Laminate Specification and Characterization

Composite Bridge Decking

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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OVERVIEW

A composite laminate is a structural plate consisting of multiple layers of fiber reinforcement encased in cured resin. The number of layers, the type of fiber (carbon, glass, or other), the fabric configuration (e.g., woven, stitched mat, uni-directional), the type of resin, and other factors can be varied to design a structural element that is suitable for a particular need. Raw materials (fiber, resin, and usually some filler) in themselves are not useful as a structural member, but when combined together, the product takes on new properties that make them desirable for use in structures. Laminates, or hardened sheets of composite material, usually are cut up into coupons for mechanical testing to validate the predicted properties.

There are numerous resins on the market, but only the most durable are suitable for use as part of a bridge deck system. For this study, the project team performed a literature search to narrow the number of resins under consideration. They also requested composite test panels (also called "witness panels") from several composite fabricators, then tested the panels that were received so that a variety of specimens could be compared. The project team also made use of data obtained from a recent project involving a composite "ice shield." In some cases, incomplete data were obtained from suppliers, but it still made a contribution to the body of knowledge that was being built. Laboratory samples were prepared to make up for samples that were not readily available from other sources.

Various manufacturing processes are being considered: hand, vacuum infusion, and pultrusion. This helps to widen the number of potential fabricators for this type of deck system, and it is hoped this will in turn promote broader acceptance and commercial adoption of the system. Various resins and fiber architectures are being evaluated.

After weighing all viable options, and in consultation with the project team's manufacturing partners, a fire-resistant vinyl ester resin (Derakane 510C from Ashland) was selected for use in the combination tube that was developed and will be pultruded. Glass reinforcement was selected, and a layup sequence was adopted based on theoretical predictions. Testing to validate these decisions is ongoing.

This report outlines characterization work and testing done to date. The development of laminate configurations is discussed, and physical test data are presented.

BACKGROUND RESEARCH

RESIN SELECTION

While the reinforcement fiber is largely responsible for determining key structural properties, such as tensile strength and stiffness in the fiber direction, the successful performance of a composite relies greatly on both constituent phases. High-level composite performance can be achieved only through correct selection of both the fiber reinforcements and the polymer matrix (resin) that binds them into a cohesive structural unit.

The primary purpose of the reinforcement in a polymer composite system is to improve the strength and stiffness of the system. Fiber reinforcements possess strength and stiffness properties two or three orders of magnitude above that of the neat polymer resin. However, a fiber reinforcement is essentially a cable-type element, in that it possesses excellent structural characteristics under tensile loading but little or no compressive or shear capacity when acting in isolation.

Therefore, the purpose of the resin is to bind the reinforcement fibers into a single cohesive structural system. In doing so, the resin must hold the reinforcement in place and act as a path for load transfer between the fibers. Through a combination of adhesive and cohesive characteristics, the resin enables the development of a single material system. The new system provides not only tensile capacity but also compressive and shear capacity.

The polymer matrix also serves to protect the reinforcement fiber from adverse environments. Selection of the appropriate matrix material for environmental durability is critical in ensuring the longer term viability of a composite system, particularly in harsh service environments such as off-shore and shoreline applications, chemical plants, and cold climates where products such as de-icing salts are used.

The polymer matrix also provides all the inter-laminar shear strength of the composite, as well as resistance to crack propagation and damage. It can also be used to contribute properties such as ductility, toughness, or electrical insulation. The resin also affects the temperature performance of the material, typically determining properties such as the maximum service temperature.

Polymers can be classified into two primary groups: thermoplastics and thermosets. In terms of fiber-reinforced polymer (FRP) systems for infrastructure applications, thermosetting polymers are by far the most common type utilized. Unlike thermoplastics, which need to be heated to relatively high temperatures, many of the thermosets used for composite matrices can be formulated for processing at ambient temperature.

In addition, most thermosets can be processed without the use of high pressure, which simplifies production and opens the door to a wide range of fabrication techniques. The low-viscosity nature of the resins also provides significantly easier impregnation and wetout of fiber reinforcements. Impregnation can be undertaken prior to the curing reaction, and upon curing, the continuous thermoset network totally encompasses the fibers. The formation of cross-links in a thermoset network typically results in a stiffer and stronger matrix than that of a thermoplastic.

However, thermosets generally tend to have lower elongations and toughness thermoplastics. Thermosets also display good resistance to a wide array of chemical environments, including acids, bases, and solvents.

Common examples of thermosetting polymer resins used for civil engineering applications include polyesters and vinylesters, epoxies, phenolics, and polyurethanes. The first three types are considered to be the materials of primary interest, in terms of their current viability for civil engineering structures. The other two represent a possible future option for civil engineering composites; however, current technology for these materials presents a number of difficulties that limit their viability at present.

Epoxy Resin

Epoxy resins are widely regarded as the high-performance family of composite resins and have grown to dominate aerospace composites and other high-performance application areas, such as motor racing and racing yachts. The higher performance of epoxy resins comes at an increased cost, but these materials are not limited to high-performance applications. A diverse array of epoxy systems is available in today's composite market, with performance ranging from high-end 350° F curing aerospace systems to general-purpose ambient cure systems with properties similar to vinyl esters.

The chemistry of epoxies provides a wide scope for alteration of processing parameters, with systems available for use with every major composite production method. Curing time and temperature, as well as parameters such as resin viscosity, can be varied through correct formulation of the resin system.

While epoxies have not been widely used in FRP deck systems to date, they are of major interest in civil engineering applications, due primarily to their structural performance and durability. These material offer exceptional adhesion characteristics between matrix and fiber, and hence enable the generation of excellent structural properties in fiber-reinforced laminates. In terms of FRP infrastructure applications, epoxies have found their widest utilization in carbon fiber strengthening systems, where the additional cost of epoxy can be justified to make full use of the properties of the carbon.

For this project, it was considered desirable to include at least one epoxy in evaluations due to their potential performance advantages. Due to the diverse array of epoxy resins and hardeners available and their wide range of end properties, it was decided that the best approach was to consult with an established epoxy resin producer and seek a recommendation for one or two specific epoxy products. As one of the largest epoxy producers, Huntsman Advanced Materials was approached regarding potentially suitable epoxy resins for the proposed bridge deck design. Huntsman identified a laminating epoxy system —Araldite LY3505 / Aradur XB3403— as a viable system offering a good balance between cost and performance. The system can be laminated at ambient temperature, and good properties can be developed with a moderate temperature post-cure. The mix viscosity is low enough for easy hand lamination and potential vacuum-assisted resin transfer molding (VARTM) fabrication.

Vinyl Ester Resins

Whereas epoxy resins typically are regarded as covering the high end of the polymer matrix performance spectrum and polyester as covering the lower end, vinyl ester resins very much hold the middle ground. Originally released into the market in the 1960s, these materials offer a number of the superior performance properties of epoxies in combination with the processing flexibility of polyesters. Vinyl ester resins have been found to offer exceptional chemical resistance characteristics and have been the matrix material of choice in harsh chemical environments for over 30 years. Many such applications are detailed in the literature. (See references 1 through 4.) Vinyl esters present several attractive characteristics from a civil engineering perspective, including a lower cost structure than epoxies. They also display several negative characteristics that must be understood and accommodated for successful use.

Standard vinyl esters can be modified to provide improved performance in areas such as toughness and impact performance. Rubber toughening is a common technique used with vinyl esters. A range of toughened products are available in the marketplace, including Dow's Derakane 8084, Interplastic's CoRezyn VE8550, and Reichhold's DION 9500. Derakane 8084 has been used in numerous infrastructure projects, including the current bridge deck design and the ice shield project undertaken by Bridge Composites prior to this current bridge project. Its improved toughness and impact resistance result in reduced matrix cracking, which may in turn enhance durability characteristics. Given the prior work with Derakane 8084 and the current deck design, this resin will be used extensively in testing for this current project.

There also are several versions of vinyl ester with improved fire resistance (commonly achieved through the incorporation of halogen material such fluorine, chlorine, or bromine). Given continued concerns by asset owners regarding the fire characteristics of FRP structures, it would seem reasonable to investigate the inclusion of this type of resin in this project's evaluation program. The brominated vinyl ester resins Derakane 510C, CoRezyn VE8441, and DION FR9300 have been recommended by manufacturers associated with this project. All three will be included in testing work to varying extents.

Polyester Resins

Unsaturated polyesters are the workhorse resins of the composite industry and are consumed in larger volume than any other resin. Traditionally, use of these materials was restricted to general-purpose applications without major structural demands. However, ongoing development over the past decade or so has seen an increasing usage of these materials in higher performance applications with significant structural loads. Offering a combination of low cost and sound structural performance, polyester resins are now widely utilized in almost all areas of composite application.

One of the major concerns in respect to polyester resins in civil engineering is their ability to maintain performance with long-term exposure to a typical civil engineering service environment. Of particular concern is their response to moisture. There are a high number of ester linkages that occur along the polyester molecule, and these segments are susceptible to attack both from water and from a range of chemicals, particularly alkaline media.(5) Cross-link density can significantly affect the susceptibility of the resin to attack. Heavily cross-linked systems form a tight three-dimensional network that physically resists penetration and attack.[6] However, this type of resistance generally comes at the sacrifice of resin flexibility and toughness.

Most laminating grade polyesters display low strain-to-failure levels. While it is possible to formulate extremely flexible polyester resins, this normally is achieved with a significant sacrifice in stiffness and temperature performance. The low strain-to-failure levels of typical laminating polyesters have been found to cause microcracking and crazing of the resin prior to failure, which appears to reduce the ultimate capacity of the laminate. Premature cracking of the resin also creates major concerns over long-term performance of polyester laminates. It is thought that these crack will create a path for moisture migration to the resin/fiber interface and that this will result in a loss of structural capacity through breakdown of the resin/fiber bond over time.[7]

Resistance to moisture attack is a significant concern with polyester resin systems in exterior civil engineering applications. Care must be taken to ensure that resin degradation from moisture attack does not reduce structural capacity to unsafe levels over time. While it is possible to formulate very high-performance polyester resins, these materials can cost as much as, or more than, competing vinyl ester systems. In such instances, it is thought that the overall performance characteristics of vinyl ester systems probably results in these materials being chosen over polyester.

Polyester resins also have been found to exhibit high volumetric shrinkage during cure. This shrinkage is an intrinsic part of the cure reaction and cannot be fully eliminated. Shrinkage has been seen to result in part distortion and residual stressing of components if not properly accommodated.

Overall, polyester systems cannot be discounted from use in civil engineering structures. Indeed, their low cost makes them a desirable option to many clients. However, their low toughness, low strain characteristics, and increased susceptibility to environmental attack may result in the preclusion of polyesters from primary structural applications such as the current bridge deck. However, in many secondary structural applications using glass reinforcements, they may represent an economical and competitive option. Polyester resin will not be included in testing for the current study.

REINFORCEMENT SELECTION

The reinforcement fibers are the primary load-carrying component of the composite; thus, the selection of an appropriate type and form of reinforcement is critical in obtaining a material with the desired engineering properties. With the diverse array of reinforcement fibers and fabrics available today, and the current limited understanding of these materials within civil engineering circles, the selection of an optimal reinforcement is a challenging task.

From a civil engineering perspective, reinforcements for composite laminates can be categorized into four basic groups:

- Glass fibers.
- Carbon fibers.
- Aramid fibers.
- Other fibers.

"Other fibers" include products such as high-density polyethylene, polybenzoxazole (PBO), boron, polyester, and nylon. While these materials are available commercially and may be suitable in a number of application fields, they are not regarded as viable options for civil engineering structures on the basis of either cost or performance. These types of materials will not be addressed further in this work. Glass, carbon, and aramid fibers are discussed in more detail in the following sections.

Glass Fibers

Glass fiber reinforcements are the most common synthetic reinforcing fiber available in today's composite industry. The development of high-quality glass fibers on a commercial scale in the early 1940s was one of the key enabling technologies in the current composites era. Since that time, glass fibers have been used in every segment of the composites industry. The success of glass fibers has been attributed to a number of factors, including cost, availability, handling and processing ability, useful properties and characteristics, and a history of past good experience in service.[8] Glass reinforcement costs less per pound than any other reinforcement type. Moreover, glass was the first type of reinforcement available. By the advent of carbon fibers on the market some 20 years later, glass fibers had already developed a successful history of application and processing. For comparison purposes, a reinforcement supplier contacted for this study provided the following costs for one yard of fabric of similar weights: carbon $40, aramid $44, and glass $10.

It is a common perception that glass fiber in composite materials is a low-tech approach that is not appropriate for civil engineering structures. However, as noted above, there are a number of advantages to using glass reinforcements which make them worthy of consideration.

One advantage with glass fibers is that the composition of the different fiber types is essentially standardized around the world. This means that a given type of glass fiber sourced from a particular country is basically the same as another originating from a different part of the world.

The most common fiber type is E-glass. Originally developed for electrical applications due to its high electrical resistance, E-glass fiber is now the workhorse fiber of the composites industry. E-glass fiber provides high tensile strength, good heat resistance, thermal stability, chemical resistance, moisture resistance, and fire resistance.

One key issue that has a major bearing on the structural properties of a fiber-reinforced laminate is the adhesion of the fiber and matrix. For a composite to perform, the material must function as a single cohesive unit rather than as individual constituents. It is therefore important to ensure a successful bond between fiber and matrix. Juska and Pucket noted a number of reports in the literature which indicate that compression strength, flexural strength, in-plane shear strength, transverse tensile strength, and mode I fracture toughness are all affected by the quality of the fiber matrix bond.[9] As an inorganic material, glass is essentially incompatible with organic resin matrix materials and thus does not form good bonds. To alleviate this problem, a chemical intermediary known as a coupling agent is applied to the glass to assist in bonding. All glass fiber designed for use as reinforcement is treated with a coupling agent. These coupling agents are specific to a certain resin chemistry. It is essential to ensure that the selected resin and glass reinforcement for a project are compatible. It is worth noting, too, that a number of manufacturers utilize a combination of coupling agents to create a reinforcement that is compatible with more than one resin, which provides manufacturing and cost benefits. The key issue, though, is still to identify the type of resin being used and to ensure its compatibility with the reinforcement.

Carbon Fibers

Carbon fibers offer an exceptional combination of high strength and stiffness, and low weight. Combined with indications of excellent long-term performance, these factors have made carbon fibers a material of significant interest in civil engineering applications.

The performance of a carbon fiber is determined by the precursor fiber used to produce the carbon. The performance properties also depend on the process parameters used in the conversion of the fiber from precursor material to carbon. Unlike glass fibers, at this time there is no system of standardized composition across the carbon fiber industry, with individual companies each utilizing different precursor compositions and producing different carbon fiber reinforcements.

The successful adhesion between a carbon fiber and the polymer matrix material is critical in obtaining high-performance laminates. However, in their “as manufactured” state, carbon fibers do not bond well to polymer resins.[10] A surface treatment is thus required to improve fiber/matrix adhesion. These surface treatments aim to boost surface reactivity and promote wetting of the fiber. Most carbon fibers sold as reinforcements are supplied with some type of surface treatment, with the most common type of process being a controlled oxidation.

From a civil engineering perspective, the primary advantage of carbon fiber reinforcements is their stiffness characteristics. The modulus of elasticity of general-purpose, high-strength carbon fibers such as T300 and AS4C is around 33 MSI. In a typical hand-fabricated laminate with unidirectional fibers, this translates to an elastic modulus for the laminate of around 11 MSI.

While a laminate modulus of 11 MSI is still significantly lower than the modulus of steel, it is a major improvement over other reinforcement options. The stiffness of standard E-glass fibers is about 11 MSI. This is less than a third of the modulus of AS4C carbon and typically translates to a unidirectional laminate modulus of only around 3.6 MSI.

Another advantage of carbon fibers is their low density, which enables the development of high strength and stiffness components at a fraction of the weight of conventional materials. Carbon fiber laminates possess some of the highest strength-to-weight and stiffness-to-weight ratios of any material. In civil engineering structures, this weight advantage does not provide the significant benefit that it does in fields such as aerospace development. Given the current cost of the reinforcement, it is anticipated that these materials would represent only a very small portion of the overall structure volume; hence, their influence on the total structure weight would be minor, unless a structural panel were made predominately of carbon, which may be the case in some unique applications.

Carbon fiber reinforcements are attractive for their performance under long-term static and cyclic loading. Carbon fiber laminates exhibit excellent creep performance for fiber dominated loading situations, and they are less susceptible to stress rupture, with little change in stress retention shown in testing over 1,000 hours.[(11)] Carbon fibers provide excellent fatigue performance. Peebles et al. noted that after 10^7 cycles, carbon/epoxy laminates retained 80 percent of durability, while glass fiber laminates retained only 30 percent and aluminum retained 55 percent.[(12)] The good long-term performance of carbon fiber composites provides some significant benefits in terms of initial design, with reduced safety factors used for these materials. In discussing material safety factors for LRFD methods, Karbhari and Seible suggested a long-term capacity reduction factor of 0.7 to 0.9 for carbon fiber laminates, compared with 0.3 to 0.5 for E-glass laminates.[(13)] This improved capacity factor can yield significant benefits for carbon fibers in design calculations and associated economics.

The most significant drawback of carbon fiber is cost. Though the actual cost per pound varies according to the type of weave, fiber orientation, and other factors, as a general rule carbon costs four times as much as glass. For the current project, the cost of carbon fiber reinforcement is too high to allow for competitive design solutions. Carbon fibers therefore will not be included in testing for this project.

Aramid Fibers

Aramid fibers are a specialist fiber for impact type situations and are not as widely used as glass or carbon reinforcements. While the basic mechanical properties offered by aramid fibers are similar to those achieved by other reinforcement types, aramids have several unique characteristics, including toughness and impact performance, low flammability, and resistance to solvents and bases. In regular applications, aramids possess several drawbacks which limit their use. These include poor off-axis properties, susceptibility to ultraviolet (UV) radiation, and excessive moisture absorption. Aramids will not be included in testing for this project.

CONCLUSION

Based on the background research and prior experience of the research team, the following materials were selected for inclusion in the testing program for this project:

Reinforcement:

- E-glass (continuous directional fiber fabrics and short random fiber mat).

Resin:

- Epoxy (room temperature curing, laminating epoxy).
- Standard vinyl ester.
- Toughened vinyl ester.
- Fire resistant vinyl ester.
- Phenolic.
- Urethane hybrid.

TESTING PROCEDURE FOR LAMINATES

To develop a broad-based specification for the bridge deck system, the researchers approached several commercial manufacturers about supplying sample panels using the identified materials. Additional panels were planned for laboratory fabrication to further knowledge on potentially suitable options and to develop a reasonable database of material data. Each company prepared a test panel with minimum dimensions of 48 inches by 36 inches with the nominal 0 degree direction being parallel to the 48-inch side. Cutting of the panels into two panels 24 inches by 36 inches was permitted to facilitate shipping.

SPECIFIED TEST METHODS

Table 1 outlines the standard test methods specified for laminate test panels in this project. The test program was developed to obtain mechanical properties required for design and analysis as well as base level properties for quality control testing during the subsequent manufacturing phase of the project. A test for degradation due to ultraviolet radiation is not included because all surfaces are to be protected in the proposed deck system. The top will have a polymer concrete wearing surface, and other exposed surfaces will be protected with paint.

Table 1. ASTM standard tests specified for sample laminates.

ASTM Test No.	Title	Properties Obtained	Symbol
D3039/ 3039M-08	Standard Test Method for Tensile Properties of Polymer Matrix Composites	Ultimate tensile strength (0°)	σ_{11T}
		Ultimate tensile strain (0°)	ε_{11T}
		Modulus of elasticity (chord) (0°)	E_{11T}
		Ultimate tensile strength (90°)	σ_{22T}
		Ultimate tensile strain (90°)	ε_{22T}
		Modulus of elasticity (chord) (90°)	E_{22T}
D6641/ D6641M-09	Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture	Ultimate compression strength (0°)	σ_{11C}
		Ultimate compression strain (0°)	ε_{11C}
		Modulus of elasticity (chord) (0°)	E_{11C}
		Ultimate compression strength (90°)	σ_{22C}
		Ultimate compression strain (90°)	ε_{22C}
		Modulus of elasticity (chord) (90°)	E_{22C}

Table1. ASTM standard tests specified for sample laminates, continued.

D7078/ D7078M-05	Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method	Ultimate shear strength (0°/90°)	ν_{12}
		Ultimate shear strain (0°/90°)	γ_{12}
		Shear modulus (chord) (0°/90°)	G_{12}
		Ultimate shear strength (90°/0°)	ν_{21}
		Ultimate shear strain (90°/0°)	γ_{21}
		Shear modulus (chord) (90°/0°)	G_{21}
D7264/ D7264M-07	Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials	Ultimate flexural strength (0°)	σ_{11F}
		Ultimate flexural strain (0°)	ε_{11F}
		Flexure Modulus (chord) (0°)	E_{11F}
		Ultimate flexural strength (90°)	σ_{22F}
		Ultimate flexural strain (90°)	ε_{22F}
		Flexure modulus (chord) (90°)	E_{22F}
D3171-09	Standard Test Method for Constituent Content of Composite Materials Test Method I, Procedure G: Matrix Burnoff in a Muffle Furnace	Fiber fraction - mass	m_f
		Fiber fraction - volume	v_f
D2344/ D2344M-00	Standard Test Method for Short-Beam Shear Strength of Polymer Matrix Composite Materials and Their Laminates	Short beam shear strength	
D635-03	Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position	Rate of burning	
		Extent of burning	
D2583-07	Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor	Barcol hardness	
D792-08	Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement	Specific gravity	SG

LAMINATE TESTING

ICE SHIELD LAMINATE CONFIGURATION

In July 2010, XC Associates fabricated a protective ice shield for a bridge in Erie County, NY, using the same FRP profile under consideration for this current project (see Figure 1).

Figure 1. Photo. Ice shield constructed by XC Associates.

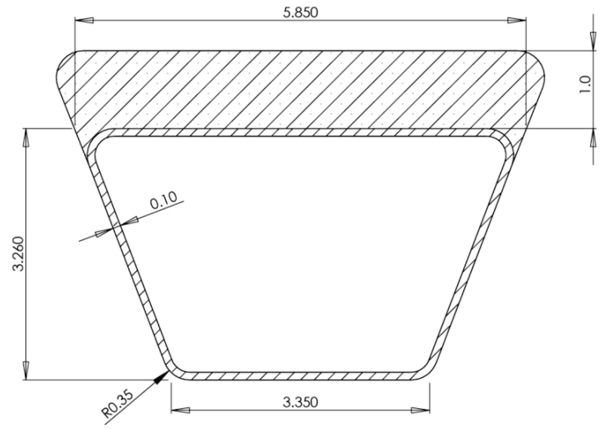

Figure 2. Diagram. Geometry of ice shield profile with single cavity (dimensions in inches).

The trapezoidal shape was slightly different than that developed for the current project, in that it only allows for a single grout cavity (see Figure 2). The newly developed shape allows for a cavity at the top and bottom, but since only the wide void is to be filled with grout for the Allegany County proof-of-concept bridge being done as part of this project, the section shown here is very similar to the proposed section. The section shown here was not pultruded, however. The inner trapezoidal tube was made using a custom mold (Figure 3) to shape the outside dimensions, then a bag was inflated on the inside to obtain the correct wall thickness. Once the inner tube was made, the grout was placed on top and the outer tube was made with a vacuum process that employed the smaller tube as tooling.

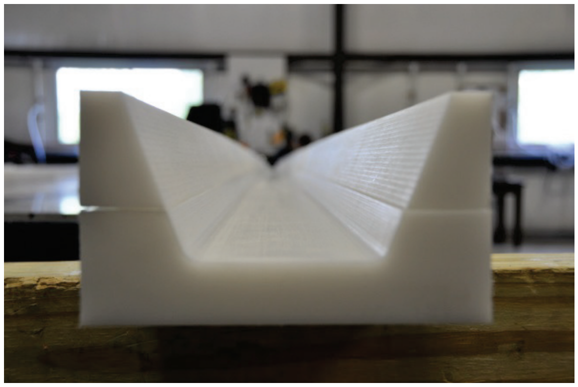

Figure 3. Photo. Plastic mold used to form the inner tube of the ice shield.

The structure was fabricated from two trapezoids each approximately 0.1 inches thick. The smaller trapezoid was designed to be adhesively bonded inside the larger trapezoid (see Figure 4). A series of these tubes would then be adhesively bonded together to form a deck unit. To ensure the structural integrity of the deck unit, the assembly would be completely wrapped by an outer laminate.

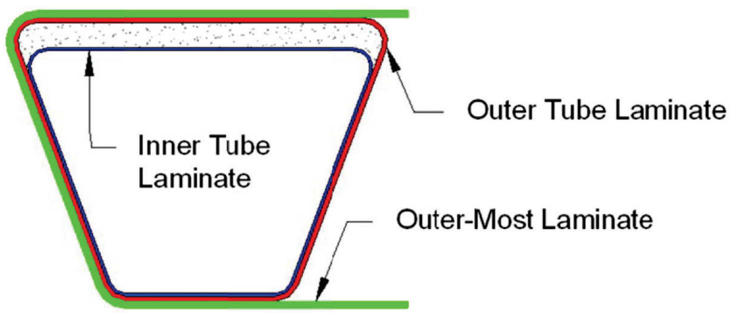

Figure 4. Diagram. Construction of deck profile from two trapezoidal tubes.

The reinforcement construction of both of these trapezoids was identical and was specified as [E-QX2600 / E-LT5500 / E-QX2600]. E-QX2600 is a 25.18-oz/yd^2 quadraxial E-glass fabric, and E-LT5500 is a 54.33-oz/yd^2 biaxial E-glass fabric. Both fabrics are manufactured by Vectorply Corporation. The resin used was Derakane 8084. They were made using a VARTM process.

A breakdown of the individual ply directions and weight in this laminate is as shown in Table 2.

Table 2. Ply sequence for ice shield laminates.

Individual Ply Direction	**Weight (oz/yd^2)**
0°	6.40
+45°	6.27
90°	6.24
-45°	6.27
0°	50.97
90°	3.36
0°	6.40
+45°	6.27
90°	6.24
-45°	6.27

This laminate layup was developed in consultation with Vectorply, who provided a table of predicted properties for the layup. The predicted properties are shown in Table 3.

Table 3. Predicted properties for ice shield trapezoid laminate.

Property	**Symbol**	**Predicted Value**	
Fiber Volume Fraction	v_f	52.84	%
Elastic Modulus – 0°	E_1	4.84	MSI
Elastic Modulus – 90°	E_2	2.77	MSI
In-Plane Shear Modulus	G_{12}	0.71	MSI
Ultimate Tensile Strength – 0°	σ_{1T}	88.6	KSI
Ultimate Tensile Strength – 90°	σ_{2T}	52.5	KSI
Ultimate Compression Strength – 0°	σ_{1C}	60.0	KSI
Ultimate Compression Strength – 90°	σ_{2C}	35.8	KSI
Ultimate Shear Strength – In Plane	υ_{12}	13.5	KSI

In developing laminate concepts for the current moveable bridge project, the ice shield laminate provided a natural starting point. Preliminary finite element analysis of the deck design indicated that if obtained properties were in line with the predictions in Table 3, then a satisfactory outcome could be achieved for the moveable bridge deck.

To assess whether the predicted properties were achievable in practice, XC Associates was contracted to produce a representative laminate panel that could be mechanically tested and compared to the predicted properties.

RESULTS OF TESTING FOR ICE SHIELD LAMINATE

Table 4 shows a comparison of the predicted property values and the actual values obtained from testing of the XC Associates sample panel. The 0° properties in tension are relatively consistent with predicted values; however, there are some variations in the corresponding compression values. For the 90° properties, there are significant differences between predicted and tested values.

The reason for the differences between predicted and measured properties is not clear. To attempt to reconcile the two data sets, the test data were reexamined to assess whether there were any obvious issues that could explain the discrepancies. No obvious problems could be seen with the data. Statistical screening using a maximum normed residual (MNR) method was performed to identify outlier specimens in each data set. Again, no outliers were identified in the data.

There is a slight variation of about 5 percent in the thickness of the test panel versus the predicted thickness. This difference does not explain the other property variations.

Table 4. Comparison of predicted values versus test values for ice shield sample laminate.

Property	**Symbol**	**Predicted Value**		**Tested Value**	
Fiber Fraction	m_f			69.82	%
	v_f	52.84	%	48.1	%
Elastic Modulus – 0°	E_1	4.84	MSI	(T) 4.37	MSI
				(C) 2.89	MSI
Elastic Modulus – 90°	E_2	2.77	MSI	(T) 1.99	MSI
				(C) 2.18	MSI
Ultimate Tensile Strength – 0°	σ_{1T}	88.6	KSI	84.53	KSI
Ultimate Tensile Strength – 90°	σ_{2T}	52.5	KSI	29.09	KSI
Ultimate Compression Strength – 0°	σ_{1C}	60.0	KSI	60.09	KSI
Ultimate Compression Strength – 90°	σ_{2C}	35.8	KSI	30.09	KSI
Laminate Thickness		0.106	in	0.112	in

Data on the behavior of a unidirectional E-glass/Derakane 8084 lamina under tension were available from a previous project. Using these data to estimate the behavior of the current ice shield laminate configuration, it was found that the predicted tensile modulus values were consistent with the actual data. The reason for the significantly lower E_2 value found in testing is not readily apparent. The strength values at 0° are in reasonable agreement, but at 90° the estimated value from the lamina data indicated a value for σ_{2T} of around 30 to 33 KSI. This is consistent with the tested value of 29.1 KSI and would suggest that the predicted value of 52.5 KSI was a significant overestimation. Corresponding lamina data in compression are not available at this time but will be obtained in future testing.

There are no apparent issues with the accuracy of the measured data, and as this represents the measured behavior of an actual panel, it should be taken as representative behavior.

ALTERNATIVE LAMINATE LAYUP PROPOSAL

In addition to XC Associates, this project proposed to evaluate alternative manufacturers for the trapezoidal tubes used in the deck. The research team approached Compmillenia, which expressed an interest in producing sample products; however, they did not carry the ice shield reinforcement products in stock and requested that alternative layups be investigated using products they had on hand.

The aim in proposing an alternative laminate ply sequence was to produce a laminate with a stiffness and load carrying capacity at least as great at the original ice shield laminate. An attempt was made to optimize the fiber architecture to help it perform better in the transverse direction so that the top of the tubes contributed to the flexural strength of the grout section. Given that the particular fabric used and the manufacturing processes significantly influence stress-based laminate properties, the approach taken in developing the new laminate configuration focused on achieving adequate reinforcement in principal directions.

Two basic assumptions were made in establishing an alternative laminate:

1. The resistance of the laminate to load is primarily a function of the amount of reinforcement aligned in the direction of load application.
2. The strength and stiffness of a unidirectional lamina in a given load direction decrease rapidly as the load line moves off the primary fiber axis of the lamina; thus, off-axis layers in a multilayer laminate make a minimal contribution to the overall load carrying capacity or elongation resistance of that laminate.

The design of an alternative laminate stacking sequence for Compmillenia was based on providing an adequate amount of reinforcement in several key directions, namely:

- The longitudinal axis of the tube – 0°.
- Normal to the longitudinal axis of the tube – 90°.
- +/-45° to the longitudinal axis in the plane of each face of the trapezoid – +/-45°.

The fibers in the longitudinal axis are responsible for carrying axial tension and compression loads as the tubes span between the stringer beams.

The 90° fibers are largely responsible for transferring local wheel loadings into the side walls of the trapezoids. It is assumed that these laminates work in conjunction with the grout as a sandwich panel under bending, spanning between the tube side walls. This results in in-plane tension and compression forces in the 90° direction (see Figure 5).

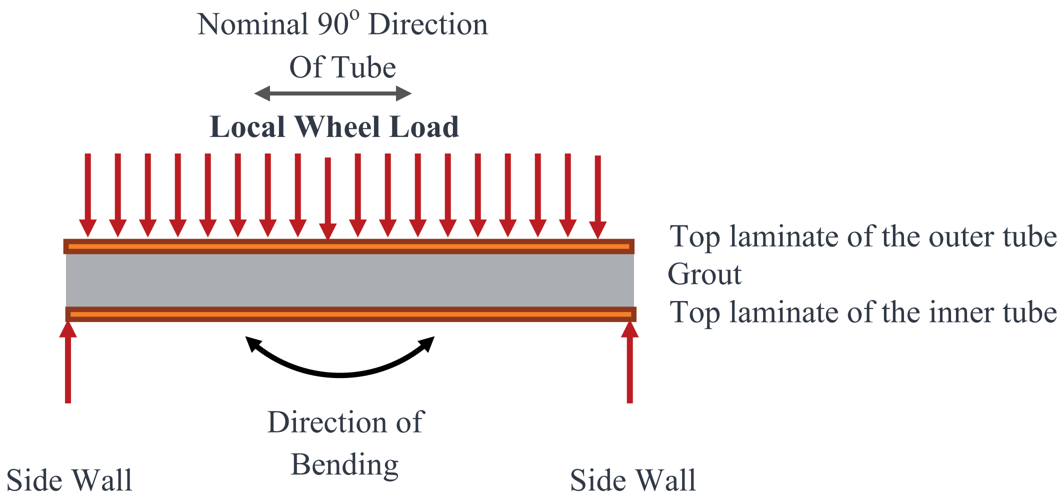

Figure 5. Diagram. Action of upper trapezoid surface under local wheel loading.

The +/-45° fibers are present primarily to transfer shear loads in the side walls of the tube. The shear loading results in tensile and compressive loads at 45° to the longitudinal tube axis in the plane of the side wall. Provision of sufficient fiber along the +/-45° direction is thus the primary consideration for the side walls.

Based on these principles, the new laminate configuration was designed to provide equal or greater fiber in each of the principal directions compared to the ice shield laminate. The total reinforcement in each primary direction of the ice shield laminate is shown in Table 5.

Table 5. Total areal weight in each primary direction – ice shield laminate.

Direction	**Areal Weight (oz/yd^2)**	**Areal Weight (g/m^2)**
0°	63.8	2162
90°	15.8	538
+/-45°	25.1	852

Compmillenia nominated the Vectorply E-glass fabrics listed in Table 6 as being available from their regularly held stock.

Table 6. Vectorply E-glass fabrics stocked by Compmillenia.

Fabric ID	**Description**	**Ply Details**	
		Dir.	**Weight (oz/yd^2)**
E-LM1810	0 warp unidirectional with mat - 27.06 oz/yd^2	0°	17.92
		90°	0.14
		CSM	9.00
E-LT3200	0/90 biaxial – 31.36 oz/yd^2	0°	17.92
		90°	13.44
E-BX2400	+45/-45 double bias – 23.90 oz/yd^2	+45°	11.95
		-45°	11.95

Using these fabrics, the laminate proposed was [E-LT3200 / E-LM1810 / E-BX2400 / E-LM1810 / E-LT3200]. The top and bottom layers of E-LT3200 are placed such that on the bottom surface the 90° layer is on the outer surface of the laminate and on the top the fabric is flipped such that the 90° layer is on the outer surface again.

The laminate yields the ply configuration shown in Table 7.

Table 7. Ply stacking sequence – Compmillenia laminate.

Individual Ply Direction	**Weight (oz/yd^2)**
90°	13.44
0°	17.92
0°	17.92
CSM	9.00
+45°	11.95
-45°	11.95
0°	17.92
CSM	9.00
0°	17.92
90°	13.44

Table 8 shows a comparison of Compmillenia layup versus the original ice shield layup.

Table 8. Comparison of ice shield and Compmillenia layups.

Direction	**Ice Shield (oz/yd^2)**	**Compmillenia (oz/yd^2)**
0°	63.8	71.7
90°	15.8	26.9
+/-45°	25.1	23.9
CSM	0	18.0

The resulting theoretical thickness of the ice shield layup is 0.106 inches, and the theoretical thickness of the Compmillenia layup is 0.15 inches.

The proposed Compmillenia panel provides an increase in both 0° and 90° reinforcements with a slight reduction in shear reinforcement. There is a 50 percent increase in laminate thickness; however, this was seen to be the most viable stacking sequence given the materials at hand.

Compmillenia provided two sample laminates with the alternative layup. The panels were produced using hand layup without vacuum consolidation. One was produced using a standard vinylester (CoRezyn VE8121), and the other was produced with an alternative fire retardant vinylester resin (CoRezyn VE8441). Both resins were manufactured by Interplastic Corporation.

COMPMILLENIA TEST PANEL RESULTS

The results of testing on the test panels from Compmillenia are given in the appendix. A summary of data for the panel is presented in the Summary chapter.

Table 9 shows a comparison of the test properties found with the Compmillenia test panels. When compared to the ice shield panel figures in Table 4, these figures appear low. However, it should be remembered that this laminate was not designed to be exactly the same as the ice shield laminate and that certain compromises were made to accommodate the materials available.

Table 9. Tested properties of Compmillenia laminates.

Property	**Symbol**	**CoRezyn 8121 Vinyl Ester**		**CoRezyn 8441 Vinyl Ester (fire-resistant)**	
Fiber Fraction	m_f	53.5	%	52.2	%
	v_f	31.5	%	33.4	%
Elastic Modulus – 0°	E_1	(T) 2.48	MSI	(T) 2.56	MSI
		(C) 2.36		(C) 2.37	MSI
Elastic Modulus – 90°	E_2	(T) 1.86	MSI	(T) 1.99	MSI
		(C) 1.84		(C) 1.93	MSI
Ultimate Tensile Strength – 0°	σ_{1T}	49.94	KSI	47.33	KSI
Ultimate Tensile Strength – 90°	σ_{2T}	29.75	KSI	28.41	KSI
Ultimate Compression Strength – 0°	σ_{1C}	54.42	KSI	45.59	KSI
Ultimate Compression Strength – 90°	σ_{2C}	32.33	KSI	27.23	KSI
Laminate Thickness		0.218	in	0.229	in

The biggest contributor to the lower test properties is the low fiber fraction achieved in the test panel. The XC Associates ice shield panel had a fiber volume fraction of around 50 percent, while the Compmillenia panels only had fiber fractions of 31.5 percent and 33.4 percent, respectively. It is thought that a significant contributor to this low fiber fraction is the mat layer on the E-LM1810 fabric. It is difficult to obtain low fiber fractions with a mat material as the structure of the mat tends to hold itself open and thus holds more resin. Significantly better stress properties may be achieved if an alternative unidirectional fabric was used which did not utilize a mat layer. An increase in fiber fraction from 31 to 50 percent would result in a thickness decrease of around 62 percent and a corresponding stress-based property increase of around 160 percent. Considering the current tensile modulus values of E_1 = 2.48MSI and E_2 = 1.86MSI, the area decrease would result in new values of E_1 = 4.00 MSI and E_2 = 3.00 MSI. This is much more in line with the ice shield properties.

However, even if the fiber fraction was increased to 50 percent, the resulting thickness of the laminate would still be around 0.15 inches. This is 50 percent greater than the original targeted laminate thickness of 0.1 inches. To achieve a 0.1-inch thickness it would be necessary to revise the laminate stacking sequence and reduce the amount of reinforcement present.

ADDITIONAL LAMINATE CHARACTERIZATION WORK CURRENTLY IN PROGRESS

PULTRUDED PROFILE LAMINATE

The research team is pursuing the production of a custom pultruded trapezoidal profile through Creative Pultrusions, Inc. The pultruded combination or “combi” tube will be a three-cavity trapezoid as shown in Figure 6. The current generation uses a fire-resistant vinyl ester resin (Derakane 510C from Ashland). The reinforcement is E-glass rovings, woven mat, and chapped strand mat from PPG and Owens-Corning.

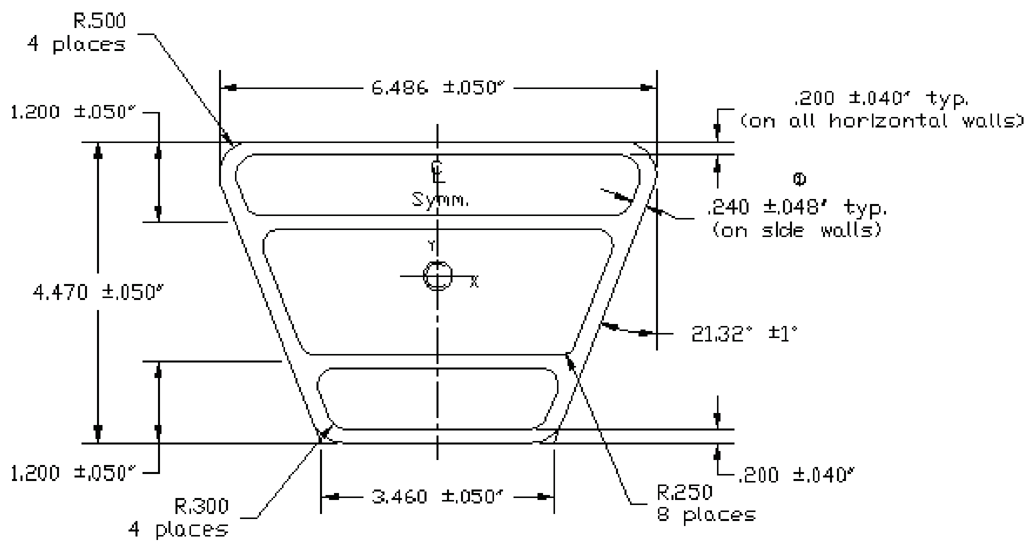

Figure 6. Diagram. Pultruded combi tube.

Due to production requirements of the pultrusion process, the laminate construction currently specified for the profile is significantly different from that of the original ice shield laminate used as the basis for design. Figure 7 shows the final laminate construction to be manufactured for the profile. The original concept involved a constant 0.2-inch wall in all areas; however, it did not appear that adequate properties could be obtained with this concept. The current concept calls for 0.2-inch horizontal walls with 0.24-inch walls for the inclined sides.

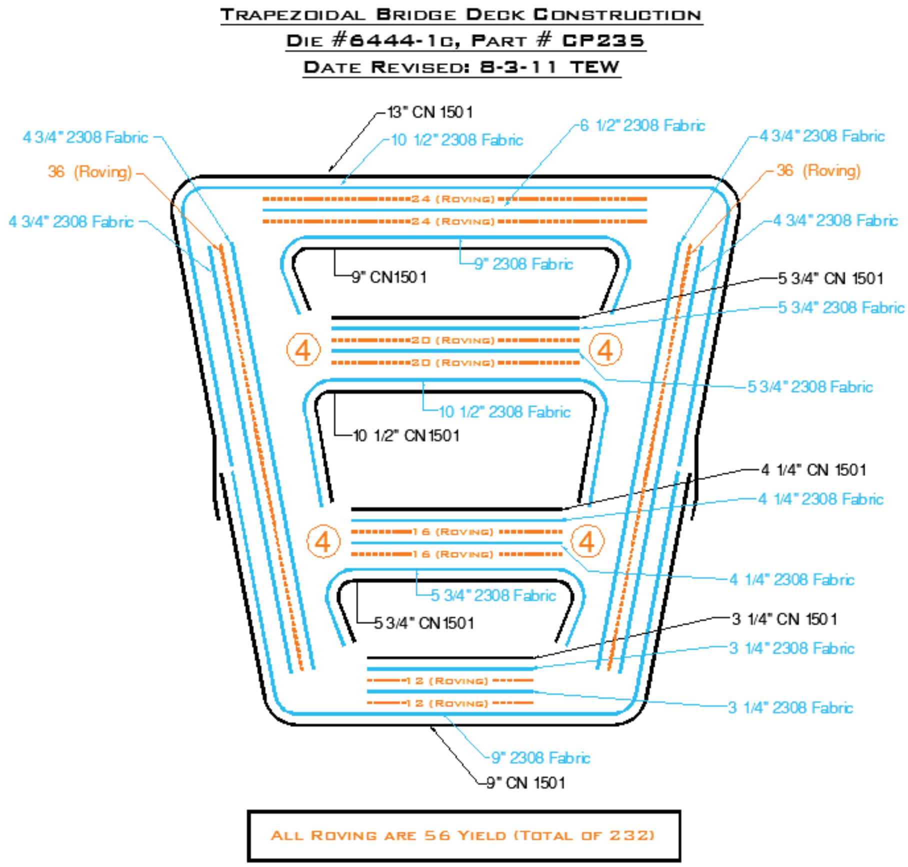

Figure 7. Diagram. Laminate construction for pultruded combi tube.

Predicted properties for this profile construction, provided by Creative Pultrusions, are given in Table 10.

Table 10. Predicted properties of pultruded tube versus tested ice shield laminate.

Property	Unit	Horizontal Walls	Vertical Walls	Ice Shield Laminate (tested)
Thickness	in	0.2	0.24	0.2
Fiber Volume Fraction	%	n/a	n/a	48.1
Elastic Modulus – 0° (tension)	MSI	3.39	3.18	4.37
Elastic Modulus – 90° (tension)	MSI	2.33	2.39	1.99
In-Plane Shear Modulus	MSI	0.74	0.75	n/a
Ultimate Tensile Strength – 0°	KSI	63.6	55.6	84.5
Ultimate Tensile Strength – 90°	KSI	20.6	22.3	29.1
Ultimate Compression Strength – 0°	KSI	54.8	52.6	60.1
Ultimate Compression Strength – 90°	KSI	22.3	23.6	30.1
Ultimate Shear Strength – In Plane	KSI	8	8.6	n/a

The individual ply details of the laminate constructions for the horizontal and vertical walls are given in Table 11 and Table 12.

Table 11. Ply details for horizontal walls of pultruded tube.

Material	**Angle (°)**	**Areal Weight (oz / yd^2)**	**Thickness (in)**
1 ½ oz CSM	n/a	1.5	0.016
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
Roving - 3.7 ends/in	0	38.3	0.038
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
Roving - 3.7 ends/in	0	38.3	0.038
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
1 ½ oz CSM	n/a	1.5	0.016
TOTALS	0	76.6	0.204
	90	34.6	
	+45/-45	37.6	
	CSM	27.3	

Note: CSM = chopped strand mat (short random fiber mat reinforcement)

Table 12. Ply details for vertical walls of pultruded tube.

Material	Angle (°)	Areal Weight (oz / yd²)	Thickness (in)
1 ½ oz CSM	n/a	1.5	0.017
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
Roving – 7.6 ends/in	0	78.6	0.078
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
E-TTXM 2308	45	6.27	0.032
	90	11.52	
	-45	6.27	
	CSM	8.10	
1 ½ oz CSM	n/a	1.5	0.017
TOTALS	0	78.6	0.240
	90	46.1	
	+45/-45	50.2	
	CSM	27.3	

Table 13 shows a comparison of the total weights of the Creative Pultrusions laminate construction versus the XC Associates ice shield panel and the Compmillenia panels. The Creative Pultrusions laminate has significantly more shopped strand mat (CSM) material than either of the previous laminates, which will likely result in a lower fiber volume fraction. For the thickness, the proposed laminates also contain significantly less unidirectional reinforcement, which may reduce the effective longitudinal strength of the tube further.

Table 13. Areal reinforcement weights (oz/yd^2) of potential tube laminates.

Fiber Direction	XC Associates Ice Shield Laminate*	Compmillenia Laminate	Creative Pultrusions Horizontal Wall	Creative Pultrusions Vertical Wall
0	127.6	71.7	76.6	78.6
90	31.6	26.9	34.6	46.1
+45/-45	50.2	23.9	37.6	50.2
CSM	0	18.0	27.3	27.3
Thickness	0.212 in	0.15 in	0.204 in	0.240 in

*Two layers of original ice shield laminate to create ~0.2-inch thickness

To examine the behavior of this construction and to assess production options with different resins and processes, series of test panels will be fabricated using the materials listed in Table 14. Test laminates will utilize a layup sequence of:

[E-BX1200/E-M0010/E-LT1800/E-LA1312/E-LT1800/E-BX1200/E-M0010/E-LA1312/E-LT1800/E-LA1312/E-LT1800/E-M0010/E-BX1200]

Table 14. E-glass reinforcements for test laminates fabricated at LeTourneau University.

<table>
<tr><th rowspan="2">Fabric ID</th><th rowspan="2">Description</th><th colspan="2">Ply Details</th><th>Nominal Thickness</th></tr>
<tr><th>Dir.</th><th>Weight (oz/yd^2)</th><th>(in)</th></tr>
<tr><td rowspan="2">E-LA1312</td><td rowspan="2">0 warp unidirectional with A-glass veil - 13.42 oz/yd^2</td><td>0°</td><td>12.22</td><td rowspan="2">0.014 – 0.021</td></tr>
<tr><td>Veil</td><td>1.20</td></tr>
<tr><td rowspan="2">E-LT1800</td><td rowspan="2">0/90 biaxial – 17.92 oz/yd^2</td><td>0°</td><td>8.96</td><td rowspan="2">0.018 – 0.026</td></tr>
<tr><td>90°</td><td>8.96</td></tr>
<tr><td rowspan="2">E-BX1200</td><td rowspan="2">+45/-45 double bias – 12.54 oz/yd^2</td><td>+45°</td><td>6.27</td><td rowspan="2">0.013 – 0.018</td></tr>
<tr><td>-45°</td><td>6.27</td></tr>
<tr><td>E-M0010</td><td>Random strand mat – 9.00 oz/yd^2</td><td>CSM</td><td>9.00</td><td>0.010 – 0.024</td></tr>
</table>

This configuration will provide directional reinforcement weights of:

- 0° – 72.50 oz/yd^2
- 90° – 35.84 oz/yd^2
- +/-45° – 37.62 oz/yd^2
- CSM – 30.60 oz/yd^2

These reinforcement weights are relatively consistent with the horizontal wall reinforcements proposed by Creative Pultrusion. Some differences do exist, but the proposed test layup is as close as can be achieved with readily available materials. Due to the use of lighter weight fabrics, the laminates will have a larger number of layers, but this allows closer approximation of the pultrusion laminate in terms of both reinforcement weight and ply position.

Test laminates will be produced using five different resins, as listed in Table 15.

Table 15. Resins for laminate testing and evaluation.

Product Name	Manufacturer	Type
Derakane 8084	Ashland	Elastomer modified vinyl ester
Derakane 510C	Ashland	Fire resistant vinyl ester
DION FR9300	Reichhold	Fire resistant vinyl ester
Cellobond FRP J2027L	Momentive	Laminating phenolic
Dion 9800	Reichhold	Hybrid urethane
TBD*	Huntsman	Laminating epoxy

*currently under assessment by Huntsman

ADDITIONAL TEST LAMINATES

Four additional unidirectional laminates will be fabricated; one with each of the fabrics listed in Table 14. These will provide base-level lamina design information for assessing alternative tube layups. These four laminates will be fabricated with Derakane 8084 vinyl ester resin.

SUMMARY

Table 16 provides a summary of test data obtained in this project to November 1, 2011. Additional detail is provided in the appendix. Testing on the other laminates outlined in previous section is ongoing, and data will be provided upon completion.

Table 16. Summary of test data as of November 1, 2011.

		XC Associates Ice Shield Predicted (Vetorply)				XC Associates Ice Shield Sample (test panel)				XC Associates Ice Shield Sample (outer wrap)				Plastochem (India) Test Laminate Properties			
Property	Symbol	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units
Modulus																	
Tension	E_{T0}	33371	MPa	4.84	MSI	30103	MPa	4.37	MSI	21426	MPa	3.11	MSI	37330	MPa	5.41	MSI
	E_{T90}	19098	MPa	2.77	MSI	13705	MPa	1.99	MSI					8795	MPa	1.28	MSI
Compression	E_{C0}					19920	MPa	2.89	MSI								
	E_{C90}					15035	MPa	2.18	MSI								
Flexure	E_{F0}					12652	MPa	1.84	MSI								
	E_{F90}					12182	MPa	1.77	MSI								
Ultimate Strength																	
Tension	σ_{T0}	610.88	MPa	88.6	KSI	582.84	MPa	84.53	KSI	341.62	MPa	49.55	KSI	524.34	MPa	76.05	KSI
	σ_{T90}	361.97	MPa	52.5	KSI	200.56	MPa	29.09	KSI					46.425	MPa	6.73	KSI
Compression	σ_{C0}	413.69	MPa	60.0	KSI	414.34	MPa	60.09	KSI								
	σ_{C90}	246.83	MPa	35.8	KSI	207.49	MPa	30.09	KSI								
Flexure	σ_{F0}					260.54	MPa	37.79	KSI								
	σ_{F90}					326.87	MPa	47.41	KSI								
Strain at Max. Stress																	
Tension	ε_{T0}					2.30	%			2.07	%			1.49	%		
	ε_{T90}					2.44	%							1.62	%		
Compression	ε_{C0}					2.62	%										
	ε_{C90}					2.38	%										
Flexure	ε_{F0}					3.52	%										
	ε_{F90}					3.58	%										
Fiber Content (%)																	
mass	m_f	70.33	%			69.8	%										
volume	v_f	52.84	%			48.0	%										
Hardness						54.76											
Short Beam Strength						40.04	MPa	5.81	ksi								
Burn Rate						11.53	mm/mi	0.038	fpm								

		Creative Pultrusions Predicted Combi Tube (0.20" Wall)				Creative Pultrusions Predicted Combi Tube (0.24" Wall)				Compmillenia Interplastic VE8121				Compmillenia Interplastic VE8441			
Property	Symbol	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units	Value	Units
Modulus																	
Tension	E_{T0}	23373	MPa	3.39	MSI	21925	MPa	3.18	MSI	17081	MPa	2.48	MSI	17665	MPa	2.56	MSI
	E_{T90}	16065	MPa	2.33	MSI	16478	MPa	2.39	MSI	12833	MPa	1.86	MSI	13706	MPa	1.99	MSI
Compression	E_{C0}									16271	MPa	2.36	MSI	16311	MPa	2.37	MSI
	E_{C90}									12709	MPa	1.84	MSI	13338	MPa	1.93	MSI
Flexure	E_{F0}									14168	MPa	2.05	MSI	13160	MPa	1.91	MSI
	E_{F90}									16446	MPa	2.39	MSI	17294	MPa	2.51	MSI
Ultimate Strength																	
Tension	σ_{T0}	438.51	MPa	63.60	KSI	383.35	MPa	55.60	KSI	344.35	MPa	49.94	KSI	326.30	MPa	47.33	KSI
	σ_{T90}	142.03	MPa	20.60	KSI	153.75	MPa	22.30	KSI	205.14	MPa	29.75	KSI	195.89	MPa	28.41	KSI
Compression	σ_{C0}	377.83	MPa	54.80	KSI	355.77	MPa	51.60	KSI	375.24	MPa	54.42	KSI	314.34	MPa	45.59	KSI
	σ_{C90}	153.75	MPa	22.30	KSI	162.72	MPa	23.60	KSI	222.92	MPa	32.33	KSI	187.73	MPa	27.23	KSI
Flexure	σ_{F0}									455.72	MPa	66.10	KSI	390.57	MPa	56.65	KSI
	σ_{F90}									445.24	MPa	64.58	KSI	424.43	MPa	61.56	KSI
Strain at Max. Stress																	
Tension	ε_{T0}									2.43	%			2.37	%		
	ε_{T90}									2.13	%			2.23	%		
Compression	ε_{C0}									2.43	%			2.14	%		
	ε_{C90}									2.07	%			1.44	%		
Flexure	ε_{F0}									4.23	%			3.84	%		
	ε_{F90}									3.06	%			2.77	%		
Fiber Content (%)																	
mass	m_f									53.5	%			52.2	%		
volume	v_f									31.6	%			33.0	%		
Hardness										54.86				50.31		50.31	
Short Beam Strength										34.37	MPa	4.98	ksi	35.58	MPa	5.16	ksi
Burn Rate										2.11	mm/min	0.0069	fpm	<25 mm		<1 in	

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APPENDIX

ASTM D3039 / D3039M - 08
Standard Test Method for
Tensile Properties of Polymer Matrix Composite Materials

Test Information

Test Date:	11/5/2011
Test Location:	Civil Engineering Materials and Structures Laboratory LeTourneau University
Test Operator:	Phil Cowles
LSC Sample ID#:	HfL CombiTube Initial Run Top/First Flange
LSC Test ID #:	LSC-11-FRP-T-019
Client:	Bridge Composites LLC
Sample Manufacturer:	Creative Pultrusions, Inc
Manufacturer Sample ID:	
Sample Production Date:	11/1/2011
Sample Fabrication Method:	Pultrusion
Reinforcement Type:	E-glass roving, fabric and mat
Resin Type:	Derakane 510C
Ply Stacking Sequence:	
Nominated Test Direction:	0 deg
Specimen Type:	25 x 250mm (as per Table 2)
Specimen Manufacturing Method:	Specimens cut on diamond blade on surface grinder and hand sanded
Tab Types and Material:	no tabs used
Specimen Condition Procedure:	stored in lab min 88 hrs @ 72F
Test Environment:	21C / 50% RH
Test Machine Information:	Instron 5582 Universal Testing Machine Calibration Date 11/11/10 100 kN Load Cell - SN48874 AVE Strain Measurement Mechanical wedge box grips - thermal spray faces
Loading Rate:	2.00 mm/min
Number of specimens in sample	7

Specimen Test Results and Statistics

	Thick (mm)	Width (mm)	Area (mm^2)	Modulus of Elasticity (MPa)	Max Load (N)	Stress at Max Load (MPa)	Strain at Max Load (%)	Load at Break (N)	Stress at Break (MPa)	Strain at Break (%)
1	4.93	24.94	122.95	22217	32529	264.57	1.11	32183	261.75	1.25
2	4.24	24.80	105.15	28962	31507	299.63	1.01	29401	279.60	1.10
3	4.56	24.80	113.09	22532	29891	264.32	1.20	29251	258.66	1.18
4	4.93	24.82	122.36	28542	33946	277.42	1.02	33598	274.58	1.01
5	5.00	24.86	124.30	31684	33748	271.50	0.99	33467	269.24	1.00
Av	4.73	24.84	117.57	26787	32324	275.49	1.07	31580	268.77	1.11
SD	0.32	0.06	8.24	4206.76	1679.90	14.55	0.09	2131.30	8.70	0.11
CoV	6.86	0.24	7.01	15.70	5.20	5.28	8.19	6.75	3.24	9.69

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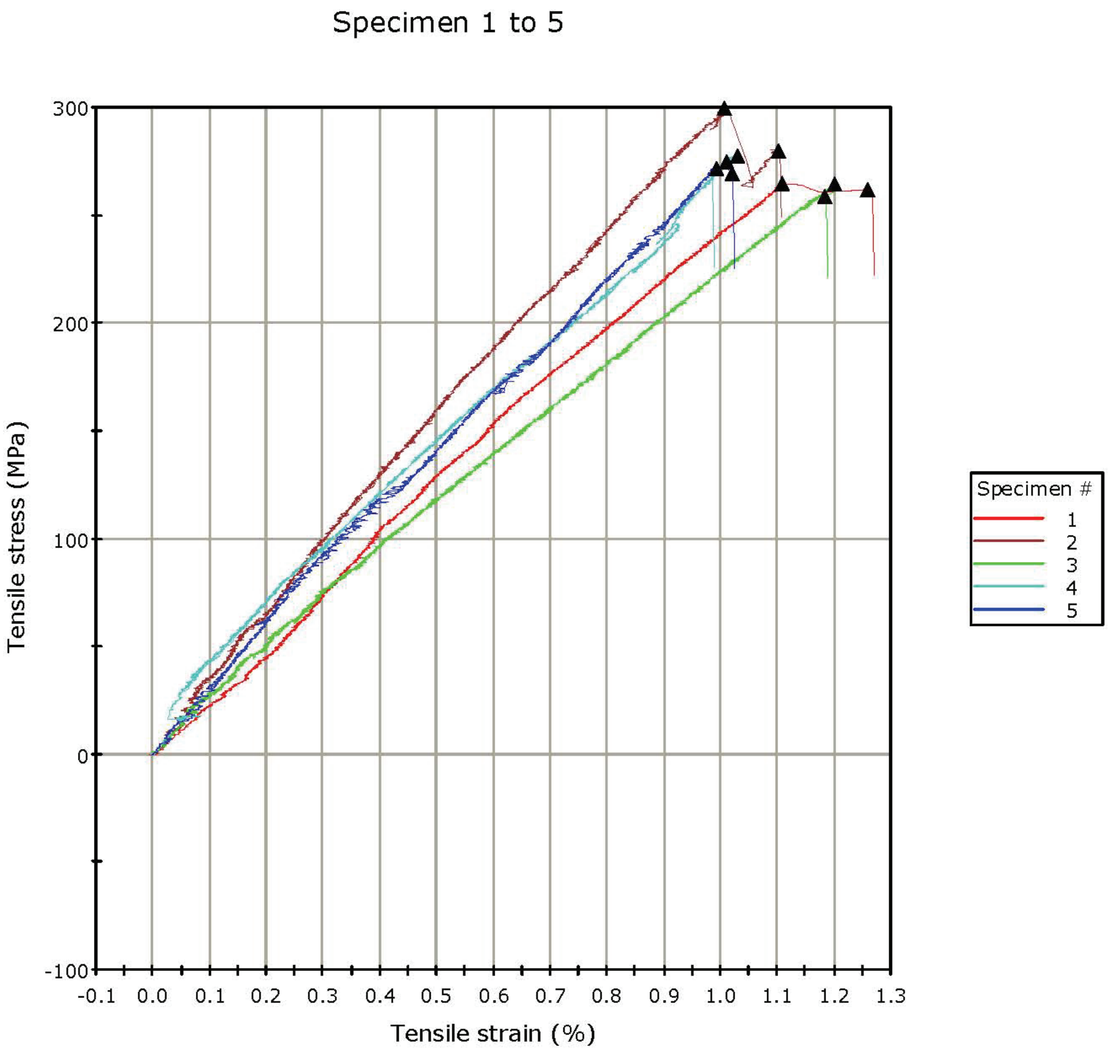
Specimen 1 to 5
Tensile stress (MPa)
300
200
100
0
-100
-0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3
Tensile strain (%)
Specimen #
1
2
3
4
5

ASTM D3039 / D3039M - 08
Standard Test Method for
Tensile Properties of Polymer Matrix Composite Materials

Test Information

Test Date:	11/10/2011
Test Location:	Civil Engineering Materials and Structures Laboratory LeTourneau University
Test Operator:	Phil Cowles
LSC Sample ID#:	HfL CombiTube Initial Run Side Wall
LSC Test ID #:	LSC-11-FRP-T-020
Client:	Bridge Composites LLC
Sample Manufacturer:	Creative Pultrusions, Inc
Manufacturer Sample ID:	
Sample Production Date:	11/1/2011
Sample Fabrication Method:	Pultrusion
Reinforcement Type:	E-glass roving, fabric and mat
Resin Type:	Derakane 510C
Ply Stacking Sequence:	
Nominated Test Direction:	0 deg
Specimen Type:	25 x 250mm (as per Table 2)
Specimen Manufacturing Method:	Specimens cut on diamond blade on surface grinder and hand sanded
Tab Types and Material:	no tabs used
Specimen Condition Procedure:	stored in lab min 88 hrs @ 72F
Test Environment:	21C / 50% RH
Test Machine Information:	Instron 5582 Universal Testing Machine Calibration Date 11/11/10 100 kN Load Cell - SN48874 AVE Strain Measurement Mechanical wedge box grips - thermal spray faces
Loading Rate:	2.00 mm/min
Number of specimens in sample	7

Specimen Test Results and Statistics

	Thick (mm)	Width (mm)	Area (mm^2)	Modulus of Elasticity (MPa)	Max Load (N)	Stress at Max Load (MPa)	Strain at Max Load (%)	Load at Break (N)	Stress at Break (MPa)	Strain at Break (%)
1	6.02	24.89	149.84	29047	37236	248.51	1.02	36154	241.29	1.02
2	6.15	25.00	153.75	34030	37556	244.27	0.90	35878	233.35	0.85
3	6.03	24.79	149.48	24717	35011	234.21	1.08	33980	227.31	1.06
Av	6.07	24.89	151.02	29264	36601	242.33	1.00	35337	233.98	0.98
SD	0.07	0.11	2.37	4660.24	1386.62	7.35	0.10	1183.90	7.01	0.11
CoV	1.19	0.42	1.57	15.92	3.79	3.03	9.60	3.35	3.00	11.47

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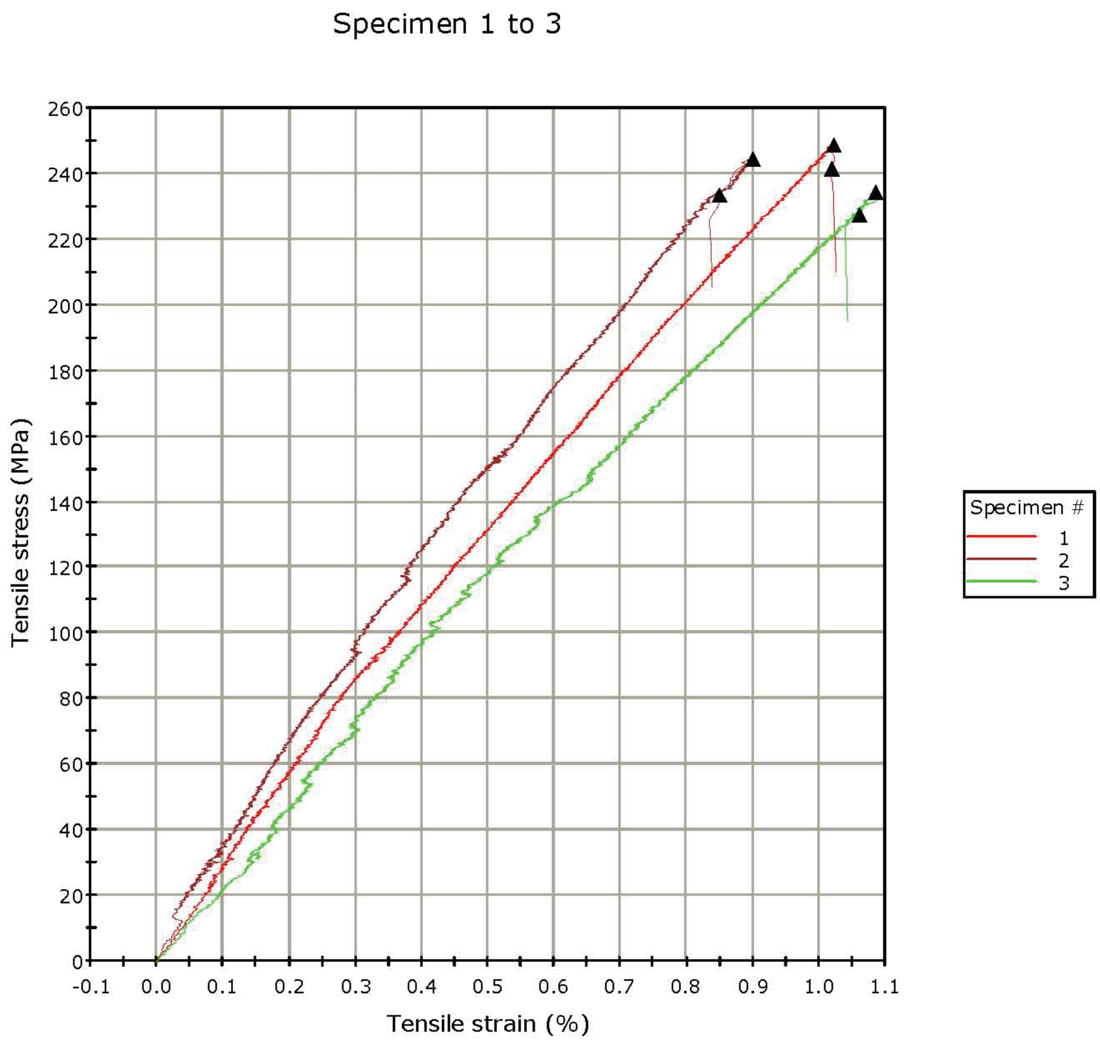
Specimen 1 to 3
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
Tensile strain (%)
Tensile stress (MPa)
Specimen #
1
2
3

ASTM D3039 / D3039M - 08
Standard Test Method for
Tensile Properties of Polymer Matrix Composite Materials

Test Information

Test Date:	11/12/2011
Test Location:	Civil Engineering Materials and Structures Laboratory LeTourneau University
Test Operator:	Phil Cowles
LSC Sample ID#:	HfL CombiTube Initial Run Top
LSC Test ID #:	LSC-11-FRP-T-021
Client:	Bridge Composites LLC
Sample Manufacturer:	Creative Pultrusions, Inc
Manufacturer Sample ID:	
Sample Production Date:	11/1/2011
Sample Fabrication Method:	Pultrusion
Reinforcement Type:	E-glass roving, fabric and mat
Resin Type:	Derakane 510C
Ply Stacking Sequence:	
Nominated Test Direction:	90 deg
Specimen Type:	25 x 250mm (as per Table 2)
Specimen Manufacturing Method:	Specimens cut on diamond blade on surface grinder and hand sanded
Tab Types and Material:	no tabs used
Specimen Condition Procedure:	stored in lab min 88 hrs @ 72F
Test Environment:	21C / 50% RH
Test Machine Information:	Instron 5582 Universal Testing Machine Calibration Date 11/11/10 100 kN Load Cell - SN48874 AVE Strain Measurement Mechanical wedge box grips - thermal spray faces
Loading Rate:	2.00 mm/min
Number of specimens in sample	5

Specimen Test Results and Statistics

	Thick (mm)	Width (mm)	Area (mm^2)	Modulus of Elasticity (MPa)	Max Load (N)	Stress at Max Load (MPa)	Strain at Max Load (%)	Load at Break (N)	Stress at Break (MPa)	Strain at Break (%)
1	4.99	24.94	124.45	18600	17045	136.96	0.99	16116	129.50	1.02
2	4.94	25.14	124.19	17056	17337	139.60	1.11	16530	133.10	1.06
3	4.99	25.20	125.75	14836	15530	123.50	0.88	14253	113.34	0.77
4	4.95	25.03	123.90	18313	16395	132.33	1.17	16117	130.08	1.12
Av	4.97	25.08	124.57	17201	16577	133.10	1.04	15754	126.51	0.99
SD	0.03	0.12	0.82	1713.26	801.35	7.07	0.13	1019.77	8.92	0.15
CoV	0.53	0.46	0.65	9.96	4.83	5.31	12.49	6.47	7.05	15.24

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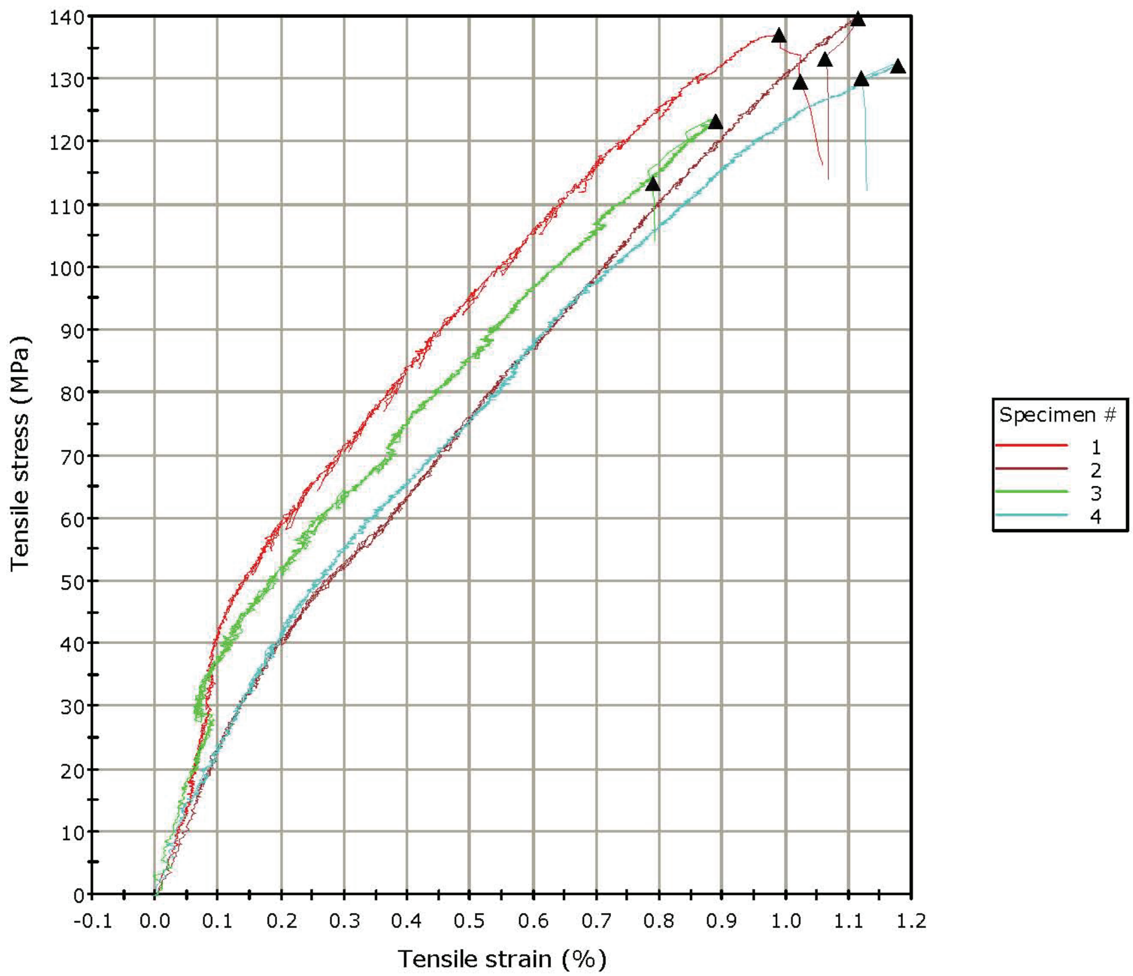
Specimen 1 to 4



ASTM D3039 / D3039M - 08
Standard Test Method for
Tensile Properties of Polymer Matrix Composite Materials

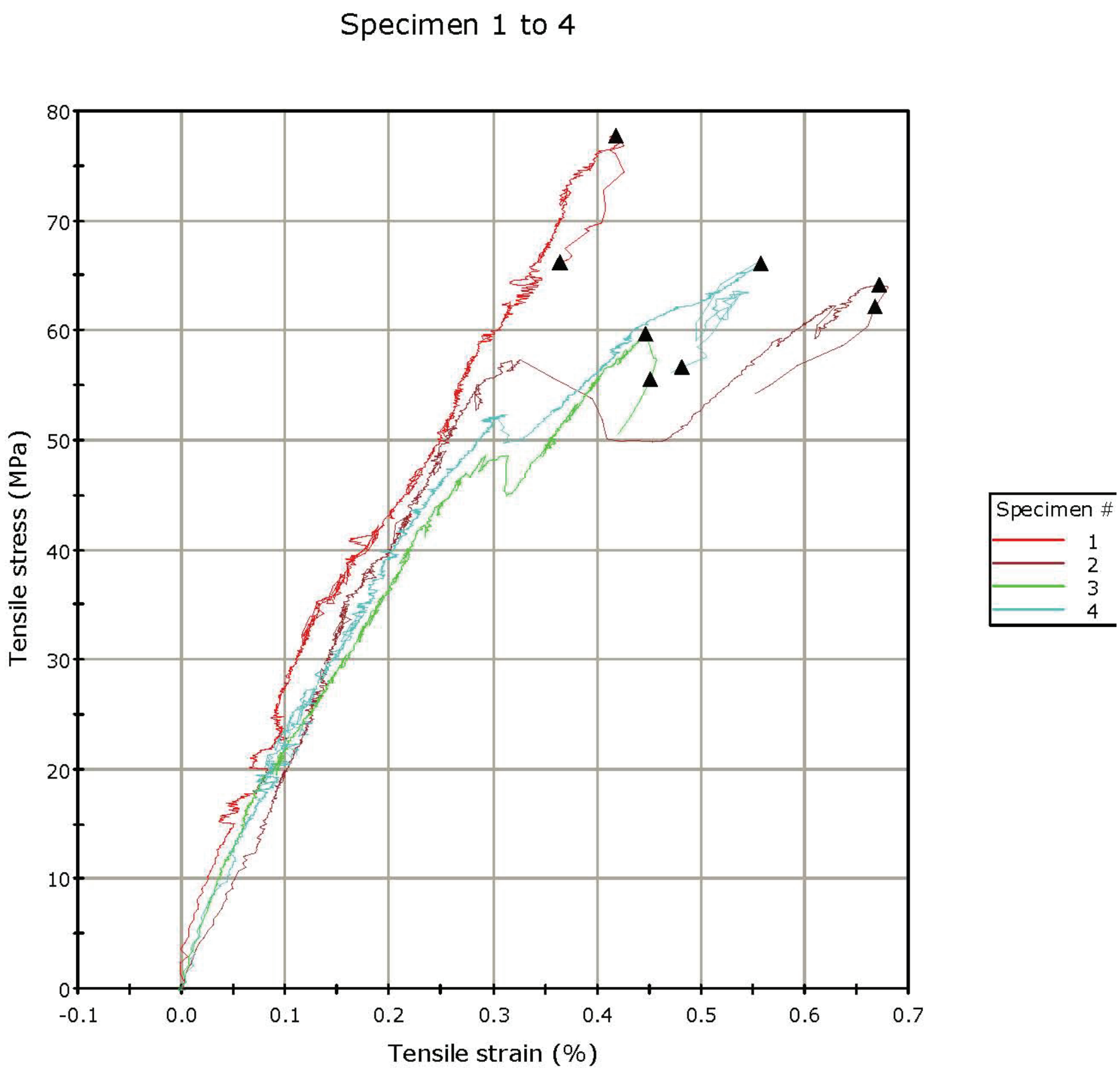
Test Information

Test Date:	11/29/2011
Test Location:	Civil Engineering Materials and Structures Laboratory LeTourneau University
Test Operator:	Phil Cowles
LSC Sample ID#:	CP Combi Tube - Initial Run
LSC Test ID #:	LSC-11-FRP-T-022
Client:	BridgeComposites
Sample Manufacturer:	Creative Pultrusions
Manufacturer Sample ID:	Interplastic 8441
Sample Production Date:	11/1/2011
Sample Fabrication Method:	Pultursions
Reinforcement Type:	E-glass
Resin Type:	Derakane 510C-350
Ply Stacking Sequence:	combi tube side walls
Nominated Test Direction:	90 deg
Specimen Type:	25 x 110 mm (not to standard)
Specimen Manufacturing Method:	Specimens cut on diamond blade on surface grinder and hand sanded
Tab Types and Material:	no tabs used
Specimen Condition Procedure:	stored in lab min 88 hrs @ 72F
Test Environment:	21C / 50% RH
Test Machine Information:	Instron 5582 Universal Testing Machine Calibration Date 11/11/10 100 kN Load Cell - SN48874 AVE Strain Measurement Mechanical wedge box grips - thermal spray faces
Loading Rate:	2.00 mm/min
Number of specimens in sample	7

Specimen Test Results and Statistics

	Thick (mm)	Width (mm)	Area (mm^2)	Modulus of Elasticity (MPa)	Max Load (N)	Stress at Max Load (MPa)	Strain at Max Load (%)	Load at Break (N)	Stress at Break (MPa)	Strain at Break (%)
1	6.19	25.01	154.81	17445	12030	77.71	0.42	10251	66.22	0.36
2	5.88	25.07	147.41	19524	9456	64.15	0.67	9167	62.19	0.67
3	5.86	24.95	146.21	15902	8730	59.71	0.45	8122	55.55	0.45
4	6.16	24.93	153.57	17204	10154	66.12	0.55	8704	56.68	0.48
Av	6.02	24.99	150.50	17519	10093	66.92	0.52	9061	60.16	0.49
SD	0.18	0.06	4.32	1498.89	1416.58	7.67	0.12	901.44	4.97	0.13
CoV	2.93	0.25	2.87	8.56	14.04	11.47	22.10	9.95	8.27	26.03

Certified By:


Specimen 1 to 4
80
70
60
50
40
30
20
10
0
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Tensile stress (MPa)
Tensile strain (%)
Specimen #
1
2
3
4