

## Properties of Structural Sandwich Core Materials: Hand Lay-up vs. Vacuum-Infusion Processing

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### Abstract:

Vacuum-Assisted Resin Transfer Molding, or “vacuum-infusion,” has grown significantly in popularity over the past decade or two in part due to advantages of a significantly reduced environmental footprint, lower weight per unit area, and debatably lower manufactured part cost. Suppliers of reinforcements and resins have undertaken considerable research on the physical properties of “single-skin” composites produced by vacuum-infusion in relation to contact molding. However, little has been presented on similar comparisons for structural sandwich composites. Thus, the objective of this study was to compare the properties of identical laminate builds comprising two plies of 1808 E-glass fabric on each side of nominal ½” (12.5 mm) thick core materials, produced by both vacuum-infusion and hand lay-up processing. Core materials investigated included pre-coated/decay-resistant end-grain balsa, two densities and two suppliers of cross-linked PVC foams, two extruded PET foam variants, an extruded polypropylene honeycomb core, one density of an SAN foam, three densities of polyurethane foam, and a special core comprised of an assembly of low-density polyurethane foam planks filament wound with E-glass rovings, bound on both sides with scrim. All core materials with the exception of the last two types were scrimmed and had either knife-cut or saw-cut kerfs. The polyurethane foam cores were not scrimmed, but instead were double-cut.

Characterizations included initial core density, laminated weight per unit area, average thickness, and strength and stiffness for both flexural as well as “flatwise” tensile testing. Significant among the findings of this study were a substantial reduction in overall panel thickness and areal weight, subtle differences in flexural strength, a significantly lower flexural stiffness, slightly greater flatwise tensile strength, and significantly greater flatwise tensile moduli, for vacuum-infusion processing in comparison to hand lay-up.

### Background:

The advantages of utilizing vacuum-infusion processing, such as substantially reduced styrene emissions and more consistent and often higher laminate physical properties, are well established and need no further validation to justify this method of lamination. One further advantage of vacuum-infusion processing when used on structural sandwich laminates is that the kerf network of contourable cores will completely fill with resin, if properly executed. The importance of resin-filled kerfs toward minimizing water permeation, and the potentially significant weight gains that accompany it for all core materials, has been extensively investigated in the past.<sup>1</sup> In relation to the flexural properties of sandwich structures with partially or unfilled kerfs, including static strength and fatigue endurance, the static shear strength of a 2-inch (50 mm) thick, 6.2 lb./cu.ft. (100 kg./cu.m.) plain sheet cross-linked PVC foam was reduced by 52% and 60%, when unfilled kerf widths of 1 mm and 10 mm, respectively were employed.<sup>2</sup> In another study, resin-filled kerfs of both 3.75 and 8.1 lb./cu.ft. (55 and 130 kg./cu.m.) cross-linked PVC foam cores exhibited the same or greater shear strength than the corresponding plain sheet, but unfilled, or even partially filled, 3 mm kerfs reduced shear strength by 50% or greater.<sup>3</sup> Even grooves on the surface, and perforations through the thickness, when filled with resin, can augment certain physical properties of a core material.<sup>4</sup> Kerf widths vary from product to product, depending upon how they are created. Generally, saw-cut kerfs tend to be much greater in width than knife-cut kerfs simply because material is being removed during the sawing operation. Thus, one of the main objectives of this study was to assess if there were any differences in select physical properties of contourable core materials having kerfs filled with resin by using vacuum-infusion processing, in comparison to (relatively) unfilled by hand lay-up processing.

### Experimental Plan:

Foremost among the various stresses imposed on a structural sandwich core material are “in-plane” shear, or shearing due to the facings displacing with respect to each other. As with an I-beam, structural sandwich beams that are simply-supported at their ends will transmit loads applied to their top “compression skin” down to their bottom “tension skin” through the core in shear. Another key stress associated with structural sandwich core materials is out-of-plane or “flatwise” tension, which can accompany outward facing buckling due to edgewise loading, for example. For the sake of assessing the performance characteristics of the various core materials as a function of method of lamination, a practical performance evaluation would be to characterize the strength and stiffness in both flexure and “flatwise” tension, and compare the pertinent metrics that resulted.

Other performance criteria that are important toward designing an efficient sandwich structure include weight per unit area and overall sandwich thickness, thus were included in the experimental matrix of responses.

## Materials and Preparation:

**CORE MATERIALS:** each of the following nominal 1/2" (12.5 mm) thick, contourable (scrimmed with knife- or saw-cut kerfs) core materials were obtained from commercial suppliers for this investigation. The "PUR" core materials had a "double-cut" kerf network, since a scrimmed and slit format was not available.

- 1). "EGB-150": end-grain balsa core, treated with an anti-fungal solution, and with resin pre-coated surfaces; nominal density of 9.4 lb./cu.ft. (150 kg./cu.m.), knife-cut kerfs.<sup>5</sup>
- 2). "XPVC1-55": a cross-linked PVC foam core material having a nominal density of 3.4 lb./cu.ft. (55 kg./cu.m.), saw-cut kerfs.<sup>6</sup>
- 3). "XPVC1-75": a cross-linked PVC foam core material having a nominal density of 4.7 lb./cu.ft. (75 kg./cu.m.), saw-cut kerfs.<sup>7</sup>
- 4). "PET2-120": a different PET-based foam core having a nominal density of 7.5 lb./cu.ft. (120 kg./cu.m.), saw-cut kerfs.<sup>8</sup>
- 5). "PET1-150": a PET-based foam core having a nominal density of 9.4 lb./cu.ft. (150 kg./cu.m.), saw-cut kerfs.<sup>9</sup>
- 6). "SAN-75": a styrene-acrylonitrile based foam having a nominal density of 5.9 lb./cu.ft. (95 kg./cu.m.), knife-cut kerfs.<sup>10</sup>
- 7). "PUR-100": a polyurethane based foam having a nominal density of 6.2 lb./cu.ft. (100 kg./cu.m.), double-cut, saw-cut kerfs.<sup>11</sup>
- 8). "PUR-130": a polyurethane based foam having a nominal density of 8.1 lb./cu.ft. (130 kg./cu.m.), double-cut, saw-cut kerfs.<sup>12</sup>
- 9). "PUR-160": a polyurethane based foam having a nominal density of 10.0 lb./cu.ft. (160 kg./cu.m.), double-cut, saw-cut kerfs.<sup>13</sup>
- 10). "XPVC2-60": a cross-linked PVC foam core material having a nominal density of 3.8 lb./cu.ft. (60 kg./cu.m.), saw-cut kerfs.<sup>14</sup>
- 11). "XPVC2-80": a cross-linked PVC foam core material having a nominal density of 5.0 lb./cu.ft. (80 kg./cu.m.), saw-cut kerfs.<sup>15</sup>
- 12). "PPHC-100": a polypropylene honeycomb core with non-woven carrier fabric on both surface; nominal density of 6.2 lb./cu.ft. (100 kg./cu.m.), knife-cut kerfs.<sup>16</sup>
- 13). "PURWEB-90": an assembly comprising 3" (75 mm) wide polyurethane foam planks, filament wound with E-glass yarns, held together with a scrim on both surface; nominal density of 5.6 lb./cu.ft. (90 kg./cu.m.).<sup>17</sup> The two orientations of this core material are designated as "L" for principal stresses applied in

the length direction of the filament-wound webs, and "W" for transverse-to-web direction.

**GLASS REINFORCEMENT MATERIALS:** the following glass reinforcements were obtained from commercial suppliers and used without further treatment or modification:

- 1). "1808 stitch mat," comprising one ply of 3/4-oz./sq.ft. (225 grams/sq.m.) chopped strand mat, stitched to one ply of 18 oz./sq.ft. (600 grams/sq.m.) woven roving.
- 2). "1-1/2 csm," 1-1/2 oz./sq.ft. (450 grams/sq.m.) chopped strand mat

**RESIN, CATALYST:** the following resins and catalysts were obtained from commercial suppliers and, after the resins were promoted, used without further treatment or modification:

- 1). **HAND LAY-UP RESIN:** vinyl ester resin, 44% styrene content, 400 cPs viscosity (#2 spindle @ 30 rpm), promoted with 0.3% Cobalt Naphthenate (6% concentration) and 0.05% Dimethyl Aniline, 30-40 min. gel time.
- 2). **VACUUM-INFUSION RESIN:** vinyl ester resin, 33% styrene content, 175 cPs viscosity (#2 spindle @ 30 rpm), promoted with 0.6% Cobalt Naphthenate (6% concentration) and 0.05% Dimethyl Aniline, 45-55 min. gel time.
- 3). **HAND LAY-UP CATALYST:** methyl ethyl ketone peroxide, 9% atomic oxygen content, used at 1½% by weight of the resin.
- 4). **VACUUM-INFUSION CATALYST:** cumene-hydroperoxide, used at 1% by weight of the resin.

**SANDWICH LAMINATION AND SPECIMEN PREPARATION:** after the determination of initial core densities, one panel of each core was laminated using hand lay-up ("HL") processing, while a second one utilized vacuum-infusion ("VIP"), on flat, waxed tables, according to the following laminate schedule (material abbreviations, resins and catalyst described above).

### (Mold Surface)

1808 at a 40/60 : glass/resin ratio by weight  
1808 at a 40/60 : glass/resin ratio by weight  
1-1/2 csm at a 20/80 : glass/resin ratio by weight  
Core material, pre-wetted with "RESIN"  
1808 at a 40/60 : glass/resin ratio by weight  
1808 at a 40/60 : glass/resin ratio by weight

The glass/resin ratios indicated above, and core pre-wetting, applied only to the hand-laid panels. Not shown, but utilized for the vacuum-infused panels, were peel-ply fabric, distribution media, vacuum-bag film, and tape. The "PPHC" polypropylene honeycomb was not vacuum-infused, as its cells would most certainly fill com-

pletely with resin if thus processed. The “PURWEB” was only laminated using vacuum-infusion, as it was considered unlikely that the webs would adequately fill with resin if hand lay-up techniques were utilized. Two panels were prepared by vacuum-infusion for the “PURWEB” core, in order to evaluate flexural properties in both the “L” and “W” directions.

Following a one-week, room-temperature post-cure, panels were squared-off on a table saw fitted with a carbide bit blade, and their average thickness and panel areal weights were determined.

### Test Methods:

**INITIAL CORE DENSITY:** prior to lamination, each core material was cut to dimensions of 24” (610 mm) x 18” (457 mm), and length, width, average thickness and weight were recorded. Initial core densities were determined in accordance with the methods of ASTM C271<sup>18</sup>. Initial core density results are graphically illustrated in Figures 3 and 4, for hand lay-up and vacuum-infusion processing, respectively.

**PANEL AREAL WEIGHT:** prior to cutting physical test specimens, each laminated panel was squared-off on a table saw, its dimensions and weight were recorded, and weight per unit area was calculated in units of pounds per square feet. Average overall panel thickness results for both methods of processing are exhibited in Figure 5. Panel areal weight results are shown, for hand lay-up in comparison to vacuum-infusion processing, in Figure 6.

**SANDWICH LAMINATE FLEXURAL TESTING:** ASTM C-393 “Flexural Test Method for Sandwich Construction” is an evaluation of the stiffness and strength of sandwich laminates, which are subjected to bending loads.<sup>19</sup> When the facings of the sandwich are over-designed to withstand a force sufficient to fail the core material, usually in a shearing mode, the shear stress at failure then becomes the shear strength of the core for flexural testing.

A total of five (5) replicate flexural test specimens measuring 17.5” (445 mm) long x 4” (100 mm) wide were cut from panels of each core type, and both methods of lamination, then evaluated against the methods of ASTM C 393-00, in four-point bending.<sup>19</sup> For the “L” orientation of the “PURWEB” panel, which in turn had filament-wound webs on a 3” (75 mm) pitch, a total of four (4) replicate flexural test specimens measuring 17.5” (445 mm) long x 3” (75 mm) wide were cut such that the web was located in the middle of the beam. A support span of 15 inches (381 mm), and a load span of 5 inches (127 mm), was utilized and both support and load points were equipped with 1-inch (25-mm) wide load pads that were allowed to freely rotate about their mating half-round steel load or support points.

As illustrated in Figure 1, a 50-kip (222 KN) capacity MTS Model 810 servo-hydraulic test machine was used to apply load to the mold-side surface of each test specimen at a crosshead rate of 0.2 in/min (5.08 mm/min) and load as well as actuator stroke were electronically recorded until the specimen failed or bottomed-out on the support fixture at a stroke of about 3 inches. The location and type of failure was recorded. From the resulting load versus deflection and the core specimen dimensions, core shear stress at failure as well as stiffness were calculated within the MTS TestWorks® software, all in accordance with the equations of ASTM C 393-00. Flexural strength results for both hand lay-up and vacuum-infusion processing are graphically compared in Figure 7, while flexural stiffness results are similarly compared in Figure 8.

**FLATWISE TENSILE TESTING:** ASTM C 297 “Flatwise Tension” Test Method is an evaluation of the tensile strength of a structural core material in a direction perpendicular to the sandwich surface. Provided that failures occur exclusively within the core, the failure stress then becomes the flatwise tensile strength for the core. A total of five (5) specimens, measuring 2” x 2” (50 x 50 mm), were cut from selected panel variants, bonded to steel fixtures, fitted with linear variable displacement transducers (LVDT), and evaluated against the methods of ASTM C 297-00, using the same test machine as described above, and appropriate TestWorks® software<sup>20</sup>. Figure 2 reveals the details about the arrangement of the specimen between steel blocks, and the two LVDT’s used to obtain an average flatwise tensile displacement from which to calculate tensile strain.

### RESULTS AND DISCUSSION:

With reference to Figures 3 and 4, the initial core densities for hand-laid and vacuum-infused cores, respectively, one can observe that the commercial cores of this study exhibited a wide range of densities. One valid assessment of quality control in their manufacture is to compare the individual density results obtained in this study to the manufacturer’s minimum and maximum density values. If the product is certified against a type approval agency, these values are typically the agency’s certificate minimums and maximums. This comparison of actual core density to minimum and maximum values is accomplished in Figures 3 and 4, again for hand-laid and vacuum-infused cores, respectively. It is noteworthy that the density of the “PUR-100” and “PURWEB-90” core materials used in this study were less than the minimum densities stated in the manufacturers’ data sheets<sup>11,17</sup>.

Average panel (overall laminate) thickness results are graphically summarized in Figure 5, conveniently comparing panel thickness for both processing methods, and for each core material. The use of vacuum-infusion results in thinner facings, and thus a lower overall panel

thickness, likely due to the compression of the reinforcements during processing. A much higher facing glass content typically accompanies vacuum-infusion processing.

Panel areal weights are similarly compared for each core materials and both processing methods in Figure 6. Suffice it to say that the resulting panel areal weight is sum of the core's areal weight plus the areal weight of the facings and any resin absorbed into the kerf network or core. Thus, a significant finding of this study was that when using the same core material, same thickness of core, and same glass fiber reinforcements, a substantial reduction in panel areal weight resulted by the use of vacuum-infusion, as opposed to hand lay-up. This study also showed that the resin savings in the thinner, vacuum-infused facings exceeded the additional resin absorptions into the kerf network, resulting in a lighter-weight infused panel, at least for the fabric build and cores used here. Note, however, that these are flat panels, and there is the possibility that a radiussed sandwich panel might result in smaller differences or in the extreme case the opposite effect when vacuum-infused, depending upon the magnitude of radius and/or width of kerfs. Another finding was that even though "EGB-150" had the greatest initial density, its resulting panel areal weight for hand lay-up was only slightly greater than for cores of 10-15% lower initial density. For vacuum-infusion, the "EGB-150" panel exhibited a lower areal weight than the much lower density "PUR-160" core material, a consequence of the much greater resin absorption into the double-cut kerf network of that latter material.

Figures 7 and 8 present the flexural strength, in metrics of core shear stress at failure, and flexural stiffness, in metrics of sandwich stiffness, respectively, for all cores, comparing results for hand lay-up and vacuum-infusion processing. Not surprisingly, "EGB-150" core material showed the greatest strength in flexure, while the polypropylene honeycomb, "PPHC-100," the least for hand lay-up processing. For the "PURWEB-90" core material, fabricated using vacuum-infusion processing, exhibited a dramatic difference in shear strength for the "L" and "W" directions, and the latter direction resulted in the lowest shear strength of all of the cores, and both methods of processing, that were evaluated in this study.

Examining Figure 7 for the effect of method of processing on resulting core shear strength, other than for the end-grain balsa core material "EGB-150," the differences in core shear strength between the two methods of processing were quite small or nil, with possibly a slight advantage for vacuum-infusion. Comparing the same core materials at different densities, there did not appear to be any consistent rationale for explaining differences in the shear strength, where differences existed.

With reference to Figure 9, the failure mode for the vacuum-infused "EGB-150" core material, careful prodding around the failure areas resulted in the conclusion that the balsa wood in the failure zone was of lower den-

sity than the average density of the core sheet. Although critical in narrow beam-flexural testing, these lower density blocks become negligible in full-panel testing, or in larger parts.

Thus, not contradictory to past findings, resin-filled kerfs slightly augmented the shear strength of these cores at best, although the greatest kerf width in any case was about 2 mm for these materials. It is speculated that not only kerf width, but core thickness, are variables influencing the reduction of shear strength, since the 1/2" (12.5 mm) thickness used for the cores of this study was much less than the 3/4" (20 mm) and 2-inch (50 mm) thicknesses employed in the above references<sup>2,3</sup>.

Figure 10, the failure mode for the "SAN-95" core shows a typical core shear failure, without stress-concentration at the kerfs. Figure 11, the failure mode for the "PUR-130" core, is a result of stress concentration at the tips of the partial depth saw-cut kerfs, whether resin-filled or not. Figure 12 shows the polypropylene honeycomb cell wall yielding that is typical for thermoplastic honeycomb core materials. Figure 13, the failure mode for the "PURWEB" core was quite similar to that of the "SAN-95" core.

A comparison of laminate flexural stiffness is presented in Figure 8, for both hand lay-up and vacuum-infusion processing. In that the vacuum-infused panels were significantly thinner than their hand-laid counterparts, the substantially lower stiffness for vacuum-infused cores of equal thickness, and reinforcements of equal build and weight, was not totally unexpected. An interesting extension of this study would be to increase the core thickness in the case of vacuum-infusion, in order to result in the same overall thickness as for the hand-laid panels. The greater glass content and resulting higher skin properties should result in an increase in stiffness and strength for these infused panels, primarily due to locating the facing centroids further from the neutral axis in the case of the vacuum-infused variants, as well as due to the greater properties of the infused skins.

Comparing the various cores in Figure 8 for flexural stiffness, just as for flexural strength, "EGB-150" core material showed the greatest flexural stiffness, while the polypropylene honeycomb, "PPHC-100," the least for hand lay-up processing. Again, the "PURWEB-90" core material, fabricated using vacuum-infusion processing, exhibited a dramatic difference in flexural stiffness in the "L" and "W" directions, and the latter direction resulted in the lowest flexural stiffness of all of the cores, and both methods of processing.

Finally, the flatwise tensile strength and modulus results for panels laminated with selected cores from among those investigated in this study are presented in Figures 14 and 15, respectively. Almost without exception, the flatwise tensile strength of each core material was slightly to somewhat greater for vacuum-infusion processing than for hand lay-up. Filling the kerfs completely with resin apparently has the effect of creating a "waffle" network of cured resin, with its superb reinforc-

ing qualities. Even more dramatic were the increases in flatwise tensile modulus for cores processed by vacuum-infusion, as shown in Figure 15. The greatest differentials in modulus between vacuum-infused and hand-laid were not surprisingly for the “PUR” and “PET” cores with their saw-cut kerfs, and for “EGB-150” presumably due to the greater absorption of resin into its wood structure for vacuum-infusion processing. Since the strength and elastic modulus of balsa wood in the grain direction is so incredibly great, the flatwise tensile response of the various foam cores paled by comparison to “EGB-150.” Actual strength and modulus values were inserted into the charts in Figures 14 and 15, to assist the reader in determining those values.

## SUMMARY & CONCLUSIONS:

By a direct comparison of hand lay-up and vacuum-infusion processing of a series of commercially available core materials, the effect of such processing on performance could be assessed. While employing equivalent core materials and thickness, and the same reinforcements, the following significant results were obtained from this study:

- Vacuum-infusion provided for a thinner and lower areal weight panel, at least for the flat or non-radiused geometry used in this study.
- Due to being thinner, vacuum-infused panels were significantly lower in flexural stiffness than the corresponding hand-laid panel.
- Having the greatest density of all core tested, not surprisingly end-grain balsa exhibited the greatest flexural and flatwise tensile strength and stiffness of all the cores evaluated.
- The polypropylene honeycomb core, and the glass filament-wound polyurethane foam in the “W” direction, exhibited the lowest flexural strength and stiffness.
- “Flatwise” tensile strength was slightly to somewhat greater, and flatwise tensile modulus was significantly greater, for cores processed by vacuum-infusion compared with hand lay-up, presumably due to the reinforcing effects of resin-filled kerfs.

In conclusion, when converting from hand-laid cored laminates to infused cored panels, it is important to increase the core thickness to compensate for the reduced skin thickness of the infused laminate, in order to retain panel stiffness.

## ACKNOWLEDGEMENTS:

Special appreciation is directed to Mr. Edison Ospina and some of the bold members of the Independ-

ent Boat Builders, Inc. group for their tedious preparation of test panels, specimens and skillful execution of the physical testing. Figure 16 is a testimony to the high level of skill with which test panels of this study were fabricated.

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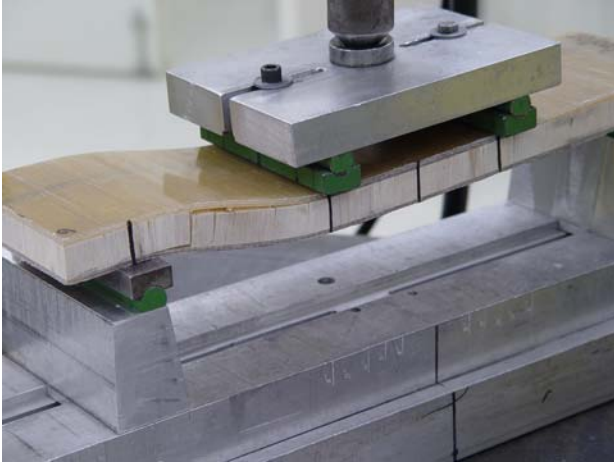


Figure 1. Apparatus for ASTM C 393-00 Sandwich Composite Flexural Testing

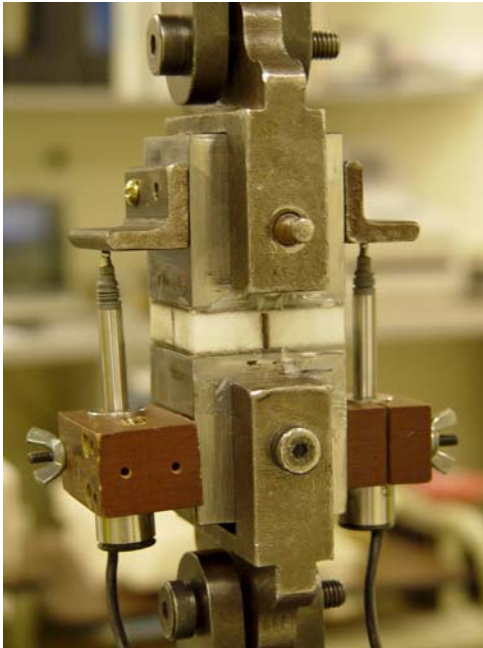


Figure 2. Apparatus for ASTM C 297-00 "Flatwise" Tensile Testing

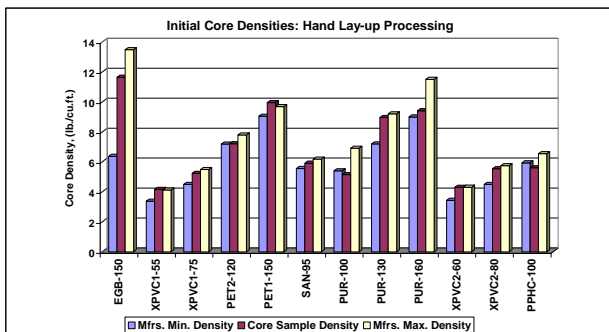


Figure 3. Initial Core Densities for Hand Lay-up Processing, vs. Manufacturer's Minimum and Maximum

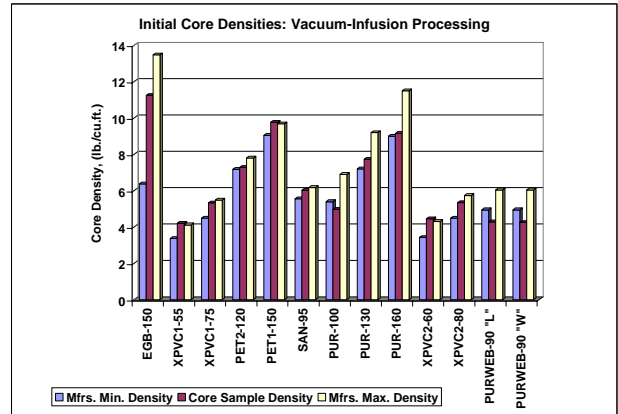


Figure 4. Initial Core Densities for Vacuum-Infusion Processing, vs. Manufacturer's Minimum and Maximum

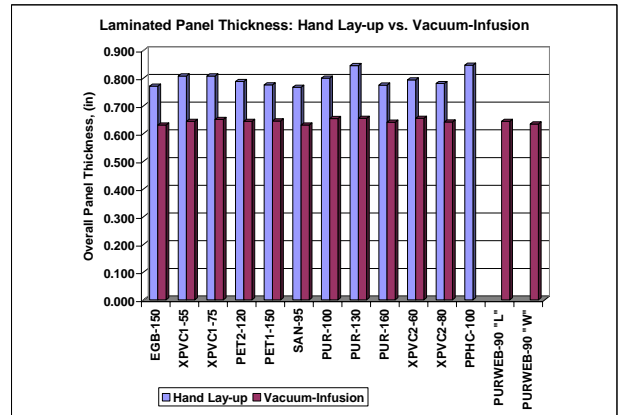


Figure 5. Panel Thickness Comparison, Hand Lay-up vs. Vacuum-Infusion Processing

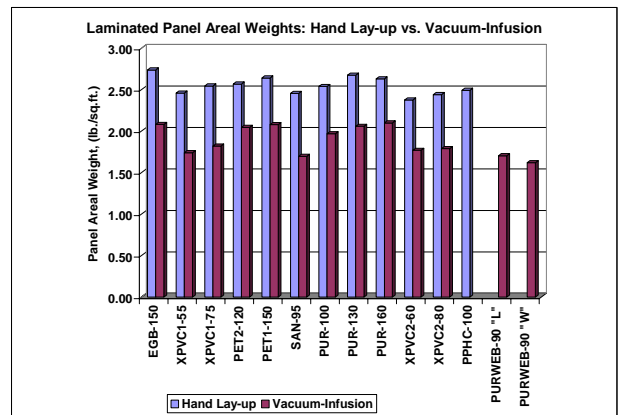


Figure 6. Panel Areal Weight Comparison, Hand Lay-up vs. Vacuum-Infusion Processing

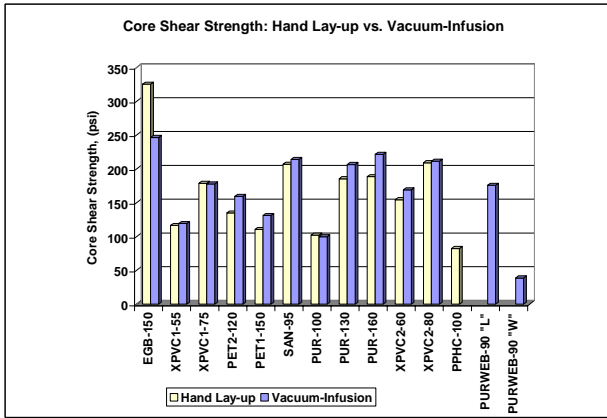


Figure 7. Flexural Strength - Core Shear Stress at Failure, Hand Lay-up vs. Vacuum-Infusion Processing

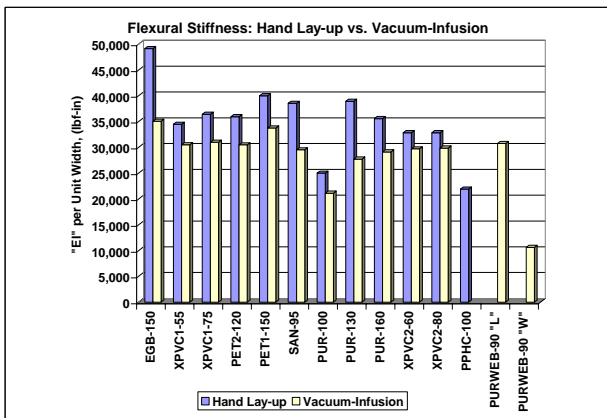


Figure 8. Flexural Stiffness – “EI” per Unit Width, for Hand Lay-up vs. Vacuum-Infusion Processing



Figure 9. Failure Mode for “EGB-150” Core Material, Top: Vacuum-Infusion, Bottom: Hand Lay-up

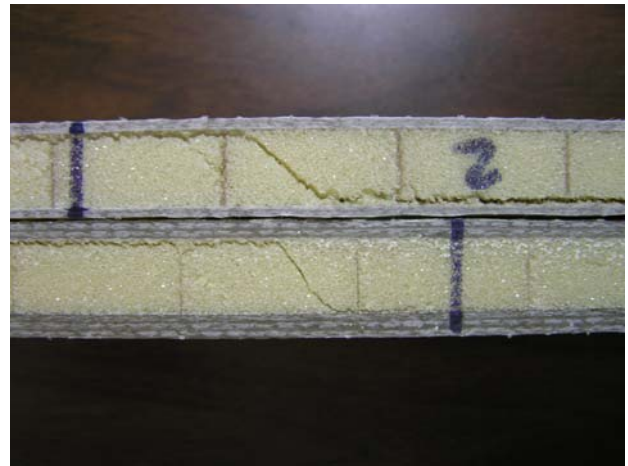


Figure 10. Failure Mode for “SAN-95” Core Material, Top: Vacuum-Infusion, Bottom: Hand Lay-up

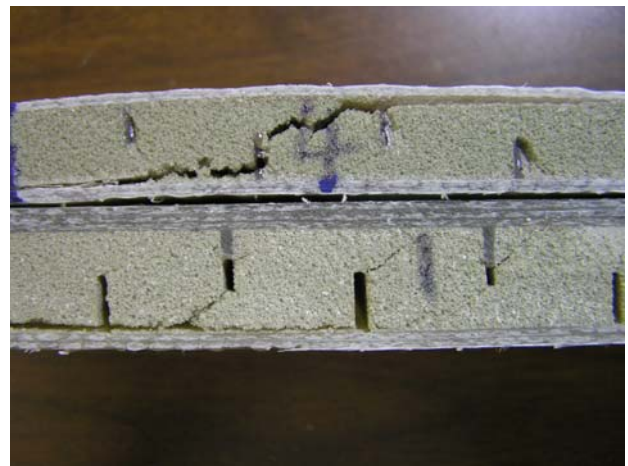


Figure 11. Failure Mode for “PUR-130” Core Material, Top: Vacuum-Infusion, Bottom: Hand Lay-up

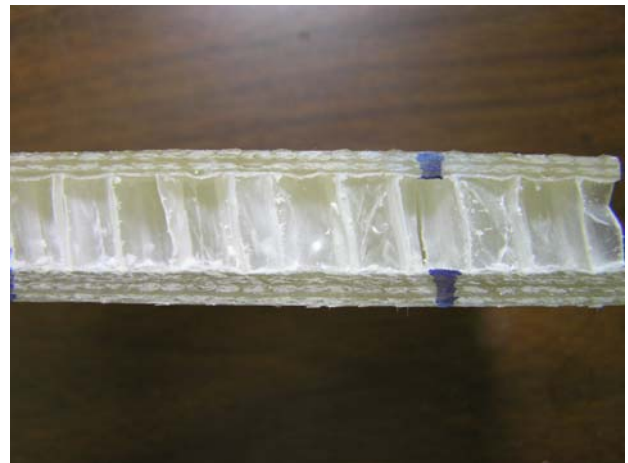


Figure 12. Failure Mode for “PPHC-100” Core Material, Hand Lay-up



Figure 13. Failure Mode for “PURWEB-90” Core Material, Top: “W” Orientation, Bottom: “L” Orientation

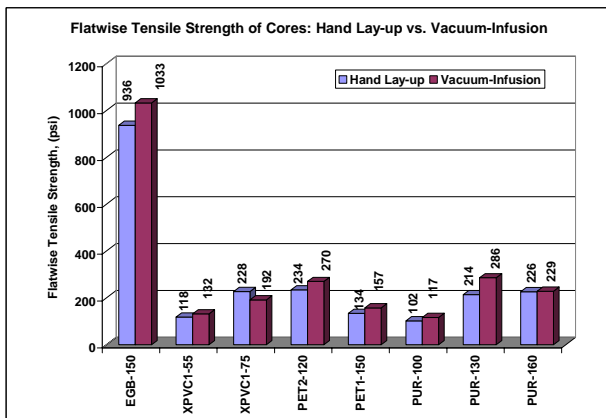


Figure 14. Flatwise Tensile Strength, Hand Lay-up vs. Vacuum-Infusion Processing

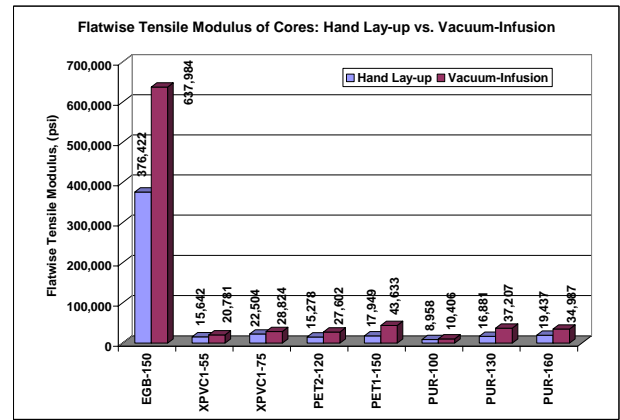


Figure 15. Flatwise Tensile Modulus, Hand Lay-up vs. Vacuum-Infusion Processing



Figure 16. Example of Talented Laminating Crew