

Comparison of Mechanical Properties of Laminates Fabricated Using Vacuum Infused Knitted Reinforcements

Abstract

The strengths of various types of knit reinforcements (0/90, +/-45, quadraxials, etc.) are well understood for products fabricated using conventional techniques, including hand layup. Closed molding vacuum-assisted manufacturing methods often produce higher fiber content laminates, with a corresponding reduction in laminate thickness. The performance of some vacuum-infused commercially available knitted reinforcements are presented and compared. It is shown that resin-infusion techniques can produce very high-strength, low void content laminates using reinforcements that are not specifically designed for infusion.

Background

Vacuum Infusion Processing (VIP) has been used in the composites industry for quite some time, but has recently become popular due to the MACT constraints on open molding. Many new raw materials have been introduced, including low-viscosity thermoset resins specifically designed for infusion. In addition, the manufacturers of knitted reinforcements (also known as “stitched” or “multiaxial” fabrics) have come up with fabric architectures which facilitate and enhance resin flow, thus reducing mold fill time, and hopefully, reducing air voids in the laminate.

Resin infusion can also be accomplished using conventional reinforcement styles. The plies used in open molding can usually be successfully wet out using resin infusion, albeit with a few modifications. Chopped strand mat may be replaced with continuous strand mat for the best results, for example. A non-thixotropic resin must also be used.

The mechanical properties of the laminate will change when an open-molded product is switched to resin-infusion. A reduction of overall part thickness, up to 30% in some cases, will occur due to the pressure on the laminate from the vacuum bag. While this will increase “strength” in the formal sense (psi or mPa), overall load capacity does not change. In fact, the laminate stiffness (EI) is reduced with the loss of thickness, causing increased deflections under design

loads. In some cases the number of plies of reinforcement must be increased to compensate. However, for structures with primarily in-plane loads, or in sandwich structures, the reduction in laminate thickness is not normally a concern.

The Experiment

The purpose of this study was to evaluate commercially available stitch bonded (a.k.a. knitted) E-glass fabric reinforcements for mechanical and physical properties. The results from this study are being used to aid in the selection of candidate materials for current and future programs utilizing stitch bonded E-glass fabrics.

To better isolate the contribution of the glass reinforcement to composite performance, the processing parameters were fixed, including using the same resin on all test panels. The resin used for all test panels was a prepromoted, toughened vinyl ester that is brominated to reduce flammability. The resin is commercially available both in the US and abroad. Polymerization and cure was effected using a methyl-ethyl-ketone peroxide (MEKP) initiator.

Consumable materials for the infusion process were all off-the-shelf products. A picture of the portable infusion test rig is shown in Figure 1 below.

The infusion parameters were formalized into a standard procedure and included the following:

- Initial vacuum drawdown
- Panel size
- Nominal panel thickness
- Final vacuum during cure
- Gel at room temperature under bag, then post cure in oven

The formulation of the resin was the same for all panels. The recipe used resulted in a gel time of around 2 hours, convenient for infusion. All of the glass used was approximately 24 oz/yd² in areal weight, and was a biaxial stitched fabric of either a 0/90 or +/-45 orientation. A proprietary list of the glass fabrics tested and their characteristics was created and is maintained for future consideration.

All manufacturers were asked to provide “a vinyl-ester compatible E-glass stitch bonded fabric for optimum mechanical properties in either a 0/90 or +/- 45 configuration”. Based on inquiries made with the vendors it can be stated that several of the manufacturers have the flexibility to manufacture customized products provided that the requirements are specified to a sufficient level of detail, and justified by the potential volume.

Results

After cure and post-cure of the laminates, test coupons were cut along the major fiber axes for determination of mechanical and physical properties. All of the testing was in accordance with the appropriate ASTM/SACMA procedures for these types of materials.

Summaries of the test results are given in Tables 1 and 2. Fiber volumes were in the 45%-60% range. There appears to be only a weak correlation between fiber volume and mechanical strength which would indicate that the strength of the panels are influenced not only by fiber volume but by the variations in the inherent strengths of the reinforcement materials themselves.

These results may be compared with published data for non-infused laminates. A quick look at manufacturer's data for 24 oz/yd² woven roving shows tensile strengths in the 38-47 ksi range, with compressive strengths shown around 30-35 ksi. These data represent laminates with lower fiber volume.

Discussions

There are several primary areas of discussion for the data shown in the tables. These are:

- a) Fiber volume / density
- b) Mechanical performance normalized to density and fiber volume
- c) Balance of mechanical properties
- d) Visual imperfections in relation to mechanical performance
- e) Filament diameter, yield, and sizing in relation to mechanical performance

Fiber Volume and Density

As mentioned above, each panel was processed in an identical manner. It is interesting to note how each fabric produces different fiber volumes for the same process. In general the fabrics that visually had the smallest gaps between rovings tended to have the highest fiber volumes. The relationship between fiber volume, laminate density, and strength is illustrated graphically below.

Normalized Mechanical Properties

The mechanical properties were normalized by dividing by the specific gravity (density) of each panel. The results are shown in Figure 2. Normalizing in this way is equivalent to a specific strength comparison. It is clear from Figure 2 that certain fabrics are stronger than others on a specific strength basis. In general it can also be seen that it is possible to have both a high tensile and compressive strength within a particular panel. In other

words, tensile strength is not necessarily improved at the detriment of compressive strength and vice versa. As shown in Figure 2 the in-plane shear strength tends to be higher in panels with lower tensile and compressive strengths, although the correlation is weak.

The mechanical properties were also normalized using the fiber volume of each panel. The results are shown in Figure 3. As would be expected, the Figure 3 shows nearly identical trends to Figure 2 as the fiber volume and density are very closely related.

The trend of Fiber Volume versus strength for the various strength parameters is shown in Figure 4. There is a general upward trend for tensile and compression strength with fiber volume. The in-plane shear strengths (not shown in graph) do not appear to exhibit a trend.

The viewing of the data normalized by fiber volume is based on the assumption that in general the reinforcement dominated properties tend to improve with an increase in the fiber fraction. (Tension is generally assumed to be reinforcement dominated and compression is also usually assumed to be strongly influenced by reinforcement but to a lesser extent than tension. In-plane shear strength is generally thought to be influenced only slightly by reinforcement.) However, as shown in Figure 4 the performance of the reinforcements show little correlation with fiber volume, therefore it can be inferred that the reinforcements differ on a more fundamental level than just fiber volume.

Balance of Mechanical Properties

The balance of the mechanical properties was also evaluated. In different design situations it would be desirable to have a different combination of properties. For example, in a push-pull rod that has fully reversing tension and compression loads you would want the material that gives the highest minimum tensile or compressive strength. However, in a structure like the flanges an I-beam which will only ever be loaded in a single direction you may want the material that has the highest combination or average of tensile and compressive strength. Figure 5 shows the average and minimum of the tensile and compressive strengths for each panel. As these are bidirectional materials, you may also want a close match of the 0° strength and the 90° strength. Note that for the +/- 45 fabrics (double bias) the 0 and 90 directions are the fiber directions, not the roll direction. Knitted fabrics with 3 (triaxial) and 4 (quadraxial) fiber axes were not tested here, but are reserved for future consideration.

Visual Imperfections

In general, the most defect-free panels had the highest mechanical properties. And in general, the most defect-free fabrics (no kinks, missing fiber bundles, runs, needling, etc.) produced the higher-strength laminates. These were subjective evaluations by experienced composites personnel. The judgment of relative appearance was based on the observed quantity and severity of imperfections. These imperfections were either glinting (white wash) or jackstraw (fiber printing). In order of best to worst the appearance of the panels was ranked as the following:

- 1) Mfr C +/-45 & Mfr A +/-45 II (tie)
- 3) Mfr A +/-45 I
- 4) Mfr A 0/90
- 5) Mfr B 0/90
- 6) Mfr E 0/90
- 7) Mfr D 0/90
- 8) Mfr F 0/90

Filament Diameter, Yield, and Sizing

The roving used for each of the reinforcements, along with the respective sizing, filament diameter, and tex of the rovings, while not shown here, were examined. While there does seem to be some correlation between roving selection and mechanical performance, this cannot wholly explain the disparities in mechanical performance. The most striking example of this is the difference between three of the reinforcements that all use the same roving.

Considerations for Fabricators

Switching from open molding to Vacuum Infusion Processing will generally result in a **thickness reduction** of the laminate. While this causes an increase in **strength**, measured in force/unit area (lb/in², kg/mm², mPA, etc), there is no corresponding increase in **load capacity**. In fact, the loss of stiffness (EI, lb-in²), may in fact require additional plies of reinforcement to maintain design deflections under load. However, for structures with primarily in-plane loads, or in sandwich structures, the reduction in laminate thickness is not normally a concern. What should be of special interest to fabricators is the exceptionally high strengths achievable using the relatively simple infusion process described here. In the case of the Mfr B 0/90 panel tensile and compressive strengths both in excess of 70 ksi were achieved.

Summary

High quality, high strength laminates are easily fabricated using conventional Vacuum Infusion Processing. In fact, the properties of the higher-strength laminates shown here easily surpass those of nearly all E-glass/epoxy prepreg materials using off the shelf materials and relatively simple processing. Compared with hand layup, strength increases of 10%-30% are easily achieved. Stiffness reduction remains an issue, however.

Multiaxial reinforcements of both the 0°/90° and +/-45° types can be utilized, as long as the resin system used is suitable for infusion. The test results indicate that improved laminate mechanical properties belong on the list along with the many other benefits of VIP fabrication.

	Density (g/cc)	% Fiber Volume	+45° Tensile Strength	-45° Tensile Strength	+45° Comp. Strength	-45° Comp. Strength	Inplane Shear Strength
Mfr A +/- 45 I	2.06	61.8	82.3	88.3	59.5	68.6	10.7
Mfr A +/- 45 II	2.03	60.0	94.3	99.0	82.3	92.3	10.1
Mfr C +/- 45	1.93	54.0	70.9	70.5	88.7	83.6	9.9

Table 1. Test Results (strength in ksi), +/-45° Fabrics

	Density (g/cc)	% Fiber Volume	0° Tensile Strength	90° Tensile Strength	0° Comp. Strength	90° Comp. Strength	Inplane Shear Strength
Mfr A 0/90	1.96	57.6	58.8	81.4	64.6	65.4	9.9
Mfr B 0/90	1.97	56.5	73.4	71.9	71.7	65.0	10.1
Mfr D 0/90	1.86	49.3	63.9	61.3	57.0	58.7	11.0
Mfr E 0/90	1.80	44.6	73.0	NA	58.0	NA	11.4
Mfr F 0/90	1.78	48.2	56.3	NA	61.9	NA	6.9

Table 2. Test Results (strength in ksi), 0/90 Fabrics



Figure 1. Infusion Test Panel Setup

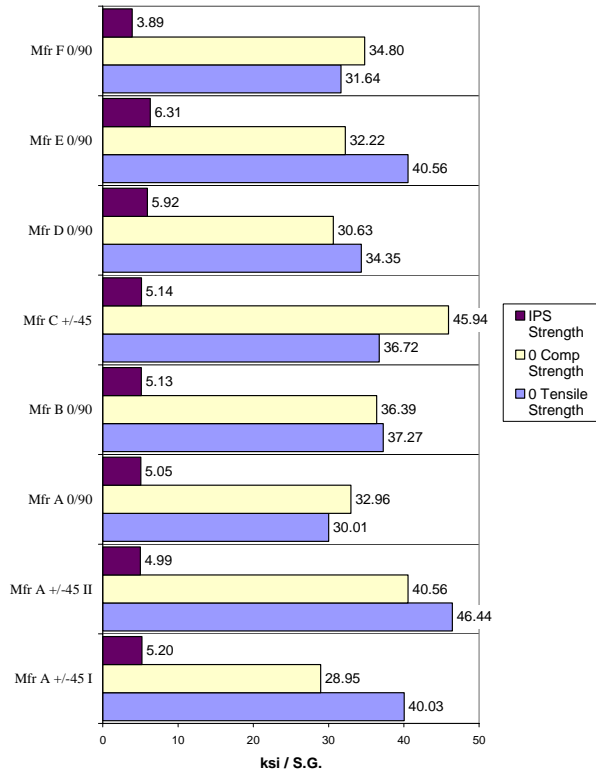


Figure 2. Specific Strengths (ksi/SG)

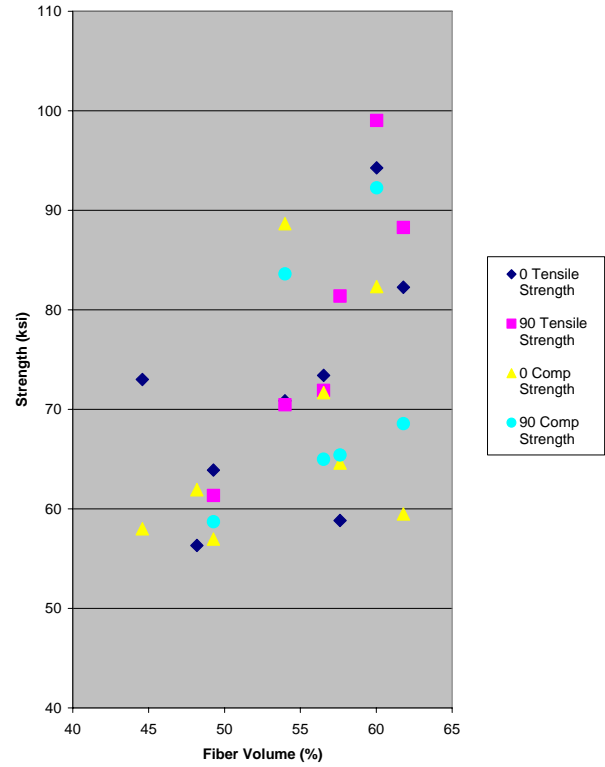


Figure 4. Strength Versus Fiber Volume

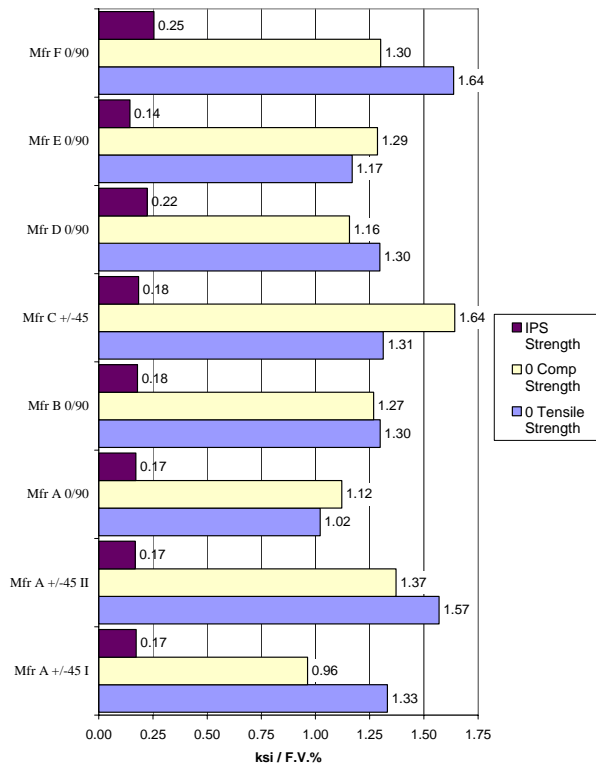


Figure 3. Strength Normalized by Fiber Volume (ksi/%FV)

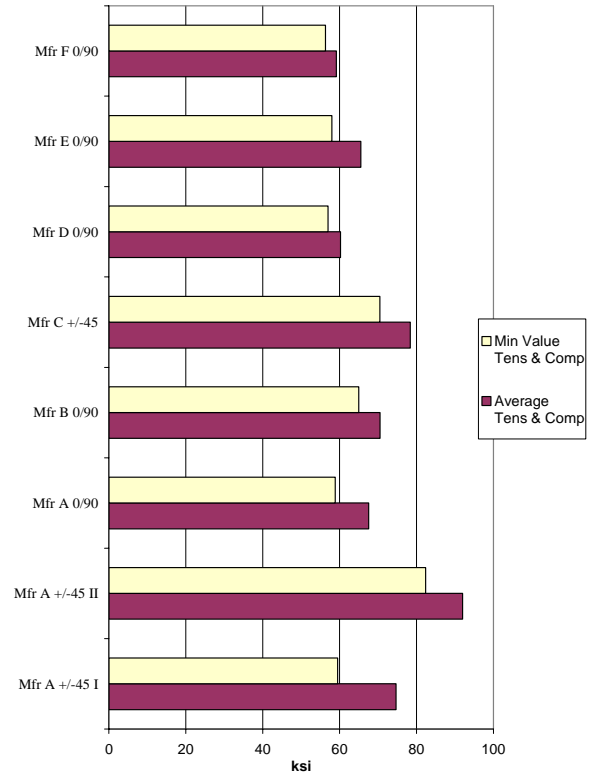


Figure 5. Minimum and Average of Tensile and Compressive Strengths

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