

Evaluation of Alternative Peel Ply Surface Preparation Methods of SC-15 Epoxy / Fiberglass Composite Surfaces for Secondary Bonding

**by Jared M. Gardner, James P. Wolbert, Larry R. Holmes Jr.,
and Daphne D. Pappas**

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14. ABSTRACT Because of the extensive costs associated with building composite laminates, the U.S. Army is exploring approaches to reduce the processing steps associated with hybridized structures. One area of focus is in surface preparation for secondary bonding. An important quality of an effective surface preparation method is its ability to consistently provide clean and highly chemically active substrates for bonding. In this report, we examine peel ply surface preparation methods for secondary bonding of composite substrates using FM 94K epoxy film adhesive by mechanical testing, elemental surface analysis, and high-resolution imaging of failure surfaces. Woven S2 fiberglass infused with SC-15-toughened epoxy resin composite laminates was fabricated by the vacuum-assisted resin transfer molding process. Tool-side surfaces of the composites were prepared using nine commercial off-the-shelf peel plies, including dry and impregnated forms. Two preparation methods for bonding were investigated: peel ply only–prepared surfaces and peel ply in combination with grit blast–prepared surfaces. This report covers testing results concluded by a quantitative and qualitative analysis of the comparative effects of the preparation methods, technical challenges, and influential factors controlling peel ply effectiveness in bond performance, and recommendations for future work.					
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1. Introduction

Lightweight composite structures offer significant long-term cost-saving opportunities for the U.S. Army as replacements for traditional metal structures. However, high-strength economical bonding processes must be developed to join composites in order for them to be viable replacements. The Army is exploring approaches, also under evaluation in the commercial aerospace industry, to reduce the process steps associated with composite bonding (1). A potential single-step process for preparing composite surfaces uses removable fabrics known as peel plies, which are cured to the composite surface during fabrication. Traditionally, peel plies have not been a reliable media for creating optimal bonding surfaces. However, preimpregnated versions, known as wet peel plies, are a fairly recent innovation that shows significantly improved potential, though at a greater cost compared to their traditional dry fabric counterparts, in creating excellent composite bonding surfaces. Still, reducing the processing steps would reduce overall cost and shorten production lead times of composite systems for the Army in applications such as composite armor and structural vehicle components.

Typically, dry peel ply fabrics have been used as a protective layer for the composite surface after fabrication. The peel ply is removed prior to surface preparation methods for secondary bonding, which include mechanical abrasion, chemical treatments, cleaning, and inspection. The success or failure of a peel ply to create a bondable surface is defined by its ability to consistently provide clean and highly chemically active substrates. Successful removal of a peel ply requires fracture within the resin matrix between the peel ply and reinforcement fibers, and complete removal of the peel ply fabric without residual fiber transfer. Undesirable modes of removal include interfacial fracture between the peel ply and the matrix, peel ply fracture, and interlaminar failure within the composite (2). Transfer of release agents used to facilitate their removal has been widely shown to have significant negative influence on bond performance (3). Virtually all previous studies that focus on the effects of peel plies on composite bonding conclude that there is no universally acceptable peel ply.

Most current commercially available peel plies are dry fabrics with or without a release coating applied. Typical yarn types are nylon, polyester, and fiberglass in various weave styles. Common release coatings include silicone, polyamide, and polytetrafluoroethylene (PTFE). Noncoated fabrics are typically polyester because it is highly inert. Several fabric characteristics reported to be critical to successful release include yarn type, weave style, and release coating. However, previous studies show varying conclusions regarding the influence of peel ply characteristics on bond performance (3–5). Developmental research by the Henkel Corp. (Rocky Hill, CT) highlights the combined influence of weave characteristics on wetting/encapsulation of the fabric, and resin toughness, significantly affecting the release of the fabric from the surface

(6). These studies are focused primarily on peel plies used for autoclave processing of preimpregnated fiber composite.

In this work, we examine surface preparation methods for secondary bonding of composite substrates using FM^{*} 94K (Cytec, Havre de Grace, MD) epoxy film adhesive. Laminates using the U.S. Army legacy composite system consisting of plain-woven S2 fiberglass (BGF, Greensboro, NC) and SC-15 epoxy resin (API) (Applied Poleramic Inc., Benicia, CA) were prepared by the vacuum-assisted resin transfer molding (VARTM) process. Two methods were used for tool-side surface preparation: peel ply only–prepared surfaces and peel ply in combination with grit blast–prepared surfaces. We also compared nonprepared virgin surfaces and grit blast only–prepared surfaces. The current preparation method incorporates Richmond A-8888, a commercial off-the-shelf (COTS) dry fabric peel ply manufactured by Richmond Aerovac (Santa Fe Springs, CA) followed by a grit-blasting process. Detailed descriptions of the laminate fabrication and specimen preparation methods used in this study are given.

Eight dry peel ply fabrics, including Richmond A-8888, seven products manufactured by Airtech International Inc. (Huntington Beach, CA), and one preimpregnated peel ply will be examined in this work. All of the materials are currently COTS-available fabrics. Henkel’s Wet Peel Ply (WPP), Hysol[†] EA 9896[‡]WPP, was an experimental epoxy preimpregnated peel ply system at the time of this work with 45 weight-percent (wt-%) resin content in a nylon carrier fabric. The following tests have been conducted in ambient conditions. Composite-to-composite lap shear tests were conducted to establish initial bond strengths and to characterize adhesive behavior. Composite-to-metal floating roller peel tests were used to observe the mode of bond failure at the composite surface in peel. Elemental surface compositions were determined by x-ray photoelectron spectroscopy (XPS). High-resolution images of the prepared composite surfaces are examined by scanning electron microscopy (SEM). In addition, qualitative assessments regarding the use and performance of the peel ply fabrics are made.

2. Experimental

2.1 Materials

The S2 fiberglass is a 240-style 5 × 5 plain weave fabric with an aerial weight of 813 g/m² (24 oz/yd²) and 463 epoxy compatible sizing (7). SC-15 is a low-viscosity two-phase toughened epoxy resin matrix designed for VARTM processes (8). The U.S. Army Research Laboratory (ARL) has previously investigated the rheological properties of SC-15 and found that they are acceptable for resin infusion processes (table 1). The typical fiber volume fraction of a cured

^{*}FM is a registered trademark of Cytec Industries Inc.

[†]Hysol is a registered trademark of the Henkel Corporation.

[‡]EA 9896 is a trademark of the Henkel Corporation.

laminate for this material system fabricated by the VARTM process ranges between 49% and 52% with a typical void volume of approximately 1%, also previously established. Nominal cured laminate thicknesses were 6.35 mm (0.25 in).

Table 1. Initial viscosities and time to reach 5000 cP at processing temperature.

Resin	Initial Viscosity at 25 °C (cP)	Time to 5000 cP at 25 °C (min)	Initial Viscosity at 60 °C (cP)	Time to 5000 cP at 60 °C (min)
SC-15 (9)	508 ± 60	301	47 ± 8	73

The cure schedule used for SC-15 was previously established based on experimental work at ARL (table 2) and varies from the manufacturer's recommended cure schedule (8). The cure schedule begins with an acclimation stage for compensation of increased bulk in thick section composites, gel times, and thermal lag during the initial temperature ramp. It also incorporates a second hold stage that eliminates a separate post cure cycle.

Table 2. ARL cure schedule for VARTM processing of SC-15.

Acclimate	Ramp 1	Ramp 2	Hold 1	Ramp 3	Hold 2	Cool
35 °C	0.3 °C/min to 52 °C	to 60 °C	45 min (to gel)	2.2 °C/min to 122 °C	180 min	Hold vacuum pressure 95 kPa (14 psi) 12 h during cool to ambient

Tool-side surfaces of the composites were prepared using COTS peel ply fabrics, including eight dry and one experimental impregnated form. The peel plies investigated in this work are listed, and the related technical data as supplied by the manufacturers are shown in table 3 (10–12). The maximum recommended use temperature for all peel plies investigated exceeds the process temperature used in this study. The dry peel plies in general all have a minimum acceptable resin compatibility with most epoxy and polyester resin systems. In addition, all of the dry peel plies are stated to have unlimited shelf life. Hysol EA 9896 WPP is stated to have an estimated 12-month shelf life stored at –18 °C (0 °F) and 14-day out time at ambient conditions (10).

Table 3. Peel ply materials examined in this study.

Peel Ply	Yarn Material	Coating Type ^a	Construction ^a End/dm × Pick/dm (End/in × Pick/in)	Weight g/m ² (oz/yd ²)	Thickness ^a mm (in)	Manufacturer
Bleeder Lease [*] A	Nylon	Silicone	158 × 158 (40 × 40)	80 (2.34)	0.15 (0.0058)	Airtech International Inc., Huntington Beach, CA
Bleeder Lease B	Nylon	Silicone	409 × 342 (104 × 87)	62 (1.83)	0.11 (0.0045)	Airtech International Inc., Huntington Beach, CA
Bleeder Lease C	Fiberglass	Silicone	224 × 213 (57 × 54)	299 (8.8)	0.33 (0.013)	Airtech International Inc., Huntington Beach, CA
Dahltext SP-2	Nylon	<i>PTFE</i>	260 × 189 (66 × 48)	140 (4.12)	0.22 (0.0087)	Airtech International Inc., Huntington Beach, CA
Econo Ply E	Polyester	None	283 × 213 (72 × 54)	95 (2.8)	0.15 (0.006)	Airtech International Inc., Huntington Beach, CA
Bleeder Lease G	Polyester	Silicone	472 × 252 (120 × 64)	83 (2.45)	0.13 (0.0050)	Airtech International Inc., Huntington Beach, CA
Hysol EA 9896 WPP	Nylon (carrier)	Epoxy (45 wt-%)	629 × 394 (160 × 100)	122 (3.59)	0.15 (0.006)	Henkel Aerospace, Bay Point, CA
Richmond A-8888	Nylon	Polyamide	158 × 158 (40 × 40)	75 (2.2)	0.11 (0.0045)	Richmond Aerovac, Santa Fe Springs, CA
Superlease Blue	Nylon	Silicone	409 × 342 (104 × 87)	62 (1.83)	0.11 (0.0045)	Airtech International Inc., Huntington Beach, CA

^aItalicized values were determined experimentally and were not provided by the manufacturer.

All bonding was conducted using Cytec's FM 94K preimpregnated modified epoxy film adhesive. FM 94K has an aerial weight of 146 g/m² (4.30 oz/yd²) and polyester knit carrier resulting in a 0.15-mm (0.006-in) cured ply thickness (13). The curing process was conducted according to the cure schedule in table 4. The technical datasheet for FM 94K Cytec recommends applying a hold pressure of 325 kPa (40 psi) at the peak of the temperature ramp of the cure schedule (13). The higher hold pressure requires the use of a high-pressure autoclave, which was not used in this study.

^{*}Bleeder Lease is a registered trademark of Airtech International Inc.

Table 4. FM 94K epoxy cure schedule as used in this study.

Ramp	Hold	Cool
Apply vacuum pressure 95 kPa (14 psi) 2.2 °C/min to 121 °C	60 min	Hold vacuum pressure 95 kPa (14 psi) 12 h during cool to ambient

2.2 Laminate Fabrication

All laminates were constructed using eight plies of plain-woven S2 fiberglass fabric in a 0/90 stacking sequence, infused with SC-15 epoxy resin system by the VARTM process. Peel ply dimensions were cut oversized by 76.2 mm (3 in) relative to the reinforcement plies allowing for approximately 38.1 mm (1.5 in) extension beyond the part edges. Fabric and peel ply cutting operations were performed using a computer-controlled Gerber Technology DC2500 (Tolland, CT) cut table with a wheel-style cutting head.

Laminate layup and curing processes were performed on the surface of an electronically controlled BriskHeat Corp. (Columbus, OH) heat table. The surface of the heat table was sanded and cleaned prior to laminate fabrication using an orbital hand sander with 120-grit sandpaper followed by an acetone solvent wipe. Three coats of Frekote^{*} 44-NC[†] made by Henkel were applied to the surface of the heat table, allowing 15 min for solvent evaporation between successive coats and 60 min prior to panel fabrication (14). The surface of the heat table had been preconditioned with 44-NC prior to this experiment and did not require a full initial conditioning.

Peel plies were placed directly on the surface of the tool beneath the reinforcement ply stack. Warp direction of the peel ply and reinforcement plies was consistently oriented in the flow direction of the resin infusion process. Richmond A-8888 peel ply was placed over the entire ply stack as a release fabric on the nontool side of the cured laminates. Two plies of distribution media were placed a minimum of 2 in from the end of the parts and 1 in from the sides. A secondary (redundant) vacuum bag was used in the fabrication of all laminates. Stretchlon SL800 bagging film made by Airtech was used for the primary and secondary vacuum bags. The layup and bagging sequence used for the VARTM process is illustrated in figure 1.

Hysol EA 9896 WPP was oriented with the paper liner side facing the laminate when tacking to the tool surface, as recommended by the manufacturer (10). Dahltexx SP-2 was oriented with the pale blue fabric side facing the laminate and the white membrane contacting the tool, as recommended by the manufacturer (11).

^{*}Frekote is a registered trademark of the Henkel Corporation.

[†]44-NC is a trademark of the Henkel Corporation.

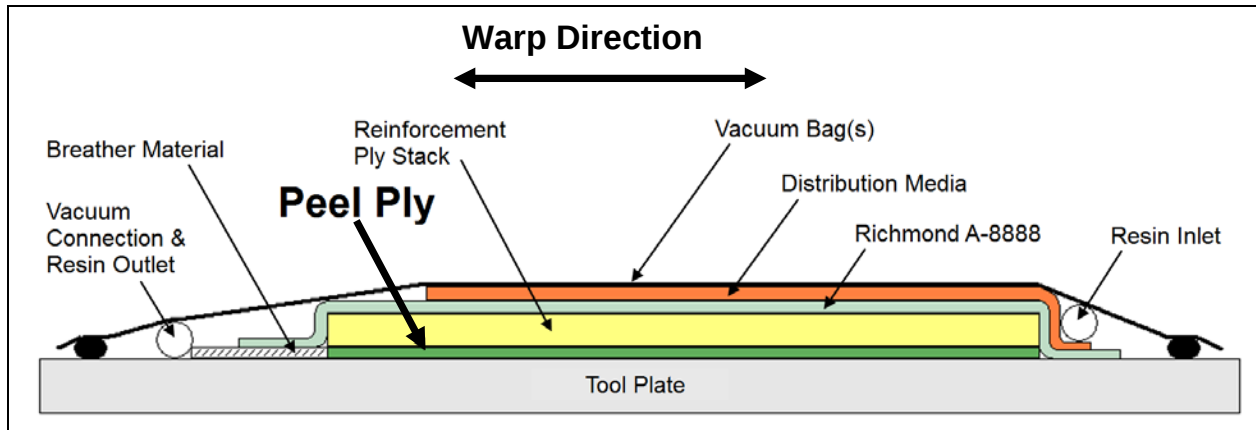


Figure 1. Schematic of the layup and bagging sequence for the VARTM process.

A leak inspection was conducted on each vacuum bag using an Inficon (East Syracuse, NY) Whisper Ultrasonic Leak Detector. Bags were also inspected by a vacuum drop test using a pressure gauge placed in-line with the vacuum source. A pressure change no greater than 10 kPa (1.5 psi) within the first minute was considered acceptable. Parts were held under vacuum pressure overnight during a debulk process prior to resin infusion (figure 2).



Figure 2. Vacuum-bagged laminate during the debulk process.

The resin was mixed for 2 min at a moderate rate using alternating mixing patterns according to the manufacturer's recommended mix ratio in the technical datasheet for SC-15 of 100:30 resin-to-hardener (R:H) by weight (8). An additional 10% resin mass was added to the calculated requirement to ensure that resin was sufficiently available during infusion. Prior to infusion, the mixed resin was degassed in a vacuum chamber for 8 to 10 min to remove trapped air. The average resin infusion process required between 15 and 20 min for complete wetting of the laminates. All laminates were cured according to the SC-15 cure schedule (table 2) on the heat table with insulating blankets placed over the laminates (figure 3).



Figure 3. Heat table with insulating blankets placed over the laminates during the curing cycle.

Specimen machining for lap shear and floating roller peel testing was performed using the Flow International Corp. (Kent, WA) water-jet cutting system. The long direction of the specimens tracked the warp direction of the laminates, corresponding to the infusion flow direction during laminate fabrication. Specimens were immediately rinsed with water to remove excess garnet, wiped dry, and further dried in an oven at 60 °C (140 °F) for 120 min. Peel plies remained on the bonding surfaces of the fully cured laminates during machining in all cases and were not removed until immediately prior to bonding.

2.3 Analysis of Peel Ply Removal

Simple observations made during the peel ply removal process can provide indicators regarding the overall performance, and practicality of their use by technicians. These observations were documented and a qualitative comparison of the process was made. We then compared these observations based on fabric architecture. The peel plies were stripped from the substrates of two 76.2- × 76.2-mm (3- × 3-in) specimens representing each peel ply, and an assessment of the relative force required for removal was recorded. Additional removal characteristics, such as edge fraying and fiber transfer, were documented during preparation of lap shear coupons. Peeling was initiated using a razor blade, starting at a square corner edge and peeling diagonally away from the initiation point. A square edge is not required for initiation; however, the condition highlights differences in fabric tenacity. The peel angle used to remove the fabrics from the lap shear specimens was not purely diagonal across the surface because of specimen geometry.

2.4 X-ray Photospectroscopy (XPS) Analysis

A Kratos Ultra165 XPS was used to characterize the elemental near-surface composition of the prepared composite surfaces. Examination of the surface compositions will show differences in makeup and identify any transfer of contaminants which occurred during the removal process. Survey and high-resolution scans were made at pass energies of 80 and 20 eV to analyze a $1 \times 0.5\text{-mm}^2$ spot size, using a 100-W monochromatic Al K α (1486.7 eV) beam. The take-off angle was 90°, and all spectra were calibrated according to the hydrocarbon peak at 285 eV. Chamber evacuation was conducted overnight to ensure that any residual moisture was removed from the specimens prior to analysis. A vacuum environment of 2×10^{-9} torr or lower was achieved.

Specimens were cut to $21.7 \times 12.7\text{-mm}$ ($0.5 \times 0.5\text{-in}$) dimensions from the laminates using a Delta International Machinery Corp. (Pittsburg, PA) band saw. Prior to the analysis, specimens were oven dried at 60 °C (140 °F) for 120 min and then stored in virgin aluminum foil. Peel plies were removed from the surfaces immediately prior to insertion into the test chamber.

2.5 Scanning Electron Microscope (SEM) Analysis

Fiber transfer or surface damage from the removal process, and surface wetting characteristics were not apparent by visual examination of the prepared surfaces. For closer examination, a Hitachi S-4700 field emission (FE)-SEM was used to obtain high-resolution images of the specimen surfaces. Specimens representing three types of surface preparations were analyzed: peel ply only, Richmond A-8888 peel ply followed by a grit blast, and grit blast only. Imaging primarily was conducted at 5 kV and 40 $\times$ magnification for a comparative analysis of the prepared surfaces.

Specimens were cut to $21.7 \times 12.7\text{-mm}$ ($0.5 \times 0.5\text{-in}$) dimensions from the laminates using the Delta band saw. The specimens were placed in an oven and dried at 60 °C (140 °F) for 120 min. The peel plies were removed from the surfaces immediately prior to sputter coating. A high-pressure nitrogen gas stream was used to remove loose particulates. In addition, an isopropyl alcohol (IPA) solvent wipe was performed on the grit blast-prepared surfaces. A gold/palladium coating was applied to the surfaces using a Denton DESK V – TSC sputter coater (Moorestown, NJ). Sputter conditions were 40 s at a sputter set point of 40 and 1×10^{-3} torr pressure.

2.6 Lap Shear Testing

Composite-to-composite lap shear tests were conducted to establish initial bond strengths and characterize adhesive behavior at ambient conditions. For this purpose, two series of samples were prepared and tested according to ASTM D 5868–01 (15). This test method is used to determine apparent shear strengths of adhesives between composite-to-composite or composite-to-metal adherends. The test is being used in this study to evaluate composite surface preparation methods. Series 1 contained peel ply-prepared surfaces and an as-tooled virgin surface sample group. Series 2 contained peel ply followed by a grit blast sample groups and a grit-blast-only sample group. Each sample group consisted of six specimens.

Laminates were fabricated to 304.8- × 304.8-mm (12- × 12-in) dimensions and machined into 25.4- × 101.6-mm (1- × 4-in) coupons using the Flow water-jet cutting system. Reference marks were made on the sides of one end of the coupons using a 25.4-mm (1-in)-wide straight edge and permanent marker. Peel plies were removed from the bonding substrates by peeling diagonally from one corner of the coupons. A high-pressure nitrogen gas stream was used to remove loose particulates. The grit-blasting process consisted of three back and forth passes over the entire surface using 180-grit aluminum oxide. The surfaces were wiped with IPA solvent using a wet-wipe followed by a dry-wipe procedure; a visual inspection determined the final wipe to be dust free. The composite surface preparation methods for lap shear testing are summarized in table 5.

Table 5. Composite surface preparation methods for lap shear testing.

Sample Group	Peel Ply Removal	Grit Blast (180-grit Al Oxide)	Blow Off (Nitrogen Gas)	Solvent Wipe (IPA)
Series 1 as-tooled	—	—	—	✓
Series 1 peel ply	✓	—	✓	—
Series 2 grit blast	—	✓	✓	✓
Series 2 peel ply	✓	✓	✓	✓

FM 94K film adhesive was cut into 37.6- × 25.4-mm (1.5- × 1-in) plies using the Gerber cut table. Two plies of FM 94K were tacked to the end of one coupon allowing for 31.7 mm (0.125 in) of overhang on both ends of the joint. The coupons were placed on their sides while the second coupon was applied, ensuring axial alignment of the joint and alignment of the joint ends with the reference mark. Finger pressure was applied to the joint area. A shim was cut from the same laminate as the coupons for placement under the elevated end of the joints. Two plies of FM 94K were tacked to the bottom of the shim to match the thickness of the bonded joints. Assembled joints were arranged on an aluminum tool plate. A schematic of the layup sequence for the lap shear specimens is shown in figure 4. All bonding was conducted according to the cure schedule shown in table 4.

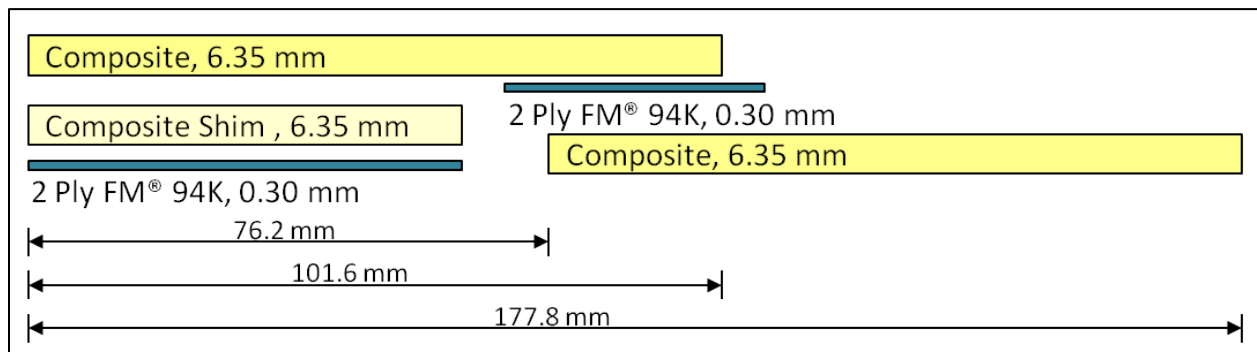


Figure 4. Schematic of the layup sequence for the lap shear specimens.

The sides of the cured adhesive joints were carefully sanded using a Jet Equipment & Tools (Canada) belt sander to remove excess adhesive (figure 5). Specimen dimensions were measured using a Mitutoyo Corp. (Japan) caliper model CD-6 in CSX. Measurements were recorded in three locations in the joint width and one location on each side of the joint length. The averages of these dimensions were used to calculate the bond area. Final bonded joint dimensions were nominally 25.4- × 25.4-mm (1- × 1-in) with a cured adhesive bond thickness of 0.30 mm (0.012 in).



Figure 5. Side view of a fully prepared lap shear sample.

Testing was performed on an Instron (Norwood, MA) model 1123 (System ID 5500R1123) electromechanical test frame equipped with a 25-kN load cell. Tests were conducted at a loading rate of 12.7 mm/min (0.5 in/min) with 25.4 mm (1 in) of each sample end held in the grips, resulting in an initial grip separation of 127 mm (5 in). The initial grip separation used varies from the 76.2 mm (3 in) recommendation in the test standard; however, the minimum requirement of 25.4 mm (1 in) of each sample end held by the grips was met. Specimen tabs were not used.

Lap shear strength is calculated using equation 1 (16):

$$LSS = \frac{P_{max}}{A} \quad (1)$$

where P_{max} is the load at failure, and A is the bond area of the joint.

2.7 Floating Roller Peel Testing

Composite-to-metal floating roller peel tests were used to establish the relative peel strengths and observe the mode of bond failure at ambient conditions. For this purpose, two series of samples were prepared and tested similarly to the recommendation given by ASTM D 3167-10 (17). Each series was prepared separately, and each sample group consisted of six specimens, resulting in a total of twelve specimens for each sample type.

Laminates were fabricated to 356- × 508-mm (14- × 20-in) dimensions and machined into two 152.4- × 203-mm (6- × 8-in) panels using the Flow water-jet cutting system. Series 1 and 2 were prepared separately following identical composite surface preparation procedures. Peel plies were removed from the bonding substrates by peeling diagonally starting at one corner of the

coupons. A high-pressure nitrogen gas stream was used to remove loose particulates. The grit-blasting process consisted of three back and forth passes over the entire surfaces at 8 to 10 in from the surfaces using 180-grit aluminum oxide. The surfaces were wiped with IPA solvent using a wet-wipe followed by a dry-wipe procedure; a visual inspection determined the final wipe to be dust free. The composite surface preparation methods are summarized in table 6.

Table 6. Composite surface preparation methods for floating roller peel testing.

Sample Group	Peel Ply Removal	Grit Blast (180-grit Al Oxide)	Blow Off (Nitrogen Gas)	Solvent Wipe (IPA)
Series 1 and 2 peel ply	✓	—	✓	—
Series 1 and 2 grit blast	—	✓	✓	✓

The flexible metal adherends were cut from clad aluminum alloy 2024-T3 sheet of thickness 0.508-mm (0.020-in) into 152.4- × 254-mm (6- × 10-in) panels using a National (Smartt, TN) pneumatic shear model NA5212. The cut metal panels were degreased and solvent cleaned with acetone. Two grit blast methods were used to prepare the flexible metal adherends so that a comparison of the methods could be made. We assumed that a prestressed state may be created in the test specimens because of grit blasting only one side of the thin metal adherends. Series 1 was prepared by grit blasting only the bonding surface. Series 2 was prepared by grit blasting both surfaces. The grit-blasting process was otherwise identical to the procedure used when preparing the composite surfaces.

The metal adherends underwent silane treatments immediately after grit blasting to improve the interfacial bonding with the adhesive interlayer. This was done in order to promote failure in the adhesive bond line between the composite and metal adherends. The silane treatments consisted of 99 wt-% (90:10 ethanol:H₂O mixture) and 1 wt-% of 3-glycidoxypropyltrimethoxysilane (GPS) (Fluka Sigma-Aldrich, St. Louis, MO). Hydrolysis of the GPS was initiated by adjusting the pH of the ethanol:H₂O to 4.5 with acetic acid. The substrates that underwent silane treatments were sprayed in the solution and kept wet for 1 min (figure 6). They were then dried in a high-pressure nitrogen gas stream to produce a thin, uniform coating (figure 7). The adherends were placed in an oven at 100 °C for 60 min to allow for full condensation and cross-linking of the siloxane groups to the surface oxide of the metal.

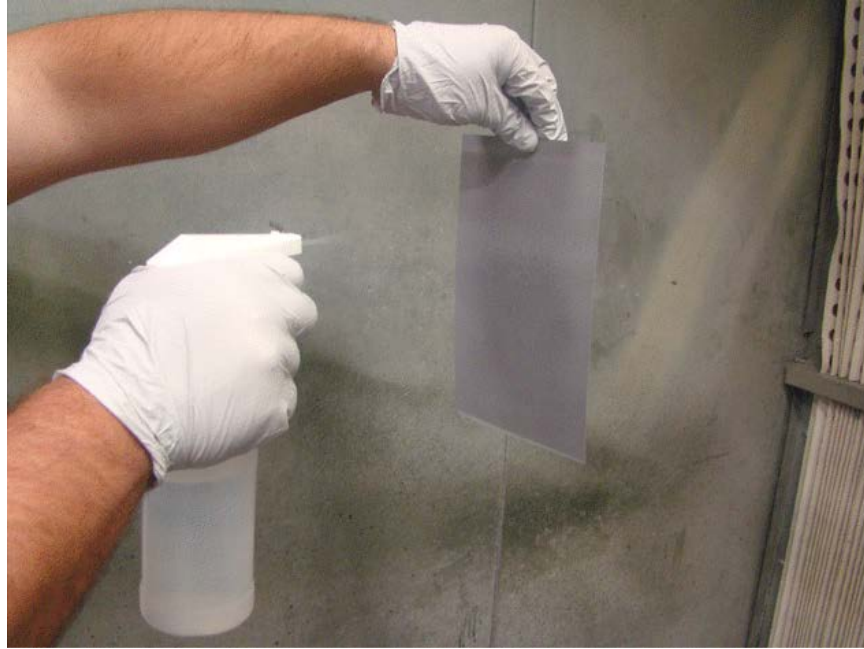


Figure 6. Image of the spray application of GPS silane to the 2024-T3 aluminum alloy flexible adherend.



Figure 7. Image of the high-pressure nitrogen gas stream-drying process to the 2024-T3 aluminum alloy flexible adherend.

Two plies of Flashbreaker*2 pressure-sensitive polyester tape (Airtech) 25.4 mm (1.0 in) wide and 0.075 mm (0.003 in) thick were stacked and applied to the surface at the end of the panel as a crack starter. FM 94K film adhesive was cut into 152.4- × 177.8-mm (6- × 7-in) plies using the Gerber cut table. One ply of FM 94K was tacked to the remaining uncovered composite surface. The flexible metal adherends were tacked to the FM 94K, allowing for 2 in of overhang beyond the end of the joint. Hand pressure was applied to the joint area. Assembled panels were arranged on aluminum tool plates with the metal adherends in contact with the plates. All bonding was conducted according to the cure schedule shown in table 4. A schematic of the layup sequence for the floating roller peel assemblies is shown in figure 8.

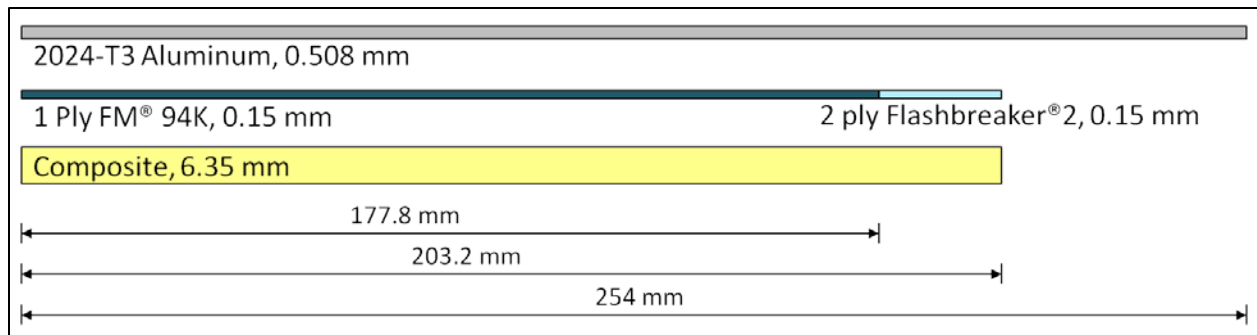


Figure 8. Schematic of the layup sequence for the floating roller peel panel assemblies.

Six 12.7-mm (0.5-in)-wide specimens were cut from the center of each of the bonded assemblies, leaving approximately 1.25-in scrap edges using the Flow water-jet cutting system. Final bonded joint dimensions were nominally 12.7 × 177.8 mm (0.5 × 7 in) with a cured adhesive bond thickness of 0.15 mm (0.006 in). Burrs were carefully removed from the edges of the metal adherends using the Jet belt sander. Specimen dimensions were measured using the Mitutoyo caliper. Specimen widths were measured at locations 63.5 mm (2.5 in), 101.6 mm (4 in), and 139.7 mm (5.5 in) from the end of the composite adherend and recorded. The average width of the specimen in this region was used to calculate the load/width of peeling force over the 76.2-mm (3-in) length of the bond line experienced during testing. Data recorded over the initial 38.1 mm (1.5 in) and final 38.1 mm (1.5 in) of peel length was disregarded in the analysis.

Testing was performed on an Instron model 1123 (system ID 5500R1123) electromechanical test frame equipped with a 500-N load cell. Tests were conducted at a loading rate of 152 mm/min (6 in/min) with 25.4 mm (1 in) of the flexible adherend held in the grip and the composite adherend held tightly against the rollers of the test fixture (figure 9).

*Flashbreaker is a registered trademark of Airtech International Inc.

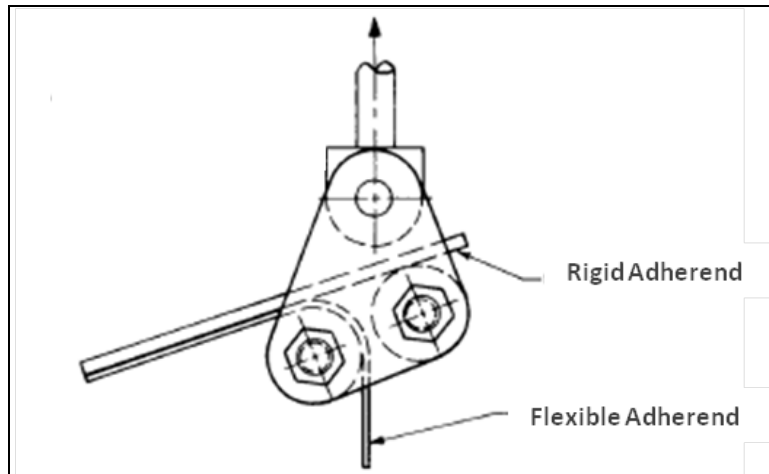


Figure 9. Roller drum peel test fixture (17).

3. Results

3.1 Analysis of Peel Ply Removal

Table 7 shows a qualitative assessment of the force required for peel ply removal in combination with fabric yarn material, coating type, and fabric weave style. The stripping force required to remove the peel plies from the surface refers to the relative force required to manually peel the fabric away from the surface after substantial initiation.

Table 7. Relative stripping force required for peel ply removal listed by material type.

Peel Ply	Yarn Material	Coating Type ^a	Generic Weave Style	Stripping Force Required
Bleeder Lease A	Nylon	Silicone	Open	Medium to high
Bleeder Lease B	Nylon	Silicone	Tight	Medium
Bleeder Lease C	Fiberglass	Silicone	Open	Low
Dahltextx SP-2	Nylon	<i>PTFE</i>	Tight	Medium
Econo Ply E	Polyester	None	Tight	Medium
Bleeder Lease G	Polyester	Silicone	Tight	Low
Hysol EA 9896 WPP	Nylon	Epoxy	Tight	Highest
Richmond A-8888	Nylon	Polyamide	Open	Medium
Superlease Blue	Nylon	Silicone	Tight	Low to medium

^aItalicized values were determined experimentally and were not provided by the manufacturer.

Hysol EA 9896, a tight woven fabric with a preimpregnated epoxy matrix, required the highest stripping force for removal. The open weave fiberglass (Bleeder Lease C) and tight weave polyester (Bleeder Lease G) fabrics coated with silicone required the lowest stripping force. Nylon fabrics coated with silicone generally required moderate force for removal, with the tighter weave styles (Bleeder Lease B, Superlease Blue) facilitating an easier release than the open weave (Bleeder Lease A). The tight weave nylon coated with PTFE (Dahltextx SP-2) and open weave nylon coated with polyamide (Richmond A-8888) required moderate force for removal. The noncoated tight weave polyester (Econo Ply E) also required moderate force for removal.

Observations of the fabrics after removal from lap shear coupons (figure 10) are as follows. All tightly woven fabrics (Bleeder Lease B, Dahltextx SP-2, Econo Ply E, Bleeder Lease G, Hysol EA 9896, and Superlease Blue) were easy to initiate and remove completely intact without edge fraying regardless of release coating. No fiber transfer was visible on the surfaces from these fabrics. Tight weave nylon coated with silicone fabrics (Bleeder Lease B and Superlease Blue) split easily during initiation, primarily because of the razor blade; however, the splitting was not difficult to reverse. The open weave fiberglass coated with silicone (Bleeder Lease C) was moderately easy to initiate, and some fiber transfer was visible on the surface. This fabric has significantly greater thickness than the other fabrics, which most likely contribute to the near intact release. The open weave nylon coated with polyamide (Richmond A-8888) was difficult to initiate; however, once peeling had begun, it removed intact. Some fiber transfer was visible on the edges of the surface. The open weave nylon coated with silicone (Bleeder Lease A) was the most difficult to initiate and to remove intact. Significant fiber transfer was visible on the surfaces particularly near the edges. All fabrics appeared to have wet completely during the infusion process with the exception of Bleeder Lease A, which did not achieve complete wetting /encapsulation through the thickness.

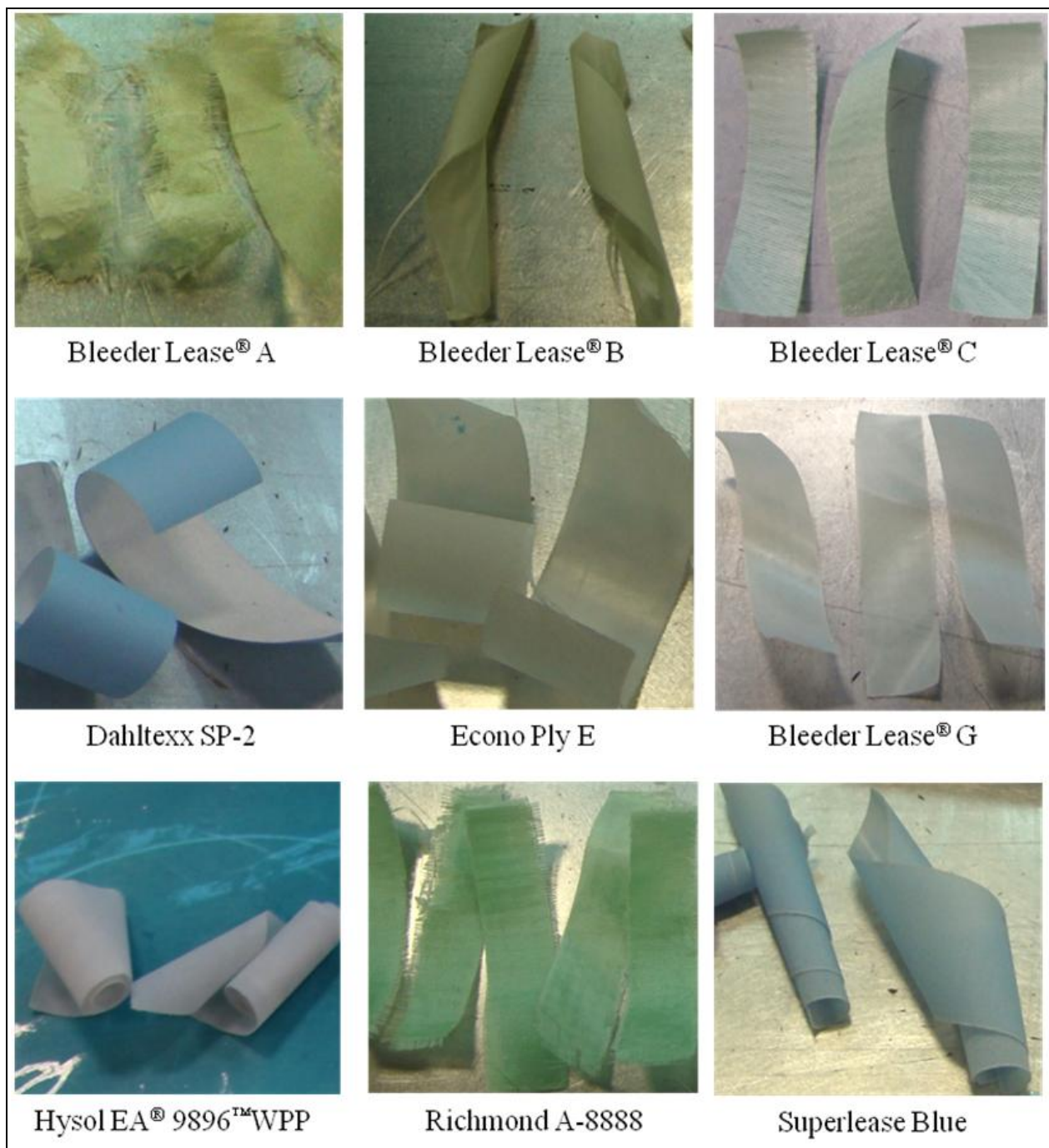


Figure 10. Peel ply fabrics removed from lap shear coupons. All fabrics were removed starting at a cleanly cut square corner edge.

In summary, the qualitative assessment regarding peel ply fabric removal in this study is as follows for this composite system:

- Tight weaves facilitate an easier initiation and more complete removal than open weaves, regardless of the type of release coating.

- Tight weaves require low to moderate stripping force to remove, with the exception of the preimpregnated fabric.
- Tight weave noncoated polyester requires moderate stripping force to remove, most likely because of the inert nature of the fiber.
- Open weave fabric constructions with the lowest end and pick counts (table 3) have an increased tendency to fray along clean cut edges.
- Silicone-coated fiberglass and polyester required the lowest stripping force to remove.
- The open weave silicone-coated nylon fabric showed poor resin wetting/encapsulation.

Because of the significant influence of edge effects on removal characteristics, any visible fiber transfer was removed from the specimen edges prior to additional testing and analysis. This was done by carefully brushing the specimen with a lint-free cloth followed by a high-pressure nitrogen gas stream.

3.2 X-ray Photospectroscopy (XPS) Analysis

XPS results showing the elemental near-surface composition of the substrates after each of the surface preparation methods are shown in table 8. Elements that indicate contamination are shown in the columns highlighted in red. The surface compositions are shown quantitatively as the atomic concentrations detected at the C_{1s}, O_{1s}, N_{1s}, Si_{2s} and Si_{2p}, Cl_{1s}, and F_{1s} shells. The approximate peak binding energy positions for the XPS analysis are as follows: Si_{2p} ~ 100 eV, Si_{2s} ~ 150 eV, C_{1s} ~ 285 eV, N_{1s} ~ 400 eV, O_{1s} ~ 530 eV, and F_{1s} ~ 685 eV. Silicone, chlorine, and fluorine are contaminants that have come into contact with the surfaces as either a result of transfer from the peel plies or from machining operations.

Table 8. XPS results of peel ply and grit blast surface preparations.

Peel Ply	Yarn Material	Coating Type ^a	Atomic %					
			C 1s	O 1s	N 1s	Si 2s and Si 2p	Cl 1s	F 1s
Bleeder Lease A	Nylon	Silicone	73.0	22.2	1.1	3.8	—	—
Bleeder Lease B	Nylon	Silicone	68.3	19.4	1.5	10.8	—	—
Bleeder Lease C	Fiberglass	Silicone	74.8	21.0	0.6	3.6	—	—
Dahltextx SP-2	Nylon	<i>PTFE</i>	74.3	17.2	1.1	—	—	8.0
Econo Ply E	Polyester	None	78.6	21.4	—	—	—	—
Bleeder Lease G	Polyester	Silicone	72.8	22.2	1.1	3.9	—	—
Hysol EA 9896 WPP	Nylon	Epoxy	84.2	12.8	3.0	—	—	—
Grit Blast	NA	NA	78.3	18.6	2.4	0.4	0.3	—
Richmond A-8888	Nylon	Polyamide	76.0	21.5	—	2.5	—	—
Superlease Blue	Nylon	Silicone	74.0	21.8	2.2	2.0	—	—

^aItalicized values were determined experimentally and were not provided by the manufacturer.

Results show varying surface compositions of carbon. The lowest percentage of carbon is found in Bleeder Lease B and the highest in Hysol EA 9896. Hysol EA 9896 also has a significantly lower percentage of oxygen detected. The highest concentrations of nitrogen, although not significantly higher, are observed in Hysol EA 9896, grit blasted, and Superlease Blue preparations with none detected in Econo Ply E or Richmond A-8888. Silicone was detected in all samples except Dahltexx SP-2, Econo Ply E, and Hysol EA 9896. The highest concentration is found in the Bleeder Lease specimens, particularly in Bleeder Lease B. The lowest concentration was found in the grit-blasted specimen, which most likely indicates residual contamination in the grit-blasting equipment. Dahltexx SP-2 shows a high concentration of fluorine. The presence of silicone and fluorine in these specimens is attributable to the release coatings on the peel plies, with the exception of the grit-blasted specimen. The polyamide release agent coating on Richmond A-8888 also appears to contain silicone. Chlorine is also detected at a low concentration in the grit-blasted specimen. This is most likely attributed to water-lubricated machining operations in which the surface was unprotected by any release fabric.

In general, the XPS analysis of the peel ply–prepared surfaces revealed the following:

- Transfer of the release agent was detected from all release-coated fabrics.
- No contaminants were detected from the noncoated polyester fabric or the preimpregnated fabric.
- Significant differences in surface composition of the preimpregnated fabric were noted compared to the dry forms.
- The polyamide release coating also contains silicone.

In addition, two types of contamination were detected in the grit-blasted specimen, most likely from machining operations and the grit blast equipment.

3.3 Scanning Electron Microscope (SEM) Analysis

Imaging at 40× magnification clearly shows texturing, resin wetting characteristics at the tool /peel ply interface, surface damage due to peel ply removal or grit blasting, and signs of significant fiber transfer that occurred. Voids at the surface of the composite generally indicate poor surface wetting and are regular in shape. Damage locations are irregular in shape and occur near void locations. Signs of potential damage from grit blasting resemble uneven erosion of the surface. Fiber transfer is recognizable in two ways: large fibers that are easily identifiable or small fiber tendrils protruding from the surface.

Figures 11 and 12 show large voids and fiber transfer on the composite surface. Small residual fiber tendrils and large fibers protruding from the surface are visible on the surface in figure 12. The moderately irregular surface texture shown in figure 11 may indicate poor fabric wetting observed in section 3.1.

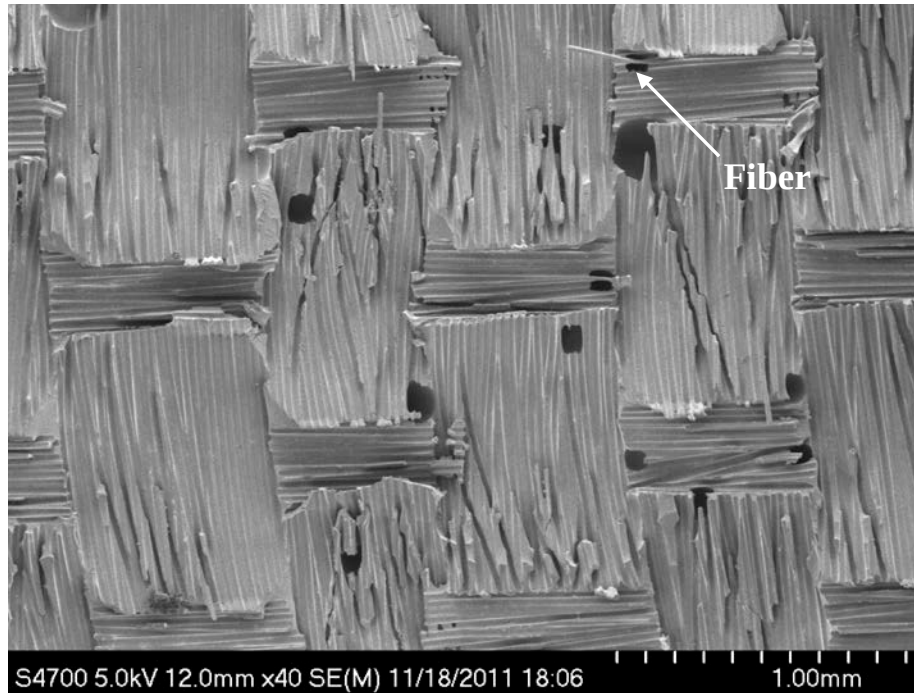


Figure 11. SEM image of composite surface prepared with Bleeder Lease A at 40× magnification.

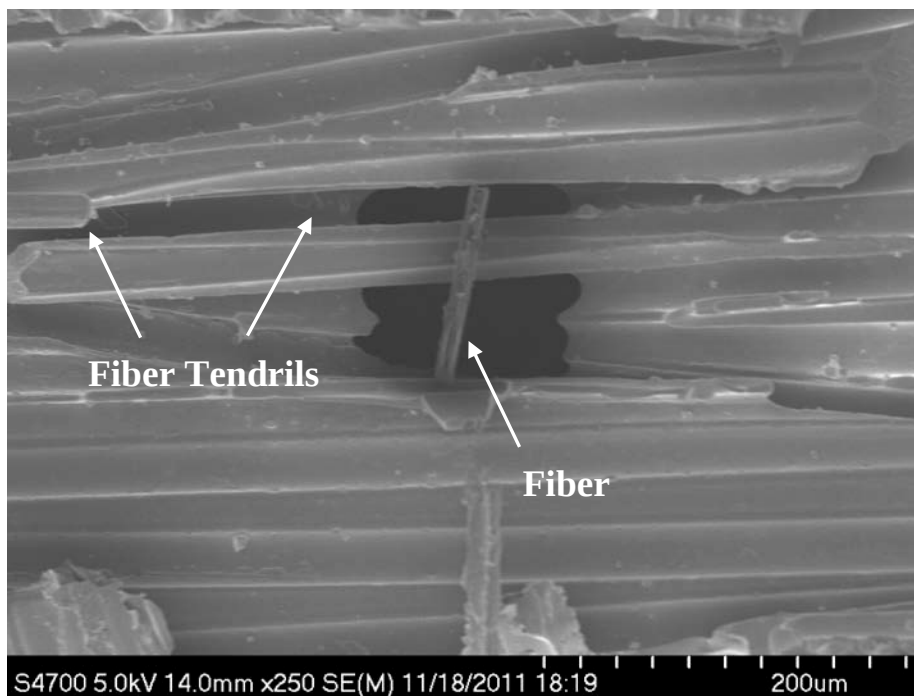


Figure 12. SEM image of composite surface prepared with Bleeder Lease A at 250× magnification.

Figure 13 shows a small amount of voids and fiber transfer on the composite surface. The image shows regular texturing of the surface by the fabric.

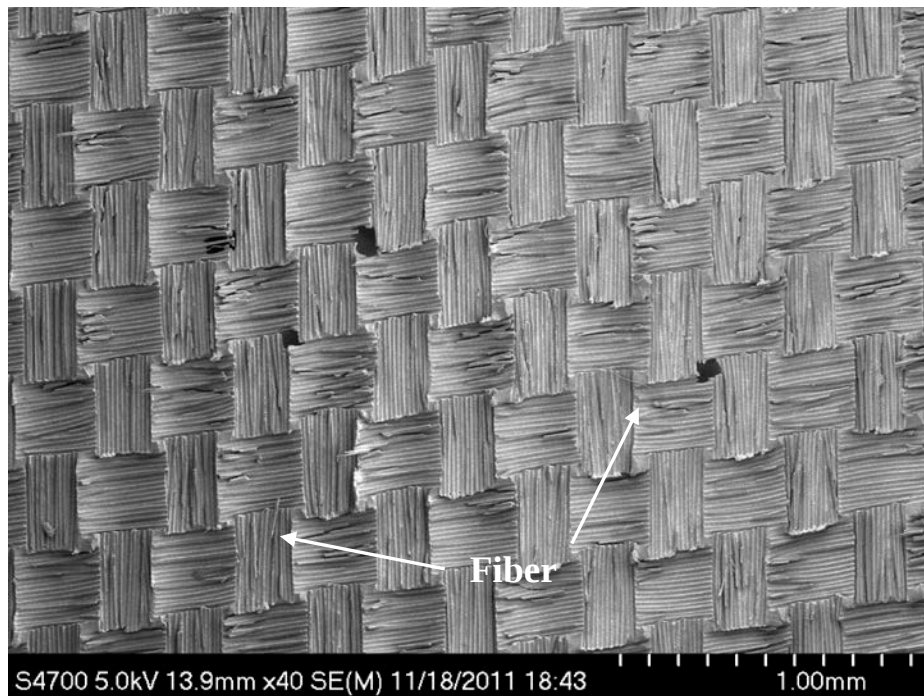


Figure 13. SEM image of composite surface prepared with Bleeder Lease B at 40× magnification.

Figures 14 and 15 show voids and fiber transfer on the composite surface. Figure 14 shows fairly regular texturing of the surface by the fabric and a fiber left behind. The texturing is markedly different than the nylon or polyester textures because of the 7781-style fabric weave. Small residual fiber tendrils and large fibers protruding from the surface are visible on the surface in figure 15.

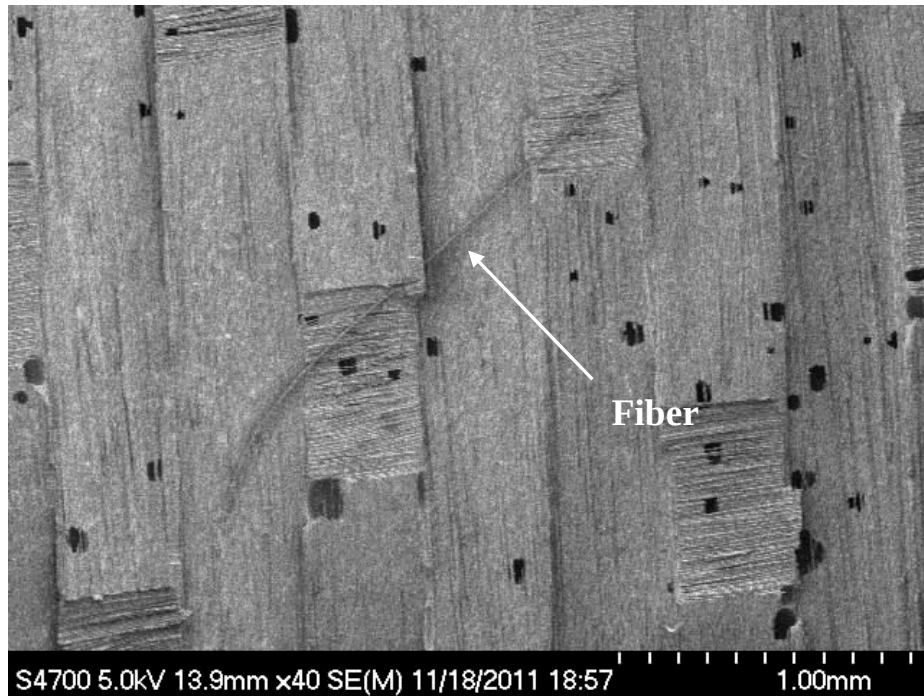


Figure 14. SEM image of composite surface prepared with Bleeder Lease C at 40× magnification.

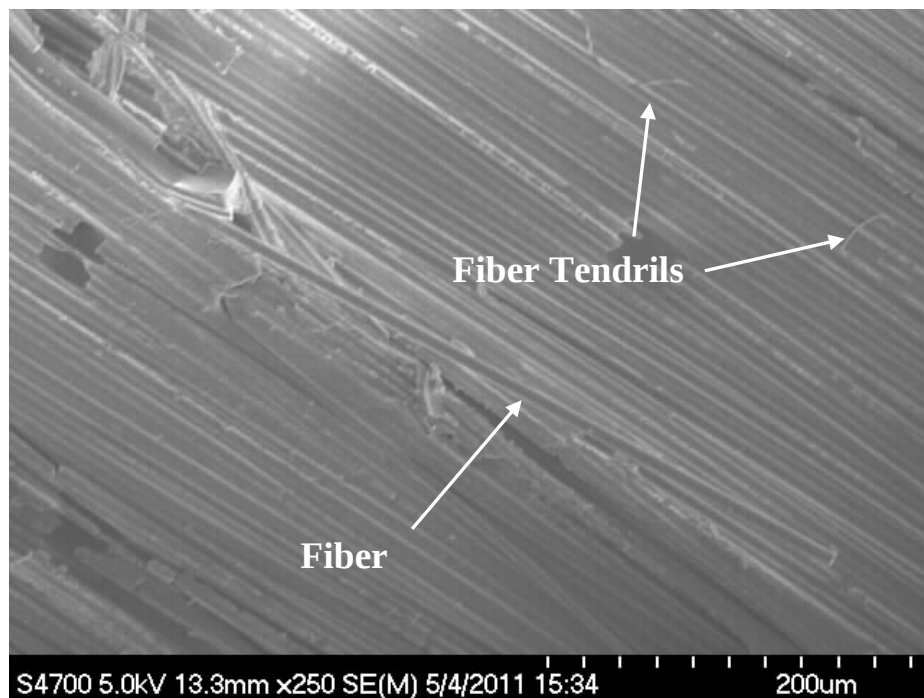


Figure 15. SEM image of composite surface prepared with Bleeder Lease C at 250× magnification.

Figure 16 shows no visible fiber transfer on the composite surface. The image shows complete wetting and regular texturing of the surface.

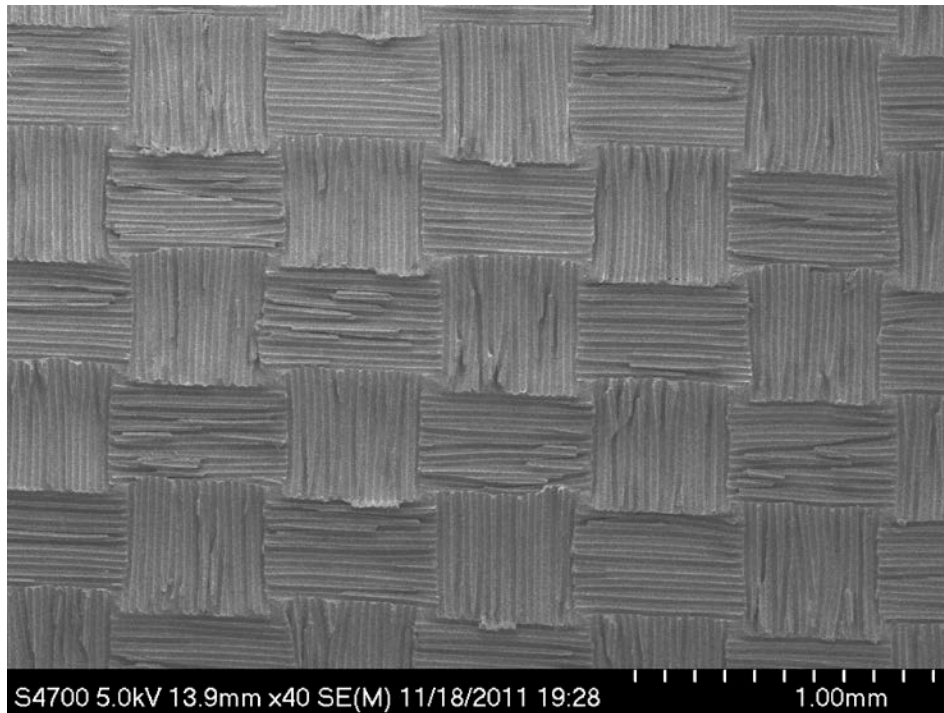


Figure 16. SEM image of composite surface prepared with Dahltextx SP-2 at 40× magnification.

Figure 17 shows large voids and a small amount of fiber transfer on the composite surface. Possible surface damage from the peel ply removal is observed around the void locations. Large areas of exposed reinforcement fibers are clearly visible in these locations. The image shows regular texturing of the surface by the fabric.

Figure 18 shows large voids and fiber transfer on the composite surface. The image shows regular texturing of the surface by the fabric and a fiber left behind.

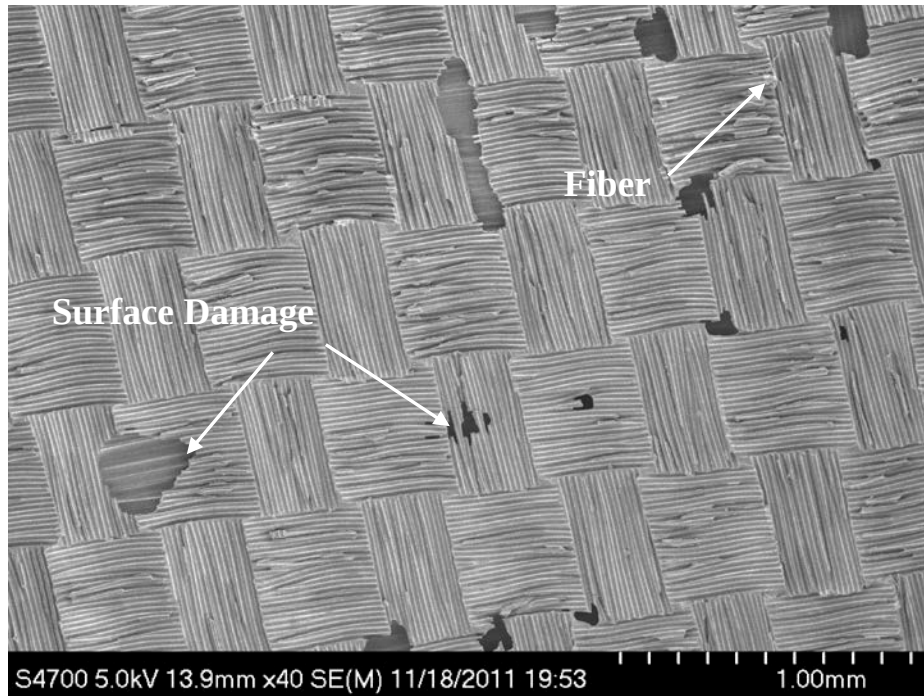


Figure 17. SEM image of composite surface prepared with Econo Ply E at 40× magnification.

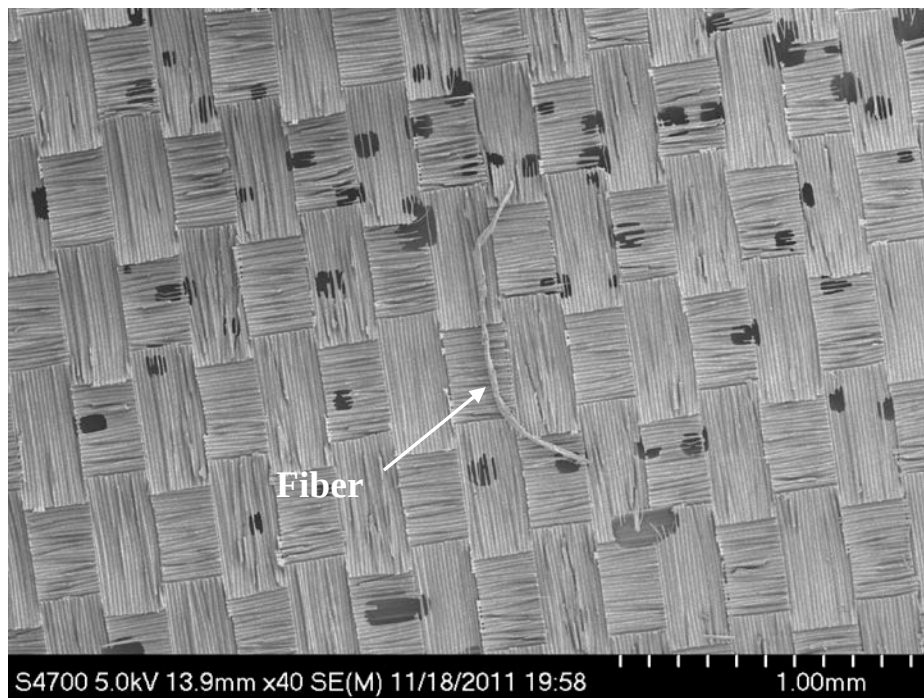


Figure 18. SEM image of composite surface prepared with Bleeder Lease G at 40× magnification.

Figure 19 shows that there is no clearly visible contamination from the blasting process. The image also shows some surface damage from the blasting process.

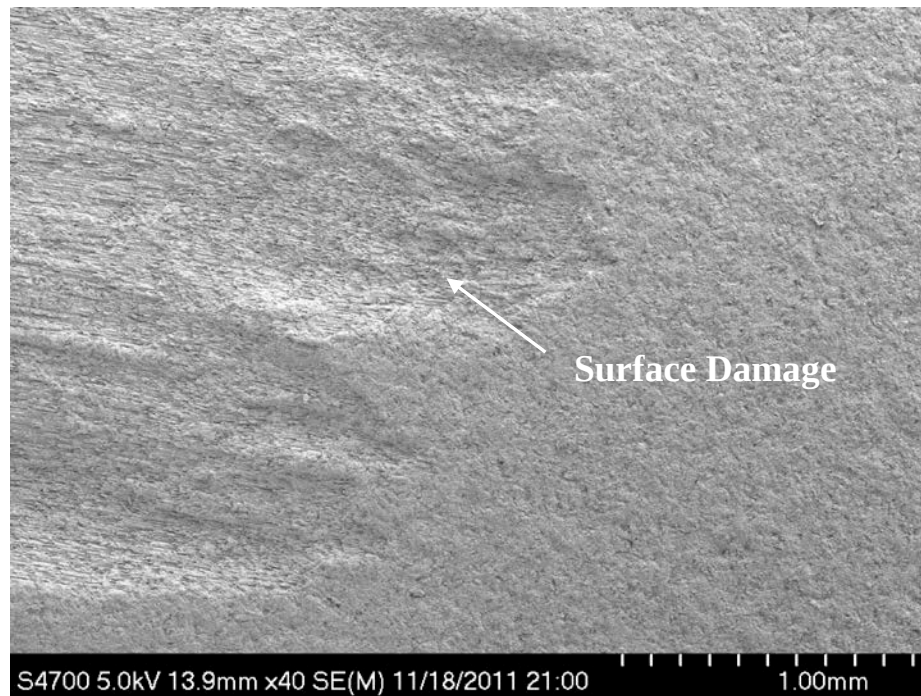


Figure 19. SEM image of composite surface prepared by grit blast at 40× magnification.

Figure 20 shows no fiber transfer, regular texturing, and complete wetting of the composite surface. Figure 21 shows a clean removal and fracture of the epoxy matrix at the composite/peel ply interface.

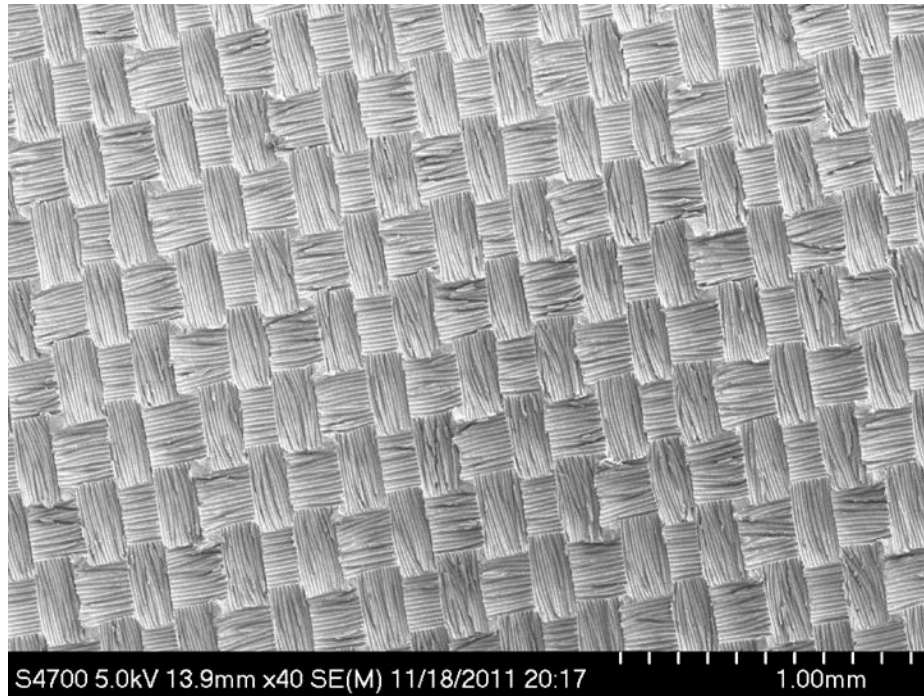


Figure 20. SEM image of composite surface prepared with Hysol EA 9896 at 40× magnification.

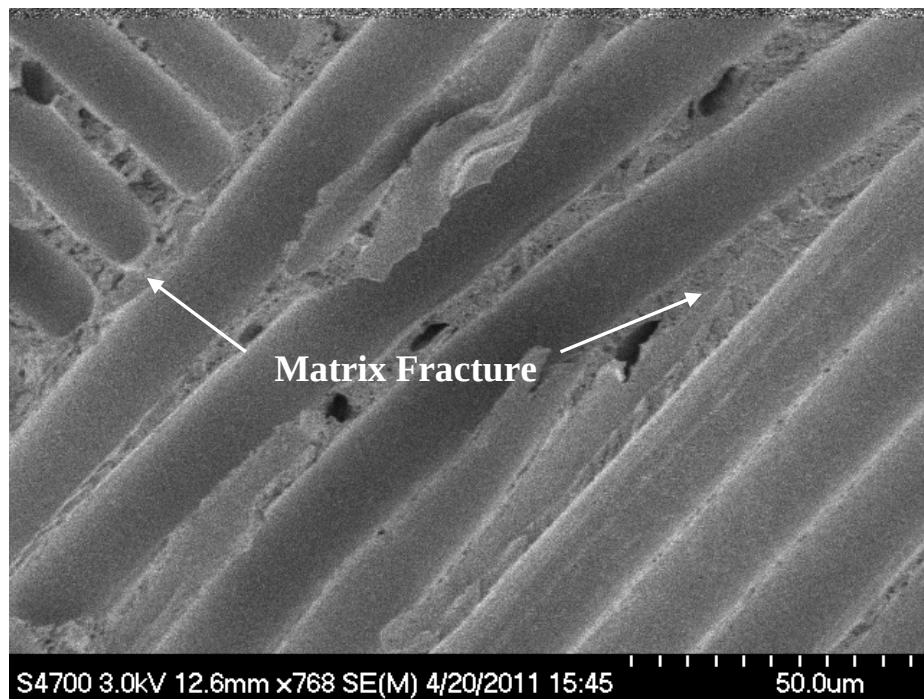


Figure 21. SEM image of composite surface prepared with Hysol EA 9896 at 768× magnification.

Figure 22 shows large voids and no fiber transfer on the composite surface. The image shows fairly regular texturing of the surface by the fabric.

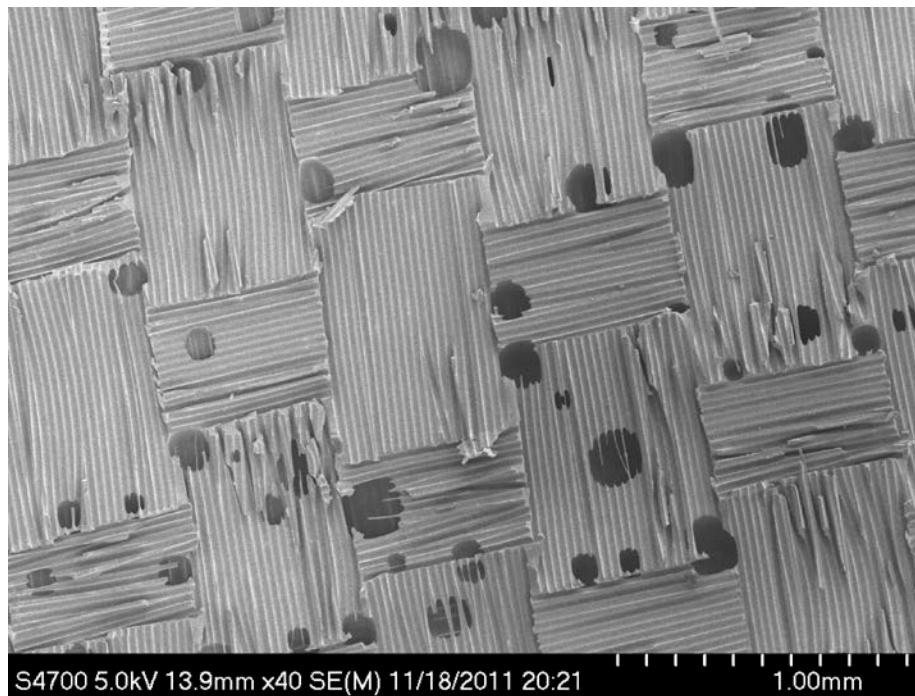


Figure 22. SEM image of composite surface prepared with Richmond A-8888 at 40× magnification.

Figure 23 shows that there is no clearly visible contamination from the blasting process. Fiber reinforcement is not visible in the void locations (figure 23) after the blasting process. The image also shows some surface damage from the blasting process. The surface displays more regular texturing versus the non-grit-blasted peel ply surface (figure 22).

Figure 24 shows a small amount of visible fiber transfer on the composite surface. The image also shows complete wetting and regular texturing of the surface.

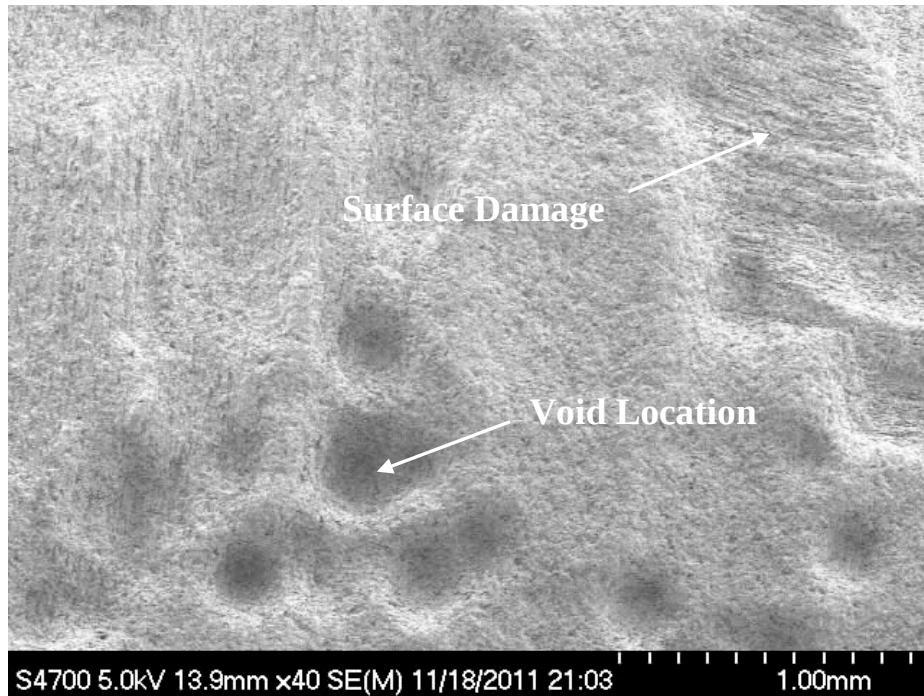


Figure 23. SEM image of composite surface prepared with Richmond A-8888 peel ply and grit blast at 40× magnification.

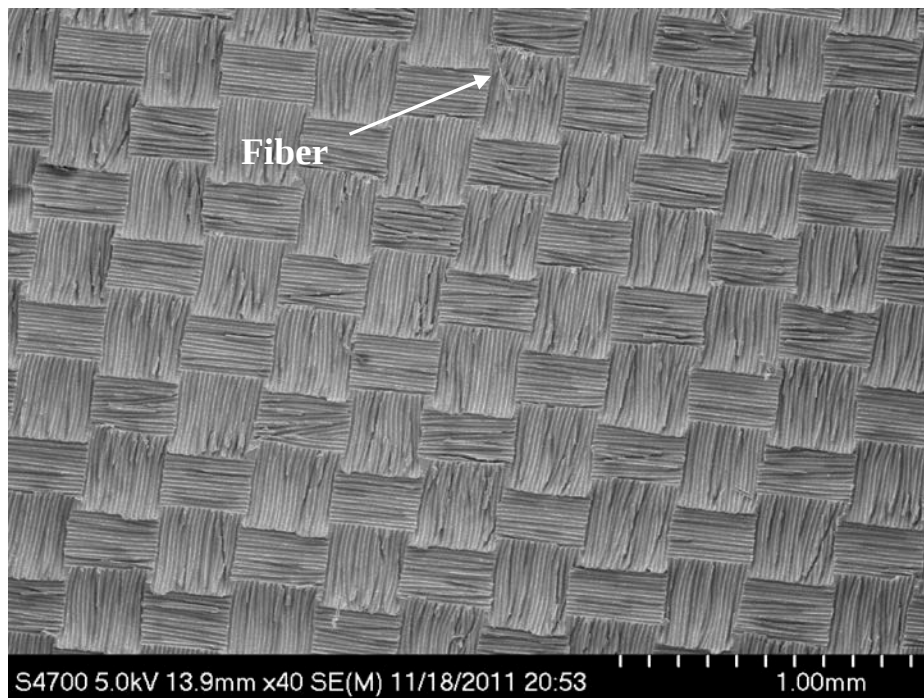


Figure 24. SEM image of composite surface prepared with Superlease Blue at 40× magnification.

In summary, the SEM analysis of the peel ply–prepared surfaces revealed the following:

- Only the three tight weave nylon fabrics showed complete wetting at the composite/fabric interface (Dahltextx SP-2, Hysol EA 9896, and Superlease Blue).
- Fiber transfer was found on the surface of all composites where incomplete wetting was observed, with the exception of the open weave polyamide-coated nylon fabric (Richmond A-8888).
- Matrix fracture at the composite/peel ply interface was clearly shown on the preimpregnated fabric–prepared surface (Hysol EA 9896).
- Surface damage was observed from the noncoated polyester fabric.
- Surface damage was observed from the grit-blasting process.
- All peel plies examined in this work appear to have fractured from the surfaces within the matrix at the composite/fabric interface.

3.4 Lap Shear Testing

The lap shear strength results for series 1 (peel ply prepared) are shown in figure 25 and table 9. Lap shear strengths show two clear groupings in the results. These groups seem distinguishable by a comparison based on fabric weave type. The tight weave fabric preparations had the highest strengths (13.9 to 15.4 MPa) with the exception of Bleeder Lease B, which had an extremely high concentration of silicone on the surface (table 8). The remainder of the group (in addition to Bleeder Lease B), which was found to have lower strengths (11.2 to 12.6 MPa), comprises the open weave fabric preparations. The grit-blasted sample was only slightly higher in strength (12.7 MPa) than the open weave fabric–prepared samples. The preimpregnated fabric preparation (Hysol EA 9896) had the highest strength (15.4 MPa) by nearly a factor of 2 over the as-tooled samples, which had the lowest strength (7.8 MPa).

The results from series 2 (peel ply followed by grit blast) lap shear testing are shown in figure 26 and table 10. Most of the lap shear strengths show reduced standard deviations compared with series 1. A tighter grouping of the different preparations is also observed compared to series 1. All sample groups prepared first by peel ply show higher strengths than the grit blast only–prepared sample. Table 10 shows that some lap shear strengths increased and some decreased by combining peel ply and grit blast preparations. The increases are most likely due to the removal of fiber and release agent transfer after grit blasting. Decreases in strength are not significant and are likely attributable to the small sample size.

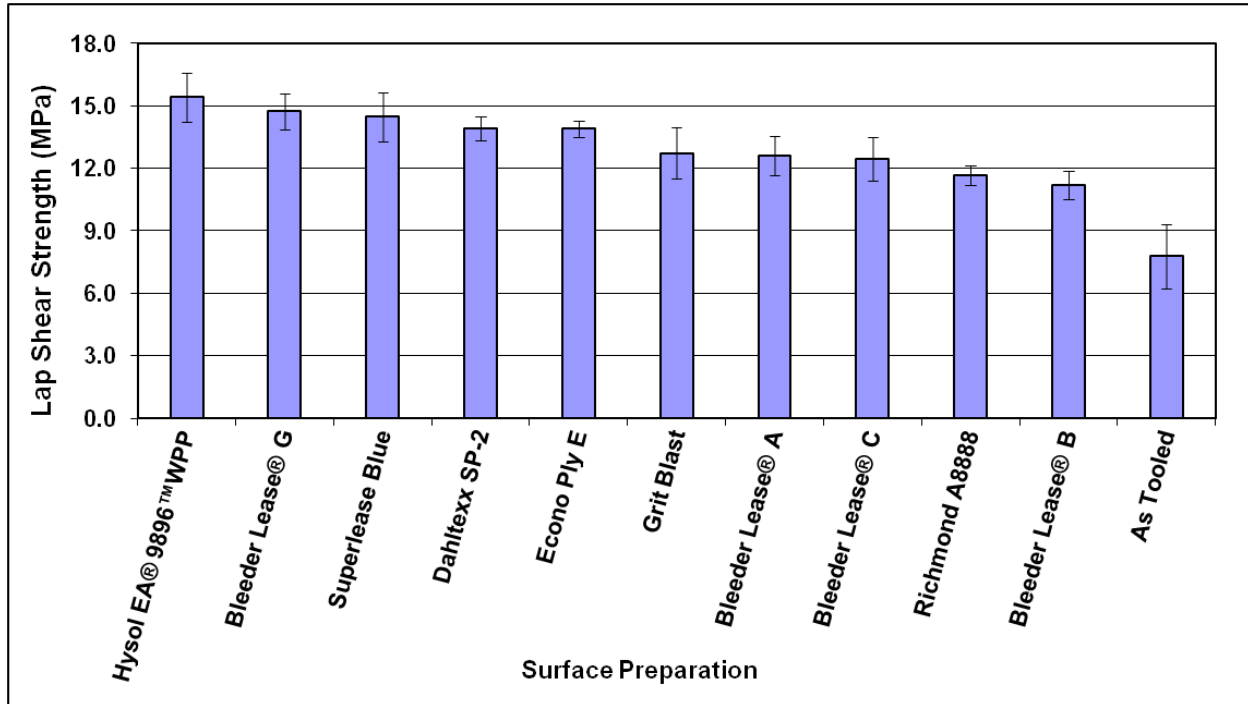


Figure 25. Series 1 lap shear strength results for the peel ply and as-tooled surface preparations plotted vs. the grit blast sample.

Table 9. Series 1 lap shear strength values.

Surface Preparation	Average MPa (psi)	Std. Dev. MPa (psi)
Hysol EA 9896 WPP	15.4 (2235)	1.2 (169)
Bleeder Lease G	14.7 (2136)	0.9 (124)
Superlease Blue	14.5 (2098)	1.2 (172)
Dahltexx SP-2	13.9 (2020)	0.6 (84)
Econo Ply E	13.9 (2016)	0.4 (58)
Grit Blast	12.7 (1845)	1.2 (178)
Bleeder Lease A	12.6 (1828)	1.0 (139)
Bleeder Lease C	12.4 (1804)	1.0 (149)
Richmond A8888	11.7 (1692)	0.5 (166)
Bleeder Lease B	11.2 (1622)	0.7 (98)
As-Tooled	7.8 (1127)	1.5 (224)

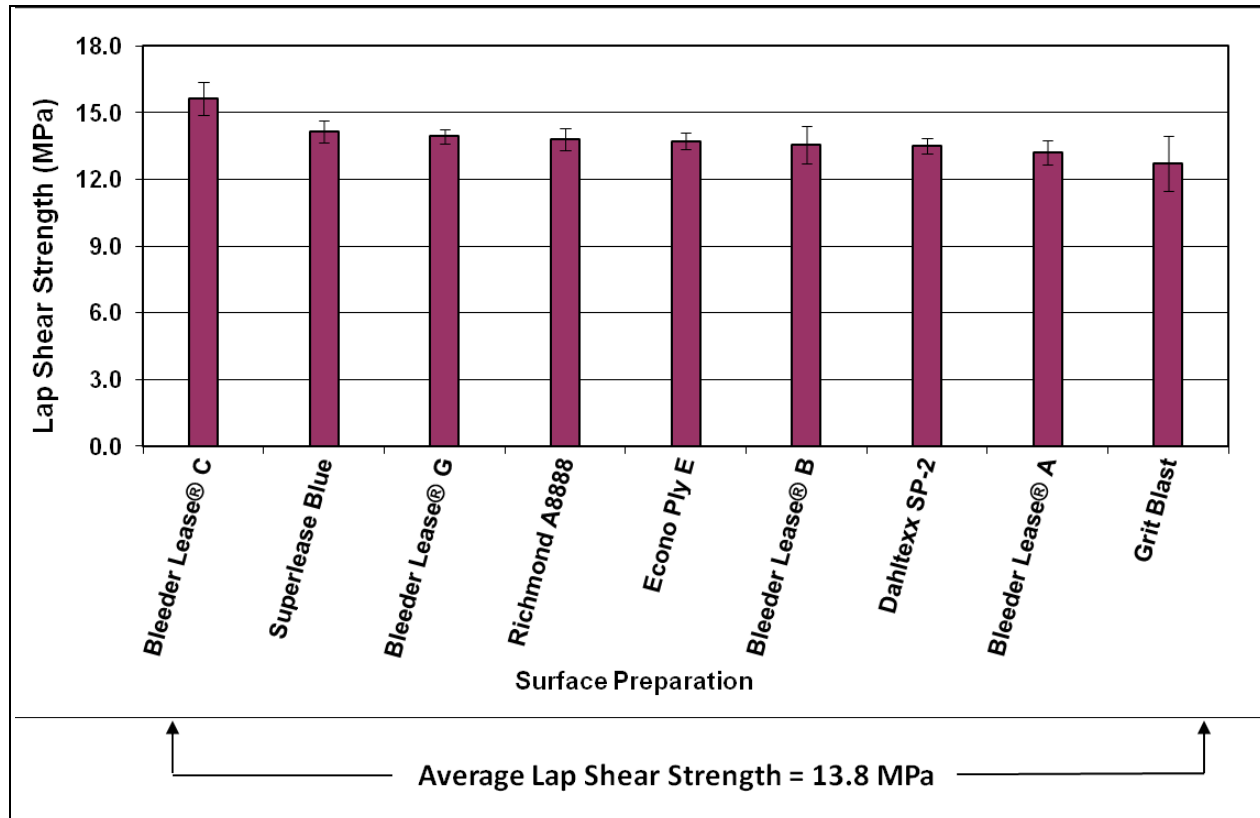


Figure 26. Series 2 lap shear strength results for the peel ply followed by grit blast surface preparations plotted vs. the grit blast sample.

Table 10. Series 2 lap shear strength values.

Surface Preparation	Average (MPa)	Std. Dev. (MPa)
Bleeder Lease C	15.6 (2268)	0.8 (110)
Superlease Blue	14.2 (2054)	0.5 (74)
Bleeder Lease G	13.9 (2021)	0.3 (45)
Richmond A8888	13.8 (2003)	0.5 (75)
Econo Ply E	13.7 (1988)	0.4 (54)
Bleeder Lease B	13.6 (1967)	0.9 (125)
Dahltexx SP-2	13.5 (1957)	0.3 (49)
Bleeder Lease A	13.2 (1917)	0.6 (80)
Grit Blast	12.7 (1845)	1.2 (178)

The failure modes observed for each sample group are shown in table 11. The open weave fabric preparations showed mixed modes of failure in the peel ply only–prepared samples. The tight weave fabric preparations showed cohesive failures. The as-tooled specimen failures were completely adhesive. All grit blast–prepared specimens showed cohesive failure.

Table 11. Primary failure modes observed in lap shear testing.

Surface Preparation	Generic Weave Style	Peel Ply (Series 1)	Grit Blast (Series 2)
Bleeder Lease A	Open	Mixed	Cohesive
Bleeder Lease B	Tight	Mixed	Cohesive
Bleeder Lease C	Open	Mixed	Cohesive
As-Tooled	Tight	Adhesive	—
Dahltextx SP-2	Tight	Cohesive	Cohesive
Econo Ply E	Tight	Cohesive	Cohesive
Bleeder Lease G	Tight	Cohesive	Cohesive
Hysol EA 9896 WPP	Tight	Cohesive	—
Grit Blast	—	—	Cohesive
Richmond A8888	Open	Mixed	Cohesive
Superlease Blue	Tight	Cohesive	Cohesive

3.5 Floating Roller Peel Testing

The angle of peel must be controlled for all specimens tested and is critical for making direct comparisons between samples. To make a valid comparison, the flexible adherend must bend over the mandrel and not at some irregular angle; an irregular angle could result in the angle of peel not being identical (17). Figures 27 and 28 show a specimen showing the proper angle of peel during testing.



Figure 27. Floating roller peel specimen during testing showing the proper angle of peel in the test fixture at the start of testing.



Figure 28. Floating roller peel specimen during testing showing the proper angle of peel in the test fixture at test completion.

Mode of failure is the dominant assessment for this test, more so than failing load. Figure 28 shows a Superlease Blue specimen from series 2 showing cohesive mode of failure in the adhesive. All cohesive failures observed during testing were of this type.

The failure modes observed during floating roller peel testing are shown in figure 29. Cohesive failure in the adhesive at the composite surface was observed for Econo Ply E, grit blast, Hysol EA 9896, and Superlease Blue specimens. Interlaminar failure was observed in Econo Ply E along the specimen edges in all specimens. This failure is most likely attributable to surface damage from the fabric removal process observed in the SEM analysis (figure 17) and edge effects during testing. This was particularly evident in one specimen in which a tracer in the reinforcement fabric was present on the bonding surface along the edge of the specimen. The interlaminar failure clearly tracked the exposed tracer in this specimen, indicating a negative impact of the tracer on composite properties. The failure mode for Bleeder Lease A and Bleeder Lease B was predominantly adhesive at the composite surface with a small percentage of the failure occurring cohesively. Bleeder Lease C, Dahltexx SP-2, Bleeder Lease G, and Richmond A-8888 peel plies produced nearly complete adhesive failures at the composite surface.

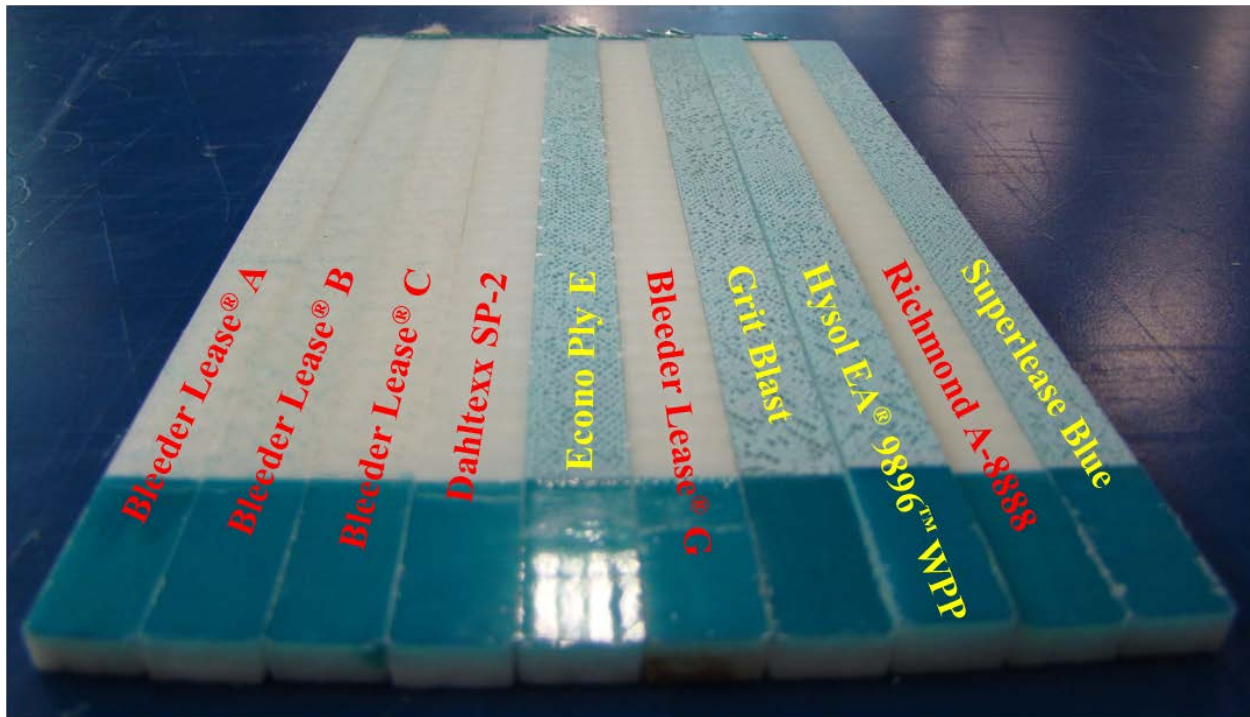


Figure 29. Image of the composite failure surfaces from floating roller peel testing. Red font indicates primarily adhesive failures. Yellow font indicates cohesive failures.

Test data generated during floating roller peel testing showed a valid comparison between Econo Ply E, grit blast, Hysol EA 9896, and Superlease Blue preparations. These samples all displayed the proper angle of peel in the test fixture. In addition, significant plastic deformation was observed in the flexible metal adherends for all of the samples in which cohesive failures were observed. All other surface preparation methods that were tested produced nonvalid strength results for this comparison because of improper angle of peel in the test fixture. Low bond strengths resulting from adhesive failure failed to produce any significant plastic deformation in the flexible metal adherends. This resulted in test data showing negative loading for most of these specimens due to the coupons pressing against the top of the test fixture, rather than being held tightly to the rollers.

The test results for the samples that generated valid results by floating roller peel testing are shown in figure 30 and table 12. The grit-blasted specimens showed the lowest standard deviation of the samples with cohesive failures. Large differences in values between series 1 and 2 for Econo Ply E, Hysol EA 9896 WPP, and Superlease Blue are observed. However, the grit-blasted sample groups do not show this difference. Additionally, the average values of series 1 and 2 are within the standard deviation of the overall average peel strengths. It is difficult to conclusively determine if grit-blasting procedures used on the flexible metal adherend in series 1 versus series 2 had a significant effect on the results.

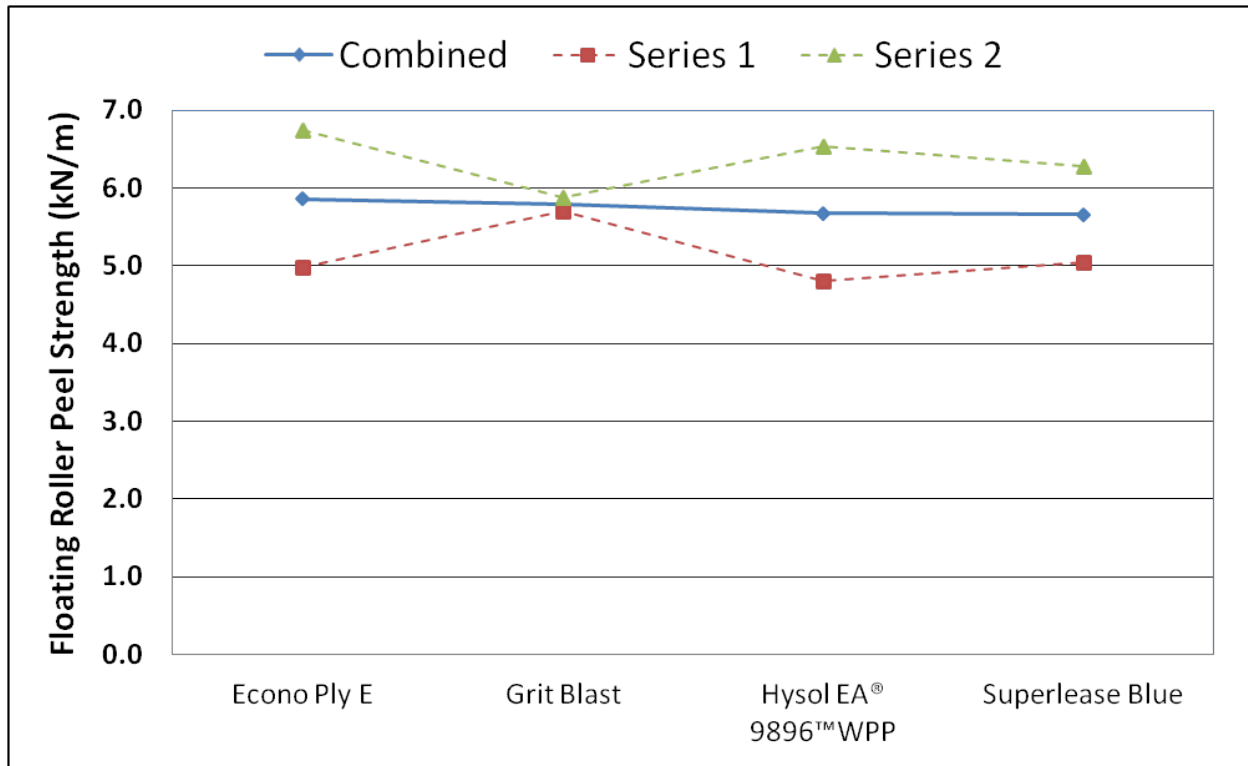


Figure 30. Floating roller peel strength results for the peel ply– and grit blast only–prepared surfaces from which cohesive bond failure modes were observed. Results from series 1, series 2, and the combined averages of all specimens are shown.

Table 12. Floating roller peel strength results.

Surface Preparation	Series 1 kN/m (lbf/in)		Series 2 kN/m (lbf/in)		Combined kN/m (lbf/in)	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Econo Ply E	5.0 (28.4)	0.6 (3.1)	6.7 (38.5)	0.6 (3.3)	5.9 (33.5)	1.0 (6.0)
Grit Blast	5.7 (32.6)	0.5 (2.7)	5.9 (33.6)	1.0 (5.7)	5.8 (33.1)	0.8 (4.5)
Hysol EA 9896 WPP	4.8 (27.4)	0.7 (3.7)	6.5 (37.4)	0.9 (5.4)	5.7 (32.4)	1.2 (6.8)
Superlease Blue	5.0 (28.8)	0.9 (4.9)	6.3 (35.8)	0.9 (5.1)	5.7 (32.3)	1.1 (6.1)

4. Conclusions

Composite surface preparation of S2 fiberglass and SC-15 epoxy composites using commercial peel ply fabrics was evaluated and compared to current grit blast preparation methods. Three peel ply preparation methods (Econo Ply E, Hysol EA 9896 WPP, and Superlease Blue) showed desirable cohesive failures in peel testing. Of these materials, only Hysol EA 9896 WPP showed desirable characteristics in all tests, bond strength, mode of failure, and fabric removal. Grit blast surface preparations showed desirable failures in all tests, although peel ply combined with grit blasting improves strengths over grit blast only. This approach most likely reduces variability in bond performance, provided a clean surface is generated after the peel ply removal and grit blasting. Transfer of release agents was discovered on most of the peel ply-prepared surfaces with the exceptions of Hysol EA 9896 preimpregnated nylon fabric and Econo Ply E noncoated polyester fabric. However, XPS and lap shear results for Hysol EA 9896 WPP indicate significant changes in surface chemistry most likely because of co-mingling of the matrix resins of the system and peel ply. In general, all peel ply fabrics most likely influence surface chemistry. It is unknown how these changes affect important bond properties such as impact and durability in military composite structures. Dry peel ply fabrics are not a desirable single-step surface preparation method for the composite surfaces examined in this study. However, their use is justified, providing a sufficiently clean surface can be obtained by grit blasting prior to bonding. The chemistry of the preimpregnating resin of wet-peel-ply fabrics may be tunable for use with specific material systems to meet the high-durability bond requirements of the U.S. Army. This is a key requirement that could allow for their use in composite bonding for Army applications, therefore allowing a reduction in process steps.

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List of Symbols, Abbreviations, and Acronyms

API	Applied Poleramic Inc.
ARL	U.S. Army Research Laboratory
COTS	commercial off-the-shelf
G _{IC}	strain energy release rate
GPS	glycidoxypopyltrimethoxysilane
IPA	isopropyl alcohol
PTFE	polytetrafluoroethylene
SEM	scanning electron microscopy
VARTM	vacuum-assisted resin transfer molding
WPP	wet peel ply
XPS	x-ray photoelectron spectroscopy

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