ADVANCES IN VACUUM INFUSION PROCESSING USING SPACER FABRICS AS ENGINEERED REINFORCING INTERLAMINAR INFUSION MEDIA[1]

Patrick E. Mack, CCT and Mitchell D. Smith
Verdant Technologies, Inc.
East Providence, Rhode Island

ABSTRACT

The US Environmental Protection Agency is expected to finalize standards for Maximum Achievable Control Technology that once promulgated could significantly restrict capacity[2]. While it is lobbying the EPA and Congress for more lenient regulations, the FRP industry is strongly encouraging manufacturers to change from open-mold to cleaner, more efficient closed-mold processes such as vacuum infusion. However, processing limitations of available technology, such as incomplete/slow infusion, uneven distribution/pooling of resin, long set-up time, and material waste has hampered this transition. Interlaminar infusion technology, and in particular the application of three-dimensional spacer fabrics as engineered reinforcing infusion media, addresses these processing concerns. This paper will discus the various applications of three-dimensional spacer fabrics to vacuum infusion processing through practical examples ranging from sporting goods to aerospace.

KEY WORDS: Vacuum Infusion, Core Materials, Advanced Composites

1. INTRODUCTION

The US Environmental Protection Agency (EPA) is expected to finalize standards for Maximum Achievable Control Technology that once promulgated could significantly restrict capacity in the fiber reinforced plastics (FRP) industry. While it is lobbying the EPA and Congress for more lenient regulations, the FRP industry is strongly encouraging manufacturers to change from open-mold to cleaner, more efficient closed-mold processes.

However, much of the composites industry literature and advertising concerning “affordable” or “low-cost” closed mold processes are based on an aerospace perspective. The price point established by the current commercial manufacturing of composite is very low compared with aerospace structures, particularly for composites with relatively demanding structural design considerations, such as wind turbine blades and marine applications. These price points have been realized within the industry through substantial fine-tuning of the current open mold manufacturing methods, and are based on well-established properties and performance for the baseline materials and structural designs.

Primary figures of merit establishing the metrics by which a commercial manufacture evaluates process conversion include: reduced weight (efficiency and mechanical properties of laminates, use of lower-density materials, efficiency of structural design), reduced cost (efficiency of material use, processing and manufacturing methods that minimize labor), and improved structural properties (fatigue properties of structural laminate, ply drops and other details, processes that increase reliability of fiber placement, orientation, and laminate composition). Although closed-mold processing is generically thought to rank well on these factors, for many emerging technologies, such as low-temperature pre-pregs, resin film infusion, and resin transfer molding, the thrust of development has been toward addressing the complex shapes, tolerances, and quality control requirements of aerospace-type applications, while reducing labor, material waste, and other costs. By comparison, manufacture of commercial composites involves high material volumes but only moderate shape complexity and tolerance requirements and relatively simple fiber architecture. Therefore, many emerging technologies that show substantial benefits for fabrication of aerospace structures have tolerance and part complexity capabilities that are under-utilized in commercial applications, and as a result, the production costs for these structures are prohibitively high [1].

It is possible that derivative closed mold technologies optimized for the requirements of the commercial marketplace could provide substantial benefits in labor and part quality while satisfying the need for reduced emissions. Vacuum infusion, often referred to as vacuum assisted resin transfer molding (VARTM), is generally thought to be representative of such a technology. However, limitations inherent to current trends in vacuum infusion processing have somewhat stymied its broad market acceptance in the commercial marketplace. The application of three-dimensional spacer fabrics as reinforcing interlaminar infusion media shows great promise as the enabling technology for widespread adoption of vacuum infusion.

2. VACUUM INFUSION PROCESS BACKGROUND

2.1. Background. Current vacuum infusion practices fall into two categories, *Surface Infusion* and *Interlaminar Infusion*. Typically both practices employ one generally rigid mold component and a flexible bag or membrane that when joined together are sealed to form a “closed” mold. In surface infusion, illustrated in Figure 1, before applying the flexible bag or membrane a disposable barrier layer, commonly referred to as a peel ply, is placed on top of the laminae pre-form. Disposable infusion medium with rigid open structures that do not buckle under vacuum and/or perforated injection tubing is then placed on top of the peel ply to aid in the delivery and distribution of the liquid resin down through the laminae stack. In the case of a reusable vacuum bag or membrane the distribution channels may be incorporated into the bag. Vacuum pressure is then applied and draws resin through feed-lines into the mold and through the fiber pre-form. This technique is commonly referred to as surface vacuum infusion processing since the resin is introduced at the top surface of the laminae assembly. Examples are described in Seemann et. al. U.S. patents 4,902,215, 5,052,906and 5,601,852. The greatest drawback of surface infusion is the high waste and non-profit stream costs in the disposal of peel plies and surface infusion media. Other drawbacks include high costs associated with steep implementation learning curves, and increased complexity with increase length scales.

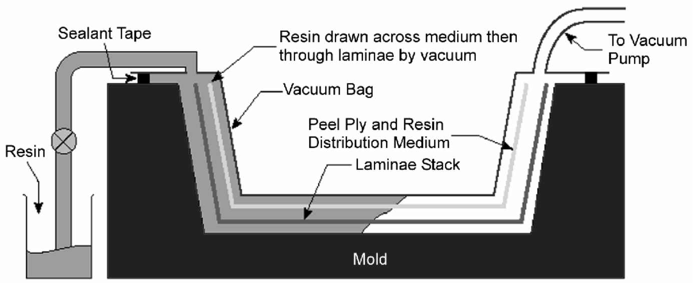

Figure 1. Surface Infusion Illustration.

As illustrated in Figure 2, as the name implies, in *interlaminar infusion* the infusion medium is integrated into the laminae and maintains high porosity while the dry laminate is being compressed under vacuum. There are numerous advantages to interlaminar infusion processing

---

[1] *Copyright 2003 by Verdant Technologies, Inc. Published by Society for the Advancement of Material and Process Engineering with permission.*

[2] For more details on the EPA’s stance on styrene and other HAPs, please refer to the EPA’s Office of Air Quality and Planning Standards website at http://www.epa.gov/ttn/oarpg/t3main.html.

other than waste and cost reduction. Surface infusion is a one-sided process in which the resin flows from the top down through the laminae stack. Interlaminar infusion mediums can be sandwiched and/or placed on either face to promote infusion on all sides of the dry laminae, greatly speeding infusion. Additionally, since the composite becomes the infusion pathway, placement of vacuum and resin feed lines is greatly simplified. Further with interlaminar infusion the opportunity to improve the properties of the composite exists through the selection of the medium form.

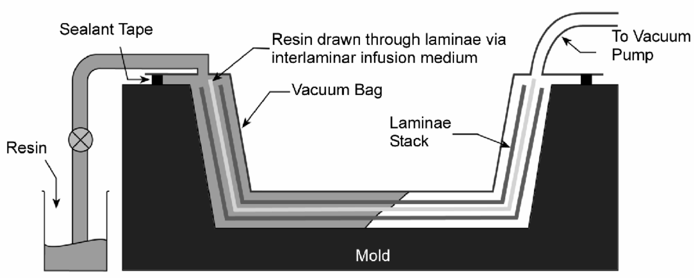

Figure 2. Interlaminar Infusion Illustration.

2.2. Length Scale Considerations. The issue of resin flow is fundamental to the scaling of infused composites. Under sealed vacuum, negative pressure exists on all sides of the dry laminate. When the resin injection point is opened, a difference in pressure is created between the vacuum port and the injection port. This pressure differential compels the resin to begin flowing through the dry laminate. As resin is pulled forward through the dry laminate, vacuum pressure is maintained only at the resin flow front, or the interface between the resin and the dry laminate, and the saturated area behind the resin flow front returns to atmospheric pressure. The effective force pulling resin through the dry laminate is therefore a function of the cross sectional area at the resin flow front. The greater the cross sectional area the more force exerted, as force is a function of pressure multiplied by area.

Viscosity is a measurement of how fast a fluid will flow against a stationary surface, or how resistant a fluid is to flowing against a surface. High viscosity fluids are more resistant to flow than low viscosity fluids. Any obstacle that fluid must move around during its flow increases the effective area of stationary surface resistance, decreases the effective open cross sectional flow area, and therefore decreases the overall fluid flow rate. Generally the denser and less uniform the fiber; the better it is as a reinforcement material for composites. Vacuum infusing standard fibrous laminae is therefore quite challenging without the use of infusion media. The ideal infusion medium maximizes available cross sectional area with minimal flow restrictions.

This intuitive conclusion is what virtually all “static” three-dimensional resin infusion media, be they designed for surface infusion or interlaminar infusion, are based upon. The problem, however, is that resin must surpass incrementally more stationary surface area as the required infusion distance is increased. “Length losses” accumulate as resin travels ever more slowly through the flow medium while encountering approximately the same frequency of restrictive fiber obstacles, which serve as the structural support to maintain maximum available cross sectional area under vacuum pressure. This is the primary reason why for the past fifty years interlaminar infusion, or infusion from within the laminate schedule, has achieved little adoption despite being naturally advantageous to surface infusion techniques like from cost, waste and property-additive standpoints, in lieu of surface infusion where adding to the number of ports where resin is introduced can accommodate the flooding of the part surface area. However, in surface infusion the through-the-thickness infusion time is a function of the preform permeability, thickness, and the resin viscosity. Thus there is also a trade-off for infused structure between permeability and fiber volume fraction. Surface infusion processes can typically achieve fiber volume fractions of about 50% with relatively few problems. Higher fiber volume fractions can be achieved, but will inhibit the resin flow through the preform. As a result of these issues, the surface infusion process cannot be scaled linearly with part thickness or complexity. These issues coupled with waste costs and learning curve complexity inherent to surface infusion have stymied widespread implementation in the commercial market place. To realize the full potential of vacuum infusion-type processes requires a synergy with alternative materials and fabric architectures. The adaptation of three-dimensional spacer fabrics generally know in the textile industry to interlaminar vacuum infusion represents such a synergy.

2.3. Three-dimensional Spacer Fabric Interlaminar Infusion Mediums. Three-dimensional spacer fabrics are comprised of two parallel “X/Y” planes of fiber fascia that are separated to a consistent “free form” thickness by sparsely separated columns of Z-directional yarns, preferably resilient in nature. Figure 3 schematically illustrates the three-dimensional spacer fabric material in a free or uncompressed relaxed form. As shown, in this illustration there is a pair of outer, generally woven or knit fabric layers, (1, 2), lying generally in the respective X - Y planes. Separating, and disposed between, these layers is a plurality of fibers or yarns (3) lying generally in a “Z” direction. The Z direction fibers need not be at an exact 90^o orientation, and generally are not. The specific angle Z may vary substantially, for instance between about 30^o and 90^o. Obviously, however, the more that the intermediate resilient fibers or yarns are normal to the planes of the outer layers (1, 2) the more spatial dimension that can be achieved therebetween. As indicated, the overall thickness dimension (d) of the three-dimensional spacer fabric may most usefully be between about 1 or 2 mm up to about 25 or 30 mm, or even more, with presently preferred dimensions in the range of about 2 mm to about 12 mm. As Figure 3 also shows, the Z direction fibers lying between the two outer layers (1, 2), retain a free space in this intermediate region for (ultimately) a flow of resin therethrough. Frequently the fiber density for the “Z” fibers may be only a minor fraction of the fiber density of the outer layers (1, 2), but this may also vary according to the architecture and fiber population of the outer layers. That is the outer layers may range from an open honeycomb structure to a more tightly woven warp and weft structure.

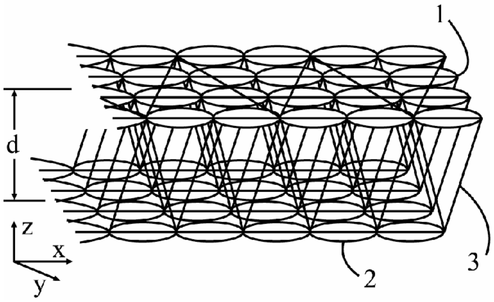

Figure 3. Spacer Fabric Architecture.

Figure 4 schematically represents how the three-dimensional spacer fabric compresses in the Z direction under vacuum pressure to a lesser thickness (d’). Even though compressed, there remains significantly and substantial open free paths for resin flow. This feature provides and maintains, even under the vacuum induced compressive forces, an advantageous and sufficient mean free path within the three-dimensional spacer fabric architecture to facilitate the rapid resin flow, penetration and distribution throughout the structure including the surrounding and adjacent plies of the entire laminae. The resin will have a flow path such that it not only fills the intermediate spaces between fibers (3) but also flows laterally so as to also fill and saturate both the outer layers (1, 2) as well as adjacent fabric layers.

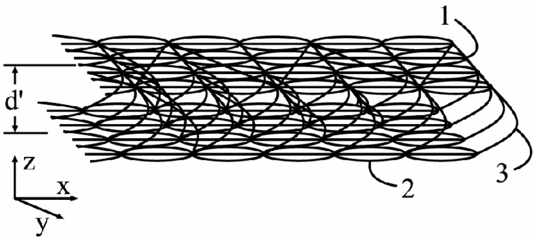

Figure 4. Vacuum Compressed Spacer Fabric.

The three-dimensional spacer fabrics' critical advantage, however, is that as vacuum pressure relents behind the resin flow front line, the resilient columns spring back. This feature creates a large resin-rich area behind the resin flow front line to feed resin flow and minimizes length loses that cripple other infusion media, vastly improving the overall speed and uniformity of infusion. Lastly, once the appropriate amount of resin has been drawn into the part the injection port is closed, eliminating the pressure differential and returning negative pressure to all sides of the infused laminate. This backpressure re-collapses all sprung columns, uniformly distributes resin to all areas of the part and increases the overall fiber-to-resin ratio.

Additionally because the three-dimensional spacer fabrics are engineered materials a vast spectrum of physical property enhancements can be tailored by designing X/Y/Z fiber architectures with hybrid combinations of polyester, glass, carbon, aramid and/or other materials.

3.0 EXPERIMENTAL

A test panel fabrication program was under taken to evaluate the adaptation of three-dimensional spacer fabrics to vacuum infusion. An additional intent of this program was to determine its efficacy as a skin to core interface in the infusion process.

3.1. Application Background. The stiffness of a panel is dependent not only on the material's flexural modulus, the measure of the stiffness of the material, but is also generally a function of the cube of the thickness of the panel. Accordingly, while the thickness of such a panel could be increased by some relatively small amount to realize a substantial increase the stiffness of the composite, this also has penalties in weight and expense. Thus one approach for stiffening an FRP panel would obviously be to make it thicker, but this can result in the disadvantage that an unnecessarily very heavy laminate would result with perhaps unnecessary strength characteristics and also one that is unnecessarily expensive and that may present practical construction problems for the final desired structure. A preferred technique to increase the stiffness of composite panel is the use of a sandwich construction. Sandwich construction in a laminate offers the comparable advantages of an I-beam configuration, but instead of the web and flanges of a typical I-beam, a sandwich construction makes use of a lightweight core material faced on one or both sides by skins of composite. The role of such skins in the composite structure is to withstand the bending moments on the panel or beam by resisting the compressive and tensile loading set up in the opposite skins when the panel is subjected to bending load forces.

For the skins to be able to resist the bending moments they must be rigidly held spaced from the neutral axis of the sandwich (the centerline) and prevented from moving relative to each other. It is the task of the selected core material, and of the bond line strength between the core and the skins, to provide and meet these requirements. For a given application, irrespective of the selected skin and core materials, the integrity of a sandwich construction is especially dependent upon the interfacial bond strength between the skins and the core elements.

Where the material for the core elements is relatively rigid and the molded part is designed so as to provide convex or concave surfaces, the core material may be scored into smaller sections, and in some cases a scrim may be applied to one side to hold the small sections together in a planer x,y fashion. However, the problem frequently encountered is that lateral dimensions of one or more of the scored, commonly rectilinear, core sections may be greater than the radius of the desired mold curvature for the intended structure. This can and does result in a void at the interface of the fiber lay-up and the core elements. In such cases, the ultimate desired intimate contact between the skin and the core can commonly only be achieved through the use of an excess of adhesive or other filler to occupy the resulting dimensional gap. Such techniques are not practical for vacuum infusion processing, and in general the skin to core void must be filled with resin. In either case the skin to core gap is filled with a media having remarkably different mechanical and strength characteristics from either the skin or the core, resulting in a region of divergent stress characteristics. Additionally, in applying vacuum infusion, severe voids at the above-described interface may be result from incomplete resin wet out. The resulting interface is then compromised for its optimum desired properties. As a result, discontinuities will be present with an adverse affect on the composites strength.

This problem is illustrated in Figure 5, where laminae (2 a&b) (ultimately, here, the outer skin) are applied to a mold of the desired shape (1). In this example, elements of the core material (3) are placed between inner (2b) and outer (2a) layers of fiber reinforcement or lamina to make up the laminae structure. In this example the curvature of the mold shape (1) is such that a void (4) is formed between the outer skin (2a) and the core elements (3). During the infusion process it is assumed that this space is filled with resin. However, frequently these voids are difficult to fill completely during fabrication and air spaces or voids occur therein with resulting detrimental effects on the bonding of the composite.

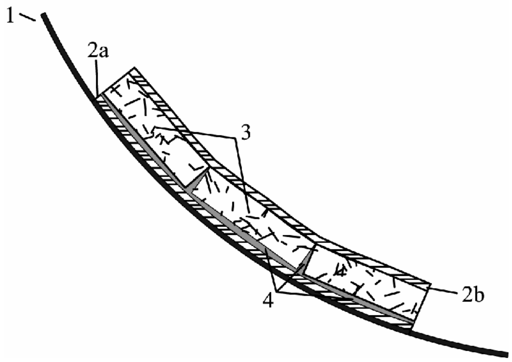

Figure 5. Non-Planar Core Cross Section.

In Figure 6 a similar tool and laminae is illustrated. However, in this figure a three-dimensional spacer fabric (5, 6) is added between the outer lamina and core. In additional to promoting flow beneath the core, since use of resilient fibers in the Z direction leaves the three-dimensional spacer fabric with a tendency to spring back and resist the deformation, the flexible fabric lends the property of conforming to the irregularities of the shapes of the core elements and of the mold surface itself so that voids there between are diminished.

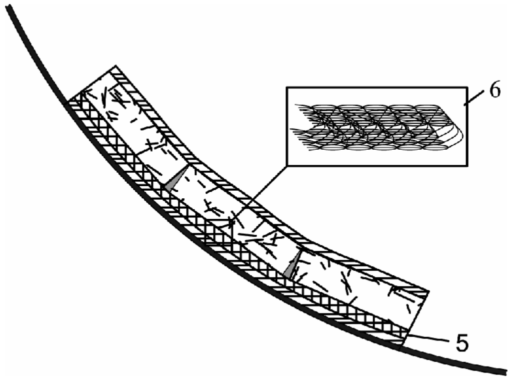

Figure 6. Spacer-Fabric Planarized Core Interface.

3.2. Test Panel Fabrication. End grain balsa core is a commonly used material in the commercial marketplace in applications ranging from marine to transportation to wind blade turbines. The balsa is arranged such that the end grain is normal to the planar surface of the resulting structure. Four test panels were fabricated with end-grain balsa core elements, as indicated in Table 1. The panels were designed to evaluate both the efficacy of three dimensional spacer fabrics as interlaminar infusion mediums as well as their efficacy in planarization of the core to lamina interface, as previously describe. Panels 1 through 3 utilize Polybeam™, a three-dimensional spacer fabric product line specifically designed for use as a reinforcing interlaminar infusion medium. Panel 4 was fabricated utilizing shade cloth as a surface infusion medium. Each panel was fabricated with a Hetron 922 vinyl ester resin supplied from Ashland promoted with 0.3% Cobalt 6% and 0.05% DMA, and 10% of styrene was added to attain a lower viscosity. The inner and outer lamina is of an orthogonally woven fiberglass material supplied from 3Tex. The end grain balsa was provided by Baltek and was prepared for contour applications via cutting and scrimming as previously described.

Panel 1: Peel Ply 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$ 19 mm CK-89 LamPrep Balsa Polybeam™ 730 466 g/m^2 3Tex Glass $[0^{\circ}_{2}]$	**Panel 2:** Peel Ply 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$ 19 mm CK-89 LamPrep Balsa Polybeam™ 703 466 g/m^2 3Tex Glass $[0^{\circ}_{2}]$
Panel 3: Peel Ply 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$ Polybeam™ 703 19 mm CK-89 LamPrep Balsa Polybeam™ 703 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$	**Panel 4:** Shade Cloth (Surface Distribution Media) Peel Ply 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$ 19 mm CK-89 LamPrep Balsa 466 g/m^2 3Tex Glass $[0^{\circ}_{3}]$

Table 1. Panel Laminae

Polybeam™ 730 fabric is a 100% monofilament polyethylene terephthalate (PET) fiber Raschel knitted three-dimensional spacer fabric from a double needle bar warp knit machine. The fabric has a free form (uncompressed) thickness of 10 mm and a vacuum compressed thickness of 2 mm. Polybeam™ 703 is a similar Raschel knitted three-dimensional spacer fabric with a free form thickness of 3 mm and a vacuum compressed thickness of 0.8 mm.

3.2.1. Fabrication Process. To allow for visual inspection of the flow front during resin infusion a glass plate was used as the tool surface. As shown by top view in Figure 7, upon assembly of the laminae (1), as outlined in Table 1, a single vacuum port (3) was fitted adjacent to the flow medium. Spiral cut tubing (2) for resin input was fitted on the opposite edge of the flow medium, again as shown in Figure 7. A flexible vacuum bag was then fitted and sealed about the laminate, the resin input tube sealed with a clamp, and vacuum drawn.

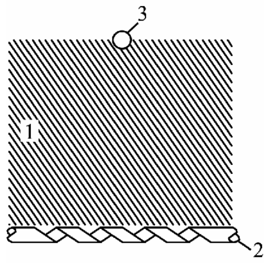

Figure 7. Fabrication

A gauge affixed to a standard resin trap read vacuum. When vacuum reached 85 kPa , the clamp was removed from the resin inlet tube, and the tube was subsequently placed in the vinylester resin (~ 1.5 Pa•s). The resin clamp was reaffixed to the inlet tube when the resin front reached the vacuum port. Full vacuum (85 kPa) was maintained during this process. At this point, excess resin within the laminate is pulled out by vacuum until the point in time at which the resin gels and can no longer flow. Full vacuum is maintained until such time. After the resin completed its exotherm and has cooled to room temperature, the panel was removed for post cure and testing.

3.3. Results. Tensile and flexural characterization of the panels were performed on the panels following ASTM C-297 “Flat-wise Tension Test” and ASTM C-393 “Flexural Test”. ASTM C-393 “Flexure Test” is an evaluation of the stiffness and strength of sandwich panel specimens subjected to bending loads. ASTM C-297 “Flat-wise Tension Test”, is an evaluation of the tensile strength and modulus of structural cores in a direction perpendicular to the sandwich facings. Edgewise loading of a sandwich panel can induce buckling on the faces of the sandwich panel. This outward buckling is representative of these flat-wise stresses. Table 2 and Table 3 summarize the results of the testing.

3.4. Discussion. These test results demonstrate no deleterious effect on the composite strength characteristics from the use of the three-dimensional spacer fabric, even though its structure having opposed spaced apart fabric layers clearly includes in both uncompressed and compressed form an interior region of greatly reduced fiber density.

A significant observed result of this testing was that tensile failure always occurred between the core (balsa element) and the skin. Failures never occurred on the side of the balsa core elements that were bonded in contact with the three-dimensional spacer fabric. In fact for Panel 3, which has Polybeam™ 703 on both sides of the core, the outer 3Tex glass fiber skins failed and the core element failed, but the Polybeam™ to core interface always remained intact.

Of additional significance is that the physical properties reflect the observed quality of the resin flow during the lamination. Polybeam™ 730 provided a good and fast resin distribution medium and allowed a good resin spreading within the laminate, as noted in the test results. Resin diffusion with Polybeam™ 703 was slower than Polybeam™ 730, even with one ply on each side of the laminate. Thus the tensile and flexural results were lower because the resin couldn’t flow as well as with Polybeam™ 730 or the shade-cloth during the infusion. Use of a resin system with an appropriately lower viscosity could address this issue.

4.0 CONCLUSIONS

The work conducted under this study has illuminated the potential of three-dimensional spacer fabrics as reinforcing interlaminar infusion mediums. The results clearly indicate that the use of said fabrics can significantly aid in the distribution of resin during the process while, particularly in the case of cored composite structures, improving the failure mode to one that occurs laminate skins rather than in the skin to core interface.

5.0 REFERENCES

1. D.A. Griffin, “Blade System Design Studies Volume I: Composite Technologies for Large Wind Turbine Blades, SAND2002-1879,” July 2002.
2. U.S. Pat. 4,902,215 (Feb. 20, 1990) W.H. Seemann III
3. U.S. Pat. 5,052,906 (Oct. 1, 1991) W.H. Seemann III (to Seemann Composite Systems, Inc.)
4. U.S. Pat. 5,601,852 (Feb. 11, 1997) W.H. Seemann III (to Scrimp Systems, LLC)
5. S.M. Lewit and J.C. Jakubowski, SAMPE International Symposium, 42, 1173 (1997)
6. Lazarus, P., SAMPE International Symposium, 41, 1447 (1996).

ASTM C-297
Tensile Strength and Modulus

Panel	Strength (MPa)	Modulus (MPa)
1	8.03	209
2	7.46	190
3	6.05	179
4	8.31	193

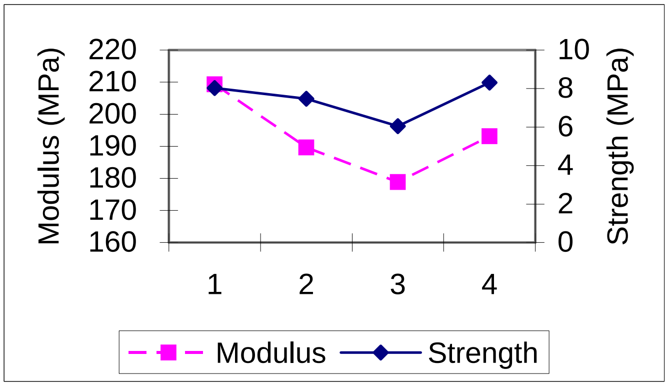

Table 2. ASTM C-297 Test Results.

ASTM C-393 Flexural Stiffness and Modulus			
Panel	Stiffness (KNm) Mold Side/Backside	Modulus (MPa) Mold Side/ Backside	Deflect @ 45 kg (mm) Mold Side/ Backside
1	9394 / 9437	143 / 145	1.143 / 1.143
2	7893 / 7592	133 / 129	1.372 / 1.422
3	9097 / 9035	146 / 141	1.194 / 1.194
4	8892 / 8652	153 / 151	1.168 / 1.245

Table 3. ASTM C-297 Test Results.