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CHAPTER ONE

1. INTRODUCTION AND BACKGROUND

Aptera (Oceanside, CA) is designing and building a three-wheeled all-electric vehicle called the 2e (Figure 1). It is important that they know the maximum use temperature of the 2e's polymer matrix composite (PMC) body to ensure that it can withstand the temperatures that it might experience during transportation to Aptera's facility or during its normal use. The mechanical behavior of Aptera's composites will be studied at temperature extremes using a dynamic mechanical analysis (DMA) system and by tensile and short beam shear testing using an Instron testing system paired with an environmental chamber. Because the 2e has not yet been released to the public and is still in the design stage, the PMC's specific composition is proprietary. However, what can be mentioned is that the PMC consists of an epoxy matrix with glass fiber reinforcement. Two different thermoset epoxy resin systems will be studied. The structural and processing variables of the PMC such as fiber orientation, fiber volume fraction, laminate thickness, curing temperature and pressure will be fixed. The goal is to find a resin system that will perform to Aptera's standards at temperature extremes.

Figure 1 – An image of Aptera's three-wheeled all-electric vehicle called the 2e[1].

1.1 Stakeholders

The stakeholders of this project are the users of the 2e, Aptera, and the general public. The users of the 2e want their vehicle's body to be able to withstand extreme temperatures and weather conditions. Aptera needs their vehicle to be safe and resistant to any environment that the 2e might be subjected to. The general public must not be put at risk while driving next to the 2e. Because Aptera would be liable, the composite body of the 2e must not fail prematurely and injure anyone.

1.2 Broader Impacts

Aptera's all-electric vehicle, the 2e, is employing state-of-the art technology to lower the environmental impact of the petroleum-based transportation infrastructure. Vehicles with combustion engines are noisy, inefficient, and emit chemicals that are toxic to the atmosphere. For each gallon of gasoline fuel combusted, 19.4 pounds of carbon dioxide is emitted[2]. The amount of oil that each continent consumes per day is shown below in Figure 2. The numbers are astounding. North America alone is consuming almost 24 million barrels of oil per day and the numbers are predicted go up[2]. The amount of CO_2 being released into the atmosphere is expected to follow the same trend (Figure 3).

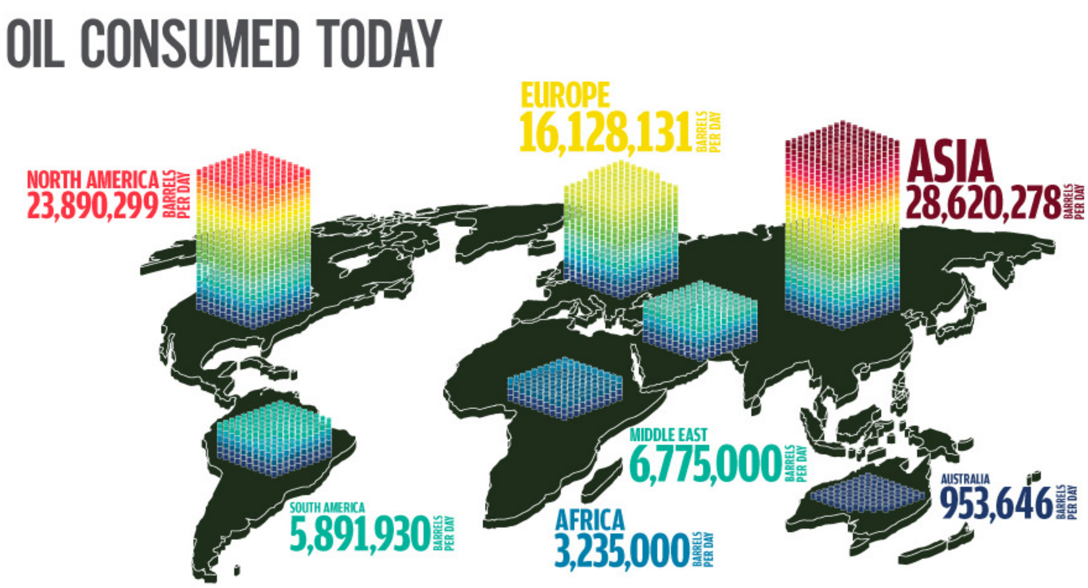


Figure 2 - Total amount of oil consumed today in barrels per day[2].

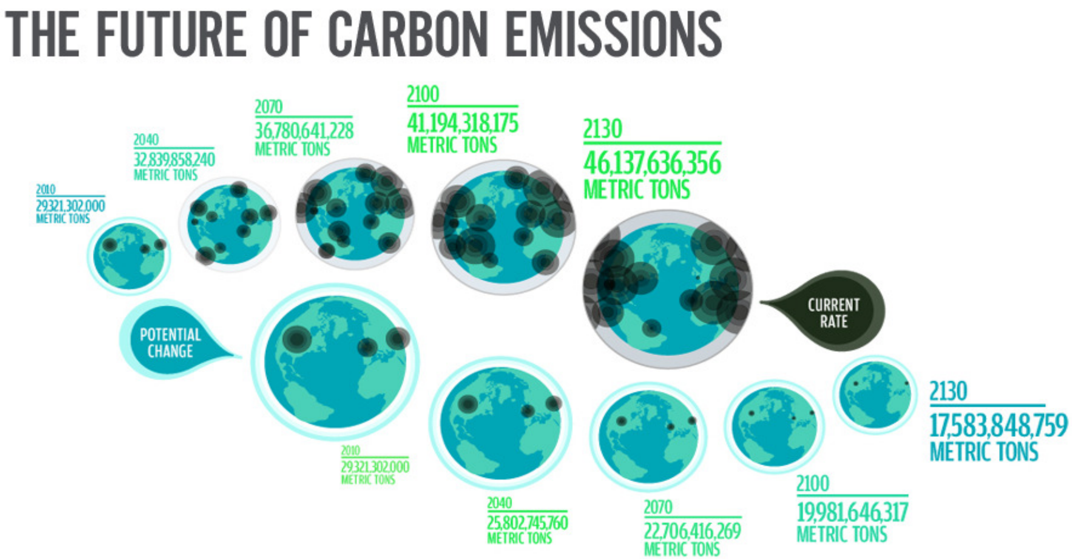


Figure 3 - The Future of Carbon Emissions[2].

When researchers compared battery-powered vehicles to their gas-fueled counterparts, they calculated that a car with an internal combustion engine would need a fuel economy of about 60 to 80 mpg to achieve a lower environmental impact than a battery-powered electric vehicle that recharged[3]. Pollution caused by the disposal of batteries, both lead acid and lithium, is very low. Ninety-seven percent of the lead acid batteries in this country are recycled making them the most recycled product[3]. Lithium, used in lithium ion batteries, is proving to have high recycle rates as well because it is rare and difficult to produce[4]. Overall, there is a profound need for more efficient automobiles. Minimizing greenhouse gas emissions, reducing oil dependence and lowering the cost to drive are all benefits offered by electric vehicles.

1.3 Composites

A composite material is a combination of two or more materials with a distinct interface between them. The resulting composite material has a set of structural properties that is greater to either constituent material alone. The improved structural properties generally result from a load-sharing mechanism. Aptera utilizes polymer matrix composites (PMCs), which are materials consisting of a polymer resin matrix combined with fiber reinforcement (Figure 4). Each layer (ply) of a continuous fiber composite typically has a specific fiber orientation direction. These layers can be stacked such that each layer has a specified fiber orientation, thereby giving the entire laminated stack (laminate) highly tailorable overall properties[5,6].

Composites are able to absorb and deflect energy, and are three times as strong as steel while weighing considerably less.

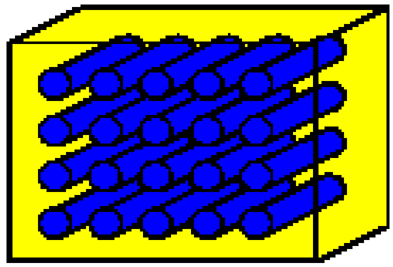


Figure 4 - Composite schematic with the matrix being represented in yellow and the fibers in blue[7].

1.3.1 Glass Fibers

Glass fibers exhibit useful bulk properties such as hardness, resistance to chemical attack, stability, as well as desirable fiber properties such as strength, flexibility, and stiffness. Both continuous and discontinuous glass-fiber-reinforced composites have found extensive application, ranging from low-performance uses, such as panels in aircraft and appliances, to high-performance applications such as rocket motor cases and pressure vessels[5,6]. The reasons for the widespread use of glass fibers in PMCs include competitive price, availability, good handleability, ease of processing, and relatively high strength. The glass fiber most commonly used is known as E-glass. E-glass is a moderate cost glass fiber with a balance of mechanical, chemical, and electrical properties. Typical strength and stiffness levels for the individual filaments are about 3450 MPa (500 ksi) tensile strength and 75.8 GPa (11×10^6 psi) Young's modulus[5,6]. Fiber orientation greatly affects the mechanical properties of PMCs. Fibers can be aligned in a woven or unidirectional orientation (Figure 5). The fiber reinforcement is usually stiffer than the matrix, thus stiffening the composite material. This stiffer reinforcement will usually be laid in a particular direction, within the matrix, so that the resulting material will have different properties in different directions. This characteristic is usually exploited to optimize the mechanical design[8].

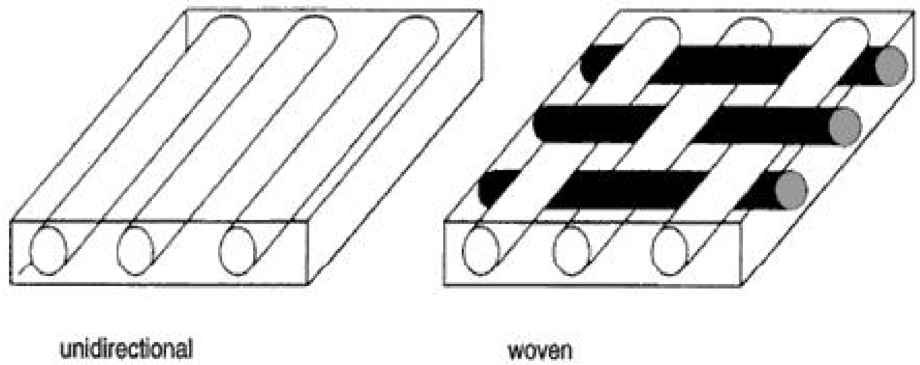


Figure 5 - Schematic showing the difference between unidirectional and woven fiber reinforcements[7].

1.3.2 Thermoset Matrix

Thermoset epoxy resins are used more than any other matrix material for composites. However, both thermosetting and thermoplastic polymers can be used for the matrix material. Common polymer composite thermosetting matrix materials include polyester, vinyl ester and epoxy[8]. They are generally two-part systems consisting of an epoxy resin and a hardener which is either an amine or anhydride. A wide variety of formulations are available that result in a broad spectrum of properties after cure. The more advanced epoxies require the application of heat during a controlled curing cycle to achieve the best properties. Prepregs can be made with epoxies where the fibers are impregnated with resin which is then partially cured[6].

Thermosets are network-forming polymers. Unlike thermosplastics, chemical reactions are involved in their use (Figure 6). These reactions result in an initial increase in viscosity and eventually cross-link and become set. In the uncured state, thermosets are mixtures of small reactive molecules called monomers. The abrupt and irreversible transformation from a viscous liquid to an elastic gel or rubber is called the gel point.

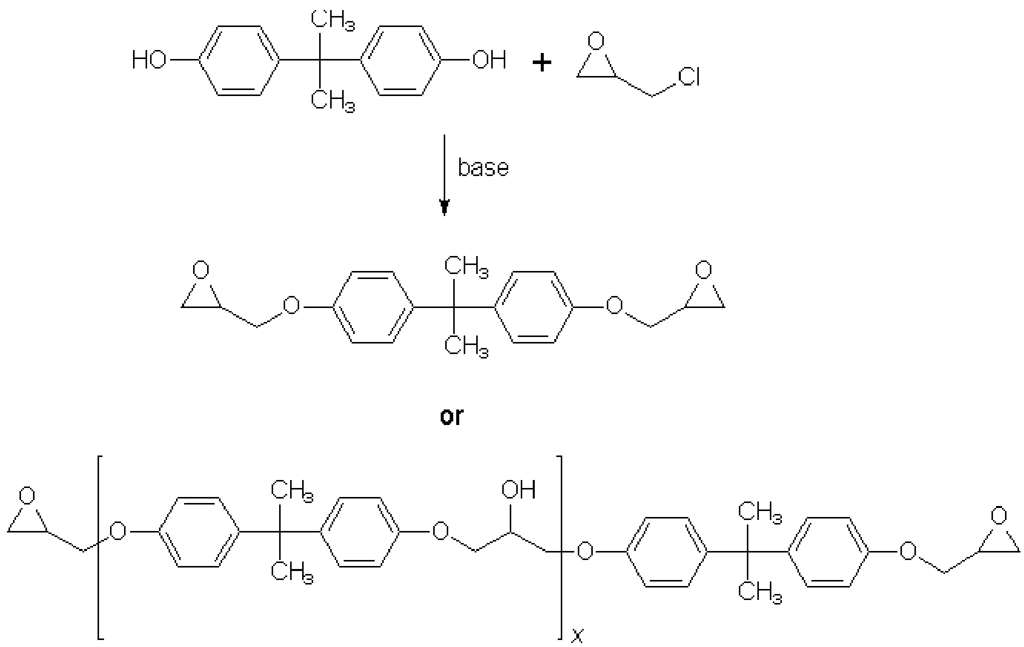


Figure 6 - Schematic of the adhesive chemistry of epoxy that leads to a crosslinked system.

Although epoxies are sensitive to moisture in both their cured and uncured states, they are generally superior to polyesters in resisting moisture and other environmental influences and offer lower cure shrinkage and better mechanical properties. Moisture absorption decreases the glass transition temperature (T_g) of an epoxy resin. Because a significant loss of epoxy properties occurs at the T_g, the T_g in most cases describes the upper-use temperature limit of the composite[5]. As a material passes through the Tg, a cure reaction takes place. The material gets less stiff (modulus decreases) as a result of the Tg and the increasing temperature despite the cure process going to completion[9] (Figure 7).

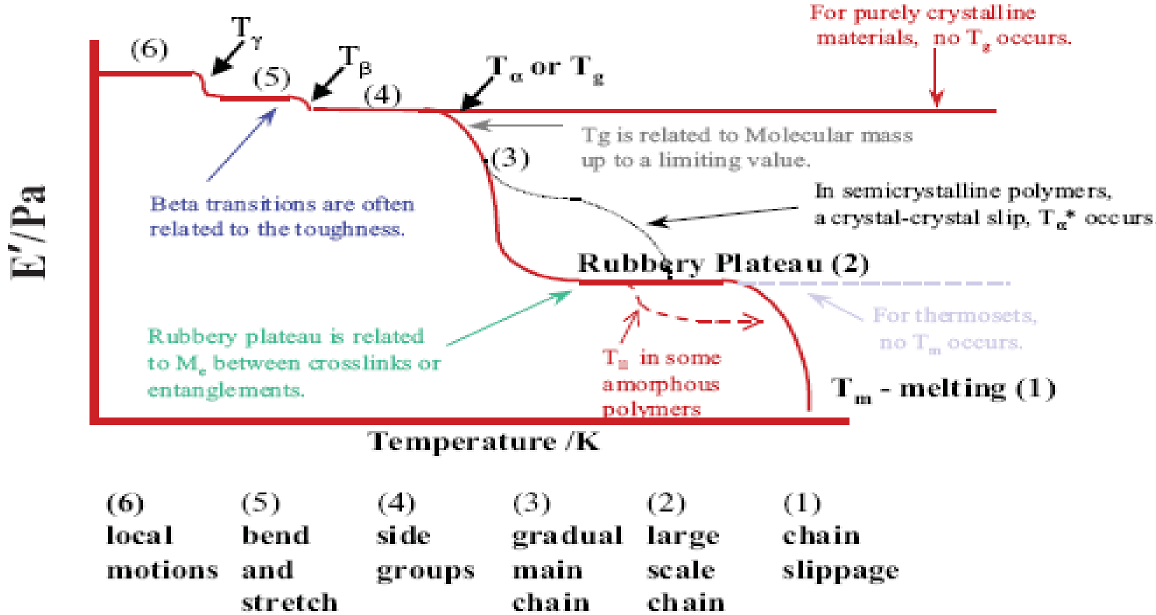


Figure 7 - Modulus VS temperature diagram representing the different stages of a thermoset's cure[9].

1.3.3 Manufacturing

Aptera primarily uses a vacuum infusion process to manufacture the composites used on the 2e. This is a resin injection technique that is derived from resin transfer molding (RTM). The first step to the vacuum infusion process is placing the dry reinforcement in a mold (Figure 8). The mold is then closed and resin flows through the mold and impregnates the reinforcement. Cure is often thermally activated, which gives rise to the term thermoset. After the curing process is complete, the mold is then opened and the part is removed. The larger the product, the more difficult and expensive this process becomes. The major disadvantage of using vacuum is the sensitivity to leakage. A leak will result in air flowing into the mold, which often results in void-rich areas in the cured part[7].

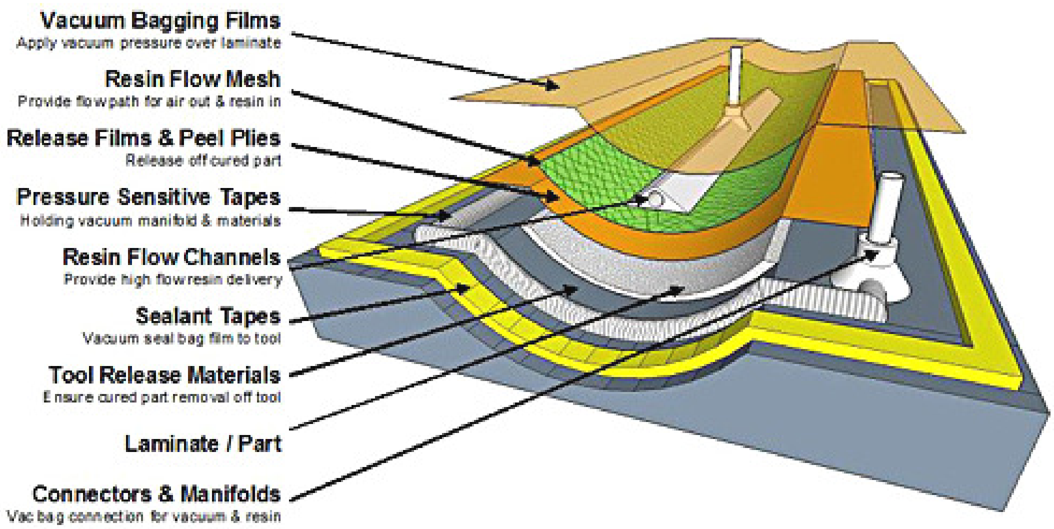


Figure 8 - Schematic of the vacuum infusion set up[12].

1.3.4 Mechanics and Testing

Structural and processing variables can have a dramatic effect on the mechanical properties of composite materials. Structural variables include: fiber orientation, fiber volume fraction, and laminate thickness. Processing variables include: layup accuracy, curing temperatures and pressure. To understand the effect of these variables on the finished material or component of Aptera's composites, mechanical testing is necessary.

The Instron load frame, load cell and grips of the testing system are not infinitely stiff and will deform slightly as force is applied to the specimen[10]. This deformation is called the machine compliance and can lead to significant errors in test results. The displacement output recorded by the system is the sum of the system compliance and the specimen deformation. A clip-on extensometer will be used to measure the actual sample displacement during tensile testing. SBS testing does not require the use of the extensometer.

Tensile tests will be done to determine the in-plane tensile properties of PMCs such as the strength, ultimate tensile strain, tensile modulus of elasticity, Poisson's ratio, and transition strain (ASTM D 3039 – Standard Test Method for Tensile Properties of PMC Materials)[11]. Short beam shear tests will be done to characterize the interlaminar failure properties of PMCs (ASTM D 2344 – Standard Test Method for Short-Beam

Strength of PMC Materials and Their Laminates)[11]. DMA testing will be used to evaluate the stiffness of the PMC, as measured by modulus, as a function of temperature (ASTM D 7028 – Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA))[11].

Developments in advanced composites have resulted in a new generation of low weight, high strength products that are being used in increasingly demanding environmental conditions. A full understanding of the performance of these materials calls for testing systems with extreme temperature capability.

1.4 ILSS

Thermal expansion differences between fiber and matrix can contribute to stresses at the interface. Debonding at the fiber/matrix interface or cracking can result if there is a very large thermal expansion mismatch due to thermal stress. The fiber/matrix interface has a major affect on the overall mechanical behavior of fiber-reinforced composites. The adhesion chemistry at the fiber/matrix interface controls the performance of fiber reinforced composites. One of the disadvantages of glass fiber is poor adhesion to matrix resin. The short beam shear test results may reflect the tendency of the bond strength where only the bonding level is a variable[6,8]. The SBS test utilizes the 3 point bend sample configuration shown in Figure 9. This configuration produces internal stresses into the composite, which results in an interlaminar shear failure mode. A schematic of the fiber-matrix interface is shown in Figure 10.

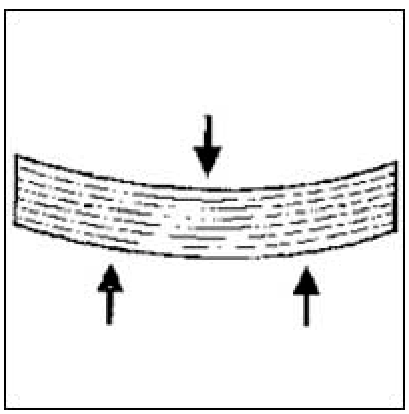


Figure 9 - Short beam shear loading configuration[5].

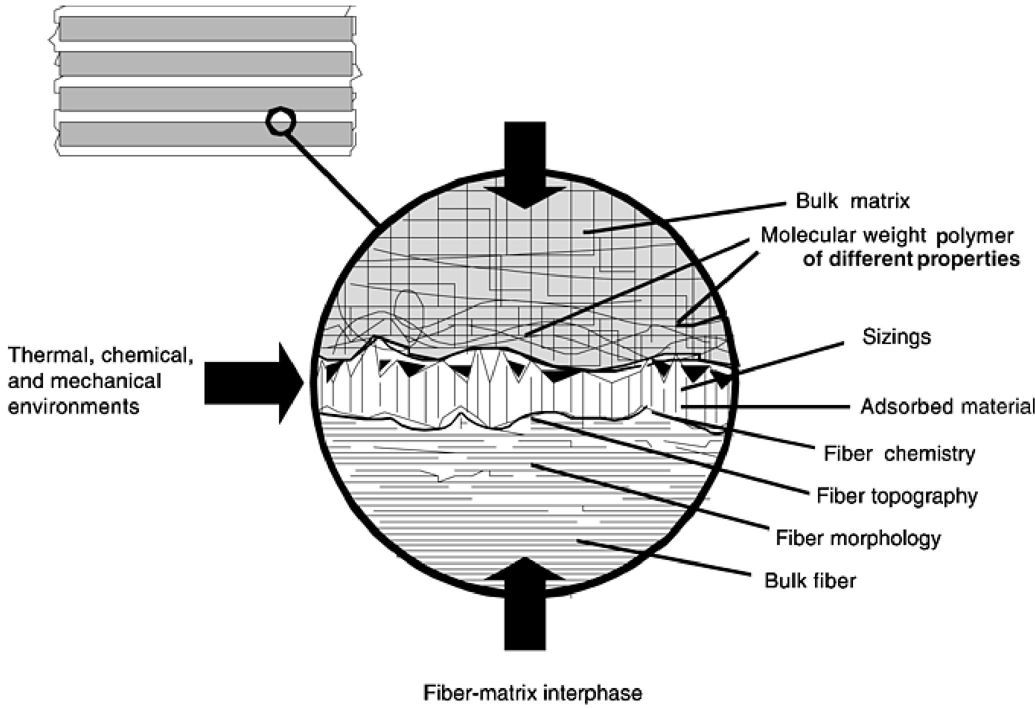


Figure 10 - Schematic diagram of the fiber-matrix interphase[8].

CHAPTER TWO

2. RESEARCH OBJECTIVES

The primary objective of this study is to determine the temperature use limits of Aptera's polymer matrix composite (PMC) materials. Aptera wants to be certain that their composite body will be able to withstand the extreme temperatures that the 2e might experience during transportation to Aptera's facility or during its normal use. The temperature use limits will determine where this vehicle can be sold. If the composite body were to soften when exposed to 120°F weather in Arizona, the body would likely fail if involved in an accident. The 2e has been designed for use in moderate climates.

A second objective of this study is to determine the temperatures where Aptera's composites begin to mechanically degrade. The maximum use temperature of the 2e's composite body will be determined by Dynamic Mechanical Analysis (DMA). This analysis will determine the composite's glass transition temperature. At this temperature, there is a significant loss of mechanical strength and stiffness. The glass transition temperature will help to define the maximum use temperature of Aptera's composites.

Two proprietary resin systems will be studied. Aptera wants to know if one resin system is particularly better than the other. If there is not a difference, this is good news for Aptera. In industry, you never want to solely rely on one distributer for anything. This concept is known as 'dual-suppliers'. If one resin company were to go bankrupt, Aptera will have a back-up. It is important that Aptera can be confident that both resin systems will perform to their standards at temperature extremes.

CHAPTER THREE

3. EXPERIMENTAL METHODS AND MATERIALS

3.1 Aptera's Polymer Matrix Composites

Aptera's composite test samples were produced using similar method's as they would in the mass production of the 2e. Tensile, short beam shear, and DMA test specimens were cut using a computer controlled router. These specimens were cut to a tolerance of $\pm$ 0.05 mm.

Developments in advanced composites have resulted in a new generation of low weight, high strength products that are being used in increasingly demanding environmental conditions. A full understanding of the performance of these materials calls for testing systems with extreme temperature capability. Instron's environmental chamber provides a controlled testing environment for extreme temperature testing[6]. To test Aptera's composites at temperature extremes, Instron's environmental chamber will be used.

3.2 Design of Experiment

Aptera wants to determine the temperature use limits of two proprietary composite resin systems to be used on the 2e. Tensile and short beam shear tests at temperature extremes will be utilized to determine the composite's mechanical properties at these temperatures. A low temperature of 0°F was chosen to simulate an extremely cold environment. A high temperature of 180°F was chosen to determine the maximum use temperature of the composite. The 2e will never see temperatures this extreme, but Aptera is still interested in how the composite performs. Dynamic mechanical analysis tests were performed to determine the glass transition temperature of each composite resin system. This temperature is defined as the temperature where there is a significant loss of mechanical properties such as Young's Modulus. A test matrix is shown in Table I.

Table I - Design of Experiment Test Matrix.

Resin System	Tensile (8-10 replicates)	Short Beam Shear (7 replicates)		Dynamic Mechanical Analysis (5 replicates)
Resin System A	0°F	0°F		Start T = 58.1°F End T = 356°F Ramp Rate = 5.0°C/min
	72°F	72°F		
	180°F	180°F		
Resin System B	0°F	0°F		Start T = 58.1°F End T = 356°F Ramp Rate = 5.0°C/min
	72°F	72°F		
	180°F	180°F		

3.3 Tensile Testing

Tensile tests were done to determine the in-plane tensile properties of PMCs such as the strength, ultimate tensile strain, tensile modulus of elasticity, Poisson's ratio, and transition strain (ASTM D 3039 – Standard Test Method for Tensile Properties of PMC Materials). These tests were done in Oceanside, CA at Aptera's Facility. Aptera's 5980 Series Instron Testing System paired with an environmental chamber was utilized to test the PMC samples at temperature extremes (Figure 11). A typical stress-strain curve can be seen in Figure 12. It is clear that the composite has the combined properties of the matrix and fibers. The fibers alone are strong in tension, but are not able to withstand large amounts of strain. The matrix alone is extremely ductile and weak, but cannot withstand large stresses. The tensile samples had dimensions of 150mm x 25mm x 2mm (2 ply), and the rate of deformation was set at 1.0 mm/min, which were both defined by the ASTM standard. The test specimens were clamped into the grips starting with the bottom first to insure that the samples were aligned vertically.

(a) (b)

Figure 11– (a) Instron 5980 Series Testing System paired with environmental chamber. (b) PMC tensile test specimen mounted in tensile test fixture.

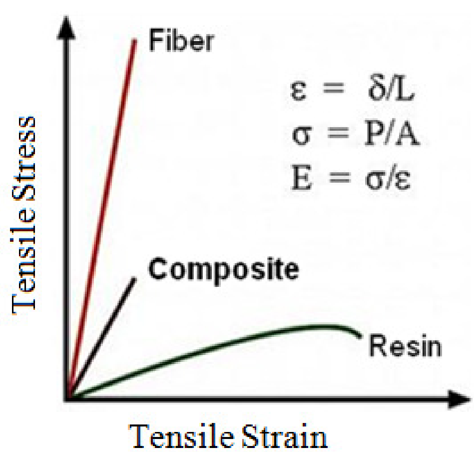


Figure 12 - Typical stress-strain curve for a composite consisting of fibers and a polymer matrix.

3.4 Short Beam Shear Testing

Short beam shear (SBS) tests were done to characterize the interlaminar failure properties of PMCs (ASTM D 2344 – Standard Test Method for Short-Beam Strength of PMC Materials and Their Laminates). These tests were done in Oceanside, CA at Aptera's Facility. Aptera's 5980 Series Instron Testing System paired with an environmental chamber was utilized to test PMCs at temperature extremes. The SBS testing configuration is shown in Figure 13. A 3-point bend test fixture is used to produce shear forces between the ply in the composite. The resultant shear force, F_{31}, can be seen in Figure 14. As a force P is applied to the test specimen, a resultant shear force is developed between the individual plys. This shear separates the composite resulting in failure. The SBS samples had dimensions of 40 mm x 13 mm x 6 mm (6 ply), with a span-to-thickness ratio equal to 4. A deformation rate of 1 mm/min was chosen, which was defined by the standard. The SBS specimens were aligned with the middle of the sample directly under the loading nose.

This test is different from most other bend tests. Bend tests usually maximize the normal stresses (tension and compression) and failure is from the maximum stress at the outer surfaces. Short beam shear tests, using relatively short and thick samples, maximize the shear stresses, τ, and not the normal stresses. The geometry of the SBS specimen produces the shear failure between the laminas. The interlaminar shear strength (ILSS) of composites is defined as the shear strength perpendicular to the plane of lamination. The ILSS depends on the matrix properties and the fiber-matrix interfacial shear strength, not the fiber properties.

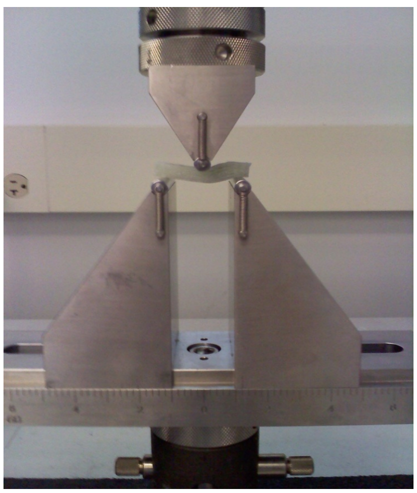


Figure 13 - Short beam shear test configuration showing a test specimen under load.

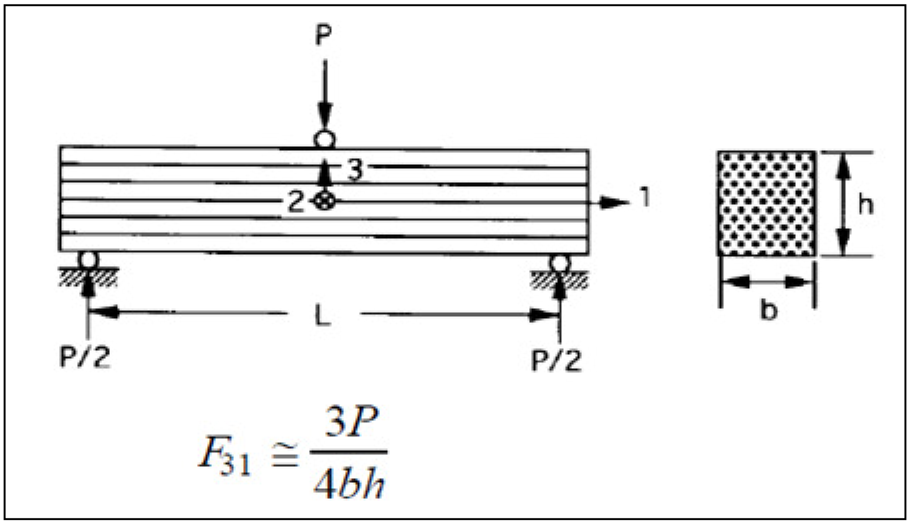


Figure 14 - Short beam shear mechanics. The resultant shear force is represented by F_{31}[5].

3.5 Dynamic Mechanical Analysis

Dynamic Mechanical Analysis (DMA) testing was utilized to determine the glass transition temperature of Aptera's proprietary composite systems. These tests were done in Oceanside, CA at Aptera's Facility. Aptera's Perkin Elmer DMA 8000 utilized a dual-cantilever bending system to stress a test specimen and the resulting strain is measured (Figures 15 & 16).

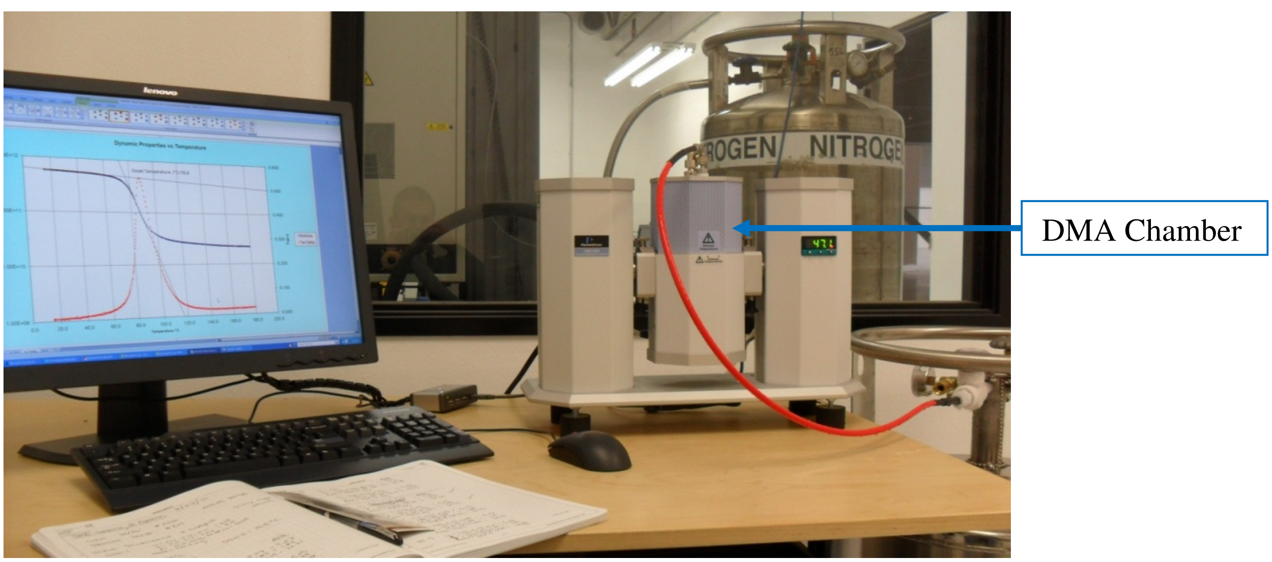


Figure 15 - Aptera's Perkin Elmer DMA 8000.

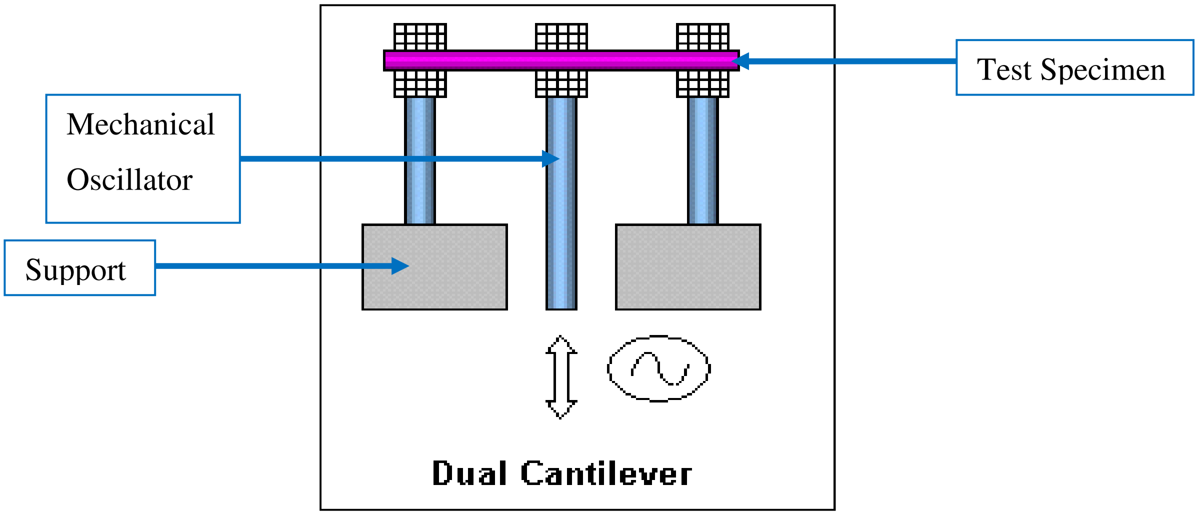


Figure 16 - Dual cantilever set up for DMA test[9].

DMA applies an oscillating force (stress) and measures the resultant dimension change (strain). A single frequency/single strain oscillation mode was used with a frequency of 1 Hz, which was defined by the ASTM standard. A displacement of 0.02 mm was used, which was also defined by the standard. A start and end temperature of 14.5°C and 180°C were used to observe the entire range of mechanical properties before the thermoset began to burn away. A ramp rate of 5°C/min was used, which again was defined by the standard. A thermocouple inside the DMA chamber monitors the temperature around the test specimen (Figure 17). Figure 17 also shows the sample specimen mounted in the DMA chamber. All six fastening bolts were first hand tightened and then the bolts were secured using a torque wrench supplied by Perkin Elmer. The order of tightening began with all for corners in a diagonal pattern, until all bolts were fastened.

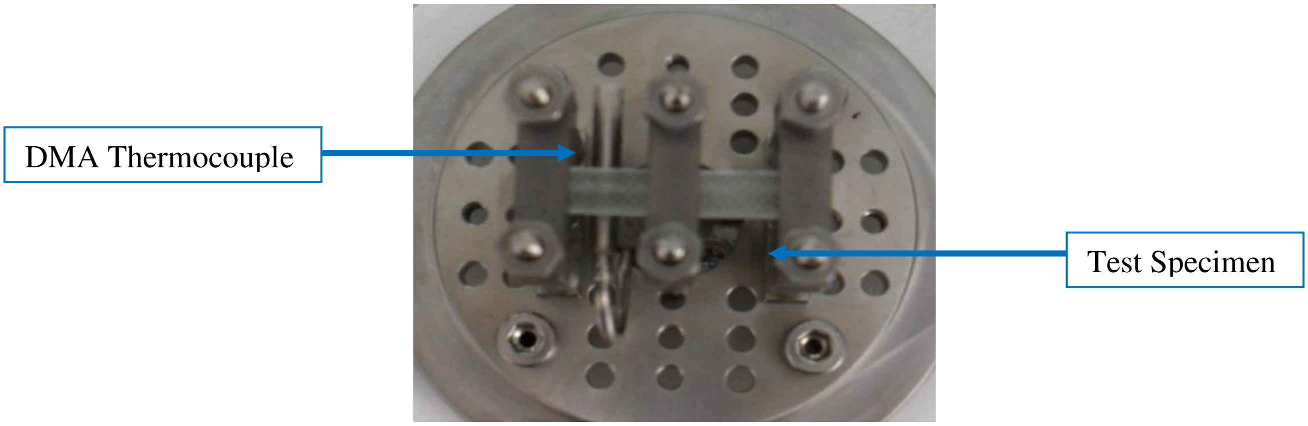


Figure 17 - DMA test specimen loaded in dual cantilever set up.

3.6 Scanning Electron Microscopy

Scanning Electron Microscope (SEM) images were captured using Cal Poly's FEI Quanta 200 Scanning Electron Microscope (Figure 18). The SEM was used to attempt to see a clear image of the fracture surfaces of both the tensile and SBS samples. The exact failure modes for each could then be confirmed. The SEM was used under standard vacuum setting using voltages from 500 to 1000 volts. A piece of copper tape was secured to each specimen to help reduce the over-charging of the samples.

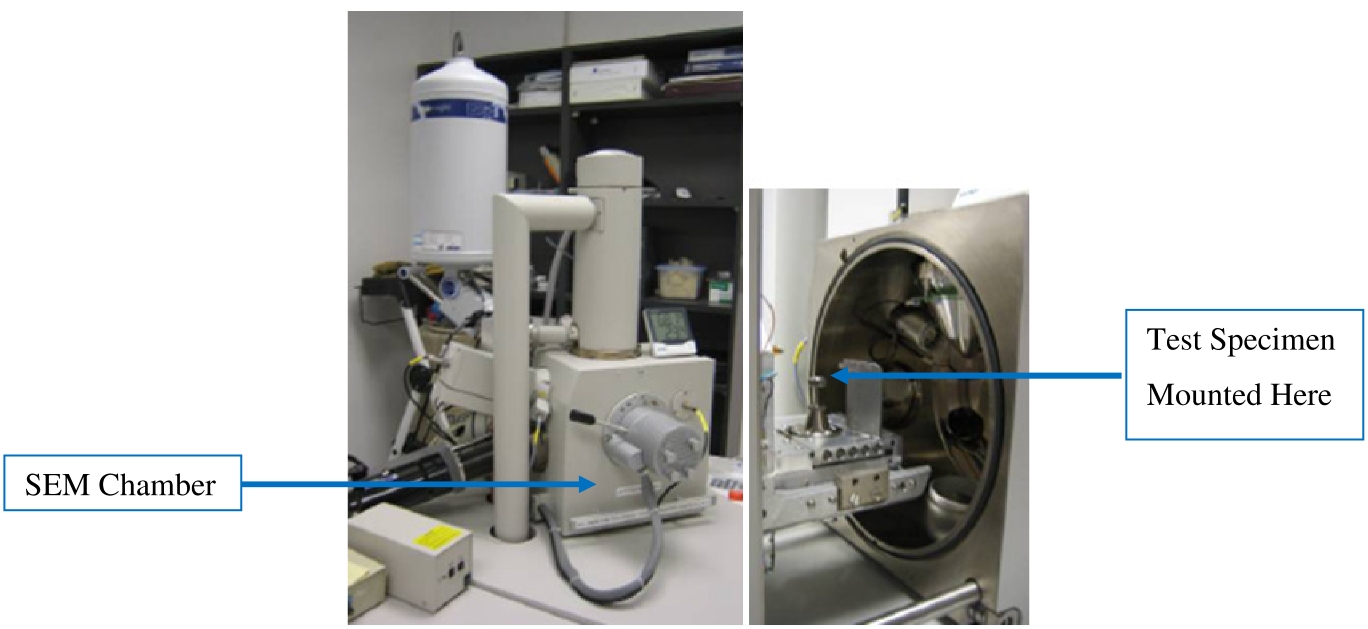


Figure 18 - Cal Poly's SEM FEI Quanta 200 Scanning Electron Microscope.

CHAPTER FOUR

4. EXPERIMENTAL RESULTS

4.1 Tensile Results

Tensile tests were done to determine the in-plane tensile properties of Aptera's PMC materials. An obvious trend can be seen as the temperature is increased from 0°F to 180°F (Figure 19). There is a significant loss in tensile strength as the temperature is increased. What is also significant is that resin system B has a higher tensile strength at 180°F. The two outliers shown in the box plot were premature failures of the tensile specimens, likely caused by the over tightening of the Instron grips.

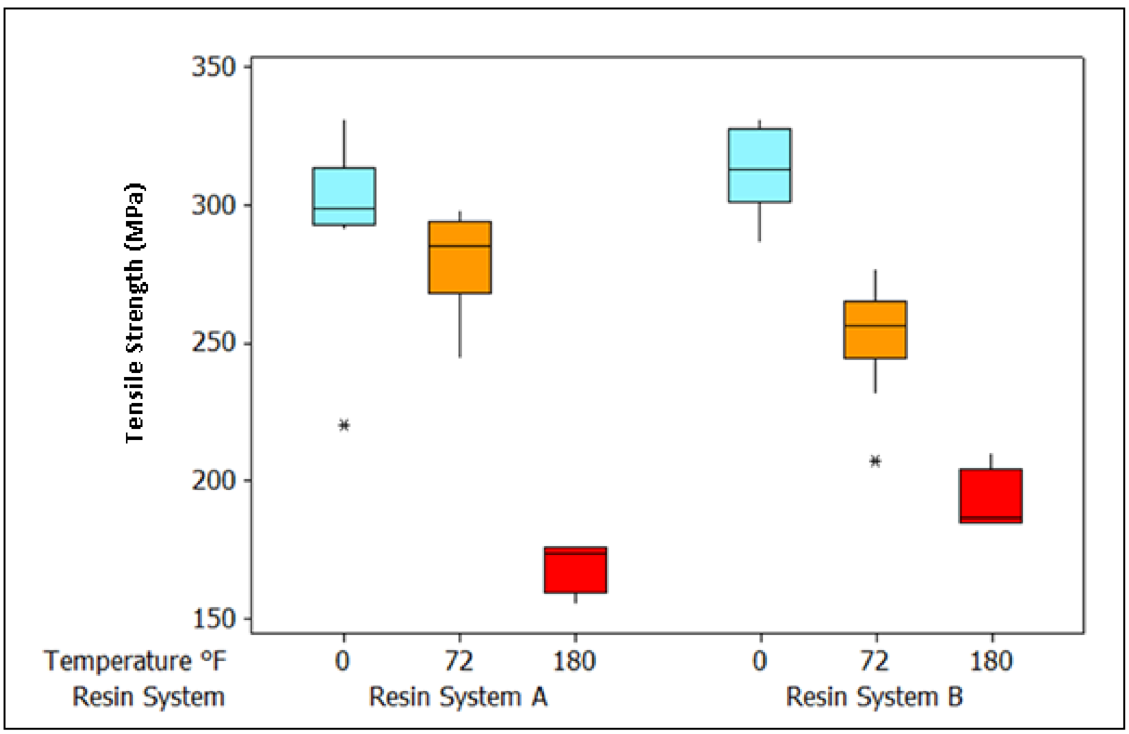


Figure 19 - Boxplot of the tensile strength (MPa) for Aptera's PMC materials at 0, 72, and 180°F. As the temperature is increased from 0°F to 180°F there is a significant loss in tensile strength for both resin systems.

Three failure modes were seen in the tensile tests of Aptera's PMC materials (Figure 20). The failure mode LIT stands for a lateral-inside grip-top failure. This failure is not preferred because of the failure inside the grip. This failure may be due to the over tightening of the Instron grips. The next failure mode witnessed was GAT, which stands for grip-at tab-top failure

mode. This failure is also not preferred because this is sometimes also caused by the over tightening of the testing grips. The preferred, and most common failure mode witnessed was XGM (Figure 21). This stands for explosive-gauge-middle failure.

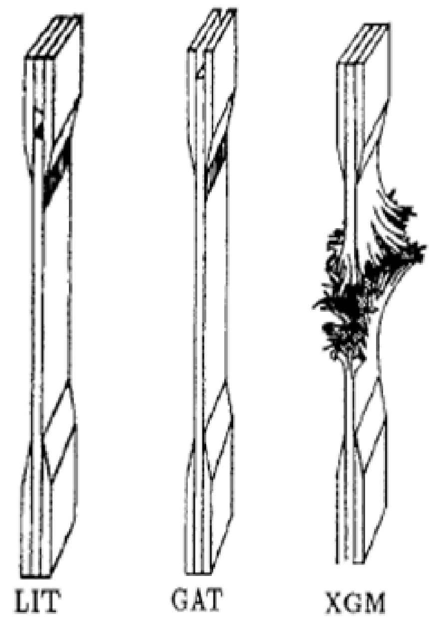


Figure 20 - The three tensile failure modes witnessed in the testing of Aptera's PMC materials[11].

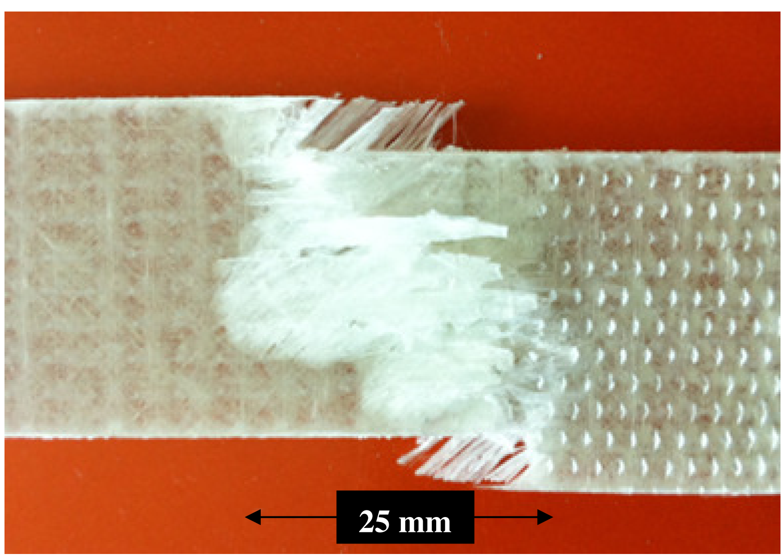


Figure 21 - An XGM failure mode seen in a tensile specimen tested at 180°F.

4.2 Short Beam Shear Results

Short beam shear (SBS) tests were performed to determine the short-beam strength of Aptera's composites. An obvious, and similar trend to the tensile results, can be seen in Figure 22. As the temperature is increased from 0°F to 180°F, there is a significant loss in SBS strength. What is also significant is that resin system B has a higher tensile strength at 180°F, which was the same result of the tensile testing.

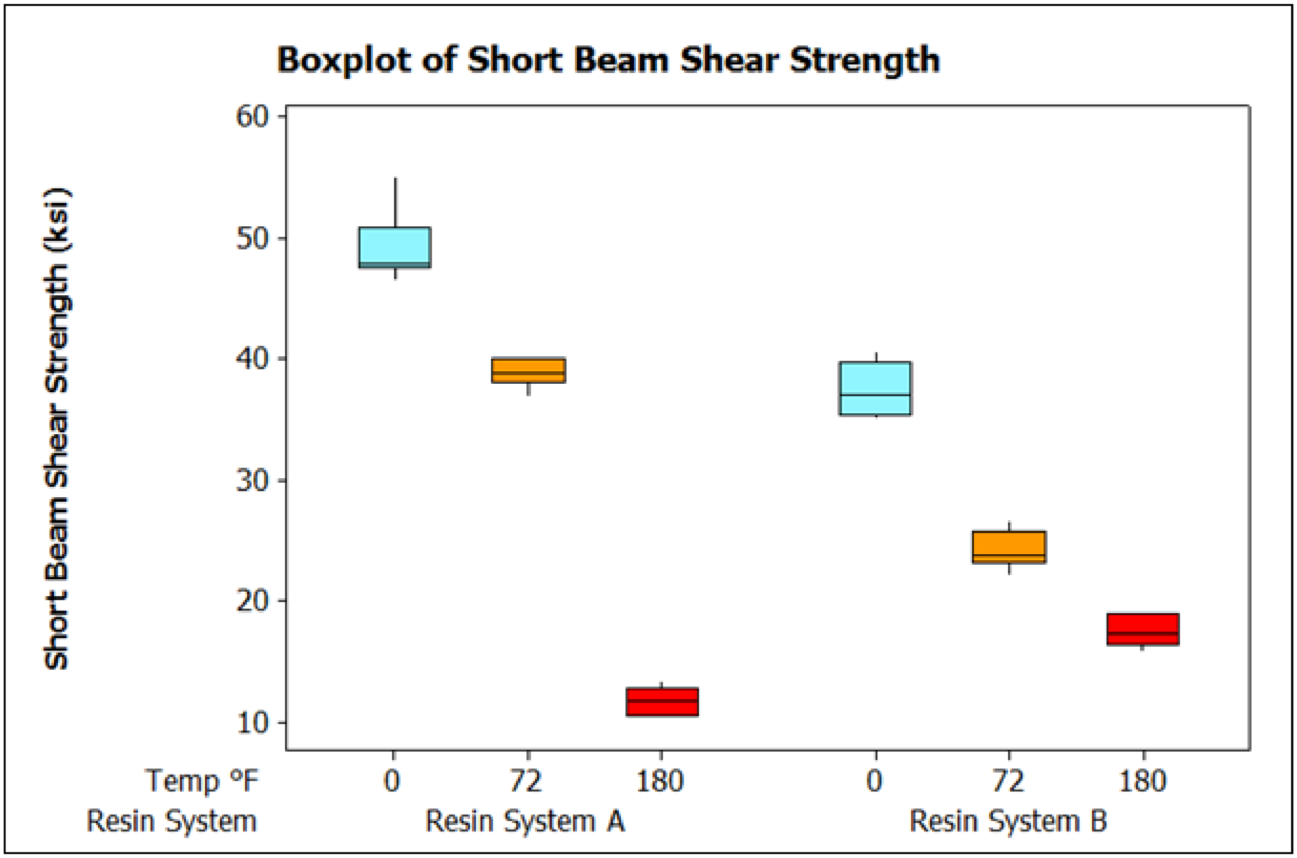


Figure 22 - A box plot of the SBS test results showing a decrease in SBS strength as the temperature is increased from 0°F to 180 °F for both resin systems.

Three different failure modes were witnessed in the SBS testing (Figure 23). An interlaminar shear failure mode is shown in Figure 24. The milky-white color shown in the figure is evidence of delamination. The modes of failure were not significantly different between the different testing temperatures. Although, at 180°F the delamination between ply was visually whiter than the samples tested at 0°F.

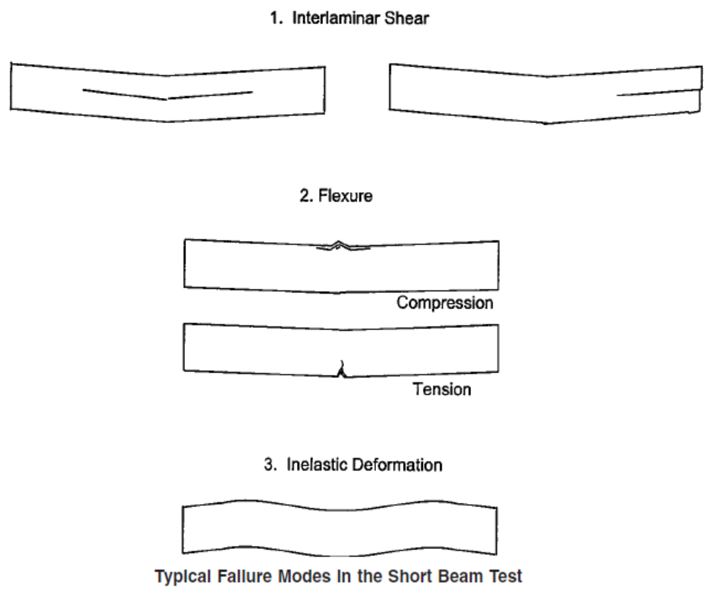


Figure 23 - The 3 failure modes seen in the SBS tests of Aptera's PMC materials[11].

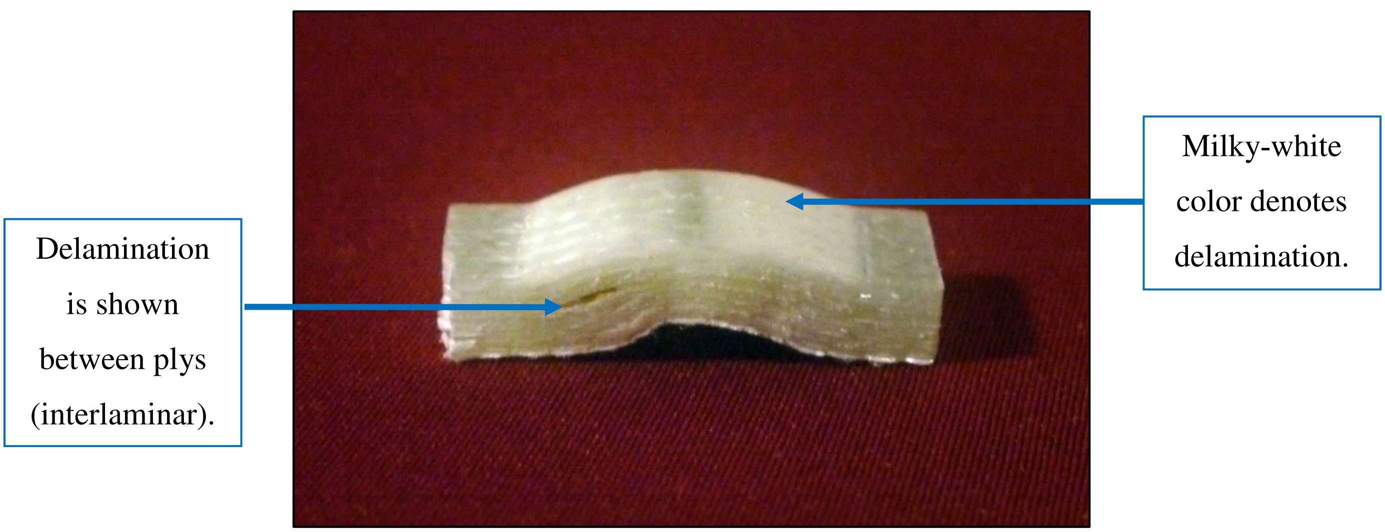


Figure 24 - SBS test specimen showing delamination at a few locations in the sample.

4.3 Dynamic Mechanical Analysis Results

Dynamic Mechanical Analysis (DMA) testing was done to determine of the glass transition temperature (T_g) of polymer matrix composites containing high-modulus fibers under a flexural oscillation mode. A DMA graph produced by the Perkin Elmer software for one sample

of Aptera's Resin System B is shown in Figure 25. The onset temperature was determined by using the software and methods defined by the ASTM standard. Two tangent lines were drawn on the blue modulus line. The intersection of these tangent lines is defined as the DMA glass transition temperature. This is the temperature where there is a significant loss in mechanical properties. The peak temperature, shown as the peak of the tan delta line, is a middle-of-the-road approximation for the T_g. This value is more representative of a T_g proved by differential scanning calorimetery. The tan delta is defined as the storage modulus (elastic response) over the loss modulus (viscous response). A box plot of the DMA data is shown in Figure 26. Resin system B is shown to have the higher glass transition temperature.

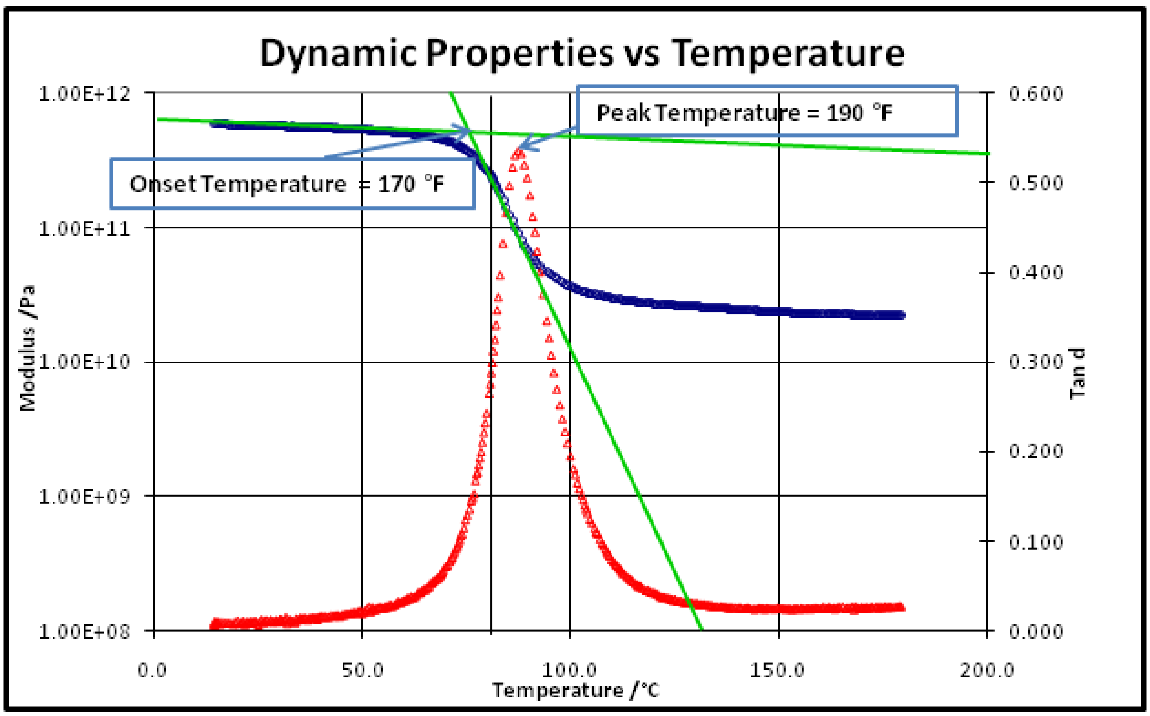


Figure 25 - DMA data plot showing the onset temperature (T_g) and peak temperature for Aptera's PMC Resin System B.

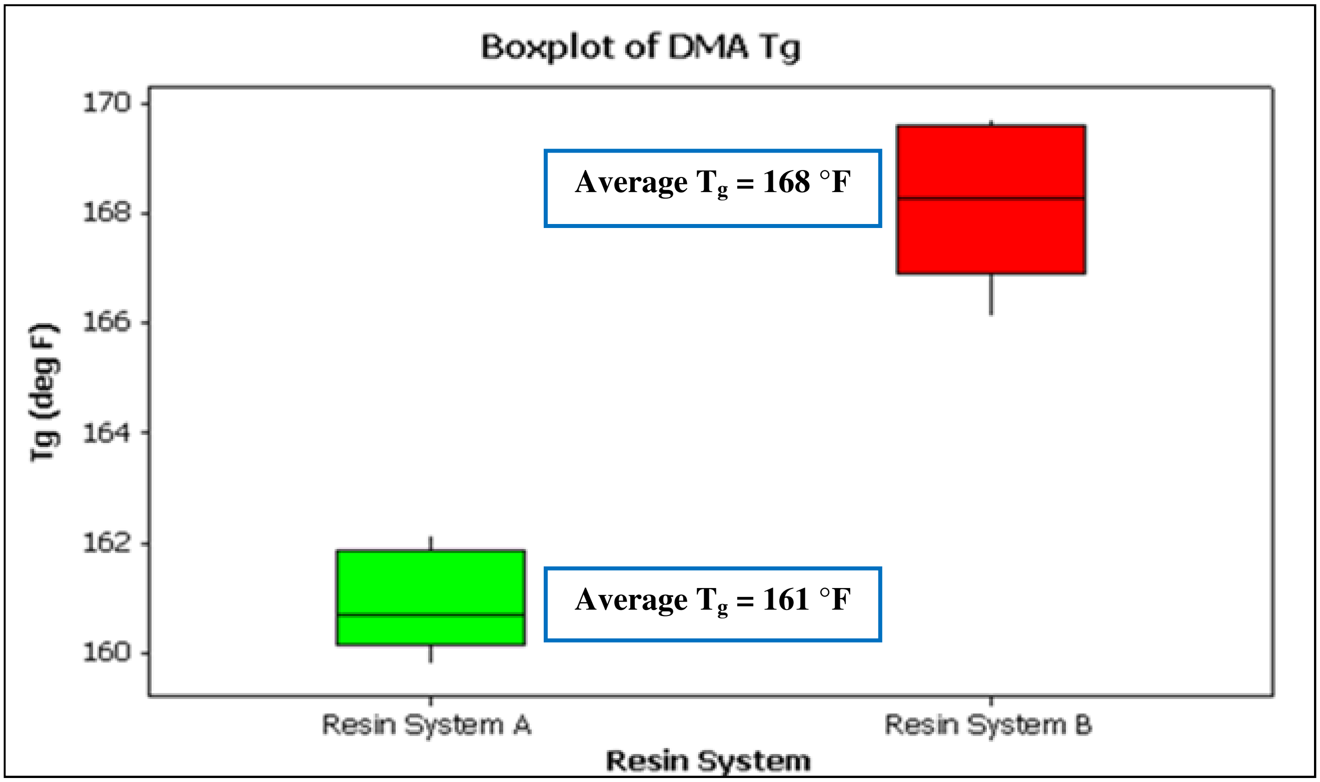
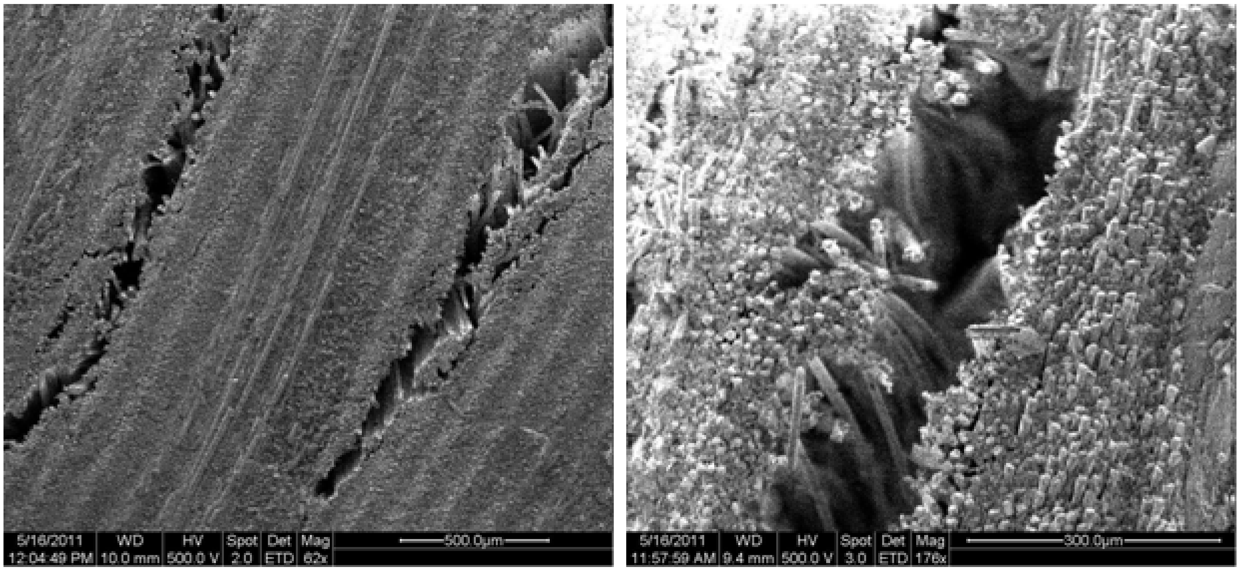


Figure 26 - Box plot of the DMA data for both of Aptera's resin systems. Resin system B has the higher glass transition temperature with an average of 168°F.

4.4 Scanning Electron Microscopy

A scanning electron microscope was used to confirm the failure modes in the SBS and tensile test specimens. Figure 27 shows the SEM images of a fractured SBS test specimen at low and high magnification. The interlaminar shear mode is present in the image. Figure 28 shows the SEM images of a fractured tensile test specimen at low and high magnification. This tensile specimen had the preferred failure mode (XGM) and was tested at 180°F. The interlaminar shear force, along with weak bonding between plys at the elevated temperature may have released the fibers from the matrix. The poor bonding resulted in a premature failure at elevated temperatures.



(a) (b)

Figure 27 - SEM images of the failure surface on a SBS specimen tested at 180°F. (a) Magnification of 62 X and (b) 178 X. The glass fibers have been pulled away from the matrix suggesting the elevated temperature caused a poor bond between the PMC plys.

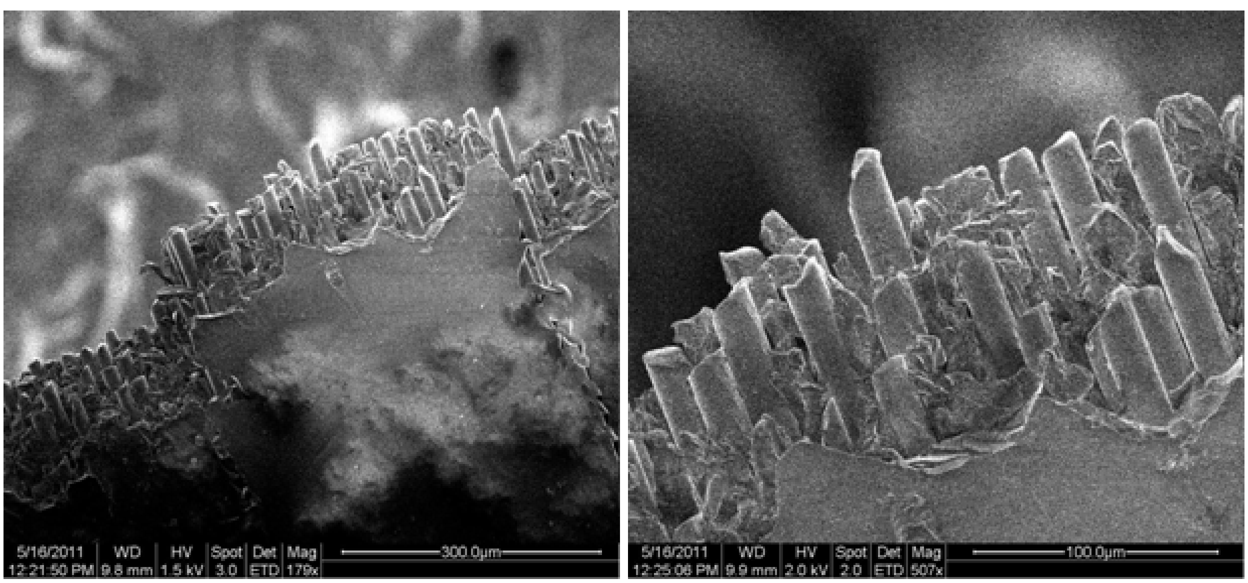


Figure 28 - SEM images of the failure surface on a tensile specimen tested at 180°F. (a) Magnification of 179 X and (b) 507 X. The glass fibers have been pulled away from the matrix suggesting the elevated temperature caused a poor bond between the PMC plys.

CHAPTER FIVE

5. DISCUSSION

An obvious trend in mechanical property degradation is seen as the temperature is increased from 0°F to 180°F. At 180°F, the mechanical properties of both PMC resin systems are significantly less than that at 0°F. Interlaminar failure at both hot and cold temperatures occurred because the bonding between the plys was insufficient. However, an increased amount of delamination was seen in the 180°F samples, which was represented by the whiter appearance. Resin system B also has the higher glass transition temperature of 168°F, compared to resin system A, which has a T_g 161°F. Both resin systems meet Aptera's standards. The vehicle will not be driven in temperatures anywhere near the point that the mechanical properties degrade in Aptera's composites. Therefore, Aptera is now confident that they have dual-suppliers for one of the most important constituent materials of the composite 2e.

CHAPTER SIX

6. CONCLUSIONS

1. Temperature extremes have been shown to have a significant effect on the tensile and short beam shear strength of Aptera's polymer matrix composites.

2. At 180°F, Resin System B has a greater SBS and Tensile Strength.

3. Both Resin Systems experienced interlaminar failure at both hot and cold temperatures because the bonding between the layers was insufficient.

4. Mechanical property degradation begins at 168°F for Resin System B and 161°F Resin System A.

5. Both Resin Systems are suitable for Aptera's vehicle. Therefore, Aptera is now confident that they have dual-suppliers for one of the most important constituent materials of the composite 2e.

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