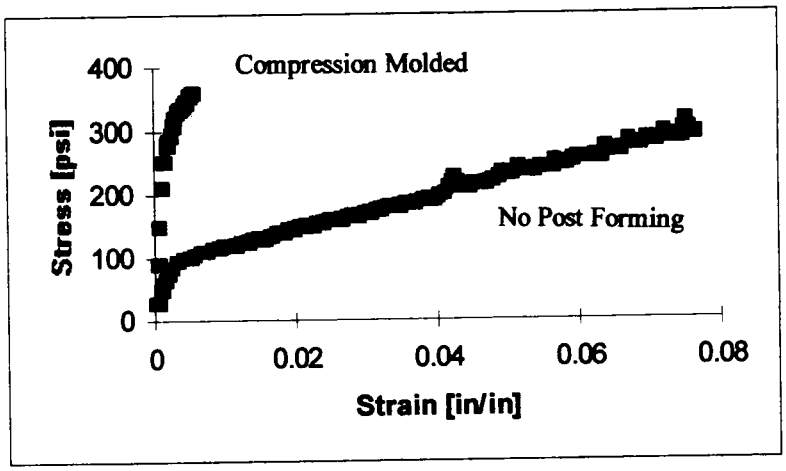


Figure 13. The Tensile Properties of a Typical 69° Compression Molded Sample Compared to a Non-Post-Formed Sample at a 0.37 Volume Fraction

A three-ply model was used that predicted the strength and the modulus for the laminate using data from the rule of mixtures and the lamina analysis [20]. These values are tabulated in Table VI. Individual test results and standard deviations are located in the appendix.

(2) $$N_y = \int_{-h/2}^{h/2} \sigma_y dz$$

N_y is the resultant force in the testing direction,

h is the thickness of the composite, and

σ_y is the stress in the testing direction for each lamina.

(3) $E_y = (A_{11}A_{22}-A_{12}^2)/hA_{22}$

E_y is the modulus in the testing direction

and $$A_{ij} = \sum_{k=1}^{n}\left(\frac{\cos^4\theta}{E_L}+\frac{\sin^4\theta}{E_T}+0.25\left(\frac{1}{G_{LT}}-2\frac{\upsilon_{LT}}{E_L}\right)\sin^2 2\theta\right)^{-1}\left(h_k-h_{k-1}\right)$$

E_L, is the modulus of the lamina in the fiber direction,

E_T is the lamina modulus transverse to the fiber,

G_{LT} is the shear modulus of the lamina, and

υ_{LT} is the poisson's ratio of the lamina in the fiber direction.

Table VI. The Tensile Results for the Three-Ply Model Compared to Experimental Results at a Fiber Volume Fraction of 0.37

	Rule of Mixtures		Theoretical Results from Lamina		Experimental from Compression Molded Samples	
Bias Configuration	*Strength [psi]*	*Modulus [psi]*	*Strength [psi]*	*Modulus [psi]*	*Strength [psi]*	*Modulus [psi]*
54°	3,330	782,000	2,280	3,900	1,130	535,000
59°	2,560	621,000	1,750	3,080	1,070	254,000
69°	1,250	452,000	856	2,180	638	198,000
Corrugated	-	-	-	-	428	94,000
Radial	-	-	-	-	134	20,000

The mechanical property predictions based on the rule of mixtures are comparatively higher than the experimental results. The compression molding obviously could not remove all of the voids and assure perfect cohesion between plies, and this is strong evidence of that. The rule of mixtures also has an inherent flaw in the prediction of properties transverse to the fiber direction. This problem is that the stresses are not equal across the composite, resulting in values being predicted to be larger than what is actually occurring. This uneven stress distribution happens because of the less-than-uniform fiber distribution. Another observation made in regards to this theoretical prediction is how the experimental values vary more widely from the model at lower bias angles. It is postulated that the cause of this is due to increased interlaminar shear. Interlaminar shear will reach a maximum at 45° in the laminate. Since the bias angles in this experiment were all larger

than 45°, it is reasonable to assume that the interlaminar shear stress will increase as the angle approaches 45°, and, thus, contribute to a cohesive failure between plies.

The Influence of the Bias Angle

Table VII. Outlines the range of bias angles used in production.

Table VII. Theoretical and Actual Bias Angles Obtained During Production for Given Velocities of the Mandrel

RPM	*Theoretical θ*	*Actual +θ/-θ*
11.8	41°	53/55°
18.1	53°	58/60°
24.2	61°	68/70°

The +θ indicates the bias angle when the delivery eye was translating in the +y-direction. Likewise, the -θ indicates the bias angle when the delivery eye was translating in the -y-direction.

It is noticed from this table that the actual values for θ did not match the theoretical values, and that these actual θs were even different from each other depending on the direction of the delivery eye travel. The reason that products did not match the theoretical values was that there was a drag on the impregnated tow during winding. When the fiber line was being wrapped with a bias angle, the line was being dragged across existing product. This drag did not allow the angle of wrap to get to the lower theoretical value because it pulled the product, and did not allow the line to slide against the tube.

The reason that the actual angles were different from each other was because the product velocity also had an influence on the translational velocity, V, in equation (1). As the delivery eye translated in the +y-direction, the product velocity added to V causing a smaller θ. Conversely, as the delivery eye translated in the -y-direction, the product velocity was subtracted from V causing a larger θ. The actual values of the bias angles were averaged to be used in the analysis of the mechanical properties. Thus, the three experimental bias angle wraps were 54°, 59°, and 69°. The 54° tube was considered to be the optimum angle for reinforcement in both the hoop and longitudinal directions that was mentioned earlier. This angle was consistent with the model in keeping the ratio of hoop stress to longitudinal stress near 2:1 (The actual ratio was 1.9:1 for 54°.).

The tubes that were used to determine the effect of the bias angle on the mechanical properties were produced with a fiber volume fraction of 0.37 ± 0.01. Table VI. shows the experimental data for the tensile properties of all the bias angles at this volume fraction. There was a drastic improvement in all cases over the radial wrapping. The strength increased by as much as a factor of eight, while the modulus was as much as twenty-six times higher. Figure 14. is an interesting graph for a comparison between the angles. In this graph the lowest bias angle proved to yield a product that was more brittle and stronger than the other two angles. All of the angles proved to have increasing mechanical properties as the angle decreased. Flexural data was also obtained and proved to be in agreement with the tensile data (See Table VIII.). Mechanical data from a uniaxial flexure test is generally higher than for tensile testing. This is because the flexure test concentrates the load over a much smaller volume, thus, producing a higher local strength [17]. This area is the distance between the loading pins in a four-point loading test. Therefore, flexure testing is a good test for quality control and comparisons to tensile measurements, but should not be used for design calculations.

Table VIII. The Flexural Properties for Samples at Different Bias Angles and a Fiber Volume Fraction of 0.37

Bias Angle	*Strength [psi]*	*Modulus [psi]*
54°	3,450	796,000
59°	2,060	488,000
69°	1,040	283,000
Corrugated	470	133,000

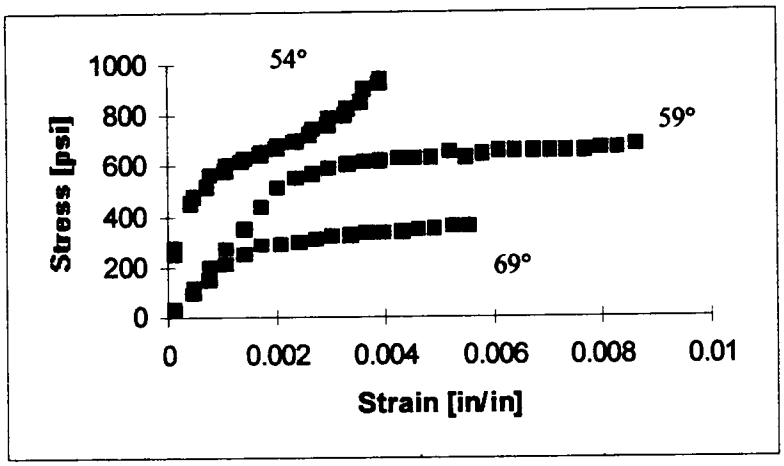


Figure 14. The Tensile Properties of the Compression Molded Samples of all Three Bias Angles at a 0.37 Volume Fraction

The samples all behaved similarly when the nature of their deformation was considered. They had a high initial modulus then they all underwent some type of yielding before fracture. This yielding was caused by the cohesive failure that was observed during experimentation. As the products were strained, the outer ply began to delaminate from the composite. Once the instron unloaded, it was noticed that the sample had not fractured at the inner radial wrap. The fracture was cohesive at the outer layer, followed by random

fiber breakage. This cohesive yielding occurred because of the interlaminar shear stress that was mentioned earlier. The interlaminar shear stress is also magnified because the bias angles were not the same in both directions. The laminate was unbalanced, which will cause an increase in shear coupling.

The feature of corrugation was examined at a bias angle of 59°. The mechanical property values obtained for these pipes were compared against those for the smooth-surfaced pipe. The corrugated samples were made by slightly increasing the mandrel rotational velocity for a smooth-surfaced 59° pipe. This caused the overlap that produced ridges along the length of the cylinder. The mechanical properties of the corrugated samples are listed in Table VI. and VIII., and the tensile data is compared graphically against the regular samples at 59° in Figure 15.

The corrugated samples had a much lower modulus and strength than the regular samples at the same angle and volume fraction. These samples behaved more like the radial samples than the bias angle wraps. The reason for this behavior was because in the corrugated samples there is less continuity at each ply. The tape is overlapped over the previous wrap instead of being laid next to it. Without the tape cohering to the previously laid tape to produce a uniform ply, the product loses a lot of its mechanical characteristics. When stress was applied to the corrugated samples there were breaks in the inner radial wrap as much as there were breaks in the outer bias wrap. This was evidence that the bias wrap was not performing as satisfactorily as the smooth-surfaced bias wraps.

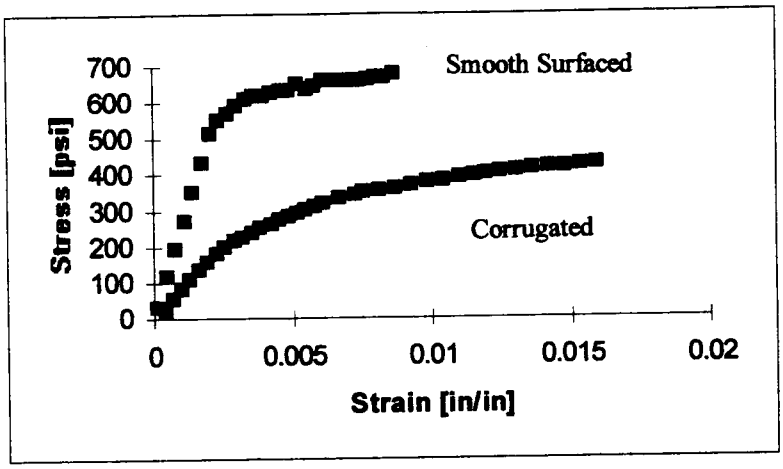


Figure 15. The Tensile Properties of a Typical Corrugated Sample Compared to a Smooth-Surfaced Sample at a Bias Angle of 59° and at a 0.37 Volume Fraction

The Influence of the Fiber Volume Fraction

The volume fractions of the 59° cylinder were compared to determine the effectiveness of the fiber volume on the mechanical properties. The experimental results due to the variation of the fiber volume fraction are presented in Table IX. When these results were compared with their respective standard deviations, it was determined that the fiber volume fraction was not a controlling factor in regards to the mechanical properties of the products in this experiment. The strength and modulus for all fiber volume fractions did not appear to vary significantly from one sample to the other. This conclusion is not consistent with the rule of mixtures.

The fiber volume fraction was varied in a rather crude fashion. In order to increase V_f, polypropylene was "squeezed out" at the fiber exit by the gate. Conversely, V_f was decreased by opening this gate to allow more polypropylene to adhere to the tow. It is

postulated that this method did not provide the control needed to produce a tape that had uniformly distributed fibers with good adhesion to the matrix.

When the polymer is "squeezed out" in this manner, the gate compresses on the tow producing a flatter tape. This does not produce a tape that has a controlled distribution of fibers throughout the lamina. Fibers were noticed to bunch up near the edges of the lamina, producing areas where there was a non-uniformity in fiber distribution. This distribution could cause problems with the matrix being able to transfer the load effectively throughout the entire fiber bundle. These edges also represent areas where wetting may be reduced because the fibers are not continuing to fan out smoothly. Inadequate wetting will also hinder the effective transfer of loading throughout the bundle. In addition to these concerns there is also the possibility of fiber damage due to the abrasion of the gate. This fiber damage, coupled with the above mentioned problems, would significantly lower the expected mechanical values due to an increase in fiber volume fraction.

The reduction of the fiber volume fraction was done in such a way that there could be numerous problem areas. Much like the case for increasing V_f, there are the problems of non-uniformity and wetting in the analysis of decreasing V_f. When polypropylene is dumped on the tow, there is no way to work the polymer throughout the tape to assure good wetting and fiber distribution. Another factor in this case is the notion of voids. There should be numerous voids in this tow because the polymer is allowed to adhere to the tow by dragging the fibers through the bath. There are no types of significant compaction in the process to remove these voids from the tape. These voids represent areas of stress concentration that can promote crack growth and/or reduce the adhesion of the fibers to the matrix.

The problem of effective fiber volume control needs to be addressed before an accurate evaluation of its influence on mechanical properties can be attempted. The method in which the fiber volume was controlled needs to be revamped in order to account for the trouble areas of fiber distribution uniformity, adhesion, fiber damage, and voids.

Table IX. The Mechanical Properties for the 59° Samples at Different Fiber Volume Fractions

	Tensile Properties of Compression Molded Samples		Flexural Properties of Compression Molded Samples	
Volume Fraction	*Strength [psi]*	*Modulus [psi]*	*Strength [psi]*	*Modulus [psi]*
0.34	973	117,000	1,060	235,000
0.37	1,070	254,000	2,060	488,000
0.46	1,010	289,000	1,860	491,000

Chapter V. Conclusions

1. The mechanical properties of composites that underwent uniaxial testing increased as the bias angle decreased. This occurred because the fibers were oriented in the direction of the applied stress more at the lower angles. The highest mechanical properties were achieved for the 54° bias angle. For a fiber volume fraction of 0.37, the tensile strength of this composite was 1,130 psi, and the modulus was 535,000 psi.

2. Corrugation did not produce a uniform bias ply, therefore, giving areas where there was radial wrap only. These areas of pure radial wrap significantly reduced the mechanical properties of the composite samples.

3. The strength and modulus for fiber volume fractions of 0.34, 0.37, and 0.46 did not appear to vary significantly from one sample to the other. When these results were compared with their respective standard deviations, it was determined that the fiber volume fraction was not a controlling factor in regards to the mechanical properties of the products in this experiment. This was attributed to the inability of the system to deliver a quality tape with an even fiber distribution, good adhesion, minimal fiber damage, and low voids at the required fiber volume fractions.

Chapter VI. Recommendations for Future Work

There are a few areas that were left unresolved by this study, and they should be expanded on in future work. First, the adhesion of the fibers to the matrix should be examined more closely. It needs to be determined exactly what mode of failure is causing unsatisfactory performance. Scanning Electron Microscopy (SEM) micrographs would be an invaluable tool in this analysis. By looking at regions of fracture, it could be determined how the fracture ensued. The categories of relevant fracture include: 1. The fiber debonding from the matrix because of poor interfacial adhesion. 2. The fiber breaking in brittle failure due to its own low strength. 3. Microcrack propagation of the matrix because of a good interface and strong fiber. 4. Delamination of the individual lamina from each other due to cohesive failure. Testing situations, such as the fiber pullout and interlaminar shear strength testing methods, could be performed in this evaluation.

Another important factor that SEM could help identify is the void content. Micrographs could show to what extent voids are present, and how these voids aid in the failure of the samples. As mentioned in an earlier chapter, the voids represent areas of high stress concentration that can promote crack growth. This growth can then test the quality of the interfacial adhesion earlier than anticipated in the life of the composite. By examining the adhesion quality and void content of the samples more closely, one could then try to minimize there negative influence on the mechanical properties of future products.

A second area for future work involves the improvement of the fiber volume fraction control of the process. The simplest change could involve the use of prepregs in order to eliminate this problem. This, however, is similar to merely putting a band-aid the problem. It would be more ambitious to develop a new wetting technique. A wetting technique needs to incorporate the action of the fiber bundle from its point of origin (the spool) all the way to the exit of the fiber wetter. The more control that is placed on the action of the fibers themselves, the better their placement will be in the matrix. Also, the impregnation of the fibers with the matrix must be done in a more precise way such that a high quality of adhesion is assured. This may be done by using different styles of exit gates along with some type of post compaction to aid in the removal of voids and assure better wetting.

Finally, as the product's processing is improved, several different types of mechanical testing should be involved. Testing of the specimen as a whole must be done (i.e. testing of a cylinder not just a flat section). Tensile and flexural tests of cylinders as a whole would be an excellent staring position. Torsion testing could also be done in order to test the in-plane shear strength of the cylinders. Longitudinal and hoop compression testing could then be performed on the cylinders to assure their use in buried pipe applications. Another important mechanical test would be fracture-toughness evaluation. This would consist of placing a notch in the sample followed by applying a tensile or flexural force. This test would determine the composite's ability to withstand crack propagation.

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APPENDIX

```
'THIS IS THE SLOW TRANSLATING PROGRAM [1.2 IN/SEC] : SLOWTRAN.BAS.

'WRITTEN BY JAY SAYRE - SPRING 1996.

DECLARE SUB TENSION ()
CLS
TIMER ON
BEGINNING = TIMER

INPUT "NUMBER OF BALL NUT STROKES"; S

P = 10000
P2 = 10000

CALL TENSION

OUT &H378, &H2
FOR I = 1 TO P
NEXT I

FOR J = 1 TO S

                T = TIMER
                FOR I = 1 TO 15
                OUT &H378, &H3
                OUT &H378, &H2
                        FOR K = 1 TO 5
                        NEXT K
                NEXT I

                FOR I = 1 TO 4500
                OUT &H378, &H3
                OUT &H378, &H2
                        FOR K = 1 TO 1
                        NEXT K
                NEXT I
                T2 = TIMER

                OUT &H378, &H0
                FOR I = 1 TO P2
                NEXT I

                T3 = TIMER
                FOR I = 1 TO 15
                OUT &H378, &H1
                OUT &H378, &H0
                        FOR K = 1 TO 5
                        NEXT K
                NEXT I

                FOR I = 1 TO 4500
                OUT &H378, &H1
                OUT &H378, &H0
                        FOR K = 1 TO 1
                        NEXT K
                NEXT I
                T4 = TIMER
                CALL TENSION

                OUT &H378, &H2
```

```
                FOR I = 1 TO P
NEXT I

PRINT ""
PRINT "STROKE NUMBER "; J; " COMPLETED"
PRINT T2 - T; " SECONDS TAKEN FOR THE 1/2 STROKE AWAY FROM THE MANDREL BASE"
PRINT T4 - T3; " SECONDS TAKEN FOR THE 1/2 STROKE TOWARDS THE MANDREL BASE"

NEXT J

OUT &H378, &H0

ENDING = TIMER

CLS
PRINT " IT TOOK "; (ENDING - BEGINNING) / 60; " MINUTES TO COMPLETE THIS RUN."

BEEP
END

SUB TENSION

OUT &H378, &H0
FOR I = 1 TO 10000
NEXT I

FOR J = 1 TO 5

        FOR I = 1 TO 15
        OUT &H378, &H4
        OUT &H378, &H0
                FOR K = 1 TO 1
                NEXT K
        NEXT I

        OUT &H378, &H8
        FOR I = 1 TO 7500
        NEXT I

        FOR I = 1 TO 15
        OUT &H378, &HC
        OUT &H378, &H8
                FOR K = 1 TO 1
                NEXT K
        NEXT I

        OUT &H378, &H0
        FOR I = 1 TO 7500
        NEXT I

 NEXT J

 END SUB
```

```
'THIS IS THE TENSIONING PROGRAM : TENSION.BAS.

'WRITTEN BY JAY SAYRE - SPRING 1996.

DECLARE SUB TENSION ()
CLS
CALL TENSION
BEEP
END

SUB TENSION

OUT &H378, &H0
FOR I = 1 TO 10000
NEXT I

FOR J = 1 TO 50

        FOR I = 1 TO 15
        OUT &H378, &H4
        OUT &H378, &H0
                FOR K = 1 TO 1
                NEXT K
        NEXT I

        OUT &H378, &H8
        FOR I = 1 TO 7500
        NEXT I

        FOR I = 1 TO 15
        OUT &H378, &HC
        OUT &H378, &H8
                FOR K = 1 TO 1
                NEXT K
        NEXT I

        OUT &H378, &H0
        FOR I = 1 TO 7500
        NEXT I

 NEXT J

 END SUB
```

Individual Test Data and Standard Deviations

Run	Bias Angle [in degrees]	Volume Fraction	Tensile Strength [psi]	Tensile Modulus [psi]	Flexural Strength [psi]	Flexural Modulus [psi]
1	transverse tape	0.37	102	2,050	-	-
2	transverse tape	0.36	123	1,150	-	-
3	transverse tape	0.37	178	1,430	-	-
4	transverse tape	0.38	145	1,820	-	-
5	transverse tape	0.37	207	1,800	-	-
Average	transverse tape	0.37±0.01	154±42	1,650±357	-	-
1	longitudinal tape	0.36	78,000	3,010,000	-	-
2	longitudinal tape	0.36	73,200	3,560,000	-	-
3	longitudinal tape	0.37	80,100	3,330,000	-	-
4	longitudinal tape	0.38	76,500	2,960,000	-	-
5	longitudinal tape	0.37	83,200	3,830,000	-	-
Average	longitudinal tape	0.37±0.01	78,200±3,760	3,338,000±368,000	-	-
1	54	0.37	1,280	591,000	3,850	865,000
2	54	0.36	1,150	518,000	3,230	768,000
3	54	0.37	1,190	526,000	3,430	806,000
4	54	0.36	1,240	542,000	3,620	812,000
5	54	0.38	790	498,000	3,120	729,000
Average	54	0.37±0.01	1,130±196	535,000±35,100	3,450±294	796,000±51,000
1	59	0.36	986	226,000	1,820	423,000
2	59	0.37	999	232,000	1,960	466,000
3	59	0.38	1,055	257,000	2,020	502,000
4	59	0.37	1,110	269,000	2,120	512,000
5	59	0.37	1,200	286,000	2,380	537,000
Average	59	0.37±0.01	1,070±88	254,000±25,100	2,060±209	488,000±44,400
1	69	0.37	496	182,000	889	229,000
2	69	0.36	554	197,000	911	265,000
3	69	0.37	669	195,000	1,010	296,000
4	69	0.36	685	206,000	1,210	298,000
5	69	0.38	786	210,000	1,180	327,000
Average	69	0.37±0.01	638±114	198,000±10,100	1,040±149	283,000±37,300
1	corrugated	0.36	434	85,400	468	88,600

2	corrugated	0.37	378	88,700	412	138,000
3	corrugated	0.38	385	89,600	456	132,000
4	corrugated	0.37	407	96,300	489	146,000
5	corrugated	0.37	536	110,000	525	160,000
Average	corrugated	0.37±0.01	428±64	94,000±9,780	470±42	133,000±27,000
1	radial	0.37	98	16,400	-	-
2	radial	0.36	105	18,600	-	-
3	radial	0.37	128	21,000	-	-
4	radial	0.38	145	21,700	-	-
5	radial	0.37	194	22,300	-	-
Average	radial	0.37±0.01	134±38	20,000±2,450	-	-
1	59	0.34	764	101,000	854	209,000
2	59	0.33	962	116,000	996	211,000
3	59	0.34	989	124,000	1,110	221,000
4	59	0.34	1,130	116,000	1,080	266,000
5	59	0.35	1,020	128,000	1,260	268,000
Average	59	0.34±0.01	973±133	117,000±10,300	1,060±150	235,000±29,600
1	59	0.46	611	229,000	1,230	442,000
2	59	0.46	999	266,000	1,860	488,000
3	59	0.47	1,010	286,000	1,880	490,000
4	59	0.45	1,210	299,000	1,990	512,000
5	59	0.46	1,220	365,000	2,340	523,000
Average	59	0.46±0.01	1,010±247	289,000±50,000	1,860±401	491,000±31,100

Vita

Jay Sayre was born on August 7, 1971 in Bellaire, Ohio. He attended public school in the St. Clairsville school district in St. Clairsville, Ohio. He attended Virginia Polytechnic Institute and State University in Blacksburg, Virginia from August of 1989 until May of 1995. It was here that he earned a Bachelor of Science degree in Chemical Engineering. During his stay at Virginia Polytech, he was employed as a co-op student at E.I. DuPont de Nemours in Martinsville, Virginia. Upon graduation, Jay entered the M.S. Polymer Engineering program at the University of Tennessee in Knoxville, Tennessee. The Master of Science degree was received for his work in composite processing in May of 1997. Jay and his wife, Kara, are currently residing in Blacksburg, Virginia with their black Lab, Jesse. He is pursuing his Doctorate in Materials Engineering Science at Virginia Polytechnic Institute and State University, where he is continuing his work in polymer composite processing.