# THERMOPLY™
# COMMINGLED E-GLASS/POLYPROPYLENE WOVEN & STITCH-BONDED BIAXIAL

Continuous reinforcement fiber thermoplastic composites offer many desirable attributes including specific high strength & modulus, damage tolerance, recyclability, and potential for high volume production. Even with these advantages impregnation of the continuous fiber by highly viscous thermoplastic resins has been a major obstacle for widespread use. Commingling of the reinforcement and resin fibers not only allows for much easier processing, but also allows for fabrics to contain both matrix and reinforcement in a single entity. In this paper, the static and dynamic mechanical properties of composites made from commingled E-glass / polypropylene woven and stitch-bonded fabric preforms are characterized and compared to standard reinforced thermoplastic and continuous fiber thermoset composites. Typical manners of processing and the effects of such on the thermoplastic composite are also discussed.

## 1. INTRODUCTION

Thermoset long and continuous fiber composites, from chopped fiberglass mat to carbon-epoxy, have traditionally dominated the structural composite landscape due to their high specific properties, relative ease in molding, and good corrosion resistance. However, there are several design aspects in which continuous fiber thermoplastic composites have been shown to be advantageous including high impact resistance, weldability, low cycle times, recyclability, and extremely long shelf life [1]. In this paper, two forms of continuous fiber thermoplastic preforms, plain weave and biaxial non-crimp fiber (NCF) stitch-bonded fabrics, made from commingled E-glass and polypropylene fibers were tested to determine key static and dynamic composite properties and compared to other standard short fiber thermoplastic, and continuous fiber thermoset and thermoplastic composites.

### 1.1 Advantages & Disadvantages of Thermoplastics

Thermoplastics do provide many desirable attributes not found with traditional thermosets; however some disadvantages are also present. Due to the long chain molecule construction of thermoplastics they are less prone to microcracking, have higher fracture toughness, and better impact resistance [2]. With only secondary van der Waals' bonds holding the molecules together, thermoplastics can be melted and reformed or welded together for repair or recycling [1, 2]. Since no chemical reactions are necessary to process thermoplastics they have an almost infinite shelf life and can produce very short process cycle times with no exotherm evolution [1]. Some semi-crystalline thermoplastics such as polypropylene (PP) generally have very good chemical resistance and fatigue strength, allowing for "living hinges" for certain applications [3, 4]. The lack of reactive diluents such as styrene, means that thermoplastics do not produce VOC emissions, and are therefore not subject to the same regulatory controls under which thermosets must abide. Some disadvantages of most thermoplastics include low resistance to environmental degradation due to UV exposure or embrittlement at low temperatures [4, 5]. Polypropylene in particular has a poor resistance to aromatic hydrocarbons and chlorinated solvents [4]. In terms of processing, the major disadvantage with thermoplastics is their high viscosities, even at elevated temperatures, making wetting of reinforcement fiber much more difficult than with the much lower viscosity thermosets [2].

In many applications the benefits of thermoplastic composites do outweigh the disadvantages, such as in many recreational products like stand up paddle (SUP) boards made by Bounce Composites. The impact resistance, toughness, and robust mechanical properties of the ThermoPly™ materials are ideal for these structures which are constantly dynamically loaded while in use.

*Photo credit: www.BounceSUP.com*

Bounce Composites (Oceanside, CA) manufactures SUPs made with Vectorply's EPP-WV 1500 (15oz/yd²) and EPP-WV 2200 (22oz/yd²) ThermoPly™ materials. Pictured are four Bounce SUPs.

# 2. EXPERIMENTATION

## 2.1 Processing of Thermoplastic Composites

While there are several manufacturing processes such as pultrusion, matched die forming, automated tape laying, and diaphragm molding [2] that can be used to produce continuous fiber thermoplastics, the main process used for these experiments is vacuum forming. This process uses a single hard mold, atmospheric pressure (~1 bar), a high temperature Nylon bag (for the counter mold), and an oven to melt and consolidate the commingled fabric preforms.

The critical processing parameters for thermoplastic composites are pressure, temperature, and time at temperature. Insufficient pressure can lead to a variety of issues include high laminate porosity, low static mechanical properties, and low fatigue properties [6, 7, 8]. Thermoplastic matrices typically have very high viscosities, on the order of $10^2$ to $10^6$ Pa-sec, but exhibit steeper decreases at higher temperatures than thermosets [2]. During flow, thermoplastics can also exhibit shear thinning behavior (reduction in viscosity due to an increase in shear stress), so the longer the polymer is above its melt/flow temperature, the less viscous it can become, allowing for better laminate consolidation [2]. Cooling rate has a large effect on crystallization, and consequently the amount of shrinkage in the polymer and the composite mechanical properties.

Typical processing temperature and pressure ranges for E-glass/polypropylene commingled fabrics are 180-230°C and 1-30 bar, respectively [9]. Removal of the consolidated composite from its mold/tooling is done at temperatures generally below 55°C, and rapid cooling is done when a low degree of crystallinity is desired [1].

## 2.2 Commingled E-Glass / Polypropylene Composite Fabrics

For these experiments, four different commingled E-glass / polypropylene fabrics were used to fabricate flat laminate panels using the vacuum forming process. These fabrics were supplied by Vectorply Corporation from the ThermoPly™ line of commingled products, which utilize Jushi Compofil™-PP roving with a nominal fiber weight fraction of 60%. All commingled fabrics are detailed in Table 1 below.

Table 1. ThermoPly™ commingled E-glass/polypropylene fabric constructions.

| Material Supplier | Trade Name | Nominal Areal Weight (gsm) | | | |
|---|---|---|---|---|---|
| | | 0° | 90° | +45° | -45° |
| Vectorply Corporation | EPP-WV 1500 | 250 | 250 | - | - |
| | EPP-WV 2200 | 375 | 375 | - | - |
| | EPP-BX 1800 | - | - | 306 | 306 |
| | EPP-BX 2400 | - | - | 394 | 394 |

## 2.3 Panel Fabrication

All laminate panels were produced via the vacuum forming process. 6 to 16 fabric layers were applied on to a 3mm thick aluminum caul sheet, which utilized a high temperature semi-permanent mold release. A polyester woven peel ply was placed over the fabric stack to function as both a release and breather layer. A high temperature Nylon vacuum bag was then affixed around the perimeter of the fabric, and placed under full atmospheric pressure (1 bar). The caul sheet was then placed in an oven and the laminate was allowed to consolidate at 204°C for 40 minutes. Once the consolidation time completed, the panels were taken out of the oven and allowed to cool to ambient temperature.

Due to significant warpage of the initial symmetric laminate schedule panels made with the EPP-BX 1800 and EPP-BX 2400 NCF fabrics, antisymmetric schedules of $[0°/90°]_6$ for the EPP-BX 1800 and $[0°/90°]_8$ for the EPP-BX 2400 were used which produced much flatter panels. The woven versions, EPP-WV 1500 and EPP-WV 2200, did not exhibit any warpage and produced symmetric laminates due to their orthotropic nature.

## 2.4 Static Property Testing

The consolidated laminates were then tested using standard ASTM test methods for the following material properties along one or both of the major fiber axes; tensile strength and modulus, compression strength and modulus, flexural strength & modulus, short beam strength, and in-plane shear strength and modulus. The results were then compared to the properties of traditional short fiber and continuous fiber composites, and are shown below in the "Results" section.

### 2.5 Dynamic Property Testing

Two dynamic tests, unnotched Charpy (ASTM D4812/ISO 179) and drop-weight impact (ASTM D7136) were also conducted on the consolidated laminates alongside similarly constructed continuous thermoset composites. Impact resistance, deformation, and absorbed energy properties both in-plane and normal to the laminate thickness were recorded and compared to traditional short fiber thermoplastic materials.

## 3. RESULTS

### 3.1 Tensile Strength & Modulus

The tensile strength and modulus along one of the ThermoPly™ major fiber axes was performed according to the test method ASTM D3039 "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." Values are given in Table 2 below.

Table 2. Tensile strength & modulus test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Tensile Strength (MPa) | Tensile Modulus (GPa) |
|---|---|---|---|---|---|
| | | | | 0° & 90° | 0° & 90° |
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_8$ | 60 | 294 | 13.23 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_6$ | 60 | 310 | 13.89 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_8$ | 60 | 317 | 14.41 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0°/90°]_6$ | 60 | 305 | 14.18 |

A comparison of the tensile properties with more traditional composite materials is given below in Figures 1 and 2. The two thermoset laminates include 600gsm chopped strand mat (CSM) in an unsaturated polyester resin (UPR), and an 800gsm biaxial NCF E-glass fabric in a vinyl ester (VE) matrix. Fiber weight fractions are normalized to 60% with the exception of the 600gsm CSM / UPR (34%), the short fiber polypropylene (20%), and the LFRT polypropylene (40%).

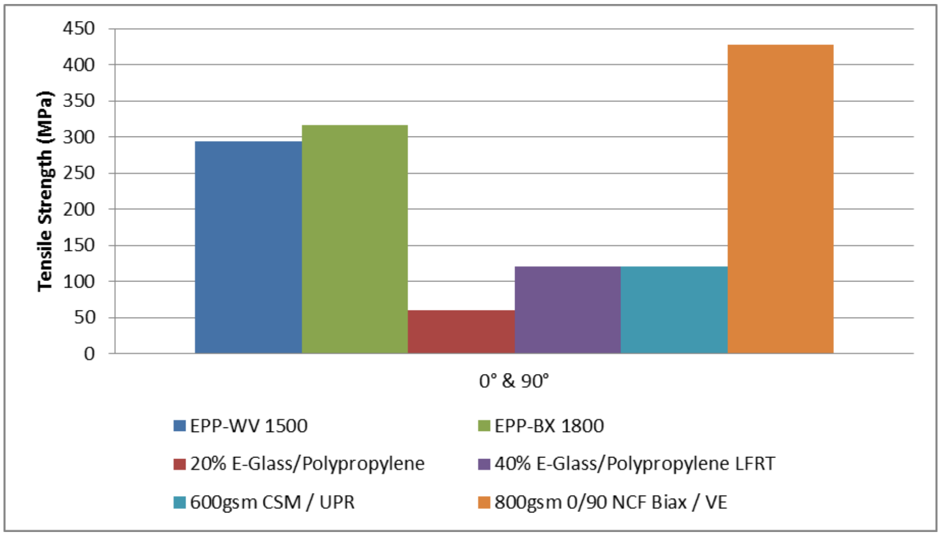


Figure 1. Tensile strength comparison of various composite materials.

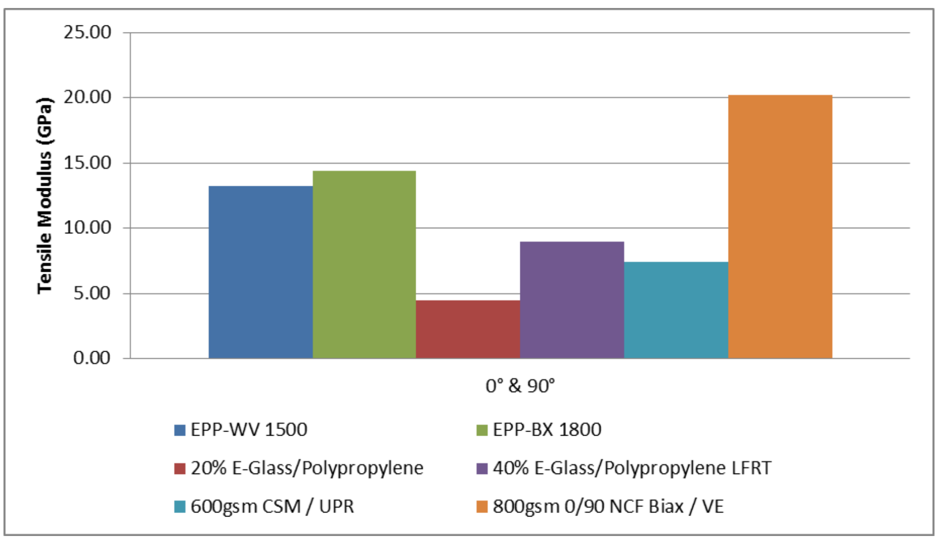


Figure 2. Tensile modulus comparison of various composite materials.

### 3.2 Compression Strength & Modulus

The compression strength and modulus along one major fiber axis of the ThermoPly™ laminates was conducted according to ASTM D6641 "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture." Values are given in Table 3 below.

Table 3. Compression strength & modulus test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Compression Strength (MPa) | Compression Modulus (GPa) |
|---|---|---|---|---|---|

| | | | | 0° & 90° | 0° & 90° |
|---|---|---|---|---|---|
| 500gsm Plain Weave | EPP-WV 1500 | $[0^\circ/90^\circ]_8$ | 60 | 169 | 15.60 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0^\circ/90^\circ]_6$ | 60 | 117 | 15.02 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0^\circ/90^\circ]_8$ | 60 | 179 | 16.03 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0^\circ/90^\circ]_6$ | 60 | 180 | 15.87 |

A comparison of the compression properties with more traditional polymer and composite materials is given below in Figures 3 and 4. The two thermoset laminates include 600gsm chopped strand mat (CSM) in an unsaturated polyester resin (UPR), and a 600gsm biaxial NCF E-glass fabric in a vinyl ester (VE) matrix. Fiber weight fractions are normalized to 60% with the exception of the 600gsm CSM / UPR (34%) and the neat polypropylene (0%).

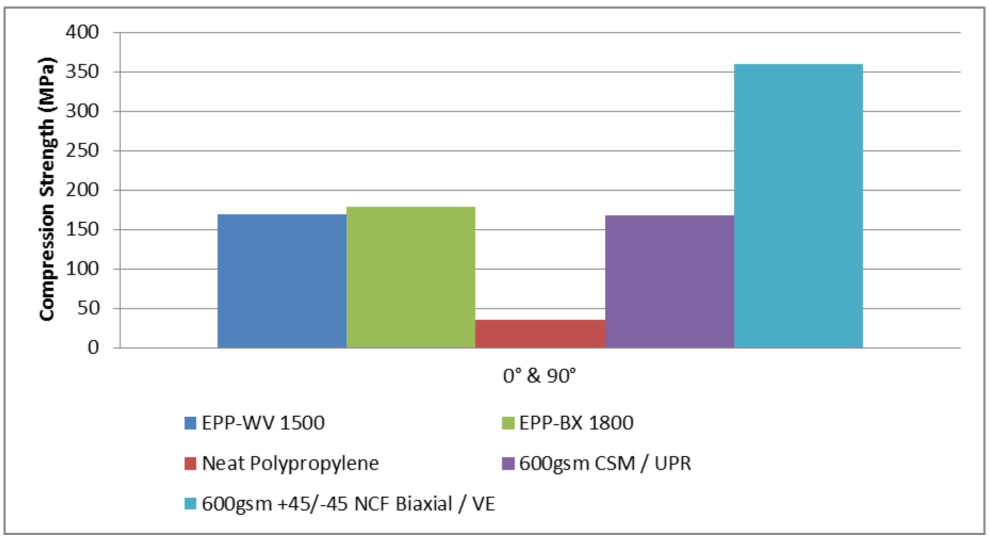


Figure 3. Compression strength comparison of various composite materials.

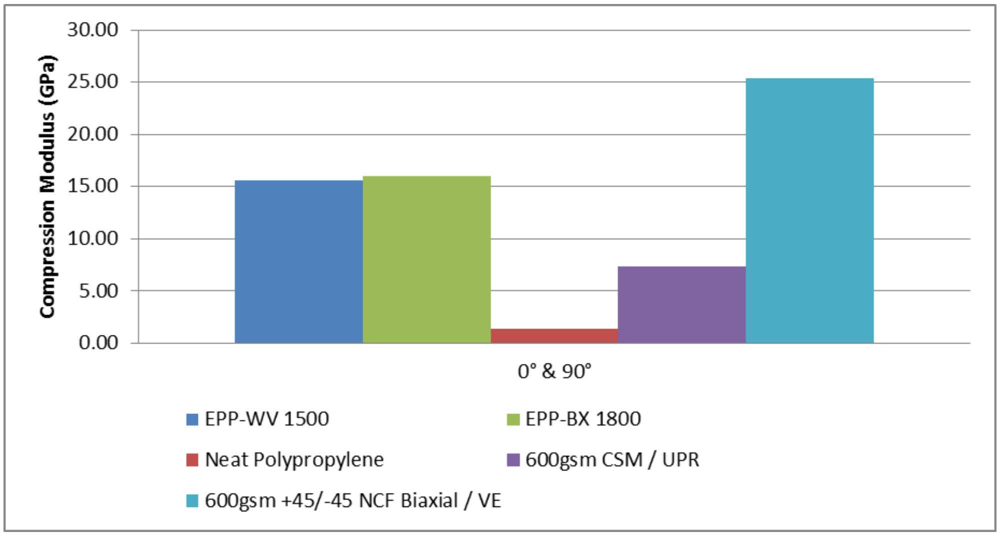


Figure 4. Compression modulus comparison of various composite materials.

### 3.3 Flexural Strength & Modulus

The flexural strength and modulus along both major fiber axes were determined according to ASTM D790 “Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.” Values are given below in Tables 4-5.

Table 4. Flexural strength test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Flexural Strength (MPa) | |
|---|---|---|---|---|---|
| | | | | 0° | 90° |
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_8$ | 60 | 268 | 242 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_6$ | 60 | 171 | 213 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_8$ | 60 | 257 | 243 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0°/90°]_6$ | 60 | 297 | 291 |

Table 5. Flexural modulus test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Flexural Modulus (GPa) | |
|---|---|---|---|---|---|
| | | | | 0° | 90° |
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_8$ | 60 | 11.25 | 11.39 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_6$ | 60 | 8.79 | 10.46 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_8$ | 60 | 11.51 | 10.84 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0°/90°]_6$ | 60 | 11.95 | 11.95 |

A comparison of the flexural properties with more traditional composite materials is given below in Figures 5 and 6. The two thermoset laminates include 600gsm chopped strand mat (CSM) in an unsaturated polyester resin (UPR), and an 800gsm biaxial E-glass NCF fabric in a vinyl ester (VE) matrix. Fiber weight fractions are normalized to 60% with the exception of the 600gsm CSM / UPR (34%) and the short fiber/LFRT polypropylene materials (20% and 40% respectively).

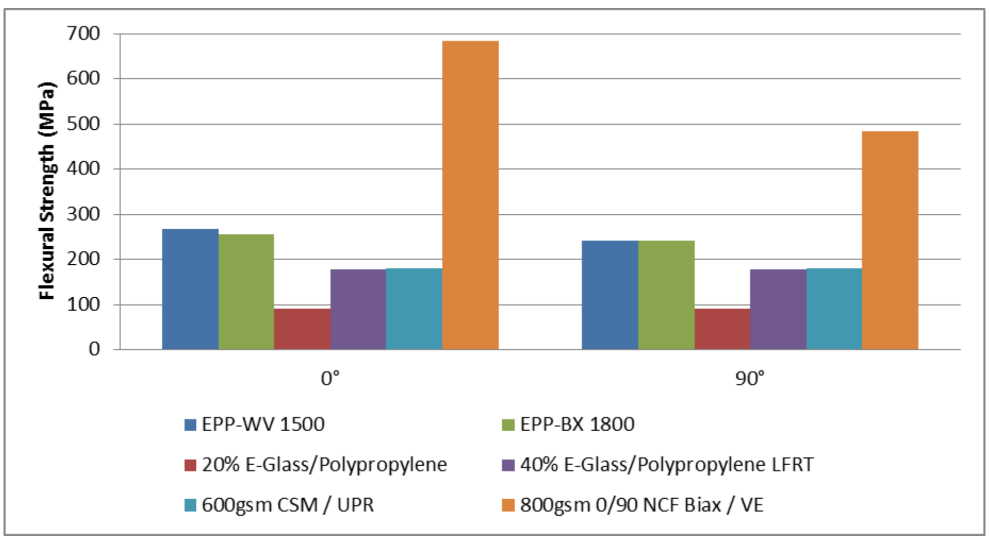


Figure 5. Flexural strength comparison of various composite materials.

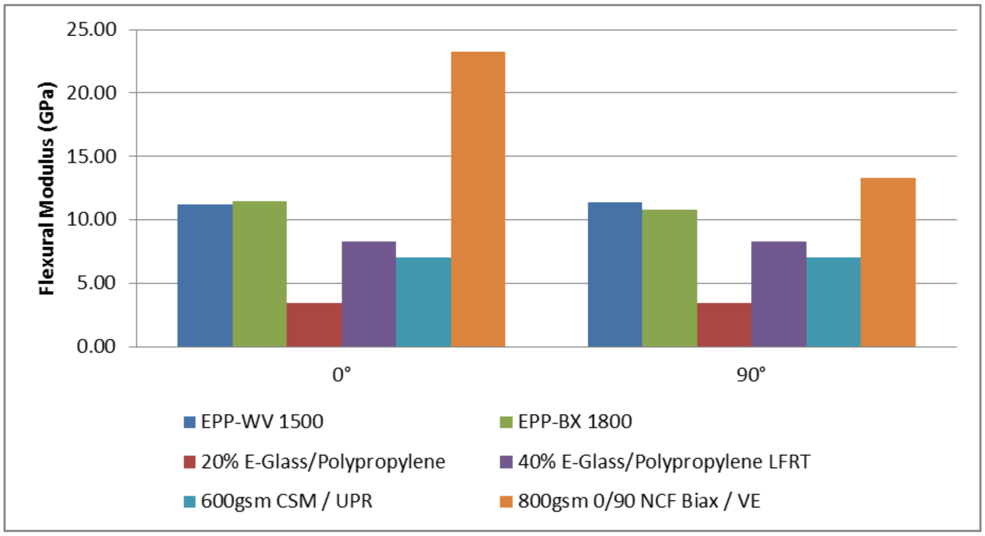


Figure 6. Flexural modulus comparison of various composite materials.

### 3.4 Short Beam Strength

The short beam strength (SBS - related to the interlaminar shear strength) along both major fiber axes was determined using the ASTM D2344 "Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates" method. Values are provided in Table 6 below. Note: the SBS data for the EPP-BX 2400 laminate was not available at the time of publication.

Table 6. Short beam strength test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Short Beam Strength (MPa) | |
|---|---|---|---|---|---|
| | | | | 0° | 90° |
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_{16}$ | 60 | 22.2 | 22.5 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_{12}$ | 60 | 18.6 | 19.0 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_{16}$ | 60 | 19.0 | 18.8 |

### 3.5 In-Plane Shear Strength & Modulus

The in-plane strength and modulus for each laminate was determined according to ASTM D5379 "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method." For the woven materials, the 0° and 90° fibers are parallel and perpendicular respectively to the loading axis while the stitch-bonded NCF fabric fiber orientations are +45°/-45° to the loading axis. These configurations mimic how the materials would respond to in-plane shear loading conditions in the manufactured roll directions. Values are provided in Table 7 below.

Table 7. In-plane shear strength & modulus test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Fiber Weight Fraction (%) | Shear Strength (MPa) | Shear Modulus (GPa) |
|---|---|---|---|---|---|
| | | | | 0° | 0° |
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_8$ | 60 | 38.4 | 1.21 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_6$ | 60 | 30.6 | 0.93 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[+45°/-45°]_8$ | 60 | 62.2 | 6.01 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[+45°/-45°]_6$ | 60 | 64.9 | 5.83 |

A comparison of the in-plane shear properties with more traditional polymer and composite materials is given below in Figures 7 and 8. The two thermoset laminates include 600gsm chopped strand mat (CSM) in an unsaturated polyester resin (UPR), and a 400gsm biaxial NCF E-glass fabric in an epoxy matrix. Fiber weight fractions are normalized to 60% with the exception of the 600gsm CSM / UPR (34%) and the neat polypropylene (0%).

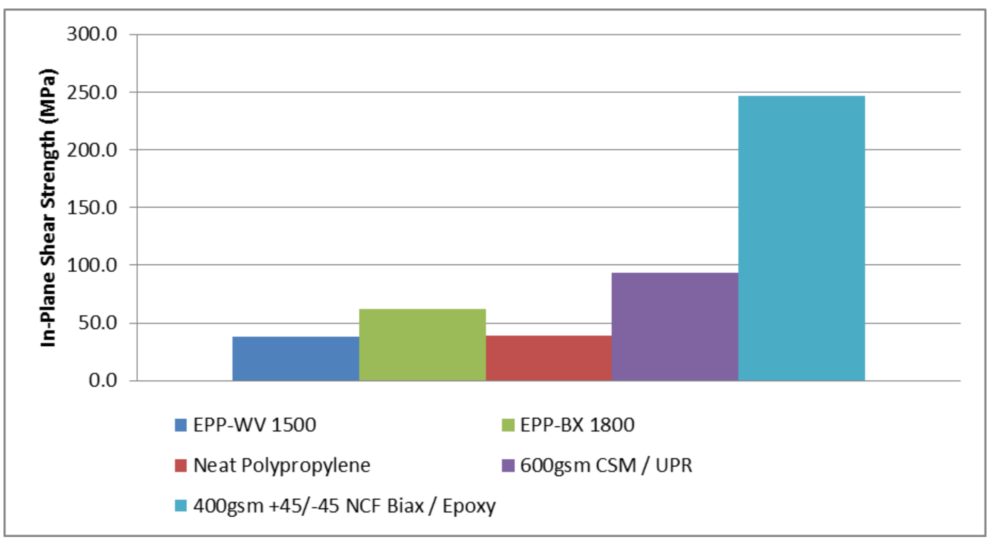


Figure 7. In-plane shear strength comparison of various composite materials.

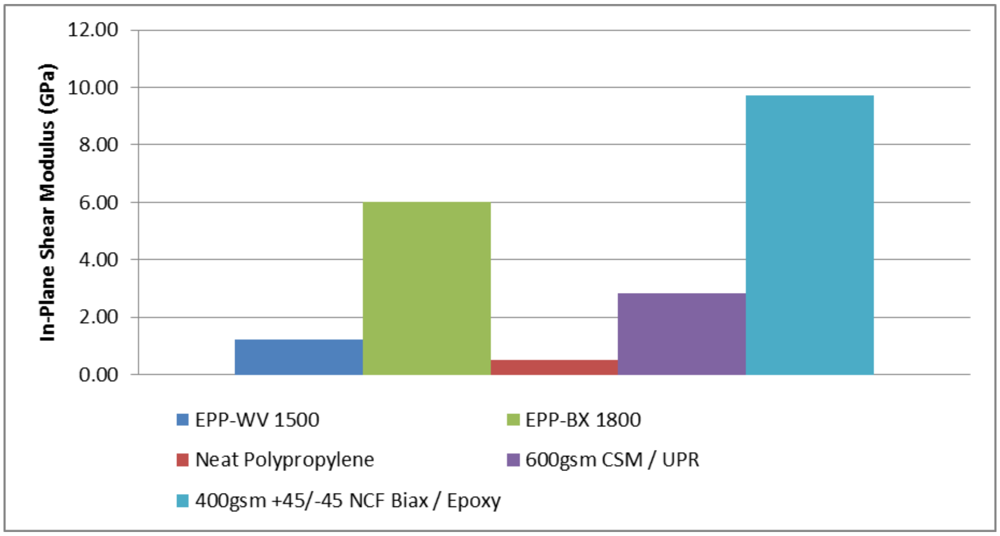


Figure 8. In-plane shear modulus comparison of various composite materials.

### 3.6 Unnotched Charpy Impact

The 16 layer consolidated laminates and similar thickness "control" E-glass/vinyl ester thermoset laminate were tested for in-plane impact resistance using portions of ASTM D4812 "Standard Test Method for Unnotched Cantilever Beam Impact Resistance of Plastics" and ISO 179 "Plastics – Determination of Charpy impact properties" test methods. The specimen test configuration conforms to the "edgewise parallel" or "ep" scheme denoted in the ISO 179 method, with a supported length of 40mm. All specimens, both thermoplastic and thermoset, failed either in a "complete break" or "partial break" mode, with the complete break being more prevalent (60% of specimens) in all sample sets. Impact resistance values are given in Table 8 below.

Table 8. Unnotched Charpy impact resistance test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Impact Resistance (ep) (kJ/m$^2$) |
|---|---|---|---|
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_{16}$ | 318 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_{12}$ | 331 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_{16}$ | 337 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0°/90°]_{12}$ | 309 |

A comparison of the impact resistance properties with more traditional composite materials is given below in Figure 9. The thermoset laminate is a 400gsm biaxial E-glass NCF fabric in a vinyl ester (VE) matrix. The short fiber thermoplastics include a 20% E-glass filled polypropylene and a 60% E-glass filled LFRT polypropylene.

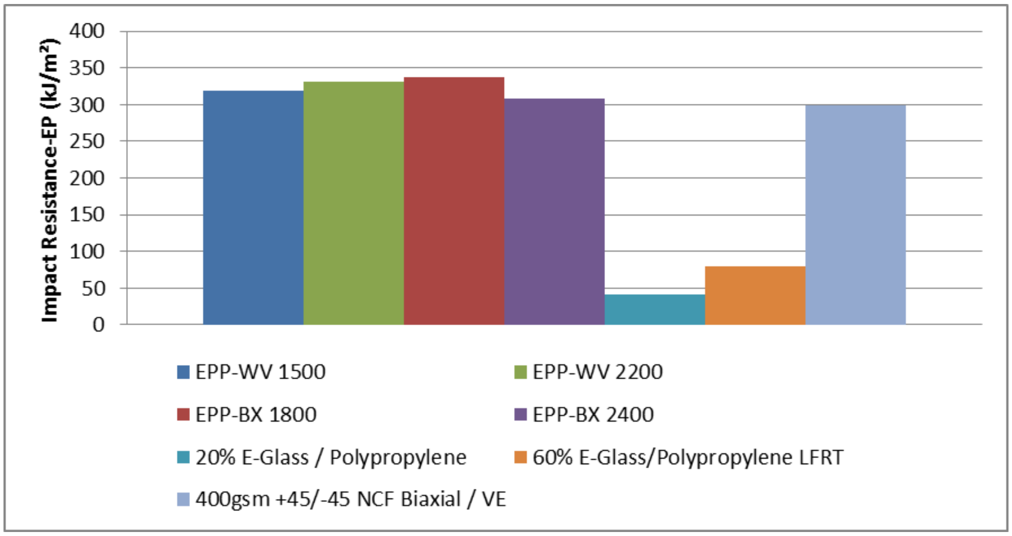


Figure 9. Charpy impact resistance comparison of various composite materials.

### 3.7 Drop Weight Impact

The 8 layer consolidated laminates and similar thickness “control” E-glass/vinyl ester thermoset laminate were tested for out-of-plane (normal) impact response utilizing the ASTM D7136 “Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event” test method. A 2.4kg impactor was dropped at a height of 0.5m producing an approximate impact energy of 13J, on to the 120mm x 102mm test laminates. Values are provided in Table 9 below.

Table 9. Drop weight impact response test results for the ThermoPly™ laminates.

| Fabric Type | Trade Name | Laminate Schedule | Deflection at Max Load (mm) | Energy to Max Load (J) |
|---|---|---|---|---|
| 500gsm Plain Weave | EPP-WV 1500 | $[0°/90°]_8$ | 8.12 | 10.16 |
| 750gsm Plain Weave | EPP-WV 2200 | $[0°/90°]_6$ | 8.03 | 10.39 |
| 600gsm +45/-45 NCF Biaxial | EPP-BX 1800 | $[0°/90°]_8$ | 7.13 | 10.63 |
| 800gsm +45/-45 NCF Biaxial | EPP-BX 2400 | $[0°/90°]_6$ | 7.22 | 10.64 |

A comparison of the out-of-plane impact response with more traditional composite materials is given below in Figure 10. The thermoset laminate is a 400gsm biaxial E-glass NCF fabric in a vinyl ester (VE) matrix.

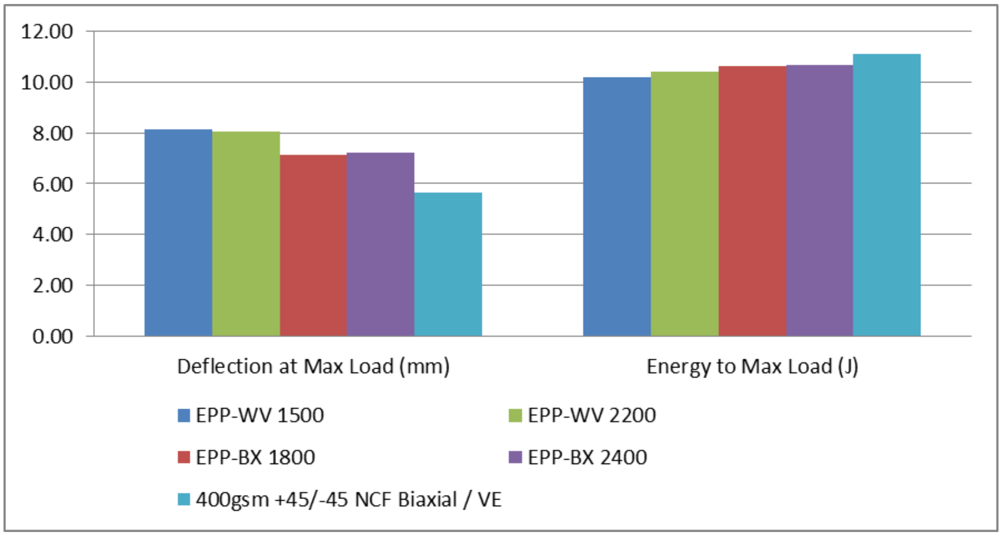


Figure 10. Drop weight impact response comparison of various composite materials.

# 4. CONCLUSIONS

The commingled E-glass/polypropylene ThermoPly™ composites produced static mechanical properties typically greater than the short fiber thermoplastic and thermoset versions, but still less than similarly constructed continuous fiber thermosets. The dynamic testing showed slight increases in energy absorption for the ThermoPly™ materials over the continuous thermoset controls, but much larger values over the short fiber reinforced thermoplastics.

## 4.1 Static Properties

### *4.1.1 Tensile Strength & Modulus*

The ThermoPly™ material tensile properties shown in Table 2 and Figures 1-2 along the major fiber axes were shown to be 2-5 times higher than the short fiber and LFRT materials, but still well below the continuous fiber thermoset version. Tensile strengths amongst the continuous commingled fiber composites were virtually the same (~300MPa), as were the moduli (~14GPa). Slight increases in modulus (5%) were seen with the stitch bonded NCF compared to the woven versions, which can be attributed to the more highly aligned reinforcement fibers. ThermoPly™ tensile strengths and moduli were several times higher than the 20% E-glass filled polypropylene, 40% filled LFRT, and chopped mat / UPR materials, confirming that higher fiber content, preferential orientation, and continuous fibers produce higher mechanical properties for a given composite material. Compared to the E-glass biaxial / vinyl ester composite, the ThermoPly™ materials were roughly 30% lower in both tensile strength and modulus. Higher static properties of the thermoset resin and better bonding between the fiber and resin could be reasons for this large difference.

#### *4.1.2 Compression Strength & Modulus*

The ThermoPly™ material compressive properties shown in Table 3 and Figures 3-4 along the major fiber axes were shown to be multiple times higher than neat polypropylene, but still well below the continuous fiber thermoset version. Compression strengths amongst the continuous commingled fiber composites were similar (~165MPa), as were the moduli (~15.5GPa). ThermoPly™ compression strengths and moduli were several times higher than neat polypropylene (no compressive data for short fiber/LFRT materials could be readily obtained), and while the strengths were on par with the chopped mat / UPR material, the moduli were roughly 2 times greater. Compared to the E-glass biaxial / vinyl ester composite, the ThermoPly™ materials were approximately 50% lower in strength and 40% lower in modulus. Higher static properties of the thermoset resin and better bonding between the fiber and resin again could be reasons for this large difference.

#### *4.1.3 Flexural Strength & Modulus*

The ThermoPly™ material flexural properties as shown in Tables 4-5 and Figures 5-6 along both of the major fiber axes were typically much higher than the short fiber and LFRT materials, but still well below the continuous fiber thermoset version. Flexural strengths amongst the continuous commingled fiber composites were similar for most fabrics (~275MPa), as were the moduli (~11.5GPa). The EPP-WV 2200 in particular had much lower strength and modulus values along the 0° orientation, which may be due to skewed plies within the laminate. ThermoPly™ flexural strengths and moduli were approximately 3 times higher than the 20% E-glass filled polypropylene, and 30-40% higher than the 40% filled LFRT and chopped mat / UPR materials, again confirming that higher fiber content, preferential orientation, and continuous fibers produce higher mechanical properties for a given composite material. Compared to the E-glass biaxial / vinyl ester composite, the ThermoPly™ materials were roughly 50% lower in both flexural strength and modulus. Higher static properties of the thermoset resin and better bonding between the fiber and resin along with slightly different stacking sequences could be reasons for this large difference.

#### *4.1.4 Short Beam Strength*

This test was conducted to determine baseline SBS values for future quality assurance testing, as it is not a true interlaminar shear stress value. The values, shown in Table 6, of 18-22MPa are roughly 60% of neat polypropylene polymer tensile strength [4] and seem to correspond to well-consolidated laminates.

#### *4.1.5 In-Plane Shear Strength & Modulus*

The ThermoPly™ material in-plane shear properties, shown in Table 7 and Figure 7-8, were markedly different depending on the laminate schedule used, and had mixed results compared to the other materials. Shear strengths amongst the woven continuous commingled fiber composites were similar to the neat polypropylene, but the moduli were approximately double (~1.0GPa). The stitch bonded NCF ThermoPly™ composites produced nearly double the strength (~45% higher) and much higher modulus (~6 times higher) compared to the woven versions. Much of this had to do with the laminate schedules used, with the NCF versions having preferential fiber orientation for the given in-plane loading. Even with the favorable fiber orientations, the ThermoPly™ NCF shear strengths were still roughly 34% lower the chopped mat / UPR material; however the moduli were roughly 50% higher. Compared to the E-glass biaxial / epoxy composite, the ThermoPly™ NCF materials were approximately 74% lower in strength and 40% lower in modulus. Higher static properties of the epoxy thermoset resin and better bonding between the fiber and resin again could be reasons for this large difference.

### 4.2 Dynamic Properties

#### *4.2.1 Unnotched Charpy Impact*

All of the ThermoPly™ laminates, as shown in Table 8, produced similar impact resistance values (~324kJ/m$^2$), which were 4 to 8 times greater than nominal data for LFRT and short fiber thermoplastic, but only slightly higher than the continuous fiber thermoset laminate. The 400gsm biaxial in vinyl ester only had about a 7% lower impact resistance compared to the ThermoPly™ materials. Possible explanations for this include the way in which the laminates were tested. The Charpy tests were impact tested (in-plane), and more of a difference may be found if impacted out-of-plane (through thickness). The toughness of the vinyl ester used for the thermoset laminate may have also contributed to its good impact resistance.

#### *4.2.2 Drop Weight Impact*

For the drop weight impact test results shown in Table 9 and Figure 10, the TP ThermoPly™ laminates deflected slightly more and absorbed about the same energy before peak load as the continuous fiber thermoset laminate. The increased deflection was expected due to the comparatively lower modulus of the thermoplastic materials, while the equivalent absorbed energy at peak load implies that the ThermoPly™ materials do absorb at least as much impact energy as the thermoset offset. None of the impacted panels exhibited puncture or any other severe failure mechanism, so a detailed inspection and measurement of any delaminated areas present in the laminates is recommended for further study.

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