DEVELOPMENT OF UNIDIRECTIONAL CARBON PREPREG USING A SOLVENT DIP PROCESS

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ABSTRACT

The vast majority of commercially available unidirectional carbon fiber prepregs are manufactured using a hot-melt process. Prepregs that are manufactured using this process typically yield some of the highest mechanical properties, though this performance comes at a higher price point. A need exists for the development of a unidirectional carbon fiber prepreg that maintains expected mechanical properties while reducing the manufacturing cost. Western Washington University and Norplex-Micarta have partnered together to develop a unidirectional carbon fiber prepreg using a solvent dip process. WWU's laboratory scale solvent prepreg treater system was used to develop an epoxy-based unidirectional carbon prepreg using VectorPly's C-LA-1812 reinforcement system. Prepregs were characterized for resin content, volatile content and resin flow in accordance with Norplex-Micarta testing standards. Resin distribution was determined using non-contact ultrasound (NCU) analysis. Mechanical testing laminates were made using compression molding to test the mechanical properties of the prepreg, including tensile, flexural, and short-beam shear properties in order to establish a direct comparison with other thermoset prepregs that use a hot-melt processing system.

Keywords: Unidirectional, Prepreg, Solvent-dip
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INTRODUCTION

Prepreg is a composite material that consists of a fiber reinforcement, often cloth or tape, that has been impregnated with a resin matrix. [1] It is frequently used in place of traditional hand layups when more control is needed over part quality and reproducibility. Prepreg is manufactured primarily using two processes: solvent dip and hot melt coating. In the case of a solvent-based system, the resin matrix is dissolved in a solvent, commonly an alcohol or acetone, to reduce its viscosity and increase its ability to penetrate the fibers during the impregnation process. In contrast, hot melt prepregging relies upon creation a resin film that is then impregnated into the fibers with a combination of heat and pressure. Although hot melt prepregging is considered the standard within the aerospace industry, solvent-based systems are still in use within many other industries. [2]

Western Washington University has the ability to perform small-scale prepreg manufacturing runs, using their solvent-based, laboratory scale prepreg treater. This machine was designed and built to test new prepreg materials (both matrix and reinforcement) at on a laboratory scale in order to reduce overhead and minimize waste associated with production scale testing. Additionally, the machine was designed to be easily reconfigurable in order to incorporate experimental manufacturing technologies, in order to expand the range of materials that can be studied.

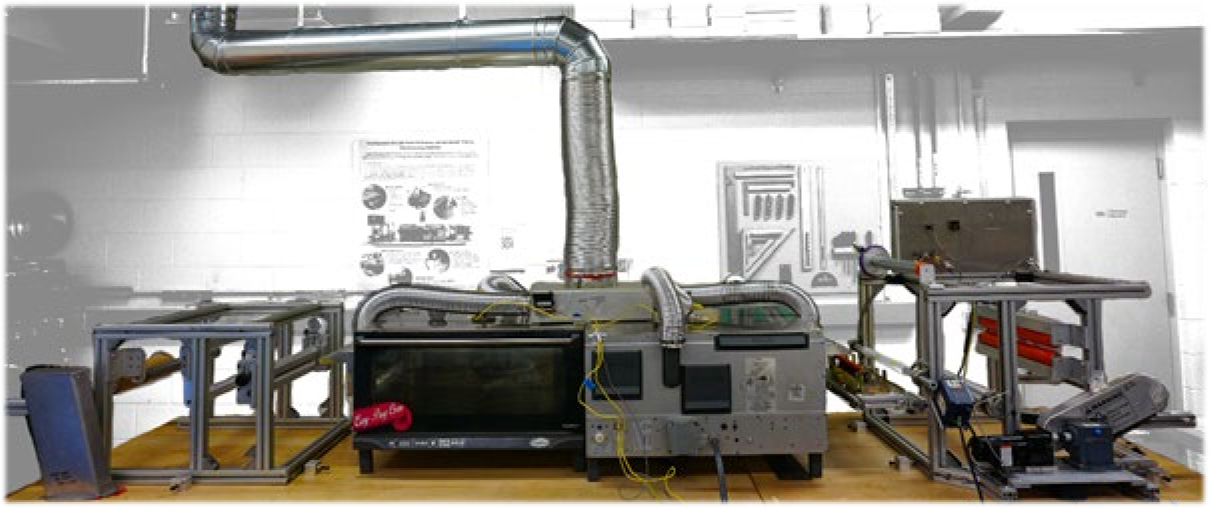

Figure 1. WWU's reconfigurable solvent treater system

Although unidirectional carbon fiber prepregs are traditionally manufactured using a hot melt coating process, solvent-based prepreg manufacturing methods offer an advantage in terms of production cost. The mechanical properties of solvent-based prepregs are typically not appropriate for aerospace applications, however there is an increasing market for moderate-cost, moderate-performance composite materials, such as those produced via solvent-prepregging. Despite this growing need, solvent-based unidirectional prepregging remains largely unstudied, likely due to the challenges associated with large scale experimentation.

In this research, Western Washington University (WWU) and Norplex-Micarta partnered to study the development of a solvent-based unidirectional prepreg system. This work included small-scale testing of a variety of unidirectional fiber reinforcement systems to determine viability for solvent based prepreg, laboratory-scale prepreg manufacturing runs, and the fabrication and mechanical testing of composite laminates using WWU made solvent-dip prepreg. The outcomes of the project will be used to conduct full-scale manufacturing runs without the need for wasting resources, including time and materials.

Initial experimentation into solvent-based unidirectional carbon fiber prepreg by Norplex-Micarta found that the structural integrity of unidirectional fiber reinforcement systems becomes a problem during the solvent-dip prepregging process, which can be seen in Figure 2 below. This necessitated significant consideration of appropriate unidirectional fiber systems for solvent processing as the starting point for this research. In this paper, small-scale testing refers to "prepreg" production in a non-continuous method that uses less than 1 meter of fiber reinforcement. This testing was performed to eliminate fiber systems that produce significant tow separation during processing. In contrast, laboratory-scale testing refers to continuous manufacturing of prepreg on WWU's solvent treater where at least 9 meters of fiber reinforcement are needed.

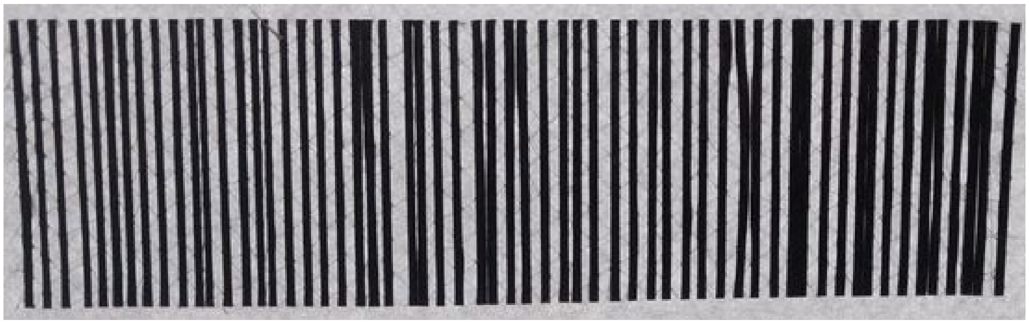

Figure 2. Severe tow separation and deterioration of structural integrity from the solvent-dip prepregging process.

EXPERIMENTATION

2.1 Materials

All materials for the project were purchased by Norplex-Micarta and sent to WWU for testing and prepreg development. The focus was to identify fiber reinforcements that would survive a solvent-dip treater, while less focus was given on modifying the resin system used.

2.1.1 Epoxy Resin

A solvent-based epoxy resin system with a proprietary composition was provided by Norplex-Micarta and was used for all production runs of unidirectional carbon prepreg. The epoxy in this formulation is an undiluted difunctional bisphenol A and epichlorohydrin derived liquid matrix system that was cured with a difunctional aromatic amine. The resin system when cross-linked boasts good mechanical, adhesive, and chemical resistance properties.

2.1.2 Fiber Reinforcement

Two variations of unidirectional carbon fiber reinforcements were investigated during the project. The first was a custom unidirectional carbon reinforcement manufactured by Atkins and Pearce (A&P) consisting of 3k carbon tows with a polyimide weaving at a 45° angle from the tow orientation. The areal weight of the A&P reinforcement system was 659 gsm and came on a roll that was 25.4 cm wide.

The second unidirectional carbon fiber reinforcement system that was investigated for testing was a commercially available product, VectorPly's C-LA 1812. [3] This reinforcement system consisted of carbon tows with an areal weight of 606 gsm in the warp direction and an attached chopped mat with an areal weight of 41 gsm and came on a roll that was 127 cm wide.

2.2 Prepreg and Composite Manufacturing – Small Scale

Due to the lack of literature surrounding the manufacturing of unidirectional prepreg, small-scale testing was performed to select a fiber reinforcement system for laboratory-scale testing. Samples of VectorPly and A&P fiber reinforcements were acquired for small-scale testing in order to select a material for laboratory-scale prepreg runs. After selecting a fiber reinforcement system and performing a treater run, the resulting prepreg was characterized for basic prepreg material properties. Mechanical properties were tested by manufacturing testing laminates and cutting test specimens from those laminates.

2.2.1 Prepreg Manufacturing – Small-Scale Testing

Test fixtures were created to closely mimic the processing variables available on WWU's solvent treater system, including line tension, line speed, oven temperatures, and pinch roller spacing. Fiber reinforcement samples from both the A&P and VectorPly materials were cut to 7.6 x 30.5 cm in dimension. Compounded resin was hand stippled into the middle of the sample and the sample was loaded into the test fixture as seen in Figure 3 below. The sample was then B-staged using the processing parameters in Table 1 below.

Figure 3. Small-scale testing fixture placed inside of oven #1 of WWU's solvent treater system.

Table 1. Small-scale testing parameters that replicate three of four processing parameters available on WWU's solvent treater.

Oven Temperature (°C)	Pinch Roller Spacing (cm)	Residence Time (mm:ss)	Residence Time Equivalent Line Speed (cm/min)
113	0.064	10:00	16.5

2.2.2 Prepreg Manufacturing – Laboratory-Scale Testing

Two prepreg manufacturing runs were conducted on WWU's laboratory scale treater. Based on the results of the small-scale tests, the VectorPly C-LA 1812 was selected for the laboratory-scale treater runs. WWU's solvent treater has a total of four processing variables that can be modified: oven temperatures, pinch roller spacing, line speed, and line tension. The processing parameters use for both production runs can be seen in Table 2 below. Further information regarding WWU's treater can be found in *Development of a Solvent-Based Prepreg Treater* by Larson et al (ASEE 2015). [4]

Table 2. Processing parameters for both laboratory-scale treater runs.

Oven #1 (°C)	Oven #2 (°C)	Pinch Roller Spacing (cm)	Line Tension (N)	Line Speed (cm/min)
110	110	0.10	44.48	15.24

WWU's solvent treater can accommodate fiber reinforcements up to 40.6 cm wide. In order to meet this requirement, the VectorPly C-LA 1812 reinforcement was manually cut to a width of 30.5 cm. During the cutting process, the tows at the cut site were damaged and without securing the damaged area, individual fibers would flow out of the tow bundle during wet out. To mitigate this, a new selvedge edge was created by sewing the damaged tows to a 1.9 cm wide fiberglass tape with polyester sewing thread in a zig-zag pattern.

Figure 4: Left: Fiber fraying seen from damage tows after cutting. Right: Zig-zag pattern securing damaged tows to fiberglass tape.

2.2.3 Laminate Manufacturing

All mechanical testing laminates were manufactured using a Wabash 20-ton compression molder. Processing parameters for these laminates were based off Norplex-Micarta processing parameters and a cold-in-cold-out cycle was selected. Processing parameters can be found in Table 3 below.

Table 3. Compression molding processing parameters for mechanical property test laminates.

Target Pressure (KPa)	Starting Temperature (°C)	Hold Temperature (°C)	Hold Time (min)	End Temperature (°C)
552	18-21	165	65	18-77

2.3 Prepreg Characterization

The prepreg that was manufactured was characterized for resin content, resin flow, and volatile following Norplex-Micarta specifications. Resin distribution was determined using WWU non-contact ultrasound (NCU) procedures.

2.3.1 Resin Content

10x10 cm samples of prepreg were cut from the start, middle, and end of the production run to understand how resin content changed over the run. Resin content was calculated using Eq.1, where W_{prepreg} represents the weight of the prepreg sample and $W_{\text{dry reinforcement}}$ represents the weight of the sample before the prepregging process. [5]

$$\text{Resin Content} = \frac{(W_{prepreg} - W_{dry\ reinforcement})}{(W_{prepreg})} \times 100\% \qquad \text{[Eq. 1]}$$

2.3.2 Volatile Content

10x10 cm samples of prepreg were cut from the start, middle, and end of the production run to understand how volatile content changed over the run. The samples were placed in a ThermoFisher Heratherm oven for 15 minutes at 160°C. Upon exiting the ovens, the samples were placed in a container with desiccant to prohibit moisture uptake in the samples. Volatile content was calculated using Eq.2, where W_{initial} represents the weight of the prepreg sample and $W_{\text{post 15 min cure}}$ represents the weight of the sample after exiting the oven. [5]

$$\text{Volatile Content} = \frac{(W_{initial} - W_{post\ 15\ min\ oven\ cure})}{(W_{initial})} \times 100\% \qquad \text{[Eq. 2]}$$

2.3.3 Resin Flow

10x10 cm samples of prepreg were cut from the start, middle, and end of the production run to understand how resin flow changed over the run. Three samples were then stacked into a laminate with the following ply schedule: [0/90/0]. The laminate was then placed in between high temperature release film and loaded into a Model C Bench Top Manual Carver Laboratory Press for 6 minutes with an applied pressure of 8274 KPa and a temperature of 160°C. Upon removal from the press, the excess resin flow was removed from the edge of the sample. Resin flow was then calculated using Eq.3, where W_{laminate} represents the weight of the laminate prior to the press cure and $W_{\text{post cure}}$ represents the weight of the laminate post press cure and after the excess resin was removed. [5]

$$\text{Resin Flow} = \frac{(W_{laminate} - W_{post\ cure})}{(W_{laminate})} \times 100\% \qquad \text{[Eq. 3]}$$

2.3.4 Resin Distribution

Resin distribution was determined using an Ultran Group laboratory-scale NCU located in WWU's polymer analysis lab. Representative 10x10 cm samples from the start, middle, and end of the production run were scanned using a frequency of 500kHz at an intensity of 45.0 dB. The NCU scans and records the decibel transmittance through every square millimeter of the sample.

2.4 Mechanical Testing

Mechanical testing was performed for the unidirectional prepreg in order to establish baseline mechanical properties. Each test required multiple laminates to be produced in order to account for panel-to-panel variation in the laminate manufacturing process. Tensile testing was performed on an MTS Insight 100, with a maximum force capacity of 100kN. Both the flexural and short-beam shear testing was performed on a Sintech 5/GL, with a maximum force capacity of 22 kN. Test specimens were cut from the laminates using a DeWalt Tile Saw with a diamond-carbide tipped blade. The critical dimensions for all test specimens and laminates can be found in Table 4 below. Longitudinal test specimens had fiberglass/epoxy tabs installed following procedures from *Tabbing Guide for Composite Test Specimens* by Adams et al (FAA 2002). [6]

Table 4. Mechanical testing specimen specification and design criteria. [7] [8] [9]

Mechanical Test	Specimen Dimensions (cm)	Laminate Dimensions (cm)	Specimens Tested	Ply Count	Testing Machine	Fixture	ASTM Standard
Tensile Longitudinal	25.4 x 1.3	30.5 x 30.5	20	6	MTS Insight 100	Tensile Grips	D3039 D3039M
Tensile Transverse	17.8 x 2.5		24	8			
Flexural Longitudinal	14.0 x 1.3		24	5	Sintech MTS 5/GL	Three-Point Bend	D790
Flexural Transverse	14.0 x 1.3		24	5			
Short-Beam Shear	2.6 x 0.86		20	6			D2344 D2344M

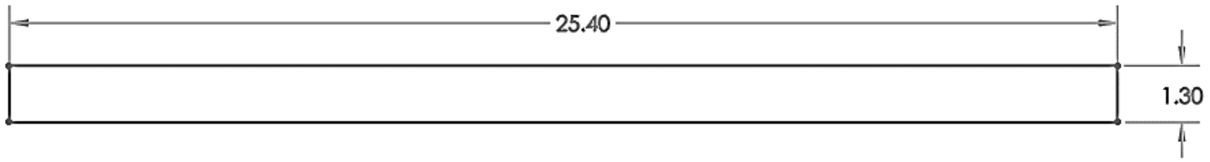

Figure 5: Dimensions for longitudinal tensile test specimens [7]

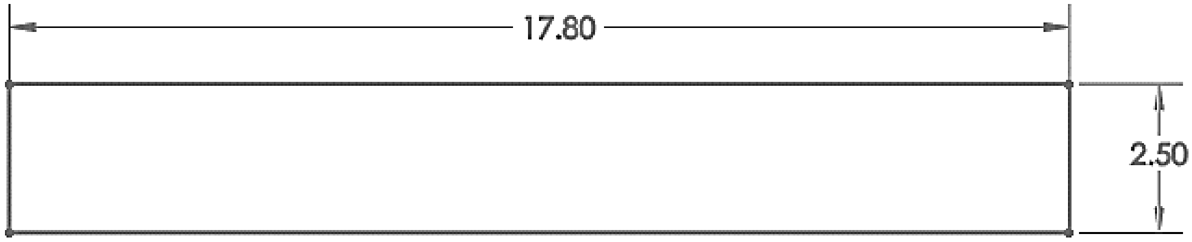

Figure 6: Dimensions for transverse tensile test specimens [7]

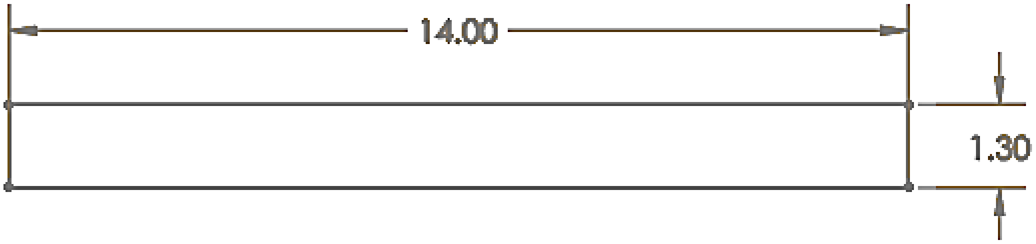

Figure 7: Dimensions for longitudinal and transverse flexural test specimens [8]

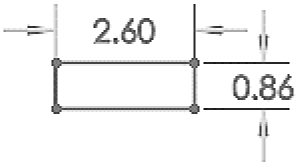

Figure 8: Dimensions for short-beam shear test specimens [9]

RESULTS

3.1 Small-Scale Prepreg Analysis

As previously mentioned, the lack of existing literature regarding the manufacturing of unidirectional prepreg using a solvent dip process warranted the use of small-scale testing to identify a suitable fiber reinforcement system for larger laboratory-scale testing. Small-scale testing required substantially less material and time to identify appropriate fiber reinforcement systems. By manually impregnating small samples of prepreg and B-staging them in similar processing conditions as WWU's solvent treater, the samples were produced that could be characterized for resin content, volatile content, and the average gap size between tows were determined. Those specifications were used to justify fiber reinforcement selection for laboratory scale testing.

3.1.1 Tow Gap Size

Early small-scale tests with the custom A&P unidirectional reinforcement system found that during the impregnation step, the cross-sectional area of the carbon tows changed, and gaps developed between the tows. Typically, with commercially available unidirectional prepregs, no gaps are found between the tows. Therefore, one of the goals of the project was to mitigate the development of gaps. Early small-scale tests with the VectorPly C-LA 1812 showed that the degree of tow separation was less than that of the custom A&P fiber reinforcement due in part to the attached fiberglass veil.

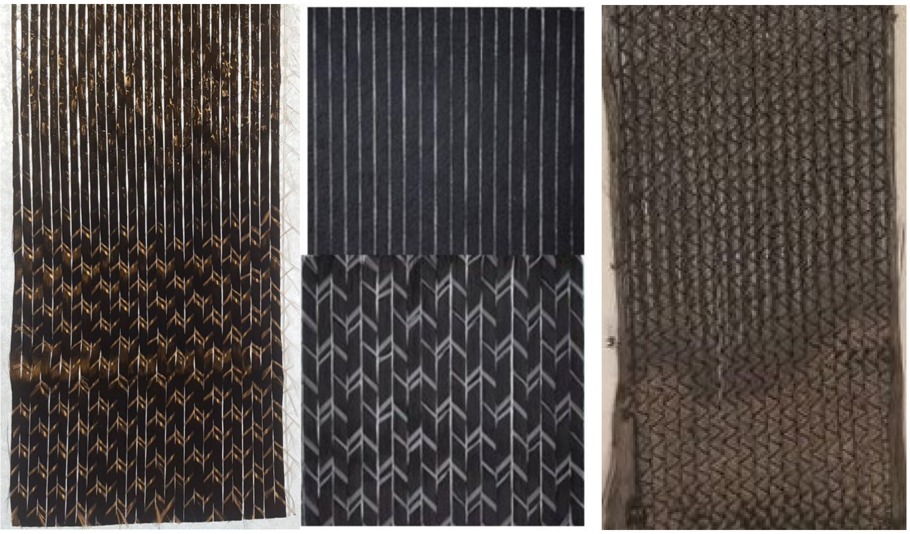

Figure 9. Left: Small-scale A&P prepreg without an attached veil. Middle: Small-scale A&P prepreg with an attached veil. Right: Small-scale VectorPly C-LA 1812 prepreg

To test the impacts of attaching a veil to the fiber reinforcement system, a lightweight 7 gsm carbon fiber veil was attached using a ChemInstruments HLCL-1000 laminator system. The custom A&P test samples with veil were then used for small-scale testing. The far-left image in Figure 9 shows the transition from dry fiber to prepreg for the custom A&P fiber reinforcement without an attached veil. The image in the middle of Figure 5 shows the dry fiber on the bottom and a sample of prepreg made with the custom A&P fiber reinforcement with an attached veil. There is a distinct difference in the magnitude of the tow spacing between the two samples with the fiber reinforcement with a veil having nearly maintained the tow spacing of the dry fabric.

ImageJ was used to calculate the average gap spacing for each of the materials. For the A&P small-scale prepreg with an attached veil, the average gap size was 0.019 cm ± 0.003 cm. This gap increased compared to the average gap size of the dry reinforcement, which was 0.011 cm prior to the resin impregnation process. The increase in tow gap size is attributed to the capillary action of the resin as it interacts with the surface of the individual tows.

The next fiber reinforcement system that was tested using small-scale testing methods was the VectorPly C-LA 1812. This fiber reinforcement system was selected for testing due to the lightweight 41 gsm fiberglass veil that is attached to one side of the fibers. The VectorPly C-LA 1812 had an average tow gap size of 0.0051 cm prior to the resin impregnation process and an average tow gap size of 0.006 cm ± 0.002 cm after.

Table 5. Average tow gap sizes before and after prepregging process (small-scale).

Specimen Condition	**Custom A&P with Veil**	**VectorPly C-LA 1812**
Dry Reinforcement (cm)	0.011	0.0051
Resin Impregnated (cm)	0.019 ± 0.003	0.006 ± 0.002

3.1.2 Resin Content

While the main goal for small scale testing was to identify a reinforcement system that mitigates the development of tow separation, the resin content was also measured in order to better understand the effectiveness of the small-scale testing system to manufacture quality prepreg. The average resin content for the custom A&P samples was 36 ± 5%, and the average resin content for the VectorPly C-LA 1812 samples was 39 ± 5%. Both of these values were slightly below Norplex's specification of 40 - 42% resin content for their commercial prepregs. The difference in resin content levels between the small-scale testing and laboratory-scale manufactured prepreg can be explained by the differences in the manufacturing methods. During small-scale testing, the residence time for the reinforcement in the resin bath of the laboratory solvent treater was not taken into account. Less time within the resin bath will lead to less resin content. Furthermore, the apparatus for mimicking the pinch rollers does not have tight tolerances compared to the pinch rollers on the solvent treater system, leading to uncertainty in controlling how much resin remained in the samples before b-staging.

3.1.3 Volatile Content

The volatile content for the small-scale specimens was also measured as part of the prepreg quality analysis. The testing found the average volatile content for the custom A&P was 0.30 ± 0.03%, and the average volatile content for the VectorPly C-LA 1812 was 0.50 ± 0.04%. Both of these average values fall within the specification range for Norplex's commercial epoxy prepregs, which requires volatile contents to be no more than 0.50% in a given sample. These results reflect well on the applicability of the small-scale testing results, enabling better decision making for larger-scale tests.

Table 6. Small-scale prepreg physical characterization results.

Specification	**Custom A&P without veil**	**VectorPly C-LA 1812**
Resin Content (%)	36 ± 5	39 ± 5
Volatile Content (%)	0.30 ± 0.03	0.50 ± 0.04

3.1.4 Final Fiber Reinforcement Selection

Upon completion of small-scale testing, a direct comparison between the two different fiber reinforcement system was made. The average gap size between the individual tows post-prepregging was determined to be the most critical response variable during the investigation. Prior to the prepregging process, both the fiber reinforcement systems had measurable gaps between the tows. The VectorPly C-LA 1812 on average was 53.6% smaller in magnitude compared to the custom A&P fiber reinforcement system. After conducting the small-scale prepregging tests, the VectorPly C-LA 1812 continued to outperform the custom A&P fiber reinforcement with the average gap size being 68.4% smaller in the VectorPly C-LA 1812 over the custom A&P fiber reinforcement. The VectorPly C-LA 1812 fabric was therefore selected for laboratory-scale prepreg manufacturing and further characterization.

3.2 Laboratory-Scale Prepreg Manufacturing and Characterization

The next stage of testing involved scaling up to laboratory-scale prepreg production runs using WWU's solvent treater. For this, two full runs were conducted and the resulting prepreg was characterized and tested for mechanical properties.

3.2.1 Resin Content

As mentioned above in the small-scale testing results for resin content, Norplex-Micarta's specification range for the resin content of epoxy-based prepregs is 40 - 42%. After analyzing samples that were taken from the start, middle, and end of the production run, the average resin content from two full production runs was 41 ± 1%. The combination of a pinch roller spacing of 0.10 cm and oven temperatures of 110 °C produced prepreg falling within that specification range.

3.2.2 Volatile Content

The target specification for volatile content of epoxy-based prepregs manufactured by Norplex-Micarta was 0 - 0.5%. The average volatile content from two full production runs was 0.40 ± 0.06%. The processing parameters that directly affect the volatile contents are the oven temperatures and the line speed of the prepreg moving through the oven system. The combination of 110 °C ovens with a line speed of 15.24 cm/min produced prepreg that met Norplex's specification range.

3.2.3 Resin Flow

The resin flow of the prepreg is a critical material property to know as during the composite design process. Manufacturing processing variables are tailored around this value to ensure the resin system flows between plies, increasing inter-laminar bonding. However, if the resin flow of a prepreg is too high, too much of the resin will flow out of the laminate resulting in resin starved sections. Norplex-Micarta's specification for resin flow states the prepreg should have a resin flow value between 14 and 24%. The average resin flow value between the final two manufacturing runs was 28 ± 2%. This value is higher than the required specification range. During testing, fiber wash was noted on the samples as the resin pushed the outer tows out of the test specimen. This loss of additional mass resulted in resin flow values that are higher than expected. Furthermore, the presence of the veil may increase the resin flow percentage compared to a prepreg without an attached veil. The structural design of veils with its network of independent fibers creates an easier path for resin to be absorbed into the reinforcement. This also creates an easy path for the resin to flow out of the reinforcement. [10]

3.2.4 Resin Distribution

Lastly, the resin distribution was determined using NCU testing. Norplex-Micarta does not have a specification for resin distribution for their prepregs, and there are no established values for unidirectional carbon fiber prepregs made with a solvent dip manufacturing process. NCU analysis was conducted to establish a baseline value for the new prepreg system. From the final prepreg production run, samples were taken from the start, middle, and end of the treater run. On average, the decibel (dB) reading from the NCU was -6 ± 6 dB. The high standard deviation for the NCU is partially due to the gaps between the tows where only a light layer of epoxy resin exists. The areas of the scan that penetrate the middle of a tow will have a much different reading from one that penetrates an area that is only resin, leading to a high standard deviation. The

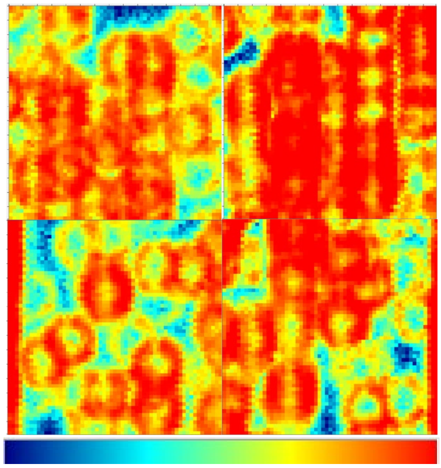

Figure 10. NCU analysis of WWU UD prepreg.

high standard deviation observed is notably different from previous research which utilized NCU analysis.

Figure 11: WWU UD prepreg after exiting the oven system.

3.3 Laminate Mechanical Properties

Mechanical properties for the newly developed unidirectional prepreg were determined to establish baseline data for engineering design purposes. The following values are initial results and are not reflective of the full potential of the prepreg, as both the manufacturing process of the prepreg and laminates were not fully optimized during the project.

3.3.1 Tensile Mechanical Properties

Following ASTM D3039/D3039M, the tensile properties of the prepreg from the final production run was tested for both tensile chord modulus of elasticity and the ultimate tensile strength. Both the longitudinal and transverse directions were tested in order to make a more thorough comparison of the Western Washington University solvent-dip unidirectional carbon prepreg with commercially available unidirectional carbon prepreg systems.

3.3.1.1 Longitudinal Tensile Properties

Upon completion of tensile testing, both the tensile chord modulus of elasticity and the ultimate tensile strength of the WWU unidirectional carbon prepreg was calculated for the longitudinal direction. The average tensile chord modulus of elasticity was 22 ± 3 GPa. Compared to both the average modulus from the technical data sheet for the VectorPly C-LA 1812 fiber reinforcement and Hexcel's HexPly M77HF unidirectional carbon-epoxy prepreg, WWU's modulus was notably lower. Accurately determining the tensile chord modulus of composite laminates is a tricky process that is extremely sensitive to error within the process. Error can occur during the preparation of the test specimens, especially when bonding on tabbing material to protect the test specimen from excessive stress concentrations from the grips. Further error can occur if the test specimen is not loaded completely vertical, as unintentional off-axis loading will yield bad data.

3.3.1.2 Transverse Tensile Properties

Following the same testing procedures for longitudinal tensile properties, the tensile properties for the transverse direction were tested. The transverse tensile properties are more representative of the properties of the matrix as no loads are transferred to any of the high strength carbon fibers. This results in notably lower mechanical properties compared to the longitudinal direction. The average tensile chord modulus of 6.4 ± 0.8 GPa. The WWU unidirectional prepreg was 32% stronger than stated the VectorPly C-LA 1812. This increase was expected because the test specimens used by VectorPly utilized a lower performance polyester/vinyl ester resin blend.

Table 7. Tensile properties of WWU UD laminates compared to commercially available materials. See figures 5 and 6 for test specimen dimensions and the number of tested specimens.

Property	**WWU UD**	**VectorPly C-LA 1812**	**Mitsubishi Press Cured UD**	**HexPly® M77HF**
Material Description	Epoxy, 40% RC	Polyvinyl ester blend	Epoxy, 12k carbon	Epoxy, 12k carbon, 36% RC
Manufacturing Process	Compression molding	Resin infusion	Compression molding	Compression molding, autoclave
Longitudinal Tensile Modulus (GPa)	22 ± 3	98.30	138	118
Transverse Tensile Modulus (GPa)	6.4 ± 0.8	5.07	-	-
Longitudinal Tensile Strength (MPa)	1200 ± 100	997.5	2650	2270
Transverse Tensile Strength (MPa)	27 ± 4	93.5	-	-

3.3.2 Flexural Mechanical Properties

To test for flexural mechanical properties, a three-point bend test method was used. Upon completion of this testing the flexural modulus and ultimate flexural strength of the prepreg was calculated. Like the tensile properties from section 3.3.1, both the longitudinal and transverse properties were tested.

3.3.2.1 Longitudinal Flexural Properties

The average longitudinal modulus of the WWU produced prepreg was 107 ± 8 GPa. Compared to the poly/vinyl ester infused VectorPly C-LA 1812 specimens, the WWU prepreg was 14% stiffer. This result was expected for the same difference in base resin properties mentioned earlier. Compared to both the Mitsubishi Press Cured UD prepreg and the HexPly M77HF epoxy prepreg, the WWU prepreg is slightly less. The average ultimate flexural strength of the WWU prepreg was 1100 ± 100 MPa, which is higher compared to the poly/vinyl ester infused VectorPly C-LA 1812 specimens. Unlike the flexural modulus, the Mitsubishi and HexPly prepregs outperform the WWU prepreg. This result was expected as the WWU solvent-dip prepreg was not optimized during manufacturing, and the Mitsubishi and HexPly prepregs are hot-melt systems which typically yield higher mechanical properties compared to solvent-based prepregs.

3.3.2.2 Transverse Flexural Properties

The transverse flexural properties of the WWU prepreg were the following: the average flexural modulus was 6.3 ± 0.8 GPa and the average flexural strength was 41 ± 3MPa. The flexural modulus followed the same trend of outperforming the VectorPly poly/vinyl ester samples and underperforming compared to both commercially available unidirectional carbon prepreg systems. The flexural strength trend breaks as the WWU prepreg is notably lower compared to both the VectorPly poly/vinyl ester samples and the Mitsubishi Press Cured prepreg.

Table 8. Flexural properties of WWU UD laminates compared to commercially available materials. See figure 7 for test specimen dimensions and the number of tested specimens.

Property	**WWU UD**	**VectorPly C-LA 1812**	**Mitsubishi Press Cured UD**	**HexPly® M77HF**
Material Description	Epoxy, 40% RC	Polyvinyl ester blend	Epoxy, 12k carbon	Epoxy, 12k carbon, 36% RC
Manufacturing Process	Compression molding	Resin infusion	Compression molding	Compression molding, autoclave
Longitudinal Flexural Modulus (GPa)	107 ± 8	93.38	124.8	114
Transverse Flexural Modulus (GPa)	6.3 ± 0.8	4.82	9.10	-
Longitudinal Flexural Strength (MPa)	1100 ± 100	795.5	1720	1480
Transverse Flexural Strength (MPa)	41 ± 3	117.7	120	-

3.3.3 Short-Beam Shear Mechanical Properties

Short-beam shear tests are smaller scale flexural test specimens where the smaller sample size minimizes the compressive and tensile properties, focusing on the shear forces on the test specimen. This test is excellent for testing manufacturing stability through panel-to-panel variation. The short-beam shear strength of the WWU prepreg was 49 ± 2 MPa. Compared to literature values from both the Mitsubishi Press Cured prepreg and the HexPly M77HF, the WWU prepreg underperforms. The testing failures for the specimens were all inelastic deformation, which according to the standard, is an acceptable failure mode.

Table 9. Short beam shear properties of WWU UD laminates compared to commercially available materials. See figure 8 for test specimen dimensions and the number of tested specimens.

Property	**WWU UD**	**Mitsubishi Press Cured UD**	**HexPly® M77HF**
Material Description	Epoxy, 40% RC	Epoxy, 12k carbon	Epoxy, 12k carbon, 36% RC
Manufacturing Process	Compression molding	Compression molding	Compression molding, autoclave
Short-Beam Shear (MPa)	49.0 ± 2.0	104	88.9

CONCLUSIONS

Overall, the project found that, with the correct fiber reinforcement system and the proper processing parameters, unidirectional carbon fiber prepreg can be produced in a continuous method using a solvent dip manufacturing method. Characterization results confirmed that critical prepreg properties such as resin content, volatile content, and resin flow can match that of pre-existing prepreg systems. Mechanical testing established initial baseline data for both tensile and flexural mechanical properties. Further testing is needed to address sources of error which skewed the mechanical properties. Furthermore, the optimization of both the prepregging processing and laminate manufacturing process will lead to improved mechanical property analysis. The findings from this paper provide confidence that scaling this process up to an industrial scale is indeed possible and can potentially unlock a new market for more affordable mid-range unidirectional prepregs.

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