TEMPERATURE AND MOISTURE EFFECTS ON COMPOSITE MATERIALS FOR WIND TURBINE BLADES

by

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ABSTRACT

Temperature and moisture effects on composite materials with E-glass fibers and different potential resins for wind turbine blades have been investigated. The purpose of this study was to identify resins that have good temperature/moisture resistance while providing improved delamination resistance relative to a baseline ortho-polyester resin. The resins included ortho and iso polyesters, vinyl esters and an epoxy. The resins in this study were all appropriate for wind turbine blades in terms of low cost and low viscosity for easy processing by resin transfer molding (RTM). Specimens were conditioned in one of three ways: room temperature dry, 50°C dry in an oven and 50°C in distilled water. Water absorption was determined at 50°C both for composites and neat resins as a function of time. Mechanical tests performed were 0° tension, 90° tension and 0°compression with the layup $[\ 0/\pm 45/0]_s$ and tension with the layup $[\pm 45]_{3.}$ Tests were run for both 20°C dry and 50°C wet conditioned specimens tested at 25°C, 40°C, 55°C and 70°C. A second series of tests involved interlaminar fracture toughness (G_{1c} and G_{11c}) using DCB and ENF tests at –20°C dry, 50°C dry and 50°C wet conditions. Finally, a series of tests were run to directly measure the fiber / matrix bond strength. The micro-debonding test was used with dry and wet conditioned specimens.

Results are presented relative to those for the baseline orthophthalic polyester resin. Epoxy SC-14 and the ortho-polyester are the most sensitive to moisture and temperature. They have relatively high saturation moisture contents and a significant reduction in interfacial bond strength after immersion in distilled water. Iso-polyester has superior environmental resistance, with no mechanical properties affected significantly in the hot-wet conditioning. However, both polyesters are relatively brittle, with low interlaminar fracture toughness, compared with the vinyl esters and epoxy. Vinyl esters provide very good delamination resistance and also good environmental resistance. In general, fiber dominated properties (0° tension) are insensitive to temperature and moisture while matrix dominated properties (±45° and 90° tension) are more sensitive. The compressive strength in the 0° direction, also a matrix dominated property, showed significant reductions under hot/wet conditions.

CHAPTER 1

INTRODUCTION

Composite materials consist of two or more physically distinct and mechanically separable components called reinforcement and matrix. These two components can be mixed in a controlled way to achieve optimum properties, which are superior to the properties of each individual component. Composite materials have been widely used in the wind turbine blade manufacture because of the following advantages: high strength and modulus to weight ratio, low cost and flexibility in material and structure design.

Wind turbine blades should have a service life of 20 to 30 years in a variety of climates, which makes environmental resistance one of the most important factors in the wind turbine blade design. Actually, it has been reported that composite materials can be degraded by environmental attack such as moisture diffusion, thermal spikes, ultraviolet radiation, and thermal oxidation, etc [1-2]. Moisture diffusion, for example, can decrease the strength of composites, degrade the fiber / matrix interface, swell and plasticize the resin to lower its glass transition temperature (the temperature where the resin transforms from the glassy solid state to a visco-elastic state) [3-13]. The relative degree of the degradation process is related to the chemistry of the reinforcement and matrix, as well as the exposure time [7,11,13-15]. Different kinds of composites, however, are also sensitive to different environmental attacks. The combination of two or more individual environmental factors can aggravate the degradation of composite performance. In this study temperature and moisture are the environmental factors of concern. Materials are soaked in distilled water at 50C to accelerate the environmental conditioning process.

Ortho-polyester is a low cost general purpose resin which has been used in wind turbine blade manufacture. Due to the disadvantages of its low temperature resistance and significant moisture sensitivity found in this study, new resin systems with the advantages of providing temperature and moisture resistance as well as easy processing by resin transfer molding (RTM) are investigated. A study of the same systems relative to matrix toughness has been reported by Orozco [16]. The first objective of this research was to evaluate moisture and temperature effects on polyester, vinyl ester and epoxy resins. Different sets of property data have been derived for wind turbine blade design in hot-wet conditioning and at different use temperatures with different resins. Tests included:

- 0 degree tension, 90 degree tension, 0 degree compression with the layup $[0/\pm45/0]_s$ and tension with layup $[\pm45]_3$, for both 20C dry and 50C wet conditioned samples tested temperatures at 25C, 40C, 55C and 70C. Initial modulus and ultimate strength are derived as a function of temperature and moisture. The purpose of these tests was to provide database results for design properties of significance, with a focus on matrix-sensitive properties.
- Interlaminar fracture toughness (G_{1c} and G_{11c}) using DCB and ENF tests at –20C dry, 50C dry and 50C wet conditions. The purpose was to provide guidelines for matrix selection in terms of composite structural integrity as expressed through the delamination resistance.

- Micro-debonding test to evaluate fiber-matrix interfacial strength dry and after wet conditioning in distilled water at 50C. These tests were run to determine whether the fiber/matrix bond was important in the environmental degradation process.
- Water absorption at 50C both for composites and neat resins. Duffusivity and maximum amount of water absorption of these candidates are calculated and compared as a basic measure of matrix sensitivity.

The second objective of the study was to identify resins that have good temperature-moisture resistance and improved toughness while providing other properties superior or similar to the baseline ortho-polyester resin. Reasonable cost and easy manufacturing by RTM were also of concern.

CHAPTER 2

BACKGROUND

Environmental Factors

Environmental effects on composite materials have to be considered in the early stages of design, or the design iterations and failure will cause a waste of time, energy and money. Usually the degree of sensitivity of composites to individual environmental factors is quite different. For wind turbine blade design, temperature and moisture are the most important environmental degradation factors taken into consideration. In the following paragraphs, the effects of these two environmental factors will be specified separately. However, it has been shown that their combination has more aggressive effects on the properties of composites than each alone, and the failure mode can also be changed at high temperatures under moisture conditioning [12,13]. The primary environmental effects are on the matrix phase and possibly the interface, while the fibers are usually relatively insensitive in the range of conditioning for polymer matrix composites. In fact, a primary role of the matrix is to protect the fibers from chemical environments.

Temperature

Composites for wind turbine blades may be exposed to low temperature conditions (-20C or below) or high temperature conditions (50C or above) in their

30-year service life. Exposure to low temperature of some tough polymers may make them more brittle and the modulus may increase [17].

In recent years, a lot of tests have been carried out to evaluate the response of composite materials to elevated temperature [24]. It has been reported that the temperature effect on the fiber-matrix interface is as strong as those of the fiber treatment and resin properties [19]. Other mechanical properties such as compression strength, ultimate tensile strength, and [±45] tensile strength (which is matrix dominated) have also been reported to decrease at elevated temperature[9,11,12,20] . Temperature effects on the fracture properties of composites were widely investigated by Marom [21]. The study showed that interlaminar fracture energy decreased 25-30% as the temperature increased from –50 to 100C. The interlaminar fracture surface characteristics of graphite/epoxy were also investigated and pronounced differences were observed in the amounts of fiber/matrix separation and resin-matrix fracture with increasing temperature.

The temperature effect on the mechanical properties of composites derives partly from the internal stresses introduced by the differential thermal coefficients of composite components. Such internal stresses change magnitude with temperature change, in some cases producing matrix cracking at very low temperatures. In practical applications each polymer has its own operating temperature rage. Usually a polymer has a maximum use temperature slightly below its glass transition temperature (T_g), at which the polymer transfers from rigid state to rubbery state and suffers substantial mechanical property loss. Elevated temperatures combined with humid environments have been found to exacerbate the problem by further reducing T_g, among other factors.

Moisture

Water molecules can diffuse into the network of composites to affect the mechanical properties. Marom [21] reported that the short-term effect of water is to increase the mode I fracture toughness, while in the long run the toughness deteriorates. Shen and Springer [22,23] reported that for 90 degree laminates the ultimate tensile strength and elastic moduli decreased with increasing moisture content. The decrease may be as high as 50-90 percent. When moisture diffuses into composites, it degrades the fiber-matrix interfacial bonding [5], lowers the glass transition temperature [24], swells, plasticizes, hydrolyzes and sometimes microcracks the matrix [3,13]. The ability to predict the diffusion of water and its influences on the resin properties are necessary to predict long term behavior.

The uptake of moisture usually is measured by weight gain and the mechanism of water diffusion is characterized by Fick's law [25]. In 1975, Shen and Springer [25], based on Fick's law, studied the absorption and desorption of water in composite materials and presented expressions for the moisture distribution and moisture content as a function of time for one-dimensional composite materials. Many experimental data support the analytical solution and this expression has been widely accepted to describe the water diffusion behavior in composites.

Water absorption behavior for some composites, however, is far from fitting the Fickian model. Such a non-Fickian mechanism has not been well understood due to the complication of absorption behavior and variation of the experimental data. Some methods and computing codes are presented trying to reduce the non-Fickian moisture content data to evaluate the diffusivity and moisture profiles across the thickness of laminates [26-28].

Chemistry of Composite Components

Chemistry of Polymer Matrix and Curing

A polymer matrix is obtained by converting liquid resins into hard and brittle solids by chemical cross-linking. Polymers can be classified as thermoplastic (capable of being softened and hardened repeatedly by increasing and decreasing temperatures) or thermoset (changing into a substantially infusible and insoluble materials when cured by the application of heat or by chemical means). In wind turbine blade manufacture, thermoset resins, including polyester, vinyl ester and epoxy are of interest. The variety of thermoset resins provides flexibility for designers. Actually, the properties of the polymer resin depend on the molecule units making up of the three-dimensional network and on the length and density of cross-links. The former is determined by the initial chemical reactions and the latter is determined by the control of processing and curing.

Polyester Resins. Generally polyester resins can be made by a dibasic organic acid and a dihydric alcohol. They can be classified as saturated polyester, such as polyethylene terephthalate, and unsaturated polyester. To form the network of the composite matrix, the unsaturated group or double bond needs to exist in a portion of the dibasic acid. By varying the acid and alcohol, a range of polyester resins can be made. Orthophthalic polyesters are made by phthalic anhydride with either maleic anhydride or fumaric acid. Isophthalic polyesters, however, are made from isophthalic acid or terephthalic acid. The polyester resin is usually dissolved in monomer (styrene is the most widely used), which will copolymerize with it and contribute to the final properties of the cured resin. The addition of catalyst will cause the resin to cure. The most frequently used catalyst is methyl ethyl ketone peroxide (MEKP) or benzoyl peroxide (BPO) and the amount varies from 1-2%. The catalyst will decompose in the presence of the polyester resin to form free radicals, which will attack the unsaturated groups (like C=C) to initiate the polymerization.

The processing temperature and the amount of the catalyst can control the rate of polymerization, the higher temperature or the more the catalyst, the faster the reaction. After the resin turned from liquid to brittle solid, post cure at higher temperature may need to be done. The purpose of the post cure is to increase T_g of the resin by complete cross-linking. The properties of the polyester resin are affected by the type and amount of reactant, catalyst and monomers as well as the curing temperature. The higher the molecular weight of polyester and the more points of unsaturation in molecules, the higher is the strength of the cured resins. Orthophthalic polyesters are environmentally sensitive and have limited mechanical properties. They have been replaced in some applications by isophthalic polyesters due to the excellent environment resistance and improved mechanical properties of the latter. The crosslinking reaction of polyester resin is shown in figure 2.1.

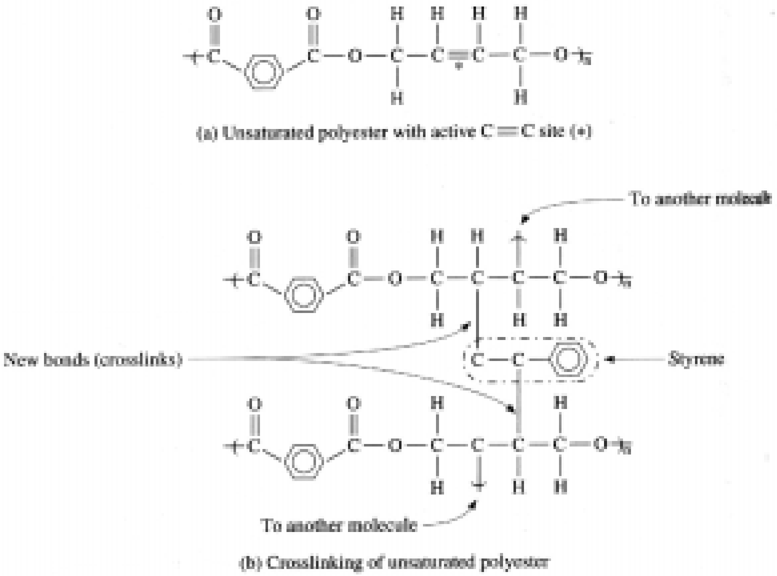


Figure 2.1 Unsaturated Polyester Showing (a) Reactive Carbon-Carbon Double Bond and (b) Crosslinking Reaction (from reference 29).

<u>Vinyl ester Resins.</u> Vinyl ester resins consist of a polymer backbone with an acrylate (R = H) or methacrylate (R = CH_3) termination R-[-O-CO-CR=C] (shown in figure 2.2). The backbone of vinyl ester can be derived from epoxy resin, polyester resin, urethane resin and so on. Among them epoxy resin as the backbone is of significant commercial interests. At present, epoxide backbones of various molecular weight are used in vinyl esters. Higher molecular weight produces higher toughness and resiliency, lower solvent resistance and lower heat resistance [30]. The source vinyl termination (methacrylate or acrylate) determines the ability to corrosion resistance. The styrenated methacrylate vinyl ester resins exhibit excellent resistance to acids, base and solvents. The acrylate vinyl ester resins, on the other hand, are

more susceptible to hydrolysis. In polymerization the unsaturated C=C termination provides the reactive site to cross-link and in this study, 1-2% volume Trigonox was mixed in the resin as the catalyst to provide free radicals. The free radicals react with the C=C to form a new bond and another free radical, and this free radical reacts with another C=C and so on to make the network. For the resins to cure at the room temperature, Cobalt Naphthalene is also added to the resin from 0.2 to 0.4% by weight as a promoter. Vinyl esters possess a lower ester content and a lower vinyl functionality than polyesters, which result in a greater resistance to hydrolysis. Vinyl esters also have higher elongation to break than polyesters, which also makes them tougher [31].

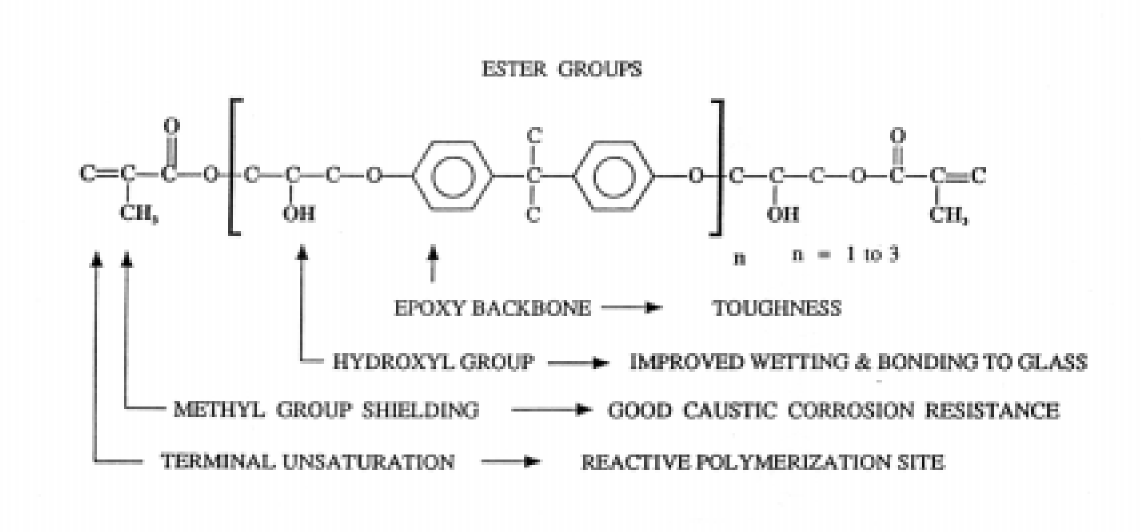
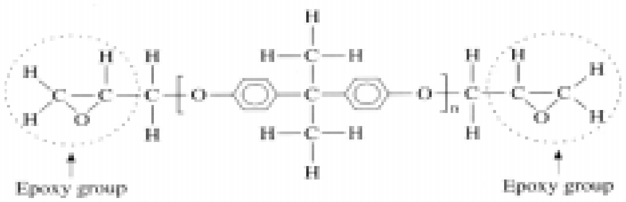
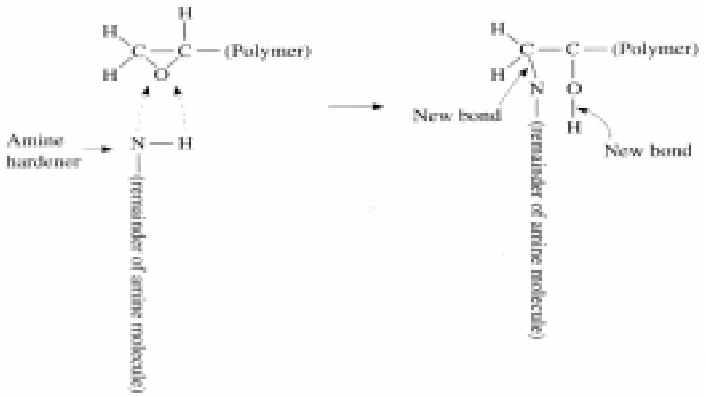


Figure 2.2 Bysphenol A Vinylester (from reference 16).

Epoxy Resins. An epoxy resin is a polymer containing two or more epoxy group rings. Such groups can be terminal, internal or cyclic structures. They can bond with other molecules, forming a large three-dimensional network (figure 2.3). The most used hardeners are aromatic and aliphatic amine as well as anhydride hardeners. All should be added into the epoxy resin with adequate weight ratio to provide cross-linking. The reaction between aliphatic amines and epoxy groups will usually proceed at room temperature. However, heat is required when rigid aromatic amines or anhydride hardeners are used. The properties of epoxy resins are related to the chemical structure of the cured resin. A greater number of aromatic rings results in higher thermal stability and chemical resistance. A lower crosslink density can improve toughness by permitting greater elongation before break. A higher crosslink density can give a higher glass transition temperature and improved resistance to chemical attack. The anhydride-cured system breaks down in strong bases and organic solvents. The Boron Trifluoride-Monoethylene Amine (BF_3MEA) -catalyzed system is seriously affected by the organic solvent and long exposure to moisture. Recently, rubber toughened epoxy resins have gained significantly in interest. Small rubber particles scattered in the epoxy resin are believed to improve the fracture toughness of the neat resin [30].



(a) Typical Epoxy



(b) Epoxy Reaction

Figure 2.3 (a) Typical Epoxy and (b) Epoxy Reaction (from reference 29).

Chemistry of Glass Fibers

E-glass fibers can be obtained from E-glass which is a family of glasses with a calcium aluminoborosilicate composition and a maximum alkali content of 2%. The composition of E-glass is shown in table 2.1.

Table 2.1 E-glass compositions (wt. %) [18].

Components	E-glass range
Silicon dioxide	52-56
Aluminum oxide	12--16
Boric oxide	5--10
Sodium Oxide and Potassium oxide	0--2
Magnesium oxide	0--5
Calcium OXIDE	16--25
Titanium dioxide	0--1.5
Iron oxide	0--0.8
Iron	0--1

At present, E-glass fibers have been widely used in fiber reinforced plastics not only because they have the advantage of low price, availability, ease of processing and high strength, but also because they have good resistance to moisture. E-glass fibers were reported to show a weight loss of 1.7 % when exposed to boiling water for 1 hour. Moisture does produce the well-known static fatigue effect in E-glass, with a loss in strength of about 4% for each factor of ten in time under tensile stress.

Chemistry of Fiber / Matrix Interface

The interface plays an important role in composite materials. Composite materials with weak interfaces have relatively low strength and stiffness but can have high resistance to fracture. On the contrary, composite materials with strong interfaces have relatively high strength and stiffness but may be brittle. The nature of the interface depends on the atomic arrangement and chemical properties of the fiber and on the molecular conformation and chemical constitution of the polymer matrix [32].

Usually a silane coupling agent in aqueous solution is applied on the surface of glass fibers to provide protection from the water degradation and to improve the bonding between the glass and the resin. The general formula for the silane coupling agent is $R\text{-}SiX_3$. The X units represent hydrolysable group. They can be hydrolysed to get the corresponding silanol [32].

$$R\text{-}SiX_3 + H_2O = R\text{-}Si(OH)_3 + 3HX$$

The trihydroxysilanols can form hydrogen bonds with hydroxyl groups on the glass surface. When the coupling agents are dried, a reversible condensation reaction occurs between the silanol and the surface, and between adjacent silanol molecules on the surface. The result is a polysiloxane layer bonded to the glass surface, which provides the chemical link with the glass fibers. The R-unit represents a compatible organo-funcitional group, which can react with the matrix resin during the curing process. The R-unit needs to be chosen for different kinds of polymer matrix to get the optimum interfacial property and good environmental resistance. Thus, the coupling agents are like a bridge, with one end bonded to glass surface and the other end bonded to polymer matrix.

Besides chemical adhesion at the interface, adsorption and mechanical adhesion also contribute to the interfacial bonding. Coupling agents have been proposed to promote better wetting between polymer matrix and reinforcement surface for reduced voids at the interface by displacing the air (especially between closely packed fibers). In composites there are a lot of internal stresses induced in the processing operations. For example, resin shrinkage and the differential thermal coefficient of fibers and matrix can bring tensile, compressive or shear stresses which will affect the fiber / matrix interfacial strength.

Environmental Effects on Components of Composites

Environmental effects on composite materials depend on the environmental effects on the individual components - fiber, matrix, and the interface between the fiber and the matrix. Actually, overall effects depend on the environmental effects on the dominant component materials. For example, transverse tension is a matrix dominant property, so the environmental degradation of this property depends on the matrix sensitivity to environment. The evaluation of environmental effects on composites can be well understood if the effects on individual components are studied.

Environmental Effects on Glass Fibers

Today, E-glass fibers have been widely used in wind turbine blade manufacture because of their cost / performance characteristics. E-glass is a kind of low-alkali content borosilicate glass, which provides good mechanical properties as well as chemical resistance. Since the glass fibers are dispersed uniformly into the matrix, the resin protects them from many environments, except where small molecules such as water can diffuse through the matrix. The degradation of glass fibers with polymer matrices is not usually as great as that of the matrix and interface between them. Shen and Springer [23] reported that for 0 degree laminates (glass fiber dominant), changes in temperature from 200K to 380K have negligible effects on the ultimate tensile strength, regardless of the moisture content. There may be a slight decrease in strength (<20%) as the temperature increases from 380K to 450K. When the moisture content is below 1%, the effects of moisture seem to be negligible. Above 1%, the tensile strength decreases with increasing moisture content. The maximum decrease reported was about 20%.

Environmental Effects on Polymer Matrices

The purpose of matrix is to bind the glass fibers together, keep them the right orientation, provide for load transfer, provide the interlaminar shear strength and protect the glass fibers from environmental attack. Generally, it is the matrix that determines the acceptable working environments and controls the environment resistance. Typical polymer literature lists environmental agents which attack particular matrix materials.

The environment has strong effects on the properties of the polymers. These effects can be classified as reversible effects and irreversible effects. For example, when water diffuses into the matrix it can plasticize and swell the polymer network, decrease the surface free energy and increase the free volume of the polymer [17], thus inducing a reduction in the glass transition temperature (T_g). The change in T_g as a function of moisture is shown in figure 2.4. This process is a reversible process, so the property will recover after drying the material.

Long term exposure to moisture can also result in irreversible damage (hydrolysis and microcracking). Hydrolysis may be a primary reason for the weight loss of polymers after long term immersion [3]. Microcracking in the matrix, on the other hand, may contribute to further mechanical property degradation and more water absorption beyond the usual equilibrium level of the undamaged matrix.

When composites are exposed to moisture, water molecules will diffuse into the matrix, passing through the open structure of the polymer even in the absence of porosity. The uptake of the moisture is a function of the chemistry of the matrix. Different kinds of resins have different diffusivity and maximum moisture content.

The diffusivity represents the rate of moisture diffusion. The equilibrium moisture content represents the degree of swelling stress. The higher the equilibrium moisture content, the higher the swelling stress is in the materials, the higher the possibility that microcracking and hydrolysis will occur [3].

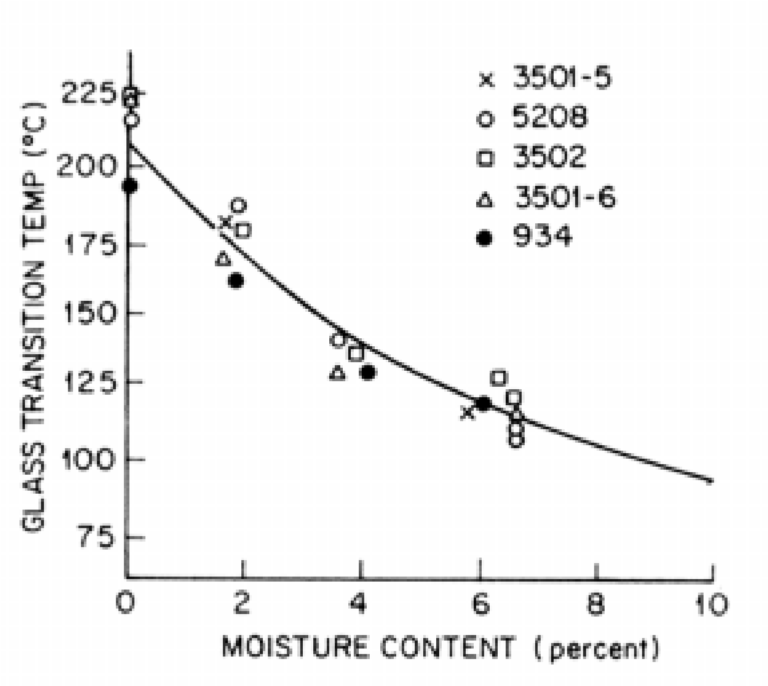


Figure 2.4. Glass Transition Temperature as a Function of the Moisture [17]

The mechanical properties of composites, especially those matrix dominated properties such as transverse tension strength and [±45] tension strength, have been widely reported to decrease in wet conditions [11]. However, Hale and Gibson [12] reported no property change due to oil exposure. Oil was not absorbed into the particular polymers like moisture was, so the degradation of properties generally occurs when the agent is taken up by the matrix. This tendency depends both on the size of the molecules of the environmental agent and the interactions with matrix chemistry.

Besides accelerating the water absorption process, temperature also has strong effects on resins. Springer et al [22] concluded that for 90 degree laminates (resin dominated), an increase in temperature can cause a decrease in elastic moduli and strength. The reduction may be as high as 60 to 90 percent. Parvatareddy et al [33] aged a Ti-6Al-4V/FM5 adhesive bonded system at three different temperatures, 150, 177 and 204C. Results showed that the greatest loss occurs at the highest aging temperature, 204C. The strain energy release rate dropped by 10-20% after aging for six months. Kamvouris [34] and the coworkers studied the physical and chemical aging effects in PMR-15 neat polyimide resin. The polymer shows weight loss and length decrease a function of aging time at 316C in nitrogen and air environment. The glass transition temperature (T_g) varied as a function of aging time as well. Thus temperature alone can cause significant permanent degradation in some polymers, depending on polymer chemistry.

Environmental Effects on the Fiber / Matrix Interface

Composite materials consist of reinforcement and matrix, which have different elastic and physical properties. It is the interface that provides the adhesion between them in order to give the macroscopic mechanical properties of composite. The chemistry, morphology and properties of the fiber-matrix interface play a major role in the properties of composites. To produce high quality composite materials, the bond between the matrix to the fibers must be strong. To retain the properties of composites under environment attack, the fiber-matrix interface must have excellent environmental resistance.

To understand environmental effects on the fiber/matrix interface, the composition and structure of fiber/matrix interface must be known. As noted earlier, coupling agents are applied on the surface of glass fibers to improve the interfacial bonding to transfer the load through the matrix to the fibers, and to resist moisture attack.

Generally speaking, the strength of the fiber/matrix interface decreases as the time of exposure to water increases. Schultheisz and his coworkers showed the degradation of the interfacial strength after immersion in water at 25C and 75C by using single fiber fragmentation test [5]. Grant and Bradley [13] studied the degradation of graphite / epoxy composites due to sea water immersion. Through observation by scanning electron microscopy (SEM), they found that the measured 17% decrease in transverse tension strength was associated with the degradation of the interface, which changed the mechanism of fracture from matrix cracking to interfacial failure. According to Pratt and Bradley [35], degradation in the interfacial strength may be related to the reduction of radial residual compressive stress. The coefficient of thermal expansion of polymer matrices is much greater than that for glass fibers. This results in a residual compressive stress across interface after the composite cools down from curing temperature (at least for isolated fibers). The residual compressive stress provides mechanical frictional bonding. However, elevated temperature and the swelling stress brought on by the water absorption in the matrix both can decrease this kind of compressive residual stress, and thus degrade the interfacial strength.

Different coupling agents have different effects on the environmental resistance of the interface. Ishida and Koenig [3] studied the effect of the chemical nature of coupling agent on the durability of coupling agents using FTIR. The authors attribute the durability of the coupling agents to their relative degree of Si-O-Si bonding. Schultheisz [5] compared the mode I and mode II interlaminar fracture toughness, which is related to interfacial strength, by using two different fiber coatings. One coating showed that there is little change in R-curve behavior (increasing toughness with increasing crack extension length), while the other showed significant change. Besides the type of coupling agent, the degree of network formation within the coupling agent and the degree of interdiffusion of coupling agent with resin influence the mechanical properties and durability of the interface[3]. All these factors provide for an on-going research field on the area of environmental resistance of the interface region, which is not completely understood at this time.

Properties of Composite Materials

Moisture Diffusion

Moisture diffusion into the resin can lead to a reduction in glass transition temperature and softening, which result in the degradation of stiffness and strength. This degradation can be aggravated and involve the interface under more severe conditioning. Thus, moisture content and its effects on resin properties are very important for designers.

Usually moisture content (weight %) is measured from experiments by the weight gain relative to dry specimens, and plotted as a function of square root of time following Fickian predictions (figure 2.5).

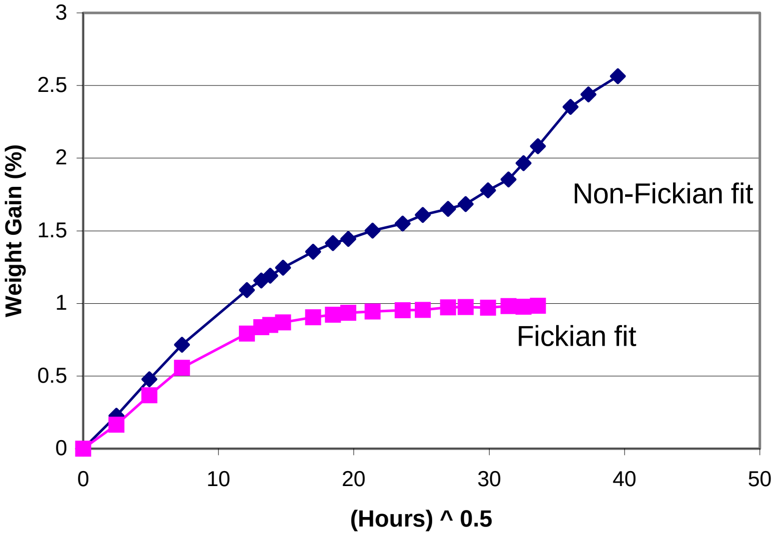


Figure 2.5. Weight Gain of Neat Resins as a Function of Square Root of time.

Some composites and neat resins have simple water absorption behavior which fits Fick’s second law, as shown in figure 2.5. Fick's second law states that

$$\frac{\partial M}{\partial t} = D \cdot \frac{\partial^2 M}{\partial Z^2} \tag{2.1}$$

where

D: diffusion coefficient

M: moisture content

t: conditioning time

z: the length in the thickness direction

Moisture absorption curves usually have two characteristics: 1. curves should be linear initially and 2. the moisture content should eventually reach a saturation level. The analytical solution of equation (2.1) is obtained by the method of separation of variables and the moisture content varies as a function of time.

$$M(t) = M_0 + (M_m - M_0) \cdot \frac{4}{h} \cdot \sqrt{\frac{D \cdot t}{\pi}} \tag{2.2}$$

where

M_0: initial amount moisture in the solid

M_m: the saturation moisture content

h: thickness

t: conditioning time

D: diffusivity in direction of the thickness

The time t_m required to attain 99.9% of the maximum moisture content can also be expressed as:

$$t_m = \frac{0.678 \cdot s^2}{D} \tag{2.3}$$

For a material exposed on two sides to the same environment s is equal to the thickness; for a material insulated on one side s is the twice the thickness.

In order to calculate the moisture content and the time required to attain 99.9% of the maximum moisture content, t_m, the maximum moisture M_m and diffusiviity D must be known. Experiments show that the maximum moisture content (M_m) does not change with the temperature and can be expressed as [25]

$$M_m = \text{constant (liquid)} \qquad (2.4)$$

$$M_m = a^* (RH\%)^b \qquad (2.5)$$

where RH is the relative humidity. Parameters a and b are materials properties and can be determined through experiment by fitting a line to the data.

The diffusivity D can be obtained by using the value of moisture content for two different values of time

$$D = \pi \cdot \left(\frac{h}{4 \cdot M_m} \right)^2 \cdot \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} \right)^2 \qquad (2.6)$$

However, some composites, especially those which have relatively large weight gain, have an irregular water absorption curve (shown in Fig 2.5) which indicates that other mechanisms are involved; in the composites, this often is associated with matrix cracking [26-28].

Tension and Compression

Tensile testing is probably the most widely used mechanical property test. This test provides information about the ultimate tensile strength and modulus of elasticity of the composites. A typical stress - strain curve for this study is shown in figure 2.6. At initial low stress and strain, the composites deform elastically, thus the slope of stress-strain curve is constant and defined as elastic modulus in a particular direction. As the stress and strain are increased, the deformation may become nonelastic as matrix cracking occurs, particularly in the ±45 plies. The maximum stress at which failure occurs is called the ultimate tensile strength (UTS).

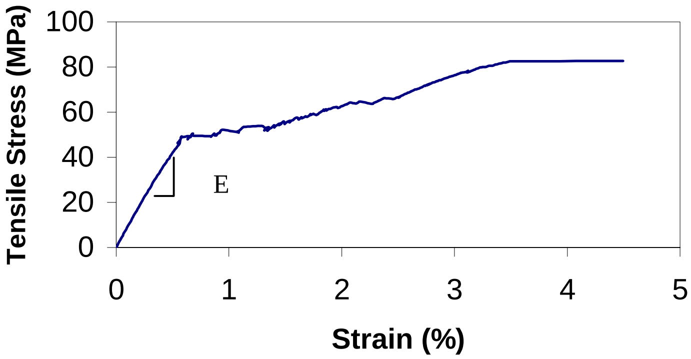


Figure 2.6. Typical Stress - Strain Curves for 90° Loaded $[0/\pm45/0]_s$ Composites

Tensile tests are identified as longitudinal or transverse for unidirectional composites according to the applied loading direction and fiber orientation. In the longitudinal tensile test, a fiber dominated property test, if we assume perfect interfacial bonding between the fibers and matrix, the fiber and matrix strain are equal. At low load and strain, the composite deforms elastically. At the ultimate stress in the longitudinal direction, the fibers break as they reach their fracture strain. In a transverse tensile test, a matrix dominated property test, the load is perpendicular to the fiber orientation, the strain is mostly in the matrix. When the composite is subjected to a transverse tensile load, the initial deformation is also elastic deformation and the slope of the stress-strain curve is measured as the elastic transverse modulus E_T. With higher load, the relatively high modulus fibers play a constraint role on matrix and cause strain concentration in the matrix adjacent to the fibers [36]. The resulting composite failure strain is lower than that of neat matrix;

the behavior is brittle with failure occurring due to the first significant matrix crack. Stress-strain curves like figure 2.6 include significant nonlinearity after first matrix cracking for materials like ±45 because the plies must also delaminate before complete separation occurs.

The static compression test is like the static tension test and the detailed experimental procedure follows ASTM D3410 approximately. When a compressive load is applied longitudinally on the composite, the glass fibers act like long columns and can buckle in the matrix. When the matrix can no longer provide enough resistance to buckling, catastrophic failure occurs and composites fail in a fiber micro-buckling mode [36]. The stress at which ultimate failure occurs is called ultimate compressive strength (UCS).

This study included tests on laminates with a ply arrangement $[0/\pm 45/0]_s$, eight plies with orientation symmetrical about the mid-thickness. When these laminates are loaded in the 0° or 90° directions, the behavior approximately follows the longitudinal and transverse directions described above except that the 90° load direction produces a significant amount of nonlinearity due to the ±45 layers. Less testing problems are encountered when ±45 layers are present, and they are typical of most applications.

Interlaminar Fracture Toughness

The moisture and temperature effects on the interlaminar fracture toughness of composites have been widely reported [37-39]. Many tests have been set up to quantify the toughness of composites since interlaminar fracture often occurs during practical applications. Interlaminar fracture, often called delamination, occurs by one or a combination of three fundamental failure modes (Fig 2.7). Each failure mode is characterized by a different fracture resistance and by a different surface morphology [21]. All interlaminar fracture tests used unidirectional laminates with the crack growing parallel to the fiber direction.

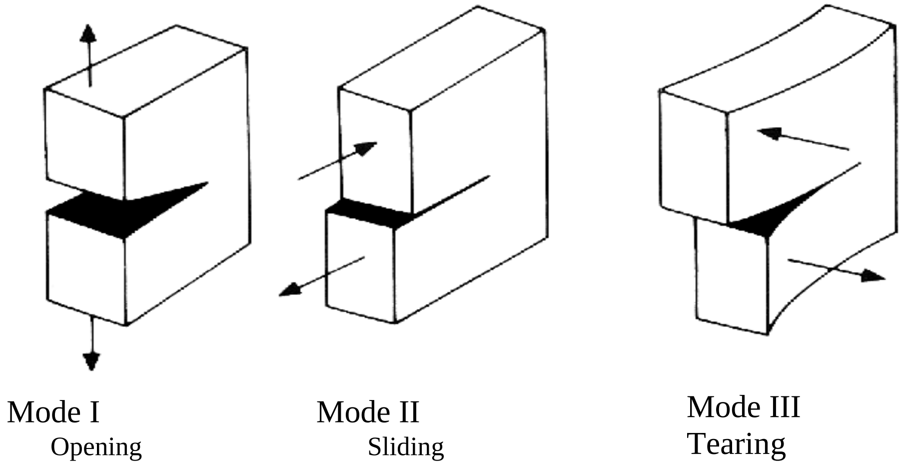


Figure 2.7 Three Fundamental Interlaminar Failure Modes

<u>Mode I Interlaminar Fracture Testing.</u> Double cantilever beam (DCB) testing has been standardized to quantify the Mode I interlaminar fracture toughness. The DCB specimen geometry and load application are shown in fig 2.8. A pair of hinges are bonded to specimen, which can be gripped by the machine to provide the delaminating load. A starter Teflon film is introduced during fabrication at the mid-

thickness of the laminate panel at one end, to provide the initial crack. The load - displacement data are recorded during the experiment (fig 2.9). With load increasing to some critical point, crack propagation will occur, and the compliance of specimen will increase, which is indicated by the onset of nonlinearity in the load-displacement curve; the load is then removed from the specimen, giving the complete loading-cracking-unloading curve shown in the figure.

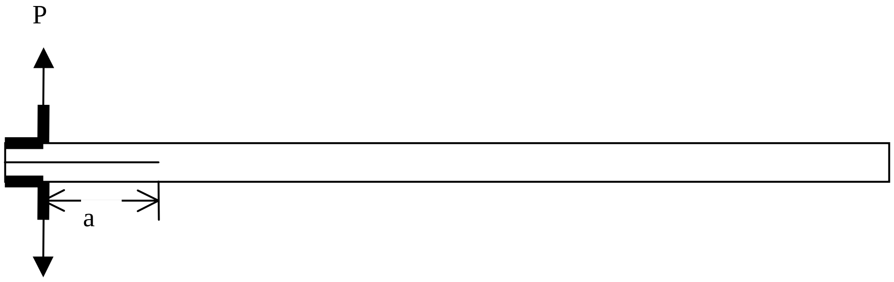


Figure 2.8 Geometry and Loading for a DCB Specimen.

In the study of mode I interlaminar fracture testi, several methods are employed to reduce the data recorded during the experiment [40]. One of the most often used is modified beam theory (MBT). In the MBT method, the Mode I strain energy release rate can be determined by

$$G_{IC} = 3 * P_C * \delta_C / (2 * b * a) \qquad (2.7)$$

Where:

P_c = critical load at the onset of nonlinearity (shown on Figure 3)

δc = critical displacement at the onset of nonlinearity b = specimen width

a = crack length measured from hinges

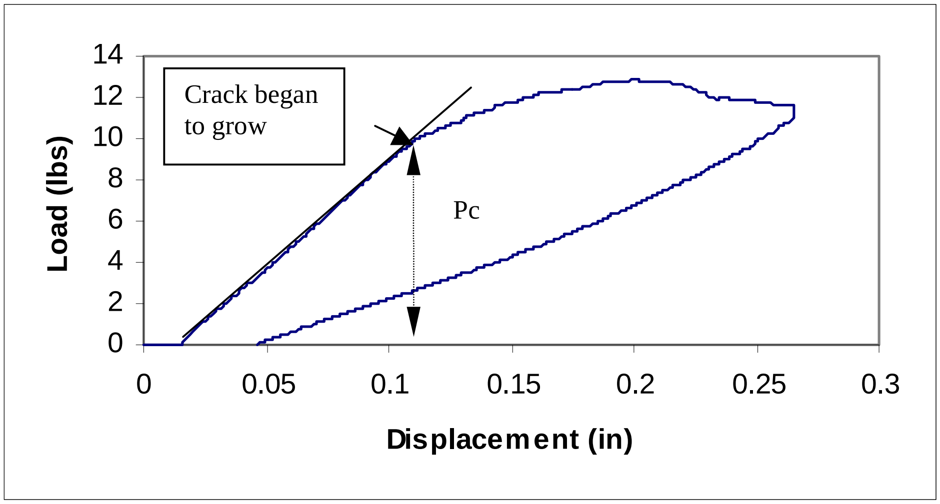


Figure 2.9 Typical Load-Displacement Curve for a DCB Specimen.

Although a stable propagation value of G_{IC} for long cracks can be obtained from experiment, its reliability has to be examined. It has been reported that stable propagation value of G_{IC} can be affected by fiber distribution and thickness [40]. Recently, attention has been turned to the initial value, which is less dependent on specimen details, and regarded as a reliable intrinsic material parameter. The initial vale is the value obtained for the first few mm of crack extension from the initial Teflon strip. Since the Teflon strip can affect these results, a small amount of extension is introduced prior to testing. The initial value is generally conservative compared with values obtained for greater amounts of crack growth.

Mode II Interlaminar Fracture Testing. The end notched flexure (ENF) specimen [40] appears to be the most frequently used test method to measure Mode

II critical strain energy release rate (G_{IIc}). The geometry of the ENF specimen and loading are shown in Fig 2.10. It looks exactly like a three point flexural specimen test, but with a pre-crack in the mid-thickness of laminate at one end of specimen. When the load is increased to the maximum value which the specimen can bear, unstable crack propagation usually occurs. Load-displacement data for the ENF test are shown in Fig 2.11, in which the maximum load and unstable crack propagation can be seen clearly.

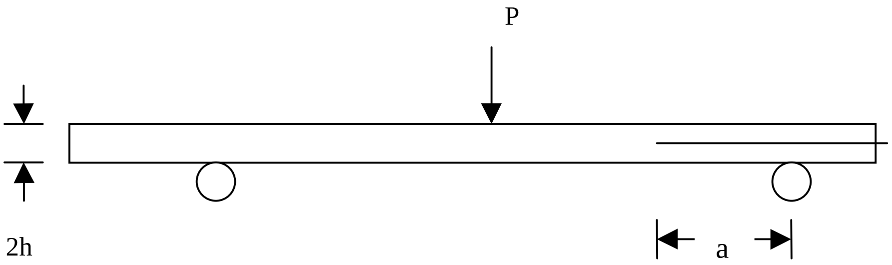


Figure 2.10 Geometry and Loading of ENF Specimen.

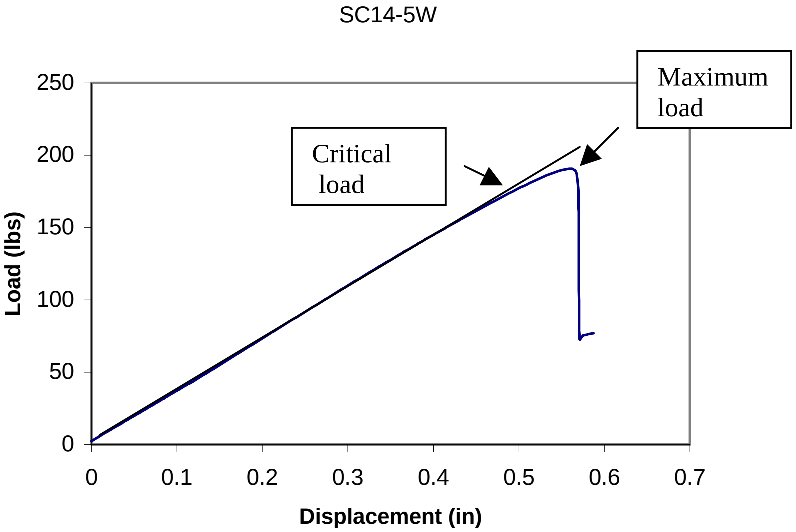


Figure 2.11 Typical Load - Displacement Curve for a ENF Specimen.

The mode two fracture energy can be determined by the following equation used by Mandell and Tsai [41]. Maximum load was used to calculate the fracture energy. For stable crack growth, the critical load can be used to give a more conservative G_{IIC} value.

$$G_{IIC} = \frac{9 \cdot a^2 \cdot P^2}{16 \cdot E \cdot w^2 \cdot h^3} \qquad (2.8)$$

where

P: maximum load for unstable crack propagation

a: crack length measured from the outer pin

E: longitudinal elastic modulus

w: specimen width

h: half thickness of specimen

In the equation, all parameters can be measured directly from the experiment except for the longitudinal elastic modulus, which is calculated from the following empirical correlation given by Mandell and Samborsky for this group of materials [42]:

$$E = E^* \times (3.1 + 65.8 \times V_f) / 32.71 \qquad (2.9)$$

where:

V_f: fiber volume fraction

E^*: property at the 45% fiber volume with a lay-up of $[0]_6$

Fiber-Matrix Bond Test

Although interfacial bonding plays an important role in the application of composites, it is difficult to quantitatively measure the bond strength for in-situ composites. Interfacial properties are usually determined indirectly through their influence on the transverse tension and interlaminar shear strength. However, these macro-mechanical tests fail by a combination of interface and matrix cracking, and do not provide a simple measure of bond strength.

Some micro-mechanical test methods have been developed to determine the fiber matrix bond strength. One approach is fiber fragmentation method [43]. A single fiber is embedded in a matrix and loaded in tension until the fiber fractures into fragments. The average fragment length and the distribution of fragment length as a function of applied strain tell us something about the interface for an isolated fiber. The second approach is the fiber pull-out test [43]. A single fiber is embedded in matrix in a controlled manner and loaded in tension until debonding initiates without breaking the fiber. The bond strength can be determined from stress conditions. The third approach is the indentation method in which fiber ends compressively loaded on a polished smooth surface, perpendicular to the fiber, to initiate debonding and / or fiber slippage. In the 1980’s Mandell et al constructed a modified microdebonding test [44] for determining the in situ fiber / matrix interfacial strength for composites. This method has the advantage of “reflecting the actual processing conditions and allowing interface characterization by the user without the need for specialized model construction”. The specimen preparation and detailed test procedure are described in the next chapter. The loading of this microdebonding test method is shown in fig. 2.12. A single fiber, which has relatively large spacing distance to the nearest neighbor fibers, is selected and the compressive load is applied by the probe at the end of this fiber. The compressive load increases in a series of steps until initiation of debonding is observed in the microscope. The interfacial shear strength (τ_{max}) can be determined from compressive stress (σ_A) by using the results of a finite element solution that correspond to the fiber diameter (D_f), distance to the nearest neighbor fiber (T_m), and the elastic properties of the fiber and matrix. For the E-glass-epoxy composite system, the effect of fiber spacing on maximum normalized shear strength from finite element analysis (FEA) is shown in table 2.2 [45].

Table 2.2 Effect of Fiber Spacing on Maximum Normalized Shear Strength From

FEA	Maximum normalized shear stress, (τ_{max} / σ_A)		
$(Gm / E_f)^{1/2}$	$Tm / D_f = 0.1$	$Tm / D_f = 0.4$	$Tm / D_f = 1.0$
0.124	0.133	0.098	0.073

The shear stress was determined for any other fiber spacing by plotting τ_{max} / σ_A as a function of T_m / D_f , then fitting a curve to get the following equation:

$$\tau_{max} / \sigma_A = 0.0833 (Tm / D_f)^2 - 0.1583 (Tm / D_f) + 0.148 \quad (2.10)$$

since $$\sigma_A = 4 F / (\pi D_f^2) \quad (2.11)$$

where F is the debonding force. The interfacial shear stress can be determined:

$$\tau_{max} = 4 F / [(\pi D_f^2) (0.0833 (Tm / D_f)^2 - 0.1583 (Tm / D_f) + 0.148)] \quad (2.12)$$

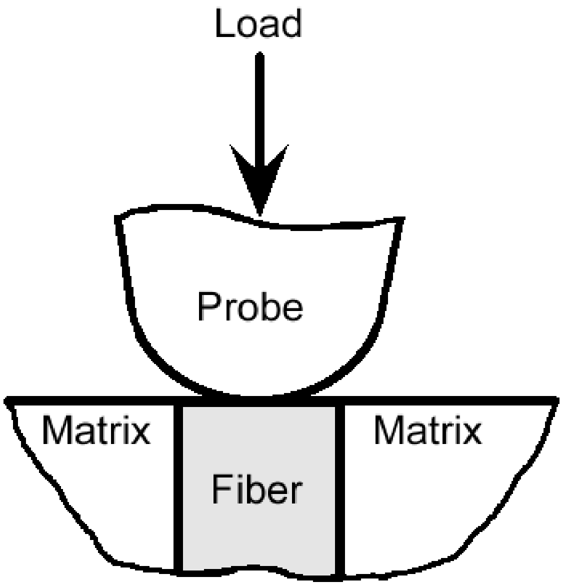


Figure 2.12 Loading of Micro-Debonding Test [45].

CHAPTER 3

EXPERIMENTAL METHODS

Materials and Processing

Glass Reinforcement Materials

The reinforcement throughout the experiments is E-glass fabric supplied by Owens-Corning (Knytex). There are two kinds of fabrics used in the specimen preparation. The 0 degree layers (relative to the load direction) were reinforecd with stitched D155 warp unidirectional fabric; the ±45 degree layers were reinforced with stitched DB 120 bias ply fabrics. All fibers included a general purpose silane based coupling agent which is compatible with all of the resin types used. Further details of the reinforcing fabrics can be found in reference 42.

Resin Matrix Materials

Five types of resins are compared for this work, representing the potential resins for wind turbine blades in terms of cost and suitable for resin transfer molding (low viscosity). The following resins were used:

1. CoRezyn unsaturated orthophthalic polyester (63-AX-051), supplied by Interplastic Corporation. The resin was cured by the addition of 1.5% methyl ethyl ketone peroxide (MEKP). This resin is the current primary resin used for DOE/ MSU fatigue

database, and has been used in blade manufacture. This is the lowest cost resin, and serves as a baseline system to which other resins are compared.

2. Derakane 411c-50 vinyl ester, supplied by Dow Chemical Co, cured with 2% Trigomox 239A as the catalyst.
3. Derakane 8084 rubber-toughened vinyl ester, supplied by Dow Chemical Company. Cobalt Naphthenate-6% (CoNap) is added as the promoter and 2% Trigomox 239A is added as the catalyst.
4. SC-14 toughened epoxy resin supplied by Applied Poleramic Inc. The mix ratio is part A : part B = 100 : 35.
5. Isophthalic Polyester (75-AQ-010) supplied by Interplastics Corporation cured with 1.5% of methyl ethyl ketone peroxide (MEKP).

Processing

All specimens were prepared using Resin Transfer Molding (RTM) at Montana State University-Bozeman. Fabrics were cut by a rolling cutter and stacked in the mold following the lay up sequence given in each case. The specific resin, mixed with corresponding catalyst, was transferred into the mold cavity using an RTM 2100 system from Radius Engineering Incorporation or a peristaltic pump from Cole Parmer Co (model 7553); choice of the equipment depended on the size of the plate and curing process requirements. Except for the SC-14 system, composite plates were left in the mold for 24 hours for curing and post cured at 60°C for 2 hours. The SC-14 epoxy plates were cured in the oven at 60°C for 3 hours and post cured at 100°C for 5 hours, following supplier’s directions.

Environmental Conditioning

All specimens were machined from plates using a water-cooled diamond saw; the edges were sanded prior to conditioning. Some dry specimens were stored in ambient air of the laboratory, which is defined as room temperature, dry; the laboratory is not temperature or moisture controlled, but is generally around 23°C and low humility. Some dry samples were stored in the oven at 50°C and are defined as 50°C dry. The wet samples were stored in a plastic container of distilled water at 50°C in an oven; this is defined as 50°C wet. Three wet samples for each experiment were selected to measure the weight gain vs. of time to trace the moisture absorption behavior.

Apparatus and Testing

Tension and Compression

The 0 degree tension, 90 degree tension and [±45] tension coupons were all 15cm long by 2.5cm wide. The compressive coupons were 10cm long by 2.5cm wide. All the static tensile and compression tests were performed on an Instron 8562 servoelectric testing machine which was calibrated before testing. An extensometer was attached to the specimen by a rubber band to measure axial strain. Load was applied to the specimen at a specific rate (table 3.1) until catastrophic failure occurred. Load and corresponding strain data were acquired and recorded to determine the ultimate strength and modulus.

An environmental chamber was constructed (by D. Samborsky) to provide different test conditions. Two symmetric hot air blowers were attached to provide the heat source and a fan was used to make the temperature uniform within the chamber. The temperature was monitored by a temperature controller and the environment conditioning chamber was capable of maintaining the temperature to within 3°C. A thermocouple was put on the surface of coupon to show the actual temperature of the specimen. The dry specimens were allowed to "soak" in the environmental chamber at the test temperature for at least 20 minutes before testing. The wet samples were soaked in water at the testing temperature for about 20 minutes, then dried by paper towel quickly and moved into the chamber for testing. At least three tests were carried out per test condition: room temperature dry, 40°C dry, 55°C dry and 70°C dry.

Table 3.1. Load rate of mechanical testing

Tests	rate of applied load (cm/sec)	layup	specimens tested
0 degree compression	1.27	[0/±45/0]s	3
0 degree tension	0.0127	[0/±45/0]s	3
±45 tension	0.0127	$[\pm45]_3$	3
90 degree tension	0.00508	[90/±45/90]s	3
DCB	0.01016	$[0]_6$	2-- 4
ENF	0.02032	$[0]_6$	2--4

DCB & ENF TEST

The DCB coupons were 20cm long by 2.5cm wide unidirectional double cantilever beams with 3.8 cm long × 0.03 mm thick Teflon film inserted in the mid-thickness plane at one end to introduce the crack in the specimen according to ASTM 5528. The coupons were pre-cracked 2mm longer than the Teflon film to avoid the resin-rich area resulting from the thickness of the Teflon film. Removable piano hinges (N121-606: V508) were bonded to the end of coupon on both sides as load application points. Hysol EA 9302.2NA was employed as the adhesive and 2 hours of post cure at 60C was allowed after 24 hours cure of room temperature. The ENF coupons were similar to the DCB coupons but without the piano hinges.

A small chamber with a heater and a fan was built up to provide the test temperature 50°C for the DCB and ENF tests. The small chamber was capable of maintaining the temperature within 5°C. A thermocouple was attached to the surface of the specimen to show the test temperature. Dry ice was used to provide -20°C or even lower test temperature. Dry specimens were soaked in the test temperature air for at least 20 minutes before testing.

The static DCB and ENF tests were performed on an Instron 8562 servoelectric testing machine which was precisely calibrated before testing. In the DCB test, the crack length is measured before the load is applied at the rate of 0.004 in/sec. When approximately 2-3mm of crack propagation was observed, the machine was stopped and the specimen unloaded. The load and corresponding strain data were recorded to calculate the mode one strain energy release rate (G_{IC}). For the ENF test, the load was applied to bend the specimen at the rate of 0.008 in/sec until unstable crack propagation occurred. The precrack length measured from the rod center and the maximum load was recorded to calculate the mode two strain energy release rate (G_{IIC}). Data -reduction methods and models are introduced in chapter two.

Microdebonding Test

The specimens for the microdebonding test consisted of a composite specimen with a carefully polished cross-section. The composite was cut into a 2cm by 1cm rectangular flat piece which was cast into a standard epoxy polishing holder following standard procedures. The specimen was supported perpendicular to the ground and polished surface. Grinding and polishing of the mounted specimen were performed on a metallographic polishing bench. The specimens were polished by using a series of Struers waterproof silicon carbide paper from PEPA P # 120 to # 4000. In the final step, 0.03 μm alumna slurry was used to polish the specimens. Surface inspection was executed under the microscope for each polishing step. When the fiber cross-sections were clearly observed without wearing on the surface, the polishing process stopped. Caution should be taken to avoid the appearance of a black ring on the fiber-resin interface, which indicated the discontinuity of fiber and resin on the surface due to polishing. Dry specimens were stored in a desiccated jar and wet specimens were tested immediately.

The testing apparatus for the microdebonding test is shown in Figure 3.1. It has a load station and an optical station. The load cell (ftd-g-100) is from Schaevitz Engineering Corporation. Vibration isolation of the whole system is essential. The specimen was mounted on the turntable with double stick tape and turned under probe tip. The probe used in this study has a ground diamond tip with a radius of about 5 μm. The probe tips were manufactured by D. TEC Inc. of Needham, MA. An SEM picture of the probe tip is shown in figure 3.2. The fine adjust knob was used to control the distance between the tip and the sample surface to 2 mm. A series of ocular lenses up to 50 power were aligned to make sure that the point under the probe tip was exactly the point in the center of the observing field on the screen. A good fiber was selected by using micrometer drive knob at the view station. The selected fiber was transferred to the load station by rotating the turntable slowly. The specimen was raised against the probe by the fine adjust knob until the desired load was obtained. The load was held for 5 seconds then released. The turntable was rotated again to transfer the fiber back under the microscope and inspect for initiation of debonding that indicates the black ring around the fiber or reflection at the interface. This procedure was repeated at higher load steps and inspection until debonding was observed. A black ring around more than one forth of the tested fiber diameter was regarded as debonding. Data recorded were the fiber pushing force, the diameter of the tested fiber and the spacing to the closest neighboring fiber. A SEM picture of a tested fiber is shown in figure 3.3.

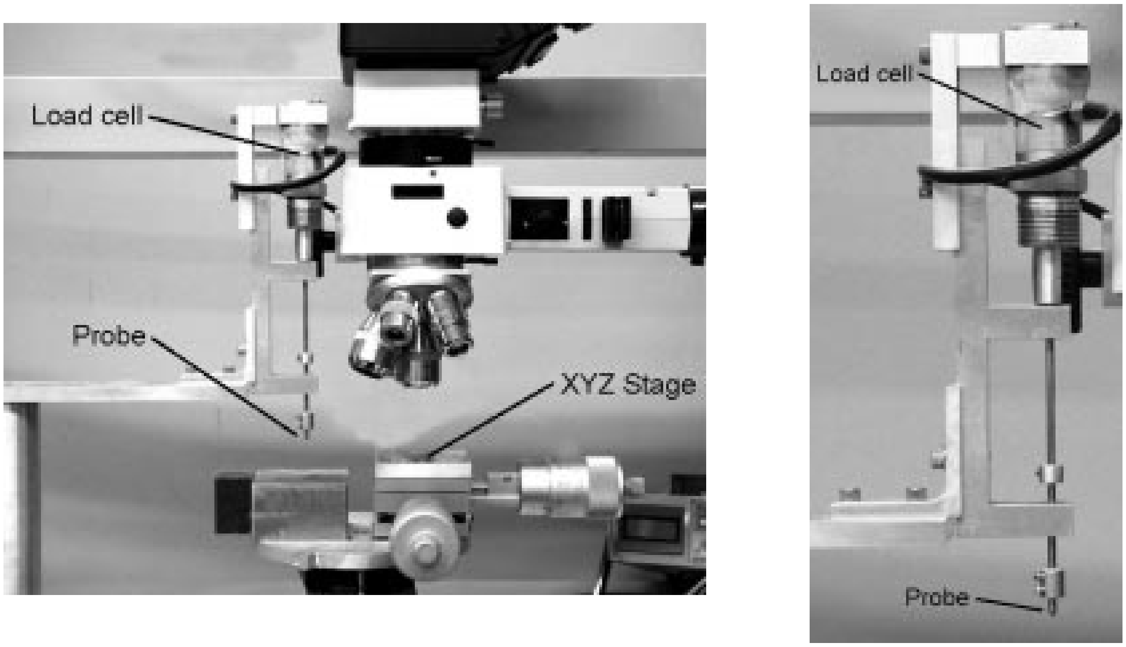


Figure 3.1 The Testing Apparatus of Micro-debonding Test.

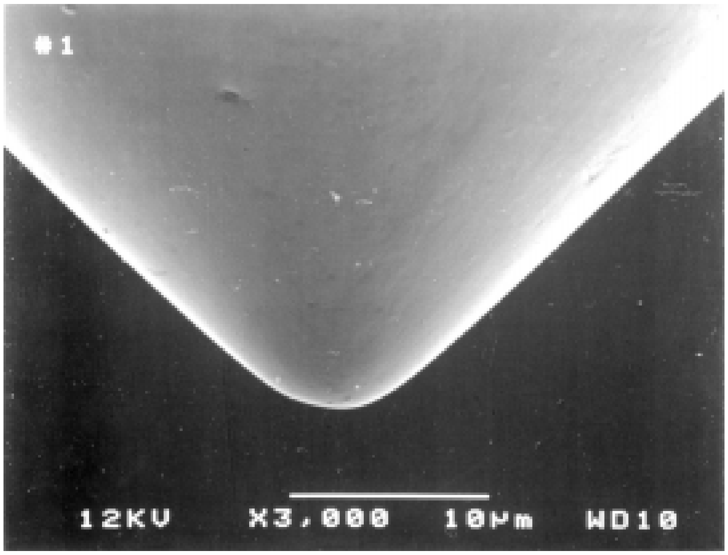


Figure 3.2 SEM Picture of the Probe Tip.

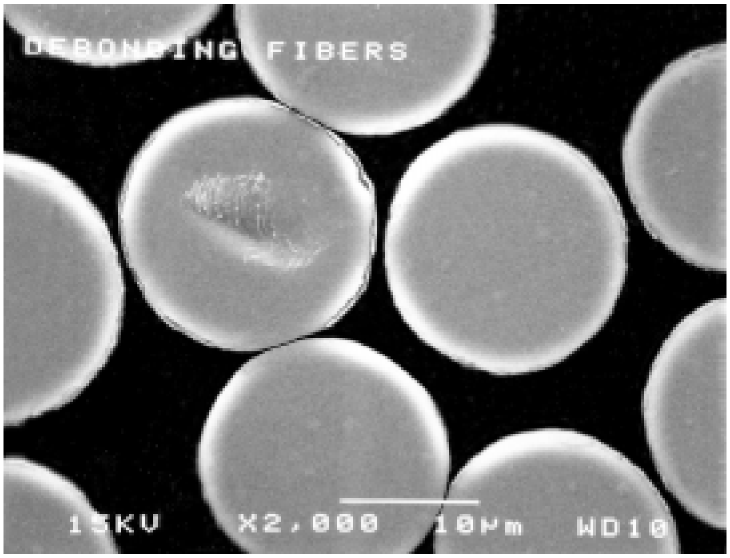


Figure 3.3 SEM Picture of a Tested Fiber.

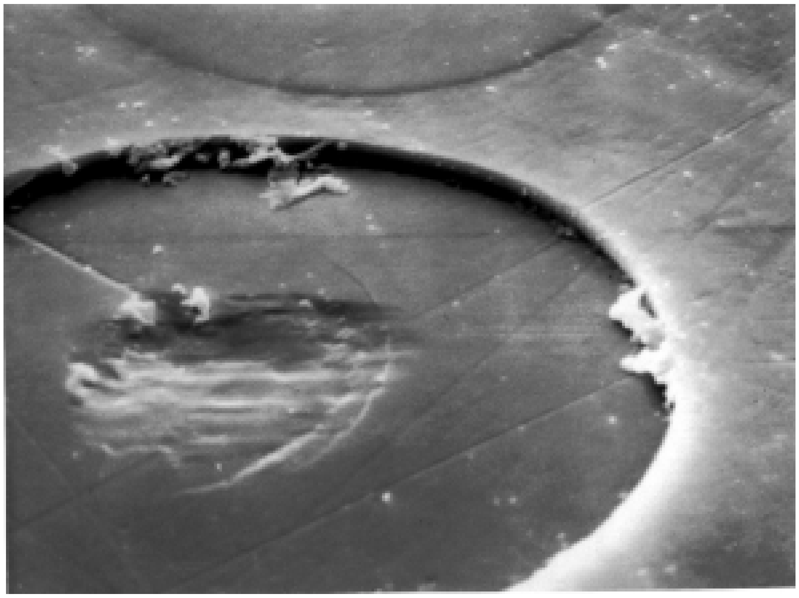


Figure 3.4 A Picture of a Debonding Fiber (from Dr. Mandell).

Water Absorption Test

The specimens of neat resin and composites were cut from the flat plate and stored at room temperature for one week to minimize the moisture content. Specimens were then soaked in distilled water at 50°C. During the conditioning time, the specimens were periodically removed from the environment, dried by paper towel and weighed using an electrical balance accurate to 0.0001g. The weight and conditioning time were recorded to calculate the moisture content. The moisture content was plotted as the weight gain against square root of conditioning time. It was found in the experiments that the weight of the wet specimen decreases as the measuring time increases. For example, within 35 minutes, the moisture content of SC-14 can change from 2.98% to 2.91%.

Since each measuring time is limited within 30 minutes, the moisture loss during measuring is neglected.

CHAPTER 4

RESULTS AND DISCUSSION

Introduction

The results of the study of environmental effects on composites with five resin systems are presented in this chapter. Water absorption behavior of the composites and the neat resins are considered first, followed by moisture and temperature effects on composite compressive strength, 0^0 tensile strength & modulus, $\pm 45^0$ tensile strength & modulus, 90^0 tensile strength & modulus and interlaminar fracture toughness. Finally, the degradation of interfacial strength due to moisture in the composites is presented. Complete data for each test are listed in the Appendix. The approximate costs of the five resins in large volumes are listed in figure 4.1 [16].

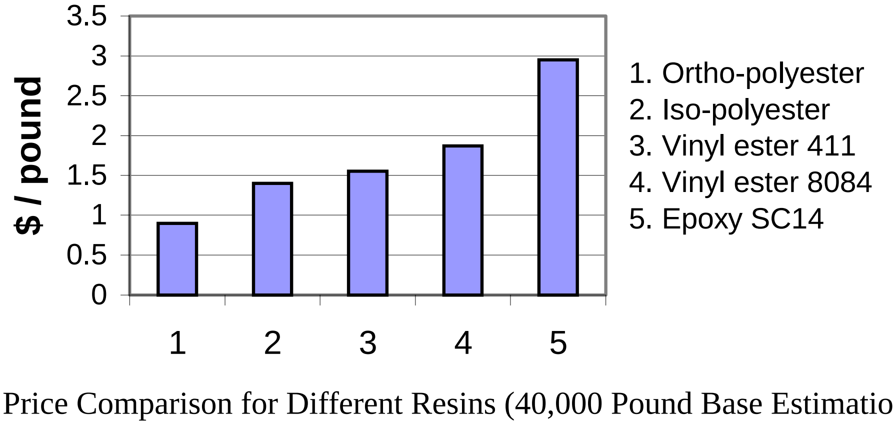


Figure 4.1 Price Comparison for Different Resins (40,000 Pound Base Estimation).

Water Absorption

Composites with the layup $[0/\pm45°/0]_s$ and their neat resins were immersed in the distilled water at 50°C for about 2500 hours. The weight gain curves as a function of square root of time are shown in figure 4.2 (composites) and figure 4.3 (neat resins). Each point on the figures is presented as an average from three specimens.

In figure 4.2, ortho-polyester, iso-polyester, vinyl ester 411 and 8084 appear to be saturated while epoxy SC-14 is close to saturation within the time frame considered. It is noted that epoxy SC-14 absorbed the most moisture when soaked in the distilled water at 50°C for the same period of conditioning time, followed in order of decreasing moisture content by: ortho-polyester, vinyl ester 8084, vinyl ester 411 and iso-polyester. This sequence is consistent with that of the neat resins in figure 4.3 with 2017 hours conditioning. After that, the ortho-polyester resin moisture exceeded that for the epoxy SC-14 resin. In the cases of epoxy SC-14, vinyl ester 8084 & 411 and iso-polyester, their water absorption behaviors approximately followed Fick's second law. As noted earlier, the two main characteristics of Fickian behavior are: (1) the absorption curve should be linear initially and (2) the moisture content should reach a saturation level at large values of time. The moisture content and time to reach moisture saturation may be calculated from two parameters: the maximum moisture content Mm, which can be read directly from the weight gain curve, and the one dimensional diffusivity D, which can be calculated by Shen and Springer's method [25]. The water absorption process for ortho-polyester is non-Fickian. The reason for this may be that the moisture transfer through the resin did not proceed according to the Fick's second law. The possible explanations are surface cracking, fiber / matrix debonding and viscoelastic behavior of polymer [26-28]. Such non-Fickian behavior has been reported previously and adds difficulty to the calculation of the diffusivity *D* [27]. In this research, results for non-Fickian behavior, only the first-level maximum moisture content was used to calculate the first-level diffusivity. Table 4.1 lists the one dimensional diffusivity and moisture contents reached at the end of the immersion interval.

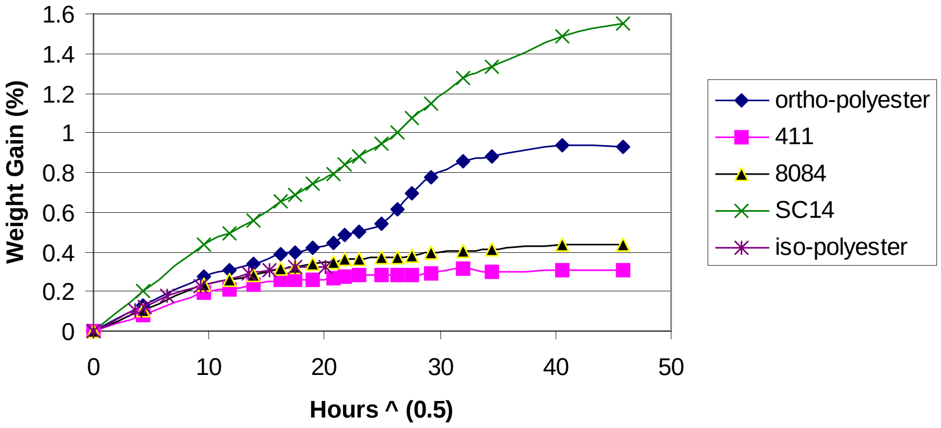


Figure 4.2 Weight Gain Curves for $[0/\pm45/0]_s$ Composites Conditioned in 50°C Distilled Water.

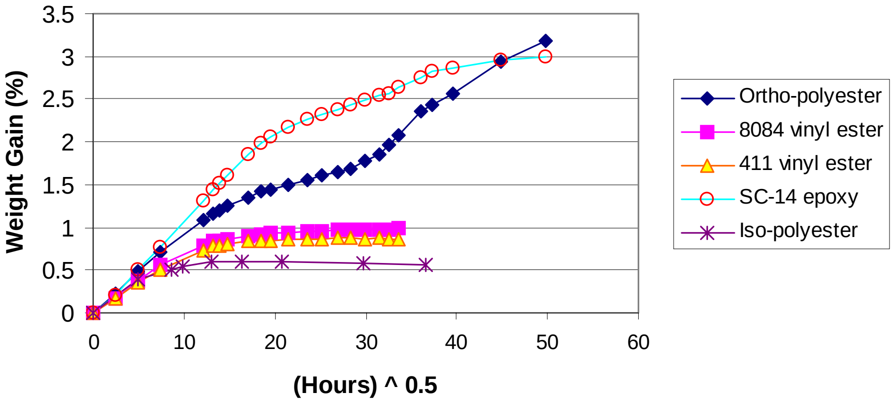


Figure 4.3 Weight Gain Curves for Neat Resins Conditioned in 50°C Distilled Water.

Table 4.1 Maximum moisture content and diffusivity of composites and neat resins.

	Mm (%)	Thickness (mm)	D(mm^2/hour)	V_f
		Neat resin		
Ortho-polyester	1.8	3.58	1.34E-02	
Vinyl ester 411	0.88	3.66	1.52E-02	
Vinyl ester 8084	0.98	3.4	1.32E-02	
Epoxy SC14	3	3.61	8.88E-03	
Iso-polyester	0.6	3.15	2.06E-02	
		Composites		
Ortho-polyester	0.93	3.18	2.00E-03	0.36
Vinyl ester 411	0.31	3.19	2.30E-03	0.36
Vinyl ester 8084	0.44	3.14	2.44E-03	0.36
Epoxy SC14	1.55	3.09	1.87E-03	0.36
Iso-polyester	0.3	3.13	2.67E-03	0.33

The data indicate that both the *Mm* and *D* are a function of the chemistry of the resins. Among the five resins, iso-polyester has the highest diffusivity and the lowest maximum moisture content. Epoxy SC-14, however, has the lowest diffusivity and the highest maximum moisture content. Ortho-polyester has the similar diffusivity to vinyl esters 8084 and 411, although it has double their *Mm*. It has been found in the research that the same kind of composites made at different times, conditioning in the same environmental condition, may have significant differences in weight gain (%). Two batches of iso-polyester were conditioned in distilled water at 50°C for 25 hours. One had 0.1% weight gain while the other had 0.3%. Large scatter of water absorption data is also reported other studies [23]. It seems that minor differences in the processing and curing conditions can significantly affect the moisture absorption behavior of composites.

Tension and Compression

To investigate the environmental effects on basic mechanical properties of composites, tension and compression tests were performed for composites with the five resin systems using the same D155 / D120 glass fabrics. The tension and compression tests included: 0° compression, 0° tension, 90° tension and ±45° tension test. All tests were run an $[0/\pm 45°/0]_s$ laminates except for the ±45° tension. Results for ultimate tension strength (UTS), ultimate compression strength (UCS) and moduli are presented as a function of test temperature in figures 4.4-4.10. In these figures the left group of curves are for dry conditioned and tested specimens, which show the temperature effect on mechanical properties. The right group of curves is for wet conditioned and tested specimens, which show the combination of temperature and moisture effects. Comparing the left curves with its corresponding right curves shows the moisture effects at each temperature. Each data point in these figures represents the average of three tests. The conditioning time, test temperature, moisture content and layup are shown in table 4.2. Complete data for ultimate strength, modulus and standard deviation are shown in the appendix.

Table 4.2 Composites tested

	0° tension	0° compression	90° tension	45° tension	
lay-up	[0/±45°/0]s	[0/±45°/0]s	[0/±45°/0]s	$[\pm 45°]_3$	
test temperature	25°C, 40°C, 55°C, 70°C dry				
	moisture content (%)				conditioning
ortho-polyester	0.92	0.87	0.92	0.86	50°C wet,1200 hours
vinyl ester 411	0.34	0.32	0.34	0.24	50°C wet,1200 hours
vinyl ester 8084	0.44	0.42	0.44	0.38	50°C wet,1200 hours
epoxy sc-14	1.34	1.41	1.34	1.24	50°C wet,1200 hours
iso-polyester	0.3	0.3	0.3	0.28	50°C wet,433 hours

The 0 degree compression strength (resin dominant property) versus test temperature, dry and wet is shown in figure 4.4. It is noted that all five composites, both dry and wet, experienced decreasing ultimate compression strength at elevated temperature. This is probably because the matrix modulus degraded at the elevated temperature and reduced the support for fibers when out of plane fiber microbuckling occurred. Among the five composites, ortho-polyester is the most sensitive to temperature. It has the highest ultimate compression strength (about 91 ksi) at ambient temperature and decreases 40% to 55 psi, the weakest strength among the five composites, when the test temperature increases from room temperature to 70°C dry. Iso-polyester is least affected by temperature and its compression strength drops only 14% over the same temperature range. In the cases of iso-polyester and vinyl esters 411 and 8084, moisture effects can be neglected since no significant change in compression strength was observed between dry and wet specimens when tested at the same temperature. Ortho-polyester and epoxy SC-14, on the other hand, are the most sensitive to moisture and the compression strength decreases up to 40% and 25%, respectively, due to moisture. This is also in agreement with the relatively high weight gain for these resins when soaked in water at 50°C for the same period of time.

Tensile modulus in the 0° direction versus test temperature dry and wet is presented in figure 4.5, where no significant change in tensile modulus was observed for all five composites both dry and wet at various temperatures ranging from room temperature to 70°C. This indicates that 0 degree tensile modulus is a fiber dominated property and is insensitive to moisture over the present temperature range, which is also in agreement with previous research results [12].

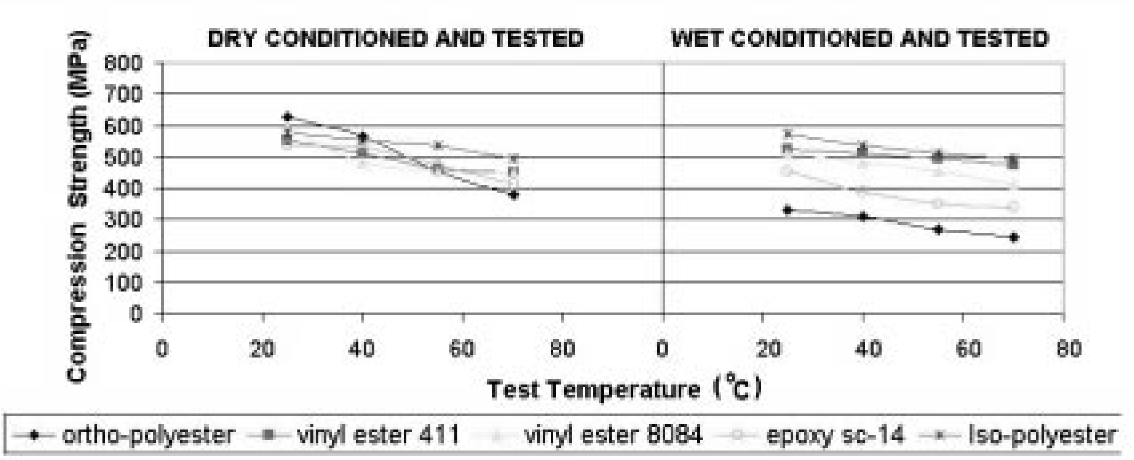


Figure 4.4 Compression Strength in the 0° Direction vs. Test Temperature, Dry and Wet ($[0/\pm45/0]_s$ Laminates).

Tensile strength in the 0° direction versus test temperature dry and wet is shown in figure 4.6. It is noted that all five composite systems, both dry and wet, are not affected much by the increased temperature. Like the modulus, the 0° tensile strength is a fiber dominated property and glass fiber strength does not significantly affected by this temperature change. In all cases epoxy SC-14 is relatively the most sensitive to temperature. For wet SC-14 specimens, the 0° tensile strength decreases approximately 27% when the test temperature increased from room temperature to 70°C. For dry SC-14 specimens, the tensile strength dropped 16% from 690 MPa to 578 MPa when test temperature increased from room temperature to 40°C, then remained almost the same when the test temperature continued to increase up to 70°C. This decrease at such low temperature is not expected and the reason is still unknown. With regard to moisture effects, vinyl esters 411 & 8084 and epoxy SC-14 are more sensitive and experienced a

25-38% drop in tensile strength over the temperature range due to moisture. In contrast, iso-polyester and ortho-polyester are not affected by the moisture since no significant change is observed. Overall the effects of moisture on 0° tensile strength were less than those on the compressive strength. The wet 0° tensile data for all systems except isopolyester are nearly identical in terms of absolute strength.

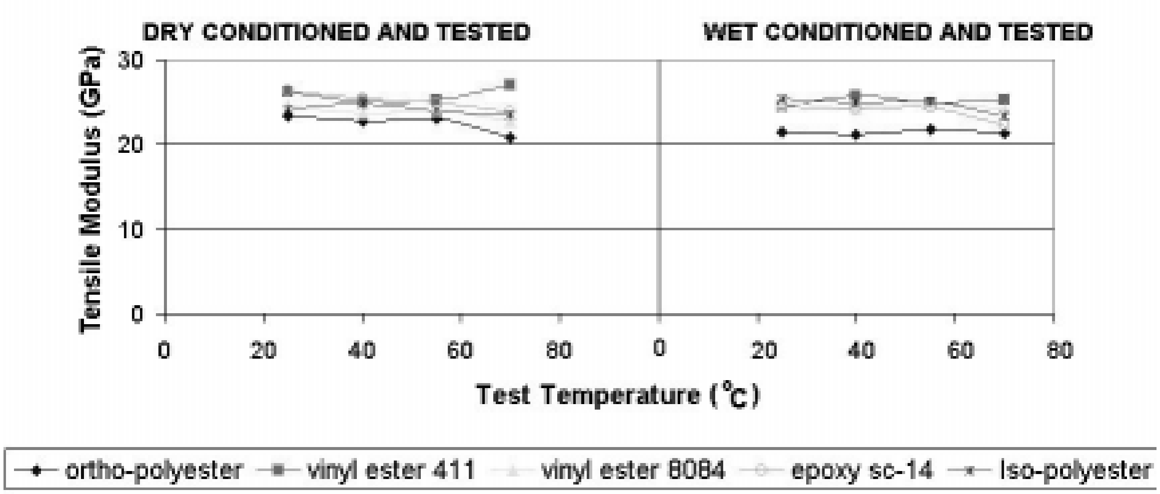


Figure 4.5 Tensile Modulus in the 0° Direction vs. Test Temperature, Dry and Wet ($[0 \pm 45/0]_s$ Laminates).

Figure 4.6 (b) shows a photograph of the failure mode for wet specimens of 8084 and iso-polyester at 40°C. The iso-polyester brooming mode is also typical of all dry tests on all resins. Except for iso-polyester, the wet specimens in figure 4.6 (a) failed in a more localized mode similar to the 8084, at all temperatures. This failure mode difference is not understood at this time, but apparently is the cause of the moisture sensitivity for all but the iso-polyester systems in figure 4.6 (a).

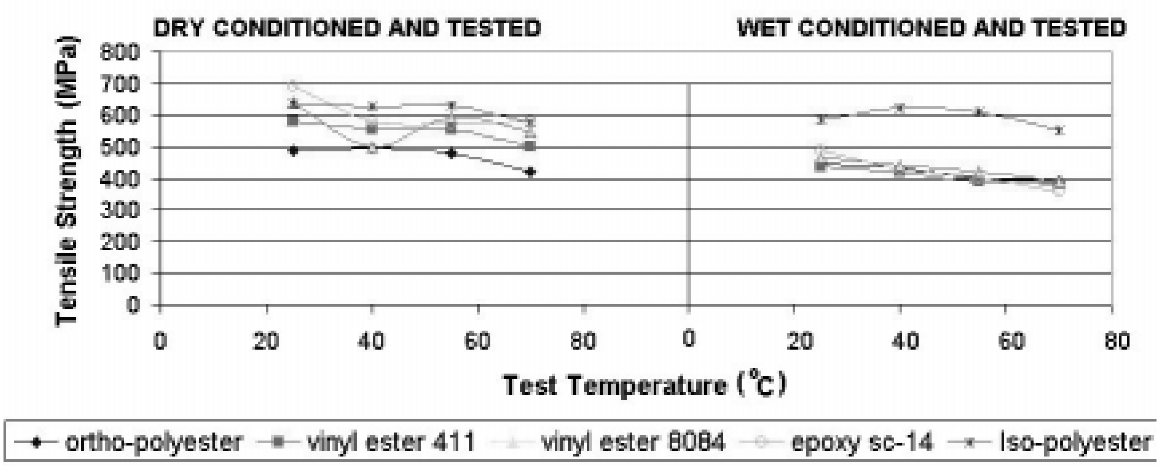


Figure 4.6 (a) Tensile Strength in the 0° Direction vs. Test Temperature, Dry and Wet ($[0/\pm45/0]_s$ Laminates).

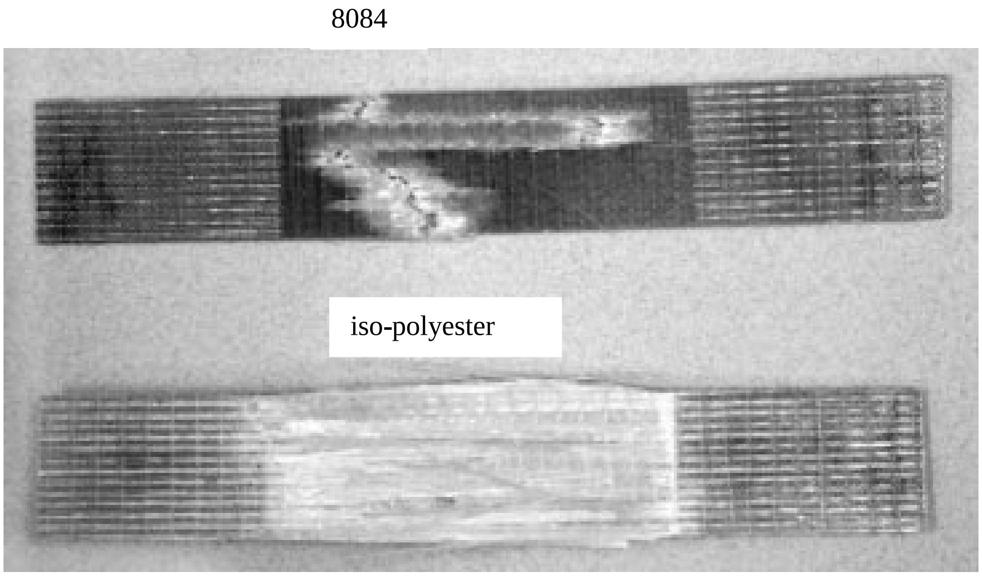


Figure 4.6 (b) Failure Mode for Wet Specimens of 8084 and Iso-polyester at 40C.

The ±45 tensile modulus (resin dominant property) versus test temperature, dry and wet are shown in figure 4.7, where all five composites show appreciable reduction in modulus with test temperature increases regardless of moisture. Among the five composites, ortho-polyester is the most sensitive to test temperature. Its tensile modulus for dry and wet conditions decreased 53% and 59% respectively, when the temperature increased from RT to 70°C. This correlates with the low T_g of the ortho-polyester (HDT=55°C) compared with other resin systems. The resin is significantly softened when temperature is close to its T_g. Epoxy SC-14 is the second most sensitive to temperature and its tensile modulus for dry and wet conditions decreased 31% and 53%, respectively, when temperature increased from RT to 70C. This correlates with the fact that the SC-14 resin has the highest water absorption amount. Moisture diffused into composites plasticizes the resin and lowers its T_g, thus the composites suffer more degradation at moderate temperature.

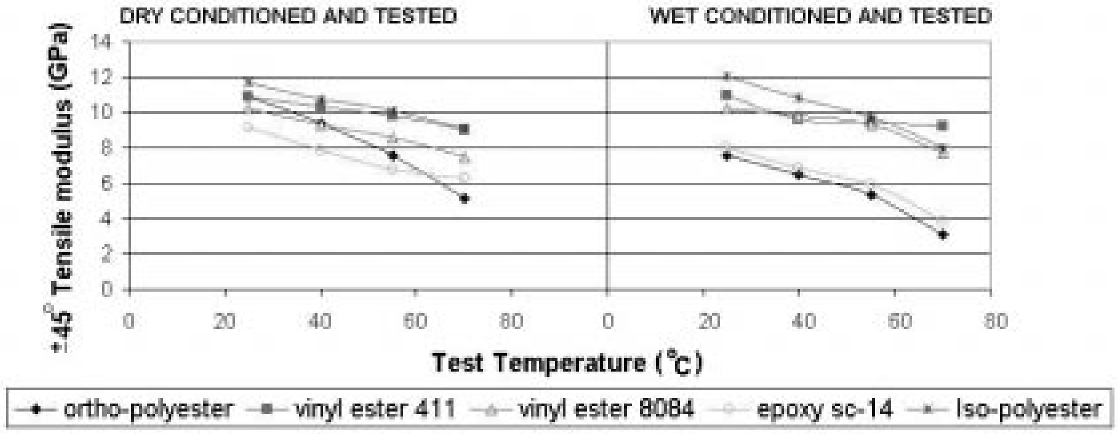


Figure 4.7 Tensile Modulus for ±45 Laminates vs. Test Temperature, Dry and Wet ($[\pm45]_3$ Laminates).

Ortho-polyester and SC-14 are not only sensitive to test temperature, but are also sensitive to moisture. Their tensile modulus for wet specimens decreased about 30% and 13%, respectively, relative to dry specimens over the temperature range 25°C to 50°C both dropping by about 40% by 70°C. This indicates that the combination of moisture and temperature produces more severe degradation than each separately, especially for hot-wet conditioning. For iso-polyester, and vinyl esters 411 and 8084, no significant changes in tensile modulus were observed between dry and wet conditioned specimens indicating that the moisture effect seems to be negligible due to their low moisture absorption shown in table 4.3. It should be emphasized that vinyl ester 8084 and epoxy SC-14 composites have slightly lower tensile modulus (10.3 GPa and 9.2 GPa) than the baseline ortho-polyester (10.9 GPa) at room temperature.

The tensile strength of ±45 laminates versus test temperature, dry and wet is presented in figure 4.8. It is clear that ±45 tensile strength has the similar trend to ±45 tensile modulus, both being resin dominated. In terms of temperature effects, all specimens show a 20% to 35% reduction in tensile strength with increased temperature. Epoxy SC-14 shows the weakest tensile strength within the temperature range from 25°C to 70°C dry, 20% lower than baseline ortho-polyester at ambient temperature. In terms of moisture effects, only ortho-polyester shows appreciable sensitivity and it sustains 34% to 40% degradation in tensile strength over this temperature range due to the presence of the moisture. No significant change is observed in tensile strength for the other four composite systems for dry versus wet results, which indicates that the moisture effect can be neglected.

The tensile modulus in the 90° direction for $[0/\pm45°/0]_s$ laminates as a function of test temperature, dry and wet, is shown in figure 4.9. The 90° tensile modulus for all five composite systems appears to decrease with the test temperature increase from RT to

70°C, regardless of moisture. Again, these are matrix dominated results in the 90° direction. The ortho-polyester and vinyl esters 411 & 8084 lose approximately 50% of their RT modulus by 70°C. The four composite systems other than ortho-polyester have higher modulus than the baseline ortho-polyester over the temperature range tested, dry and wet. With regard to moisture effects, iso-polyester shows no sensitivity over this range of temperatures. However, vinyl esters 411 & 8084 and ortho-polyester show a 20% to 34% decrease in tensile modulus relative to the dry specimens over the range 25°C to 55°C. In the temperature range 55°-70°C, moisture effects are small and these three composites show 10% to 20% degradation relative to the dry specimens. In contrast, for epoxy SC-14 the moisture effect is small at RT since only 9% reduction is shown in modulus and the effect is aggravated at elevated temperature, 70°C, with 31% reduction due to moisture.

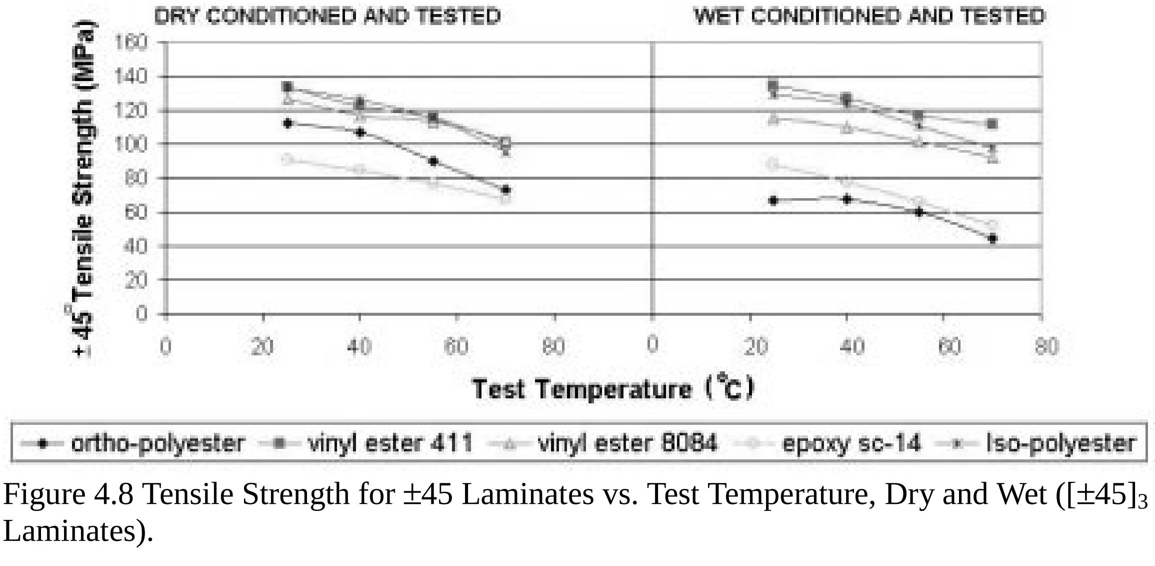


Figure 4.8 Tensile Strength for ±45 Laminates vs. Test Temperature, Dry and Wet ($[\pm45]_3$ Laminates).

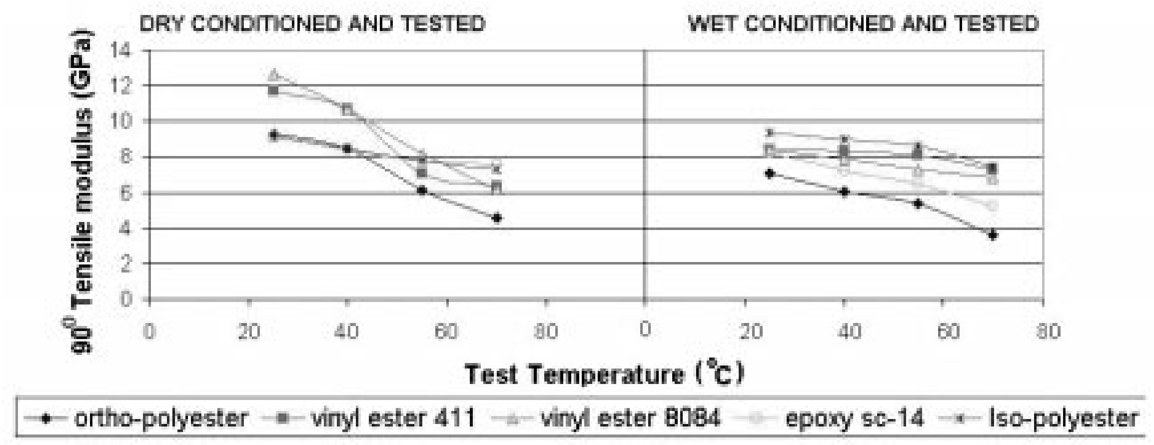


Figure 4.9 Tensile Modulus in the 90° direction for [0/±45/0]s Laminates vs. Test Temperature, Dry and Wet.

The 90 degree tensile strength (resin or interface dominated) versus test temperature is shown in figure 4.10. It appears that temperature effects on tensile strength are quite different from those on modulus. The temperature effect on strength can be neglected both for wet and dry specimens except for 8084, which shows a drop only at the highest temperature, dry. The 90° tensile strength results are surprising in their general insensitivity to temperature and moisture despite a clearly decreasing matrix property in the other matrix dominated tests. The reasons could be similar to those for the unusual trend in the Mode I interlaminar fracture toughness described later. It should also be noticed that iso-polyester (67 MPa) and vinyl ester 411 (56 MPa) have lower ultimate tensile strength than the baseline ortho-polyester (74 MPa) and this does not change over the temperature range tested. With regard to moisture effects, iso-polyester and vinyl ester 411 are insensitive to moisture. However epoxy sc-14, ortho-polyester and vinyl ester 8084 sustain up to 28%, 35% and 40% reduction in 90 degree tensile strength due to the moisture existence at the various temperatures.

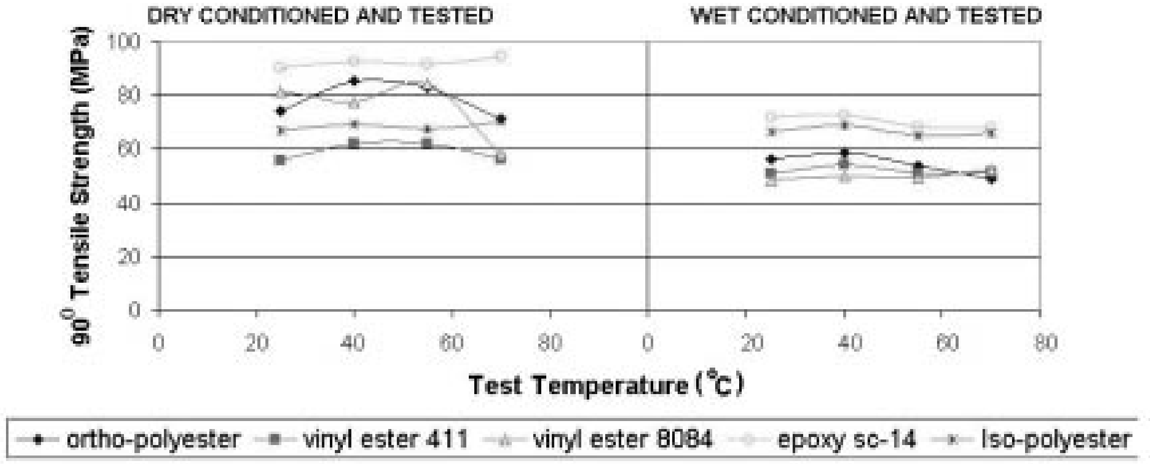


Figure 4.10 Tensile Strength in the 90° direction for [0/±45/0]s Laminates vs. Test Temperature, Dry and Wet

A summary of the experimental data on the effects of moisture and temperature on the elastic modulus and strength of composite materials are shown in tables 4.3 and 4.4. For the fiber dominated properties (0 degree tension), the moisture and temperature effects are small and can be neglected for all the five composites for modulus; moderate effect are evident on 0° tensile strength. For resin dominated properties (45 degree tension, 0 degree compression and 90 degree tension), the environmental effects depend on the chemistry of the resins. Ortho-polyester shows the most sensitivity to temperature and moisture and experienced strong degradation at elevated temperature and moisture conditioning. Epoxy SC-14 is the second most environmentally sensitive system, followed by vinyl esters 8084 and 411. Iso-polyester is the least sensitive to environment and has the lowest water absorption amount. In various mechanical property tests, no property of the iso-polyester is lower than that for the baseline ortho-polyester. So, in terms of environmental sensitivity and this group of mechanical properties, iso-polyester seems to be the best candidate in the manufacture of wind turbine blades. However, iso-polyester is a relatively brittle matrix, similar to ortho-polyester and is less advantageous in terms of delamination resistance than are the vinyl esters and epoxy, as discussed in the following.

Table 4.3. Summary of experimental data on effects of moisture and temperature on elastic modulus.

Resin system	0 degree tension		±45 degree tension		90 degree tension	
	Moisture	Temp.	Moisture	Temp.	Moisture	Temp.
ortho-polyester	N	N	S	S	M	S
vinyl ester 411	N	N	N	M	M	S
vinyl ester 8084	N	N	N	M	M@	S
epoxy sc-14	N	N	M*	S	M*	M
iso-polyester	N	N	N	M	N	M

N = Negligible effect (<10%)
m= Moderate effect (<30%)
S = Strong effect (>30%)
M@= Strong effect only at RT. Otherwise M
M*= Strong effect only at 70C Otherwise M

In figures 4.4-4.10, those trends for which moisture and temperature show strong effects (>30%) on either the modulus or the ultimate stress are all meaningful since the reduction in the properties is greater than the standard deviations greater in the Appendix. Those trends that show moderate effect (<30%) are partly meaningful. In figure 4.6, the trend for 411 and 8084 dry specimens are not meaningful and only reflects data scatter. Three specimens for a test is the minimum. More specimens need to be tested to give more reliable results.

Table 4.4. Summary of experimental data on effects of moisture and temperature on ultimate strength

Resin system	0° tension		±45° tension		90° tension		0° compression	
	Moisture	Temp.	Moisture	Temp.	Moisture	Temp.	Moisture	Temp.
ortho-polyester	M	M	S	S	S	N	S	S
vinyl ester 411	M	M	N	M	M	N	N	M
vinyl ester 8084	M	M	N	M	S	N*	N@	M
epoxy sc-14	M*	M	M	M	M	N	M	M
iso-polyester	N	N	N	M	N	N	N	M

N = Negligible effect (<10%)
M= Moderate effect (<30%)
S = Strong effect (>30%)
N@= Moderate effect only at RT. Otherwise N
N*= Moderate effect only at 70°C Otherwise N
M*= Strong effect only at 70°C Otherwise M

Delamination Resistance

To investigate the degradation of interlaminar fracture toughness due to environment attack, the same five composite systems were tested as unidirectional $[0]_6$ composites, conditioned 50°C dry and 50°C wet for 889hours, 1000 hours and 2900 hours. Tests run were Mode I (DCB) & Mode II (ENF) at three different temperatures, -20°C, room temperature (RT), and 50°C. Table 4.5 presents the test temperature, conditioning time, fiber volume fraction, moisture content, initial value of mode one critical strain energy release rate G_{Ic} and mode two critical strain energy release rate G_{IIc}. Each entry represents the mean of two to four specimens given in the appendix. The G_{IC} and G_{IIC} values for ortho-polyester, vinyl ester 411, vinyl ester 8084 and epoxy SC-14 tested at room temperature were provided by R. Orozco [16].

Table 4.5. Results for G_{Ic} and G_{IIc} for different conditionings.

Resin systems	ortho-polyester	411	8084	sc-14	iso-polyester
Environment Conditioning	50°C distilled water 1000 hours	50°C distilled water 1000 hours	50°C distilled water 1000 hours	50°C distilled water 1000 hours	50°C distilled water 889 hours
Test Temp	50°C dry	50°C dry	50°C dry	50°C dry	50°C dry
moisture(%)	1.81	0.42	0.53	2.18	0.25
Initial G_{Ic} (J/m^2)	580	558	918	886	419
G_{IIc} (J/m^2)	773	2173	2523	841	1752
Environment Conditioning	50°C distilled water 2900 hours	50°C distilled water 2900 hours	50°C distilled water 2900 hours	50°C distilled water 2900 hours	
Test Temp	50°C dry	50°C dry	50°C dry	50°C dry	
moisture(%)	2.16	0.54	0.69	2.9	
Initial G_{Ic} (J/m^2)	409	578	822	874	
G_{IIc} (J/m^2)	1338	2785*	2174*	1717	
Environment Conditioning	50°C dry for 1000 hours	50°C dry for 1000 hours	50°C dry for 1000 hours	50°C dry for 1000 hours	50°C dry for 889 hours
Test Temp	50°C dry	50°C dry	50°C dry	50°C dry	50°C dry
Initial G_{Ic} (J/m^2)	259	482	781	861	302.6
G_{IIc} (J/m^2)	1372	2481	2529	1654	2386
Environment Conditioning	room temperature dry	room temperature dry	room temperature dry	room temperature dry	room temperature dry
Test Temp	RT dry	RT dry	RT dry	RT dry	RT dry
Initial G_{Ic} (J/m^2)	159	396	595	638	200
G_{IIc} (J/m^2)	977	2557	2638	3223	1359
Environment Conditioning	room temperature dry	room temperature dry	room temperature dry	room temperature dry	room temperature dry
Test Temp	-20 to -35°C	-20 to -35°C	-20 to -35°C	-20 to -35°C	-20 to -35°C
Initial G_{Ic} (J/m^2)	214	385	468	570	239
G_{IIc} (J/m^2)	1112	1967	2485	2202	1484
* Fail in tension failure instead of interlaminar fracture					

The measurements of mode one initial fracture toughness of the five systems conditioned 50C wet are plotted as a function of moisture content (weight gain %) in Figure 4.11. The weight of composites conditioned at 50°C dry were used as the base line for zero weight gain.

For the first period of moisture exposure (1000 hours) most composites have an increasing initial G_{IC} value except for epoxy SC-14, whose G_{IC} is insensitive to moisture (although it absorbed the most moisture, 2.2%, of all five resins in the same period of conditioning time). For the second period of moisture exposure(1000 hours to 2900 hours), G_{IC} values for ortho-polyester and vinyl ester 8084 decrease 33% and 10% compared with those (after 1000 hours conditioning time. For vinyl ester 411 and epoxy SC-14, no significant changes are observed in this time period. The increase of G_{IC} in short term conditioning could have resulted from the relaxation of residual stress in the water due to the moisture absorption during the short term of moisture exposure. When composites cool down from the curing temperature to room temperature, the residual stress in the matrix in the longitudinal direction is tensile due to the differential thermal expansion coefficient. When soaked in moisture, the matrix swells, reversing the differential thermal expansion effects. This could result in more fiber bridging in mode one interlaminar fracture and increase the G_{IC} value. For the longer conditioning term, moisture will finally degrade composites and lead to the deserved drop of G_{IC}. Since the moisture sensitivity and moisture saturation amount depend on the chemistry of the matrix, different resins experienced different interlaminar fracture behavior for the same period of conditioning time.

The measurements of mode two fracture toughness for the five systems conditioned in 50°C dry and 50°C wet are plotted as a function of moisture content (weight gain %) in figure 4.12. Again, the weight of composites conditioned at 50C dry is used as the base line and the weight gain was regarded as 0%.

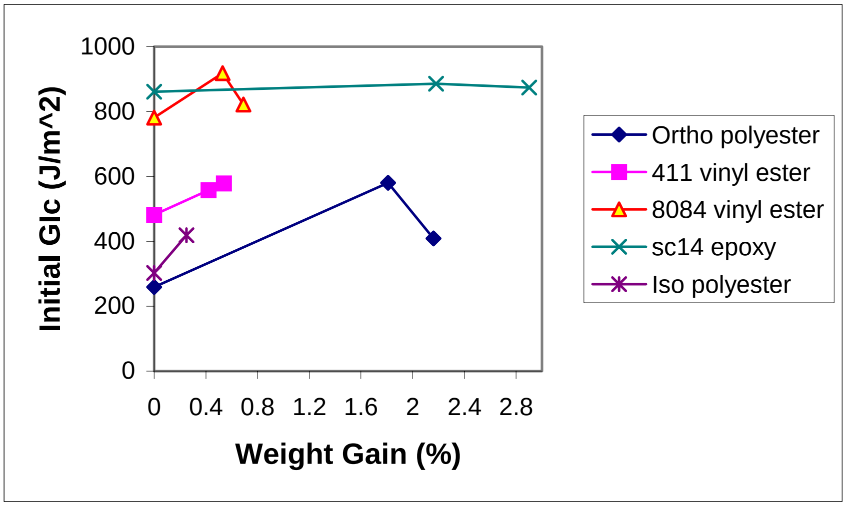
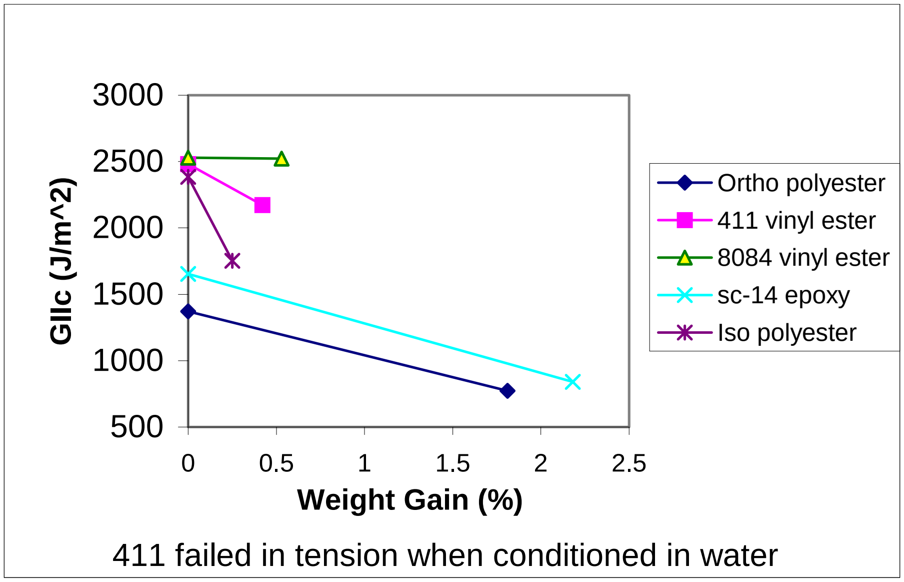


Figure 4.11. Moisture Effects on Initial Mode One Fracture Toughness, Tested at 50°C.

Since the mode II fracture toughness is a matrix dominated property with few complications from fiber bridging, it is clear that moisture effects on G_{IIC} depend on the chemistry of the matrix and the interface. For vinyl ester 8084, the moisture effect on G_{IIC} is insignificant, while for ortho-polyester and epoxy SC14, the G_{IIC} of wet specimens drop to less than half the value for dry specimens. This is in agreement with the fact that ortho-polyester and epoxy SC14 absorbed the most moisture (1.8% and 2.2%) of the five resins, indicating that the degradation in G_{IIC} is related to the softening of the matrix due to the moisture absorption. As noted later, the bond strength for these two systems also decreased with hot/wet conditioning. For vinyl ester 411, the two specimens conditioned in 50C wet both failed in tensile failure instead of mode II interlaminar fracture, so the calculated G_{IIC} value, using the load at tensile failure would be a lower bound on the real G_{IIC} value. The reduction of 25% in the G_{IIC} value for iso-polyester after 889 hours moisture exposure at 50°C is observed and unexpected since iso-polyester had the least weight gain (about 0.25%) among the five resins tested. The G_{IIC} experimental data for iso-polyester are presented in table 4.6. Iso-polyester--50°C--1,2,3 are three test specimens conditioned at 50°C dry and iso-polyester--w--1,2,3 are three test specimens conditioned at 50°C wet. All the specimens were cut from the same plate and tested at the same time. However 50°C-3 had a G_{IIC} value 8074 J/m^2, almost three times than that for the other two specimens (2176 and 2574 J/m^2). A similar difference is observed for w-3 specimen. Due to uncertainty in the data, these two results were not included in the average in the tables and figures. The reason for the large data scatter may be due to multiple cracks at different layers. Thus, the validity of the isopolyester data is questionable.

To evaluate the temperature effect on the mode one fracture toughness, initial G_{IC} is plotted as a function of test temperature in figure 4.13. At elevated temperature, all five composites experienced relatively higher initial G_{IC}. Ortho-polyester is the most temperature sensitive and the G_{IC} increased 63% at the elevated temperature. Vinyl ester 411 is the least temperature sensitive since no significant change can be observed. The increase of initial G_{IC} at elevated temperature may be due to the increase in multiple cracking and fiber bridging for conditioning at 50°C dry for 1000 hours.



411 failed in tension when conditioned in water

Figure 4.12. Moisture Effects on Mode Two Fracture Toughness, Tested at 50°C.

Table 4.6. Experimental data of G_{IIC} for iso-polyester

	Crack (m)	Max Load (N)	Thickness (m)	Width (m)	Vf (%)	EL* (GPa)	GIIC (J/m2)
Dry							
50C-1	0.04	494	0.003	0.0268	0.42	34.93	2176.47
50C-2	0.04	498	0.003	0.0268	0.45	37.11	2594.92
50C-3	0.04	876	0.003	0.0268	0.45	37.11	8074.02
Wet							
w-1	0.04	382	0.003	0.0268	0.45	37.35	1562.65
w-2	0.04	418	0.0029	0.0268	0.46	37.84	1941.68
w-3	0.04	818	0.003	0.0267	0.45	37.11	7097.34

Since some polymers, particularly with rubber toughening like vinyl ester 8084, exhibit embrittlement and sustain a loss of toughness at low temperature; thus, it is necessary to characterize the behavior in the cold service temperature range. At -20C, vinyl ester 8084 exhibits a 21% decrease in initial G_{IC}, relative to RT; for the other four resins, no significant change is observed compared with the value in room temperature.

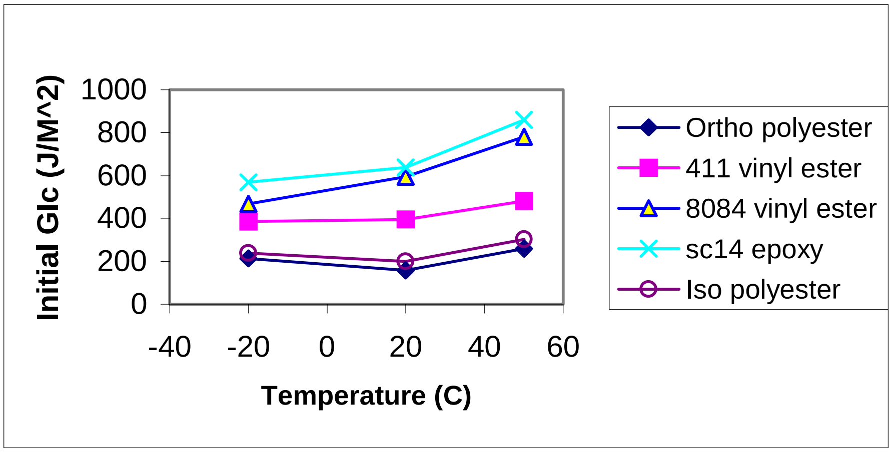


Figure 4.13.Temperature Effect on Initial Mode One Fracture Toughness, Tested at 50°C.

The measurements of mode two critical energy release rate versus test temperature are shown in Figure 4.14. When exposed to low temperature below -20C, the G_{IIC} values for iso-polyester, ortho-polyester and vinyl ester 8084 do not change much compared with those at room temperature. However for epoxy sc-14 and vinyl ester 411, the G_{IIC} values decreased by approximately 30% and 20% of their values at room temperature. When exposed to elevated temperature, different resins showed different trends of change in G_{IIC} values. Compared with their G_{IIC} values at room temperature, iso-polyester and ortho-polyester increased 75% and 40% respectively, while epoxy SC-14 decreased by almost half and no significant change was observed for vinyl esters 411& 8084. The more brittle polyester resins may increase in matrix toughness at elevated temperature.

The results discussed on the proceeding are represented on bar charts in figure 4.15 and 4.16. The initial G_{IC} values in figure 4.15 show the polyesters to be the most brittle at RT, with SC14 and 8084 the toughest. Compared with values in room temperature, all five resins show higher mode one fracture toughness under hot and hot-wet conditioning and no significant drop at cold temperatures. Compared with the baseline of ortho-polyester, all the other four candidates show the equal or higher initial G_{IC} regardless of environment conditioning. As noted earlier, G_{IC} test values can often complicated by multiple cracking and fiber bridging, even for small value of crack extension.

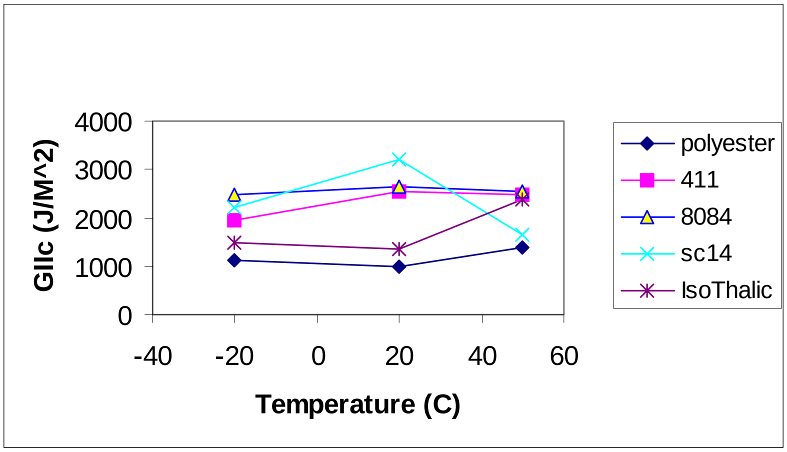


Figure 4.14. Temperature Effect on Mode Two Fracture Toughness, Tested at 50°C

In figure 4.16 vinyl ester 8084 shows the least sensitivity to environment and no difference is observed in G_{IIC} value tested under four kinds of environment conditioning. The order of G_{IIC} for the different resins at RT is the same as for G_{IC} . Although epoxy SC-14 shows the highest G_{IIC} value among the five composites at room temperature, it shows the most sensitivity to environment. In hot and hot-wet conditioning, its G_{IIC} value drops 49% and 74% respectively. In hot-wet conditioning, its G_{IIC} value is even lower than that of the baseline ortho-polyester. Except for epoxy SC-14, all the other resins show a higher G_{IIC} value under hot, cold and hot-wet conditioning than the base-line ortho-polyester.

Micro-debonding Test

The five unidirectional composite systems were tested for fiber-matrix bond strength after conditioning in 50°C distilled water for 2900 hours and then soaking in water at room temperature until tested. The results of micro-debonding tests for dry and wet samples, which indicates the moisture effects on the interface strength of composites, are shown in table 4.7. Each value represents the average of 8-9 specimens (see appendix).

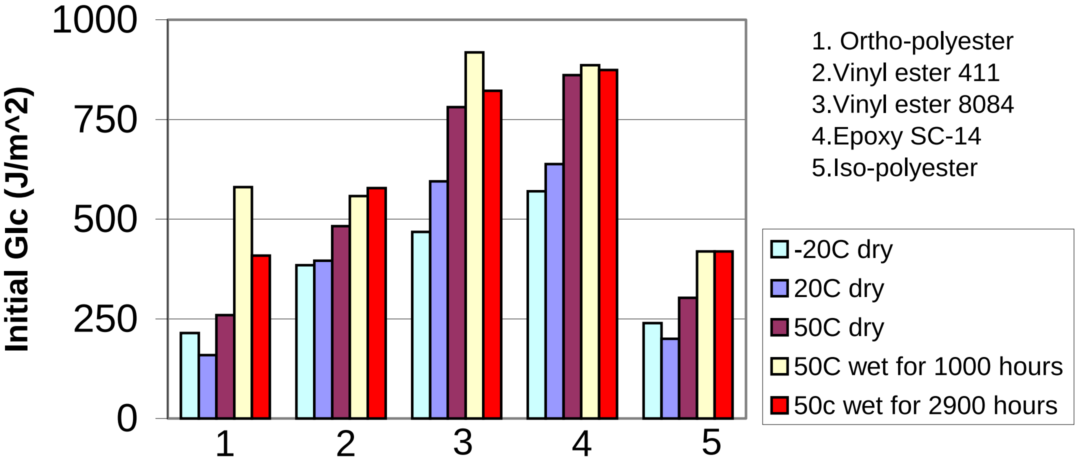


Figure 4.15. Effect of Matrix on Initial Mode One Interlaminar Fracture Toughness, Tested 50°C Dry (0 degree D155).

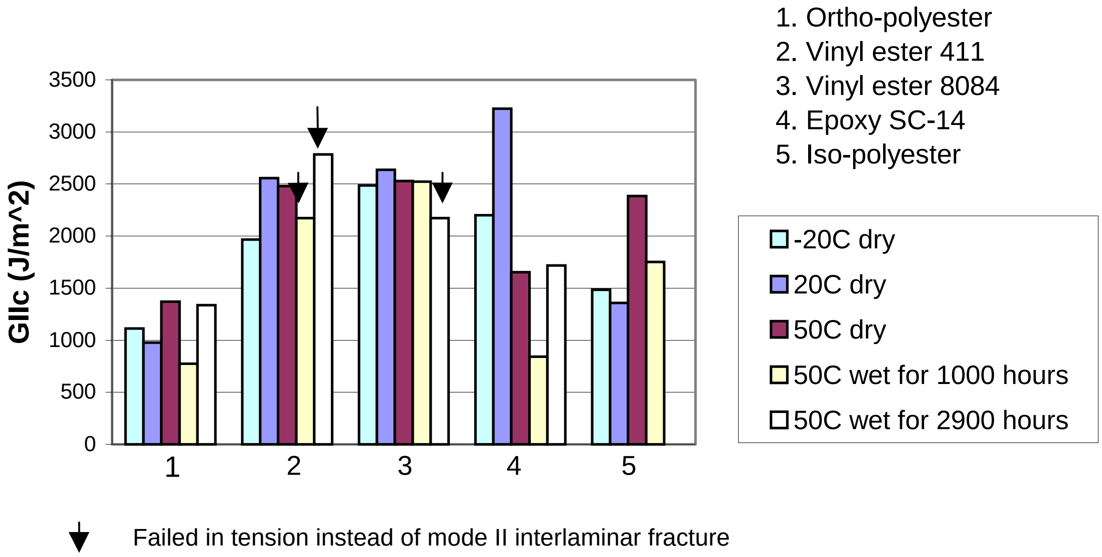


Figure 4.16. Effect of Matrix on Mode II Interlaminar Fracture Toughness, Tested at 50°C dry (0 degree D155).

Table 4.7 Test results for interfacial strength, dry and wet (tested at RT)

Resin system	Dry specimens		Wet specimens			Inter. strength
	Interface	Stdev.	Interface	Stdev.	Moisture	% change
	strength (MPa)		strength (MPa)		content (%)	Dry vs.Wet
orthopolyester	66.28	[4.58]	50.75	[4.68]	2.16	23.43
vinyl ester 411	48.49	[4.33]	45.25	[6.54]	0.53	6.68
vinyl ester 8084	52.53	[6.47]	47.89	[11.9]	0.69	8.83
epoxy sc-14	60.95	[4.82]	43.74	[3.87]	2.94	28.24
isopolyester	67.21	[8.37]	67.06	[9.99]	0.32	0.22

The two polyesters have the strongest interfacial strength of about 67 MPa at room temperature, followed by epoxy SC-14. Dry vinyl ester 8084 and 411 have relatively the similar lowest interfacial strengths (48-52 MPa). Soaking at 50°C in distilled water gave a 28% and 23% reduction in interfacial strength for epoxy SC-14 and ortho-polyester respectively. No significant interfacial strength reduction was observed in wet iso-polyester, vinyl ester 8084 and 411 samples, relative to dry conditions. This result is consistent with the results for water absorption. Epoxy SC-14 and ortho-polyester absorbed the first and second most moisture amount under the same conditioning and the same period of time. This indicates that the more weight gain at saturation, the more severe the degradation of the fiber / matrix interface. This result is also consistent with the test results on 90 degree tension strength: ortho-polyester and epoxy SC-14 experienced 24% and 20% degradation in 90^0 ultimate tensile strength due to the moisture at the room temperature, while 411 and iso-polyester do not show significant reductions. Vinyl ester 8084 is the only one that is not consistent between micro-debonding and 90 degree tension test. In micro-debondng test, the interfacial strength for wet vinyl ester 8084 sample is 48MPa, a little bit lower than that of dry samples (53 MPa). This difference, however, is within the data scatter. In the 90° tension test, vinyl ester 8084 lost up to 40% of dry tensile strength due to moisture diffusion at the room temperature. This result contradicts all other moisture results for 8084, and may not be meaningful. The bond strength changes with moisture also correlate with the G_{IIC} results.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The moisture content of composites and neat resins depends on the chemistry of matrix. Of the five resins, epoxy SC-14 absorbed the most moisture when conditioned in distilled water at 50C, followed closely by ortho-polyester; vinyl esters 411 & 8084 and iso-polyester absorbed much less waters. The moisture diffusion constant followed the opposite trend with resin system..
- The fiber dominated properties (0 degree tensile modulus and strength) showed little sensitivity to the moisture and temperature. Reduction in modulus was negligible (reduction < 10% for all systems, while the strength was reduced moderately in some case at the high temperature (reduction < 30% for all systems).
- The resin dominated properties (45 degree tensile test, 90 degree tensile test and compression test as well as the interlaminar fracture resistance) showed significant sensitivity to temperature and moisture. The effects of moisture and temperature are summarized for each resin system in the following.
  - ❖ Ortho-polyester. The baseline Ortho-polyester resin is a brittle and low cost resin. Its primary mechanical properties appear deficient for the wind turbine blades application in the area of delamination resistance (structural integrity) and hot/wet resistance. Both temperature and moisture have very strong effects (reduction

>30%) on the modulus and ultimate strength for matrix dominated properties over the temperature range 25 to 70C. In terms of delamination resistance, it has the poorest interlaminar fracture toughness of the five candidates. The delamination resistance at ambient condition is not reduced by temperature or moisture over the range tested.

- Vinyl esters 411 & 8084. Derakane 8084 is a toughened vinyl ester and Derakane 411 is untoughened. Both of them provide up to double the interlaminar toughness of the baseline ortho-polyester at the room temperature. They are insensitive to temperature and moisture in G_{IIC} values and have increased values in G_{IC} in hot-wet conditioning. Temperatures around –20C seem not to significantly change their toughness. These resins have the similar sensitivity to moisture and temperature in tensile and compression tests. Their sensitivities are much lower than for the baseline ortho-polyester. Their costs are moderately higher than the ortho-polyester.
- Epoxy SC-14. SC-14 is a toughened epoxy resin; it is the most costly resin tested. It yielded the highest interlaminar toughness among the five resins at room temperature. However, its G_{IIC} value is very sensitive to temperature and moisture, dropping about 50% when the temperature increases from room temperature to 50C. In hot-wet conditioning its G_{IIC} value is less than one third of the value in room temperature and is lower than the baseline ortho-polyester at the same condition. In tensile and compression tests, sc-14 also has higher sensitivity to temperature and moisture corresponding to vinyl esters.

  - ❖ Iso-polyester. Iso-polyester is least sensitive to the environment among the five resin systems. Temperature and moisture have negligible effects on the modulus and ultimate compression and tensile strength. It also has the similar interlaminar toughness to the baseline ortho-polyester, but is significantly less tough than vinyl esters and epoxy. Low temperature (-20C), high temperature (50C), and moisture does not further diminish the delamination resistance.

- At ambient conditions, the two polyesters appear to have the highest interfacial strength of around 67MPa, then, by decreasing order, epoxy SC-14, vinyl esters 8084 & 411. After hot/wet conditioning epoxy SC-14 and ortho-polyester show the greatest bond strength decrease, dropping 28% and 23% respectively. No significant reduction on bond strength for wet samples of the vinyl esters 411and 8084 and the iso-polyester was observed.
- Overall, vinyl esters 411 & 8084 and iso-polyester appear to have the greatest potential for the wind turbine blade application. They have low maximum moisture contents. Vinyl esters can provide excellent delamination resistance and improved environment resistance compared with baseline ortho-polyester. Iso-polyester has excellent environmental resistance and similar interlaminar fracture toughness to ortho-polyester.

Recommendations

Based on the final conclusions, the vinyl esters and iso-polyester warrant further study. Further tests, such as DCB & ENF tests at higher temperature such as 70C, fatigue tests under hot/wet condition, and structural integrity performance in substructural elements at hot-wet conditioning, need to be investigated to provide enough information for making final resin selection.

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APPENDIX

Individual Test Results

Table A.1. 0 degree compression tests

	Dry specimens at 25C					
sample	thickness	width	max load	UCS*	UCS*	Test Temp.
polyester	(in)	(in)	(lbs)	(ksi)	(MPa)	(C)
p-c-1	0.122	1.002	10710	88	604	25
p-c-2	0.118	1.001	10860	92	634	25
p-c-3	0.12	0.991	11060	93	641	25
			average	**91**	**626**	
			std.dev.	**3**	**20**	
411						
411-c-1	0.124	1.004	1003.0	81	555	25
411-c-2	0.134	1.002	9921	74	509	25
411-c-3	0.124	0.999	10670	86	594	25
			average	**80**	**553**	
			std.dev.	**6**	**42**	
8084						
8084-c-1	0.125	0.983	10700	87	600	25
8084-c-2	0.126	0.991	10310	83	569	25
8084-c-3	0.127	0.984	11070	89	611	25
			average	**86**	**593**	
			std.dev.	**3**	**22**	
sc14						
sc14-c-1	0.121	0.983	9715	82	563	25
sc14-c-2	0.12	0.991	8767	74	508	25
sc14-c-3	0.119	0.992	9107	77	532	25
			average	**78**	**534**	
			std.dev.	**4**	**28**	
Iso-polyester						
tp-c-1	0.135	0.994	10340	77	531	25
tp-c-2	0.134	0.997	11130	83	574	25
tp-c-3	0.132	0.99	11870	91	626	25
			average	**84**	**577**	
			std.dev.	**7**	**48**	
	Dry specimens at 40C					
p-c-4	0.123	1.003	9348	76	522	40
p-c-5	0.12	0.999	10270	86	591	40
p-c-6	0.118	1.003	9964	84	580	40
			average	**82**	**565**	
			std.dev.	**5**	**37**	

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
411						
411-c-4	0.13	0.909	8649	73	505	40
411-c-5	0.124	1.001	9232	74	513	40
411-c-6	0.131	1.003	9598	73	504	40
			average	**74**	**507**	
			std.dev.	**1**	**5**	
8084						
8084-c-4	0.125	0.997	8929	72	494	40
8084-c-5	0.125	0.99	8573	69	478	40
8084-c-6	0.131	0.992	8859	68	470	40
			average	**70**	**481**	
			std.dev.	**2**	**12**	
sc14						
sc14-c-4	0.118	0.988	8644	74	511	40
sc14-c-5	0.114	0.989	9069	80	555	40
sc14-c-6	0.115	0.933	8354	78	537	40
			average	**77**	**534**	
			std.dev.	**3**	**22**	
Iso-polyester						
tp-c-4	0.133	0.995	10720	81	559	40
tp-c-5	0.125	0.999	9514	76	525	40
tp-c-6	0.122	1	10070	83	569	40
			average	**80**	**551**	
			std.dev.	**3**	**23**	
	Dry specimens at 55C					
polyester						
p-c-7	0.123	1.006	8174	66	455	55
p-c-8	0.117	1.002	8163	70	480	55
p-c-9	0.124	1.006	7899	63	437	55
			average	**66**	**457**	
			std.dev.	**3**	**22**	
411						
411-c-7	0.133	1.003	8484	64	438	55
411-c-8	0.133	1.006	8674	65	447	55
411-c-9	0.125	1.009	8992	71	492	55
			average	**67**	**459**	
			std.dev.	**4**	**29**	

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
8084						
8084-c-7	0.129	0.999	8676	67	464	55
8084-c-8	0.126	1.004	8139	64	444	55
8084-c-9	0.126	1.002	8339	66	455	55
			average	**66**	**454**	
			std.dev.	**1**	**10**	
sc14						
sc14-c-7	0.115	0.975	8005	71	492	55
sc14-c-8	0.116	0.987	7698	67	464	55
sc14-c-9	0.116	0.974	7871	70	480	55
			average	**69**	**479**	
			std.dev.	**2**	**14**	
Iso-polyester						
tp-c-7	0.132	0.975	10170	79	545	55
tp-c-8	0.13	0.988	9979	78	536	55
tp-c-9	0.129	0.992	10020	78	540	55
			average	**78**	**540**	
			std.dev.	**1**	**5**	

	Dry specimens at 70C					
polyester						
p-c-10	0.124	1.007	6303	50	348	70
p-c-11	0.12	1.008	6805	56	388	70
p-c-12	0.117	1.007	6916	59	405	70
			average	**55**	**380**	
			std.dev.	**4**	**29**	
411						
411-c-10	0.131	1.001	8461	65	445	70
411-c-11	0.127	0.98	8177	66	453	70
411-c-12	0.125	0.968	7853	65	447	70
			average	**65**	**448**	
			std.dev.	**1**	**4**	
8084						
8084-c-10	0.125	0.997	8037	64	445	70
8084-c-11	0.123	0.998	7906	64	444	70
8084-c-12	0.125	0.989	8052	65	449	70
			average	**65**	**446**	
			std.dev.	**0**	**3**	

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
sc14						
sc14-c-10	0.119	0.994	7097	60	414	70
sc14-c-11	0.118	0.992	6893	59	406	70
sc14-c-12	0.118	0.991	7186	61	424	70
			average	**60**	**414**	
			std.dev.	**1**	**9**	
Iso-polyester						
tp-c-10	0.127	0.996	9066	72	494	70
tp-c-11	0.123	0.988	8813	73	500	70
tp-c-12	0.129	0.993	9182	72	494	70
			average	**72**	**496**	
			std.dev.	**0**	**3**	

Wet Specimens at 25C

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
polyester						
w-p-c-1	0.125	1.009	5980	47	326.90	25
w-p-c-2	0.127	0.997	6267	49	341.26	25
w-p-c-3	0.123	1.002	5975	48	334.26	25
			average	**48**	**334.14**	
			std.dev.	**1**	**7.18**	
411						
w-411-c-1	0.129	1.007	9770	75	518.55	25
w-411-c-2	0.125	1	9716	78	535.92	25
w-411-c-3	0.134	1.011	9981	74	507.97	25
			average	**76**	**520.81**	
			std.dev.	**2**	**14.11**	
8084						
w-8084-c-1	0.128	1.005	9720	76	520.97	25
w-8084-c-2	0.127	1.003	9081	71	491.53	25
w-8084-c-3	0.13	0.993	9604	74	512.95	25
			average	**74**	**508.48**	
			std.dev.	**2**	**15.22**	
sc14						
w-sc14-c-1	0.117	1.009	7774	66	454.03	25
w-sc14-c-2	0.121	1.012	8106	66	456.41	25
w-sc14-c-3	0.119	1.016	8099	67	461.86	25
			average	**66**	**457.44**	
			std.dev.	**1**	**4.01**	

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
Iso-polyester						
w-tp-c-1	0.127	0.993	10890	86	595.38	25
w-tp-c-2	0.13	0.996	10950	85	583.08	25
w-tp-c-3	0.133	0.994	10490	79	547.09	25
			average	**83**	**575.18**	
			std.dev.	**4**	**25.10**	
	Wet Specimens at 40C					
polyester						
w-p-c-4	0.124	1.01	5559	44	306.04	40
w-p-c-5	0.125	1.007	5611	45	307.34	40
w-p-c-6	0.126	1.001	5804	46	317.28	40
			average	**45**	**310.22**	
			std.dev.	**1**	**6.15**	
411						
w-411-c-4	0.129	1.006	9824	76	521.94	40
w-411-c-5	0.126	1.015	9532	75	513.89	40
w-411-c-6	0.133	1.007	9800	73	504.50	40
			average	**74**	**513.44**	
			std.dev.	**1**	**8.73**	
8084						
w-8084-c-4	0.126	1	8902	71	487.12	40
w-8084-c-5	0.125	0.99	9009	73	501.94	40
w-8084-c-6	0.13	1.009	8569	65	450.42	40
			average	**70**	**479.83**	
			std.dev.	**4**	**26.52**	
sc14						
w-sc14-c-4	0.119	1.014	7488	62	427.86	40
w-sc14-c-5	0.127	1.006	6197	49	334.43	40
w-sc14-c-6	0.122	1.01	7363	60	412.00	40
			average	**57**	**391.43**	
			std.dev.	**7**	**50.00**	
Iso-polyester						
w-tp-c-4	0.131	0.992	10070	77	534.28	40
w-tp-c-5	0.132	0.997	9447	72	494.93	40
w-tp-c-6	0.132	0.995	11050	84	580.08	40
			average	**78**	**536.43**	
			std.dev.	**6**	**42.61**	

Wet Specimens at 55C

sample	thickness	width	max load	UCS	UCS	Test Temp
polyester	(in)	(in)	(lbs)	(ksi)	(MPa)	(C)
w-p-c-10	0.126	1.011	4920	39	266.29	55
w-p-c-11	0.126	1.007	5100	40	277.13	55
w-p-c-12	0.122	0.964	4571	39	267.97	55
			average	**39**	**270.47**	
			std.dev.	**1**	**5.83**	
411						
w-411-c-10	0.125	1.011	9449	75	515.52	55
w-411-c-11	0.128	1.006	8905	69	476.81	55
w-411-c-12	0.127	1.006	9014	71	486.45	55
			average	**71**	**492.92**	
			std.dev.	**3**	**20.15**	
8084						
w-8084-c-10	0.127	0.975	7740	63	430.97	55
w-8084-c-11	0.129	1.002	8742	68	466.31	55
w-8084-c-12	0.133	1.005	9010	67	464.76	55
			average	**66**	**454.01**	
			std.dev.	**3**	**19.97**	
sc14						
w-sc14-c-10	0.126	1.005	5833	46	317.60	55
w-sc14-c-11	0.125	1.007	6776	54	371.15	55
w-sc14-c-12	0.124	1.013	6706	53	368.09	55
			average	**51**	**352.28**	
			std.dev.	**4**	**30.08**	
Iso-polyester						
w-tp-c-10	0.131	0.993	8973	69	475.59	55
w-tp-c-11	0.126	0.995	9344	75	513.88	55
w-tp-c-12	0.128	0.987	9873	78	538.82	55
			average	**74**	**509.43**	
			std.dev.	**5**	**31.85**	

Wet Specimens at 70C

polyester						
w-p-c-7	0.128	1.003	4477	35	240.43	70
w-p-c-8	0.123	1.003	4345	35	242.83	70
w-p-c-9	0.123	1.009	4368	35	242.66	70
			average	**35**	**241.98**	
			std.dev.	**0**	**1.34**	

sample	thickness (in)	width (in)	max load (lbs)	UCS (ksi)	UCS (MPa)	Test Temp (C)
411						
w-411-c-7	0.127	1.01	8470	66	455.28	70
w-411-c-8	0.125	1.01	8706	69	475.45	70
w-411-c-9	0.125	1.005	8995	72	493.68	70
			average	**69**	**474.80**	
			std.dev.	**3**	**19.21**	
8084						
w-8084-c-7	0.128	1.002	7692	60	413.50	70
w-8084-c-8	0.13	1.002	8226	63	435.41	70
w-8084-c-9	0.134	0.999	7524	56	387.52	70
			average	**60**	**412.15**	
			std.dev.	**3**	**23.97**	
sc14						
w-sc14-c-7	0.119	1.009	6530	54	374.97	70
w-sc14-c-8	0.125	1.005	5338	**42**	292.97	70
w-sc14-c-9	0.121	0.995	6102	51	349.45	70
			average	**49**	**339.13**	
			std.dev.	**6**	**41.96**	
Iso-polyester						
w-tp-c-7	0.129	0.993	8921	70	480.17	70
w-tp-c-8	0.127	0.994	9145	72	499.47	70
w-tp-c-9	0.124	0.985	9015	74	508.89	70
			average	**72**	**496.18**	
			std.dev.	**2**	**14.64**	

*UCS: Ultimate compression strength

Table A.2. 0 degree tension tests

Dry specimens at 25C

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
polyester						
p-t-1	0.125	1.098	9523	478.39	23.67	25
p-t-2	0.127	1.098	9895	489.25	23.41	25
p-t-3	0.125	1.076	9652	494.78	22.90	25
			average	**487.47**	**23.33**	
			std.dev.	**8.34**	**0.39**	
411						
411-t-1	0.126	0.999	10930	598.69	27.00	25
411-t-2	0.132	1	10050	524.94	25.60	25
411-t-3	0.123	0.998	11050	620.65	25.91	25
			average	**581.43**	**26.17**	
			std.dev.	**50.13**	**0.74**	
8084						
8084-t-1	0.125	0.988	12500	697.85	24.85	25
8084-t-2	0.125	0.986	12230	684.16	25.10	25
8084-t-3	0.125	1	9776	539.23	23.91	25
			average	**640.41**	**24.62**	
			std.dev.	**87.90**	**0.63**	
sc14						
sc14-t-1	0.113	0.991	11300	695.74	26.59	25
sc14-t-2	0.109	0.987	11350	727.40	28.01	25
sc14-t-3	0.122	0.978	11210	647.78	24.60	25
			average	**690.30**	**26.40**	
			std.dev.	**40.09**	**1.71**	
Iso-polyester						
tp-t-1	0.126	0.97	12310	694.44	24.89	25
tp-t-2	0.125	0.98	11580	651.77	23.77	25
tp-t-3	0.131	0.998	10560	556.90	23.92	25
			average	**634.37**	**24.19**	
			std.dev.	**70.40**	**0.61**	

Dry specimens at 40C

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
polyester						
p-t-15	0.125	1.093	9454	477.09	21.88	40
p-t-5	0.119	1.096	9783	517.17	22.66	40
p-t-6	0.12	1.095	9454	496.07	23.45	40
			average	**496.78**	**22.66**	
			std.dev.	**20.05**	**0.79**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
411						
411-t-4	0.125	0.996	9858	545.93	24.64	40
411-t-5	0.124	0.993	9247	517.78	25.38	40
411-t-6	0.124	0.997	10660	594.51	25.17	40
			average	**552.74**	**25.06**	
			std.dev.	**38.81**	**0.38**	
8084						
8084-t-4	0.131	1.125	10260	480.00	22.85	40
8084-t-5	0.126	1	8607	470.98	24.00	40
8084-t-6	0.123	0.995	9761	549.90	24.36	40
			average	**500.29**	**23.74**	
			std.dev.	**43.20**	**0.79**	
sc14						
sc14-t-4	0.118	0.991	9512	560.84	25.10	40
sc14-t-5	0.118	0.987	10180	602.65	25.32	40
sc14-t-6	0.119	0.988	9748	571.65	25.77	40
			average	**578.38**	**25.40**	
			std.dev.	**21.71**	**0.34**	
Iso-polyester						
tp-t-4	0.129	0.993	12180	655.58	23.94	40
tp-t-5	0.13	0.978	10650	577.55	25.34	40
tp-t-6	0.125	1.003	11750	646.17	25.00	40
			average	**626.43**	**24.76**	
			std.dev.	**42.60**	**0.73**	
	Dry	**specimen**	**at**	**55C**		
polyester						
p-t-7	0.12	1.097	8785	460.12	22.04	55
p-t-8	0.12	1.087	9116	481.85	23.49	55
p-t-9	0.119	1.088	9338	497.28	23.90	55
			average	**479.75**	**23.14**	
			std.dev.	**18.67**	**0.98**	
411						
411-t-7	0.124	0.996	9784	546.20	25.61	55
411-t-8	0.124	0.985	9886	558.06	25.43	55
411-t-9	0.124	0.995	10050	561.62	24.45	55
			average	**555.29**	**25.16**	
			std.dev.	**8.07**	**0.62**	

8084	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
8084-t-7	0.124	0.999	9557	531.93	24.38	55
8084-t-8	0.126	0.986	11820	655.98	23.61	55
8084-t-9	0.125	0.959	10230	588.39	24.14	55
			average	**592.10**	**24.04**	
			std.dev.	**62.11**	**0.39**	
sc14						
sc14-t-7	0.119	0.986	9938	583.97	24.21	55
sc14-t-8	0.118	0.98	9197	548.35	26.97	55
sc14-t-9	0.122	0.982	10050	578.38	23.50	55
			average	**570.23**	**24.89**	
			std.dev.	**19.16**	**1.83**	
Iso-polyester						
tp-t-7	0.133	0.994	12060	628.97	23.83	55
tp-t-8	0.134	0.975	11500	606.89	23.99	55
tp-t-9	0.131	0.995	12470	659.62	24.22	55
			average	**631.82**	**24.01**	
			std.dev.	**26.48**	**0.20**	
		Dry specimens at 70C				
polyester						
p-t-10	0.121	1.096	8118	422.06	19.85	70
p-t-11	0.12	1.093	8216	431.89	22.19	70
p-t-12	0.123	1.095	7870	402.88	20.54	70
			average	**418.94**	**20.86**	
			std.dev.	**14.76**	**1.20**	
411						
411-t-10	0.124	1.001	8341	463.32	30.01	70
411-t-11	0.124	1	9682	538.35	27.85	70
411-t-12	0.125	0.998	9079	501.78	23.19	70
			average	**501.15**	**27.02**	
			std.dev.	**37.52**	**3.49**	
8084						
8084-t-10	0.125	0.987	9958	556.50	23.49	70
8084-t-11	0.128	0.983	9789	536.41	22.49	70
8084-t-12	0.125	0.988	9851	549.96	22.26	70
			average	**547.62**	**22.75**	
			std.dev.	**10.25**	**0.65**	

sc14	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
sc14-t-10	0.119	0.97	9537	569.66	23.52	70
sc14-t-11	0.119	0.995	9770	568.91	23.43	70
sc14-t-12	0.117	0.99	10000	595.25	24.78	70
			average	**577.94**	**23.91**	
			std.dev.	**15.00**	**0.75**	
Iso-polyester						
tp-t-10	0.132	0.992	11420	601.31	24.18	70
tp-t-11	0.132	0.992	10050	529.18	23.50	70
tp-t-12	0.133	0.991	11490	601.05	23.02	70
			average	**577.18**	**23.57**	
			std.dev.	**41.57**	**0.58**	
	Wet Specimens at 25C					
polyester						
w-p-t-1	0.13	0.985	8064	434.20	20.29	25
w-p-t-2	0.125	0.984	7862	440.70	21.18	25
w-p-t-3	0.123	0.991	8052	455.45	23.01	25
			average	**443.45**	**21.49**	
			std.dev.	**10.89**	**1.39**	
411						
w-411-t-1	0.124	1.001	8006	444.71	24.29	25
w-411-t-2	0.125	0.998	7971	440.55	25.89	25
w-411-t-3	0.125	1	7558	416.88	23.28	25
			average	**434.05**	**24.49**	
			std.dev.	**15.01**	**1.32**	
8084						
w-8084-t-1	0.124	0.991	8218	461.09	25.57	25
w-8084-t-2	0.125	0.995	8359	463.38	25.11	25
w-8084-t-3	0.125	0.997	8532	472.02	24.26	25
			average	**465.50**	**24.98**	
			std.dev.	**5.76**	**0.66**	
sc14						
w-sc14-t-1	0.121	0.999	9970	568.67	25.02	25
w-sc14-t-2	0.122	1.002	7752	437.23	23.91	25
w-sc14-t-3	0.118	1	7767	453.83	24.32	25
			average	**486.58**	**24.42**	
			std.dev.	**71.58**	**0.56**	

sample **Iso-polyester**	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
w-tp-t-1	0.129	0.993	10820	582.38	26.60	25
w-tp-t-2	0.129	0.981	11660	635.27	24.05	25
w-tp-t-3	0.129	1.003	9970	531.28	25.48	25
			average	**582.98**	**25.38**	
			std.dev.	**52.00**	**1.28**	

Wet Specimens at 40C

polyester						
w-p-t-4	0.122	0.987	7751	443.81	20.60	40
w-p-t-5	0.123	0.993	7822	441.55	22.72	40
w-p-t-6	0.128	0.993	7579	411.12	20.15	40
			average	**432.16**	**21.16**	
			std.dev.	**18.26**	**1.37**	
411						
w-411-t-4	0.125	0.998	7481	413.46	25.92	40
w-411-t-5	0.124	1	7813	434.43	25.04	40
w-411-t-6	0.128	0.998	7579	409.06	26.25	40
			average	**418.98**	**25.74**	
			std.dev.	**13.55**	**0.63**	
8084						
w-8084-t-4	0.128	1	8229	443.26	24.57	40
w-8084-t-5	0.127	1.001	8020	434.97	23.58	40
w-8084-t-6	0.126	0.995	7931	436.17	24.80	40
			average	**438.13**	**24.32**	
			std.dev.	**4.48**	**0.65**	
sc14						
w-sc14-t-4	0.122	0.998	7520	425.84	23.56	40
w-sc14-t-5	0.117	1	7270	428.42	25.35	40
w-sc14-t-6	0.12	0.999	7549	434.17	23.31	40
			average	**429.48**	**24.07**	
			std.dev.	**4.27**	**1.11**	
Iso-polyester						
w-tp-t-4	0.127	0.99	11270	618.02	24.98	40
w-tp-t-5	0.126	0.987	10530	583.79	24.98	40
w-tp-t-6	0.124	0.99	11190	628.48	24.95	40
			average	**610.10**	**24.97**	
			std.dev.	**23.37**	**0.02**	

Wet Specimens at 55C

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
polyester						
w-p-t-7	0.124	0.99	7284	409.10	22.15	55
w-p-t-8	0.121	0.991	6729	386.91	22.48	55
w-p-t-9	0.125	0.992	7215	401.17	20.76	55
			average	**399.06**	**21.80**	
			std.dev.	**11.25**	**0.91**	
411						
w-411-t-7	0.123	1	7223	404.88	25.85	55
w-411-t-8	0.122	0.998	6782	384.05	25.13	55
w-411-t-9	0.125	0.999	6940	383.18	23.88	55
			average	**390.70**	**24.95**	
			std.dev.	**12.29**	**1.00**	
8084						
w-8084-t-7	0.125	0.998	7648	422.69	23.87	55
w-8084-t-8	0.123	0.997	7450	419.19	24.85	55
w-8084-t-9	0.127	1	7610	413.14	26.22	55
			average	**418.34**	**24.98**	
			std.dev.	**4.83**	**1.18**	
sc14						
w-sc14-t-7	0.119	1.002	6850	395.83	23.49	55
w-sc14-t-8	0.12	0.995	6990	403.92	25.48	55
w-sc14-t-9	0.12	1	7095	407.65	23.78	55
			average	**402.47**	**24.25**	
			std.dev.	**6.04**	**1.08**	
Iso-polyester						
w-tp-t-7	0.126	0.972	10810	608.57	24.94	55
w-tp-t-8	0.124	0.99	10660	598.71	25.22	55
w-tp-t-9	0.127	0.985	11220	618.40	25.00	55
				average	**608.56**	**25.05**
				std.dev.	**9.84**	**0.15**
		Wet Specimens at 70C				
polyester						
w-p-t-10	0.119	0.988	6649	389.92	21.37	70
w-p-t-11	0.118	0.994	6675	392.38	21.33	70
w-p-t-12	0.124	0.996	6866	383.30	21.08	70
			average	**388.53**	**21.26**	
			std.dev.	**4.69**	**0.16**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp (C)
411						
w-411-t-10	0.122	0.995	6662	378.39	25.46	70
w-411-t-11	0.123	0.994	6756	380.99	26.38	70
w-411-t-12	0.127	1.003	7028	380.40	24.07	70
			average	**379.93**	**25.30**	
			std.dev.	**1.36**	**1.16**	
8084						
w-8084-t-10	0.125	1	6869	378.88	23.84	70
w-8084-t-11	0.123	0.997	7069	397.44	24.22	70
w-8084-t-12	0.124	0.994	7027	393.08	24.43	70
			average	**389.80**	**24.16**	
			std.dev.	**9.71**	**0.30**	
sc14						
w-sc14-t-10	0.123	1	6451	361.61	22.07	70
w-sc14-t-11	0.12	0.997	6098	351.42	21.79	70
w-sc14-t-12	0.125	0.997	6447	356.67	23.06	70
			average	**356.57**	**22.31**	
			std.dev.	**5.09**	**0.67**	
Iso-polyester						
w-tp-t-10	0.129	0.994	10350	556.52	22.80	70
w-tp-t-11	0.126	0.995	10060	553.25	24.44	70
w-tp-t-12	0.127	0.988	9837	540.53	22.95	70
			average	**550.10**	**23.40**	
			std.dev.	**8.45**	**0.91**	

*UTS: Ultimate Tensile Strength

Table A.3 45 degree tensile tests

	Dry Specimens at 25C					
sample	thickness	width	max load	UTS	Tensile E	Test Temp.
polyester	(in)	(in)	(lbs)	(MPa)	(GPa)	(C)
p-45t-1	0.132	1.041	2209	110.84	10.20	25
p-45t-2	0.126	1.021	2148	115.12	11.32	25
p-45t-3	0.12	1.035	1993	110.64	11.27	25
			average	**112.20**	**10.93**	
			std.dev.	**2.53**	**0.63**	
411						
411-45t-1	0.122	1.064	2632	139.80	11.01	25
411-45t-2	0.121	1.063	2475	132.67	10.83	25
411-45t-3	0.126	1.055	2499	129.62	10.91	25
			average	**134.03**	**10.92**	
			std.dev.	**5.22**	**0.09**	
8084						
8084-45t-1	0.122	1.057	2291	122.49	9.72	25
8084-45t-2	0.124	1.028	2478	134.03	10.35	25
8084-45t-3	0.122	1.061	2347	125.01	10.77	25
			average	**127.18**	**10.28**	
			std.dev.	**6.07**	**0.53**	
sc14						
sc14-45t-1	0.121	0.991	1600	92.00	9.56	25
sc14-45t-2	0.119	0.979	1480	87.59	9.16	25
sc14-45t-3	0.121	0.985	1602	92.67	8.81	25
			average	**90.75**	**9.18**	
			std.dev.	**2.76**	**0.38**	
Iso-polyester						
tp-45t-1	0.124	0.996	2387	133.26	11.52	25
tp-45t-2	0.123	0.997	2396	134.71	12.32	25
tp-45t-3	0.127	0.996	2413	131.53	11.15	25
			average	**133.17**	**11.66**	
			std.dev.	**1.59**	**0.60**	
	Dry Specimens at 40C					
Ortho-polyester						
p-45t-4	0.119	1.043	1937	107.60	8.94	40
p-45t-5	0.118	1.045	1883	105.29	10.05	40
p-45t-6	0.117	1.044	1916	108.15	9.20	40
			average	**107.01**	**9.40**	
			std.dev.	**1.52**	**0.58**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
411						
411-45t-4	0.125	1.063	2341	121.47	10.54	40
411-45t-5	0.12	1.054	2225	121.29	10.61	40
411-45t-6	0.125	1.048	2343	123.32	9.77	40
			average	**122.03**	**10.31**	
			std.dev.	**1.12**	**0.47**	
8084						
8084-45t-4	0.123	1.062	2230	117.70	9.02	40
8084-45t-5	0.122	1.061	2197	117.02	9.59	40
8084-45t-6	0.123	1.063	2198	115.91	9.26	40
			average	**116.88**	**9.29**	
			std.dev.	**0.91**	**0.29**	
sc14						
sc14-45t-4	0.121	0.984	1483	85.88	8.55	40
sc14-45t-5	0.126	0.996	1529	84.00	7.39	40
sc14-45t-6	0.119	0.987	1449	85.06	7.74	40
			average	**84.98**	**7.89**	
			std.dev.	**0.94**	**0.60**	
Iso-polyester						
tp-45t-4	0.132	0.997	2372	124.27	11.52	40
tp-45t-5	0.125	1.002	2303	126.78	10.70	40
tp-45t-6	0.126	0.997	2327	127.72	10.04	40
			average	**126.25**	**10.75**	
			std.dev.	**1.78**	**0.74**	
	Dry Specimens at 55C					
polyester						
p-45t-7	0.118	1.043	1633	91.48	7.64	55
p-45t-8	0.118	1.024	1583	90.33	7.69	55
p-45t-9	0.119	1.043	1600	88.88	7.32	55
			average	**90.23**	**7.55**	
			std.dev.	**1.30**	**0.20**	
411						
411-45t-7	0.12	1.057	2059	111.92	9.83	55
411-45t-8	0.127	1.055	2255	116.04	9.60	55
411-45t-9	0.12	1.058	2156	117.08	10.03	55
			average	**115.02**	**9.82**	
			std.dev.	**2.73**	**0.22**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
8084						
8084-45t-7	0.124	1.059	2145	112.62	8.69	55
8084-45t-8	0.126	1.056	2192	113.59	8.63	55
8084-45t-9	0.125	1.062	2170	112.71	8.45	55
			average	**112.97**	**8.59**	
			std.dev.	**0.53**	**0.12**	
sc14						
sc14-45t-7	0.12	0.986	1299	75.70	6.40	55
sc14-45t-8	0.121	0.987	1384	79.90	7.06	55
sc14-45t-9	0.12	0.989	1285	74.65	6.90	55
			average	**76.75**	**6.79**	
			std.dev.	**2.78**	**0.34**	
Iso-polyester						
tp-45t-7	0.126	0.994	2103	115.77	10.07	55
tp-45t-8	0.126	0.99	2100	115.98	10.17	55
tp-45t-9	0.125	0.968	1998	113.85	9.97	55
			average	**115.20**	**10.07**	
			std.dev.	**1.17**	**0.10**	
	Dry Specimens at 70C					
polyester						
p-45t-10	0.119	1.038	1304	72.79	5.06	70
p-45t-11	0.121	1.037	1318	72.42	4.91	70
p-45t-12	0.123	1.039	1352	72.94	5.43	70
			average	**72.72**	**5.13**	
			std.dev.	**0.27**	**0.27**	
411						
411-45t-10	0.121	1.061	1920	103.11	9.69	70
411-45t-11	0.122	1.059	1870	99.79	8.45	70
411-45t-12	0.122	1.055	1871	100.23	8.93	70
			average	**101.04**	**9.02**	
			std.dev.	**1.81**	**0.63**	
8084						
8084-45t-10	0.125	1.054	1919	100.43	7.41	70
8084-45t-11	0.124	1.062	1985	103.93	7.84	70
8084-45t-12	0.126	1.057	1984	102.71	7.30	70
			average	**102.35**	**7.52**	
			std.dev.	**1.78**	**0.29**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
sc14						
sc14-45t-10	0.12	0.985	1101	64.22	6.40	70
sc14-45t-11	0.124	0.987	1307	73.63	6.71	70
sc14-45t-12	0.12	0.983	1110	64.88	5.67	70
			average	**67.58**	**6.26**	
			std.dev.	**5.25**	**0.53**	
Iso-polyester						
tp-45t-10	0.127	0.992	1703	93.20	8.89	70
tp-45t-11	0.125	0.993	1678	93.21	9.58	70
tp-45t-12	0.13	1	1879	99.66	8.84	70
			average	**95.35**	**9.10**	
			std.dev.	**3.72**	**0.41**	
	Wet Specimens at 25C					
polyester						
w-p-45t-1	0.131	1.045	1306	65.78	7.55	25
w-p-45t-2	0.127	1.048	1340	69.42	7.66	25
w-p-45t-3	0.126	1.052	1281	66.63	7.52	25
			average	**67.27**	**7.58**	
			std.dev.	**1.90**	**0.07**	
411						
w-411-45t-1	0.121	1.053	2497	135.12	11.38	25
w-411-45t-2	0.121	1.052	2491	134.92	11.36	25
w-411-45t-3	0.129	1.056	2633	133.27	10.17	25
			average	**134.44**	**10.97**	
			std.dev.	**1.02**	**0.69**	
8084						
w-8084-45t-1	0.121	1.062	2137	114.66	10.31	25
w-8084-45t-2	0.121	1.061	2139	114.88	10.08	25
w-8084-45t-3	0.122	1.052	2156	115.82	10.33	25
			average	**115.12**	**10.24**	
			std.dev.	**0.62**	**0.14**	
sc14						
w-sc14-45t-1	0.119	1.062	1706	93.07	8.10	25
w-sc14-45t-2	0.118	1.06	1476	81.36	7.83	25
w-sc14-45t-3	0.119	1.063	1632	88.95	8.20	25
			average	**87.80**	**8.04**	
			std.dev.	**5.94**	**0.19**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
Iso-polyester						
w-tp-45t-1	0.126	0.989	2373	131.30	11.93	25
w-tp-45t-2	0.126	0.981	2247	125.34	12.00	25
w-tp-45t-3	0.13	0.99	2467	132.16	12.11	25
			average	**129.6**	**12.01**	
			std.dev.	**3.72**	**0.09**	
	Wet Specimens at 40C					
polyester						
w-p-45t-4	0.124	1.044	1286	68.49	6.13	40
w-p-45t-5	0.122	1.05	1286	69.22	7.12	40
w-p-45t-6	0.121	1.049	1190	64.64	6.24	40
			average	**67.45**	**6.50**	
			std.dev.	**2.46**	**0.54**	
411						
w-411-45t-4	0.121	1.052	2380	128.91		40
w-411-45t-5	0.123	1.046	2336	125.19	9.72	40
w-411-45t-6	0.126	1.055	2448	126.97	9.48	40
			average	**127.02**	**9.60**	
			std.dev.	**1.86**	**0.17**	
8084						
w-8084-45t-4	0.124	1.059	2051	107.69	9.57	40
w-8084-45t-5	0.121	1.064	2084	111.61	10.13	40
w-8084-45t-6	0.122	1.057	2064	110.36	9.66	40
			average	**109.88**	**9.79**	
			std.dev.	**2.00**	**0.30**	
sc14						
w-sc14-45t-4	0.12	1.042	1523	83.98	7.19	40
w-sc14-45t-5	0.12	1.063	1363	73.67	6.79	40
w-sc14-45t-6	0.12	1.062	1393	75.36	6.52	40
			average	**77.67**	**6.83**	
			std.dev.	**5.53**	**0.34**	
Iso-polyester						
w-tp-45t-4	0.126	0.997	2254	123.71	11.26	40
w-tp-45t-5	0.125	0.998	2271	125.51	10.78	40
w-tp-45t-6	0.125	0.984	2182	122.31	10.47	40
			average	**123.85**	**10.84**	
			std.dev.	**1.61**	**0.40**	

	Wet Specimens at 55C					
sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
polyester						
w-p-45t-7	0.12	1.043	1066	58.72	5.36	55
w-p-45t-8	0.12	1.051	1090	59.59	5.10	55
w-p-45t-9	0.123	1.043	1138	61.16	5.52	55
			average	**59.82**	**5.33**	
			std.dev.	**1.24**	**0.21**	
411						
w-411-45t-7	0.125	0.971	1943	110.37	9.01	55
w-411-45t-8	0.129	1.053	2340	118.77	9.15	55
w-411-45t-9	0.12	1.046	2194	120.52	10.30	55
			average	**116.55**	**9.49**	
			std.dev.	**5.42**	**0.71**	
8084						
w-8084-45t-7	0.122	1.057	1914	102.34	9.06	55
w-8084-45t-8	0.122	1.054	1905	102.14	9.41	55
w-8084-45t-9	0.122	1.056	1879	100.56	9.38	55
			average	**101.68**	**9.28**	
			std.dev.	**0.97**	**0.19**	
sc14						
w-sc14-45t-7	0.119	1.058	1212	66.37	6.05	55
w-sc14-45t-8	0.119	1.059	1235	67.57	5.95	55
w-sc14-45t-9	0.119	1.065	1195	65.01	5.65	55
			average	**66.32**	**5.88**	
			std.dev.	**1.28**	**0.21**	
Iso-polyester						
w-tp-45t-7	0.125	0.995	2061	114.25	9.98	55
w-tp-45t-8	0.123	0.996	1900	107.13	9.94	55
w-tp-45t-9	0.126	0.996	2010	110.43	9.24	55
			average	**110.60**	**9.72**	
			std.dev.	**3.56**	**0.42**	
	Wet Specimens at 70C					
polyester						
w-p-45t-10	0.122	1.043	803.6	43.54	3.03	70
w-p-45t-11	0.122	1.042	831.5	45.10	3.27	70
w-p-45t-12	0.121	1.043	846.2	46.23	3.03	70
			average	**44.96**	**3.11**	
			std.dev.	**1.35**	**0.14**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
411						
w-411-45t-10	0.12	1.052	2021	110.38	9.18	70
w-411-45t-11	0.123	1.054	2113	112.38	9.21	70
w-411-45t-12	0.123	1.052	2100	111.90	9.34	70
			average	**111.55**	**9.24**	
			std.dev.	**1.04**	**0.09**	
8084						
w-8084-45t-10	0.122	0.985	1656	95.01	8.00	70
w-8084-45t-11	0.127	0.997	1612	87.78	7.33	70
w-8084-45t-12	0.124	0.987	1671	94.14	7.82	70
			average	**92.31**	**7.72**	
			std.dev.	**3.95**	**0.35**	
sc14						
w-sc14-45t-10	0.12	1.06	1015	55.02	4.02	70
w-sc14-45t-11	0.121	1.06	965.2	51.89	3.82	70
w-sc14-45t-12	0.124	1.061	943.7	49.46	3.54	70
			average	**52.12**	**3.79**	
			std.dev.	**2.79**	**0.24**	
Iso-polyester						
w-tp-45t-10	0.126	0.987	1710	94.80	7.68	70
w-tp-45t-11	0.126	0.998	1766	96.83	7.45	70
w-tp-45t-12	0.125	0.994	1845	102.38	8.85	70
			average	**98.00**	**7.99**	
			std.dev.	**3.92**	**0.75**	

Table A.4. 90 degree tensile tests

	Dry Specimens at 25C					
sample	thickness	width	max load	UTS	Tensile E	Test Temp.
polyester	(in)	(in)	(lbs)	(MPa)	(GPa)	(C)
p-tt-1	0.127	1.04	1507	78.67	8.93	25
p-tt-2	0.122	1.04	1381	75.04	9.63	25
p-tt-3	0.122	1.042	1263	68.50	9.25	25
			average	**74.07**	**9.27**	
			std.dev.	**5.15**	**0.35**	
411						
411-tt-1	0.132	1.015	1106	56.92	11.08	25
411-tt-2	0.132	1.021	1098	56.17	11.73	25
411-tt-3	0.127	1.021	1031	54.82	12.39	25
			average	**55.97**	**11.73**	
			std.dev.	**1.06**	**0.65**	
8084						
8084-tt-1	0.127	0.987	1446	79.54	12.78	25
8084-tt-2	0.127	0.991	1512	82.83	12.34	25
8084-tt-3	0.128	0.99	1507	81.99	13.00	25
			average	**81.45**	**12.71**	
			std.dev.	**1.71**	**0.33**	
sc14						
sc14-tt-14	0.122	1.036	1588	86.63	9.05	25
sc14-tt-2	0.117	1.039	1630	92.45	9.48	25
sc14-tt-3	0.117	1.039	1618	91.77	8.84	25
			average	**90.28**	**9.12**	
			std.dev.	**3.18**	**0.33**	
Iso-polyester						
tp-tt-1	0.125	0.984	1209	67.77	9.15	25
tp-tt-2	0.125	0.982	1217	68.36	9.00	25
tp-tt-3	0.125	0.988	1160	64.76	9.25	25
			average	**66.96**	**9.13**	
			std.dev.	**1.93**	**0.13**	
	Dry Specimens at 40C					
polyester						
p-tt-4	0.122	1.025	1559	85.96	8.31	40
p-tt-5	0.122	1.04	1559	84.72	8.78	40
p-tt-6	0.123	1.036	1572	85.06	8.27	40
			average	**85.24**	**8.45**	
			std.dev.	**0.64**	**0.28**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
411						
411-tt-4	0.124	1.015	1122	61.46	10.88	40
411-tt-5	0.126	1.017	1158	62.31	10.34	40
411-tt-6	0.127	1.013	1181	63.29	10.84	40
			average	**62.35**	**10.69**	
			std.dev.	**0.92**	**0.30**	
8084						
8084-tt-4	0.129	0.993	1620	87.20	10.99	40
8084-tt-5	0.128	0.985	1511	82.63	10.68	40
8084-tt-13	0.125	0.997	1131	62.57	10.38	40
			average	**77.47**	**10.68**	
			std.dev.	**13.10**	**0.30**	
sc14						
sc14-tt-4	0.12	1.035	1748	97.04	8.67	40
sc14-tt-5	0.119	1.038	1607	89.70	8.43	40
sc14-tt-6	0.12	1.038	1664	92.11	8.20	40
			average	**92.95**	**8.43**	
			std.dev.	**3.74**	**0.24**	
Iso-polyester						
tp-tt-4	0.126	0.981	1286	71.73	8.31	40
tp-tt-5	0.126	0.941	1178	68.50	8.78	40
tp-tt-6	0.127	0.984	1235	68.14	8.27	40
			average	**69.46**	**8.45**	
			std.dev.	**1.98**	**0.28**	
	Dry Specimens at 55C					
polyester						
p-tt-7	0.122	1.041	1549	84.09	6.05	55
p-tt-8	0.118	1.041	1496	83.97	5.99	55
p-tt-9	0.119	1.036	1450	81.09	6.34	55
			average	**83.05**	**6.13**	
			std.dev.	**1.70**	**0.19**	
411						
411-tt-7	0.126	1.012	1169	63.21	6.85	55
411-tt-8	0.125	1.013	1129	61.47	7.12	55
411-tt-9	0.127	1.013	1147	61.47	7.30	55
			average	**62.05**	**7.09**	
			std.dev.	**1.00**	**0.23**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
8084						
8084-tt-7	0.127	0.991	1469	80.48	8.32	55
8084-tt-8	0.127	0.983	1618	89.36	8.24	55
8084-tt-9	0.127	0.979	1499	83.13	7.89	55
			average	**84.32**	**8.15**	
			std.dev.	**4.56**	**0.23**	
sc14						
sc14-tt-7	0.122	1.038	1715	93.37	7.92	55
sc14-t-8	0.122	1.034	1704	93.13	7.57	55
sc14-t-9	0.122	1.031	1610	88.25	7.70	55
			average	**91.59**	**7.73**	
			std.dev.	**2.89**	**0.18**	
Iso-polyester						
tp-tt-7	0.126	0.993	1169	64.42	7.66	55
tp-tt-8	0.125	0.994	1259	69.86	7.92	55
tp-tt-9	0.125	0.987	1232	68.85	7.91	55
			average	**67.71**	**7.83**	
			std.dev.	**2.90**	**0.15**	
	Dry Specimens at 70C					
polyester						
p-tt-10	0.119	1.042	1274	70.84	4.73	70
p-tt-11	0.122	1.102	1409	72.26	5.32	70
p-tt-12	0.12	1.084	1332	70.60	3.76	70
			average	**71.23**	**4.60**	
			std.dev.	**0.90**	**0.79**	
411						
411-tt-10	0.131	1.025	1176	60.39	6.64	70
411-tt-11	0.13	1	991.4	52.58	6.04	70
411-tt-12	0.127	1.003	1042	56.40	6.35	70
			average	**56.46**	**6.34**	
			std.dev.	**3.90**	**0.30**	
8084						
8084-tt-10	0.125	0.987	1044	58.34	6.18	70
8084-tt-11	0.126	1	1084	59.32	6.18	70
8084-tt-12	0.125	1.006	1051	57.63	6.18	70
			average	**58.43**	**6.18**	
			std.dev.	**0.85**	**0.00**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
sc14						
sc14-tt-10	0.117	1.022	1739	100.27	7.62	70
sc14-tt-11	0.117	1.039	1646	93.36	7.41	70
sc14-tt-12	0.116	1.035	1569	90.10	7.63	70
			average	**94.58**	**7.55**	
			std.dev.	**5.19**	**0.12**	
Iso-polyester						
tp-tt-10	0.125	0.982	1230	69.09	7.41	70
tp-tt-11	0.126	1	1310	71.68	7.20	70
tp-tt-12	0.127	1.002	1298	70.33	7.38	70
			average	**70.37**	**7.33**	
			std.dev.	**1.30**	**0.11**	
	Wet Specimens at 25C					
polyester						
w-p-tt-1	0.118	1.04	1003	56.35	7.27	25
w-p-tt-2	0.12	1.029	999	55.78	7.06	25
w-p-tt-3	0.117	1.039	992.9	56.31	6.98	25
			average	**56.15**	**7.10**	
			std.dev.	**0.32**	**0.15**	
411						
w-411-tt-1	0.126	1.022	954.6	51.11	8.56	25
w-411-tt-2	0.13	1.026	994.3	51.40	8.17	25
w-411-tt-3	0.127	1.018	953.9	50.87	8.54	25
			average	**51.13**	**8.42**	
			std.dev.	**0.26**	**0.22**	
8084						
w-8084-tt-1	0.124	1.012	864.5	47.50	8.42	25
w-8084-tt-2	0.125	1.01	887	48.44	8.47	25
w-8084-tt-3	0.125	1.006	901.9	49.45	8.26	25
			average	**48.46**	**8.38**	
			std.dev.	**0.98**	**0.11**	
sc14						
w-sc14-tt-1	0.128	1.033	1462	76.24	8.63	25
w-sc14-tt-2	0.119	1.026	1241	70.08	8.24	25
w-sc14-tt-3	0.117	1.03	1221	69.86	7.84	25
			average	**72.06**	**8.24**	
			std.dev.	**3.62**	**0.40**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
Iso-polyester						
w-tp-tt-1	0.127	0.998	1191	64.79	9.40	25
w-tp-tt-2	0.126	0.997	1254	68.83	9.67	25
w-tp-tt-3	0.127	0.999	1225	66.57	9.10	25
			average	**66.73**	**9.39**	
			std.dev.	**2.02**	**0.29**	
	Wet Specimens at 40C					
polyester						
w-p-tt-4	0.121	1.038	1078	59.18	6.06	40
w-p-tt-5	0.118	1.036	1037	58.49	6.15	40
w-p-tt-6	0.118	1.034	1047	59.16	5.81	40
			average	**58.94**	**6.01**	
			std.dev.	**0.40**	**0.18**	
411						
w-411-tt-4	0.127	1.02	1052	55.99	8.52	40
w-411-tt-5	0.126	1.021	1036	55.52	8.17	40
w-411-tt-6	0.127	1.019	955.8	50.92	8.37	40
			average	**54.15**	**8.35**	
			std.dev.	**2.80**	**0.18**	
8084						
w-8084-tt-4	0.124	0.998	921.1	51.32	8.29	40
w-8084-tt-5	0.126	1.012	916.2	49.54	7.38	40
w-8084-tt-6	0.125	1.011	910.8	49.69	7.95	40
			average	**50.18**	**7.87**	
			std.dev.	**0.99**	**0.46**	
sc14						
w-sc14-tt-4	0.121	1.022	1325	73.88	7.48	40
w-sc14-tt-5	0.12	1.022	1214	68.25	7.13	40
w-sc14-tt-6	0.118	1.027	1351	76.86	7.13	40
			average	**73.00**	**7.25**	
			std.dev.	**4.37**	**0.20**	
Iso-polyester						
w-tp-tt-4	0.127	0.997	1223	66.60	8.98	40
w-tp-tt-5	0.127	0.979	1245	69.04	9.06	40
w-tp-tt-6	0.124	0.994	1265	70.76	8.98	40
			average	**68.80**	**9.01**	
			std.dev.	**2.09**	**0.05**	

Wet Specimens at 55C

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
polyester						
w-p-tt-7	0.118	1.032	937.6	53.09	5.41	55
w-p-tt-8	0.117	1.03	947.4	54.20	5.41	55
w-p-tt-9	0.121	1.038	979.5	53.77	5.41	55
			average	**53.69**	**5.41**	
			std.dev.	**0.56**	**0.00**	
411						
w-411-tt-7	0.13	1.024	935.3	48.44	8.08	55
w-411-tt-8	0.129	1.025	998.5	52.07	7.92	55
w-411-tt-9	0.126	1.017	967.8	52.07	8.23	55
			average	**50.86**	**8.08**	
			std.dev.	**2.09**	**0.16**	
8084						
w-8084-tt-7	0.125	1.011	901.3	49.17	7.29	55
w-8084-tt-8	0.125	1	961.9	53.06	7.28	55
w-8084-tt-9	0.125	1.005	832.1	45.67	7.39	55
			average	**49.30**	**7.32**	
			std.dev.	**3.70**	**0.06**	
sc14						
w-sc14-tt-7	0.123	1.032	1253	68.06	6.33	55
w-sc14-tt-8	0.119	1.032	1178	66.14	6.83	55
w-sc14-tt-9	0.121	1.036	1293	71.12	6.25	55
			average	**68.44**	**6.47**	
			std.dev.	**2.51**	**0.31**	
Iso-polyester						
w-tp-tt-7	0.124	0.994	1214	67.91	8.51	55
w-tp-tt-8	0.125	0.992	1193	66.33	8.86	55
w-tp-tt-9	0.127	1.003	1138	61.60	8.43	55
			average	**65.28**	**8.60**	
			std.dev.	**3.29**	**0.23**	

Wet Specimens at 70C

polyester						
w-p-tt-10	0.12	1.026	842.8	47.20	3.83	70
w-p-tt-11	0.117	1.031	848	48.47	3.73	70
w-p-tt-12	0.123	1.042	946.8	50.93	3.38	70
			average	**48.87**	**3.65**	
			std.dev.	**1.90**	**0.24**	

sample	thickness (in)	width (in)	max load (lbs)	UTS (MPa)	Tensile E (GPa)	Test Temp. (C)
411						
w-411-tt-10	0.129	1.021	1005	52.61	7.29	70
w-411-tt-11	0.128	1.016	980.1	51.96	7.48	70
w-411-tt-12	0.129	1.023	958.7	50.09	7.19	70
			average	**51.55**	**7.32**	
			std.dev.	**1.31**	**0.15**	
8084						
w-8084-tt-10	0.125	1.012	979.8	53.40	6.62	70
w-8084-tt-11	0.125	1.009	937.4	51.24	7.03	70
w-8084-tt-12	0.125	1.01	951.3	51.95	6.83	70
			average	**52.20**	**6.83**	
			std.dev.	**1.10**	**0.21**	
sc14						
w-sc14-tt-10	0.12	1.034	1202	66.79	5.17	70
w-sc14-tt-11	0.118	1.031	1187	67.27	5.10	70
w-sc14-tt-12	0.119	1.033	1256	70.45	5.47	70
			average	**68.17**	**5.25**	
			std.dev.	**1.99**	**0.20**	
Iso-polyester						
w-tp-tt-10	0.126	0.996	1175	64.55	7.64	70
w-tp-tt-11	0.127	1	1219	66.18	7.55	70
w-tp-tt-12	0.126	1	1238	67.74	7.12	70
			average	**66.16**	**7.44**	
			std.dev.	**1.59**	**0.28**	

Table A.5. DCB tests

Layup: $[0]_6$

DRY SAMPLE TESTED AT 50C, DRY

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
Ortho-polyester							
1-D	1.0048	0.139	1.124				
			1.592	10	0.113	262.83	
			2.007	10.4	0.260	444.05	
			2.452	8.25	0.434	466.4	
2-D	0.9955	0.130	1.072				
			1.44	11.8	0.119	345.65	
			1.919	12.8	0.241	565.29	
			2.258	8.83	0.390	473.54	
3-D	1.002	0.129	1.096				
			1.244	10.1	0.104	251.62	
			1.433	11.198	0.158	371.76	
				10.26	0.205	384.42	
4-D	0.993	0.135	1.051				
			1.215	8.509	0.082	175.2	
			1.455	13.095	0.165	470.67	
				12.886	0.226	529.49	G I, initial
					average	**395.08**	**258.82**
					stdev.	**119.05**	**69.76**
411							
1-D	1.0022	0.123	1.157				
			1.434	12.3	0.183	509.93	
			1.752	12.7	0.254	589.63	
			2.317	8.98	0.435	584.42	
2-D	0.9937	0.127	1.0975				
			1.1865	12.1	0.141	410.95	
			1.4195	10.6	0.174	410.94	
			1.6975	10.9	0.297	602.89	
3-D	1.005	0.125	1.22				
			1.384	12.865	0.190	524.99	
			1.554	11.865	0.243	543.54	
				11.15	0.318	595.73	

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
4-D	0.995	0.123	1.379				
			1.805	12.699	0.282	685.53	
			2.07	8.822	0.401	517.1	
				8.8428	0.599	675.52	G I, initial
					average	**554.26**	**481.96**
					stdev.	**87.167**	**113.66**
8084							
1-D	1.003	0.137	1.1675				
			1.4435	17.8	0.218	870.49	
			1.8655	13.8	0.308	771.18	
			2.4065	11.4	0.469	750.63	
2-D	1.0082	0.133	1.296				
			1.53	16.1	0.238	770.36	
			1.789	15.21	0.354	916.94	
			2.287	11.5	0.475	795.57	
3-D	1.009	0.131	0.949				
			1.154	18.597	0.131	666.61	
			1.316	17.402	0.189	740.12	
				17.068	0.269	908.85	
4-D	1.002	0.132	1.203				
			1.522	17.881	0.212	818.45	
			2.199	13.629	0.290	676.08	
				9.7528	0.629	726.29	G I, initial
					average	**784.3**	**781.48**
					stdev.	**82.133**	**86.81**
SC-14							
1-D	1.0072	0.148	1.085				
			1.375	16.3	0.188	736.62	
			1.621	22.4	0.350	1487.1	
			1.969	20.4	0.529	1736.3	
2-D	1.0078	0.148	0.966				
			1.223	20	0.192	1036.2	
			1.507	21	0.313	1400.9	
			1.833	20.2	0.475	1659.6	
3-D	1.009	0.147	1.0395				
			1.389	18.381	0.193	887.25	
			1.669	20.174	0.366	1385.2	
				17.965	0.518	1451.6	

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
4-D	1.009	0.144	1.101				
			1.277	18.11	0.183	782.35	
			1.628	18.611	0.335	1269.2	
				16.985	0.493	1338.1	G I, initial
					average	**1264.2**	**860.59**
					stdev.	**331.32**	**132.95**
iso-polyester							
1-D	1.055	0.126	1.048				
			1.156	11.667	0.112	310.88	
			1.411	13.75	0.165	488.56	
				10.953	0.226	436.59	
2-D	1.057	0.117	1.123				
			1.287	10.558	0.145	338.8	
			1.451	10.474	0.213	430.26	
				10.766	0.292	538.96	
3-D	1.054	0.117	1.235				
			1.364	8.433	0.152	258.17	
			1.534	8.835	0.221	357.54	
				8.314	0.252	339.9	G I, initial
					average	**388.85**	**302.61**
					stdev.	**90.49**	**40.94**

WET SAMPLE IN 50 WATER FOR 1000 HOURS

ortho-polyester							
5-W	1.0098	0.132	Hinges fail				
6-W	1.007	0.133	Hinges fail				
7-w	1.0037	0.139	1.201				
			1.386	12.1	0.220	580.1	
			1.683	11.4	0.243	523.1	
			2.026	8.55	0.429	570.4	G I, initial
					average	**557.87**	580.10
					stdev.	**30.496**	
411							
5-W	1.0037	0.135	Hinge fail				
6-W	1.0055	0.133	1.3305				
			1.6065	13.4	0.212	557.81	
			1.7805	12	0.267	521.04	
			2.1755	10	0.400	586.92	G I, initial
					average	**555.26**	557.81
					stdev.	**33.013**	

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
8084							
5-W	1.0068	0.134	1.1445				
			1.4745	16.6	0.243	920.79	
			1.8515	14.3	0.374	946.38	
			1.8835	11.8	0.515	856.38	
6-W	1.007	0.132	1.1				
			1.573	14.9	0.259	915.18	
			2.257	**12**	0.367	730.35	
			2.948	9.96	0.687	790.86	G I, initial
					average	**859.99**	917.99
					stdev.	**84.621**	3.96
SC-14							
5-W	1.0155	0.147	0.8675				
			1.1205	14.9	0.164	734.23	
			fail in hinges				
6-W	1.0183	0.149	0.956				
			1.364	17.6	0.242	1161.3	
			1.588	14.5	0.400	1108.4	
			1.89	13.25	0.576	1252.7	G I, initial
					average	**1064.2**	947.76
					stdev.	**227.89**	301.98

Conditioning in distilled water at 50C for 2900 hours

ortho-polyester							
5w	1.0098	0.132	1.419				
			1.563	8.8034	0.192	309.48	
			1.733	9.5324	0.285	451.67	
				9.824	0.396	584.27	
6w	1.007	0.1328	1.021				
			1.5085	12.115	0.178	550.98	
			1.756	10.49	0.276	499.97	
				9.4699	0.378	531.51	
8w	0.993	0.135	1.544				
			1.807	9.1922	0.232	366.11	
			2.156	9.7962	0.338	484.47	
				8.0052	0.492	483.44	$G_{\text{I, initial}}$
					average	**473.54**	**408.857**
					stdev.	**87.655**	**126.2938**

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
411							
7w	1.007	0.128	1.197				
			1.349	12.566	0.171	466.92	
			1.857	12.712	0.244	599.31	
				10.566	0.516	765.44	
8w	1.01	0.135	1.442				
			1.585	13.732	0.278	688.28	
			1.796	12.774	0.325	682.25	
				11.838	0.459	786.86	$G_{\text{I, initial}}$
					average	**664.84**	**577.5993**
					stdev.	**117.75**	**156.5246**
8084							
7w	1.009	0.132	1.031				
			1.196	18.981	0.148	711.2	
			1.423	18.002	0.205	801.69	
				16.19	0.305	901.95	
8w	1.001	0.133	1.096				
			1.223	20.556	0.189	932.02	
			1.57	17.973	0.227	875.22	
				15.557	0.408	1062	$G_{\text{I, initial}}$
					average	**880.68**	**821.6092**
					stdev.	**119.13**	**156.1486**
SC-14							
7w	1.027	0.145	1.271				
			1.4375	17.135	0.270	932.47	
			1.5845	13.703	0.329	802.17	
			1.7985	14.224	0.387	889.47	
				14.932	0.564	1198.2	
8w	0.993	0.135	1.385				
			1.476	16.302	0.262	816.12	
			1.8135	17.64	0.361	1141.3	$G_{\text{I, initial}}$
					average	**963.29**	**874.2947**
					stdev.	**167.86**	**82.27344**

Conditioning in distilled water at 50C for 889 hours

	width (in)	thickness (in)	crack (in)	load (lbs)	disp. (in)	G I (J/m^2)	
Iso-polyester							
1	1.056	0.116	1.139				
			1.269	10.418	0.154	350.4	
			1.439	11.772	0.226	520.97	
				13.12	0.365	828.36	
2	1.056	0.114	1.192				
			1.296	10.099	0.223	469.23	
			1.603	9.4953	0.238	433.81	
				8.9121	0.322	445.87	
3	1.05	0.117	1.077				
			1.243	13.307	0.142	437.98	
			1.391	12.124	0.219	535.04	
				13.312	0.254	607.06	$G_{I, initial}$
					average	**514.3**	**419.2042**
					stdev.	**138.56**	**61.60175**

Table A.6. ENF tests.

Dry ENF samples tested at 50c,dry

Layup $[0]_6$

Sample	a1 (in)	Max Load (lbs)	Tickness (in)	Width (in)	Vf	EL* (GPa)	G_{IIC} (J/m^2)
Ortho-polyester							
1-D	0.874	189	0.139	1.005	0.38	31.89	1732.90
2-D	0.797	180	0.130	0.996	0.41	33.88	1504.57
3-D	0.56	222	0.129	1.002	0.41	34.20	1139.33
4-D	0.625	204	0.135	0.993	0.39	32.74	1111.92
						average	**1372.18**
						stdev.	**299.78**
411							
1-D	0.964	187	0.123	1.002	0.43	35.73	2665.40
2-D	0.74	220	0.127	0.994	0.42	34.64	2047.21
3-D	0.783	208	0.125	1.005	0.43	35.17	2077.36
4-D	1.65	118	0.123	0.995	0.43	35.65	3135.77
						average	**2481.44**
						stdev.	**520.84**
8084							
1-D	0.976	211	0.137	1.003	0.39	32.26	2761.45
2-D	0.754	223	0.133	1.008	0.40	33.27	1938.23
3-D	0.627	261	0.131	1.009	0.41	33.71	1885.79
4-D	2.001	112	0.132	1.002	0.40	33.47	3530.88
						average	**2529.09**
						stdev.	**779.00**
SC-14							
1-D	1.486	132	0.148	1.007	0.35	29.63	2152.76
2-D	0.98	181	0.148	1.008	0.35	29.67	1761.67
3-D	0.869	188	0.147	1.009	0.35	29.83	1503.14
4-D	0.73	196	0.144	1.009	0.36	30.56	1197.30
						average	**1653.72**
						stdev.	**404.84**

Sample	a1 (in)	Max Load (lbs)	Tickness (in)	Width (in)	Vf	EL* (GPa)	G_{IIC} (J/m^2)
Iso-polyester							
50C-1	1.59	111	0.126	1.055	0.42	34.93	2176.47
50C-2	1.59	112	0.117	1.057	0.45	37.11	2594.92
50C-3	1.59	197	0.117	1.054	0.45	37.11	8074.02
						average	**2385.69**
						stdev.	296.00

ENF samples conditioning in distilled water at 50C for 1000 hours tested at 50C dry

Ortho-polyester							
7-w	0.897	123	0.139	1.004	0.38	31.85	773.00
411							
5-w	0.951	189	0.135	1.004	0.39	32.66	2152.38
6-w	1.009	177	0.133	1.006	0.40	33.23	2192.69
						average	**2172.53**
						stdev.	**28.51**
8084							
5-w	0.843	211	0.134	1.007	0.40	32.95	2131.34
6-w	1.186	173	0.132	1.007	0.40	33.39	2915.12
						average	**2523.23**
						stdev.	**554.22**
sc14							
5-w	0.619	191	0.147	1.016	0.35	29.83	777.17
6-w	0.866	149	0.149	1.018	0.35	29.47	903.98
						average	**840.57**
						stdev.	**89.67**
Iso-polyester							
w-1	1.59	86	0.116	1.056	0.45	37.35	1562.65
w-2	1.59	94	0.114	1.056	0.46	37.84	1941.68
w-3	1.59	184	0.117	1.050	0.45	37.11	7097.34
						average	**1752.16**
						stdev.	**268.01**

Table A.7. Microdebonding Results

Dry Samples for Micro-debonding Test

sample	Force (v)	Diameter (10^8 m)	Distance (10^8 m)	σ (Mpa)	T_m/D_f	τ/σ	τ (Mpa)
Ortho-polyester							
1	0.706	1620	700	676.616	0.432	0.095	64.38
2	0.822	1875	700	588.08	0.373	0.101	59.11
3	0.77	1779	454	611.936	0.255	0.113	69.17
4	0.883	2007	568	551.358	0.283	0.110	60.58
5	0.656	1599	511	645.319	0.320	0.106	68.35
6	0.735	1761	321	596.123	0.182	0.122	72.67
7	0.725	1761	416	588.013	0.236	0.115	67.77
8	0.618	1590	435	614.839	0.274	0.111	68.20
						average	**66.28**
						stdev	**4.58**
411							
1	0.435	1590	227	432.775	0.143	0.127	55.00
2	0.555	1856	397	405.233	0.214	0.118	47.80
3	0.499	1711	227	428.714	0.133	0.128	55.07
4	0.544	1869	397	391.695	0.212	0.118	46.27
5	0.54	1801	416	418.73	0.231	0.116	48.52
6	0.51	1723	511	432.083	0.297	0.108	46.83
7	0.64	2049	511	383.41	0.249	0.114	43.59
8	0.591	1914	530	405.762	0.277	0.111	44.86
						average	**48.49**
						stdev	**4.33**
8084							
1	0.646	1837	606	481.484	0.330	0.105	50.48
2	0.57	1780	359	452.483	0.202	0.119	54.05
3	0.559	1685	1117	495.199	0.663	0.080	39.45
4	0.592	1756	246	482.881	0.140	0.127	61.55
5	0.567	1742	511	469.953	0.293	0.109	51.10
6	0.437	1496	549	491.118	0.367	0.101	49.66
7	0.539	1628	340	511.502	0.209	0.119	60.65
8	0.573	1742	473	474.926	0.272	0.111	52.79
9	0.571	1734	473	477.645	0.273	0.111	53.03
						average	**52.53**
						stdev	**6.47**

sample	Force (v)	Diameter (10^8 m)	Distance (10^8 m)	σ (MPa)	T_m/D_f	τ/σ	τ (MPa)
sc14							
1	0.643	1734	378	537.873	0.218	0.117	63.17
2	0.668	1756	340	544.872	0.194	0.120	65.64
3	0.706	1824	321	533.731	0.176	0.123	65.50
4	0.609	1666	454	551.867	0.273	0.111	61.28
5	0.608	1621	795	581.976	0.490	0.090	52.61
6	0.715	1846	378	527.728	0.205	0.119	62.84
7	0.623	1704	625	539.655	0.367	0.101	54.58
8	0.693	1761	492	562.059	0.279	0.110	61.98
						average	**60.95**
						stdev	**4.82**
iso-polyester							
1	0.694	1644	246	645.837	0.150	0.126	81.49
2	0.716	1799	530	556.44	0.295	0.109	60.43
3	0.722	1818	473	549.436	0.260	0.112	61.79
4	0.57	1532	757	610.836	0.494	0.090	55.05
5	0.531	1496	321	596.759	0.215	0.118	70.34
6	0.679	1647	435	629.579	0.264	0.112	70.51
7	0.572	1535	303	610.586	0.197	0.120	73.27
8	0.569	1572	416	579.128	0.265	0.112	64.83
						average	**67.21**
						stdev	**8.37**

Wet Samples for Micro-debonding Test

Ortho-polyester							
1	0.491	1723	321	415.986	0.186	0.121	50.50
2	0.475	1711	340	408.095	0.199	0.120	48.90
3	0.424	1486	265	482.943	0.178	0.122	59.12
4	0.41	1477	340	472.705	0.230	0.116	54.82
5	0.47	1621	606	449.883	0.374	0.100	45.20
6	0.471	1628	454	446.971	0.279	0.110	49.32
7	0.527	1742	568	436.799	0.326	0.105	45.97
8	0.603	1869	530	434.176	0.284	0.110	47.68
9	0.513	1723	246	434.624	0.143	0.127	55.24
						average	**50.75**
						stdev	**4.68**

sample	Force (v)	Diameter (10^8 m)	Distance (10^8 m)	σ (MPa)	T_m/D_f	τ/ σ	τ (MPa)
411							
1	0.385	1621	246	368.521	0.152	0.126	46.39
2	0.386	1644	359	359.212	0.218	0.117	42.17
3	0.336	1576	719	340.247	0.456	0.093	31.68
4	0.504	1761	359	408.77	0.204	0.119	48.72
5	0.449	1628	359	426.093	0.221	0.117	49.91
6	0.605	1914	435	415.374	0.227	0.116	48.32
7	0.626	1912	454	430.691	0.237	0.115	49.58
						average	**45.25**
						stdev	**6.54**
8084							
1	0.568	1742	1496	470.781	0.859	0.073	34.60
2	0.605	1982	227	387.361	0.115	0.131	50.73
3	0.591	1837	303	440.49	0.165	0.124	54.69
4	0.416	1420	397	518.9	0.280	0.110	57.21
5	0.512	1666	359	463.967	0.215	0.118	54.64
6	0.464	1496	227	521.461	0.152	0.126	65.65
7	0.577	1969	284	374.327	0.144	0.127	47.50
8	0.576	1856	1568	420.566	0.845	0.074	31.00
9	0.623	2007	996	389.01	0.496	0.090	34.99
						average	**47.89**
						stdev	**11.89**
sc14							
1	0.384	1621	340	367.564	0.210	0.118	43.54
2	0.39	1666	265	353.413	0.159	0.125	44.15
3	0.395	1628	454	374.848	0.279	0.110	41.36
4	0.605	1988	852	385.026	0.429	0.095	36.75
5	0.509	1801	303	394.691	0.168	0.124	48.83
6	0.482	1756	549	393.156	0.313	0.107	41.93
7	0.547	1824	416	413.528	0.228	0.116	48.06
8	0.522	1837	416	389.063	0.226	0.116	45.30
						average	**43.74**
						stdev	**3.87**

sample	Force (v)	Diameter (10^8 m)	Distance (10^8 m)	σ (MPa)	T_m/D_f	τ/ σ	τ (MPa)
iso-polyester							
1	0.632	1685	303	559.867	0.180	0.122	68.43
2	0.463	1250	340	745.295	0.272	0.111	82.81
3	0.638	1628	587	605.451	0.361	0.102	61.61
4	0.656	1723	473	555.777	0.275	0.111	61.59
5	0.604	1590	681	600.911	0.428	0.095	57.38
6	0.636	1666	227	576.334	0.136	0.128	73.76
7	0.568	1553	265	592.342	0.171	0.123	73.10
8	0.546	1420	416	681.057	0.293	0.109	74.08
9	0.614	1628	871	582.676	0.535	0.087	50.78
						average	**67.06**
						stdev	**9.99**